Evaluating Maintenance Requirements and Water Quality Benefits of Alternative Linings in Roadside Swales

NCDOT Project 2021-02
FHWA/NC/2021-02
March 2024

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1. Report No. FHWA/NC/2021-02	2. Government Accession No. *…leave blank…*	3. Recipient's Catalog No. *…leave blank…*
4. Title and Subtitle Evaluating Maintenance Requirements and Water Quality Benefits of Alternative Linings in Roadside Swales		5. Report Date March 20, 2024 6. Performing Organization Code *…leave blank…*
7. Author(s) William F. Hunt, III, PhD, PE et al. Emily Leupp Pettruny, MS Amber Ellis, MS, EI		8. Performing Organization Report No. *…leave blank…*
9. Performing Organization Name and Address NC State University Biological and Agricultural Engineering Department 3110 Faucette Drive Raleigh, North Carolina 27695		10. Work Unit No. (TRAIS) *…leave blank…* 11. Contract or Grant No. *…leave blank…*
12. Sponsoring Agency Name and Address North Carolina Department of Transportation Research and Analysis Group 1 South Wilmington Street Raleigh, North Carolina 27601		13. Type of Report and Period Covered Final Report 01/01/2021 – 03-31/2023 14. Sponsoring Agency Code *2021-02*
Supplementary Notes: *…leave blank…*		

16. Abstract

Maintenance of linear rights-of-way is a major concern of Departments of Transportation (DOTs). Swales are a stormwater control measure (SCM) placed in the roadway right-of-way that remove pollutants and safely convey stormwater. A common SCM, swales often erode from concentrated water flow and sparse vegetation cover (NCDEQ, 2017a). A potential means for limiting swale erosion is to replace the typical turf grass with an alternative lining, such as riprap or native grasses. This research examined the impacts of maintaining eroding swales with riprap and native grasses by comparing pollutant concentrations and loads from turf-lined conventional swales and bioswales that have been replaced with a riprap or a native grass lining.

A total of eight swales (four conventional and four bioswales) located at North Carolina State University's Sediment and Erosion Control Research and Education Facility (SECREF) were utilized for this research. Swale parameters tested included swales lined with riprap vs deep-rooted, native grasses, a slope of 1% vs 4%, and conventional swale vs bioswale. Each swale was tested with a medium and large storm event (i.e., 0.75 and a 1.5 inch events, respectively) to examine the water quality effects. During the simulated storm events using synthetic runoff, flow volumes and discharges were measured, and water quality samples were collected for total suspended solids (TSS), total Kjeldahl nitrogen (TKN), ammoniacal nitrogen (NH_3), nitrate/nitrite nitrogen (NO_x), total nitrogen (TN), total phosphorus (TP), ortho-phosphate (OP), and a series of dissolved metals (Cd, Cu, Pb, and Zn). Class B riprap and a 50/50 combination of River Oats (*Chasmanthium latifolium*) and Big Bluestem (*Andropogon gerardii*) was chosen as the alternative linings for this study.

All four conventional swales had significantly and substantially higher volume reduction than those in literature and crediting documents (Davis et al., 2012; NCDEQ, 2017). Both native grass and riprap-lined conventional swales on the 1% slope significantly reduced TSS concentrations. Native grass-lined conventional swales tended to reduce nutrient and dissolved metal concentrations more so than those lined with riprap. Both native grass and riprap-lined conventional swales had generally high nutrient and dissolved metal load reduction. Turf-lined swales tended to have better dissolved metal concentration reductions than those lined with native grasses and riprap. Each of the riprap and native grass-lined swales had substantially more volume reduction than the turf-lined swales. Mean Manning's roughness coefficients for native grass-lined swales for low and high flow conditions were 0.187 and 0.078, respectively. Alternative liners herein are a competitive option over turf because of their simple maintenance procedures.

Results indicate that riprap-lined bioswales significantly reduced volumes more than native grass-lined bioswales. Bioswales herein had volume reductions within range, and slightly lower than those noted by other researchers (Poresky et al., 2011; Osouli et al., 2017).

Peak flow reduction results for all four bioswales are consistent with literature (Ainan et al., 2003; Wu et al., 1998). Native grass-lined bioswales significantly reduced TSS concentrations in the underdrain of the 1% slope as well as the overflow and underdrain of the 4% slope. Native grass-lined bioswales tended to reduce sediment and nutrient concentrations in the overflow and underdrain more so than those lined with riprap.

This research provides evidence for the use of native grasses and riprap as alternative linings, especially using native grasses in conventional swales. However, continued research on conventional and bioswales under further design parameters (such as a wider range of slopes, various swale lengths, "real" rainfall/runoff, and the implementation of an IWS zone in bioswales) is necessary to more fully understand the impacts of alternative liners herein.

17. Key Words	18. Distribution Statement
Drainage Structure, Swale, Bioswale, Bioinfiltration swale, Native plants, Grass, Riprap, Protective works	*…leave blank…*

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	63	*…leave blank…*

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ACKNOWLEDGMENTS

The authors would like to acknowledge Dr. Rich McLaughlin, Jamie Luther, Shawn Kennedy, Chris Niewoehner, and Marty Parish, for their technical expertise and guidance. A special thanks to Sujit Ekka and Dr. Rebecca Purvis, whose swale research laid the foundations for this project. Thanks to the Center for Applied Aquatic Ecology Water Resources Lab at NCSU and to Hoffman Nursery for supporting our efforts. Lastly, many thanks to the North Carolina Department of Transportation for the opportunity to conduct this research.

EXECUTIVE SUMMARY

Eight swales (four conventional and four bioswales) located at North Carolina State University's Sediment and Erosion Control Research and Education Facility (SECREF) were utilized for this research. Parameters tested included swales lined with riprap vs deep-rooted, native grasses, a longitudinal slope of 1% vs 4%, medium and large storm event (0.75 and a 1.5 inch events, respectively) and conventional swale vs bioswale. During simulated storm events using synthetic runoff, flow volumes and discharges were measured, and water quality samples were collected for total suspended solids (TSS), total Kjeldahl nitrogen (TKN), ammoniacal nitrogen (NH_3), nitrate/nitrite nitrogen (NO_x), total nitrogen (TN), total phosphorus (TP), ortho-phosphate (OP), and a series of dissolved metals (Cd, Cu, Pb, and Zn). Class B riprap and a 50/50 combination of River Oats (*Chasmanthium latifolium*) and Big Bluestem (*Andropogon gerardii*) was chosen as the alternative linings for this study.

All four conventional swales had significantly and substantially higher volume reduction than those in literature and crediting documents. Both native grass and riprap-lined conventional swales on the 1% slope significantly reduced TSS concentrations. Native grass-lined conventional swales tended to reduce nutrient and dissolved metal concentrations more so than those lined with riprap. Both native grass and riprap-lined conventional swales had generally high nutrient and dissolved metal load reduction. Turf-lined swales tended to have better dissolved metal concentration reductions than those lined with native grasses and riprap. Each of the riprap and native grass-lined swales had substantially more volume reduction than the turf-lined swales. Mean Manning's roughness coefficients for native grass-lined swales for low and high flow conditions were 0.187 and 0.078, respectively. Alternative liners herein are a competitive option over turf because of their simple maintenance procedures.

Results indicate that riprap-lined bioswales significantly reduced volumes more than native grass-lined bioswales. Bioswales herein had volume reductions within range, and slightly lower than those noted by other researchers. Peak flow reduction results for all four bioswales are consistent with literature. Native grass-lined bioswales significantly reduced TSS concentrations in the underdrain of the 1% slope as well as the overflow and underdrain of the

4% slope. Native grass-lined bioswales tended to reduce sediment and nutrient concentrations in the overflow and underdrain more so than those lined with riprap.

This research provides evidence for the use of native grasses and riprap as alternative linings, especially using native grasses in conventional swales. However, continued research on conventional and bioswales under further design parameters (such as a wider range of slopes, various swale lengths, “real” rainfall/runoff, and the implementation of an IWS zone in bioswales) is necessary to more fully understand the impacts of alternative liners herein.

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INTRODUCTION

Maintenance of linear rights-of-way is a major concern of Departments of Transportation (DOTs). Swales are a stormwater control measure (SCM) placed in the roadway right-of-way that remove pollutants and safely convey stormwater. A common SCM, swales often erode from concentrated water flow and sparse vegetation cover (NCDEQ, 2017a). A potential means for limiting swale erosion is to replace the typical turf grass with an alternative lining, such as riprap or native grasses. This research examined the impacts of maintaining eroding swales with riprap and native grasses by comparing pollutant concentrations and loads from turf-lined conventional swales and bioswales that have been replaced with a riprap or a native grass lining.

The overall goals of this research were to:

- Observe how the linings affect the pollutant concentrations and loads.
- Compare hydrologic performance of swales with the alternative linings.
- Determine a Manning's roughness coefficient for the native grass-lined swales.

These will be done by testing the following hypotheses:

- Native grass-lined conventional swales significantly ($p < 0.05$) reduce pollutant loads and concentrations of TSS, TKN, NH_3, NO_x, TN, TP, OP, Cd, Cu, Pb, and Zn at higher rates than riprap-lined conventional swales (Chapter 2)

- Native grass-lined bioswales significantly ($p < 0.05$) reduce pollutant loads and concentrations of TSS, TKN, NH_3, NO_x, TN, TP, OP, Cd, Cu, Pb, and Zn at higher rates than riprap-lined bioswales (Chapter 3)

- Native grasses will have a higher Manning's roughness coefficient than standards used for turf grass (Chapter 4)

To test these hypotheses, the following objectives will be completed:

- Determine peak flow reduction and volume mitigation provided by conventional and bioswales with riprap and native grass linings.

- Determine the pollutant removal rates in conventional and bioswales with riprap and native grass linings for the following pollutants: TSS, TKN, NH_3, NO_x, TN, TP, OP, Cd, Cu, Pb, and Zn.

- Determine the Manning's roughness coefficient of native grass in conventional swales.

RESULTS OF LITERATURE REVIEW

While turf grass-lined swale is most common, the use of an alternative lining may be a viable option if they are stable hydraulically and improve water quality while reducing maintenance requirements. Successful alternative linings will decrease the likelihood of swale erosion. It is common for flow to create “shortcuts” resulting in erosion, scouring, and channelization (Li, 2015). Narrow swales with higher longitudinal slopes are at greater risk (Li, 2015). The use of a riprap or native grass lining may provide more stability in swales that are at increased risk of erosion.

Riprap Lining

Riprap are large stones used to stabilize and protect a soil surface against erosion. Swales on steeper slopes will be less likely to erode when lined with riprap rather than turf (Minnesota Pollution Control Agency, 2022; Massachusetts Department of Environmental Protection, 2003). Rice et al. (1998) conducted a study to determine the Manning’s roughness coefficients of riprap laid on steep slopes. Trials were administered in a flume with the D_{50} of riprap ranging from 52 to 278 mm and bed slopes, S_0, ranging from 0.028 to 0.333 m/m. The Darcy-Weisbach and Manning roughness coefficients were determined. Results indicated channel roughness would increase concomitantly with bed slope or riprap size (Rice et al., 1998).

Swales constructed along roadways that require a steeper bed slope, and prone to experience persistent erosion, may benefit from a riprap lining because of the protection it provides the underlying soil. Riprap prevents erosion by dissipating high-energy stormwater flows (Minnesota Pollution Control Agency, 2023). Decreasing runoff flow rate allows for: 1) lower shear stress, 2) a longer HRT and, 3) thus, higher rates of pollutant removal.

Native Grass Lining

Native grasses offer an alternative lining to turf grass in a roadside swale. NCDEQ (2017a) states the turf lining in swales should be maintained at an average of 0.15 m (6 in). Many turf grasses will not remain sufficiently rigid in the face of flow, especially as they grow taller (Mugaas et al., 2005). This leads to minimal flow retardance, concomitantly limiting pollutant removal (Ekka et al., 2021). However, certain deep-rooted native grass species can grow taller than 0.9 m (3 ft) while maintaining their rigidity. Maintaining native grasses is cheaper than turf grass: lower labor, water, fertilizer, herbicides, insecticides, fungicides, and moving costs (U.S. EPA, 2016). Native grasses provide other benefits including reduced soil erosion, improved water quality, reduced air and noise pollution, reduced greenhouse effect, habitat restoration and protection, and beautification (U.S. EPA, 2016). Future research could establish native grasses as a viable option for the lining of swales, assuming they provide similar (or better) water quality benefits to turf grass.

It is important to consider hydraulic properties such as flow retardance and erosion control when considering an alternative lining, such as native grasses. The maximum permissible velocity is that which a lining can withstand before erosion occurs (Gwinn and Ree, 1980). Gwinn and Ree (1980) studied flow through various states of cover in vegetative-lined channels, including native grasses that were uncut or mowed to determine scour rates and maintenance effects. Gwinn and Ree (1980) reported that uncut native grasses had similar average velocities to native grasses cut to a height of 0.1 m (3.6 in). The maximum permissible velocity for cut grass at 3% slope was 1.5 m/s (5 ft/s). At this velocity, all native grass cover protected the channel with limited scouring. The maximum permissible velocity at 6% slope was 1.1 m/s (3.6 ft/s). Again, all uncut and cut grasses in the 6% sloped channels protected the channel with limited scouring. This study provides evidence that taller grasses protect against erosion.

Maintenance Considerations

Grass swales are popular for their simple design and inexpensive construction cost. The current maintenance regime for grass swales includes mowing and routine inspection. Other maintenance needs are clearing inlets, outlets, and check dams of any accumulated trash, debris, and silt (Sañudo-Fontaneda et al., 2020). When swales are insufficiently maintained, they can lose capacity for runoff conveyance and water quality treatment. For example, flow retardance may be minimized if the grass lining does not remain sufficiently rigid as a result of being left un-mowed. Circumstances, such as COVID-19, where maintenance labor is limited, budgets are reduced, and uncontrolled vegetation growth and silt accumulation impact the performance should be considered during the design of a swale (Sañudo-Fontaneda et al., 2020).

Swale maintenance currently involves periodic mowing which is a part of normal right-of-way mowing operations. Maintenance challenges arise when swales are sited outside of normal mowing patterns. Such swales may be overgrown with non-grass vegetation or become shaded from overhead canopy, thereby potentially limiting grass coverage (Hunt et al., 2015; Mazer et al., 2001) This can lead to erosion within the swale (Minnesota Pollution Control Agency, 2023). The implementation of riprap or native grasses as an alternative lining to swales would decrease maintenance labor and costs considerably by way of reducing mowing frequency. Riprap and native grasses may also be more resistant to erosion than turf-lined swales.

1. Materials and Methods

1.1 Field Survey and Design

Topographic survey data were previously collected by Ekka and Hunt (2020a) to develop construction documents for each swale. Construction of SECREF bioswales is described by Purvis (2018). Multiple runoff simulations were conducted on each swale rather than building replicates of each design. A preliminary layout was created and approved by the SECREF personnel and the North Carolina Department of Transportation (NCDOT. Original design for the swales included varying lengths (10 m vs 30 m) and channel shapes (trapezoidal vs triangular). Details of original swale construction are included in Appendix B. Only swales with a length of 10 m were used for this project. Additionally, two of the existing triangular cross-sectional swales were converted to a trapezoidal cross-section by SECREF personnel. Table 2-1 provides a summary of the design configuration for the current project. Design drawings including site layout, swale design and profiles, and construction details for conventional swales (Ekka and Hunt, 2020a) and bioswales (Purvis, 2018) are provided in Appendix A.

Table 2-1: List of parameters to be tested at SECREF. Note that every test was run in triplicate. All tests were with a trapezoidal cross-section and 10-m channel length.

Swale ID	Swale Type	Lining Type	Slope	Storm Sizes*	Manning's Test?
CR1	Conventional	Riprap	1%	2	N
CG1	Conventional	Native Grasses	1%	2	Y
BR1	Bioswale	Riprap	1%	2	N
BG1	Bioswale	Native Grasses	1%	2	N
CR4	Conventional	Riprap	4%	2	N
CG4	Conventional	Native Grasses	4%	2	Y
BR4	Bioswale	Riprap	4%	2	N
BG4	Bioswale	Native Grasses	4%	2	N

*Storm sizes were medium (19 mm or 0.75 in) and large (36 mm or 1.4 in)

1.2 Site Description

1.2.a Current Swale Construction

Two of the four conventional swales needed for this project had been previously altered to a triangular cross-section to fit the parameters of a separate study. Prior to the installation of alternative liners for this project, the cross-sections of the triangular swales were adjusted to create trapezoidal cross-sections. In May of 2021, SECREF staff, under the direction of project personnel, used an excavator to widen the base of the swale, in accordance with minimum design criteria listed in the North Carolina Department of Environmental Quality (NCDEQ) Stormwater Design Manual (NCDEQ, 2020).

1.2.b Alternative Lining Installation and Maintenance

To study the impact of alternative linings, the existing sod was replaced with either a Class B riprap or a deep-rooted grass (Figure 1-1). Riprap was hand-placed in each of the swales to ensure full coverage of the swales' wetted perimeter. A fabric geotextile lining was installed prior to the riprap to prevent the migration of fine soil particles through voids in the riprap, to permit relief of hydrostatic pressures within the soils, and to distribute the weight of the riprap to provide more uniform settlement (FHWA, 1989). The geotextile was installed according to NCDOT's geotextile under riprap requirements (NCDOT, 2018a). The vegetated lining was a 50/50 blend of two grasses, Big Bluestem (*Andropogon*

Gerardii) and River Oats (*Chasmanthium Latifolium*). Big Bluestem and River Oats are both native to the entire state of North Carolina and per NCDEQ (2020) are deep-rooted grasses. The grasses were provided by Hoffman Nursery of Rougemont, NC.

Figure 1-1: Riprap (left) and native grass (right) lined swales.

Weeds began to grow on the perimeter of the riprap swales. To avoid any effect the vegetation may have on the water quality treatment of riprap, an herbicide was considered. Herbicides are a standard NCDOT procedure for weed management (NCDOT, 2023). In April 2022, during the data collection phase of this study, herbicide was applied around the perimeter of the four riprap-lined swales. The dead weeds were manually pulled one week post-application, and an additional week was allowed before conducting experiments to avoid any effects the herbicide could have on the water quality samples (Mirzaei et al., 2023).

1.3 Plot Experiments

Experiments were conducted and data were collected when average daily temperature exceeded 50°F. Testing occurred over two periods: September - October 2021 and March - September 2022. Experimental procedures included general weekly preparation, sampler set up, sampling, nutrient collection, clean up, sample transportation, and metal filtration. A detailed list of materials and procedures necessary to conduct field experiments are provided in Appendix B.

1.3.a Hydrology

Experiments were conducted after a minimum 24-hour antecedent dry period (ADP) to avoid impacting infiltration rates in the swales. Flow data were recorded by the ISCO 6712 sampler and ISCO 730 bubble module at the inlet and outlet of the swale. A 30° V-notch weir was installed in the inlet monitoring structure and a 60° V-notch weir installed in each of the eight outlet structures to measure flow. Weir equations (Eq D-1, D-2) were used to convert stage to flow rate, described by Grant and Dawson (2001).

Design flow volumes to generate runoff simulations representative of a typical highway environment were calculated for a typical DOT drainage area. NCDOT's (2014) Design Criteria Summary for swales states that "swale length of 100 feet per contributing acre of drainage area is recommended." The swales examined herein each had a length of 10 m (33 ft), and two center-weighted storm events from an equivalent 0.13 ha (0.31-acre) watershed were routed to them. A "medium" (19 mm or 0.75 in) and a "large" storm (36 mm or 1.4 in) were devised. These storm depths for the medium and large storms had intended volumes of 23,300 L (821 cf) and 43,970 L (1553 cf), respectively. Volumes were calculated by multiplying the watershed area by the storm depth.

Synthetic hydrographs, modeled in a stepwise function, were necessary to simulate storm events. Time step increments used by Ekka and Hunt (2020a) were utilized herein. This was accomplished by adjusting (turning) a valve to regulate flow. For medium storms the valve controlling the flow of pond water was turned every 10 minutes, for large storms, time steps were 20 minutes. The valve was turned in a manner to create a center-weighted hydrograph (Ramírez, 2000), so as to have the most intense portion of the storm in the middle of the event. The highest flow rate occurred during the fourth of seven time steps (Figure D-1). Water was sourced from a pond connected to the swales through an underground pipe network. Efforts were made to have the pond filled to the same starting level, before trials began. Slight variations in the flow rates did occur at each turn of the valve and required further in-field adjustments. A conceptual schematic of the swale experimental setup is shown in Appendix D (Figure D-2). Hydrologic performance was quantified using volume reduction and peak flow rate reduction (Equations D-3 and D-4).

1.3.b Water Quality Sampling

Pollutant Preparation

Onsite soil was mixed with flow to introduce pollutants. The sediment was dried at 105 ℃ for 24 hours in a Thelco Model 17 (Precision Scientific) oven. The sediment was ground with a mortar and pestle to break any aggregates. Two sieves, ASTM #'s 10 and 35, ensured sediment particles smaller than 500 μm in diameter (Figure D-3).

The dosage of pollutants was determined by the typical highway concentrations and runoff volumes from the hypothetical drainage area to represent pollutant concentrations observed in North Carolina. NCDOT developed median event mean concentrations (EMCs) for roadway environments. Pollutants evaluated herein included total suspended solids (TSS), total kjeldahl nitrogen (TKN), total nitrogen (TN), ammoniacal nitrogen (NH_3), nitrate/nitrite nitrogen (NO_x), ortho-phosphate (OP), total phosphorus (TP), dissolved Cd, dissolved Cu, dissolved Pb, and dissolved Zn. The dried and sieved sediment was weighed for each time step and combined with the remaining pollutant dosage (Tables D-1 and D-2).

The EMCs were determined to be as follows: median TSS of 28 mg/L, TN of 1.39 mg/L, and median TP of 0.19 mg/L for primary roadways (Ekka and Hunt, 2020a). The median concentrations for dissolved metals were as follows: 0.1 µg/L (Cd), 10.95 µg/L (Cu), 2.57 µg/L (Pb), and 69.2 µg/L (Zn) (Ekka and Hunt, 2020a). These values fall within ranges observed in literature (Wu et al., 1998; Winston and Hunt, 2017; Han et al., 2006; Kayhanian et al., 2007).

Data Collection

Prepared spiked samples were brought to SECREF in plastic bags (Figure D-4). A 50-gallon tank with an attached mixer (Figure 1-2) was filled with pond water and spiked with known concentrations of synthetic pollutants. The solution was discharged from the tank into the inlet box (Figure 1-3).

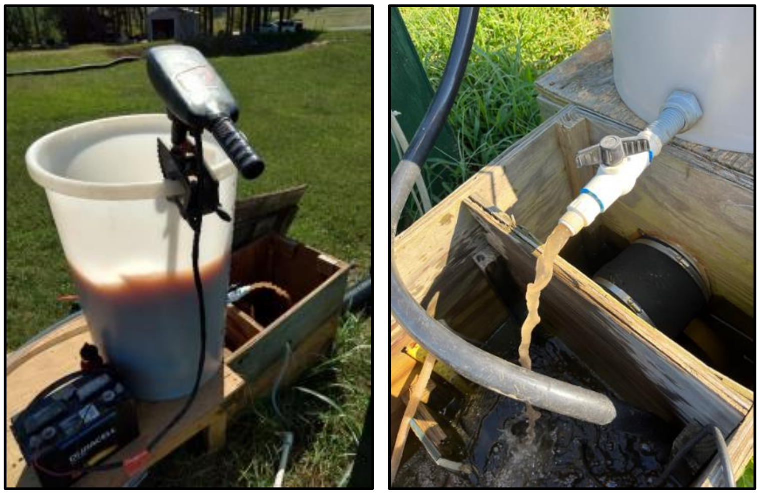

Figure 1-3: 50-gallon tank to simulate synthetic runoff (left). Spiked pond water discharging from tank into inlet box (right).

An ISCO 6712 portable sampler with attached ISCO 730 bubbler flowmeter collected flow-paced composite samples at the inlet and outlet of each swale. Flow pacing was set to collect samples after 18 cf of flow at the inlet and 15 cf at the outlet for medium storm events. For large storm events, these numbers increased to 28 cf and 25 cf, respectively. The concentration of outflow composite samples represents EMCs. The inflow composite samples are considered surrogate EMCs as the inflow sampler flow measurements were initially incorrect at high flow rates (see section Appendix C). After each experiment, the composite samples were transferred to labeled bottles provided by the lab performing analyses and stored on ice or in a refrigerator. Samples were delivered to the lab within 24 hrs (Figure D-5).

Data Analysis

The sediment and nutrient samples were analyzed at the NCSU Center for Applied Aquatic Ecology (CAAE) Laboratory, and dissolved metal samples were analyzed by the NCDEQ Water Sciences Laboratory using the standard methods (APHA, 2012) (Table D-3). Water quality treatment was quantified using removal efficiency (RE) and load reduction (Equations D-5 through D-7) for all pollutants.

1.3.c Riprap Combined with Native Grass Consideration

While not an initial consideration for this study, the blending of riprap and native grasses as an alternative lining became of interest when one of the riprap-lined bioswales, BR1, became overgrown with native grasses (Figure D-6). Starting 25-AUG-2022, one month after all other experiments were completed, three more large storms were simulated to test the effect that riprap blended with native grasses had on swale hydrology and water quality treatment.

1.4 Soil Characterization

1.4.a Bulk Density

Bulk density samples were collected, with the assistance of Department of Crop and Soil Science personnel, in February 2022. The direct measurement method was used to collect the bulk density samples (ASTM Standard D7263-21, 2021). Six samples were collected from each of the eight swales, for a total of 48 bulk density samples. Two samples, a surface and a subsurface, were collected from each of the swales' inlets (A), centers (B), and outlets (C) (Figure D-7). Surface samples were collected from the top 0.08 m (3 in) of the soil and subsurface samples were collected from the successively deeper 0.08 m (3 in). Soil samples were returned to the Crop and Soil Science laboratory, dried at 105 °C, and weighed. Bulk density was calculated (Equation D-8). Results are given in Appendix B (Tables D-4, D-5).

1.4.b Particle Size Distribution

A particle size distribution (PSD) analysis was conducted for on-site soil used to spike the influent (ASTM D7928-21e1, 2021) (Figure D-8). The soil was found to have 64% sand, 24% silt, and 12% clay, characterizing it as a sandy loam.

1.5 Manning's Roughness Coefficient

Determination of the Manning's roughness coefficient, "n," in the native grass-lined swales will impact future design recommendations. Manning's equations in Imperial and metric units are listed as equations D-9 and D-10, respectively.

Flow data were collected in October 2022. Data were collected from two native grass, conventional swales. Two flow level experiments, low and high, were conducted and replicated. Flags were placed at 0.9, 3.7, 6.4, and 9 m (3, 12, 21, and 30 ft) along the longitudinal length of the swale to indicate where the water depth and wetted perimeter measurements were to be taken. For each experiment a steady flow and level was achieved before more flags were placed at the edge of the water surface (Figure D-9). These additional flags indicated the wetted perimeter of the swale and allowed for cross-sectional flow area to be calculated.

Survey points of each flag were taken with a Sokkia SET530R prism less surveying total station and Carlson Explorer data collector. Area and wetted perimeter were obtained from the created AutoCAD surfaces (Figure D-10) and used, along with slope and flow rate, to determine the adjusted "n" values for each swale.

1.6 Statistical Analysis

Statistical analysis was conducted to determine if any design parameters influenced hydrology or water quality treatment. To investigate statistical significance, all data were imported into SAS® Studio software (Copyright © 2012-2020, Version 3.81, SAS Institute Inc., Cary, NC). Example SAS Studio Software code is included in Appendix D.

The significance of each swale parameter's (i.e. lining, slope, and storm size) on removal efficiency (RE), volume reduction, load reduction, and peak flow reduction rates were tested with a two-tailed t-test (H_0: RE = 0; H_a: RE $\neq$ 0). Data were visually inspected for extreme divergences from normality, but no formal tests were conducted as sample sizes (n = 3) were too small to generate necessary power. Required t-test assumptions were considered met, given that, with the exception of cases with extreme skew, two-tailed t-tests are sufficiently robust against type I errors for many non-normal distributions (Lumley et al., 2002; Sawilowsky & Blair, 1992).

Differences in the REs and load reduction for each pollutant, along with volume and peak flow reductions, were each tested using a 3-factor analysis of covariance (ANCOVA). Lining type was a fixed, categorical, independent variable, while RE was the dependent variable. Additional ANCOVA were run with volume reduction, load reduction, and peak flow reduction rates as the dependent variables. The models also included slope and storm size as fixed, categorical, blocking factors that were crossed with lining type for a full 2X2X2 factorial cross. If the ANCOVA displayed an insignificant interaction for storm size, the medium and large storm data were then analyzed together (pooled) in an additional t-test. Each model was fit with lining*slope, lining*storm size, and storm size*slope, as well as a three-way interaction effect for lining*storm size*slope. An alpha value of 0.05 was used for all analyses.

2. Alternative Linings in Conventional Swales

2.1 Hydrologic Performance Results and Discussion

2.1.a Volume Reduction

Most swales herein tested significantly reduced inflow volume (Tables E-1, E-2). Neither lining type, slope, nor storm size had a significant effect on the volume reduction of conventional swales. CR1, CG1, CR4, and CG4 had significant volume reduction during medium storms and CR1, CR4, and CG4 during large storms (Table 2-1). CG1 was on the cusp of significance ($p = 0.0506$) during the large storm. A significant interaction between lining*slope for volume reduction was present in the ANCOVA (Table 2-2). Because the ANCOVA displayed an insignificant interaction for storm size, the medium and large storm data were then analyzed together (pooled). When data were pooled, all swales had significant volume reduction (Table 2-1).

Mean volume reductions observed herein are generally higher than noted by other researchers. Rushton (2001) observed 30% volume reduction in grass swales while Deletic (2001) and Barrett (2005) noted rates of 45.7 and 47%, respectively. While it is possible the swales herein have unexpectedly high rates of infiltration, it should also be considered that, due to limitations in this controlled field study, flow rates were never particularly high. In compliance with current design criteria, the flow rates for this study never overtopped the grass in swales (NCDEQ, 2020).

Table 2-1: Mean volume reduction (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0. Negative values represent greater than that of inflow.

Swale ID	Volume Reduction 70 min.	Volume Reduction 140 min.	Volume Reduction Pooled
CR1	**62.00 ± 24.88**	**77.33 ± 10.21**	**69.67 ± 18.97**
CG1	**63.67 ± 22.59**	54.33 ± 22.01	**59.00 ± 20.59**
CR4	**37.00 ± 4.00**	**58.67 ± 7.23**	**47.83 ± 12.97**
CG4	**74.33 ± 5.13**	**74.67 ± 11.15**	**74.50 ± 7.77**

Table 2-2: Volume reduction ANCOVA results. Bolded values are statistically significant.

Factor	Volume Reduction p-value
Lining	0.2329
Slope	0.6312
Storm Size	0.5285
Lining*Storm Size*Slope	0.9173
Lining*Slope	**0.0018**
Lining*Storm Size	0.1158
Storm Size*Slope	0.6460

Native grass-lined swales had higher volume reduction than riprap-lined swales during both medium and large storms on the 4% slope, and lower in large storms on the 1% slope in the volume reduction interaction plot (Figure E-1). Native grass and riprap had similar volume reductions during medium storms on the 1% slope.

2.1.b Peak Flow Reduction

Swales CG1, CR4, and CG4 had significant peak flow reductions during medium storms and all four swales during large storms (Table 2-3). A significant interaction between lining*slope was present (Table 2-4). All four swales had significant peak flow reductions when storm data were pooled (Table 2-3). Peak flow reduction results for all four swales are higher than that of other studies. Stagge (2006) observed vegetated swale peak flow reductions between 50 - 53%, while Ainan et al. (2003) and Wu et al. (1998) noted reductions of 25.7 - 55.9% and 10 - 20%, respectively. The high rates of volume reduction support peak flow reduction conclusions. The ability of swales to mitigate peak flow is highly dependent on soil infiltration rate (Davis et al., 2009; Finotti et al., 2023). Stagge (2006) reported mean volume reductions of 45.7 and 53.7% in two swales with length of 198 and 152.2 m (650 and 500 ft), respectively. Similarly, Ainan et al. (2003) observed volume reductions of 24.1 and 19.4% from rainfall intensities of 13.8 and 33.6 mm/hr, respectively. Their lower volume reductions than herein are likely the reason for lower peak flow reductions. Other factors such as soil characteristics (Davis et al., 2012), channel roughness, grass height and density (Bäckström, 2002; Deletic and Fletcher, 2006), and compaction of swale bed during construction (Gregory et al., 2006; Pitt et al., 2008) may contribute to higher peak flow reductions herein than observed in literature.

Table 2-3: Mean peak flow reduction (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0.

Swale ID	Peak Flow Reduction 70 min.	Peak Flow Reduction 140 min.	Peak Flow Reduction Pooled
CR1	63.33 ± 33.33	**72.33 ± 9.02**	**67.83 ± 22.33**
CG1	**71.67 ± 14.47**	**63.33 ± 15.95**	**67.50 ± 14.36**
CR4	**52.33 ± 9.07**	**69.00 ± 5.20**	**60.67 ± 11.27**
CG4	**79.00 ± 1.73**	**75.33 ± 10.69**	**77.17 ± 7.14**

Table 2-4: Peak flow reduction ANCOVA results. Bolded values are statistically significant.

Factor	Peak Flow Reduction p-value
Lining	0.4743
Slope	0.4597
Storm Size	0.7981
Lining*Storm Size*Slope	0.1737
Lining*Slope	**0.0082**
Lining*Storm Size	0.3151
Storm Size*Slope	0.0996

Native grass-lined swales had higher peak flow reductions than riprap swales on the 4% slope during medium and large storms in the lining*slope interaction (Figure E-2). As discussed in Chapter 5, Manning's roughness coefficients (n) of the native grass-lined swales for this study ranged from 0.078 - 0.187 while typical rock-lined channels have n values of approximately 0.04 - 0.05 (Chow, 1959). While significant differences between lining did not occur, it is possible that higher n values for native grass-lined swales on a 4% slope resulted in greater peak flow reductions.

2.2 Water Quality Performance Results and Discussion

Results on pollutant removal are first presented as changes in pollutant concentration and then as changes in pollutant loads. Load discussion draws upon the results in concentrations and those of change in volume and is discussed at length in Appendix G.

2.2.a Concentration Change

Sediment

Swales typically improved TSS concentrations, both in the medium and large storms of CR1 and the large storms of CG1 (Table 32-5). Swales CR4 and CG4 yielded statistically insignificant increased TSS concentrations. An outlier was present in a CR4 experiment so median values for RE were included (Table 2-5). This outlier did not impact the significance of

RE. No crossed interactions between lining type, storm size, and slope were statistically significant (Table 2-6). Storm size had no significant effect on TSS RE, so storm data were pooled and reanalyzed. When storm sizes were pooled, CR1 and CG1 significantly reduced concentrations of TSS (Table 2-5). This result is not surprising as erosion is less likely to occur in shallower slopes, as indicated by higher rates of TSS reduction. Still, there was no visible erosion in the 4% slope swales. It should also be noted that sedimentation is more likely to occur in shallower slopes (Cerdà and García-Fayos, 1997), an even more likely reason for higher TSS RE in 1% slope swales.

Outliers were determined by pooling storm size and observing data points outside the interquartile range (IQR) multiplied by 1.5. One CR4 large storm had an outlier. During this experiment, the outlet sampler had an error and stopped collecting during the experiment's fourth step (see 3/30/2022 notes in Appendix F). It is likely the concentration of the outlet sample was higher because it didn't collect the storm in its entirety. Raw data are listed in Tables E-3 and E-4 in Appendix E.

Table 2-5: Mean ± standard deviation and median TSS RE (%) for each swale and storm size. Bolded values are significantly different from 0. Negative values represent greater than that of inflow.

Swale ID	TSS Mean 70 min.	TSS Median 70 min.	TSS Mean 140 min.	TSS Median 140 min.	TSS Mean Pooled
CR1	**43.97 ± 8.09**	39.57	**41.53 ± 6.62**	44.21	**42.75 ± 6.74**
CG1	55.53 ± 30.20	66.44	**61.03 ± 23.66**	72.82	**58.28 ± 24.45**
CR4	15.13 ± 41.46	-0.31	-89.53 ± 208.20*	25.73	-37.20 ± 146.0*
CG4	-32.50 ± 61.19	-14.38	7.73 ± 70.06	33.70	-12.38 ± 62.82

Note: Swale IDs are represented as C (conventional swale), R/G (riprap or native grass, and 1/4 (1 or 4% slope) *Contains an outlier

Table 3-6: TSS concentration reduction ANCOVA results. Bolded values are statistically significant.

Factor	TSS p-value
Lining	0.5908
Slope	0.0823
Storm Size	0.8448
Lining*Storm Size*Slope	0.4158
Lining*Slope	0.5851
Lining*Storm Size	0.4099
Storm Size*Slope	0.6847

Nutrients

TKN

No swale had significant TKN reductions, nor were there any significant interactions (Tables 2-7 and 2-8). Pooled storm data revealed a significant export of TKN in swale CR1 (Table 2-7). TKN is comprised of organic and ammonia forms of nitrogen. The export of TKN is possible when forms of nitrogen, such as ammonia, is available in the soil having not been taken up by plants. Although not significant, native grasses tended to export less TKN than riprap (Table 2-7). Riprap appeared more likely to have higher exports of TKN because it is lacking plant roots that nitrogen fix to (Mylona et al., 1995). The export of NH_3 (ammonia) accounts for TKN export. Decomposition of organic matter may result in NH_3 and, thus, TKN exports (ACS, 2021). External organic nitrogen inputs, independent of the controlled influent concentrations, could also result in TKN exports.

Table 2-7: TKN RE (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0. Negative values represent greater than that of inflow.

Swale ID	TKN 70 min.	TKN 140 min.	TKN Pooled
CR1	-7.27 ± 9.15	-13.33 ±7.82	**-10.30 ± 8.31**
CG1	-8.27 ± 9.85	-1.67 ± 4.79	-4.97 ± 7.82

CR4	-16.43 ± 18.80	-33.77 ± 49.99	-25.10 ± 35.09
CG4	-13.37 ± 19.08	1.07 ± 16.90	-6.10 ± 17.93

Table 2-8: TKN concentration reduction ANCOVA results. Bolded values are statistically significant.

Factor	**TKN p-value**
Lining	0.1921
Slope	0.3844
Storm Size	0.9883
Lining*Storm Size*Slope	0.5755
Lining*Slope	0.5159
Lining*Storm Size	0.2622
Storm Size*Slope	0.8441

NH_3

The swales tended to release ammonia (NH_3), but not significantly. CR1 did significantly export NH_3 during the large storm event (Table 2-9). No significant interactions existed in the ANCOVA (Table 2-10). Swales CR1, CR4, and CG4 significantly exported NH_3 when data were pooled (Table 2-9). NH_3 is produced from the decomposition of organic matter (ACS, 2021) and is primarily removed through the process of nitrification. Bacteria in the soil will consume atmospheric nitrogen and convert it to NH_3, which is available for plant uptake. When bacteria are not present and plant uptake does not occur, NH_3 is exported. The sum of NH_3 and organic nitrogen is total kjeldahl nitrogen (TKN). TKN is exported because of the export of NH_3. Organic nitrogen was likely not exported and did not contribute to the export of TKN. Although lining was not a significant factor, native grass-lined swales appeared to export less NH_3.

NH_3 in gaseous form is present when soil pH is above 7 and may be conveyed to the atmosphere by nonbiological volatilization (Lance, 1972). NH_3 removal in swales by nonbiological volatilization is unlikely as it is more dependent on nitrification/denitrification. Still, because ammonia has a strong affinity for water, its reactions in water will affect the rate of volatilization (Freney et al., 1983). Volatilization of ammonia is likely to occur in moist, warm soils (Killpack and Buchholz, 2022), similar to the conditions necessary for denitrification. It is likely the lack of ammonia volatilization only furthered its export.

Table 2-9: NH_3 RE (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0. Negative values represent greater than that of inflow.

Swale ID	NH_3 70 min.	NH_3 140 min.	NH_3 Pooled
CR1	-67.40 ± 89.38	**-72.47 ± 8.28**	**-69.93 ± 56.84**
CG1	-3.93 ± 14.93	-67.30 ± 60.63	-35.62 ± 52.58
CR4	-58.60 ± 30.83	-42.70 ± 53.09	**-50.65 ± 39.80**
CG4	-32.13 ± 17.75	-15.80 ± 25.93	**-23.97 ± 21.80**

Table 2-10: NH_3 concentration reduction ANCOVA results. Bolded values are statistically significant.

Factor	NH_3 p-value
Lining	0.1589
Slope	0.4057
Storm Size	0.7050
Lining*Storm Size*Slope	0.5069
Lining*Slope	0.7988
Lining*Storm Size	0.4324
Storm Size*Slope	0.2016

NO_x

Lining type impacted NO_x treatment. NO_x was significantly exported during large storms from CR1 and CR4 (Table 2-11). There were significant differences in RE between lining and storm size (Table 2-12). Because storm size was significant, storm data for NO_x were not pooled. NO_x is the combination of nitrite (NO2-) and nitrate (NO3-). NO_x is primarily removed through denitrification, a process that happens in wet soils in which the oxygen (O_2) supply is limited, and bacteria utilize the oxygen in nitrate for respiration (IPNI, 2023). Denitrification permanently removes nitrate from a swale by converting it to N_2 gas (Collins et al., 2010), yet may result in an export of NO_x if nitrate is not fully converted. Runoff's contact time from the inlet to the outlet of the swale may not have been enough to allow for denitrification, possibly causing the export of NO_x. Additionally, because experiments were conducted after an antecedent dry period of at least 24 hours, it is likely the soil in the swale did not provide the necessary anoxic conditions for denitrification to occur. The lack of denitrification probably furthered the export of NO_x.

Table 2-11: NO_x RE (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0. Negative values represent greater than that of inflow.

Swale ID	NO_x 70 min.	NO_x 140 min.
CR1	-28.50 ± 17.57	**-59.13 ± 15.08**
CG1	13.37 ± 7.70	-3.17 ± 12.70
CR4	-12.60 ± 22.13	**-39.13 ± 3.70**
CG4	0.67 ± 1.67	6.80 ± 7.80

Table 2-12: NO_x concentration reduction ANCOVA results. Bolded values are statistically significant.

Factor	NO_x p-value
Lining	**<.0001**
Slope	0.1656
Storm Size	**0.0447**
Lining*Storm Size*Slope	0.4011

Lining*Slope	0.1090
Lining*Storm Size	0.0686
Storm Size*Slope	0.2794

NO_x may also be produced during nitrification, a process that occurs in aerobic conditions. Nitrification, the process in which ammonia is converted to nitrite then nitrate, may be happening as a result of the antecedent dry period. This may be another cause of NO_x export. Soil temperature, moisture content, microbial activity, aeration, and organic matter content influence the export of NO_x (Wilson et al., 2017).

Significant differences were observed between the removal of NO_x in riprap and native grass-lined swales. For both medium and large storms, native-grass lined swales were better for NO_x. Native grasses will aerate the soil more than riprap, due to their plant roots and higher organic matter content (Grable, 1966; Epstein and Kohnke, 1957), and thus may be the reason native grasses have fewer NO_x exports.

TN

Lining type mattered with regard to TN export (Table 2-13). CR1 significantly exported TN during the large storms (Table 2-14) and when data were pooled (Table 2-13). TN concentrations are calculated by the addition of TKN and NO_x concentrations. Because TKN and NO_x were both often exported, it is evident TN would also be exported. As runoff passes through a swale, nitrogen may be removed via three main processes: assimilation (also referred to as N uptake), denitrification, and adsorption (Collins et al., 2010). Assimilation is more likely to occur in native grass-lined swales where plant roots are available for uptake, perhaps this is the reason they exported less TN than riprap-lined swales. Denitrification most commonly occurs in wet soils where the oxygen supply is limited (IPNI, 2023).

The lack of anoxic conditions in both riprap and native grass-lined swales may also reduce the likelihood of TN removal by denitrification.

Table 2-13: TN concentration reduction ANCOVA results. Bolded values are statistically significant.

Factor	TN p-value
Lining	**0.0467**
Slope	0.4771
Storm Size	0.5906
Lining*Storm Size*Slope	0.5548
Lining*Slope	0.6473
Lining*Storm Size	0.1757
Storm Size*Slope	0.8610

Table 2-14: TN RE (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0. Negative values represent greater than that of inflow.

Swale ID	TN 70 min.	TN 140 min.	TN Pooled
CR1	-10.00 ± 5.37	**-20.83 ± 8.21**	**-15.42 ± 8.59**
CG1	-2.73 ± 8.82	-1.97 ± 3.75	-2.35 ± 6.08
CR4	-15.00 ± 11.85	-33.47 ± 41.75	-24.23 ± 29.26
CG4	-10.63 ± 15.43	1.80 ± 14.52	-4.42 ± 15.03

TP

Linings had a significant impact on TP removal (Table 2-15). TP was significantly exported during the medium storms from CR4 and large storms from CR1, while being significantly reduced during the medium storms in CG1 (Table 2-16). When data were pooled, swales CR1 and CR4 significantly exported TP while CG1 significantly reduced it (Table 2-16). TP is comprised of dissolved and particulate forms. Particulate phosphorus will readily adsorb to soil particles (Sparks, 2003) and could cause an export of TP if resuspension of particles occurs.

Some TP export can be attributed to TSS export. TP and TSS results for the grassed swales are consistent. CG1 significantly reduced both TP and TSS. CG4 exported both TP and TSS, yet insignificantly so. Although slope was not a significant factor, particle-bound phosphorus may be more likely to export on steeper slopes, similar to TSS. Similar to TN, native grass-lined swales may remove more TP due to plant uptake (fixation) (Holford, 1997; Murphy, 2007).

Table 2-15: TP concentration reduction ANCOVA results. Bolded values are statistically significant.

Factor	TP p-value
Lining	**0.0063**
Slope	0.1002
Storm Size	0.3675
Lining*Storm Size*Slope	0.8969
Lining*Slope	0.7862
Lining*Storm Size	0.5785
Storm Size*Slope	0.7035

Table 2-16: TP RE (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0. Negative values represent greater than that of inflow.

Swale ID	TP 70 min.	TP 140 min.	TP Pooled
CR1	-17.33 ± 10.63	**-37.43 ± 10.28**	**-27.38 ± 14.44**
CG1	**12.07 ± 3.31**	4.47 ± 7.31	**8.27 ± 6.55**
CR4	**-34.53 ± 5.35**	-51.50 ± 61.04	**-43.02 ± 39.85**
CG4	-13.63 ± 22.01	-12.00 ± 14.36	-12.82 ± 16.65

Dissolved forms of phosphorus, particularly ortho-phosphate (OP), may also contribute to the export of TP. Lining had a significant effect on the removal of OP. Because OP was significantly exported in both riprap swales, similar to TP, it is reasonable to conclude that OP was the reason for TP exports.

OP

Lining type was the significant parameter to determine whether a swale removed or exported OP (Table 2-17). CR1 significantly exported OP during both the medium and large storms (Table 2-18). CR1 and CR4 significantly exported OP when data were pooled, while CG1 significantly reduced OP (Table 2-18). OP is a stable, dissolved form of phosphorus that is easily assimilated by plants (Murphy, 2007). The lack of plant roots in the riprap-lined swales may, again, explain why they exported OP. Additionally, OP binds to iron oxides and aluminum in soils (Syers and Curtin, 1988). Under conditions, such as particle resuspension, OP may be released from the oxides and sediment, furthering export. OP may also be exported from residual grass clippings (Rushton, 2001). Due to higher mowing frequency onsite in the spring and summer, this could be a likely cause of OP export observed herein.

Table 2-17: OP concentration reduction ANCOVA results. Bolded values are statistically significant.

Factor	OP p-value
Lining	**<.0001**
Slope	0.8201
Storm Size	0.2186
Lining*Storm Size*Slope	0.1315
Lining*Slope	0.6334
Lining*Storm Size	0.8070
Storm Size*Slope	0.5834

Table 2-18: OP RE (%) ± standard deviation for each swale and storm event. Bolded values are significantly different from 0. Negative values represent greater than that of inflow.

Swale ID	OP 70 min.	OP 140 min.	OP Pooled
CR1	**-31.80 ± 12.15**	**-39.93 ± 13.92**	**-35.87 ± 12.50**
CG1	15.47 ± 6.28	6.03 ± 11.30	**10.75 ± 9.67**

CR4	-47.50 ± 34.20	-24.43 ± 22.94	**-35.97 ± 28.95**
CG4	2.17 ± 3.41	-8.90 ± 7.47	-3.37 ± 7.98

OP concentration reduction results support TP results for each swale. Swales CR1 and CR4 both significantly export OP and TP while CG1 significantly reduced OP and TP. While particulate forms of phosphorus may have contributed to TP exports, it is clear OP had an impact.

Dissolved Metals

Cd

As with TP, and OP, lining type was the significant reason Cd was removed (Table 2-19). Both CG1 and CG4 significantly reduced Cd during the medium storms and CG4 during the large storms (Table 2-20). Swales CG1, CR4, and CG4 significantly reduced Cd when data were pooled (Table 2-20). Cd will readily bind to dissolved organic carbon (DOC) (Sparks, 2003) and be taken up by plant roots. Depending on the availability and concentration, small amounts of Cd may also be taken up directly from the atmosphere (Ismael et al., 2019). Factors such as soil pH, the rhizosphere, and presence or organic acids may affect the availability of Cd to plants (Ismael et al., 2019). Plant uptake likely explains why grass-lined swales had better Cd removal than riprap-lined swales.

Table 2-19: Dissolved metal concentration reduction ANCOVA results. Bolded values are statistically significant.

Factor	**Cd p-value**	**Cu p-value**	**Pb p-value**	**Zn p-value**
Lining	**0.0272**	0.1950	**0.0026**	**0.0027**
Slope	0.1606	**0.0292**	0.3368	0.3560
Storm Size	0.8732	0.8918	0.1615	0.9778
Lining*Storm Size*Slope	0.8434	0.3556	0.7795	0.4899

Lining*Slope	0.2515	0.4886	0.1962	0.3204
Lining*Storm Size	0.4565	0.8983	0.1110	**0.0301**
Storm Size*Slope	0.1904	0.5579	0.4807	0.5807

Table 2-20: Dissolved Cd RE (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0.

Swale ID	Cd 70 min.	Cd 140 min.	Cd Pooled
CR1	12.80 ± 24.88	29.37 ± 15.28	21.08 ± 20.58
CG1	**43.73 ± 17.27**	28.87 ± 13.05	**36.30 ± 15.93**
CR4	25.23 ± 19.34	19.17 ± 24.28	**22.20 ± 19.91**
CG4	**62.27 ± 3.61**	**40.43 ± 12.59**	**51.35 ± 14.55**

Cu

All swales exported Cu once data were pooled (Table 2-21). The only significant relationship predicting Cu RE was steepness of slope (Table 2-19). CG4 during medium storms was the only swale to significantly export Cu. Cu was the only metal to consistently increase in concentration from inlet to outlet. This outcome is not consistent with literature, as swales generally remove Cu more effectively than Pb and Cd (Stagge et al., 2012). While the cause of Cu export is not clear, it may be concluded that changes in soil pH, ion exchange, aeration and agitation, or metal binding had an effect (Borne and Tanner, 2013; Sansalone and Ying, 2008). Sirova (2015) reported an export of Cu because of its inability to compete with other pollutants to bind to organic matter. Greater aeration and agitation in steeper slopes may have resulted in more Cu exports than shallower slopes.

Table 2-21: Dissolved Cu RE (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0. Negative values represent greater than that of inflow.

Swale ID	Cu 70 min.	Cu 140 min.	Cu Pooled
CR1	-32.33 ± 25.28	-32.83 ± 32.89	**-32.58 ± 26.24**
CG1	-13.33 ± 12.67	-58.43 ± 27.74	**-35.84 ± 31.38**

CR4	-48.23 ± 32.60	-71.97 ± 45.63	**-60.10 ± 37.77**
CG4	**-85.67 ± 13.46**	-77.53 ± 31.36	**-81.60 ± 22.04**

Pb

Lining type was the significant parameter to determine whether a swale removed Pb (Table 2-19). CG1 and CG4 significantly reduced Pb during medium storms and when data were pooled (Table 2-22). Though all four heavy metals readily adsorb to sediment, Pb has the least affinity for DOC and primarily exists in suspended particulate matter (Shafer et al., 1997). Pb's higher likelihood of removal via sedimentation could explain the positive removal efficiencies. Thick vegetation enhances sedimentation rates (Nardin and Edmonds, 2014), as evidenced by higher removal efficiencies in native grass-lined swales compared to riprap. This conclusion is also supported by the significance of lining type in the ANCOVA (Table 2-19).

Table 2-22: Dissolved Pb RE (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0. Negative values represent greater than that of inflow.

Swale ID	Pb 70 min.	Pb 140 min.	Pb Pooled
CR1	-5.93 ± 22.82	2.73 ± 8.06	-1.60 ± 16.03
CG1	**14.57 ± 4.52**	8.43 ± 13.39	**11.50 ± 9.49**
CR4	4.67 ± 18.41	-0.77 ± 12.74	1.95 ± 14.47
CG4	**39.87 ± 4.24**	16.83 ± 13.30	**28.35 ± 15.40**

Zn

Similar to Pb, results clearly indicate native grass-lined swales reduce Zn concentrations at a higher rate than riprap-lined swales when data were pooled (Table 2-23). Zn was significantly removed during the medium events in CG1 and large events in CG4 (Table 2-23). The lining and lining*storm size interactions were significant in the ANCOVA (Table 2-19). Dissolved portions of zinc are primarily removed by binding to particulate and organic matter (Legret and Pagotto, 1999). Native grass-lined swales likely removed more Zn than riprap due to a higher organic matter content for the Zn to bind to. Results are consistent with literature, as swales generally remove Zn more effectively than Cd, Cu, and Pb (Stagge et al., 2012).

Table 2-23: Dissolved Zn RE (%) ± standard deviation in vegetated swales. Bolded values are significantly different from 0. Negative values represent greater than that of inflow.

Swale ID	Zn 70 min.	Zn 140 min.	Zn Pooled
CR1	-1.30 ± 16.97	17.73 ± 22.42	8.22 ± 20.62
CG1	**53.30 ± 17.53**	36.83 ± 27.85	**45.02 ± 22.66**
CR4	0.57 ± 29.50	14.87 ± 25.07	7.72 ± 25.71
CG4	53.70 ± 5.79	**41.47 ± 10.28**	**47.58 ± 10.03**

Native grass-lined swales have higher REs than riprap-lined swales at both 1% and 4% slopes during the medium storm event as well as the 4% slope during the large storm event in the lining*storm size interaction (Figure E-3).

2.2.b Pollutant Loads

Load reduction results generally mirrored changes in concentration. Load changes were more pronounced because of high volume reductions that occurred in all four tested swales, and a full analysis and discussion can be found in Appendix G.

Both native grass and riprap-lined swales had generally high pollutant load reduction. Sediment, all nutrients, and all dissolved metals were significantly reduced in swales CR1 and CG4. CG4 had the highest overall rates of nutrient and dissolved metal load reduction. Infiltration and biological processes, enhanced by the presence of vegetation, could explain higher load reductions in CG4. Comparing both swales on the 1% slope, CR1 may be the more desirable option as it tended to decrease sediment, nutrient, and dissolved metal loads more than CG1, though this result is an artifact of CR1, having a higher mean volume reduction. Swales CG1 and CG4 both exceeded NCDEQ’s grassed swale pollutant credit requirements of 35%, 20%, and 20% for TSS, nitrogen, and phosphorus, respectively (NCDEQ, 2009).

However, the NCDEQ credits are based upon swales monitored during actual weather events, rather than simulations such as those presented herein.

2.3 Turf Lining Comparison

A full discussion of results is included in Appendix H, and a summary is included below. Turf had better sediment and dissolved metal concentration reductions than native grasses and riprap. Native grasses and turf were essentially the same for nutrient concentrations. The native grass-lined swale on the 4% slope (CG4) provides the highest overall rates of nutrient and dissolved metal load reduction. Each of the riprap and native grass-lined swales had substantially more volume reduction than the turf-lined swales. Because experiments herein were conducted on the same swales as the turf, it is possible the lining had an effect on volume reduction. Alternative liners herein are a competitive option over turf because of their simple maintenance procedures. Turf-lined swales require routine mowing, whereas, riprap and native grass-lined swales may only require minimal weed management (Harper-Lore, 2023).

3. Alternative Linings in Bioswales

Several outliers existed in the data collected for alternative linings in bioswales, thus, median values for pollutant concentration and load reductions as well as volume and peak flow reductions were reported. Outliers were determined by pooling storm size and observing data points outside of 1.5 times the interquartile range (IQR). Because data were not normally distributed, the Wilcoxon Signed-Rank test (Rey and Neuhäuser, 2011) and Quade's (1967) Rank ANCOVA were used to analyze median pollutant and parameter significance, respectively. Although the rank analysis reduced the model's sensitivity to outliers, it also made the response correlated (non-individually distributed) (Tian et al., 2014; personal communication, NC State Data & Visualization Services, May 5, 2023). All raw data are included in Appendix J.

3.1 Hydrologic Performance Results and Discussion

3.1.a Volume Partitioning

Water Balance

Overflow is flow that remained on the surface of the swale, while underdrain flow is flow that passed through the engineered media into the underdrain. Water balances for medium and large storm events are shown in Figures 3–1 and 3-2, respectively. The majority of the stormwater passed through as overflow for native grass-lined bioswales on the 4% slope during medium storms (Figure 3-1). During large storms, a volume partitioning pattern is not as clear.

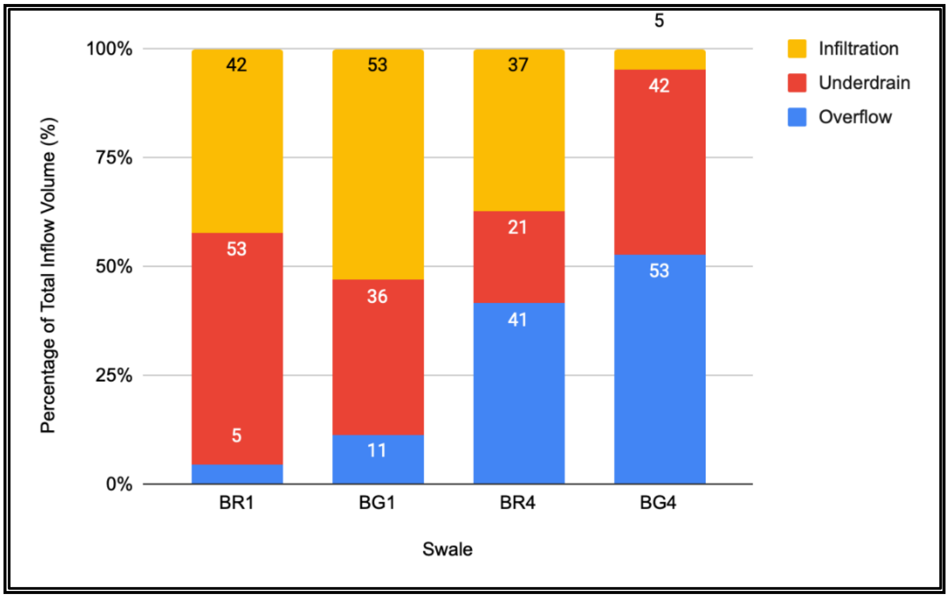

Figure3-1: Hydrologic pathways in bioswales as a percentage of the total inflow volume measured during medium storm events.

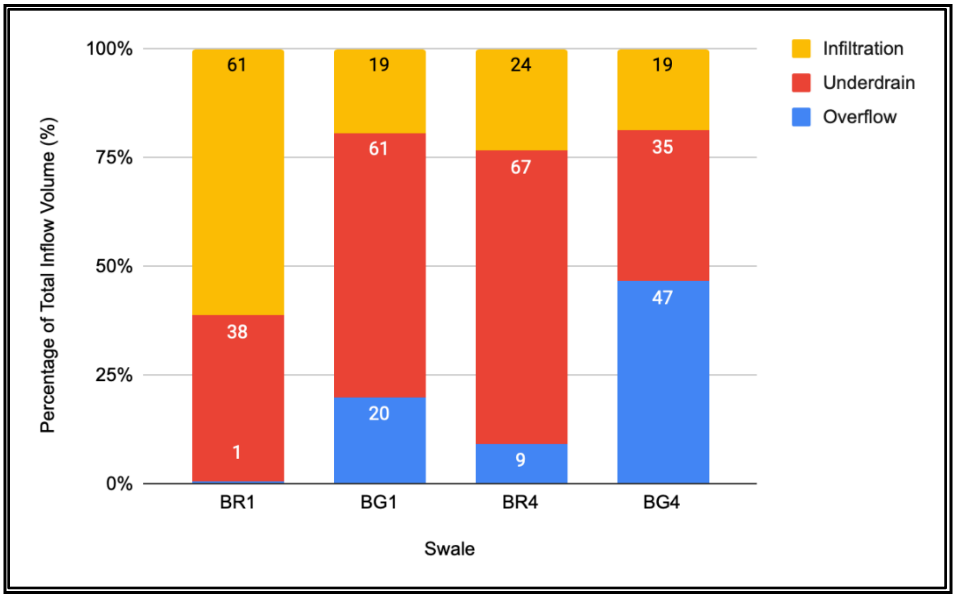

Figure 3-2: Hydrologic pathways in bioswales as a percentage of the total inflow volume measured during large storm events.

Total Volume Reduction

Riprap-lined bioswales significantly reduced total volumes, but only when data were pooled (Table I-1). When viewed individually, each of the four bioswales had insignificant total volume reduction during medium and large storms (Table 3-1). This lack of significance may be a result of the rank analyses. Lining and slope were both significant factors for total volume reduction (Table 3-2). Lining*storm size*slope and storm size*slope were the only significant crossed interaction, indicating there was a combination of lining type, slope, and storm size that produced a significant result. Results indicate that riprap-lined bioswales tested significantly reduce total volumes more than native grass-lined bioswales. The level of compaction during construction can reduce rates of volume reduction (Gregory, 2006). It is possible the soil in native grass-lined bioswales was more compacted than that of riprap-lined bioswales, lowering volume reduction. Additionally, 1% slopes reduce volumes significantly more than those on 4% slopes.

Table 3-1: Median total volume reductions for each bioswale and storm size, as taken from Wilcoxon Signed-Rank.

Swale ID	Total Volume Reduction 70 min. (L)	Total Volume Reduction 70 min. (%)	Total Volume Reduction 140 min. (L)	Total Volume Reduction 140 min. (%)	Total Volume Reduction Pooled (L)	Total Volume Reduction Pooled (%)
BR1	6,895	42	17,202	61	**9,405**	**52**
BG1	7,996	53	6,216	19	7,835	42
BR4	6,006	37	8,155	24	**6,372**	**25**
BG4	865	5	6,046	19	2,909	12

Table 3-2: Total volume reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	Total Volume Reduction p-value
Lining	**0.0326**
Slope	**0.0019**
Storm Size	0.0752
Lining*Storm Size*Slope	**0.0188**
Lining*Slope	0.7445
Lining*Storm Size	0.8565
Storm Size*Slope	**0.0324**

Bioswales herein had total volume reductions within range, and/or slightly lower than those observed in literature (Table I-2). The International BMP Database reports average volume reductions of 35% to 65% for bioswales with underdrains (Poresky et al., 2011). Osouli et al. (2017) reported volume reductions in a 10-year-old bioswale of 27, 44, and 57% under 10-year, 2-year, and 9-month return storm event, respectively.

Perhaps underlying soil hydraulic conductivity (K) herein affected their ability to infiltrate water (Purvis, 2018). Surface clogging is often due to internal erosion caused by concentrated flow along the perimeter of the bioswale (Blecken et al., 2017; Wardynski and

Hunt, 2012). Although not observed along the entire perimeter of the bioswales, there was erosion observed around the outlet box of one bioswale herein, causing some of the flow to bypass the weir (Figure I-1).

3.1.b Peak Flow Reduction

Peak flow is the maximum rate of discharge during a storm. Only combined peak flow (Qoverflow +Qunderdrain)) reduction in bioswales is reported so as to compare the mitigation of inflow peak flow relative to outflow peak flow.

Bioswales on the 1% slope both significantly reduced peak flows, when data were pooled (Table I-3) but not when storm size was evaluated individually (Table 3-3). Slope was a significant factor for peak flow reduction (Table 3-4). No crossed interactions between lining type, storm size, and slope were statistically significant, and results for three of the four bioswales (23-41%) are within range or slightly lower than reported in literature (Table I-4).

Table 3-3: Median combined peak flow reduction (L/s) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank.

Swale ID	Peak Flow Reduction 70 min. (L/s)	Peak Flow Reduction 70 min. (%)	Peak Flow Reduction 140 min. (L/s)	Peak Flow Reduction 140 min. (%)	Peak Flow Reduction Pooled (L/s)	Peak Flow Reduction Pooled (%)
BR1	2.26	25	2.86	31	**2.56**	**28**
BG1	5.36	59	1.96	22	**3.66**	**41**
BR4	3.14	33	1.96	22	2.10	23
BG4	1.16	13	1.94	21	1.29	17

Table 3-4: Combined peak flow reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	Peak Flow Reduction p-value
Lining	0.5628

Slope	**0.0323**
Storm Size	0.1178
Lining*Storm Size*Slope	0.2248
Lining*Slope	0.3757
Lining*Storm Size	0.9813
Storm Size*Slope	0.3220

Similar to volume reduction, varying hydraulic conductivity of the media and underlying soil may have affected peak flow reduction (Takaijudin et al., 2016). Hydraulic conductivity, the capacity of a porous media to transmit water, is a determining factor to soil infiltration, and concomitantly, peak flow mitigation (Peña et al., 2016). The ability of swales to mitigate peak flow is also highly dependent on soil infiltration rate (Davis et al., 2009; Finotti et al., 2023) and compaction of swale bed during construction (Gregory et al., 2006; Pitt et al., 2008), as discussed in section 4.2.1.3. Other factors such as soil characteristics (Davis et al., 2012), channel roughness, and grass height and density (Bäckström, 2002; Deletic and Fletcher, 2006) may minimally contribute to peak flow reductions.

1.2 Water Quality Performance Results and Discussion

Results on pollutant removal are first presented as changes in pollutant concentration and then as changes in pollutant loads. Load discussion draws upon the results in concentrations and those of change in volume. Raw data for inflow, overflow, and underdrain EMCs are found in Appendix J.

3.2.a Concentration Change

Sediment

None of the four bioswales had significant TSS concentration reductions (Table I-5). Modest increases in BR1 overflow TSS concentrations were statistically insignificant during the medium storms. Slope and influent concentration were significant factors to TSS concentrations in the overflow (Table 3-5). No crossed interactions between lining type, storm size, and slope were statistically significant for either overflow or underdrain. Storm size had no significant effect on overflow and underdrain TSS concentration reduction, so storm data were pooled and reanalyzed. When storm sizes were pooled, BG1 had significantly lower concentrations from the underdrain and BG4 significantly reduced concentrations in both the overflow and underdrain (Table 3-6). It is surprising that bioswales with steeper slopes appeared to have generally higher rates of TSS concentration reduction. Sedimentation, the process in which particles fall out of the water column, is more likely to occur in more shallow slopes because of the increased HRT (Cerdà and García-Fayos, 1997). It does appear that, except for the case of BG4, underdrain TSS concentrations are less than that of overflow. This is likely a result of the additional filtration through the bioswales' engineered media (Ekka and Hunt, 2020).

Table 3-5: TSS concentration reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	**TSS Overflow p-value**	**TSS Underdrain p-value**
Lining	0.1280	0.9516
Slope	**0.0306**	0.1965
Storm Size	0.1063	0.5679
Influent Concentration	**0.0068**	0.0830
Lining*Storm Size*Slope	0.2965	0.8752
Lining*Slope	0.2665	0.3160
Lining*Storm Size	0.3435	0.1920
Storm Size*Slope	0.9451	0.3804

Table 3-6: Median reduction of TSS concentrations (mg/L) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow concentration significantly different from outflow concentration. Negative values represent greater outflow than inflow.

Swale ID	Median Influent Concentration	TSS Overflow	p-value Overflow	TSS Underdrain	p-value Underdrain
BR1	24.7	-4.25	0.8438	12.41	0.4375
BG1	16.0	1.64	0.8438	**6.58**	0.0313
BR4	33.5	21.26	0.4375	27.85	0.0625
BG4	21.0	**11.16**	0.0313	**10.88**	0.0313

Nutrients

TKN

None of the four bioswales significantly reduced TKN concentrations (Table I-6). Results are unclear as to which lining type was better for TKN concentration reductions. All four bioswales had statistically insignificant TKN concentration increases in the overflow during the medium storms. Bioswales BR1, BG1, and BR4 had statistically insignificant TKN concentration increases in the overflow during the large storms. BR1 and BR4 had statistically insignificant TKN exports from the underdrains during the medium and large storms, respectively. No crossed interactions between lining type, storm size, and slope were statistically significant for either overflow or underdrain (Table 3-7). When data were pooled across storm sizes, BG1 significantly exported concentrations in the overflow (Table 3-8). TKN is comprised of ammonia and organic forms of nitrogen. The export of TKN is possible when either ON or ammonia are available in the soil having not been fixed to plants. The export of NH_3 (ammonia), is likely the reason for the potential TKN export. Decomposition of organic matter may result in NH_3 and, thus, TKN exports (ACS, 2021).

Table 3-7: TKN concentration reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	TKN Overflow p-value	TKN Underdrain p-value
Lining	0.0714	0.0511
Slope	0.1214	0.7721
Storm Size	0.9031	0.8814
Lining*Storm Size*Slope	0.4620	0.7718
Lining*Slope	0.7837	0.4789
Lining*Storm Size	0.7224	0.4718
Storm Size*Slope	0.8498	0.8302

Table 3-8: Median reduction of TKN concentrations (µg/L) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow concentration significantly different from outflow concentration. Negative values represent greater outflow than inflow.

Swale ID	TKN Overflow	p-value Overflow	TKN Underdrain	p-value Underdrain
BR1	-229.35	0.3125	-5.04	1.0000
BG1	**-89.25**	0.0313	54.88	0.2188
BR4	-139.39	0.0938	30.42	1.0000
BG4	-4.00	0.5625	51.50	0.3125

Runoff passing through the engineered media of a bioswale is likely the reason underdrain concentrations are generally improved while overflow concentrations are exported. Similar to the media in a bioretention cell, the silt and clay fraction promote pollutant attenuation (Davis et al., 2001; Purvis, 2018).

NH_3

Lining significantly impacted NH_3 export from the overflow and underdrain (Table 3-9). No crossed interactions between lining type, storm size, and slope were statistically significant for overflow. Lining*storm size was the only significant interaction in the underdrain. None of the four bioswales had any significant NH_3 concentration reductions (Table I-7). BR1, BG1, and BR4 insignificantly exported NH_3 in both the overflow and underdrain during medium and large storms. BG4 insignificantly exported NH_3 in the overflow and underdrain during medium storms as from well as the underdrain during large storms. When storm sizes were pooled, BG1 and BR4 significantly exported concentrations in the overflow (Table 3-10).

Table 3-9: NH_3 concentration reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	NH_3 Overflow p-value	NH_3 Underdrain p-value
Lining	**0.0355**	**0.0209**
Slope	0.4715	0.2824
Storm Size	0.8523	0.6463
Lining*Storm Size*Slope	0.0767	0.7882
Lining*Slope	0.0532	0.4227
Lining*Storm Size	0.8118	**0.0351**
Storm Size*Slope	0.9744	0.2729

Table 3-10: Median reduction of NH_3 concentrations (µg/L) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow concentration significantly different from outflow concentration. Negative values represent greater outflow than inflow.

Swale ID	NH_3 Overflow	p-value Overflow
BR1	-13.78	0.2188
BG1	**-7.51**	0.0313
BR4	**-19.08**	0.0313
BG4	1.84	0.7188

NH_3 is primarily removed through the process of nitrification. Nitrification, which occurs in aerobic conditions, is the process in which ammonia is converted to nitrite (then nitrate by bacteria) (Ward et al., 2011). NH_3 can be produced through either the process of ammonification (Bernhard, 2010, ACS, 2021) or nitrogen fixation (Postgate, 1998). Ammonification is the process in which NH_3 is produced from the decomposition of organic matter. Nitrogen fixation occurs when bacteria in the soil consume atmospheric nitrogen and convert it to NH_3, which is available for plant uptake. When bacteria are not present and plant uptake does not occur, NH_3 is exported.

The sum of NH_3 and organic nitrogen is total kjeldahl nitrogen. TKN in the overflow was exported because of the export of NH_3 and, likely, organic nitrogen. While unclear, because lining was a significant factor in the overflow and underdrain, it appears native grass-lined bioswales export less NH_3 concentrations than riprap-lined bioswales in the overflow. This result may be influenced by a substantial export of NH_3 in the overflow of BR4 during large storm events (Table I-7).

NO_x

Lining was a significant factor for both the overflow and underdrain concentration reduction (Table 3-11). Slope was also significant to NO_x concentration reduction in the underdrain. Lining*storm size*slope was the only significant crossed interaction for overflow for NO_x, indicating there was a combination of lining type, slope, and storm size that produced a significant result. While lining was shown to have significant impact, no changes in concentration were statistically significant (Table I-8). Nearly all riprap-lined bioswales had insignificant export, while native grass-lined bioswales were more likely to sequester NO_x than release it. When storm sizes were pooled for underdrain data, BG1 significantly reduced NO_x concentrations (Table 3-12).

Table 3-11: NO_x concentration reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	NO_x Overflow p-value	NO_x Underdrain p-value
Lining	**0.0036**	< **0.0001**
Slope	0.3245	**0.0083**
Storm Size	0.0874	0.0505
Lining*Storm Size*Slope	**0.0297**	0.1859
Lining*Slope	0.1384	0.7235
Lining*Storm Size	0.4445	0.5485
Storm Size*Slope	0.3969	0.6117

Table 3-12: Median reduction of NO_x concentrations (µg/L) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow concentration significantly different from outflow concentration. Negative values represent greater outflow than inflow.

Swale ID	NO_x Underdrain	p-value Underdrain
BR1	**-494.01**	0.0313
BG1	**28.95**	0.0313
BR4	**-901.43**	0.0313
BG4	-6.57	0.8438

NO_x, inorganic nitrogen, is the combination of nitrite (NO2-) and nitrate (NO3-). NO_x is primarily removed through denitrification, a condition where the oxygen (O_2) supply in the soil is limited and bacteria utilize the oxygen in nitrate for respiration (IPNI, 2023). Denitrification permanently removes nitrate from a swale by converting it to N_2 gas (Collins et al., 2010), yet

NO_x may export if nitrate is not fully converted. Runoff's contact time from the inlet to the outlet of the swale may not have been sufficient for denitrification, perhaps causing the export of NO_x especially in the riprap swales. Additionally, because experiments were conducted after an antecedent dry period of at least 24 hours, it is likely the soil in the bioswale did not provide the necessary anoxic conditions for denitrification to occur. While bioswales were designed to promote free drainage, a zone, known as internal water storage (IWS), may be incorporated to create the anoxic environment necessary for denitrification (Purvis, 2018; Kim et al., 2003). An IWS was not utilized herein.

NO_x may also be produced during nitrification, a process that occurs in aerobic conditions. Nitrification, the process in which ammonia is converted to nitrite (then nitrate by bacteria), may be happening as a result of unsaturated soils following the antecedent dry period. This may be another cause of NO_x exports. Soil temperature, moisture content, microbial activity, aeration, and organic matter content influence the export of NO_x (Wilson et al., 2017).

Significant differences were observed between the removal of NO_x in riprap and native grass-lined bioswales in both the overflow and the underdrain. It can be reasonably concluded that native grass-lined bioswales, especially on the 1% slope had better NO_x removals. Native grass-lined bioswales likely lowered NO_x concentrations in the underdrain more than riprap-lined bioswales did. Native grasses may provide a greater resistance to flow and allow the runoff to have a greater contact time between inlet to outlet, and thus may be the reason native grasses have fewer NO_x exports.

TN

Lining type mattered vis-à-vis TN removal in the overflow and underdrain (Table 3-13). While lining was shown to have significant impact, no changes in concentration were statistically significant (Table I-9). All riprap-lined bioswales had insignificant export, while native grass-lined bioswales were more likely to sequester TN than release it. No crossed interactions between lining type, storm size, and slope were statistically significant for either overflow or underdrain. When data across storm sizes were pooled, BG1 significantly exported concentrations from the overflow while BR1 and BR4 significantly exported TN concentrations in the underdrain (Table 3-14).

Table 3-13: TN concentration reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	TN Overflow p-value	TN Underdrain p-value
Lining	**0.0346**	**< 0.0001**
Slope	0.0815	0.2453
Storm Size	0.4158	0.2455
Lining*Storm Size*Slope	0.2446	0.8199
Lining*Slope	0.9127	0.8368
Lining*Storm Size	0.9074	0.8986
Storm Size*Slope	0.9489	0.6159

Table 3-14: Median reduction of TN concentrations (µg/L) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow concentration significantly different from outflow concentration. Negative values represent greater outflow than inflow.

Swale ID	TN Overflow	p-value Overflow	TN Underdrain	p-value Underdrain
BR1	-345.66	0.2188	**-451.50**	0.0313
BG1	**-62.82**	0.0313	99.96	0.0938
BR4	-125.42	0.1563	**-863.36**	0.0313
BG4	-1.84	0.8438	44.93	0.3125

TN concentrations are calculated by the addition of TKN and NO_x concentrations. In cases where TKN and NO_x were both often exported, it is clear that TN would also be exported. As runoff passes through a bioswale, nitrogen may be removed via three main processes: assimilation (also referred to as N uptake), denitrification, and adsorption (Collins et al., 2010). Assimilation is more likely to occur in native grass-lined bioswales where plant roots are available for fixation, perhaps this is the reason they exported less (or even sequestered) TN than riprap-lined swales. Denitrification most commonly occurs in wet soils where the oxygen supply is limited (IPNI, 2023). The lack of anoxic conditions in both riprap and native grass-lined bioswales likely limited NO_x and, therefore, TN removal by denitrification. Results indicate that native grass-lined bioswales significantly reduce TKN concentrations more than riprap-lined bioswales in both the overflow and underdrain.

TP

Lining had a significant impact on TP concentration reduction from the underdrain (Table 3-15). No crossed interactions between lining type, storm size, and slope were statistically significant for either overflow or underdrain. While lining (for underdrain flow) was shown to have significant impact, no changes in concentration were statistically significant (Table I-10). Nearly all riprap-lined bioswales had insignificant export, while native grass-lined bioswales were more likely to sequester TP than to release it. When storm sizes were pooled, none of the four bioswales significantly changed TP in the overflow or underdrain (Table 3-16). TP is comprised of dissolved and particulate forms. Particulate phosphorus will readily adsorb to soil particles (Sparks, 2003) and could cause an export of TP if (re)suspension of particles occurs. Some TP export can be attributed to TSS export. TP and TSS results for BG4 are consistent. The overflow and underdrain reduced both TP and TSS. Similar to TN, native grass-lined bioswales may remove more TP due to plant uptake (fixation) (Holford, 1997; Murphy, 2007). It is also likely that plants make the (re)suspension of particles less likely to occur.

Table 3-15: TP concentration reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	TP Overflow p-value	TP Underdrain p-value
Lining	0.1293	**0.0008**
Slope	0.2985	0.8842
Storm Size	0.1748	0.0954
Lining*Storm Size*Slope	0.2065	0.2758
Lining*Slope	0.7561	0.2884
Lining*Storm Size	0.5875	0.1607
Storm Size*Slope	0.4316	0.8860

Table 3-16: Median reduction of TP concentrations (µg/L) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Negative values represent greater outflow than inflow. No results were significant.

Swale ID	TP Overflow	p-value Overflow	TP Underdrain	p-value Underdrain
BR1	-64.72	0.4375	-15.50	0.5625
BG1	-5.32	0.2188	1.48	1.0000
BR4	-12.53	0.2188	-61.57	0.0625
BG4	2.74	1.0000	5.30	0.6875

Dissolved forms of phosphorus, particularly ortho-phosphate (OP), may also contribute to the export of TP. Lining significantly affected the removal of OP from the underdrain. Because OP was exported from both riprap swales, similar to TP, it could be concluded that OP was the reason for TP exports.

OP

Lining was a significant factor to OP concentration change from the underdrain (Table 3-17). A significant interaction between lining*slope was also present in the underdrain. The significant 3-way interaction between lining*storm size*slope in the overflow and underdrain indicates there was a combination of lining type, slope, and storm size that produced a significant result. Data were not pooled because of these significant interactions with storm size. While lining (for underdrain flow) was shown to have a significant impact, no changes in concentration were statistically significant (Table 3-18). Several riprap-lined bioswales had insignificant export, while native grass-lined bioswales were more likely to sequester OP than release it.

Table 3-17: OP concentration reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	**OP Overflow p-value**	**OP Underdrain p-value**
Lining	0.1979	**< 0.0001**
Slope	0.8269	0.4867
Storm Size	0.8803	0.8578
Lining*Storm Size*Slope	**0.0300**	**0.0301**
Lining*Slope	0.5365	**< 0.0001**
Lining*Storm Size	0.9515	0.4020
Storm Size*Slope	0.1634	0.4353

Table 3-18: Median reduction of OP concentrations (µg/L) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. Negative values represent greater outflow concentration than inflow.

Swale ID	**Median Influent Concentration 70 min.**	**OP Overflow 70 min.**	**OP Underdrain 70 min.**	**Median Influent Concentration 140 min.**	**OP Overflow 140 min.**	**OP Underdrain 140 min.**
BR1	50.6	-23.21	12.20	41.4	20.87	3.39
BG1	47.0	2.19	19.66	16.4	1.70	-6.80

BR4	57.3	8.41	-38.39	25.0	-55.37	-94.29
BG4	37.2	-1.78	25.35	23.9	5.23	13.70

OP is a stable, dissolved form of phosphorus that is easily assimilated by plants (Murphy, 2007). The lack of plant roots in the riprap-lined bioswales may, again, explain why they exported OP. Additionally, OP binds to iron oxides and aluminum in soils (Syers and Curtin, 1988). Throughout particle resuspension, OP may be released from the oxides and sediment, furthering an export. OP may also be exported from residual grass clippings (Rushton, 2001). Due to occasional higher mowing frequency (approximately twice per month) onsite in the spring and summer, this could be another cause of OP export observed herein.

OP concentration change results support TP results for bioswales BR4 and BG4. BR4 tended to export OP and TP while BG4 tended to reduce OP and TP concentrations in both the overflow and the underdrain. While particulate forms of phosphorus also contributed to TP exports, it is clear OP had an impact. This is supported by the raw data provided in Appendix M; the concentration change of OP in the overflow and the underdrain account for the majority of the concentration change of TP.

Dissolved Metals

Cd

When storm data were pooled, all four bioswales significantly reduced Cd concentrations in the overflow (Table 3-19). Slope was the only significant factor in the overflow (Table 3-20). A significant interaction between lining*storm size was present in the underdrain. While slope (for overflow) was shown to have a significant impact, no concentration reductions were statistically significant (Table I-11).

Table 3-19: Median reduction of dissolved Cd concentrations (μg/L) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow concentration significantly different from outflow concentration.

Swale ID	Cd Overflow	p-value Overflow
BR1	**1.90**	0.0313
BG1	**0.89**	0.0313
BR4	**1.15**	0.0313
BG4	**0.60**	0.0313

Table 3-20: Dissolved Cd concentration reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	Cd Overflow p-value	Cd Underdrain p-value
Lining	0.9081	0.9722
Slope	**0.0160**	0.2569
Storm Size	0.6781	0.9613
Lining*Storm Size*Slope	0.5037	0.3192
Lining*Slope	0.6921	0.8627
Lining*Storm Size	0.4313	**0.0113**
Storm Size*Slope	0.2384	0.7148

Cd will readily bind to dissolved organic carbon (DOC) (Sparks, 2003) and be taken up by plant roots. Depending on the availability and concentration, small amounts of Cd may also be taken up by plants directly from the atmosphere (Ismael et al., 2019). Factors such as soil pH, the rhizosphere, and presence or organic acids may affect the availability of Cd to plants (Ismael et al., 2019). Riprap and native grass-lined bioswales significantly reduced Cd concentrations in the overflow and underdrain, yet riprap had higher reductions. Additionally, the underdrain reduced concentrations moreso than the overflow for every bioswale. This could be due to the additional source of organic matter in the engineered media that Cd can bind to.

Cu

No changes in Cu concentration were statistically significant (Table I-12). Lining*slope was the only statistically significant interaction for the underdrain (Table 3-21). The significant 3-way interaction between lining*storm size*slope in the overflow indicates there was a combination of lining type, slope, and storm size that produced a significant result. When storm sizes were pooled, BR1, BR4, and BG4 significantly exported Cu concentrations from the underdrain (Table 3-22).

Table 3-21: Dissolved Cu concentration reduction Rank ANCOVA results.

Factor	**Cu Overflow p-value**	**Cu Underdrain p-value**
Lining	0.1220	0.4640
Slope	0.1048	0.7606
Storm Size	0.2044	0.2076
Lining*Storm Size*Slope	**0.0317**	0.2339
Lining*Slope	0.5328	**0.0468**
Lining*Storm Size	0.9638	0.6663
Storm Size*Slope	0.2549	0.6634

Table 3-22: Median reduction of dissolved Cu concentrations (µg/L) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow concentration significantly different from outflow concentration. Negative values represent greater outflow than inflow.

Swale ID	**Cu Underdrain**	**p-value Underdrain**
BR1	**-9.00**	0.0313
BG1	-5.50	0.0625
BR4	**-8.00**	0.0313

BG4	**-11.40**	0.0313

Cu was the only metal to increase in concentration in both the overflow and underdrain of every bioswale. This outcome is not consistent with literature, as bioswales generally remove Cu more effectively than Pb and Cd (Stagge et al., 2012). While the case of Cu export is not clear, it may be concluded that changes in soil pH, ion exchange, aeration and agitation, or metal binding had an effect (Borne and Tanner, 2013; Sansalone and Ying, 2008). Sirova (2015) reported an export of Cu because of its inability to compete with other pollutants to bind to organic matter. According to Purvis (2018), the upper 0.6 m of the bioswales herein were filled with a high-flow media comparable to the North Carolina Department of Environmental Quality standard (NCDENR, 2009). This soil mixture contained approximately 3-6% organic matter.

Pb

No changes in Pb concentration were statistically significant (Table I-13). No individual or crossed interactions between lining type, storm size, and slope were statistically significant for the overflow or underdrain (Table 3-23). When storm sizes were pooled, BR1 significantly reduced Pb concentrations in the overflow and underdrain. BR4 did so as well from the underdrain (Table 3-24).

Table 3-23: Dissolved Pb concentration reduction Rank ANCOVA results.

Factor	**Pb Overflow p-value**	**Pb Underdrain p-value**
Lining	0.5964	0.1506
Slope	0.2514	0.7545
Storm Size	0.8428	0.4487
Lining*Storm Size*Slope	0.2065	0.2938

Lining*Slope	0.2405	0.4233
Lining*Storm Size	0.8877	0.4887
Storm Size*Slope	0.2562	0.8729

Table 3-24: Median reduction of dissolved Pb concentrations (µg/L) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow concentration significantly different from outflow concentration.

Swale ID	Pb Overflow	p-value Overflow	Pb Underdrain	p-value Underdrain
BR1	**1.75**	0.0313	**2.20**	0.0313
BG1	0.50	0.4375	0.95	0.0625
BR4	0.80	0.1250	**2.35**	0.0313
BG4	0.60	0.0625	1.10	0.0625

Though all four heavy metals readily adsorb to sediment, Pb has the least affinity for DOC and primarily exists in suspended particulate matter (Shafer et al., 1997). Pb's higher likelihood of removal via sedimentation could explain the concentration reductions. Thick vegetation enhances sedimentation rates (Nardin and Edmonds, 2014), yet this was not obvious herein. Additionally, the underdrain provided better concentration reduction than the overflow for every bioswale. This could be due to the engineered media's ability to filter. Filtration through an engineered media is often sand based, also with percentages of clay, silt, and organic matter that Pb can bind to (Hunt et al., 2012; Purvis, 2018).

Zn

When storm data were pooled, BR4 and BG4 significantly reduced Zn concentrations in both the overflow and underdrain (Table 3-25). Discharge from the underdrain had lower concentrations than that of the overflow for every bioswale. Lining in the overflow was the only significant factor to influence Zn concentrations change (Table 3-26). While lining (for overflow) was shown to be a significant factor, no changes in concentration were statistically significant in unpooled data (Table I-14).

Table 3-25: Median reduction of dissolved Zn concentrations (µg/L) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow concentration significantly different from outflow concentration.

Swale ID	**Zn Overflow**	**p-value Overflow**	**Zn Underdrain**	**p-value Underdrain**
BR1	16.00	0.3125	**37.50**	0.0313
BG1	**12.00**	0.0313	21.50	0.0625
BR4	**12.50**	0.0313	**35.00**	0.0313
BG4	**13.00**	0.0313	**33.00**	0.0313

Table 3-26: Dissolved Zn concentration reduction Rank ANCOVA results.

Factor	**Zn Overflow p-value**	**Zn Underdrain p-value**
Lining	**0.0452**	0.9383
Slope	0.9421	0.3204
Storm Size	0.0882	0.1571
Lining*Storm Size*Slope	0.5035	0.6374
Lining*Slope	0.9828	0.8318
Lining*Storm Size	0.8859	0.7515
Storm Size*Slope	0.6637	0.9337

Dissolved portions of zinc are primarily removed by binding to particulate and organic matter (Legret and Pagotto, 1999). Zn is dependent on the presence of suspended particulate matter and DOC (Shafer et al., 1997). This dependency and the additional organic matter present in the media pre-underdrain may have resulted in greater Zn concentrations reductions in the underdrain than those in the overflow. Similar to Pb, the underdrain likely had improved concentration reductions than the overflow because of the engineered media’s ability to act as a filter. It appears that all bioswales herein admirably reduced Zn concentrations, although riprap-lined bioswales may be more proficient.

3.2.b Pollutant Loads

Results presented for load removal will often reflect the observed changes in concentration. Load changes are impacted by the volume reduction that occurred in all four tested swales. For a full analysis and discussion see Appendix K.

Moderate load reductions were expected because they were highly dependent on volume reduction, which had reductions comparable to these found in literature. Both native grass-lined bioswales had significant TSS load reductions. BG1 had generally higher nutrient load reductions than the other three bioswales, with significant reductions of TKN, NO_x, TN, and TP. Filtration and biological processes, enhanced by the presence of vegetation, could explain higher load reductions in BG1. Flatter slopes would increase contact time, which should likewise benefit pollutant removal. While all four bioswales produced some significant reductions in dissolved metal loads, riprap swales generally were best at reducing Cd and Pb loads. The generally higher rates of sedimentation in the riprap bioswales herein may have contributed to these significant reductions.

3.3 Combined Riprap and Native Grass Performance

While not an initial consideration for this study, the blending of riprap and native grasses as an alternative lining became of interest when one of the riprap-lined bioswales, BR1, became overgrown with native grasses. Starting 25-AUG-2022, one month after all other experiments were completed, three more large storms were simulated to test the effect that riprap blended with native grasses had on swale hydrology and water quality treatment. A full analysis and discussion of results is included in Appendix L.

3.4 Turf Lining Comparison

Riprap and native grass-lined bioswales tended to better reduce nutrient concentrations in the overflow and the underdrain than the turf-lined bioswales. A full analysis and discussion of results is included in Appendix M.

Concentration reductions for TP and OP were greater for turf-lined bioswales because the inlet concentrations were substantially higher than those of riprap and native grasses. Native grasses had higher TKN, NO_x, and TN load reductions than both riprap and turf. Native grasses also had higher volume reduction than turf. Alternative liners herein may be a competitive option to turf because of their simpler, or less frequent, maintenance needs. Turf-lined swales require routine mowing, whereas riprap and native grass-lined swales may only require minimal weed management. The number of mowing cycles in a given season is regulated by the amount of turf growth, but is, on average, five cycles per year (Trogdon et al., 2017). Weed management includes the use of a non-selective herbicide for postemergence control and is careful to avoid undesired residual effects, such as damage from drainage runoff (Connect NCDOT, 2023). This maintenance task can be performed throughout the year, as necessary.

4. Manning's Roughness Coefficient Determination for Deep Rooted Native Grasses

This study completed experiments to determine roughness coefficients for swales lined with native grasses. To account for the relationship between roughness and flow depth, two flow depths were considered. A full analysis and discussion of results is included in Appendix N.

Results for Manning's roughness values are found in Tables 4-1. Average Manning's "n" values were 0.187 and 0.078 for the low and high flows, respectively. Flow rate had a more substantial impact on roughness than slope. In accordance with expectations (based on Chow, 1959; Lau & Afshar, 2013), the shallower slopes exhibited lower roughness than steeper slopes.

Table 4-1: Manning's "n" values for native grass lined swales.

Swale ID	Flow Level	Calculated n
CG1	Low	0.146

CG1	High	0.066
CG4	Low	0.227
CG4	High	0.089

North Carolina Department of Agriculture and Consumer Services (NCDA&CS) provides roughness coefficients for swales lined with turf grass, riprap, and turf reinforcement matting (Table 4-2). It is likely these values are associated with submerged grasses maintained at 0.10 - 0.15 m (4 - 6 in). Roughness values for native grasses were found to be higher than the established values for turf grass, riprap, and turf reinforcement matting, as could be expected with an unsubmerged, deep-rooted, native grass.

Table 4-2: Manning's "n" values for various channels (NCDA&CS, 2023).

Channel Lining	**Design n**
Turf Grass	0.033
Riprap	0.035
Turf Reinforcement Matting	0.038
Mean Native Grass Low Flow, herein	0.187
Mean Native Grass High Flow, herein	0.078

Variations in roughness values will impact swale design. Sample calculations were completed to demonstrate how a native grass lining impacts the required swale cross-sectional area and length. Results indicate native grasses require shorter lengths but larger cross-sections to accommodate the same flow rates and sediment trapping efficiencies as turf or riprap-lined swales.

FINDINGS AND CONCLUSIONS

Conventional Swales

- All four swales significantly and substantially infiltrated more runoff than those in literature and crediting documents (Davis et al., 2012; NCDEQ, 2017). However, volume reductions in literature and crediting documents are based upon swales monitored during actual weather events, rather than simulations such as those presented herein. Differences in volume reduction from this study to those observed ranged from approximately 1 - 60%. Native grass-lined swales reduced greater volumes than riprap at a 4% longitudinal slope, yet at a lower rate at a 1% slope.

- Similarly to volume reduction, peak flow rates were significantly and substantially reduced in all four swales, and more so than observed in literature (Ainan et al., 2003). Again, peak flow reductions in literature are based upon swales monitored during actual weather events, rather than simulations such as those presented herein. Higher volume reduction likely helped yield improved peak flow mitigation (Davis et al., 2009; Finotti et al., 2023). Greater peak flow reductions in native grass-lined swales likely occurred because of their greater dissipation of high-energy flows.

- Native grass-lined swales tended to reduce nutrient and dissolved metal concentrations more so than those lined with riprap. Both riprap and native grass swales significantly reduced the concentration of TSS in the 1% slope swales. All nutrients were significantly exported from swale CR1. Cu was also significantly exported from all four swales, possibly due to the influence of pH values, ion exchange, aeration and agitation, or metal binding (Borne and Tanner, 2013; Sansalone and Ying, 2008).

- Both native grass and riprap-lined swales have generally high nutrient and dissolved metal load reduction. Both TSS and TP were significantly reduced in both native grass-lined swales, but only reduced in the 1% riprap-lined swale. Sediment, all nutrients, and all dissolved metals were significantly reduced in swales CR1 and CG4. CG4 had the highest overall rates of nutrient and dissolved metal load reduction. Substantial load reductions were mostly the result of substantial volume reduction.

- When compared to turf-lined swales of the same slopes and storm sizes, it may be concluded that turf provides better sediment and dissolved metal concentration reductions. Native grasses and turf were essentially the same for nutrient concentrations. Native grasses and riprap had better sediment, nutrient, and dissolved metal load reductions than turf because of their high-volume reductions. There is reason to believe the lining had an effect on volume reduction. Additionally, alternative liners herein prove to be a competitive option over turf because of their simple, and/or less frequent maintenance procedures.

Bioswales

- Bioswales BR1, BG1, and BR4 infiltrated runoff comparable to those in literature (Davis et al., 2012), yet results herein were plot trials while those in literature were field studies. They also infiltrated runoff substantially higher than listed in crediting documents (NCDEQ, 2017). Riprap-lined swales reduced greater volumes than native grass when compared on a 1% slope. Differences in underlying soil hydraulic conductivity may have a pronounced effect on their ability to reduce volumes.

- Peak flow reductions were generally consistent with literature. No significant difference between linings was observed. Bioswales on the 1% slope significantly reduced peak flows at a higher rate than those on the 4% slope.

- Flatter slopes appear to yield better results. This may be due to an increased HRT caused by the flatter slope and greater resistance to flow (in the case of deep-rooted native grasses).

- Native grass-lined bioswales tended to reduce sediment and nutrient concentrations in the overflow and underdrain more so than those lined with riprap. Native grass bioswales significantly reduced TSS concentrations in the underdrain of the 1% slope as well as the overflow and underdrain of the 4% slope.

- Riprap-lined bioswales tended to reduce dissolved concentrations in the overflow and underdrain more so than those lined with native grasses. Cd concentrations were significantly removed from the overflow and underdrain of all four swales.

- TSS loads were significantly reduced in both native grass-lined bioswales. It is less clear which lining is best for nutrient load removal, but when factoring in slope, it appears BG1 had the best rates of nutrient load removal. Both riprap and native grass-lined bioswales had generally high metal load reductions. Considering sediment, nutrient, and dissolved metals, BG1 had the highest load reductions.

- Results associated with 1% slopes herein were compared to those of turf-lined bioswales studied by Purvis (2018), although there were differences in the conduct of experiments. Native grasses may be a competitive alternative lining to turf in bioswales because of their better nutrient removal and their less frequent maintenance needs. When considering load reductions, native grasses had higher TKN, NO_x, and TN load reductions than both riprap and turf. To have a complete comparison of turf-lined bioswales to those with alternative liners, bioswales on a 4% slope need to be tested. Ideally, three side-by-side plot trials would be conducted with turf grass and the alternative liners in bioswales to make a more confident recommendation. Additionally, field testing, rather than plot trials, should be conducted.

Manning's N

- Roughness values for native grasses were found to be higher than the established values for turf grass, riprap, and turf reinforcement matting, with a mean value of 0.13.

RECOMMENDATIONS

Conventional Swales

All four swales had significantly and substantially higher volume reduction than those in literature and crediting documents (Davis et al., 2012; NCDEQ, 2017). However, volume reductions in literature and crediting documents are based upon swales monitored during actual weather events, rather than simulations such as those presented herein. While it is possible the swales herein have unexpectedly high rates of infiltration, it should also be considered that, due to limitations in this controlled field study, flow rates were never particularly high. Native grass-lined swales reduced runoff volumes more so than riprap on a 4% longitudinal slope, yet not on 1% slopes.

Peak flow rates were significantly and substantially reduced in all four swales, and more so than observed in literature. Stagge (2006) observed vegetated swale peak flow reductions between 50 - 53%, while Ainan et al. (2003) and Wu et al. (1998) noted reductions of 25.7 - 55.9% and 10 - 20%, respectively. Higher volume reduction likely helped yield improved peak flow mitigation. Stagge (2006) reported mean volume reductions of 45.7 and 53.7% in two swales with length of 198 and 152.2 m (650 and 500 ft), respectively. Similarly, Ainan et al. (2003) observed volume reductions of 24.1 and 19.4% from rainfall intensities of 13.8 and 33.6 mm/hr, respectively. Their lower volume reductions than herein are likely the reason for lower peak flow reductions. Other factors such as soil characteristics (Davis et al., 2012), channel roughness, grass height and density (Bäckström, 2002; Deletic and Fletcher, 2006), and compaction of swale bed during construction (Gregory et al., 2006; Pitt et al., 2008) may contribute to higher peak flow reductions herein than observed in literature. Native grass-lined swales reduced peak flow rates more than riprap-lined swales at a 4% longitudinal slope. Greater peak flow reductions in native grass-lined swales likely occurred because of their higher Manning's roughness coefficients.

This study completed experiments to determine roughness coefficients for swales lined with native grasses. To account for the relationship between roughness and flow depth, two flow depths (low and high) were considered. Average Manning's "n" values were 0.187 and 0.078 for the low and high flows, respectively. Flow rate had a more substantial impact on roughness than slope. In accordance with expectations (based on Chow, 1959; Lau & Afshar, 2013), the shallower slopes exhibited lower roughness than steeper slopes. North Carolina Department of Agriculture and Consumer Services (NCDA&CS) provides roughness coefficients for swales lined with turf grass (n = 0.033), riprap (n = 0.035), and turf reinforcement matting (n = 0.038) (NCDA&CS, 2023). It is likely these values are associated with submerged grasses maintained at 0.10 - 0.15 m (4 - 6 in). Roughness values for native grasses were found to be higher than the established values for turf grass, riprap, and turf reinforcement matting, as could be expected with an unsubmerged, deep-rooted, native grass.

Both native grass and riprap-lined swales on the 1% slope significantly reduced TSS concentrations. Results indicated that shallower slopes yielded higher TSS concentration reductions, likely due to their higher rates of sedimentation. Native grass-lined swales tended to reduce nutrient and dissolved metal concentrations more so than those lined with riprap. In the case of nutrients, it is likely the vegetation in native grass-lined swales enhanced concentration reductions due to infiltration and biological processes throughout the length of the swale. Vegetation in the native grass-lined swales may have also enhanced dissolved metal concentration reduction via sedimentation and sorption. Dissolved metals cannot be removed by physical filtration like particulate metals are able but may bind to sediment to be removed

(Ranyuk, 2021). Both native grass and riprap-lined swales have generally high nutrient and metal load reduction. Sediment, all nutrients, and all dissolved metals were significantly reduced in swales CR1 and CG4. CG4 had the highest overall rates of nutrient and dissolved metal load reduction. Swales designed on a 4% slope rather than a 1% slope may be more advantageous for sites that require more runoff conveyance to maintain a flow depth of less than 0.15 m (6 in).

Considering sediment, nutrients, and dissolved metals results, native grasses have more consistent concentration and load reductions than those lined with riprap. Comparing native grasses, turf, and riprap, the native grass-lined swale on the 4% slope (CG4) provided the highest overall rates of nutrient and dissolved metal load reduction. If the installation of a swale on a 1% slope is necessary, a riprap lining should be considered, as it tended to decrease sediment, nutrient, and dissolved metal loads more than the turf and native grass-lined swales at 1%. Each of the riprap and native grass-lined swales had substantially more volume reduction than the turf-lined swales. It is likely the turf had lower volume reductions due to the presence of thatch. The development of thatch can alter the swale’s hydrological processes at the soil surface by changing the partitioning of rainfall into infiltration, runoff, and evaporation (Liang et al., 2017). The implementation of native grasses or riprap would greatly decrease maintenance requirements of conventional roadside swales, as they would not require regular mowing. Maintenance of native grass and riprap-lined swales would require routine inspections and, possibly, occasional weed management.

Bioswales Swales

Results indicate that riprap-lined bioswales significantly reduce volumes more than native grass-lined bioswales. The level of compaction during construction can reduce rates of volume reduction (Gregory, 2006). It is possible the soil in native grass-lined bioswales was more compacted than that of riprap-lined bioswales, lowering volume reduction. Additionally, 1% slopes reduce volumes significantly more than 4% slopes. This may be due to an increased HRT caused by the flatter slope and greater resistance to flow (in the case of deep-rooted native grasses).

Bioswales herein observed volume reductions within range, and slightly lower than noted by other researchers (Poresky et al., 2011; Osouli et al., 2017). Peak flow results for three of the four bioswales are within range or slightly lower than reported in literature (Stagge, 2006; Ainan et al., 2003; Wu et al., 1998).

Native grass-lined bioswales on the 4% slope significantly reduced TSS concentrations in the overflow and underdrain. Riprap on the 4% slope insignificantly reduced TSS concentrations in the overflow and underdrain. Surprisingly, results indicated that steeper slopes yielded higher TSS concentration reductions, possibly due to the influence of an underdrain and the engineered media. The engineered media introduces filtration as an additional pollutant removal mechanism. Native grass-lined swales tended to reduce nutrient concentrations in the overflow and underdrain more so than those lined with riprap. It is likely the vegetation in native grass-lined swales enhanced concentration reductions due to filtration and biological processes throughout the length of the swale and the engineered media. Considering sediment, nutrient, and dissolved metal concentration and load reductions, BG1 had the most occurrences of significant reductions, making it likely the most desirable of all four bioswales. Infiltration and biological processes, enhanced by the presence of vegetation, could explain higher reductions in the native grass swales.

Riprap-lined bioswales may be a competitive alternative to turf when focusing on TSS load reduction. Native grass swales had higher TKN, NO_x, and TN load reductions than those lined with either riprap or turf on 1% slopes. Native grass-lined bioswales also had higher volume reduction than turf-lined bioswales on the 1% slope during simulated medium storms. More data are needed for the alternative linings in bioswales to make a confident recommendation with regard to their replacement of turf. The implementation of native grasses or riprap as a liner would greatly decrease maintenance requirements of roadside bioswales, as they would not require regular mowing. Still bioswales, no matter the lining type, will require routine inspection of the underdrain along with unclogging or periodic replacement or amendment of the media mix (Blecken et al., 2017).

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Appendix A - Full Literature Review

Introduction

Developing practices to treat stormwater runoff has become more important as the rate of urbanization increases. Stormwater runoff collects and conveys pollutants to receiving waters. Certain pollutant concentrations of urban runoff often exceed those of treated wastewater, degrading surface water quality and ecosystem health (LeFevre et al., 2015). Since the Clean Water Act of 1972, the United States has taken intentional action to address both point and nonpoint sources of pollution, including the development and deployment of stormwater control measures (SCMs). Municipal, industrial, and transportation agencies are required to obtain national pollutant discharge elimination system (NPDES) permits to discharge pollutants to surface waters (Chang et al., 2018).

In recent years, stormwater has begun to be viewed as a valuable resource that provides ecosystem services (Ekka et al., 2021). Grass swales are one SCM designed to convey stormwater runoff and provide pollutant treatment. One of the oldest and most common SCMs, swales remain an ideal practice for linear environments. Design guidance has been developed and standardized for the hydraulic management and water quality treatment of swales (NCDEQ, 2017a; MEDEP, 2016; PADEP, 2006). Ongoing research furthers understanding of swales such that future design guidance can be informed.

Methodology

The literature search was conducted in Google Scholar ® and Web of Science ® databases accessed through the North Carolina State University libraries. Search terms such as “swale, bioswale, stormwater, maintenance, and water quality” were utilized. There is currently not extensive research on non-turf grass linings in roadside swales, so search terms such as “riprap”, “grass-lined channel,” and “native grasses” were added. The literature review evaluates peer-reviewed articles, textbooks, extension factsheets, design manuals, and academic theses and dissertations.

Swale Design

The foundation of swale design was based upon conveyance of runoff. Water quality treatment is now often additionally required (NCDEQ, 2009; Gavrić et al., 2019). Designers thus account for hydraulic retention time (HRT) to promote infiltration and pollutant removal. Flow retardance, soil permeability, underdrains, filter strips, and check dams are several design considerations for volume reduction and water quality treatment (Davis et al., 2012; Abida and Sabourin, 2006; Van Seters et al., 2006; Winston et al., 2019; Kaighn and Yu, 1996; Dunn et al., 1995). The physical, chemical, and biological pollutant removal mechanisms taking place in a swale include sedimentation, infiltration, filtration, sorption, microbial degradation, and vegetation uptake (Barrett et al., 1998; Lucke et al., 2014).

Current Design Considerations

Shape and Lining

Swale shape and lining impact runoff volume attenuation and pollutant removal. Flow retardance, or the swale's ability to slow down runoff, is dependent on the channel's shape and roughness, grass height, and grass density (Bäckström, 2002; Deletic and Fletcher, 2006; Ree, 1949). Swales should be designed as a trapezoidal channel with a base width not exceeding 1.83 m (6 ft), so as to avoid preferential flow paths (NCDEQ, 2017a). Their side slopes should be no steeper than 3:1 for ease of maintenance. The grass lining chosen for the swale should be non-clumping, deep-rooted, and rigid (NCDEQ, 2017a). Grass species that are deep-rooted and rigid have a greater ability to maintain their integrity and position against the flow of runoff. The grass should be maintained at an average height of 0.15 m (6 in) to provide optimal runoff treatment by preventing flow from submerging or overtopping the vegetation (Fiener and Auerswald, 2005; NCDEQ, 2017a).

Longitudinal Slope

Several studies indicate that total suspended solid (TSS) trapping and removal efficiency improves as the longitudinal slope decreases (Winston et al., 2017; Hwang and Weng, 2015; Yousef et al., 1987). Although there are limited field data to suggest an optimal slope, Yu et al. (2001) recommended swales be at least 75 m (246 ft) in length with a maximum slope of three percent.

Designers balance swale length and slope to achieve a desired HRT. Steeper slopes must be made longer than shallower sloped swales to meet HRT needs. The NCDEQ (2017a) Stormwater Design Manual currently states a swale's longitudinal slope should not exceed seven percent and should maintain a HRT of at least four minutes for pollutant treatment.

Conventional vs. Bioswale

Although conventional swales and bioswales look similar from the surface, bioswales have differing design elements that can be viewed from their cross-sections (Figures A-1 and A-2). A bioswale is a channel with an underlying permeable engineered media, a gravel layer, and a perforated underdrain. Pollutants are removed from runoff by filtration, sedimentation, straining, and infiltration as the runoff percolates through the media or flows on the surface (in the case of grass swales) (NCDEQ, 2017a).

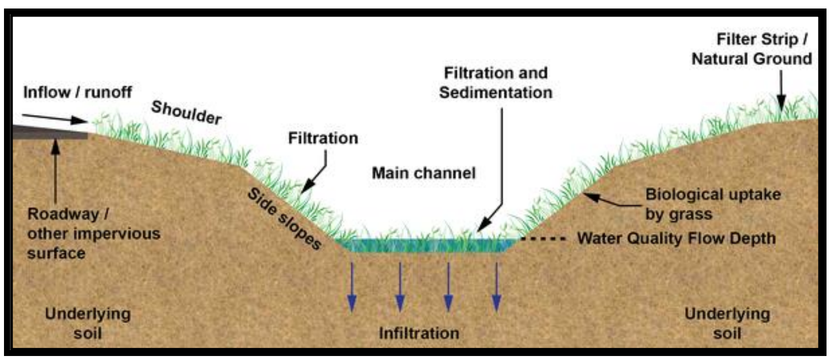


Figure A-1: Typical cross-section of a grass swale and its stormwater treatment processes (taken from Ekka and Hunt, 2020).

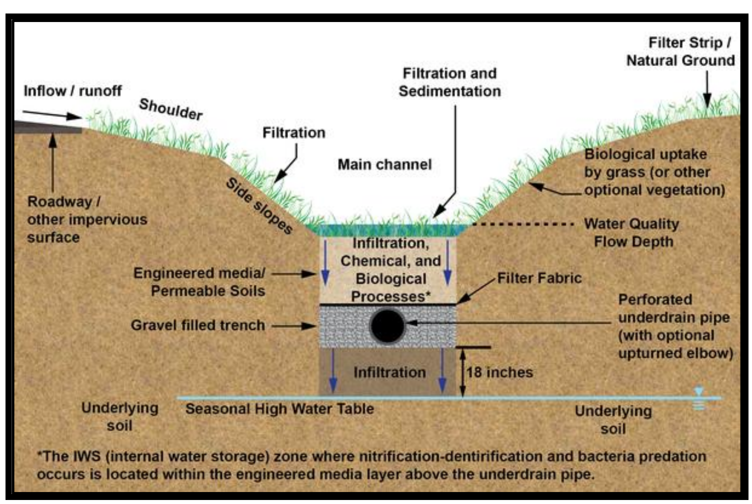


Figure A-2: Typical cross-section of a bioswale and its stormwater treatment processes (taken from Ekka and Hunt, 2020).

Manning's Roughness Coefficient

The Manning's roughness coefficient represents the hydraulic resistance offered by the swale liner (Kirby et al., 2005). Roughness values for turf-lined channels can range from 0.035 - 0.112, varying with depth of flow, and density and height of vegetation, but can decrease to 0.025 - 0.035 when grass is submerged (Arcement and Schneider, 1989; Chow, 1959; Barling and Moore, 1994). Kirby et al. (2005) extended the Stillwater retardance curves to estimate a Manning's roughness coefficient range (0.26 - 1.35) for a swale's transition from turbulent to laminar flow when grass is not submerged during flow (Ekka et al., 2021; Temple, 1982). These values may be considered high, as Bäckström (2002) has suggested a roughness coefficient range of 0.15 - 0.34, with grass height ranging from 0.001 - 0.003 m (0.003 - 0.01 ft) and not submerged. Roughness values used by NCDA&CS (2023) for grass channels in North Carolina range from 0.033 - 0.038, which is representative of unsubmerged grasses maintained at 0.10 - 0.15 m (0.33 - 0.5 ft).

Suggested roughness, side and longitudinal slopes, hydraulic radius, and vegetation height values are included in Temple's (1987) handbook on grass-lined open channels. Designers should refer to this handbook for guidance on constructing swales where vegetation is used as a lining for erosion protection. Seeking counsel from a local turf specialist may also be beneficial for vegetation selection.

Hydrologic Mitigation

The inclusion of underdrains, filter strips, and/or check dams in swales may increase volume attenuation (Abida and Sabourin, 2006). Underdrains enhance volume attenuation by way of increased infiltration (Davis et al., 2009). Groundwater interception by the underdrain should be avoided by placing them far enough above the water table (Abida and Sabourin, 2006).

Filter strips are permanently vegetated strips of land that diffuse flow by filtering, slowing, and infiltrating runoff (Figure A-3) (NCDOT, 2014). A swale with some underlying permeability that has been modified to include a check dam is called an "Infiltration Swale" (Figure A-4). The site's soil permeability can dictate whether to include filter strips and check dams into a swale. Compaction in the swale should be minimized to maintain the soil's permeability (Ahmed et al., 2015).

Figure 1-3: Filter strip (taken from Sundrain, 2023).

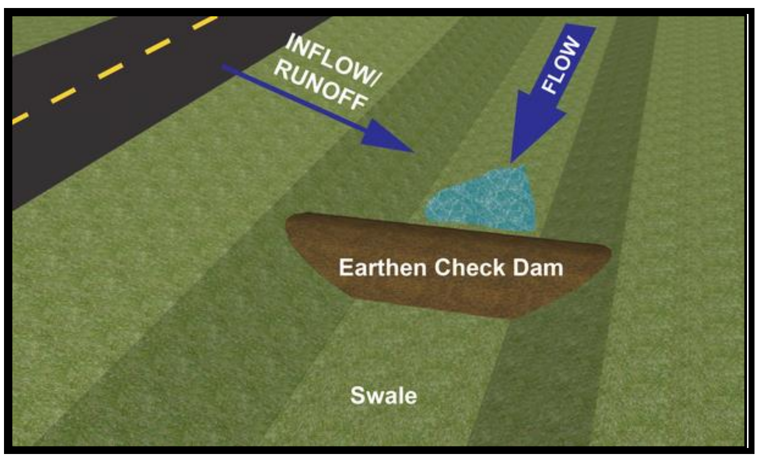


Figure A-4: Stylized cross-section of an infiltration swale with inclusion of a check dam (taken from Ekka and Hunt, 2020).

Davis et al. (2012) examined the hydraulic performance of a typical vegetated swale with a pre-treating grass filter strip and check dams. These design alternatives were compared for 52 storm events for volume and peak flow attenuation. They observed the addition of a filter strip hindered the swale's ability to attenuate runoff volume, perhaps due to swales' limited storage volume. Alternatively, the swale with both a filter strip and a check dam improved its volume attenuation. No discernible difference in the capture of small storm events (4 mm - 22 mm or 0.2 - 0.9 in) between the filter strip with the check dam were observed. For moderate events (23 mm – 33 mm or 0.9 in – 1.3 in), both designs significantly reduced the total volume and attenuated dynamic flow. Table A-1 provides swale design components as a summary of current peak flow mitigation guidance.

Table A-1: Swale design for stormwater conveyance and volume reduction (taken from Ekka et al., 2021).

Design Component	Common Design Guidance	Supporting Literature
Main channel	Increase the cross-sectional area to provide higher conveyance capacity. This can be achieved by a trapezoidal channel. If right-of-way space is limited a longer section of triangular channel with side slopes 6:1 (H:V), or shallower is better.	Chow (1959); Winston et al. (2017)
Vegetation type	Select a blend of species with tall and stiff grass blades	Fiener and Auerswald (2005)
Grass density	Non-clumping grasses with high density to prevent concentrated flow. Aim for grass cover of good-excellent for selected species (3000-9000 stems/m²).	Ree (1949); Temple (1982); Bäckström et al. (2006)
Channel roughness	Manning's roughness coefficient (n) between 0.26 and 0.35 for different grass types. Significantly lower at high flows when water depth exceeds grass height.	Kirby et al. (2005); Bäckström (2002); Barling and Moore (1994)
Check dams	Add earthen or rock structures located at the downstream end of swale or at drop inlet. Maximum height 60 cm	Kaighn and Yu (1996); Dunn et al. (1995); Winston et al. (2019)
Underdrains (optional)	Install perforated pipe systems in permeable soils with a minimum infiltration rate of 1 cm/h (0.5 in/h) and maintain sufficient separation from groundwater table	Abida and Sabourin (2006)
Construction technique	Minimize compaction in the main swale channel to maintain soil permeability	Ahmed et al. (2015)

Storm Design

Pitt (1999) defined five rainfall groupings for rainfall depth impacts: extra-small (< 5 mm or 0.2 in), small (5 mm - 13 mm or 0.2 - 0.5 in), medium (13 mm - 25 mm or 0.5 - 1.0 in), large (25 mm - 38 mm or 1.0 - 1.5 in), and extra-large (> 38 mm or 1.5 in). Storms ranging between 13 and 38 mm (0.5 and 1.5 in) are typically responsible for approximately 75% of the runoff pollutant discharges and were suggested by Pitt (1999) as the "water quality design storm," also commonly referred to as the "first flush." In North Carolina, water quality design storms range from 25 - 38 mm (1 - 1.5 in) (NCDEQ, 2017b).

Although Pitt (1999) defines rainfall groupings in terms of depth of rainfall, swales are not designed based on depth or volume of runoff. Rather, swales are designed based on a flow rate. In North Carolina, swales are designed for a 19 mm/hr (0.75 in/hr) storm that will result in a depth of flow of 15 cm (6 in) or less (NCDEQ, 2017a). The 19 mm/hr storm was chosen as a design standard because it falls within range of the "water quality design storm."

Water Quality Treatment Design

Gross filtration, sedimentation, infiltration, chemical precipitation, microbial degradation, and vegetation uptake are all pollutant removal mechanisms employed by types of grassed swales. As many are constructed along highways, swales typically treat runoff polluted by nitrogen, phosphorus, sediment, and heavy metals. How well these pollutant removal mechanisms work is dependent on the swale's surface area, length, depth, longitudinal and side slope, cross-sectional geometry, grass/vegetation, roughness coefficient, soil characteristics, and HRT as discussed previously herein and presented in detail by Ekka et al. (2021).

Sediment

While sediment is a pollutant needing treatment, it also conveys attached pollutants, such as heavy metals, pesticides, and polycyclic aromatic hydrocarbons (PAHs) (Megahan, 1999). Swales trap sediment particles exceeding 6-15 μm and sediment-borne pollutants (Ekka et al., 2021; Bäckström et al., 2002). Particles smaller than 6 μm are more difficult to capture because of the limited HRT in swales (Bäckström et al., 2006; Deletic and Fletcher, 2006). Particle settling is a function of HRT and particle size, and, thus, is dependent on the length of the swale and the flow velocity of the runoff.

The Aberdeen Equation (Equation A-1) can be used to design swales for sediment removal (Deletic, 2005). This method calculates the length of the swale needed to meet a target removal rate for TSS. The removal efficiency is calculated as:

$$Tr_s = \frac{N_f^{0.69}}{N_f^{0.69}+4.95} \tag{A-1}$$

Where:

- Tr_s is the trapping efficiency (%), and
- N_f is the particle fall number (dimensionless)

An equation to predict the particle fall number, N_f, was developed (Equation A-2). It is a ratio between the time of travel of a particle in the direction of flow and in the vertical direction (Deletic, 2005). N_f is calculated as:

$$N_f = \frac{xV_s}{hV} \tag{A-2}$$

Where:

- x is the distance traveled by the particle (m),
- V_s is the velocity at which the particle falls (m/s),
- h is the flow depth (m), and
- V is the flow velocity (m/s)

Winston et al. (2017) created a coupled hydraulics, hydrologic, and particle-settling model to predict the TSS removal for highway swales and filter strips based on the Aberdeen equation. TSS removal was calculated as a function of catchment area, longitudinal slope, side slope, cross section type, and length. To create their model, Winston et al. (2017) utilized field-collected road runoff particle size distributions (PSD) from a previous study by Winston and Hunt (2016). In total, 756 different swales were modeled for this experiment. Catchment areas of 0.1, 0.2, and 0.3 hectares, ranges of bed slope (0.5-10%), side slope (3:1 - 6:1), and swale shape (triangular and trapezoidal) were modeled.

Swale length significantly affected the TSS removal efficiency. The increased swale length concomitantly increased the HRT, thereby allowing more opportunity for filtration and sedimentation. Keeping design factors the same, trapezoidal swales removed, on average, 10% more TSS than the triangular swales (Figure A-5). The larger wetted perimeter of the trapezoidal swale resulted in lower flow depths that did not exceed grass height (Winston et al., 2017). Other researchers have monitored the highest rates of sediment removal to occur in the first 10 - 15 m (33 - 49 ft) of a swale (Lucke et al., 2014).

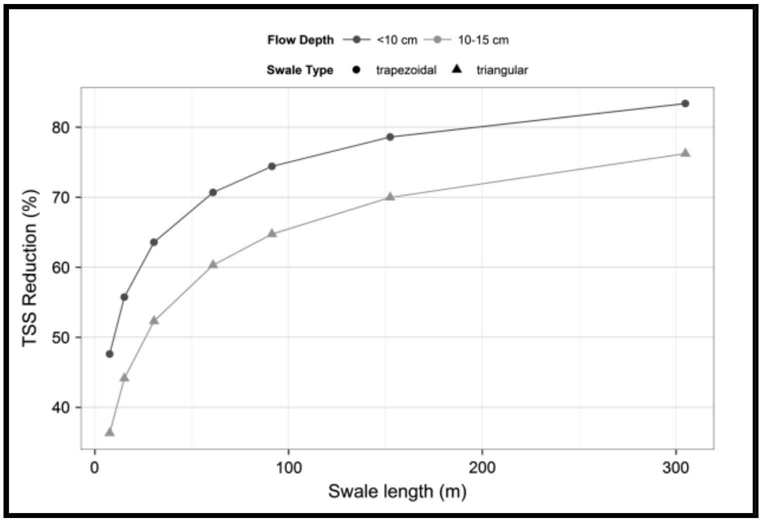


Figure A-5: TSS reduction (%) as a function of swale length for triangular and trapezoidal swales with 6:1 side slope, 1.5% longitudinal slope, and 0.1-ha catchment area (taken from Winston et al., 2017).

Nitrogen

How well swales treat nitrogen is inconclusive. Some researchers, such as Lucke et al. (2014), observed no removal of nitrogen by a grass swale, while others (Barrett et al., 1998; Winston et al. 2012) reported reduction in both total and dissolved nitrogen. Swales have contributed nitrogen to runoff, as extraneous organic matter, possibly from grass clippings and other plant debris, were deposited on the swale through maintenance activities (Davis et al., 2012; Ekka et al., 2021).

Other SCMs more effectively treat nitrogen. Bioretention and stormwater wetlands remove nitrogen, but are not ideally suited for a linear environment (NCDEQ, 2018a; NCDEQ, 2018b). Anaerobic conditions are required for nitrification-denitrification processes to occur and can be achieved through internal water storage (IWS) zones in a bioretention cell and permanent pooling in a stormwater wetland; nitrogen removal is enhanced by the presence of dense vegetation (NCDEQ, 2018a; NCDEQ, 2018b; Collins et al., 2010). Nitrogen-removing SCMs that align with roadway right-of-way traffic include bioswales and wet swales (Figures A-2 and A-6). These practices combine elements of bioretention cells and stormwater wetlands, respectively, with a grass swale to more effectively treat nitrogen. Wet swales, also known as wetland swales, appear to remove nitrogen better than grass swales or bioswales (Tang et al., 2016; Winston et al., 2012). Similar to stormwater wetlands, they provide unit processes of nitrification-denitrification, filtration, sedimentation, sorption, and plant uptake that enhance nitrogen removal in both particulate and dissolved forms of nitrogen (Tang et al., 2016; Winston et al., 2012).

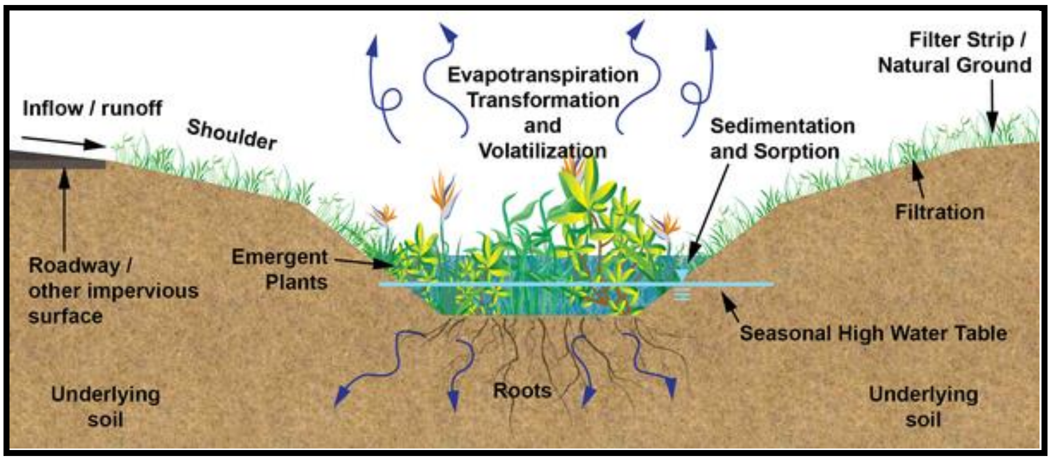


Figure A-6: Typical cross-section of a wet swale and its stormwater treatment processes (taken from Ekka and Hunt, 2020).

Phosphorus

Similar to nitrogen, research is not definitive regarding how effective grass swales treat phosphorus. Particulate phosphorus is sequestered through sedimentation, leaving only the dissolved fraction of phosphorus to be untreated by physical means.

Although there are no standardized swale design criteria targeting the removal of phosphorus, SCMs that force runoff to percolate through engineered media (Hatt et al., 2009; Hunt et al., 2006) often remove dissolved phosphorus. The media can chemically sorb phosphorus, likely making a bioswale the best choice for phosphorus treatment (Ekka et al., 2021). Purvis (2018) recommended geometry for bioswales, including having a forebay and at least one check dam in the bioswale to increase the HRT.

Heavy Metals

How swales treat heavy metals is well-documented in literature (Huber et al., 2016; Stagge et al., 2012). Common heavy metals existing in runoff are cadmium, copper, lead, nickel, and zinc in dissolved forms, while chromium and lead are particle-bound (Huber et al, 2016). Grass swales have been reported to remove metals more effectively than bioswales or wet swales (Gavrić et al., 2019), yet their performance depends on the height of the grass. Well-maintained grass height, so flow depth does not exceed grass height, and density is crucial to heavy metal removal by swales (Garvić et al., 2019, Kirby et al., 2005).

Purvis (2018) reported effective removal of cadmium, copper, lead, and zinc in a bioswale. The inclusion of a forebay increased the bioswale's ability to remove these metals. The engineered media, used in the construction of bioswales and bioretention cells, is ideal for the adsorption of metals. Metal adsorption increases with neutral or higher pH levels. Because typical urban runoff has low metal concentrations (10^1 - 10^2 μg/L), effective adsorption tends to occur within a pH of 6-7 (Hunt et al., 2012).

Use of Alternative Linings

While the grass-lined swale is most common, the use of an alternative lining may be a viable option if they are stable hydraulically and improve water quality while reducing maintenance requirements.

Successful alternative linings will decrease the likelihood of swale erosion. It is common for flow to create "shortcuts" resulting in erosion, scouring, and channelization (Li, 2015). Narrow swales with higher longitudinal slopes are at greater risk (Li, 2015). The use of a riprap or native grass lining may provide more stability in swales that are at increased risk of erosion.

Riprap Lining

Riprap are large stones used to stabilize and protect a soil surface against erosion. Swales on steeper slopes will be less likely to erode when lined with riprap rather than turf (Minnesota Pollution Control Agency, 2022; Massachusetts Department of Environmental Protection, 2003). Rice et al. (1998)

conducted a study to determine the Manning's roughness coefficients of riprap laid on steep slopes. Trials were administered in a flume with the D_{50} of riprap ranging from 52 to 278 mm and bed slopes, S_o, ranging from 0.028 to 0.333 m/m. The Darcy-Weisbach and Manning roughness coefficients were determined. Results indicated channel roughness would increase concomitantly with bed slope or riprap size (Figure A-7) (Rice et al., 1998). Equations A-3 and A-4 were developed and recommended for calculating the Darcy-Weisbach and Manning roughness coefficients, respectively, for channels constructed with riprap and slopes ranging from 2.8% and 33.3%.

$$\left(\frac{8}{f}\right)^{1/2} = 5.1log\left(\frac{d}{D_{84}}\right) + 6 \qquad \text{(A-3)}$$

Where:

- f is the Darcy-Weisbach friction coefficient (dimensionless),
- $\frac{d}{D_{84}}$ is the relative submergence (dimensionless),
- d is the flow depth (mm), and
- D_{84} is the bed material size (mm)

$$n = 0.029(D_{50}S_0)^{0.147} \qquad \text{(A-4)}$$

Where:

- n is Manning's roughness coefficient (dimensionless),
- D_{50} is the riprap size for which 50% of material is finer (mm), and
- S_0 is the tangent of the bed slope angle

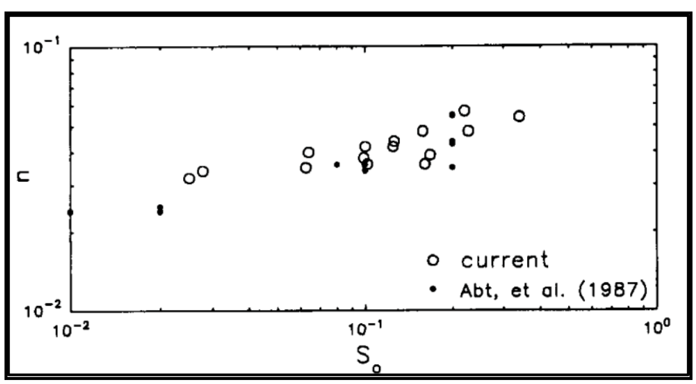


Figure A-7: Manning's n vs. bed slope (taken from Rice et al., 1998).

Swales constructed along roadways that require a steeper bed slope, and prone to experience persistent erosion, may benefit from a riprap lining because of the protection it provides the underlying soil. Riprap prevents erosion by dissipating high-energy stormwater flows (Minnesota Pollution Control

Agency, 2023). Decreasing runoff flow rate allows for: 1) lower shear stress, 2) a longer HRT and, 3) thus, higher rates of pollutant removal.

Native Grass Lining

Native grasses offer an alternative lining to turf grass in a roadside swale. NCDEQ (2017a) states the turf lining in swales should be maintained at an average of 0.15 m (6 in). Many turf grasses will not remain sufficiently rigid in the face of flow, especially as they grow taller (Mugaas et al., 2005). This leads to minimal flow retardance, concomitantly limiting pollutant removal (Ekka et al., 2021). However, certain deep-rooted native grass species can grow taller than 0.9 m (3 ft) while maintaining their rigidity. Maintaining native grasses is cheaper than turf grass: lower labor, water, fertilizer, herbicides, insecticides, fungicides, and moving costs (U.S. EPA, 2016). Native grasses provide other benefits including reduced soil erosion, improved water quality, reduced air and noise pollution, reduced greenhouse effect, habitat restoration and protection, and beautification (U.S. EPA, 2016). Future research could establish native grasses as a viable option for the lining of swales, assuming they provide similar (or better) water quality benefits to turf grass.

Native Grass Erosion Protection

It is important to consider hydraulic properties such as flow retardance and erosion control when considering an alternative lining, such as native grasses. Manning's equation (Equation A-5) can be manipulated to calculate the resistance to flow provided by the native grass lining, and therefore, the flow retardance.

$$V = \frac{1}{n} R^{2/3} S^{1/2} \tag{A-5}$$

Where:

- V is the velocity (m/s),
- n is Manning's roughness coefficient (dimensionless),
- R is the channel's hydraulic radius (m), and
- S is the slope of the energy line (m/m)

The maximum permissible velocity is that which a lining can withstand before erosion occurs (Gwinn and Ree, 1980). Gwinn and Ree (1980) studied flow through various states of cover in vegetative-lined channels, including native grasses that were uncut or mowed to determine scour rates and maintenance effects. Native grasses planted for this study were blue grama (*Bouteloua gracilis*), sideoats grama (*Bouteloua curtipendula*), and little bluestem (*Andropogon scoparius*). Gwinn and Ree (1980) reported that uncut native grasses had similar average velocities to native grasses cut to a height of 0.1 m (3.6 in) (Table A-2). The maximum permissible velocity for cut grass at 3% slope was 1.5 m/s (5 ft/s). At this velocity, all native grass cover protected the channel with limited scouring. The maximum permissible velocity at 6% slope was 1.1 m/s (3.6 ft/s). Again, all uncut and cut grasses in the 6% sloped channels protected the channel with limited scouring. This study provides evidence that taller grasses protect against erosion.

Maintenance Considerations

Grass swales are popular for their simple design and inexpensive construction cost. The current maintenance regime for grass swales includes mowing and routine inspection. Other maintenance needs are clearing inlets, outlets, and check dams of any accumulated trash, debris, and silt (Sañudo-Fontaneda et al., 2020). When swales are insufficiently maintained, they can lose capacity for runoff conveyance and water quality treatment. For example, flow retardance may be minimized if the grass lining does not remain sufficiently rigid as a result of being left un-mowed. Circumstances, such as COVID-19, where maintenance labor is limited, budgets are reduced, and uncontrolled vegetation growth and silt accumulation impact the performance should be considered during the design of a swale (Sañudo-Fontaneda et al., 2020).

Bioswales require modestly more maintenance than the typical grass swale, as their design includes an underdrain and engineered media. Similar to bioretention cells, the underdrain will need routine inspection along with unclogging or periodic replacement of the media mix (Blecken et al., 2017). Like stormwater wetlands, wet swales may need their forebays cleared, invasive vegetation removed, and inlet and outlet structural repair (Blecken et al., 2017). The routine care and attention given to the maintenance of SCMs such as these will prolong their design lives and could prevent future otherwise unnecessary restoration costs.

Swale maintenance currently involves periodic mowing which is a part of normal right-of-way mowing operations. Maintenance challenges arise when swales are sited outside of normal mowing patterns. Such swales may be overgrown with non-grass vegetation or become shaded from overhead canopy, thereby potentially limiting grass coverage (Hunt et al., 2015; Mazer et al., 2001) This can lead to erosion within the swale (Minnesota Pollution Control Agency, 2023). The implementation of riprap or native grasses as an alternative lining to swales would decrease maintenance labor and costs considerably by way of reducing mowing frequency. Riprap and native grasses may also be more resistant to erosion than turf-lined swales.

Summary and Conclusions

The objective of this review was to analyze how typical roadside swales are designed and assessed, while examining maintenance and water quality impacts of lining swales with riprap and native grasses. Existing guidance is often based on previous research. Volume attenuation in an infiltration swale may be improved with the inclusion of a filter strip. Swales with a trapezoidal cross-section may have higher TSS removal than those with triangular cross-sections due to lower flow depths not exceeding grass height. Wet swales are the most effective swale alternative for nitrogen removal while bioswales are most effective in treating phosphorus and bacteria. Both wet swales and bioswales remove heavy metals.

Using channel linings alternative to turf grass may better protect against erosion and reduce maintenance burdens, by reducing mowing frequency, while still sufficiently treating pollutants. Swales constructed along roadways that require a steeper bed slope, and are prone to experience persistent erosion, may benefit from a riprap lining because of the higher roughness coefficient. Additionally, evidence exists suggesting native grass-lined swales will sufficiently prevent erosion in swales by dissipating energy and decreasing runoff flow rates. Ease of maintenance, cost, and labor should be considered prior to the design and construction of a swale. Ongoing and future research on alternatively lined swales is needed to formulate these recommendations.

Appendix B – Materials and Methods Background

Original Conventional Swale Construction

A small dike/berm was placed around the perimeter of the northeastern-most swales to divert run-on from adjacent lands to the construction site during rainfall events (Ekka and Hunt, 2020a). Figure B-1 presents a typical grading operation for swale construction. Compaction of the native soil in the swale beds and main channels was avoided as much as possible so as to limit its impact on infiltration.

Figure B-1: Grading operation for construction of conventional swale.

The initial lining installed in the swales was tall fescue sod. Figure B-2 displays the installation of the sod after grading had been completed (Ekka and Hunt, 2020a). Once the roots had grown beyond the sod mats into the underlying soil, the grass was considered established.

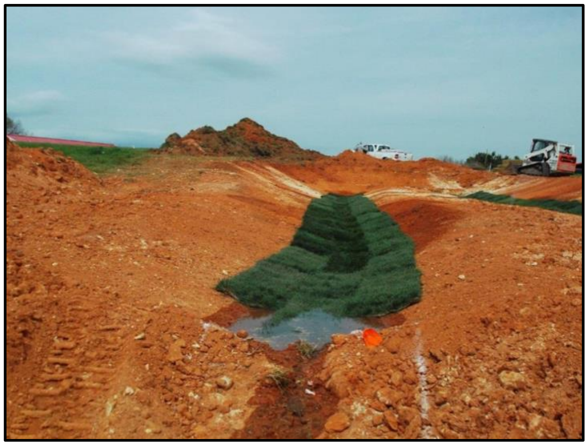


Figure B-2: Sod installation in swales.

After the swales were established, wooden outlet monitoring boxes (Figure B-3) were installed at the downstream end of each swale. The monitoring boxes were constructed from plywood with dimensions of 1.2 m x 1.2 m x 0.6 m, L x W x D (4 ft x 4 ft x 2 ft) (Figure B-3). Each box included a 60° v-notch weir to collect the water samples and measure the water level to determine the flowrate. A 20 cm (8 in) PVC drainage pipe was attached at the outlet of each monitoring box to discharge the runoff collected from the simulated experiments and rainfall events. All surrounding areas were reseeded after the outlet monitoring boxes were installed (Figure B-4).

Figure B-3: Outlet structure/monitoring box installation.

Figure B-4: Conventional swale completed with turf and outlet structure.

The swales received routine maintenance, including mowing the turf grass. No fertilizer, herbicide, or pesticides were applied in or around the swales during the construction phase.

Original Bioswale Construction

To construct the bioswales, a trench with a width of 0.9 m (3 ft) and depth of 0.9 m (3 ft) was excavated and lined with a woven geotextile (AASHTO M-288, Class 3; approx. 163 L/min/m^2) (Purvis, 2018). The base of the trench was filled with 0.15 m (6 in) of ASTM standard #57 stone (0.2 to 3.8 cm stone size (NCDOT, 2016)). A perforated high-density polyethylene (HDPE) pipe with a 0.15 m (6 in) outer diameter (OD) was wrapped with a filter sock and placed over the stone layer along the entire length of the bioswale. The pipe was then covered with another layer of ASTM #57 stone, providing a depth of 0.3 m (1 ft) of stone and underdrain within the layer (Purvis, 2018). The underdrain/stone layer was covered with Type 2 geotextile (Propex™ Geotex ® 801; 6111.87 L/min/m^2) (NCDOT, 2018b) to prevent the media from migrating to the underdrain and stone layer (Purvis, 2018). The remaining 0.6 m (2 ft) of the depth of the trench was filled with high-flow media comparable to the NCDEQ standard (NCDEQ, 2009), with 12% fines and 88% sand, and covered with Centipede sod (*Eremochloa ophiuroides*).

Appendix C – Inflow Corrections

After data collection was completed, the research team realized that during the most intense portion of each simulated storm, the inlet weir was no longer acting under free-flow conditions. This resulted in an inaccurate inlet flow rate and an over-estimation of the cumulative inflow. To correct for this error, an additional weir box with no tailwater conditions was installed slightly downstream of the original weir box (Figure C-1). A trial was then conducted to collect flow rates from both the original and additional downstream weir box. Results showed that above a level of approximately 0.23 m (0.75 ft) in the original weir box, free-flow conditions were lost. An accurate flow rate corresponding to 0.23 m (0.75 ft) was determined with sampling equipment in the additional weir box. An average flow rate of 9×10^{-3} cms (0.3186 cfs) was substituted when water levels exceeded 0.23 m (0.75 ft) (Figure C-2).

Figure C-1: Downstream weir box leveling (left) and installation (right).

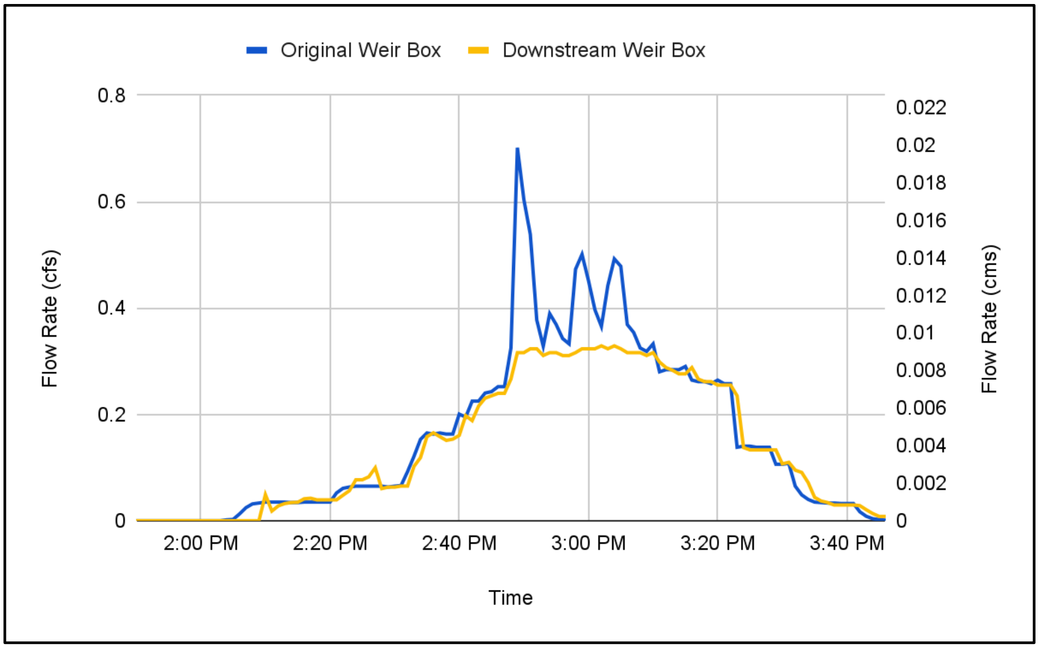


Figure C-2: Original vs downstream weir box flow rates.

Example Inflow Correction Calculations

Table C-1 gives an example data-set of the flow rate and volume from the original weir used in all experiments then the corrected flow rate and volume. An average flow rate of 0.3186 cfs was used in the corrected flow rate if the stage was higher than 0.75 ft (shown in bold). For the given experiment on 8/25/22, the original total volume was 652.4 cf and the corrected total volume was 524.6 cf. The following equations were used to calculate the inflow correction:

$$Q\ (cfs) = 0.676 * Stage^{2.5}$$

$$Corrected\ Q\ (cfs) = 0.676 * Stage^{2.5}\ OR\ 0.3186\ if\ Stage\ is\ higher\ than\ 0.75\ ft$$

$$V\ (cf) = Q\left(\frac{ft^3}{s}\right) * (t_2 - t_1)(sec)$$

Table C-1: Example data-set of inflow volume correction (from CG4 experiment on 8/25/22). Bold values when volume was corrected to average.

Date and Time	Stage (ft)	Q (cfs)	V (cf)	Corrected Q (cfs)	Corrected V (cf)
8/25/22 9:49	0	0.00	0.00	0.00	0.00
8/25/22 9:50	0	0.00	0.00	0.00	0.00
8/25/22 9:51	0	0.00	0.00	0.00	0.00
8/25/22 9:52	0.015	0.00	0.00	0.00	0.00
8/25/22 9:53	0.067	0.00	0.05	0.00	0.05
8/25/22 9:54	0.113	0.00	0.17	0.00	0.17
8/25/22 9:55	0.139	0.00	0.29	0.00	0.29
8/25/22 9:56	0.11	0.00	0.16	0.00	0.16
8/25/22 9:57	0.011	0.00	0.00	0.00	0.00
8/25/22 9:58	0	0.00	0.00	0.00	0.00
8/25/22 9:59	0	0.00	0.00	0.00	0.00
8/25/22 10:00	0.015	0.00	0.00	0.00	0.00
8/25/22 10:01	0.116	0.00	0.19	0.00	0.19
8/25/22 10:02	0.172	0.01	0.50	0.01	0.50
8/25/22 10:03	0.167	0.01	0.46	0.01	0.46
8/25/22 10:04	0.182	0.01	0.57	0.01	0.57
8/25/22 10:05	0.143	0.01	0.31	0.01	0.31
8/25/22 10:06	0.166	0.01	0.46	0.01	0.46
8/25/22 10:07	0.199	0.01	0.72	0.01	0.72
8/25/22 10:08	0.222	0.02	0.94	0.02	0.94
8/25/22 10:09	0.304	0.03	2.07	0.03	2.07
8/25/22 10:10	0.363	0.05	3.22	0.05	3.22
8/25/22 10:11	0.416	0.08	4.53	0.08	4.53
8/25/22 10:12	0.416	0.08	4.53	0.08	4.53
8/25/22 10:13	0.376	0.06	3.52	0.06	3.52
8/25/22 10:14	0.376	0.06	3.52	0.06	3.52
8/25/22 10:15	0.429	0.08	4.89	0.08	4.89
8/25/22 10:16	0.531	0.14	8.33	0.14	8.33
8/25/22 10:17	0.563	0.16	9.65	0.16	9.65
8/25/22 10:18	0.895	0.51	30.73	**0.3186**	19.11
8/25/22 10:19	0.872	0.48	28.80	**0.3186**	19.11
8/25/22 10:20	0.99	0.66	39.55	**0.3186**	19.11
8/25/22 10:21	1.049	0.76	45.71	**0.3186**	19.11
8/25/22 10:22	0.98	0.64	38.56	**0.3186**	19.11
8/25/22 10:23	0.76	0.34	20.42	**0.3186**	19.11
8/25/22 10:24	0.885	0.50	29.88	**0.3186**	19.11
8/25/22 10:25	0.931	0.57	33.92	**0.3186**	19.11
8/25/22 10:26	0.895	0.51	30.73	**0.3186**	19.11
8/25/22 10:27	0.665	0.24	14.63	0.24	14.63
8/25/22 10:28	0.763	0.34	20.62	**0.3186**	19.11
8/25/22 10:29	0.553	0.15	9.22	0.15	9.22
8/25/22 10:30	0.35	0.05	2.94	0.05	2.94
8/25/22 10:31	0.284	0.03	1.74	0.03	1.74
8/25/22 10:32	0.35	0.05	2.94	0.05	2.94
8/25/22 10:33	0.376	0.06	3.52	0.06	3.52
8/25/22 10:34	0.36	0.05	3.15	0.05	3.15
8/25/22 10:35	0.393	0.07	3.93	0.07	3.93
8/25/22 10:36	0.406	0.07	4.26	0.07	4.26
8/25/22 10:37	0.376	0.06	3.52	0.06	3.52

8/25/22 10:38	0.396	0.07	4.00	0.07	4.00
8/25/22 10:39	0.409	0.07	4.34	0.07	4.34
8/25/22 10:40	0.389	0.06	3.83	0.06	3.83
8/25/22 10:41	0.38	0.06	3.61	0.06	3.61
8/25/22 10:42	0.403	0.07	4.18	0.07	4.18
8/25/22 10:43	0.396	0.07	4.00	0.07	4.00
8/25/22 10:44	0.37	0.06	3.38	0.06	3.38
8/25/22 10:45	0.409	0.07	4.34	0.07	4.34
8/25/22 10:46	0.416	0.08	4.53	0.08	4.53
8/25/22 10:47	0.429	0.08	4.89	0.08	4.89
8/25/22 10:48	0.498	0.12	7.10	0.12	7.10
8/25/22 10:49	0.498	0.12	7.10	0.12	7.10
8/25/22 10:50	0.471	0.10	6.17	0.10	6.17
8/25/22 10:51	0.57	0.17	9.95	0.17	9.95
8/25/22 10:52	0.609	0.20	11.74	0.20	11.74
8/25/22 10:53	0.675	0.25	15.18	0.25	15.18
8/25/22 10:54	0.57	0.17	9.95	0.17	9.95
8/25/22 10:55	0.599	0.19	11.26	0.19	11.26
8/25/22 10:56	0.645	0.23	13.55	0.23	13.55
8/25/22 10:57	0.603	0.19	11.45	0.19	11.45
8/25/22 10:58	0.55	0.15	9.10	0.15	9.10
8/25/22 10:59	0.619	0.20	12.23	0.20	12.23
8/25/22 11:00	0.639	0.22	13.24	0.22	13.24
8/25/22 11:01	0.55	0.15	9.10	0.15	9.10
8/25/22 11:02	0.606	0.19	11.59	0.19	11.59
8/25/22 11:03	0.609	0.20	11.74	0.20	11.74
8/25/22 11:04	0.426	0.08	4.80	0.08	4.80
8/25/22 11:05	0.33	0.04	2.54	0.04	2.54
8/25/22 11:06	0.307	0.04	2.12	0.04	2.12
8/25/22 11:07	0.271	0.03	1.55	0.03	1.55
8/25/22 11:08	0.248	0.02	1.24	0.02	1.24
8/25/22 11:09	0.219	0.02	0.91	0.02	0.91
8/25/22 11:10	0.212	0.01	0.84	0.01	0.84
8/25/22 11:11	0.196	0.01	0.69	0.01	0.69
8/25/22 11:12	0.193	0.01	0.66	0.01	0.66
8/25/22 11:13	0.196	0.01	0.69	0.01	0.69
8/25/22 11:14	0.199	0.01	0.72	0.01	0.72
8/25/22 11:15	0.193	0.01	0.66	0.01	0.66
8/25/22 11:16	0.186	0.01	0.61	0.01	0.61
8/25/22 11:17	0.193	0.01	0.66	0.01	0.66
8/25/22 11:18	0.186	0.01	0.61	0.01	0.61
8/25/22 11:19	0.176	0.01	0.53	0.01	0.53
8/25/22 11:20	0.183	0.01	0.58	0.01	0.58
8/25/22 11:21	0.173	0.01	0.50	0.01	0.50
8/25/22 11:22	0.166	0.01	0.46	0.01	0.46
8/25/22 11:23	0.163	0.01	0.44	0.01	0.44
8/25/22 11:24	0.156	0.01	0.39	0.01	0.39
8/25/22 11:25	0.163	0.01	0.44	0.01	0.44
8/25/22 11:26	0.153	0.01	0.37	0.01	0.37
Total			652.37		524.59

Appendix D – Materials and Methods Details

Additional Figures and Tables

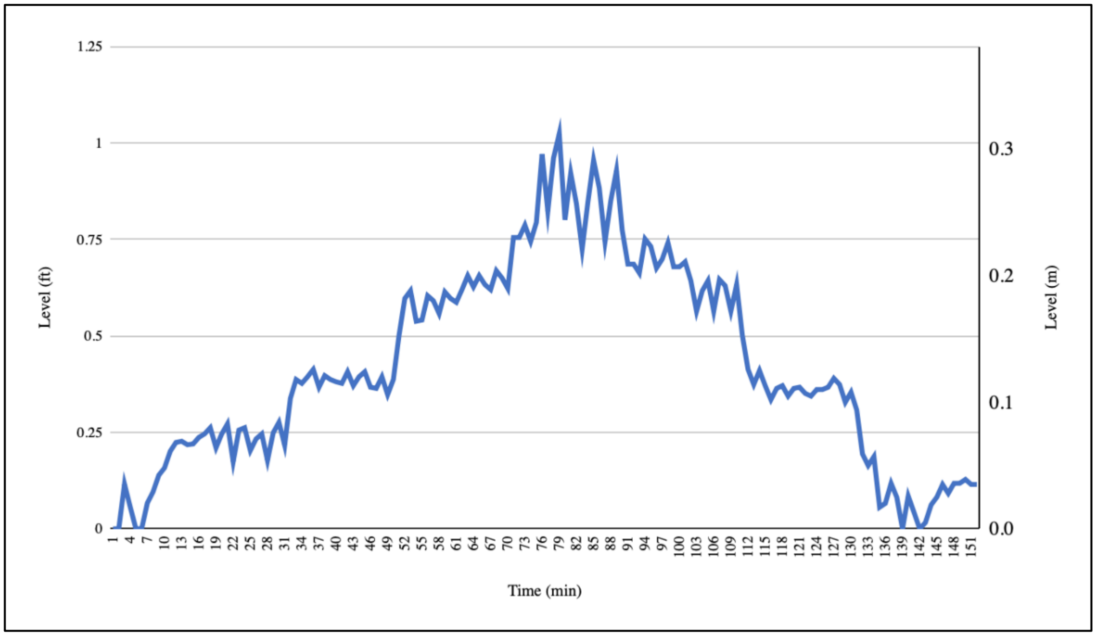
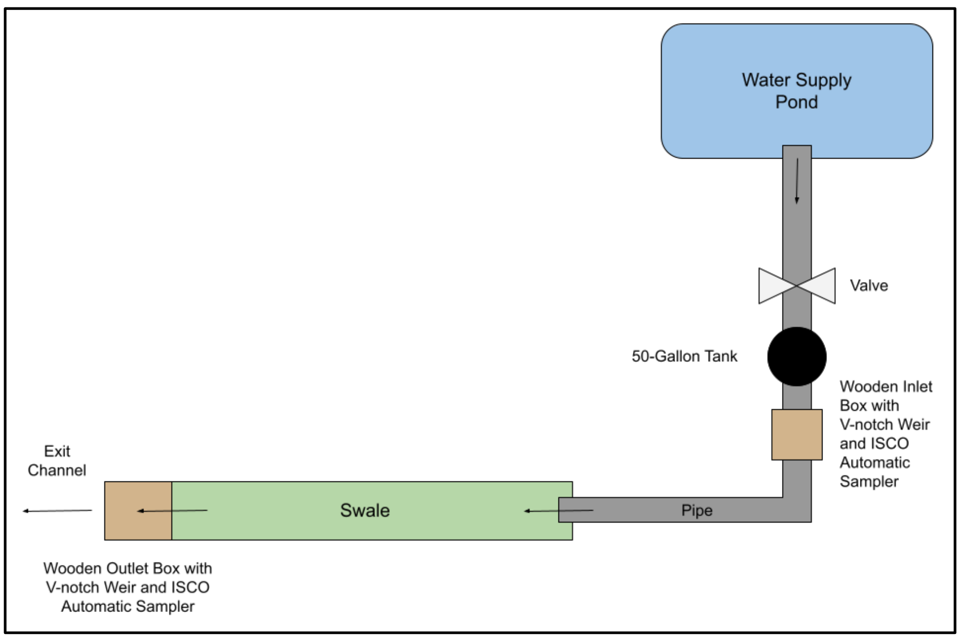


Figure D-1: Example center-weighted hydrograph for experiment of swale BG4 on 7/7/2022.



D-2: Conceptual swale experimental setup.

Figure D-3: ASTM sieves #'s 10 and 35 with mortar and pestle used to prepare pollutant spikes.

Table D-1: Amounts of sediment, nutrients, and metals for medium-sized storm experiments.

Step #	Sediment (g)	N (g)	P (g)	Copper (g)	Lead (g)	Cadmium (g)	Zinc (g)
1	59	0.36	0.13	0.01	0.01	0.003	0.09
2	99	0.61	0.22	0.02	0.01	0.01	0.15
3	311	1.91	0.69	0.08	0.04	0.02	0.48
4	466	2.86	1.03	0.11	0.05	0.03	0.72
5	423	2.59	0.94	0.10	0.05	0.02	0.65
6	344	2.11	0.76	0.08	0.04	0.02	0.53
7	201	1.23	0.45	0.05	0.02	0.01	0.31
	1903	**11.67**	**4.22**	**0.45**	**0.22**	**0.113**	**2.93**

Table D-2: Amounts of sediment, nutrients, and metals for large-sized storm experiments.

Step #	Sediment (g)	N (g)	P (g)	Copper (g)	Lead (g)	Cadmium (g)	Zinc (g)
1	106	0.54	0.20	0.02	0.01	0.005	0.14
2	183	0.94	0.34	0.04	0.02	0.01	0.23
3	414	2.13	0.77	0.08	0.04	0.02	0.53
4	596	3.07	1.10	0.12	0.06	0.03	0.76

5	541	2.78	1.00	0.11	0.05	0.03	0.69
6	466	2.40	0.86	0.09	0.04	0.02	0.60
7	282	1.45	0.52	0.06	0.03	0.01	0.36
	2588	**13.31**	**4.79**	**0.52**	**0.25**	**0.125**	**3.31**

Figure D-4: Spiked sample mixing with water.

Figure D-5: Composite samples for lab analyses.

Table D-3: Analytical methods, reporting limits, and sample hold times of pollutants.

Pollutant	Analytical Method	PQL (µg/L)	Maximum Sample Hold Time	Preservation
Total Suspended Solids (TSS)	Std. Method 2540D	2,500	7 days	On ice
Total Kjeldahl Nitrogen (TKN)	EPA Method 351.1	280	28 days	On ice
Nitrate/Nitrite Nitrogen (NO_x)	Std. Method 4500 NO3 F EPA Method 353.3	11.2	28 days	On ice
Total Nitrogen (TN)	TN = TKN + NO_x	-	-	-
Ammoniacal Nitrogen (NH_3)	Std. Method 4500 NH3 H EPA Method 350-1	17.5	28 days	On ice
Total Phosphorus (TP)	Std. Method 4500 P F EPA Method 365.1	10	28 days	On ice
Ortho-Phosphate (OP)	Std. Method 4500 P F EPA Method 365.1	12	48 hours	On ice; bottle pre-acidified by lab
Dissolved Cadmium (Cd)	EPA 200.8 Rev. 5.4 EPA 200.9 Rev. 2.2	0.50	6 months	1+1 HNO_3 to pH < 2[26]
Dissolved Copper (Cu)	EPA 200.8 Rev. 5.4 EPA 200.9 Rev. 2.2	2.0	6 months	1+1 HNO_3 to pH < 2[26]
Dissolved Lead (Pb)	EPA 200.8 Rev. 5.4 EPA 200.9 Rev. 2.2	2.0	6 months	1+1 HNO_3 to pH < 2[26]
Dissolved Zinc (Zn)	EPA 200.7 Rev. 4.4 EPA 200.8 Rev. 5.4	10	6 months	1+1 HNO_3 to pH < 2[26]

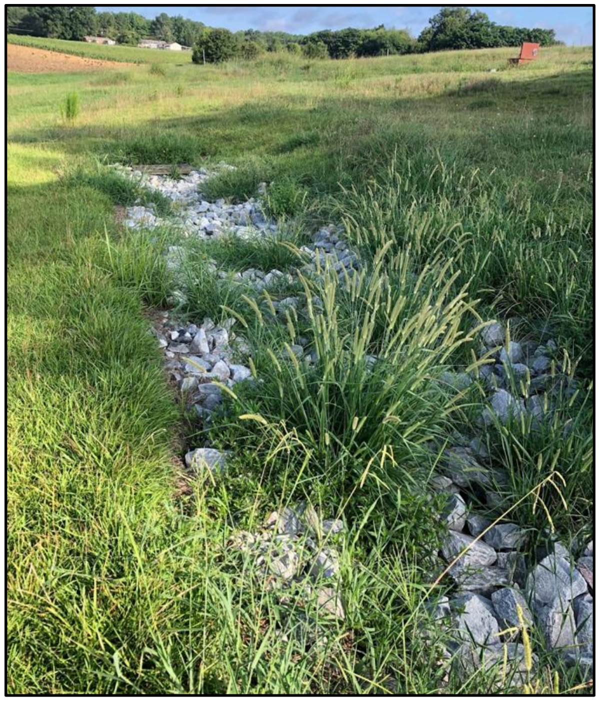


Figure D-6: Riprap-lined bioswale overgrown by native grasses.

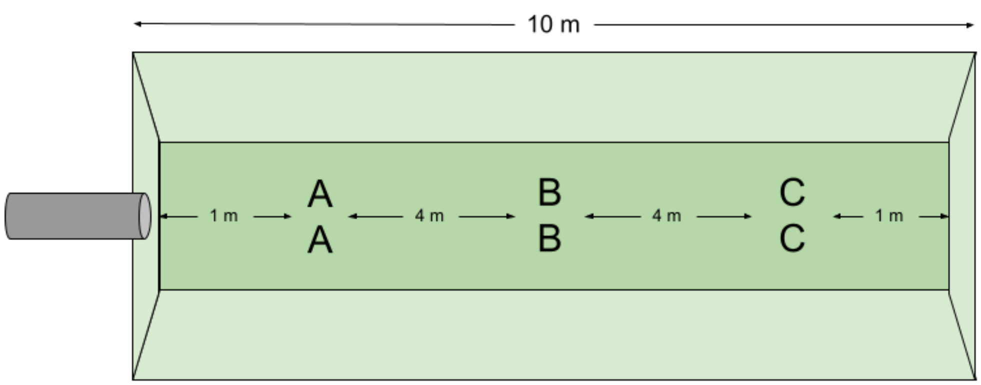


Figure D-7: Bulk density sampling placement.

Table D-4: Bulk density results for conventional swales.

Treatment	Location	Rep	Bulk Density (g/cm³)
CR1	A	surface	1.08
		sub	1.22
	B	surface	1.06
		sub	1.38
	C	surface	1.36
		sub	1.32
CG1	A	surface	1.19
		sub	1.30

	B	surface	1.26
		sub	1.12
	C	surface	1.28
		sub	1.22
CR4	A	surface	1.21
		sub	1.30
	B	surface	1.14
		sub	1.22
	C	surface	1.16
		sub	1.22
CG4	A	surface	0.99
		sub	0.97
	B	surface	1.03
		sub	1.32
	C	surface	0.97
		sub	1.14

Table D-5: Bulk density results for bioswales.

Treatment	Location	Rep	Bulk Density (g/cm³)
BR1	A	surface	1.37
		sub	1.35
	B	surface	1.42
		sub	1.39
	C	surface	1.24
		sub	1.20
BG1	A	surface	1.34
		sub	1.33
	B	surface	1.37
		sub	1.35
	C	surface	1.21
		sub	1.11
BR4	A	surface	1.17
		sub	1.20
	B	surface	1.35
		sub	1.37
	C	surface	1.14
		sub	1.33
BG4	A	surface	1.36
		sub	1.35
	B	surface	1.36
		sub	1.40
	C	surface	1.36
		sub	1.00

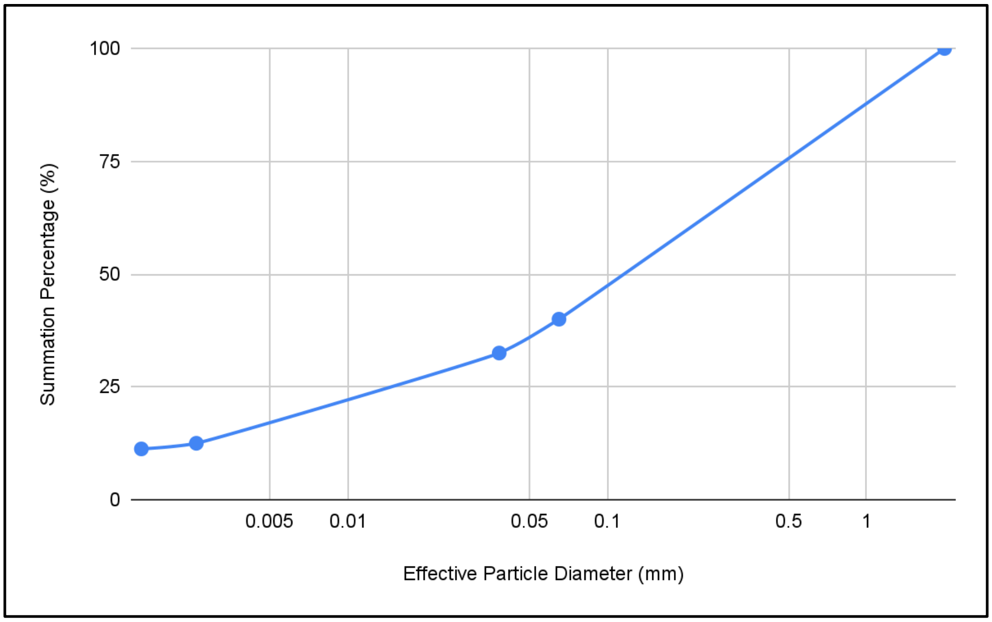


Figure D-8: Particle size distribution of onsite soil.

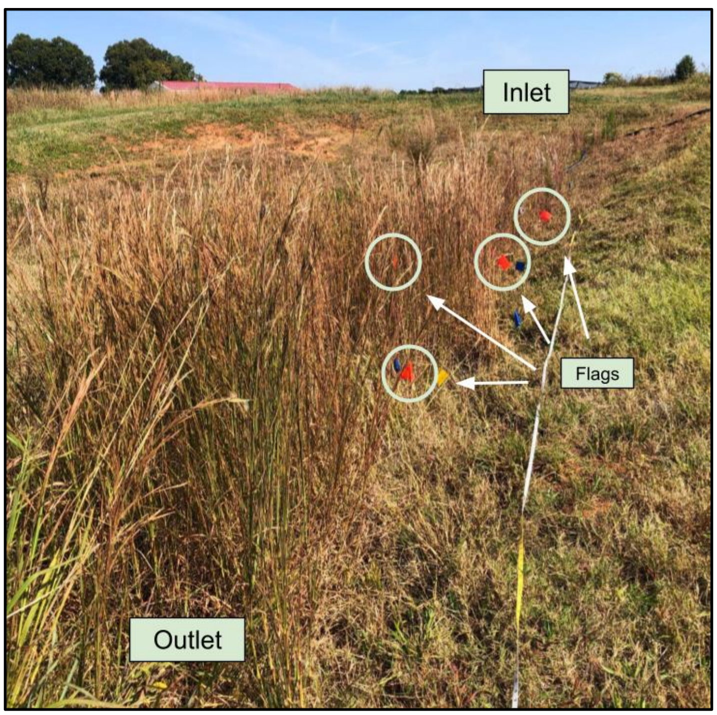


Figure D-9: Flags placed for Manning’s roughness experiment.

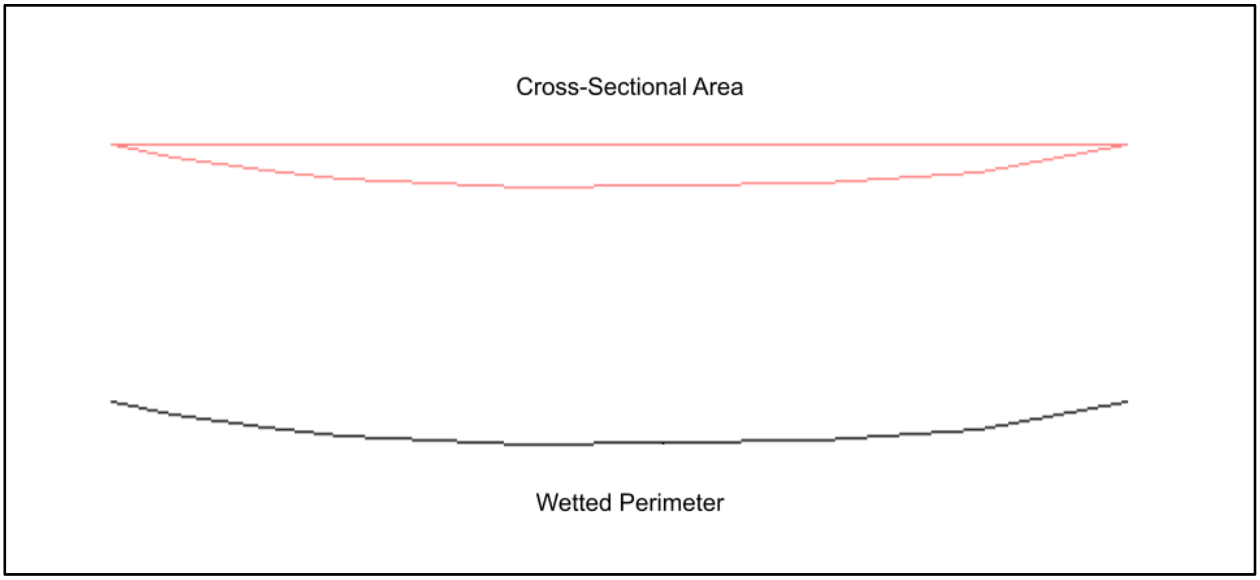


Figure D-10: Example Civil 3D drawing of CG1, Station 1 inlet cross-sectional area and wetted perimeter.

SAS Code and Methods

All sample code uses Zn data for RE as the example, but code was written for each pollutant parameter.

Step 1: Load data set.

```
data Zn;
        input Lining$ Storm_Size$ Slope$ Influent RE;
        datalines;
Riprap                  70          1%         36      -16.7
Riprap                  70          1%         49       -4.1
Riprap                  70          1%         89       16.9
Riprap                 140          1%         62       38.7
Riprap                 140          1%         54       20.4
Riprap                 140          1%         34       -5.9
NativeGrass             70          1%        140       57.9
NativeGrass             70          1%        190       67.9
NativeGrass             70          1%         74       33.8
NativeGrass            140          1%         82       36.6
NativeGrass            140          1%        110        9.1
NativeGrass            140          1%        540       64.8
Riprap                  70          4%         42       14.3
Riprap                  70          4%         90      -33.3
Riprap                  70          4%         82       20.7
Riprap                 140          4%         32        6.3
Riprap                 140          4%         65       43.1
Riprap                 140          4%         21       -4.8
NativeGrass             70          4%         76       57.9
NativeGrass             70          4%         82       56.1
NativeGrass             70          4%         87       47.1
NativeGrass            140          4%         50         40
NativeGrass            140          4%         50         32
NativeGrass            140          4%         42       52.4
;
run;
```

Step 2: Two-tailed T-test for H_o: RE = 0; H_a: RE $\neq$ 0 and visual inspection for normality

```
proc ttest
data = Zn H0=0;
var RE;
run;
```

Example SAS output used to visually inspect for normality

The TTEST Procedure

Variable: RE

N	Mean	Std Dev	Std Err	Minimum	Maximum
24	27.1333	27.4554	5.6043	-33.3000	67.9000

Mean	95% CL Mean		Std Dev	95% CL Std Dev	
27.1333	15.5399	38.7267	27.4554	21.3387	38.5134

DF	t Value	Pr > |t|
23	4.84	<.0001

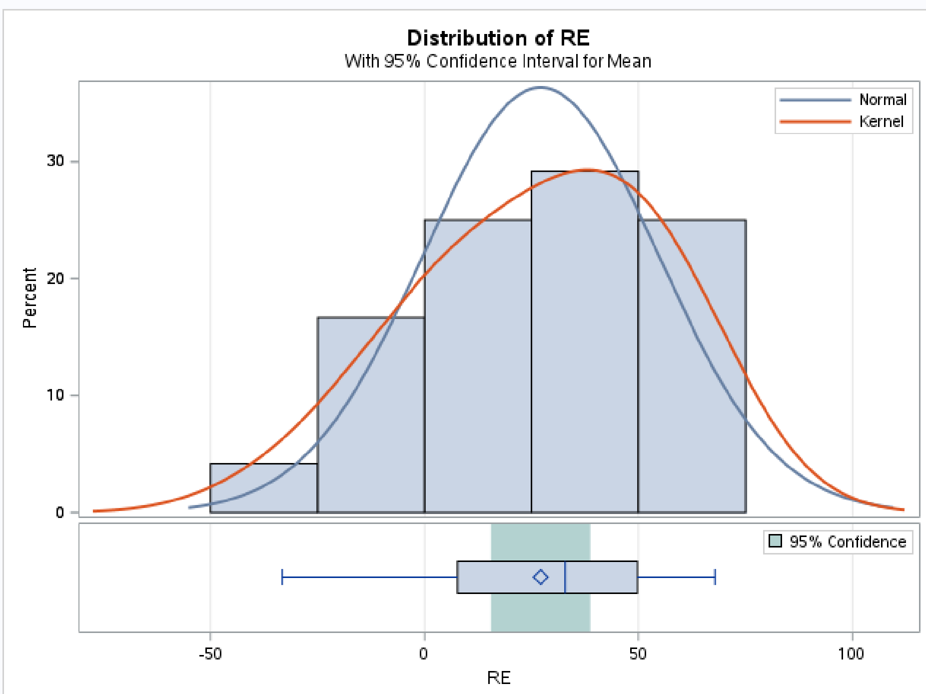
The TTEST Procedure

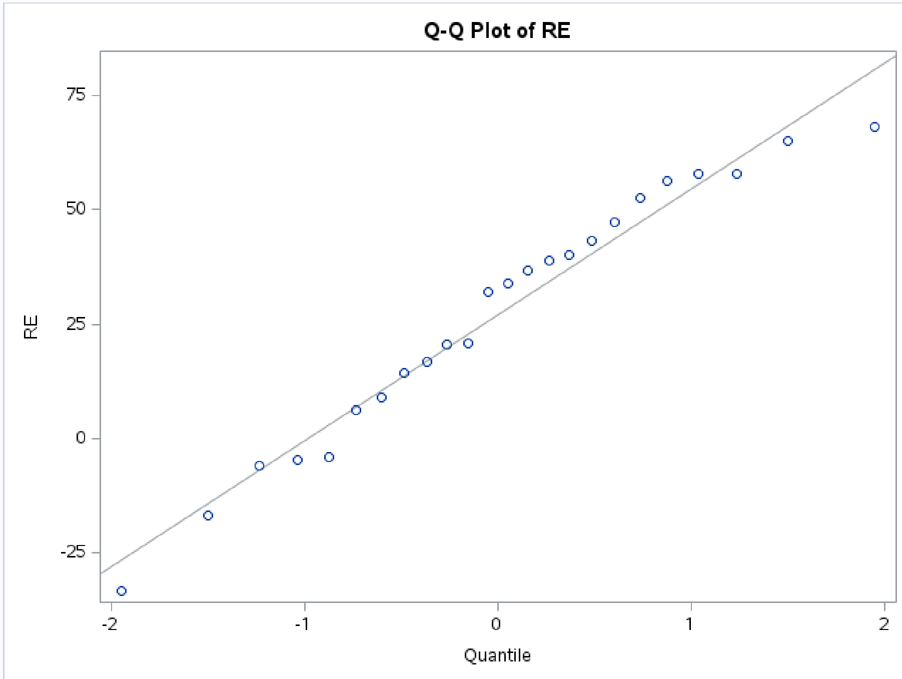
Variable: RE

N	Mean	Std Dev	Std Err	Minimum	Maximum
24	27.1333	27.4554	5.6043	-33.3000	67.9000

Mean	95% CL Mean		Std Dev	95% CL Std Dev	
27.1333	15.5399	38.7267	27.4554	21.3387	38.5134

DF	t Value	Pr > |t|
23	4.84	<.0001





Step 3: ANCOVA

```
proc glm
data=Zn plots=residuals;
class Lining Storm_Size Slope;
model RE=Lining Slope Storm_Size Influent Lining*Storm_Size*Slope Lining*Slope Lining*Storm_Size Storm_Size*Slope;
lsmeans Lining / stderr pdiff out=adjmeans;
store model;
run;
```

Step 4: Interaction Plots

Code to create an interaction plot for lining*storm size

```
proc plm restore=model;
    effectplot interaction(x=Lining plotby=Slope plotby=Influent);
run;
```

Equations

$$Q = 0.6760 * H^{2.5} \tag{D-1}$$

$$Q = 1.443 * H^{2.5} \tag{D-2}$$

Where:

- Q is the flow rate (cfs), and
- H is height (stage) of flow upstream of the weir (ft)

$$Volume\ Reduction\ (\%) = \left(1 - \frac{Outflow\ Volume}{Inflow\ Volume}\right) * 100 \tag{D-3}$$

$$Peak\ Flow\ Rate\ Reduction\ (\%) = \left(\frac{Peak\ Inflow - Peak\ Outflow}{Peak\ Inflow}\right) * 100 \tag{D-4}$$

$$RE = \left(1 - \frac{EMC_{effluent}}{EMC_{influent}}\right) * 100 \tag{D-5}$$

Where:

- RE is the removal efficiency (%),
- EMCeffluent is the effluent event mean concentration (mg/L for TSS and µg/L for all others), and
- EMCinfluent is the influent event mean concentration (mg/L for TSS and µg/L for all others)

$$L = EMC * Volume\ of\ Water \tag{D-6}$$

Where:

- L is the load (mg for TSS and µg for all others),
- EMC is the event mean concentration (mg/L for TSS and µg/L for all others), and
- Volume of Water (L)

$$Load\ Reduction = \frac{Inlet\ Load - Outflow\ Load}{Inlet\ Load} \tag{D-7}$$

Where:

- Load Reduction (%),
- Inlet Load (mg for TSS and µg for all others), and
- Outflow Load (mg for TSS and µg for all others)

$$\rho_b = \frac{M_s}{V_t} \tag{D-8}$$

Where:

- b is the bulk density ($\frac{g}{cm^3}$),
- M_s is the mass of solids (g), and
- V_t is the total soil volume (cm^3)

$$Q = VA = \left(\frac{1.49}{n}\right) AR^{2/3}\sqrt{S} \qquad \text{(D-9)}$$

$$Q = VA = \left(\frac{1.00}{n}\right) AR^{2/3}\sqrt{S} \qquad \text{(D-10)}$$

Where:

- Q is the flow rate (cfs or cms),
- n is Manning's roughness coefficient (unitless),
- A is the cross-sectional area (ft^2 or m^2),
- R is the hydraulic radius (ft or m), and
- S is the slope (ft/ft or m/m)

Appendix E – Traditional Swale Discussion Details

Hydrologic Results

Table E-1: Hydrologic behavior of conventional swales during the 70 min. storms.

Swale ID	Event	Inflow Volume (L)	Outflow Volume (L)	Outflow Rate (%)	Volume Reduction (%)	Peak Inflow (L/s)	Peak Outflow (L/s)	Peak Flow Reduction Rate (%)
CR1	1	8,690	5,620	65	35	3.4	2.5	25
	2	12,307	4,046	33	67	9.1	1.7	81
	3	14,855	1,646	11	89	9.1	3.4	63
CG1	1	16,615	5,589	34	66	9.3	1.4	84
	2	16,080	2,462	15	85	9.1	1.7	81
	3	33,595	20,264	6	40	9.3	4.2	55
CR4	1	18,033	12,123	67	33	9.3	5.4	42
	2	14,511	8,566	59	41	9.1	4.0	56
	3	14,928	9,373	63	37	9.1	3.7	59
CG4	1	15,133	3,017	20	80	9.1	1.7	81
	2	16,518	4,428	27	73	9.1	2.0	78
	3	14,855	4,410	30	70	9.1	2.0	78
	Mean	17,470	6,496	34	66	8.5	2.4	69
	Median	15,606	5,009	33	67	9.1	2.3	70

Table E-2: Hydrologic behavior of conventional swales during the 140 min. storms.

Swale ID	Event	Inflow Volume (L)	Outflow Volume (L)	Outflow Rate (%)	Volume Reduction (%)	Peak Inflow (L/s)	Peak Outflow (L/s)	Peak Flow Reduction Rate (%)
CR1	1	35,361	5,631	16	84	9.1	1.4	84
	2	35,156	10,529	30	70	9.1	1.7	81
	3	34,723	9,500	27	73	9.3	2.5	73
CG1	1	30,964	7,400	24	76	9.1	1.7	81
	2	15,767	7,055	45	55	9.1	3.7	59
	3	26,289	18,008	68	32	9.1	4.5	50
CR4	1	28,342	12,631	45	55	9.1	2.5	72
	2	34,435	15,844	46	54	9.1	3.4	63
	3	37,510	12,525	33	67	9.1	2.5	72
CG4	1	31,428	6,614	21	79	9.1	1.7	81
	2	31,884	5,550	17	8	9.3	1.7	82
	3	26,194	9,974	38	62	9.1	3.4	63
	Mean	30,671	10,105	34	66	9.1	2.6	72
	Median	31,656	9,737	32	68	9.1	2.5	72

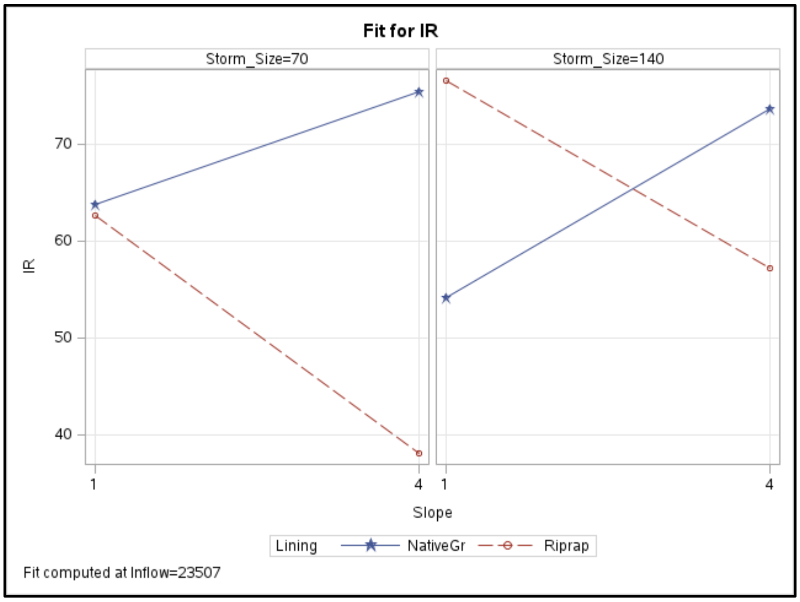


Figure E-1: Volume reduction lining*slope interaction plot.

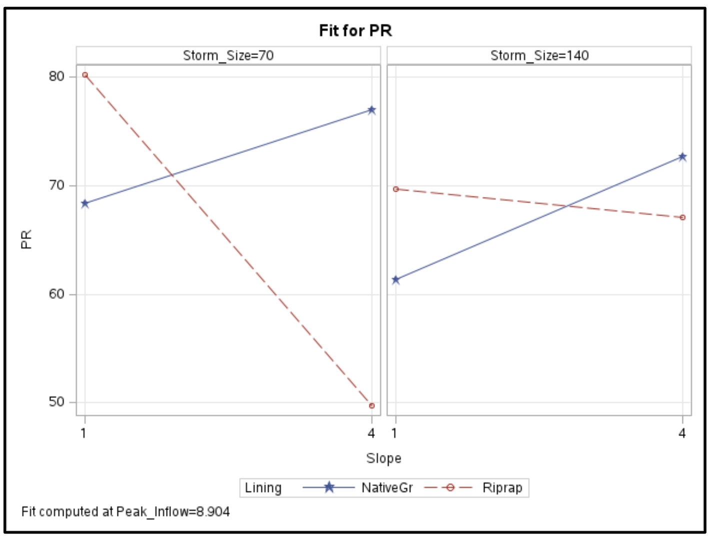


Figure E-2: Peak flow reduction lining*slope interaction plot.

Water Quality Results

Table E-3: Inlet EMCs. TSS in mg/L all other in µg/L.

Storm Date	Swale ID	Storm Size (mins.)	TSS	TKN	NH_3	NO_x	TN	TP	OP	Cd	Cu	Pb	Zn
9/3/2021	CR1	70	41.77	1318.5	25.93	182.62	1501.12	152.17	48.86	2.8	12	11	36
9/20/2021	CR1	70	31.79	1464.52	30.1	287.29	1751.81	186.84	80.74	4.2	13	10	49
10/4/2021	CR4	70	**16.18**	**1101.9**	**26.61**	**174.58**	**1276.48**	**114.2**	**39.13**	3.7	11	3.3	42
10/15/2021	CR4	140	15.13	1019.98	27.69	130.44	1150.42	91.58	27.27	2	7.2	3.4	32

3/30/2022	CR4	140	9.79	1082.35	232.71	238.15	1320.5	110.55	48.97	3.6	10	5.8	65
5/16/2022	CR4	140	17.84	710.45	44.84	120.08	830.53	91.34	51.72	1.9	9	4.8	21
5/23/2022	CR1	140	24.29	923.43	27.14	144.97	1068.4	114.89	40.35	2.6	15	5.1	62
5/25/2022	CG1	70	18.44	725.02	31.21	269.83	994.85	161.8	96.73	5.4	18	11	140
5/26/2022	CR1	140	12.03	672.28	26.88	144.73	817.01	91.86	52.23	3.3	12	4.3	54
5/30/2022	CR1	140	14.59	721.82	30.69	141.29	863.11	90.39	53.46	2.4	9.4	5.5	34
5/31/2022	CG1	70	47.44	903.15	44.62	376.77	1279.92	221.84	143.71	10	21	10	190
6/2/2022	CG1	140	59.09	1007.71	22.28	194.37	1202.08	138.6	61.25	2.8	12	6	82
6/6/2022	CG1	70	48.89	975	24.86	200.97	1175.97	148.04	62.86	3.3	14	6.3	74
6/21/2022	CG4	140	15.55	892.26	26.09	115.36	1007.62	94.2	31.25	2.5	11	4.1	50
6/27/2022	CG4	140	16.59	879.59	44.84	102.15	981.74	86.61	38.23	2.7	12	4.1	50
7/12/2022	CG4	140	13.65	1008.34	29.76	102.07	1110.41	81.2	29.41	1.9	11	3.5	42
7/28/2022	CG4	70	19.28	937.27	27.82	212.44	1149.71	147.28	60.19	4.3	16	6.6	76
8/3/2022	CG4	70	21.76	866.81	35.62	206.6	1073.41	124.71	73.45	4.5	15	7	82
8/25/2022	CG4	70	23.36	940.81	35.48	197.96	1138.77	153.83	52.26	4.2	9.8	6.5	87
8/30/2022	CR4	70	39.12	782.3	20.37	185.56	967.86	116.8	64.22	2.6	18	5.8	90
9/6/2022	CR4	70	58.5	720.08	30.49	119.42	839.5	94.14	41.48	2.8	13	4.1	82
9/15/2022	CR1	70	17.32	610.02	21.53	163.92	773.94	98.5	60.56	2.7	16	5.4	89
9/15/2022	CG1	140	7.85	574.63	20.51	97.44	672.07	77.55	45.42	1.1	8.5	2.9	110
9/22/2022	CG1	140	18.91	681.44	20.6	126.49	807.93	72.5	38.62	2.5	13	3.3	540

Bold numbers analyzed outside of holding time.

Table E-4: Overflow EMCs. TSS in mg/L all other in µg/L.

Storm Date	Swale ID	Storm Size (mins.)	TSS	TKN	NH_3	NO_x	TN	TP	OP	Cd	Cu	Pb	Zn
9/3/2021	CR1	70	19.5	1327.01	31.84	264.9	1591.91	169.72	67	3	14	13	42
9/20/2021	CR1	70	31.79	1515.41	32.84	374.34	1889.75	207.12	95.2	4	21	12	51
10/4/2021	CR4	70	**18.83**	**1149.88**	**47.08**	**207.64**	**1357.52**	**154.93**	**69.96**	3.4	20	3.6	36
10/15/2021	CR4	140	9.75	1020.48	50.39	187.09	1207.57	114.56	39.67	1.9	9.3	3.9	30
3/30/2022	CR4	140	42.09	2069.11	381.14	326.56	2395.67	244.64	62.57	1.9	22	5.2	37
5/16/2022	CR4	140	13.35	782.52	36.9	164.34	946.86	98.7	51.72	1.8	15	4.7	22
5/23/2022	CR1	140	13.01	1086.7	47.42	216.51	1303.31	171.55	62.95	1.5	18	4.5	38
5/25/2022	CG1	70	14.49	866.43	37.46	256.88	1123.31	147.74	88.49	2.7	23	9	59
5/26/2022	CR1	140	7.94	793.54	48.23	255.4	1048.94	120.65	68.98	2.2	13	4.3	43

5/30/2022	CR1	140	8.14	753.11	50.13	214.22	967.33	119.05	70.43	2.1	16	5.7	36
5/31/2022	CG1	70	15.92	940.78	45.21	302.46	1243.34	188.28	114.01	4.3	22	8.4	61
6/2/2022	CG1	140	13.89	995.42	22.18	228.73	1224.15	142.88	52.69	1.9	16	6.4	52
6/6/2022	CG1	70	10.37	985.25	22.5	169.66	1154.91	129.66	52.02	2.5	15	5.7	49
6/21/2022	CG4	140	10.31	938.64	25.94	102.78	1041.42	104.85	35.87	1.3	22	3.3	30
6/27/2022	CG4	140	6.45	983.61	45.86	90.16	1073.77	84.89	38.41	2	17	4	34
7/12/2022	CG4	140	23.43	804.25	43.36	104.32	908.57	102.87	32.75	1	21	2.5	20
7/28/2022	CG4	70	38.7	1251.65	32.05	207.82	1459.47	195.88	56.49	1.8	32	4.2	32
8/3/2022	CG4	70	24.89	959.54	53.65	208.79	1168.33	147.46	73.45	1.6	26	4.3	36
8/25/2022	CG4	70	19.24	899.21	46.35	196.27	1095.48	137.92	52.04	1.5	18	3.6	46
8/30/2022	CR4	70	39.24	1079.97	35.84	163.35	1243.32	162.64	71.27	1.4	21	4.4	120
9/6/2022	CR4	70	22.18	769.1	37.5	156.35	925.45	121.12	63.32	2.2	19	4	65
9/15/2022	CR1	70	10.57	717.93	58.19	180.51	898.44	127.66	85.02	1.6	19	4.3	74
9/15/2022	CG1	140	5.2	615.88	44.42	95.1	710.98	68.66	40.41	0.94	16	2.5	100
9/22/2022	CG1	140	5.14	674.9	38.26	119.16	794.06	68.88	41.29	1.5	20	2.7	190

Bold numbers analyzed outside of holding time.

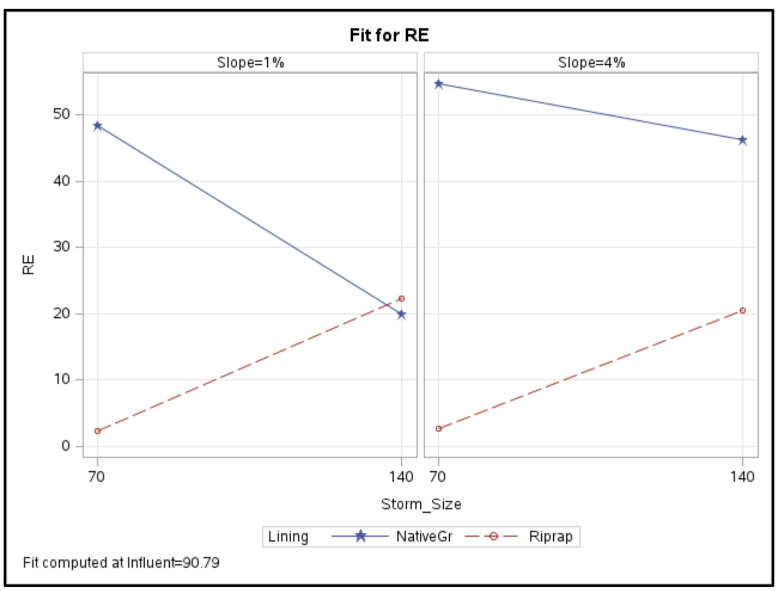


Figure E-3: Zn RE lining*storm size interaction plot.

Appendix F – Conventional Swale Raw Data and Field Notes

Conventional Swale Hydrology Data

Table F-1: Hydrologic behavior of conventional swales during the 70 min. storms.

Swale ID	Event	Inflow Volume (L)	Outflow Volume (L)	Outflow Rate (%)	Volume Reduction (%)	Peak Inflow (L/s)	Peak Outflow (L/s)	Peak Flow Reduction Rate (%)
CR1	1	8,690	5,620	65	35	3.4	2.5	25
	2	12,307	4,046	33	67	9.1	1.7	81
	3	14,855	1,646	11	89	9.1	3.4	63
CG1	1	16,615	5,589	34	66	9.3	1.4	84
	2	16,080	2,462	15	85	9.1	1.7	81
	3	33,595	20,264	6	40	9.3	4.2	55
CR4	1	18,033	12,123	67	33	9.3	5.4	42
	2	14,511	8,566	59	41	9.1	4.0	56
	3	14,928	9,373	63	37	9.1	3.7	59
CG4	1	15,133	3,017	20	80	9.1	1.7	81
	2	16,518	4,428	27	73	9.1	2.0	78
	3	14,855	4,410	30	70	9.1	2.0	78
	Mean	17,470	6,496	34	66	8.5	2.4	69

Table F-2: Hydrologic behavior of conventional swales during the 140 min. storms.

Swale ID	Event	Inflow Volume (L)	Outflow Volume (L)	Outflow Rate (%)	Volume Reduction (%)	Peak Inflow (L/s)	Peak Outflow (L/s)	Peak Flow Reduction Rate (%)
CR1	1	35,361	5,631	16	84	9.1	1.4	84
	2	35,156	10,529	30	70	9.1	1.7	81
	3	34,723	9,500	27	73	9.3	2.5	73
CG1	1	30,964	7,400	24	76	9.1	1.7	81
	2	15,767	7,055	45	55	9.1	3.7	59
	3	26,289	18,008	68	32	9.1	4.5	50
CR4	1	28,342	12,631	45	55	9.1	2.5	72
	2	34,435	15,844	46	54	9.1	3.4	63
	3	37,510	12,525	33	67	9.1	2.5	72
CG4	1	31,428	6,614	21	79	9.1	1.7	81
	2	31,884	5,550	17	8	9.3	1.7	82
	3	26,194	9,974	38	62	9.1	3.4	63
	Mean	30,671	10,105	34	66	9.1	2.6	72
	Median	31,656	9,737	32	68	9.1	2.5	72

Conventional Swale Water Quality Data

Concentrations

Table F-3: Inlet EMCs. TSS in mg/L all other in µg/L.

Storm Date	Swale ID	Storm Size (mins.)	TSS	TKN	NH_3	NO_x	TN	TP	OP	Cd	Cu	Pb	Zn
9/3/2021	CR1	70	41.77	1318.5	25.93	182.62	1501.12	152.17	48.86	2.8	12	11	36
9/20/2021	CR1	70	31.79	1464.52	30.1	287.29	1751.81	186.84	80.74	4.2	13	10	49
10/4/2021	CR4	70	**16.18**	**1101.9**	**26.61**	**174.58**	**1276.48**	**114.2**	**39.13**	3.7	11	3.3	42
10/15/2021	CR4	140	15.13	1019.98	27.69	130.44	1150.42	91.58	27.27	2	7.2	3.4	32
3/30/2022	CR4	140	9.79	1082.35	232.71	238.15	1320.5	110.55	48.97	3.6	10	5.8	65
5/16/2022	CR4	140	17.84	710.45	44.84	120.08	830.53	91.34	51.72	1.9	9	4.8	21
5/23/2022	CR1	140	24.29	923.43	27.14	144.97	1068.4	114.89	40.35	2.6	15	5.1	62
5/25/2022	CG1	70	18.44	725.02	31.21	269.83	994.85	161.8	96.73	5.4	18	11	140
5/26/2022	CR1	140	12.03	672.28	26.88	144.73	817.01	91.86	52.23	3.3	12	4.3	54
5/30/2022	CR1	140	14.59	721.82	30.69	141.29	863.11	90.39	53.46	2.4	9.4	5.5	34
5/31/2022	CG1	70	47.44	903.15	44.62	376.77	1279.92	221.84	143.71	10	21	10	190
6/2/2022	CG1	140	59.09	1007.71	22.28	194.37	1202.08	138.6	61.25	2.8	12	6	82
6/6/2022	CG1	70	48.89	975	24.86	200.97	1175.97	148.04	62.86	3.3	14	6.3	74
6/21/2022	CG4	140	15.55	892.26	26.09	115.36	1007.62	94.2	31.25	2.5	11	4.1	50
6/27/2022	CG4	140	16.59	879.59	44.84	102.15	981.74	86.61	38.23	2.7	12	4.1	50
7/12/2022	CG4	140	13.65	1008.34	29.76	102.07	1110.41	81.2	29.41	1.9	11	3.5	42
7/28/2022	CG4	70	19.28	937.27	27.82	212.44	1149.71	147.28	60.19	4.3	16	6.6	76
8/3/2022	CG4	70	21.76	866.81	35.62	206.6	1073.41	124.71	73.45	4.5	15	7	82
8/25/2022	CG4	70	23.36	940.81	35.48	197.96	1138.77	153.83	52.26	4.2	9.8	6.5	87
8/30/2022	CR4	70	39.12	782.3	20.37	185.56	967.86	116.8	64.22	2.6	18	5.8	90
9/6/2022	CR4	70	58.5	720.08	30.49	119.42	839.5	94.14	41.48	2.8	13	4.1	82
9/15/2022	CR1	70	17.32	610.02	21.53	163.92	773.94	98.5	60.56	2.7	16	5.4	89
9/15/2022	CG1	140	7.85	574.63	20.51	97.44	672.07	77.55	45.42	1.1	8.5	2.9	110
9/22/2022	CG1	140	18.91	681.44	20.6	126.49	807.93	72.5	38.62	2.5	13	3.3	540

Bold numbers analyzed outside of holding time.

Table F-4: Overflow EMCs. TSS in mg/L all other in µg/L.

Storm Date	Swale ID	Storm Size (mins.)	TSS	TKN	NH_3	NO_x	TN	TP	OP	Cd	Cu	Pb	Zn
9/3/2021	CR1	70	19.5	1327.01	31.84	264.9	1591.91	169.72	67	3	14	13	42
9/20/2021	CR1	70	31.79	1515.41	32.84	374.34	1889.75	207.12	95.2	4	21	12	51
10/4/2021	CR4	70	**18.83**	**1149.88**	**47.08**	**207.64**	**1357.52**	**154.93**	**69.96**	3.4	20	3.6	36
10/15/2021	CR4	140	9.75	1020.48	50.39	187.09	1207.57	114.56	39.67	1.9	9.3	3.9	30
3/30/2022	CR4	140	42.09	2069.11	381.14	326.56	2395.67	244.64	62.57	1.9	22	5.2	37
5/16/2022	CR4	140	13.35	782.52	36.9	164.34	946.86	98.7	51.72	1.8	15	4.7	22
5/23/2022	CR1	140	13.01	1086.7	47.42	216.51	1303.31	171.55	62.95	1.5	18	4.5	38
5/25/2022	CG1	70	14.49	866.43	37.46	256.88	1123.31	147.74	88.49	2.7	23	9	59
5/26/2022	CR1	140	7.94	793.54	48.23	255.4	1048.94	120.65	68.98	2.2	13	4.3	43
5/30/2022	CR1	140	8.14	753.11	50.13	214.22	967.33	119.05	70.43	2.1	16	5.7	36
5/31/2022	CG1	70	15.92	940.78	45.21	302.46	1243.34	188.28	114.01	4.3	22	8.4	61
6/2/2022	CG1	140	13.89	995.42	22.18	228.73	1224.15	142.88	52.69	1.9	16	6.4	52
6/6/2022	CG1	70	10.37	985.25	22.5	169.66	1154.91	129.66	52.02	2.5	15	5.7	49
6/21/2022	CG4	140	10.31	938.64	25.94	102.78	1041.42	104.85	35.87	1.3	22	3.3	30
6/27/2022	CG4	140	6.45	983.61	45.86	90.16	1073.77	84.89	38.41	2	17	4	34
7/12/2022	CG4	140	23.43	804.25	43.36	104.32	908.57	102.87	32.75	1	21	2.5	20
7/28/2022	CG4	70	38.7	1251.65	32.05	207.82	1459.47	195.88	56.49	1.8	32	4.2	32
8/3/2022	CG4	70	24.89	959.54	53.65	208.79	1168.33	147.46	73.45	1.6	26	4.3	36
8/25/2022	CG4	70	19.24	899.21	46.35	196.27	1095.48	137.92	52.04	1.5	18	3.6	46
8/30/2022	CR4	70	39.24	1079.97	35.84	163.35	1243.32	162.64	71.27	1.4	21	4.4	120
9/6/2022	CR4	70	22.18	769.1	37.5	156.35	925.45	121.12	63.32	2.2	19	4	65
9/15/2022	CR1	70	10.57	717.93	58.19	180.51	898.44	127.66	85.02	1.6	19	4.3	74
9/15/2022	CG1	140	5.2	615.88	44.42	95.1	710.98	68.66	40.41	0.94	16	2.5	100
9/22/2022	CG1	140	5.14	674.9	38.26	119.16	794.06	68.88	41.29	1.5	20	2.7	190

Bold numbers analyzed outside of holding time.

Load Reductions

Table F-5: TSS load reductions (%). Negative values represent greater than that of inflow.

Swale ID	Event	TSS 70 min.	TSS 140 min.
CR1	1	70	84
	2	80	82
	3	90	94
CG1	1	74	89
	2	95	60
	3	95	81
CR4	1	22	78
	2	55	-154
	3	83	53
CG4	1	58	87
	2	80	90
	3	69	49
	Mean	72	58
	Median	77	82

Table F-6: Nutrient load reductions (%) during 70 min. storms. Negative values represent greater than that of inflow.

Swale ID	Event	TKN	NH_3	NO_x	TN	TP	OP
CR1	1	35	21	6	31	28	11
	2	66	64	57	65	64	61
	3	81	57	82	82	79	78
CG1	1	60	60	68	62	69	69
	2	84	84	88	85	87	88
	3	76	78	80	77	79	80
CR4	1	30	-19	20	29	9	-20
	2	38	22	61	43	38	51
	3	51	43	40	49	41	30
CG4	1	72	76	79	73	72	80
	2	81	74	82	81	79	83
	3	64	50	62	63	66	62
	Mean	61	50	59	61	58	55
	Median	65	58	65	64	68	66

Table F-57: Nutrient load reductions (%) during 140 min. storms. Negative values represent greater than that of inflow.

Swale ID	Event	TKN	NH_3	NO_x	TN	TP	OP
CR1	1	65	48	55	63	55	53
	2	68	51	52	65	64	64
	3	88	82	83	88	85	85
CG1	1	56	55	47	54	54	62
	2	35	-31	41	36	47	46
	3	32	-27	35	33	35	27
CR4	1	67	39	52	65	58	51
	2	-13	3	19	-7	-31	25
	3	31	48	14	28	32	37
CG4	1	79	80	82	79	78	77
	2	70	73	76	71	74	73
	3	76	57	70	76	62	67
	Mean	55	40	52	54	51	56
	Median	66	50	52	64	57	57

Table F-8: Dissolved metal load reductions (%) during 70 min. storms. Negative values represent greater than that of inflow.

Swale ID	Event	Cd	Cu	Pb	Zn
CR1	1	31	25	24	25
	2	69	47	61	66
	3	91	81	87	87
CG1	1	83	57	72	86
	2	93	84	87	95
	3	92	74	78	84
CR4	1	38	-22	24	42
	2	76	48	66	41
	3	64	33	55	64
CG4	1	91	58	87	91
	2	94	70	89	92
	3	86	30	79	80
	Mean	74	48	67	70
	Median	83	53	75	82

Table F-9: Dissolved metal load reductions (%) during 140 min. storms. Negative values represent greater than that of inflow.

Swale ID	Event	Cd	Cu	Pb	Zn
CR1	1	83	64	74	82
	2	82	70	73	78
	3	90	81	89	88
CG1	1	70	40	52	72
	2	48	-14	48	45
	3	59	-5	44	76
CR4	1	68	57	62	69
	2	69	-30	47	66
	3	41	-5	39	34
CG4	1	90	60	84	88
	2	80	62	74	82
	3	84	43	79	86
	Mean	72	35	64	72
	Median	75	50	67	77

Conventional Swale Field Notes

Table F-10: Conventional swale simulated storm log.

Storm Date	Swale ID	Storm Size (mins.)	Relevant Field Notes
9/3/2021	CR1	70	
9/20/2021	CR1	70	
10/4/2021	CR4	70	
10/15/2021	CR4	140	
3/30/2022	CR4	140	Outlet sampler error in 4th step; stopped sampling
5/16/2022	CR4	140	
5/23/2022	CR1	140	
5/25/2022	CG1	70	
5/26/2022	CR1	140	
5/30/2022	CR1	140	
5/31/2022	CG1	70	
6/2/2022	CG1	140	
6/6/2022	CG1	70	Inlet bottle didn't collect sample #'s 1-3
6/21/2022	CG4	140	
6/27/2022	CG4	140	
7/12/2022	CG4	140	
7/28/2022	CG4	70	
8/3/2022	CG4	70	Sampler power failure in last 10 minutes of experiment
8/25/2022	CG4	70	
8/30/2022	CR4	70	
9/6/2022	CR4	70	
9/15/2022	CR1	70	
9/15/2022	CG1	140	
9/22/2022	CG1	140	

Conventional Swale Turfgrass Lining Water Quality Data

Table F-11: Inlet EMCs for turf-lined swales. TSS in mg/L all other in µg/L.

Storm Date	Slope (%)	Storm Size	TSS	TKN	NO_x	TN	TP	OP	Cd	Cu	Pb	Zn
10/15/2018	1	Medium	32.38	592.89	206.92	799.81	78.06	48.99	3.4	8.9	5.7	51
10/24/2018	4	Medium	45.45	797.24	237.18	1034.42	130.84	76.26	5.7	20	13	110
10/29/2018	4	Medium	41.93	712.24	136.67	848.91	95.2	45.67	3.7	11	7.6	68
10/31/2018	1	Large	23.96	800.72	84.27	884.99	71.68	24.72	1.9	6.8	4.5	39
11/4/2018	4	Large	33.22	662.4	85.08	747.48	65.63	27.68	4	8.1	5.2	48
11/11/2018	1	Medium	52.73	651.8	138.63	790.43	107.11	49.69	4.1	12	8.6	76
11/21/2018	4	Medium	47.72	716.86	239.18	956.04	107.8	44.2	3.1	11	8.2	68
11/28/2018	1	Medium	48.53	679.68	161.66	841.34	110.02	60.63	3.8	11	8.5	79
12/5/2018	4	Large	25.51	619.27	178.89	798.16	71.71	28.4	1.9	7.7	4.7	38
12/5/2018	1	Large	60.74	690.74	201.04	891.78	92.7	32.97	2.5	11	7.2	110
12/19/2018	4	Large	35.49	710.94	224.5	935.44	95.48	26.22	1.9	7.3	5.2	42
12/19/2018	1	Large	36.15	762.57	208	970.57	86.86	25.38	1.6	6.7	4.7	36

Table F-12: Overflow EMCs for turf-lined swales. TSS in mg/L all other in µg/L.

Storm Date	Slope (%)	Storm Size	TSS	TKN	NO_x	TN	TP	OP	Cd	Cu	P	Zn
10/15/2018	1	Medium	5.17	701.74	174.96	876.7	93.21	65.08	1.6	8.5	4.3	24
10/24/2018	4	Medium	9.02	1010.56	193.87	1204.43	142.77	102.06	1.9	10	6.4	35
10/29/2018	4	Medium	12.17	776.13	131.91	908.04	111.45	59.77	1.8	9.2	6.1	33
10/31/2018	1	Large	7.1	926.64	74.98	1001.62	75.35	28.09	1.3	7.9	3.7	26
11/4/2018	4	Large	9.39	659.54	84.4	743.94	71.37	36.12	1.9	6.2	3.7	20
11/11/2018	1	Medium	14.1	724.37	137.21	861.58	104.33	59.96	2.1	12	6.1	40
11/21/2018	4	Medium	14.97	757.77	218.58	976.35	121.1	59.68	1.6	10	5	32
11/28/2018	1	Medium	13.98	730.81	145.65	876.46	97.2	58.18	2.2	10	5.9	47
12/5/2018	4	Large	8.14	637.44	181.77	819.21	69.71	33.2	1.2	6.9	3.4	25
12/5/2018	1	Large	10.87	645.68	184.79	830.47	68.25	32.14	1.4	7.7	3.5	30
12/19/2018	4	Large	14.11	779.92	224.21	1004.13	79.7	32.42	1.3	6.7	4	29
12/19/2018	1	Large	11.87	749.94	204.6	954.54	69.59	27.28	1.4	7.2	3.4	31

Appendix G – Conventional Swale Pollutant Load Analysis

Results presented for load removal will often reflect what was observed for changes in concentration. Load changes are always "better" because of volume reduction that occurred in all four tested swales.

Sediment

Three of the four swales significantly reduced TSS loads for both medium and large storms (Table G-1). An outlier was present in a CR4 experiment so median values for RE were included (Table G-2). Neither lining type, slope, nor storm size had a significant effect on the TSS load reductions (Table G-2). No crossed interactions between lining, storm size, or slope were statistically significant. CR1, CG1, and CG4 also significantly reduced TSS loads when storm data were pooled (Table G-3).

An outlier was present during one CR4 large storm. See field notes for 3/30/2022 in Appendix F. Raw data can be found in Appendix F.

Table G-1: Mean ± standard deviation and median TSS load reduction (%) for each swale and storm size. Bolded values are significantly different from 0. Negative values represent greater than that of inflow.

Swale ID	TSS Mean 70 min.	TSS Median 70 min.	TSS Mean 140 min.	TSS Median 140 min.
CR1	**80.07 ± 10.25**	80.13	**86.57 ± 6.35**	83.96
CG1	**87.80 ± 12.30**	94.86	**76.97 ± 15.24**	81.38
CR4	53.33 ± 30.45	55.30	-7.30 ± 127.50*	53.37
CG4	**68.83 ± 11.15**	68.64	**75.13 ± 22.68**	86.78

*Contains an outlier

Table G-2: TSS load reduction ANCOVA results. Bolded values are statistically significant.

Factor	TSS p-value
Lining	0.1977

Slope	0.0817
Storm Size	0.9621
Lining*Storm Size*Slope	0.5124
Lining*Slope	0.0909
Lining*Storm Size	0.5463
Storm Size*Slope	0.9104

Table G-3: Mean TSS load reduction (%) ± standard deviation, pooled across storm size. Bolded values are significantly different from 0.

Swale ID	TSS	p-value
CR1	**83.82 ± 8.42**	< 0.0001
CG1	**82.38 ± 13.73**	< 0.0001
CR4	22.97 ± 89.29*	0.5563
CG4	**71.98 ± 16.35**	0.0001

*Contains an outlier

Nutrients

TKN

All swales typically reduced TKN loads. TKN had significant load reductions during medium and large storms for swales CR1, CG1, and CG4 as well as CR4 during only the medium storms (G-4). Significant interactions between lining, lining*storm size*slope, and lining*slope existed for TKN (Table G-5). The significant 3-way interaction between lining*storm size*slope indicates there was a combination of lining type, slope, and storm size that produced a significant result. There were significant load reductions in all four swales when data were pooled (Table G-6).

Table G-4: Mean TKN load reduction (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0.

Swale ID	TKN 70 min.	TKN 140 min.

CR1	**60.73 ± 23.64**	**73.63 ± 12.87**
CG1	**73.30 ± 12.31**	**41.13 ± 12.80**
CR4	**39.73 ± 10.60**	28.20 ± 39.76
CG4	**72.07 ± 8.55**	**75.10 ± 4.62**

Table G-5: TKN load reduction ANCOVA results. Bolded values are statistically significant.

Factor	TKN p-value
Lining	**0.0443**
Slope	0.1651
Storm Size	0.5502
Lining*Storm Size*Slope	**0.0410**
Lining*Slope	**0.0039**
Lining*Storm Size	0.7015
Storm Size*Slope	0.3751

Table G-6: Mean TKN load reduction (%) ± standard deviation for each swale, pooled across storm size. Bolded values are significantly different from 0.

Swale ID	TKN	p-value
CR1	**67.18 ± 18.43**	0.0003
CG1	**57.17 ± 20.85**	0.0011
CR4	**33.97 ± 26.78**	0.0267
CG4	**73.58 ± 6.37**	< 0.0001

There appears to be a benefit for using native grass-lined swales vis-à-vis riprap swales for TKN removal, when pooling data from Tables 3-42 and 3-43. Native grass-lined swales had higher load reductions than riprap swales for both 1% and 4% slopes during the medium storms and 4% during the large storms in the lining*slope interaction (Figure 3-4).

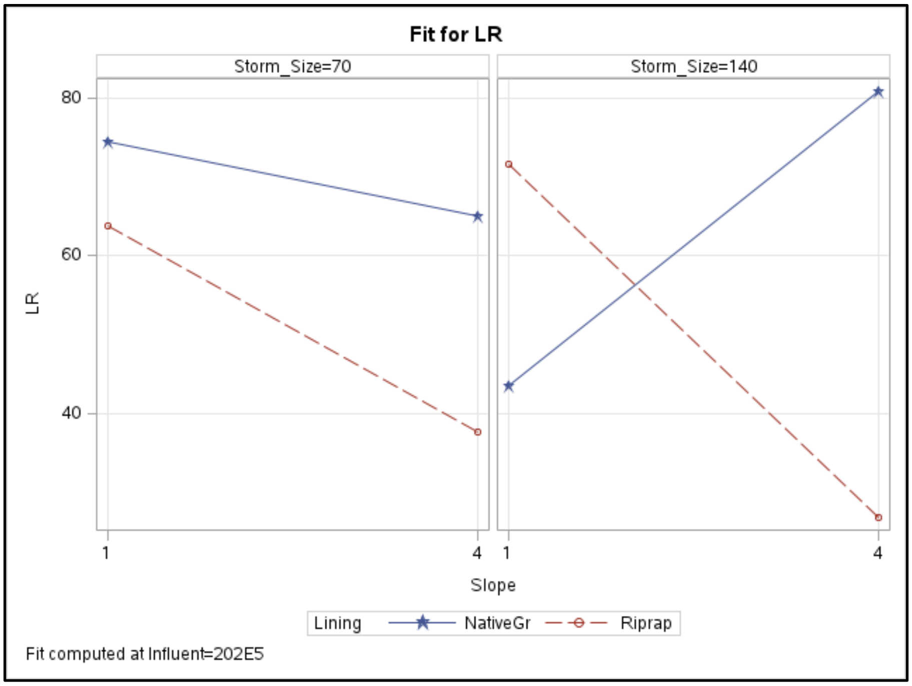


Figure G-1: TKN load reduction lining*slope interaction plot.

NH_3

Swales CG1 and CG4 had significant NH_3 load reductions during medium storms and swales CR1 and CG4 during large storms (Table G-7). Significant interactions between lining*slope and lining*storm size were present (Table G-8). Swales CR1 and CG4 had significant load reductions when storm data were pooled (Table G-9).

Table G-7: Mean NH_3 load reduction (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0. Negative values represent greater than that of inflow.

Swale ID	**NH_3 70 min.**	**NH_3 140 min.**
CR1	47.23 ± 23.34	**60.17 ± 18.89**
CG1	**74.17 ± 12.98**	-0.77 ± 48.76
CR4	15.37 ± 31.61	30.27 ± 23.79
CG4	**66.63 ± 14.18**	**69.83 ± 11.99**

Table G-8: NH_3 load reduction ANCOVA results. Bolded values are statistically significant.

Factor	NH_3 p-value
Lining	0.3190
Slope	0.6490
Storm Size	0.4344
Lining*Storm Size*Slope	0.1649
Lining*Slope	**0.0184**
Lining*Storm Size	**0.0182**
Storm Size*Slope	0.0617

Table G-9: Mean NH_3 load reduction (%) ± standard deviation for each swale, pooled across storm size. Bolded values are significantly different from 0.

Swale ID	NH_3	p-value
CR1	**53.70 ± 20.27**	0.0013
CG1	36.70 ± 51.99	0.1443
CR4	22.82 ± 26.32	0.0871
CG4	**68.23 ± 11.88**	< 0.0001

In general, native grass-lined swales appeared to reduce NH_3 loads better than riprap swales did. Native grass-lined swales had higher load reductions than riprap swales for both 1% and 4% slopes during the medium storms and 4% during the large storms in the lining*slope interaction (Figure G-2). In the lining*storm size interaction, native grass-lined swales had higher load reduction rates than riprap swales for both medium and large storms in the 4% slope and medium storms for the 1% slope (Figure G-3). Results reflect the findings of the NH_3 concentration exports.

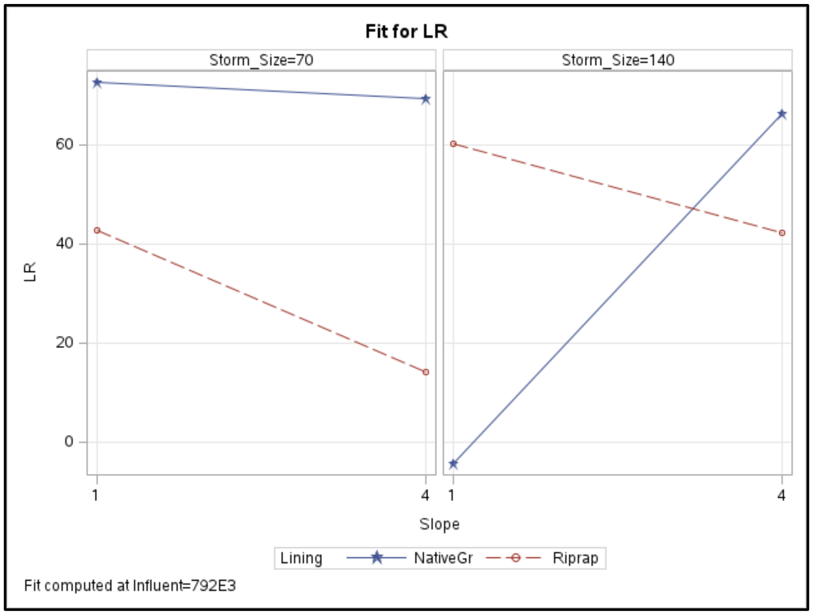


Figure G-2: NH_3 load reduction lining*slope interaction plot.

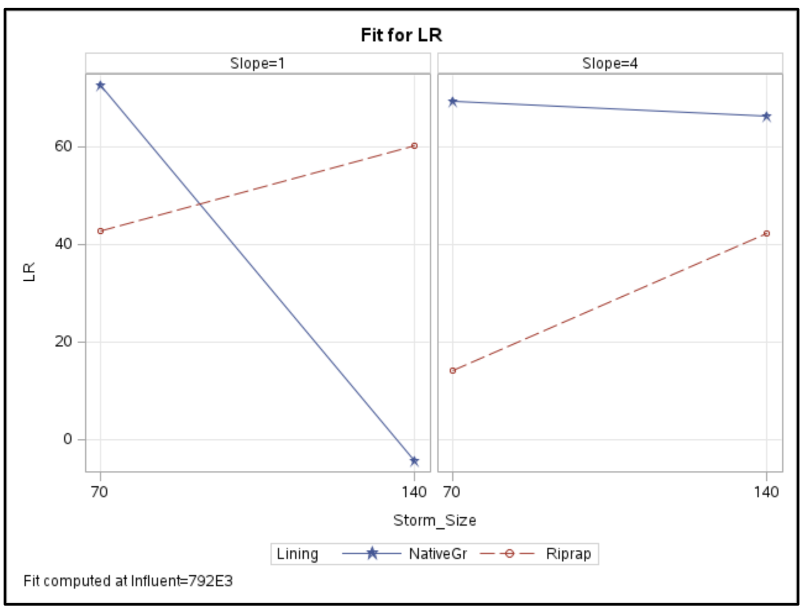


Figure G-3: NH_3 load reduction lining*storm size interaction plot.

NO_x

Swale lining appears to more reliably lead to reduced NO_x loads. Both medium and large storms for CG1 and CG4 as well as CR1 during the large storms had significant NO_x load reductions (Table G-10 and Figure G-4). ANCOVA presented significant differences in load reductions between linings as well as the lining*storm size*slope and lining*slope interactions (Table G-11). The significant 3-way interaction between lining*storm size*slope indicates there was a combination of lining type, slope, and storm size that produced a significant result. There were significant load reductions in all four swales when data were pooled (Table G-12).

Table G-10: Mean NO_x load reduction (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0.

Swale ID	NO_x 70 min.	NO_x 140 min.
CR1	48.63 ± 38.86	**63.40 ± 17.24**
CG1	**78.50 ± 9.91**	**41.30 ± 5.90**
CR4	40.20 ± 20.40	28.43 ± 20.65
CG4	**74.67 ± 10.90**	**76.07 ± 6.25**

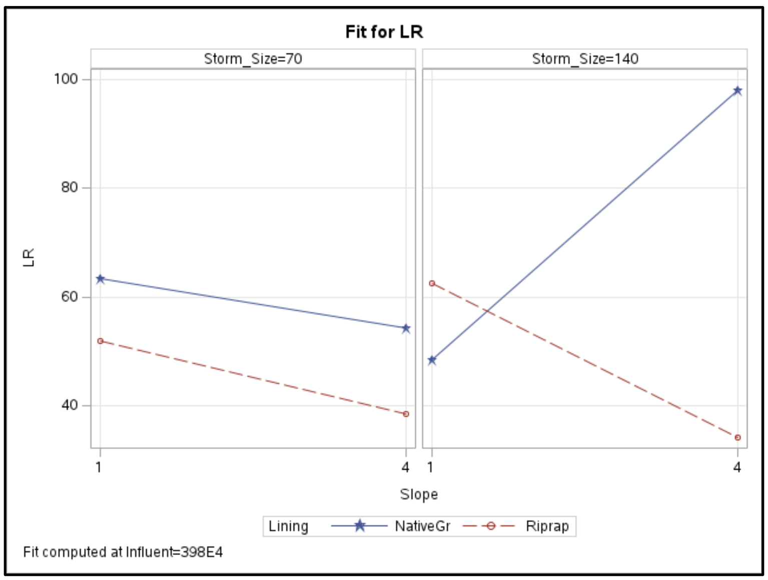


Figure G-4: NO_x load reduction lining*slope interaction plot.

Table G-11: NO_x load reduction ANCOVA results. Bolded values are statistically significant.

Factor	NO_x p-value
Lining	**0.0092**
Slope	0.9558
Storm Size	0.3168

Lining*Storm Size*Slope	**0.0117**
Lining*Slope	**0.0058**
Lining*Storm Size	0.5008
Storm Size*Slope	0.1338

Table G-12: Mean NO_x load reduction (%) ± standard deviation for each swale, pooled across storm size. Bolded values are significantly different from 0.

Swale ID	NO_x	p-value
CR1	**56.02 ± 28.08**	0.0045
CG1	**59.90 ± 21.64**	0.0011
CR4	**34.32 ± 19.46**	0.0076
CG4	**75.37 ± 7.98**	< 0.0001

TN

As with some other nitrogen species, the native grass-lined swales tended to reduce TN loads more often than those lined with riprap (Tables G-13, G-14, and Figure G-5). Both medium and large storms for CG1 and CG4 as well as CR4 in medium storms and CR1 during the large storms had significant load reductions (Table G-13). Lining, lining*storm size*slope, and lining*slope interactions were significant (Table G-14). The significant 3-way interaction between lining*storm size*slope indicates there was a combination of lining type, slope, and storm size that produced a significant result. When storm data were pooled, all four swales had significant TN load reduction (Table G-15).

Table G-13: Mean TN load reduction (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0.

Swale ID	TN 70 min.	TN 140 min.
CR1	59.13 ± 25.48	**72.00 ± 13.53**
CG1	**74.53 ± 11.67**	**41.10 ± 11.65**
CR4	**40.17 ± 10.63**	28.73 ± 36.00
CG4	**72.60 ± 8.87**	**75.27 ± 4.37**

Table G-14: TN load reduction ANCOVA results. Bolded values are statistically significant.

Factor	TN p-value
Lining	**0.0295**
Slope	0.2001
Storm Size	0.6243
Lining*Storm Size*Slope	**0.0307**
Lining*Slope	**0.0037**
Lining*Storm Size	0.7413
Storm Size*Slope	0.3200

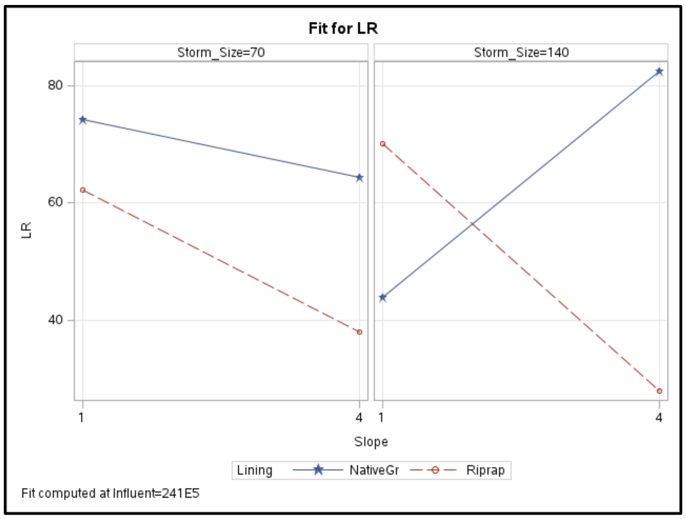


Figure G-5: TN load reduction lining*slope interaction plot.

Table G-15: Mean TN load reduction (%) ± standard deviation for each swale, pooled across storm size. Bolded values are significantly different from 0.

Swale ID	TN	p-value
CR1	**65.57 ± 19.56**	0.0004
CG1	**57.82 ± 21.08**	0.0011
CR4	**34.45 ± 24.55**	0.0185
CG4	**73.93 ± 6.42**	< 0.0001

TP

Liner type appears to be an important parameter vis-à-vis TP removal. Both native grass swales during medium and large storms as well as CR1 during large storms had significant TP load reductions (Table G-16). There were significant differences in TP load reductions between linings as well as the crossed interaction between lining*slope (Table 3-5 G-175). When storm data were pooled, swales CR1, CG1, and CG4 had significant TP load reductions (Table G-18).

Table G-16: Mean TP load reduction (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0.

Swale ID	**TP 70 min.**	**TP 140 min.**
CR1	56.97 ± 26.38	**68.27 ± 15.48**
CG1	**78.47 ± 8.87**	**45.13 ± 9.58**
CR4	29.17 ± 17.70	19.93 ± 45.65
CG4	**72.43 ± 6.76**	**71.30 ± 7.98**

Table G-17: TP load reduction ANCOVA results. Bolded values are statistically significant.

Factor	**TP p-value**
Lining	**0.0283**
Slope	0.1422
Storm Size	0.7893
Lining*Storm Size*Slope	0.1142
Lining*Slope	**0.0100**
Lining*Storm Size	0.9524
Storm Size*Slope	0.3126

Table G-18: Mean TP load reduction (%) ± standard deviation for each swale, pooled across storm size. Bolded values are significantly different from 0.

Swale ID	**TP**	**p-value**
CR1	**62.62 ± 20.31**	0.0006
CG1	**61.80 ± 20.04**	0.0006

CR4	24.55 ± 19.59	0.1134
CG4	**71.87 ± 6.64**	< 0.0001

Native grass-lined swales had higher load reduction rates than riprap swales for both 1% and 4% slopes during the medium storms and 4% during the large storms in the lining*slope interaction (Figure G-6).

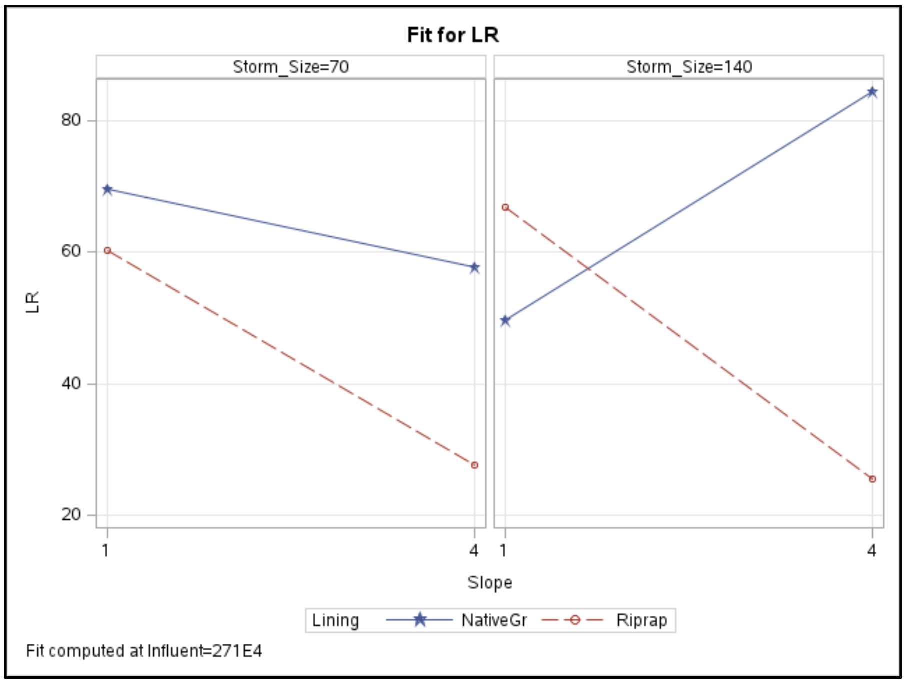


Figure G-6: TP load reduction lining*slope interaction plot.

<u>OP</u>

Lining type appears to be an important predictor of how well a swale removes OP, but all swale combinations rather reliably reduced OP. Swales CG1 and CG4 had significant OP load reductions during medium storms and all four swales during large storms (Table G-19). OP had significant differences in load reductions between linings as well as the crossed interactions between lining*slope and storm size*slope (Table G-20). All four swales had significant load reductions when storm data were pooled (Table G-21).

Table G-19: Mean OP load reduction (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0.

Swale ID	**OP 70 min.**	**OP 140 min.**
CR1	50.03 ± 34.53	**67.53 ± 16.36**
CG1	**79.10 ± 9.40**	**44.87 ± 17.39**
CR4	20.03 ± 36.35	**37.73 ± 13.41**
CG4	**74.97 ± 11.21**	**72.37 ± 5.14**

Table G-20: OP load reduction ANCOVA results. Bolded values are statistically significant.

Factor	**OP p-value**
Lining	**0.0198**
Slope	0.8609
Storm Size	0.0688
Lining*Storm Size*Slope	0.2934
Lining*Slope	**0.0037**
Lining*Storm Size	0.5062
Storm Size*Slope	**0.0388**

Table G-21: Mean OP load reduction (%) ± standard deviation for each swale, pooled across storm size. Bolded values are significantly different from 0.

Swale ID	**OP**	**p-value**
CR1	**58.78 ± 26.00**	0.0026
CG1	**61.98 ± 22.54**	0.0011
CR4	**28.88 ± 26.35**	0.0436
CG4	**73.67 ± 7.93**	< 0.0001

Native grass-lined swales had higher load reduction rates than riprap swales for both 1% and 4% slopes during the medium storms and 4% during the large storms in both the lining*slope and storm size*slope interactions (Figures G-7 and G-8).

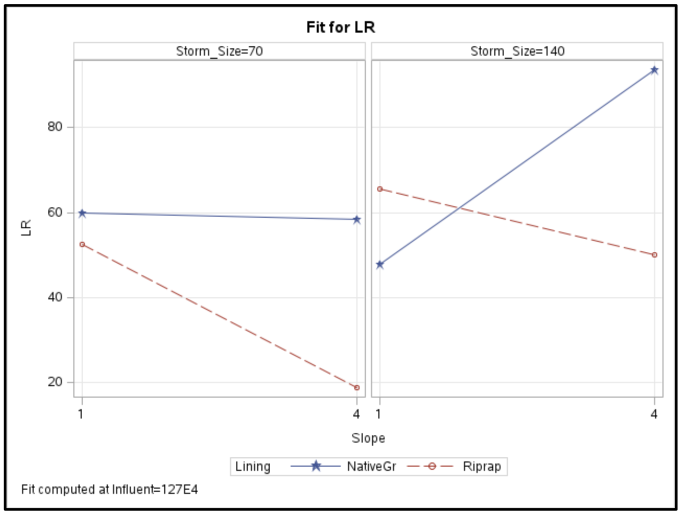


Figure G-7: OP load reduction lining*slope interaction plot.

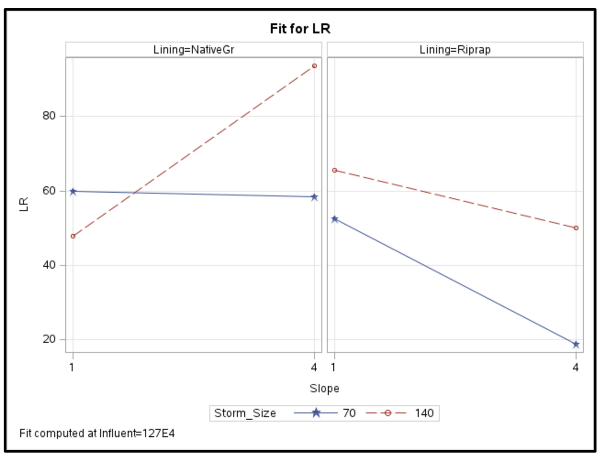


Figure G-8: OP load reduction storm size*slope interaction plot.

Dissolved Metals

Cd

Liner type did not appear to impact Cd load removal. Swales CG1, CR4, and CG4 during medium and large storms as well as CR1 during large storms had significant load reductions

(Table G-22). Only significant interactions between lining*slope were present for Cd (Table G-23). All four swales had significant load reductions when storm data were pooled (Table G-24).

Table G-22: Mean dissolved Cd load reduction (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0.

Swale ID	**Cd 70 min**	**Cd 140 min.**
CR1	63.33 ± 30.31	**84.93 ± 4.67**
CG1	**86.17 ± 6.30**	**59.00 ± 10.55**
CR4	**59.33 ± 19.29**	**59.20 ± 16.20**
CG4	**90.47 ± 3.75**	**84.70 ± 4.76**

Table G-23: Dissolved Cd load reduction ANCOVA results. Bolded values are statistically significant.

Factor	**Cd p-value**
Lining	0.1442
Slope	0.9186
Storm Size	0.2528
Lining*Storm Size*Slope	0.1221
Lining*Slope	**0.0170**
Lining*Storm Size	0.7383
Storm Size*Slope	0.3896

Table G-24: Mean dissolved Cd load reduction (%) ± standard deviation for each swale, pooled across storm size. Bolded values are significantly different from 0.

Swale ID	**Cd**	**p-value**
CR1	**74.13 ± 22.72**	0.0005
CG1	**72.58 ± 16.79**	0.0001
CR4	**59.27 ± 15.93**	0.0003
CG4	**87.58 ± 4.97**	< 0.0001

Native grass-lined swales had higher load reduction rates than riprap swales for both 1% and 4% slopes during the medium storms and 4% during the large storms in the lining*slope interaction (Figure G-9).

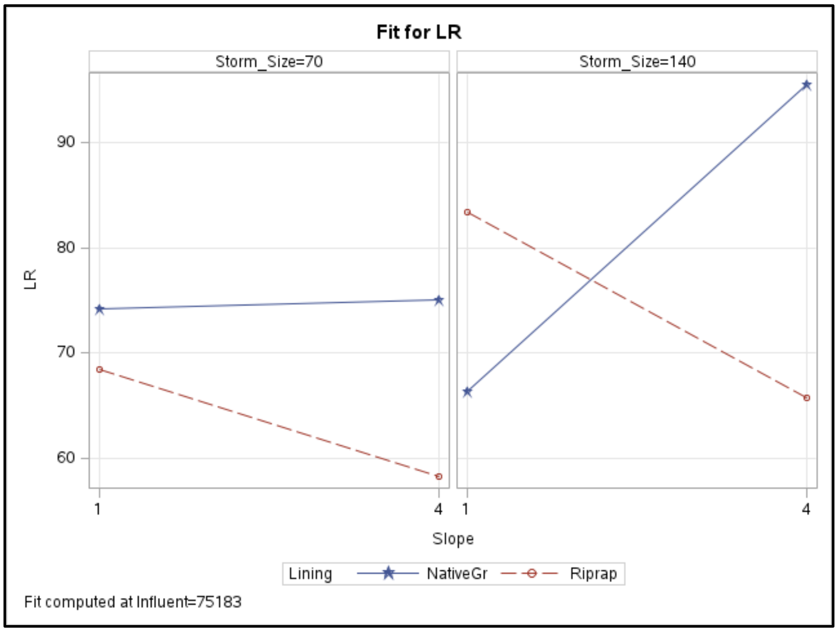


Figure G-9: Cd load reduction lining*slope interaction plot.

<u>Cu</u>

As with Cd, liner type appeared to have a muted impact on Cu load removal. Significant reductions only occurred because of volume reduction rates. Swales CG1 and CG4 had significant load reductions during medium storms and swales CR1 and CG4 during large storms (Table G-25). Significant interactions between lining*storm size*slope and lining*slope were present for Cu (Table G-26). The significant 3-way interaction between lining*storm size*slope indicates there was a combination of lining type, slope, and storm size that produced a significant result. When storm data were pooled, swales CR1 and CG4 were the only swales significantly reducing Cu loads (G-27).

Table G-25: Mean dissolved Cu load reduction (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0.

Swale ID	Cu 70 min.	Cu 140 min.
CR1	50.83 ± 28.50	**71.87 ± 8.59**
CG1	**71.80 ± 13.69**	7.13 ± 29.01
CR4	19.53 ± 36.93	7.47 ± 44.64
CG4	**52.60 ± 20.37**	**55.13 ± 10.29**

Table G-26: Dissolved Cu load reduction ANCOVA results. Bolded values are statistically significant.

Factor	Cu p-value
Lining	0.3745
Slope	0.1725
Storm Size	0.7859
Lining*Storm Size*Slope	**0.0430**
Lining*Slope	**0.0073**
Lining*Storm Size	0.2149
Storm Size*Slope	0.1027

Table G-27: Mean dissolved Cu load reduction (%) ± standard deviation for each swale, pooled across storm size. Bolded values are significantly different from 0.

Swale ID	Cu	p-value
CR1	**61.35 ± 22.07**	**0.0010**
CG1	39.47 ± 40.82	0.0641
CR4	13.50 ± 37.23	0.4152
CG4	**53.87 ± 14.50**	**0.0003**

Native grass-lined swales had higher load reduction rates than riprap swales for both 1% and 4% slopes during the medium storms and 4% during the large storms in the lining*slope interaction (Figure G-10).

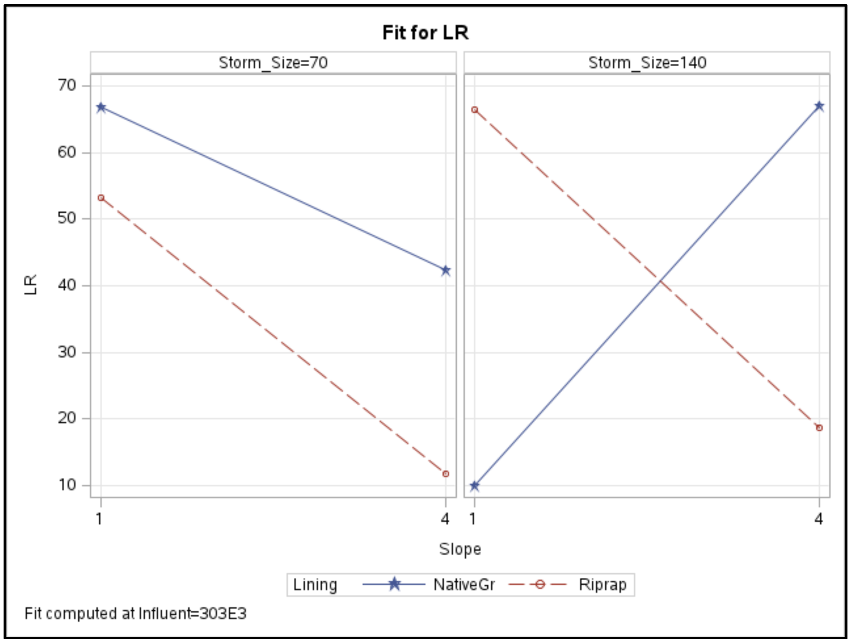


Figure G-10: Cu load reduction lining*slope interaction plot.

Pb

Native grass-lined swales appear to promote more Pb load removal than riprap swales (Tables G-28, G-29, and Figure G-11). Swales CG1 and CG4 had significant reductions of Pb during medium storms and all four swales during large storms (Table G-28). Pb had a significant difference in linings as well as significant interactions between lining*storm size*slope and lining*slope (Table G-29). The significant 3-way interaction between lining*storm size*slope indicates there was a combination of lining type, slope, and storm size that produced a significant result. All four swales had significant Pb load reductions when data were pooled (Table G-30).

Table G-28: Mean dissolved Pb load reduction (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0.

Swale ID	**Pb 70 min.**	**Pb 140 min.**

CR1	57.13 ± 31.98	**78.23 ± 8.91**
CG1	**79.33 ± 7.34**	**48.10 ± 4.15**
CR4	48.57 ± 21.65	**49.10 ± 11.73**
CG4	**84.93 ± 5.40**	**78.87 ± 5.10**

Table G-29: Dissolved Pb load reduction ANCOVA results. Bolded values are statistically significant.

Factor	Pb p-value
Lining	**0.0377**
Slope	0.4235
Storm Size	0.1008
Lining*Storm Size*Slope	**0.0192**
Lining*Slope	**0.0084**
Lining*Storm Size	0.8330
Storm Size*Slope	0.2390

Table G-30: Mean dissolved Pb load reduction (%) ± standard deviation for each swale, pooled across storm size. Bolded values are significantly different from 0.

Swale ID	Pb	p-value
CR1	**67.68 ± 23.97**	0.0010
CG1	**63.72 ± 17.92**	0.0003
CR4	**48.83 ± 15.58**	0.0006
CG4	**81.90 ± 5.75**	< 0.0001

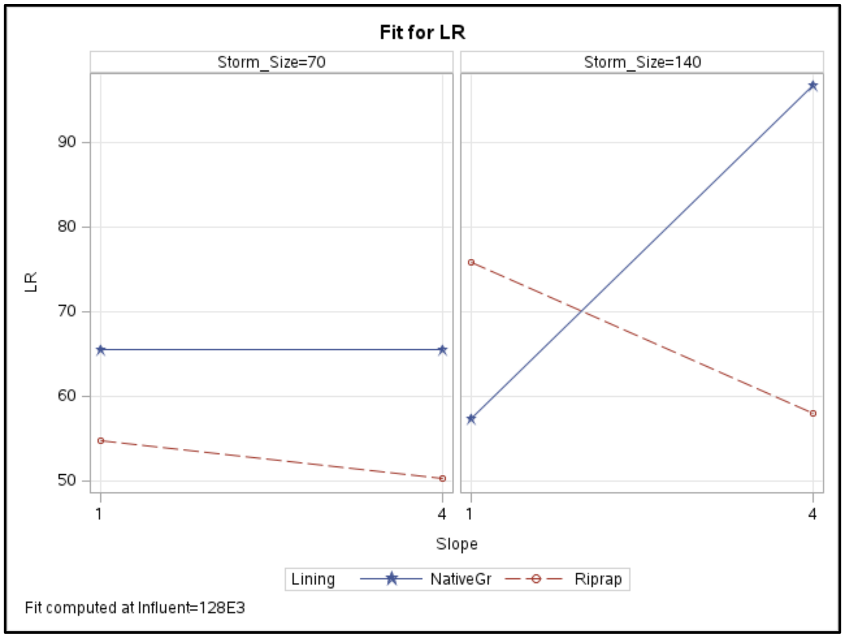


Figure G-11: Pb load reduction lining*slope interaction plot.

Zn

While marginal, it appears that swales lined with grass might remove more Zn than those lined with riprap (Tables G-31, G-32, and Figure G-12). Swales CG1, CR4, and CG4 had significant Zn load reductions during medium storms and all four swales during large storms (Table G-31). ANCOVA revealed a significant difference in linings for Zn as well as significant interactions between lining*slope and lining*storm size (Table G-32). All four swales had significantly reduced Zn when data were pooled (Table G-33).

Table G-31: Mean dissolved Zn load reduction (%) ± standard deviation for each swale and storm size. Bolded values are significantly different from 0.

Swale ID	Zn 70 min.	Zn 140 min.
CR1	59.03 ± 31.70	**82.70 ± 5.14**
CG1	**88.37 ± 5.89**	**64.23 ± 16.62**
CR4	**48.83 ± 12.73**	**56.43 ± 19.29**
CG4	**87.80 ± 6.87**	**85.23 ± 3.15**

Table G-32: Dissolved Zn load reduction ANCOVA results. Bolded values are statistically significant.

Factor	Zn p-value
Lining	**0.0257**
Slope	0.8819
Storm Size	0.9269
Lining*Storm Size*Slope	0.0885
Lining*Slope	**0.0184**
Lining*Storm Size	**0.0211**
Storm Size*Slope	0.4668

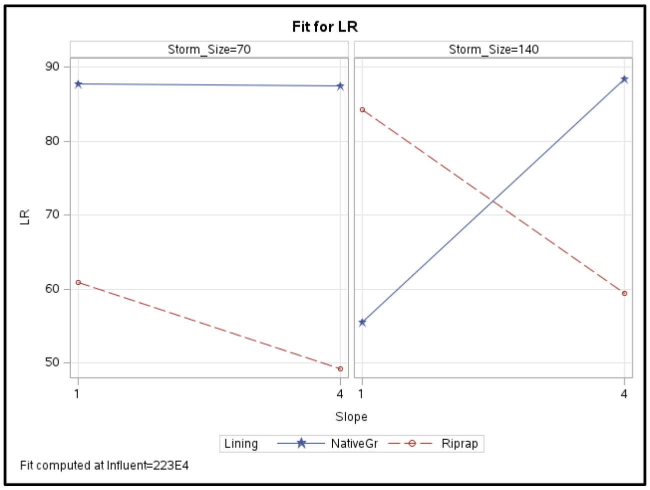


Figure G-12: Zn load reduction lining*slope interaction plot.

Table G-33: Mean dissolved Zn load reduction (%) ± standard deviation for each swale, pooled across storm size. Bolded values are significantly different from 0.

Swale ID	Zn	p-value
CR1	**70.87 ± 24.09**	0.0008
CG1	**76.30 ± 17.30**	0.0001
CR4	**52.63 ± 15.20**	0.0004
CG4	**86.52 ± 4.99**	< 0.0001

Native grass-lined swales had higher load reduction rates than riprap swales for both 1% and 4% slopes during the medium storms and 4% during the large storms in the lining*slope interaction (Figure 3-15). Native grass-lined swales had higher load reduction rates than riprap swales for both medium and large storms in the 4% slope and medium storms for the 1% slope in the lining*storm size interactions (Figure G-13).

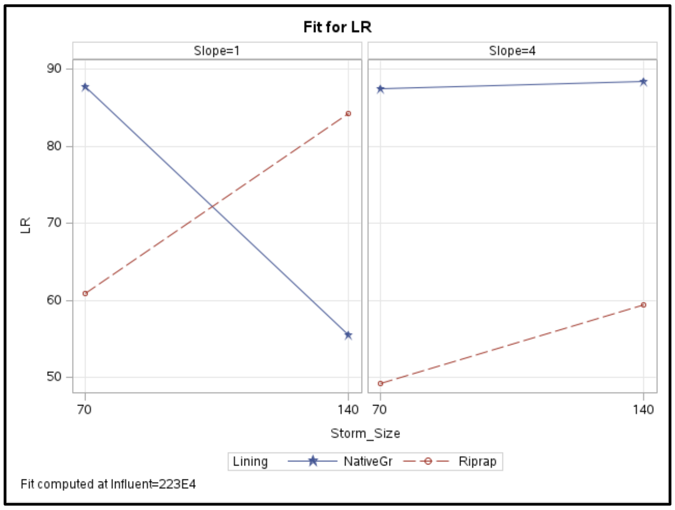


Figure G-13: Zn load reduction lining*storm size interaction plot.

Load Reduction Conclusions

Significant load reductions are expected because they are highly dependent on volume reduction. Because of high volume reductions provided by all four swales, no swale exported pollutants on a load basis.

Both native grass and riprap-lined swales had generally high pollutant load reduction. Sediment, all nutrients, and all dissolved metals were significantly reduced in swales CR1 and CG4. CG4 had the highest overall rates of nutrient and dissolved metal load reduction. Infiltration and biological processes, enhanced by the presence of vegetation, could explain higher load reductions in CG4. Comparing both swales on the 1% slope, CR1 may be the more desirable option as it tended to decrease sediment, nutrient, and dissolved metal loads more than CG1, though this result is an artifact of CR1, having a higher mean volume reduction. Swales CG1 and CG4 both exceeded NCDEQ's grassed swale pollutant credit requirements of 35%, 20%, and 20% for TSS, nitrogen, and phosphorus, respectively (NCDEQ, 2009). However, the NCDEQ credits are based upon swales monitored during actual weather events, rather than simulations such as those presented herein.

Appendix H – Conventional Swale Turfgrass Comparison

Ekka (2023) conducted a study to compare how channel geometry of turf-lined swales impacts water quality and hydrology. This study was conducted on some of the same swales utilized herein, prior to the installation of the alternative linings. The experiments herein were designed to be directly comparable to Ekka (2023). Therefore, experimental procedures were consistent between this study and Ekka and Hunt (2020). The depth of rainfall for medium and large storm events was similar between studies.

Volume Reduction

For medium and large storms, riprap and native grass-lined swales both had higher volume reduction rates than the turf-lined swales in the 1% and 4% slope (Table H-1). It is likely the turf had lower volume reductions due to the presence of thatch. Turfgrass thatch is a compact layer of organic matter that develops between the zone of vegetation and soil surface (Beard, 1972). Liang et al. (2017) reported that the presence of thatch on turf grass can delay the onset of infiltration compared to soil surfaces without a thatch. The development of thatch can alter the swale's hydrological processes at the soil surface by changing the partitioning of rainfall into infiltration, runoff, and evaporation (Liang et al., 2017). Prior to installation of riprap and native grasses, all turf and existing thatch were stripped. Alternative linings were installed on bare soil. Additionally, the level of compaction can reduce rates of volume reduction (Gregory, 2006). According to Ekka and Hunt (2020), swale beds were compacted during construction, resulting in a negative impact on volume reduction. It is likely the soil in turf-lined swales was more compacted than that of riprap or native grass-lined swales, lowering volume reduction.

Table H-1: Mean volume reduction for conventional swales lined with riprap, native grass, and turf.

Lining	Slope (%)	Storm Size	Volume Reduction (%)
Riprap	1	Medium	62
		Large	77
	4	Medium	37
		Large	59
Native Grass	1	Medium	64
		Large	54
	4	Medium	74
		Large	75
Turf	1	Medium	6
		Large	9
	4	Medium	13
		Large	12

Concentration Change Comparisons

Because of volume reduction, only concentrations were compared among swale types. Ranges between inlet and outflow concentrations for riprap, native grass, and turf-lined swales were larger than expected. Wide ranges are likely due to the inaccurate inlet flow rate and an over-estimation of the cumulative inflow, discussed in chapter 2. Because there appeared to be a discrepancy, an additional ANCOVA was conducted to compare inlet concentrations to outflow concentrations, in addition to the RE ANCOVA analysis.

Sediment

Turf-lined swales had higher mean TSS RE than native grasses and riprap for both slopes and storm sizes (Table H-2). No significant factors or interactions existed for TSS RE (Table H-3). In the effluent concentration analysis, lining and slope were significant factors (Table H-4). Influent concentration did not significantly impact TSS removals. However, small sample size may influence significance. The density of vegetation may have influenced TSS RE. Grass density can be defined as the number of leaves or shoots per area. Turf is perhaps denser than the native grasses herein, although no shoot density analysis was conducted. The denser turf grass may have resulted in an increase of biomass and, thus, sedimentation (Kretz et al., 2021). Khandouzi et al. (2020) reported grass cover (*Festuca arundinacea*) significantly removed TSS concentrations more than riprap from forest road ditches. It is likely the presence of fine and unwashed particles in the riprap led to lower TSS RE (Khandouzi et al. (2020). An outlier in the riprap-lined swale on a 4% slope during large storms may have skewed TSS RE.

Table H-2: Mean TSS inlet concentration, overflow concentration, and RE (%) for conventional swales lined with riprap, native grass, and turf.

Lining	Slope (%)	Storm Size	TSS Inlet Concentration (mg/L)	TSS Overflow Concentration (mg/L)	TSS RE (%)
Riprap	1	Medium	30.29	16.43	44
		Large	16.97	9.70	42
	4	Medium	37.93	26.75	15
		Large	14.25	21.70	-90
Native Grass	1	Medium	38.26	13.59	56
		Large	28.62	8.08	61
	4	Medium	21.47	27.61	-33
		Large	15.26	13.40	8
Turf	1	Medium	44.5	11.08	76
		Large	40.28	9.95	73
	4	Medium	45.03	12.05	73
		Large	30.58	8.90	67

Table H-3: TSS RE ANCOVA results for swales lined with riprap, native grass, and turf.

Factor	TSS p-value
Lining	0.3219
Slope	0.0673

Storm Size	0.8694
Influent Concentration	0.1921
Lining*Storm Size*Slope	0.5259
Lining*Slope	0.3190
Lining*Storm Size	0.5442
Storm Size*Slope	0.7195

Table H-4: TSS effluent concentration ANCOVA results for swales lined with riprap, native grass, and turf.

Factor	**TSS p-value**
Lining	**0.0443**
Slope	**0.0101**
Storm Size	0.1221
Influent Concentration	0.3829
Lining*Storm Size*Slope	0.6490
Lining*Slope	0.1768
Lining*Storm Size	0.4723
Storm Size*Slope	0.6452

Nutrients

Inlet and outflow nutrient concentrations for swales lined with riprap, native grass, and turf are given in Table H-5. Lining was a significant factor for NO_x, TP, and OP RE (Table H-6). Storm size was significant for NO_x and OP RE as well as the interaction lining*storm size for NO_x RE. Influent concentration was significant to OP RE. In the effluent concentration analysis, lining was a significant factor for NO_x, TP, and OP (Table H-7). Storm size was also significant for NO_x and OP effluent concentrations. Influent concentrations were significant factors in all the nutrients.

Due to significance between linings in OP RE, native grass-lined swales appear to be equal to, or slightly better, than turf-lined swales. Both native grasses and turf were better than riprap swales vis-à-vis nutrient removal. Riprap had the lowest mean REs of all tested swale linings for measured nutrient species (Table H-8). Native grass-lined swales removed more TKN and OP than turf-lined swales. Turf and native grass-lined swales were similar, and generally better than riprap, regarding NO_x removal. Aeration and organic matter content may be the reason native grasses and turf had fewer NO_x export than riprap. The export of NH_3 (ammonia) is likely the reason for TKN export in riprap, native grass, and turf-lined swales. Decomposition of organic matter may result in NH_3 and, thus, TKN exports (ACS, 2021). Mowing of the turf may have resulted in more decomposed organic matter in the form of grass clippings (Ekka and Hunt, 2020). External organic nitrogen inputs, independent of the controlled influent concentrations, could also result in TKN exports. Similarly, residual grass clippings may cause exports of OP (Rushton, 2001). Because routine maintenance did not occur in native grass-lined swales, they were likely to have less decomposed organic matter than turf-lined swales.

Table H-5: Mean nutrient inlet and overflow concentrations (µg/L) for conventional swales lined with riprap, native grass, and turf.

Lining	Slope (%)	Storm Size	TKN Inlet	TKN Overflow	NO_x Inlet	NO_x Overflow	TN Inlet	TN Overflow	TP Inlet	TP Overflow	OP Inlet	OP Overflow
Riprap	1	Medium	1131.01	1186.78	211.28	273.25	1342.29	1460.03	145.84	168.17	63.39	82.41
		Large	772.51	877.78	143.66	228.71	916.17	1106.49	99.05	137.08	48.68	67.45
	4	Medium	868.1	999.7	159.9	175.8	1027.9	1175.4	108.4	146.2	48.3	68.2
		Large	937.6	1290.7	162.9	226.0	1100.5	1516.7	97.8	152.6	42.7	51.3
Native Grass	1	Medium	867.72	930.82	282.52	243.00	1150.25	1173.82	177.23	155.23	101.10	84.84
		Large	754.59	762.07	139.43	147.66	894.03	909.73	96.22	93.47	48.43	44.80
	4	Medium	915.0	1036.8	205.7	204.3	1120.6	1241.1	141.9	160.4	62.0	60.7
		Large	926.7	908.8	106.5	99.1	1033.3	1007.9	87.3	97.5	33.0	35.7
Turf	1	Medium	641.46	718.97	169.07	152.61	810.53	871.58	98.40	98.25	53.10	61.07
		Large	751.34	774.09	164.44	154.79	915.78	928.88	83.75	71.06	27.69	29.17
	4	Medium	742.11	848.15	204.34	181.45	946.46	1029.61	111.28	125.11	55.38	73.84
		Large	664.20	692.30	162.82	163.46	827.03	855.76	77.61	73.59	27.43	33.91

Table H-6: Nutrient RE ANCOVA results for swales lined with riprap, native grass, and turf. Bolded values are statistically significant.

Factor	**TKN p-value**	**NO_x p-value**	**TN p-value**	**TP p-value**	**OP p-value**
Lining	0.2749	**< 0.0001**	**0.0422**	**0.0007**	**< 0.0001**
Slope	0.3563	0.2226	0.4378	0.0583	0.3419
Storm Size	0.6280	**0.0106**	0.8261	0.9972	**0.0381**
Influent Concentration	0.8176	0.7636	0.8182	0.8035	**0.0167**
Lining*Storm Size*Slope	0.8063	0.2811	0.7549	0.9789	0.2170
Lining*Slope	0.6374	0.0585	0.7906	0.8806	0.1586
Lining*Storm Size	0.3135	**0.0286**	0.1766	0.1783	0.4568
Storm Size*Slope	0.8892	0.4542	0.8776	0.8017	0.5901

Table H-7: Nutrient effluent concentration ANCOVA results for swales lined with riprap, native grass, and turf. Bolded values are statistically significant.

Factor	**TKN p-value**	**NO_x p-value**	**TN p-value**	**TP p-value**	**OP p-value**
Lining	0.3502	**< 0.0001**	0.0893	**0.0024**	**< 0.0001**
Slope	0.3241	0.3734	0.3719	0.0791	0.4356
Storm Size	0.9268	**0.0163**	0.6151	0.8090	**0.0061**
Influent Concentration	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.0002**	**< 0.0001**
Lining*Storm Size*Slope	0.7525	0.0889	0.6578	0.7920	0.8328
Lining*Slope	0.5468	0.0546	0.6706	0.7304	**0.0117**
Lining*Storm Size	0.2726	0.5480	0.2030	0.4458	**0.0257**
Storm Size*Slope	0.9119	0.7830	0.9543	0.4981	0.1433

Table H-8: Mean nutrient RE (%) for conventional swales lined with riprap, native grass, and turf.

Lining	Slope (%)	Storm Size	TKN	NO_x	TN	TP	OP
Riprap	1	Medium	-7	-29	-10	-17	-32
		Large	-13	-59	-21	-38	-40
	4	Medium	-16	-13	-15	-35	-48
		Large	-34	-39	-33	-52	-24
Native Grass	1	Medium	-8	13	-3	12	15
		Large	-2	-3	-2	4	6
	4	Medium	-14	1	-11	-14	2
		Large	1	7	2	-12	-9
Turf	1	Medium	-12	9	-8	-2	-16
		Large	-3	7	-2	14	-6
	4	Medium	-14	10	-9	-13	-33
		Large	-4	0	-3	4	-24

<u>Dissolved Metals</u>

Inlet and outflow dissolved metal concentrations for swales lined with riprap, native grass, and turf are given in Table H-9. Lining was significant to all metal concentration reductions (Table H-10). Influent concentrations were significant for Cd, Cu, and Zn RE. The interaction lining*storm size was significant for Zn RE. In the effluent concentration analysis, lining was a significant factor for all metal effluent concentrations (Table H-11). Slope was significant for Cd and Pb. Influent concentration was significant for Cd and Zn. The lining*slope interaction was significant for Cu and Pb while the lining*storm size was significant for Pb and Zn.

From a metals removal standpoint, turf was best, followed by native grasses. The least effective liner was riprap. Turf-lined swales had better metal removal than native grasses in the cases of Cu and Pb (Table H-12). Riprap had the least removal of the three liners for all metals except in the case of Cu where native grasses had the least removal. Native grasses and turf had similar Cd and Zn RE. Plant uptake perhaps explains why native grass and turf-lined swales had better Cd removal than riprap-lined swales. Higher sedimentation rates in turf may have resulted in greater Pb and Zn RE in turf grass than riprap or native grasses (Nardin and Edmonds, 2014; Legret and Pagotto, 1999).

Table H-9: Mean dissolved metal inlet and overflow concentrations (µg/L) for conventional swales lined with riprap, native grass, and turf.

Lining	Slope (%)	Storm Size	Cd Inlet	Cd Overflow	Cu Inlet	Cu Overflow	Pb Inlet	Pb Overflow	Zn Inlet	Zn Overflow
Riprap	1	Medium	3.23	2.87	13.67	18.00	8.80	9.77	58.00	55.67
		Large	2.77	1.93	12.13	15.67	4.97	4.83	50.00	39.00
	4	Medium	3.0	2.3	14.0	20.0	4.4	4.0	71.3	73.7
		Large	2.5	1.9	8.7	15.4	4.7	4.6	39.3	29.7
Native Grass	1	Medium	6.23	3.17	17.67	20.00	9.10	7.70	134.67	56.33
		Large	2.13	1.45	11.17	17.33	4.07	3.87	244.00	114.00
	4	Medium	4.3	1.6	13.6	25.3	6.7	4.0	81.7	38.0
		Large	2.4	1.4	11.3	20.0	3.9	3.3	47.3	28.0
Turf	1	Medium	3.77	1.97	10.63	10.17	7.60	5.43	68.67	37.00
		Large	2.00	1.37	8.17	7.60	5.47	3.53	61.67	29.00
	4	Medium	4.17	1.77	14.00	9.73	9.60	5.83	82.00	33.33
		Large	2.60	1.47	7.70	6.60	5.03	3.70	42.67	24.67

Table H-10: Dissolved metal RE ANCOVA results for swales lined with riprap, native grass, and turf. Bolded values are statistically significant.

Factor	Cd p-value	Cu p-value	Pb p-value	Zn p-value
Lining	**0.0055**	**< 0.0001**	**<0.0001**	**< 0.0001**
Slope	0.0631	0.0565	0.1003	0.2131
Storm Size	0.9131	0.7516	0.6541	0.6317
Influent Concentration	**0.0340**	**0.0373**	0.6256	**0.0118**
Lining*Storm Size*Slope	0.5452	0.5602	0.9603	0.6044
Lining*Slope	0.3483	0.0784	0.2937	0.4858
Lining*Storm Size	0.4390	0.8226	0.4108	**0.0412**
Storm Size*Slope	0.2067	0.4857	0.0896	0.6829

Table 3- H-11: Dissolved metal effluent concentration ANCOVA results for swales lined with riprap, native grass, and turf. Bolded values are statistically significant.

Factor	Cd p-value	Cu p-value	Pb p-value	Zn p-value
Lining	**0.0020**	**0.0012**	**0.0025**	**0.0054**
Slope	**0.0495**	0.1235	**0.0028**	0.2201
Storm Size	0.5272	0.1778	0.1010	0.3530
Influent Concentration	**0.0002**	0.9833	0.4017	**< 0.0001**
Lining*Storm Size*Slope	0.7449	0.5385	0.0627	0.2553
Lining*Slope	0.7007	**0.0181**	**0.0401**	0.1839
Lining*Storm Size	0.2198	0.4965	**0.0082**	**0.0100**
Storm Size*Slope	0.1070	0.5521	0.9592	0.1513

Table H-12: Mean dissolved metal RE (%) for conventional swales lined with riprap, native grass, and turf.

Lining	Slope (%)	Storm Size	Cd	Cu	Pb	Zn
Riprap	1	Medium	13	-32	-6	-1
		Large	29	-33	3	18
	4	Medium	25	-48	5	1
		Large	19	-72	-1	15
Native Grass	1	Medium	44	-13	15	53
		Large	29	-58	9	37
	4	Medium	62	-86	40	54
		Large	40	-78	17	41
Turf	1	Medium	48	5	28	48
		Large	29	2	32	40
	4	Medium	55	25	37	58
		Large	40	14	27	41

Pollutant Loads

Sediment, nutrient, and metal load reductions for riprap, native grass, and turf-lined swales are presented (Table H-13). Pollutant loads are highly dependent on volume reduction. Because of substantially more volume reduction, it is not surprising that load reductions were also substantially different (and higher) in native grass and riprap-lined swales than turf-lined.

Table H-13: TSS, nutrient, and dissolved metal load reductions (%) for conventional swales lined with riprap, native grass, and turf.

Lining	Slope (%)	Storm Size	TSS	TN	TP	OP	Cd	Cu	Pb	Zn
Riprap	1	Medium	80	59	57	50	68	51	57	59
		Large	87	72	68	68	85	72	78	83
	4	Medium	53	40	29	20	59	20	49	49
		Large	-7	29	20	38	59	8	49	56

Native Grass	1	Medium	88	75	78	79	86	72	79	88
		Large	77	41	45	45	59	2	48	64
	4	Medium	69	73	72	75	91	53	85	88
		Large	75	75	71	72	85	55	79	85
Turf	1	Medium	78	-1	5	-9	51	10	33	50
		Large	76	8	22	4	36	11	39	46
	4	Medium	76	6	1	-16	61	34	44	63
		Large	71	9	15	-9	47	24	35	48

Turf Lining Comparison Conclusions

Turf had better sediment and dissolved metal concentration reductions than native grasses and riprap. Native grasses and turf were essentially the same for nutrient concentrations. The native grass-lined swale on the 4% slope (CG4) provides the highest overall rates of nutrient and dissolved metal load reduction. Each of the riprap and native grass-lined swales had substantially more volume reduction than the turf-lined swales. Because experiments herein were conducted on the same swales as the turf, it is possible the lining had an effect on volume reduction. Alternative liners herein are a competitive option over turf because of their simple maintenance procedures. Turf-lined swales require routine mowing; whereas, riprap and native grass-lined swales may only require minimal weed management (Harper-Lore, 2023).

Appendix I – Bioswale Swale Discussion Details

Table I-1: Median total volume reductions for each bioswale as taken from Wilcoxon Signed Rank, pooled across storm size. Bolded values represent inflow reduction significantly different from outflow.

Swale ID	Total Volume Reduction (L)	Total Volume Reduction (%)	p-value
BR1	**9,405**	**52**	0.0313
BG1	7,835	42	0.0625
BR4	**6,372**	**25**	0.0313
BG4	2,909	12	0.0938

Note: Bioswale IDs are represented as B (bioswale), R/G (riprap or native grass, and 1/4 (1 or 4% slope)

Table I-2: Comparison of volume reduction results.

Source	Volume Reduction (%)
Bioswales herein	12 - 52
Poresky et al. (2011)	25 - 65
Osouli et al. (2017)	27 - 57

Figure I-1: Slight erosion observed along perimeter of outlet box.

Table I-3: Median combined peak flow reduction (L/s) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size.

Swale ID	Peak Flow Reduction (L/s)	Peak Flow Reduction (%)	p-value
BR1	**2.56**	**28**	0.0313
BG1	**3.66**	**41**	0.0313
BR4	2.10	23	0.4688
BG4	1.29	17	0.0938

Table I-4: Comparison of peak flow reduction results.

Source	Peak Flow Reduction (%)
Bioswales herein	17 - 41
Stagge (2006)	50 - 53
Ainan et al. (2003)	28.9 - 55.9
Wu et al. (1998)	10 - 20

Table I-5: Median reduction of TSS concentrations (mg/L) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. Negative values represent greater outflow concentration than inflow.

Swale ID	Median Influent Concentration 70 min.	TSS Overflow 70 min.	TSS Underdrain 70 min.	Median Influent Concentration 140 min.	TSS Overflow 140 min.	TSS Underdrain 140 min.
BR1	24.0	-14.00	13.28	25.4	5.50	11.53
BG1	16.1	0.20	5.79	11.6	3.08	7.36
BR4	38.5	24.24	31.52	13.4	4.79	9.66
BG4	22.8	11.79	13.28	16.3	10.52	8.48

Table 1-6: Median reduction of TKN concentrations (µg/L) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. Negative values represent greater outflow concentration than inflow.

Swale ID	Median Influent Concentration 70 min.	TKN Overflow 70 min.	TKN Underdrain 70 min.	Median Influent Concentration 140 min.	TKN Overflow 140 min.	TKN Underdrain 140 min.
BR1	867.3	-209.66	-29.20	982.2	-249.04	13.21

BG1	857.2	-115.37	31.33	890.1	-63.13	163.13
BR4	953.1	-122.79	75.67	861.0	-199.15	-95.13
BG4	942.6	-14.36	38.51	877.4	6.37	60.58

Table I-7: Median reduction of NH_3 concentrations (µg/L) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. Negative values represent greater outflow concentration than inflow.

Swale ID	Median Influent Concentration 70 min.	NH_3 Overflow 70 min.	NH_3 Underdrain 70 min.	Median Influent Concentration 140 min.	NH_3 Overflow 140 min.	NH_3 Underdrain 140 min.
BR1	42.6	-17.63	-12.11	19.8	-0.13	-29.89
BG1	31.0	-2.86	-10.56	20.2	-12.57	-5.24
BR4	27.2	-9.02	-13.97	26.0	-134.87	-31.23
BG4	31.0	-4.80	-14.91	37.7	4.80	-6.90

Table I-8: Median reduction of NO_x concentrations (µg/L) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. Negative values represent greater outflow concentration than inflow. No results were significant.

Swale ID	Median Influent Concentration 70 min.	NO_x Overflow 70 min.	NO_x Underdrain 70 min.	Median Influent Concentration 140 min.	NO_x Overflow 140 min.	NO_x Underdrain 140 min.
BR1	160.8	-217.52	-526.19	100.8	-15.09	-461.83
BG1	149.4	17.93	23.50	76.4	8.25	34.40
BR4	170.2	27.25	-1047.96	81.0	-8.20	-655.89
BG4	115.9	-2.33	-21.69	80.2	15.52	0.32

Table I-9: Median reduction of TN concentrations (µg/L) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. No results were significant.

Swale ID	Median Influent Concentration 70 min.	TN Overflow 70 min.	TN Underdrain 70 min.	Median Influent Concentration 140 min.	TN Overflow 140 min.	TN Underdrain 140 min.
BR1	1015.6	-427.18	-454.37	1083.0	-264.13	-448.62

BG1	1010.1	-68.79	98.71	966.6	-56.85	197.53
BR4	1123.4	-122.10	-972.29	939.4	-200.82	-715.33
BG4	1058.4	-23.74	16.82	967.6	15.12	60.90

Table I-10: Median reduction of TP concentrations (µg/L) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. Negative values represent greater outflow concentration than inflow. No results were significant.

Swale ID	Median Influent Concentration 70 min.	TP Overflow 70 min.	TP Underdrain 70 min.	Median Influent Concentration 140 min.	TP Overflow 140 min.	TP Underdrain 140 min.
BR1	104.7	-75.03	-11.31	112.4	33.54	-19.69
BG1	110.0	-5.30	0.31	66.7	-5.34	11.93
BR4	128.0	-4.53	-37.87	81.5	-87.81	-88.45
BG4	99.0	-9.76	2.09	82.9	10.11	8.51

Table I-11: Median reduction of dissolved Cd concentrations (µg/L) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. No results were significant.

Swale ID	Median Influent Concentration 70 min.	Cd Overflow 70 min.	Cd Underdrain 70 min.	Median Influent Concentration 140 min.	Cd Overflow 140 min.	Cd Underdrain 140 min.
LBR1	3.9	2.0	3.4	2.4	1.1	1.9
BG1	3.0	1.6	2.5	1.7	0.69	1.2
BR4	3.7	1.4	3.2	2.1	0.5	1.6
BG4	2.4	0.6	1.9	2.3	0.6	1.6

Table I-12: Median reduction of dissolved Cu concentrations (µg/L) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. Negative values represent greater outflow concentration than inflow. No results were significant.

Swale ID	Median Influent Concentration 70 min.	Cu Overflow 70 min.	Cu Underdrain 70 min.	Median Influent Concentration 140 min.	Cu Overflow 140 min.	Cu Underdrain 140 min.
BR1	16.0	-29.0	-6.0	11.0	-9.0	-12.0
BG1	17.0	-3.0	-5.0	10.0	-6.0	-7.0

BR4	11.0	-5.0	-8.0	11.0	-17.0	-7.0
BG4	14.0	-5.0	-11.0	9.9	-4.0	-11.7

Table I-13: Median reduction of dissolved Pb concentrations (µg/L) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. No results were significant.

Swale ID	Median Influent Concentration 70 min.	Pb Overflow 70 min.	Pb Underdrain 70 min.	Median Influent Concentration 140 min.	Pb Overflow 140 min.	Pb Underdrain 140 min.
BR1	4.9	2.2	2.9	3.3	0.5	1.3
BG1	4.8	1.2	1.5	3.1	0.0	0.4
BR4	6.5	1.8	4.5	2.3	0.0	0.3
BG4	4.0	0.6	1.2	3.0	0.5	1.0

Table I-14: Median reduction of dissolved Zn concentrations (µg/L) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. No results were significant.

Swale ID	Median Influent Concentration 70 min.	Zn Overflow 70 min.	Zn Underdrain 70 min.	Median Influent Concentration 140 min.	Zn Overflow 140 min.	Zn Underdrain 140 min.
BR1	65.0	16.0	55.0	45.0	14.0	29.0
BG1	62.0	27.0	52.0	35.0	10.0	15.0
BR4	73.0	24.0	63.0	37.0	7.0	26.0
BG4	48.0	12.0	38.0	39.0	14.0	23.0

Bioswale Interaction Plots

In the storm size*slope interaction, riprap-lined bioswales had higher total volume reductions than native grass-lined bioswales on the 1% slope during large storms and on the 4% slope during medium storms (Figure I-2).

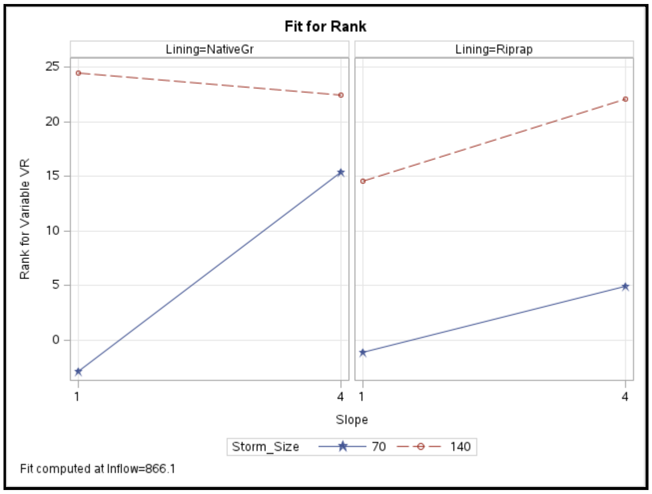


Figure I-2: Total volume reduction storm size*slope interaction plot.

In the lining*storm size interaction, native grass-lined bioswales had less NH_3 export than riprap bioswales for both medium and large storms on the 1% slope and large storms for the 4% slope (Figure I-3).

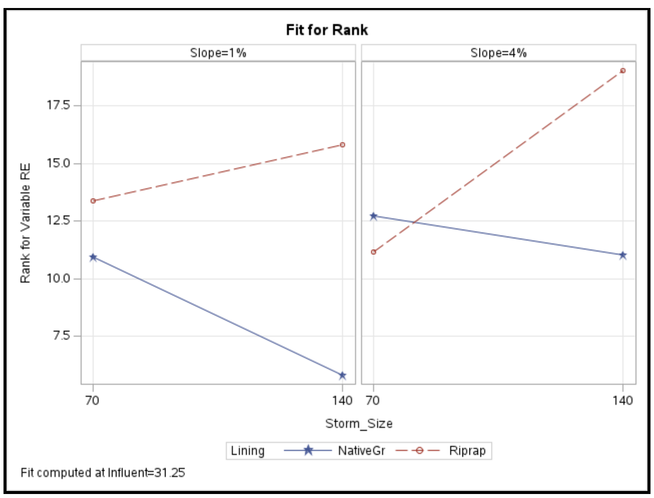


Figure I-3: NH_3 underdrain lining*storm size interaction plot.

Native grass-lined bioswales reduced OP concentrations more than riprap bioswales in the underdrain of the 1% and 4% slopes during medium and large storms in the lining*slope interaction (Figure I-4).

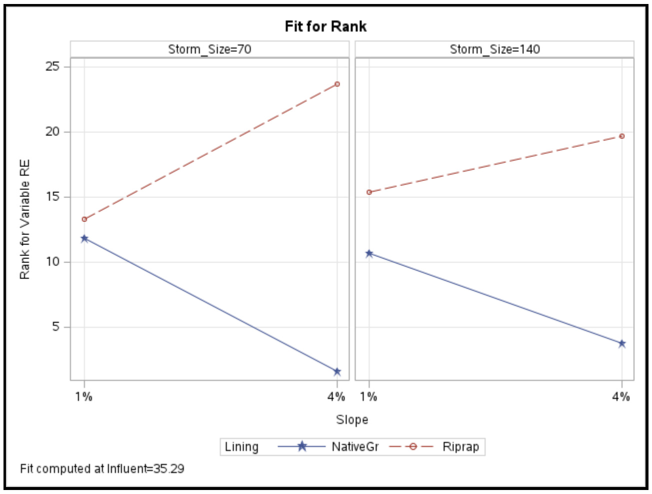


Figure I-4: OP underdrain lining*slope interaction plot.

Riprap and native grass-lined dissolved Cd concentration results were comparable in the underdrain lining*storm size interaction (Figure I-5). Native grass-lined bioswales had higher reductions during medium storms while riprap-lined bioswales had higher reductions during large storms.

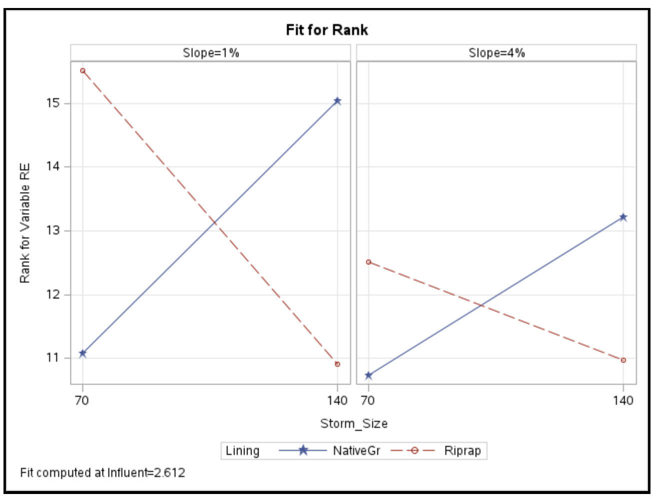


Figure I-5: Cd underdrain lining*storm size interaction plot.

Native grass-lined bioswales generally had lower dissolved Cu exports than riprap bioswales in the underdrain in the lining*slope interaction (Figure I-6).

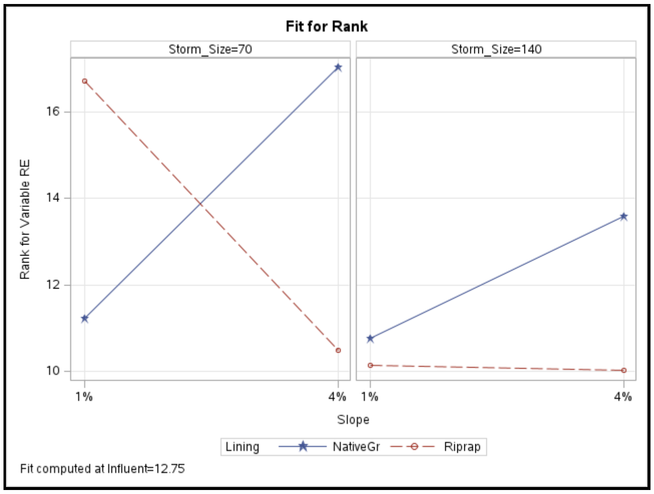


Figure I-6: Cu underdrain lining*slope interaction plot.

Native grass-lined bioswales had higher OP load reductions than riprap bioswales on the 4% slope during medium and large storms in the lining*slope interaction (Figure I-7).

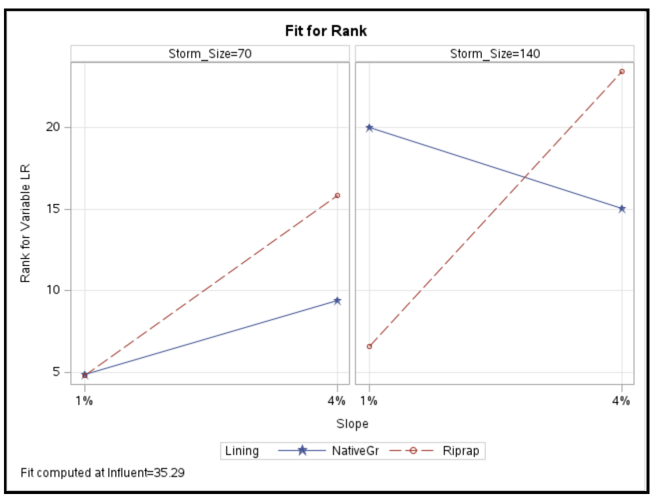


Figure I-7 OP load reduction slope*storm size interaction

Appendix J – Bioswale Raw Data and Field Notes

Bioswale Raw Hydrology Data

Table J-1: Hydrologic behavior for bioswales during the 70 min. storms.

Swale ID	Event	Inflow Volume (L)	Outflow Volume (L)	Underdrain Volume (L)	Combined Outflow (L)	Outflow Rate (%)	Volume Reduction (%)
BR1	1	17,986	16	6,056	6,072	34	66
	2	16,582	347	9,405	9,751	59	41
	3	16,292	747	8,649	9,396	58	42
BG1	1	14,932	1,075	6,182	7,257	49	51
	2	18,250	964	5,813	6,777	37	63
	3	15,064	1,719	5,348	7,068	47	53
BR4	1	16,499	7,357	2,404	9,761	59	41
	2	17,168	8,396	5,633	14,029	82	18
	3	16,141	6,691	3,444	10,135	63	37
BG4	1	18,029	6,606	12,698	19,305	107	-7
	2	18,120	9,568	7,687	17,255	95	5
	3	15,151	6,261	7,242	13,503	89	11
	Mean	16,685	4,145	6,714	10,859	65	35
	Median	16,541	3,990	6,119	9,756	59	41

Table J-2: Hydrologic behavior for bioswales during the 140 min. storms.

Swale ID	Event	Inflow Volume (L)	Outflow Volume (L)	Underdrain Volume (L)	Combined Outflow (L)	Outflow Rate (%)	Volume Reduction (%)
BR1	1	28,031	190	10,638	10,829	39	61
	2	28,950	1,253	25,661	26,914	93	7
	3	36,538	7,581	3,160	10,741	29	71
BG1	1	34,654	3,096	20,099	23,195	67	33
	2	32,220	6,411	19,594	26,005	81	19
	3	34,043	8,388	27,343	35,732	105	-5
BR4	1	35,312	3,206	23,786	26,993	76	24
	2	31,462	19,348	6,643	25,990	83	17
	3	30,824	19,086	3,584	22,669	74	26
BG4	1	33,888	6,904	17,920	24,825	73	27
	2	30,388	9,295	16,924	26,219	86	14
	3	32,050	14,906	11,099	26,005	81	19
	Mean	32,364	8,305	15,538	23,843	74	26
	Median	32,135	7,243	17,422	25,997	79	21

Table J-3: Peak flow behavior for bioswales during the 70 min. storms.

Swale ID	Event	Peak Inflow (L/s)	Peak Outflow (L/s)	Peak Underdrain (L/s)	Peak Combined Outflow (L/s)	PFR Rate Outflow (%)	PFR Rate Underdrain (%)	PFR Rate Combined (%)
BR1	1	9.1	0.0	6.8	6.8	100	25	25
	2	9.1	0.8	6.8	7.6	91	25	16
	3	9.1	1.4	4.5	5.9	84	50	34
BG1	1	9.1	1.1	3.7	4.8	88	59	47
	2	9.1	1.1	5.4	6.5	88	41	28
	3	9.1	2.3	3.4	5.7	75	63	38
BR4	1	9.3	5.1	1.4	6.5	45	85	30
	2	9.1	5.1	2.5	7.6	44	72	16
	3	9.3	5.1	1.7	6.8	45	82	27
BG4	1	9.1	4.5	4.2	8.8	50	53	3
	2	9.1	6.2	2.0	8.2	31	78	9
	3	9.1	5.1	2.0	7.1	44	78	22
	Mean	9.1	3.2	3.7	6.9	65	59	25
	Median	9.1	3.4	3.5	6.8	63	61	26

Table J-4: Peak flow behavior for bioswales during the140 min. storms.

Swale ID	Event	Peak Inflow (L/s)	Peak Outflow (L/s)	Peak Underdrain (L/s)	Peak Combined Outflow (L/s)	PFR Rate Outflow (%)	PFR Rate Underdrain (%)	PFR Rate Combined (%)
BR1	1	9.1	0.0	6.2	6.2	100	31	31
	2	9.1	1.1	7.9	9.1	88	13	0
	3	9.3	5.4	1.4	6.8	42	85	27
BG1	1	9.1	1.7	6.2	7.9	81	31	13
	2	9.1	2.3	5.1	7.4	75	44	19
	3	9.1	2.8	2.5	5.4	69	72	41
BR4	1	9.1	5.4	11.6	17.0	41	-28	-88
	2	9.3	5.7	2.0	7.6	39	79	18
	3	9.1	6.2	1.4	7.6	31	84	16
BG4	1	9.1	9.6	4.0	13.6	-6	56	-50
	2	9.1	4.0	5.9	9.9	56	34	-9
	3	9.3	5.7	2.3	7.9	39	76	15
	Mean	9.1	4.2	4.7	8.9	55	48	3
	Median	9.1	4.7	4.5	7.8	49	50	15

Bioswale Raw Water Quality Data

Table J-5: Bioswale inlet EMCs. TSS in mg/L all other in µg/L

Storm Date	Swale ID	Storm Size (mins.)	TSS	TKN	NO_x	TN	NH_3	TP	OP	Cd	Cu	Pb	Zn
5/31/2022	BR4	140	9.32	775.16	81.01	856.17	34.09	81.49	28.96	2.8	9.8	2.6	37
6/3/2022	BR4	140	56.85	1111.61	105.63	1217.24	25.99	101.79	17.83	1.4	11	2.3	35
6/6/2022	BR4	70	61.25	958.45	174.2	1132.65	27.21	128	57.28	4.4	11	6.5	77
6/7/2022	BR1	140	39.07	1070.56	99.78	1170.34	19.77	110.76	20.87	2.3	9.5	3.3	45
6/10/2022	BR1	140	25.35	944.99	111.93	1056.92	26.24	112.35	41.37	2.7	11	3.9	44
6/13/2022	BR1	70	26.21	854.83	160.81	1015.64	42.62	104.32	50.55	4	16	4.6	65
6/13/2022	BR4	70	38.52	945.69	150.57	1096.26	32.97	115.38	48.83	2.8	10	6.1	53
6/15/2022	BR4	140	13.38	860.99	78.4	939.39	24.34	75.13	24.95	2.1	15	2.2	38
6/16/2022	BR1	140	15.54	982.17	100.84	1083.01	17.64	155.62	54.2	2.4	12	2.6	49
6/20/2022	BR1	70	24	978.79	176.05	1154.84	46.6	147.6	57.79	3.9	19	6.5	82
6/20/2022	BR4	70	28.53	953.13	170.22	1123.35	22.84	147	57.61	3.7	13	7.3	73
7/5/2022	BG4	140	16.28	877.44	90.11	967.55	53.95	82.89	31.71	2.3	10	4.4	49
7/6/2022	BG1	140	11.6	814.47	72.81	887.28	47.42	66.07	26.68	2	7.4	3.1	35
7/7/2022	BG4	140	15.03	812.03	75.15	887.18	37.69	84.19	23.87	2.4	9.9	3	39
7/13/2022	BG4	70	24.82	822.69	109.38	932.07	45.13	89.42	37.22	2.4	14	4.1	48
7/13/2022	BG1	70	15.96	844.05	166.01	1010.06	30.99	127.33	53.6	4	17	5.4	79
7/25/2022	BG1	70	23.17	917.16	149.42	1066.58	45.56	109.97	47.01	3	17	3.5	62
7/25/2022	BR1	70	20.89	867.33	124.32	991.65	31.46	104.72	35	3	12	4.9	50
7/26/2022	BG4	140	28.2	932.2	80.17	1012.37	21.68	82.81	<u>3.78</u>	1.1	9.3	2.2	33
7/28/2022	BG4	70	19.25	951.65	130.79	1082.44	20.41	99.55	27.05	2.9	16	3.2	52
8/3/2022	BG1	70	16.05	857.18	115.15	972.33	26.56	87.98	41.27	2	13	4.8	28
8/5/2022	BG1	140	18.4	955.04	80.98	1036.02	17.61	89.56	<u>5.08</u>	1.5	19	<u>4</u>	35
8/8/2022	BG1	140	11.14	890.14	76.41	966.55	20.22	66.74	16.42	1.7	10	2.4	25
8/9/2022	BG4	70	22.8	942.55	115.88	1058.43	31.02	99.04	37.95	1.9	14	4	47
8/25/2022	BR1	140	13.84	858.91	79.63	938.54	<u>16.54</u>	84.02	<u>9.39</u>	1.6	13	2.3	160
8/30/2022	BR1	140	21.37	797.05	88.48	885.53	20.46	77.1	21.19	1.3	101	2.7	77
9/6/2022	BR1	140	40.22	714.52	69.16	783.68	23.65	65.35	27.85	1.2	14	<u>2</u>	90

Underlined numbers are less than PQL (Practical Quantitation Limit)

Table J-6: Bioswale overflow EMCs. TSS in mg/L all other in µg/L.

Storm Date	Swale ID	Storm Size (mins.)	TSS	TKN	NO_x	TN	NH_3	TP	OP	Cd	Cu	Pb	Zn
5/31/2022	BR4	140	69.34	2273.24	132.85	2406.09	381.8	400.34	165.12	1.4	63	2.1	24
6/3/2022	BR4	140	13.69	1310.76	107.3	1418.06	160.86	189.6	73.2	1.1	28	2.3	28
6/6/2022	BR4	70	18.99	1114.43	146.95	1261.38	56.34	132.53	48.87	2.7	17	4.7	47
6/7/2022	BR1	140	*	*	*	*	*	*	*	*	*	*	*
6/10/2022	BR1	140	242.11	2141.18	215.32	2356.5	173.29	273.29	69.19	2	64	3.4	78
6/13/2022	BR1	70	11.08	1064.49	378.33	1442.82	60.25	183.98	108.83	1.7	58	3.3	49
6/13/2022	BR4	70	14.28	1068.48	149.88	1218.36	41.99	135.91	55.22	1.9	13	5	41
6/15/2022	BR4	140	8.59	848.03	86.6	934.63	29.47	72.7	26.95	1.6	13	2.3	33
6/16/2022	BR1	140	10.04	1231.21	115.93	1347.14	17.77	122.08	25.26	1.3	21	2.1	35
6/20/2022	BR1	70	44.5	1119.08	260.71	1379.79	56.52	202.01	78.39	1.9	47	4.3	54
6/20/2022	BR4	70	10.26	961.83	140.59	1102.42	23.19	126.94	46.86	2.3	18	4.5	49
7/5/2022	BG4	140	5.79	918.83	67.52	986.35	45	72.78	23.21	1.3	14	2.9	27
7/6/2022	BG1	140	15.68	1050.38	64.56	1114.94	66.59	115.23	38.14	0.93	23	2.5	25
7/7/2022	BG4	140	4.51	805.66	59.63	865.29	32.89	73.8	18.64	1.8	10	2.2	25
7/13/2022	BG4	70	9.8	837.05	118.76	955.81	49.93	99.18	39	1.8	19	3.5	36
7/13/2022	BG1	70	12.84	984.23	94.62	1078.85	32.85	132.63	36.79	1.4	20	2.3	35
7/25/2022	BG1	70	27.12	1032.53	131.49	1164.02	57.71	131.64	44.82	1.4	20	2.3	35
7/25/2022	BR1	70	34.88	1469.99	2338.8	3808.79	92.22	179.75	58.21	1.2	41	2.2	34
7/26/2022	BG4	140	8.05	923.95	73.3	997.25	20.72	83.86	<u>3.13</u>	0.53	14	2	23
7/28/2022	BG4	70	7.46	921.69	129.96	1051.65	17.69	93.03	21.13	2	17	2.6	35
8/3/2022	BG1	70	15.85	912.32	111.87	1024.19	29.42	93.07	45.01	1.3	19	4.4	22
8/5/2022	BG1	140	9.83	1010.44	68.68	1079.12	30.18	83.43	<u>3.38</u>	0.81	11	<u>4</u>	21
8/8/2022	BG1	140	8.06	953.27	70.13	1023.4	21.13	72.08	14.62	1.3	16	<u>4</u>	20
8/9/2022	BG4	70	16.26	1161.53	118.21	1279.74	38.71	129.61	41.53	1.6	24	<u>4</u>	35
8/25/2022	BR1	140	12.67	850.55	268.21	1118.76	26.49	87.77	<u>10.03</u>	0.88	19	<u>2</u>	62
8/30/2022	BR1	140	12.38	851.5	134.31	985.81	50.22	78.13	16.79	0.82	20	<u>2</u>	58
9/6/2022	BR1	140	10.6	728.22	128.54	856.76	37.91	78.56	52.27	0.87	21	<u>2</u>	59

Underlined numbers are less than PQL (Practical Quantitation Limit)

Table J-7: Bioswale underdrain EMCs. TSS in mg/L all other in µg/L.

Storm Date	Swale ID	Storm Size (mins.)	TSS	TKN	NO_x	TN	NH_3	TP	OP	Cd	Cu	Pb	Zn
5/31/2022	BR4	140	13.49	1191.76	966.48	2158.24	144.78	276.26	180.31	0.5	19.0	2.0	11
6/3/2022	BR4	140	4	807.73	761.52	1569.25	45.58	173.06	112.12	0.5	18	2	11
6/6/2022	BR4	70	8.11	882.78	1222.16	2104.94	41.18	165.87	95.67	0.5	22.0	2.0	11
6/7/2022	BR1	140	17.49	1093.84	1178.28	2272.12	64.62	174.98	55.04	0.5	24.0	2.0	18
6/10/2022	BR1	140	13.82	931.78	573.76	1505.54	56.13	132.04	37.98	0.5	23	2.1	15
6/13/2022	BR1	70	12.93	884.03	472.36	1356.39	54.73	115.63	38.35	0.5	22.0	2.0	10
6/13/2022	BR4	70	7	960.52	1426.36	2386.88	49.93	167.25	95.16	0.5	18	2.0	10
6/15/2022	BR4	140	3.72	956.12	698.6	1654.72	55.57	163.58	95.13	0.5	22.0	2.0	11
6/16/2022	BR1	140	6.28	768.04	344.16	1112.2	34.25	104.49	33.34	0.5	15.0	2.0	10
6/20/2022	BR1	70	6.16	906.97	702.24	1609.21	32.69	98.4	29.68	0.5	22	2.1	10
6/20/2022	BR4	70	4.36	790.17	1087.6	1877.77	32.37	143.7	76.62	0.5	21	2.0	10
7/5/2022	BG4	140	8.25	816.86	89.79	906.65	46.68	74.38	10.25	0.7	26.0	2.0	26
7/6/2022	BG1	140	8.91	900.12	62.43	962.55	49.18	109.4	35.23	0.8	22.0	2.0	10
7/7/2022	BG4	140	6.55	739.22	66.22	805.44	44.59	63.54	10.17	0.5	21	2.0	10
7/13/2022	BG4	70	9.93	784.18	131.07	915.25	45.26	87.33	11.87	0.5	25.0	2.0	10
7/13/2022	BG1	70	10.17	814.93	96.42	911.35	41.55	124.69	32.03	0.5	22.0	2.0	10
7/25/2022	BG1	70	22.15	885.83	125.92	1011.75	51.17	129.35	27.35	0.5	21	2	10
7/25/2022	BR1	70	158.48	1410.16	1093.72	2503.88	69.44	428.84	26.32	0.77	45	2.0	14
7/26/2022	BG4	140	6.35	889.78	93.63	983.41	40.75	85.34	5	0.5	21.0	2.0	10
7/28/2022	BG4	70	5.97	709.03	100.38	809.41	46.89	68.74	4.8	0.5	22	2	10
8/3/2022	BG1	70	7.1	778.76	92.36	871.12	46.08	87.67	25.91	0.5	19	4.0	10
8/5/2022	BG1	140	3.61	667.19	39.42	706.61	24.52	67.55	11.88	1	18	4	20
8/8/2022	BG1	140	3.78	727.01	42.01	769.02	25.46	54.81	17.41	0.5	17.0	2.0	25
8/9/2022	BG4	70	20.54	1030.16	144.61	1174.77	45.93	142.14	10.31	0.5	32	4.0	10
8/25/2022	BR1	140	11.83	866.46	289.61	1156.07	58	115.99	14.65	0.5	31	2.0	44
8/30/2022	BR1	140	9.17	736.13	141.62	877.75	42.03	85.12	14.68	0.5	26	2.0	37
9/6/2022	BR1	140	9	733.23	140.02	873.25	54.33	80.79	17.6	0.5	20.0	2.0	110

Underlined numbers are less than PQL (Practical Quantitation Limit)

Table J-8: Bioswale TSS load reductions (%). Negative values represent greater than that of inflow.

Swale ID	Event	TSS 70 min.	TSS 140 min.
BR1	1	81	96
	2	69	49
	3	-156	76
BG1	1	56	57
	2	52	77
	3	81	55
BR4	1	88	-311
	2	73	84
	3	82	68
BG4	1	71	66
	2	71	66
	3	10	77
	Mean	48	38
	Median	71	67

Table J-9: Bioswale nutrient load reductions (%) for 70 min. storms. Negative values represent greater than that of inflow.

Swale ID	Event	TKN	NO_x	TN	NH_3	TP	OP
BR1	1	60	-13	48	50	57	70
	2	13	-260	-29	33	35	49
	3	45	-198	15	25	-38	75
BG1	1	34	61	38	13	34	59
	2	52	59	53	44	43	49
	3	65	69	66	39	63	74
BR4	1	28	-380	-35	-21	3.3	-20
	2	9	-161	-14	-10	-3	-11
	3	43	-30	32	34	47	44
BG4	1	29	15	27	24	26	62
	2	29	27	29	-55	33	66
	3	-22	-25	-23	-50	-9	41
	Mean	32	-70	17	11	21	48
	Median	31	-19	28	25	33	60

Table J-10: Bioswale nutrient load reductions (%) for 140 min. storms. Negative values represent greater than that of inflow.

Swale ID	Event	TKN	NO_x	TN	NH_3	TP	OP
BR1	1	91	-2	86	72	86	77
	2	39	-195	15	-35	28	44
	3	53	-87	40	-8	61	65
BG1	1	46	59	47	47	21	37
	2	37	54	38	-19	36	-56
	3	8	33	10	-27	7	-7
BR4	1	-94	-372	-120	-587	-252	-383
	-2	19	-47	13	-304	-35	-227
	3	36	136	21	1	13	-26
BG4	1	19	31	20	31	28	55
	2	9	21	10	4	22	41
	3	13	6	13	-29	9	3
	Mean	23	-53	16	-71	2	-31
	Median	27	2	17	-13	21	20

Table J-11: Bioswale metal load reductions (%) for 70 min. storms. Negative values represent greater than that of inflow.

Swale ID	Event	Cd	Cu	Pb	Zn
BR1	1	95	45	83	94
	2	87	-13	69	86
	3	91	-27	86	91
BG1	1	90	14	75	89
	2	90	40	72	89
	3	89	46	69	85
BR4	1	87	-49	73	85
	2	55	-18	43	48
	3	70	15	69	68
BG4	1	74	-22	57	74
	2	69	-9	40	69
	3	50	-124	-7	58
	Mean	79	-8	91	78
	Median	87	-11	69	85

Table J-12: Bioswale metal load reductions (%) for 140 min. storms. Negative values represent greater than that of inflow.

Swale ID	Event	Cd	Cu	Pb	Zn
BR1	1	98	78	95	97
	2	88	-31	68	77
	3	87	26	56	86
BG1	1	80	-41	68	82
	2	49	31	19	53
	3	58	-76	-8	0
BR4	1	70	-278	35	59
	2	47	-77	28	47
	3	63	33	37	58
BG4	1	63	-55	54	56
	1	52	-43	33	55
	3	58	-70	19	57
	Mean	68	-42	42	60
	Median	63	-42	36	57

Field Notes

Table J-13: Bioswale Simulated Storm Log

Storm Date	Swale ID	Storm Size (mins)	Relevant Field Notes
5/31/2022	BR4	140	Underdrain RTD not recognized by sampler; only able to offload 7 data points
6/3/2022	BR4	140	
6/6/2022	BR4	70	
6/7/2022	BR1	140	Runoff flowing upstream; missed peak of storm so no overflow samples collected
6/10/2022	BR1	140	Piping moved forward so runoff would not flow upstream
6/13/2022	BR1	70	Limited runoff in overflow; manual samples were taken every 5 minutes
6/13/2022	BR4	70	
6/15/2022	BR4	140	
6/16/2022	BR1	140	~0.25 mm rain event during last 20 minutes of experiment
6/20/2022	BR1	70	Limited runoff in overflow; manual sample taken last 10 minutes of experiment
6/20/2022	BR4	70	
7/5/2022	BG4	140	
7/6/2022	BG1	140	
7/7/2022	BG4	140	
7/13/2022	BG4	70	
7/13/2022	BG1	70	
7/25/2022	BG1	70	
7/25/2022	BR1	70	
7/26/2022	BG4	140	
7/28/2022	BG4	70	
8/3/2022	BG1	70	Manual sample taken from overflow at end of experiment to have enough sample for lab analysis
8/5/2022	BG1	140	
8/8/2022	BG1	140	
8/9/2022	BG4	70	
8/25/2022	BR1	140	Riprap + Native Grass Experiment
8/30/2022	BR1	140	Riprap + Native Grass Experiment
9/6/2022	BR1	140	Riprap + Native Grass Experiment

Native Grass and Riprap Combination

Table J-14: Hydrologic behavior for bioswale BR1 with Riprap + Native Grass combination

Event	Inflow Volume (L)	Outflow Volume (L)	Underdrain Volume (L)	Combined Outflow (L)	Outflow Rate (%)	Volume Reduction (%)
1	37,062	10,380	8,032	18,411	50	50
2	33,920	10,222	22,003	32,226	95	5
3	33,509	8,338	15,137	23,475	70	30
Mean	34,831	9,646	15,057	24,704	72	28
Median	33,920	10,222	15,137	23,475	70	30

Table J-15: Peak flow behavior for bioswale BR1 with Riprap + Native Grass combination

Event	Peak Inflow (L/s)	Peak Outflow (L/s)	Peak Underdrain (L/s)	Peak Combined Outflow (L/s)	PFR Rate Outflow (%)	PFR Rate Underdrain (%)	PFR Rate Combined (%)
1	9.1	4.2	2.0	6.2	53	78	31
2	9.3	3.4	4.2	7.6	64	55	18
3	9.1	3.1	5.4	8.5	66	41	6
Mean	9.2	3.6	3.9	7.5	61	58	19
Median	9.1	3.4	4.2	7.6	64	55	18

Table J-16: TSS load reductions (%) for BR1 with Riprap + Native Grass combination.

Event	TSS
1	56
2	55
3	83
Mean	65
Median	56

Table J-17: Nutrient load reductions (%) for BR1 with Riprap + Native Grass combination. Negative values represent greater than that of inflow.

Event	TKN	NO_x	TN	NH_3	TP	OP
1	50	-73	40	-21	41	36
2	8	-50	2	-107	-2	31
3	28	-38	23	-44	14	25
Mean	29	-54	22	-57	18	31
Median	28	-50	23	-44	14	31

Table J-18: Metal load reductions (%) for BR1 with Riprap + Native Grass combination. Negative values represent greater than that of inflow.

Event	Cd	Cu	Pb	Zn
1	78	7	57	83
2	56	77	30	46
3	63	-2	30	29
Mean	66	28	39	53
Median	63	7	30	46

Turfgrass-lined Bioswale Raw Data

Table J-19: Inlet EMCs for turf-lined bioswales (mg/L).

Slope (%)	TKN	NOX	TN	TP	OP	TSS
1	0.95	0.11	1.06	1.46	1.16	20.52
1	0.73	0.14	0.86	2.07	2.04	39.80
1	0.71	-	-	2.15	2.09	48.02
1	0.79	0.13	0.92	2.19	2.16	51.93
1	0.76	0.11	0.88	1.59	1.54	40.51
1	0.64	0.11	0.75	1.92	1.84	40.64
1	0.67	0.14	0.81	1.78	1.78	29.06
1	0.55	0.14	0.69	1.82	1.65	53.57
1	-	0.13	-	1.39	1.43	24.27
1	0.55	0.15	0.70	1.83	1.74	47.22
4	0.82	0.09	0.91	1.44	1.41	20.75
4	0.66	0.12	0.79	2.20	2.22	43.35
4	0.66	-	-	1.90	1.85	36.76
4	0.79	0.11	0.90	1.52	1.44	48.03
4	0.59	0.11	0.70	1.96	1.92	58.44
4	0.55	0.13	0.68	1.77	1.57	53.47
4	-	0.13	-	1.49	1.53	30.12
4	0.55	0.13	0.69	1.81	1.74	42.21
4	0.80	0.21	1.01	2.19	2.13	57.69

Table J-20: Overflow EMCs for turf-lined bioswales (mg/L).

Slope (%)	TKN	NOX	TN	TP	OP	TSS
1	-	-	-	-	-	-
1	0.73	0.14	0.87	2.26	2.34	21.29
1	0.73	-	-	2.30	2.31	30.50
1	0.83	0.14	0.97	2.05	2.12	30.77
1	0.77	0.13	0.91	1.93	1.92	28.17
1	0.57	0.12	0.68	2.22	2.12	28.50
1	0.68	0.13	0.81	1.84	1.86	16.48
1	0.62	0.16	0.78	1.81	1.99	27.53
1	-	0.16	-	1.82	1.89	17.29
1	0.65	0.17	0.82	2.09	2.06	31.03
4	1.10	0.27	1.37	1.68	1.55	21.25
4	0.97	0.26	1.23	1.97	1.97	41.66
4	0.88	-	-	1.89	1.85	23.54
4	1.16	0.27	1.43	1.84	1.75	33.80
4	0.91	0.26	1.17	1.87	1.86	26.25
4	0.63	0.20	0.83	2.01	1.70	27.81
4	-	0.19	-	1.85	1.87	21.63
4	0.61	0.16	0.78	1.88	1.96	18.90
4	0.87	0.18	1.04	1.74	1.74	17.05

Table J-21: Underdrain EMCs for turf-lined bioswales (mg/L).

Slope (%)	TKN	NOX	TN	TP	OP	TSS
1	0.95	0.17	1.12	1.52	1.27	58.10
1	0.88	0.15	1.03	1.43	1.28	57.81
1	0.82	-	-	1.35	1.29	30.93
1	0.86	0.14	0.99	1.58	1.46	50.57
1	0.78	0.09	0.88	1.09	1.02	30.10
1	0.57	0.10	0.67	1.37	1.27	19.58
1	0.59	0.11	0.69	1.25	1.25	10.27
1	0.56	0.10	0.67	1.31	1.30	8.04
1	-	0.11	-	1.30	1.29	8.14
1	0.46	0.10	0.56	1.38	1.42	5.15
4	1.16	0.18	1.34	1.38	1.18	45.34
4	0.89	0.14	1.02	1.45	1.37	37.03
4	0.76	-	-	1.29	1.22	26.08
4	0.96	0.16	1.12	1.52	1.00	43.55
4	0.66	0.13	0.79	1.50	1.47	18.17
4	0.62	0.15	0.77	1.43	1.33	16.56
4	-	0.13	-	1.53	1.50	10.05
4	0.57	0.11	0.68	1.59	1.67	9.42
4	0.66	0.15	0.81	1.48	1.45	8.09

Table J-22: Combined outflow EMCs for turf-lined bioswales (mg/L).

Slope (%)	TKN	NOX	TN	TP	OP	TSS
1	0.95	0.17	1.12	1.52	1.27	58.10
1	0.86	0.15	1.01	1.51	1.39	54.07
1	0.80	-	-	1.55	1.51	30.84
1	0.85	0.14	0.99	1.65	1.56	47.49
1	0.78	0.11	0.89	1.47	1.43	29.23
1	0.57	0.11	0.67	1.57	1.47	21.60
1	0.62	0.12	0.74	1.49	1.50	12.80
1	0.59	0.13	0.71	1.52	1.59	16.24
1	-	0.13	-	1.47	1.48	11.15
1	0.55	0.13	0.68	1.72	1.72	17.24
4	1.12	0.24	1.36	1.57	1.41	30.34
4	0.94	0.22	1.15	1.79	1.76	39.91
4	0.83	-	-	1.67	1.63	24.44
4	1.09	0.23	1.31	1.72	1.47	37.48
4	0.82	0.22	1.04	1.74	1.72	23.42
4	0.63	0.19	0.81	1.84	1.60	24.50
4	-	0.18	-	1.79	1.79	19.23
4	0.60	0.15	0.76	1.83	1.90	17.05
4	0.82	0.17	0.99	1.68	1.67	14.92

Appendix K – Bioswale Pollutant Load Analysis

Sediment

When storm data were pooled, native grass swales significantly reduced TSS loads (Table K-1). All four bioswales had insignificant TSS load reductions during medium and large storms (Table K-2). Influent concentration was the only significant factor to TSS load changes (Table K-3).

Table K-1: Median reduction of TSS loads (g) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow load significantly different from outflow load.

Swale ID	TSS	p-value
BR1	343.7	0.2188
BG1	**222.3**	0.0313
BR4	636.9	0.1563
BG4	**337.4**	0.0313

Table K-2: Median reduction of TSS loads (g) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. No results were significant.

Swale ID	Median Influent Load 70 min.	TSS 70 min.	Median Influent Load 140 min.	TSS 140 min.
BR1	694.8	481.0	420.4	206.5
BG1	346.0	236.4	379.2	208.3
BR4	1211.9	889.1	216.0	145.7
BG4	585.0	414.6	427.3	330.9

Table K-3: TSS load reduction Rank ANCOVA results.

Factor	TSS p-value
Lining	0.9386
Slope	0.7843

Storm Size	0.7213
Influent	**0.0272**
Lining*Storm Size*Slope	0.5658
Lining*Slope	0.9478
Lining*Storm Size	0.6335
Storm Size*Slope	0.7191

Nutrients

<u>TKN</u>

When storm sizes were pooled, BR1 and BG1 both significantly reduced TKN loads (Table K-4). All four bioswales had insignificant TKN load reductions during medium and large storms (Table K-5). Slope was the only significant factor to TKN load changes (Table K-6).

Table K-4: Median reduction of TKN loads (g) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow load significantly different from outflow load.

Swale ID	TKN	p-value
BR1	**7.74**	0.0313
BG1	**8.47**	0.0313
BR4	5.64	0.4375
BG4	3.63	0.1563

Table K-5: Median reduction of TKN loads (g) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. No results were significant.

Swale ID	Median Influent Load 70 min.	TKN 70 min.	Median Influent Load 140 min.	TKN 140 min.
BR1	23.96	7.04	16.00	8.44

BG1	15.64	9.82	30.30	5.65
BR4	29.75	6.75	13.90	4.93
BG4	27.88	8.05	14.71	1.89

Table K-6: TKN load reduction Rank ANCOVA results.

Factor	TKN p-value
Lining	0.4531
Slope	**0.0054**
Storm Size	0.5759
Influent	0.8949
Lining*Storm Size*Slope	0.2341
Lining*Slope	0.8889
Lining*Storm Size	0.3408
Storm Size*Slope	0.7307

NH_3

Slope was the significant factor for NH_3 load change (Table K-7). No crossed interactions between lining type, storm size, and slope were statistically significant. Flatter slopes appear to be better, likely due to the increased HRT (Cerdà and García-Fayos, 1997). An increased slope could result in higher volume and rate for the overflow, limiting hydraulic retention time for infiltration along the surface. While slope was shown to have a significant impact, no load changes were statistically significant (Table K-8). Nearly all riprap-lined bioswales had insignificant export, while native grass-lined bioswales were more likely to sequester NH_3 than release it. When storm sizes were pooled, BR4 and BG4 both insignificantly exported NH_3 loads (Table K-9).

Table K-7: NH_3 load reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	NH_3

	p-value
Lining	0.7119
Slope	**0.0131**
Storm Size	0.3996
Influent	0.0576
Lining*Storm Size*Slope	0.1625
Lining*Slope	0.9770
Lining*Storm Size	0.5012
Storm Size*Slope	0.9922

Table K-8: Median reduction of NH_3 loads (g) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. Negative values represent greater outflow load than that of inflow. No results were significant.

Swale ID	Median Influent Load 70 min.	NH_3 70 min.	Median Influent Load 140 min.	NH_3 140 min.
BR1	1.19	0.44	0.44	-0.02
BG1	0.68	0.19	0.69	-0.11
BR4	0.96	-0.11	0.59	-2.43
BG4	0.62	-0.28	0.68	0.03

Table K-9: Median reduction of NH_3 loads (g) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Negative values represent greater outflow than inflow. No results were significant.

Swale ID	NH_3	p-value
BR1	0.29	0.2188
BG1	0.16	0.2188
BR4	-0.15	0.2188
BG4	-0.04	0.8438

NO$_x$

Bioswale lining and slope are the lone statistical factors leading to differences in discharged NO$_x$ loads (Table K-10). No crossed interactions between lining type, storm size, and slope were statistically significant. No load changes were statistically significant (Table K-11). Nearly all riprap-lined bioswales had insignificant export, while native grass-lined bioswales were more likely to sequester NO$_x$ than release it. When storm sizes were pooled, riprap-lined bioswales significantly exported NO$_x$ loads while BG1 significantly reduced them (Table K-12).

The runoff's contact time between inlet and outlet likely led to better reductions in flatter slopes and the native grass-lined bioswales. Both the flatter slopes and native grasses allow for a greater HRT.

Table 4-5K-100: NO$_x$ load reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	**NO$_x$ p-value**
Lining	**< 0.0001**
Slope	**0.0171**
Storm Size	0.7534
Influent	0.8493
Lining*Storm Size*Slope	0.4215
Lining*Slope	0.1330
Lining*Storm Size	0.5501
Storm Size*Slope	0.7351

Table K-11: Median reduction of NO$_x$ loads (g) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. Negative values represent greater outflow load than that of inflow. No results were significant.

Swale ID	**Median**	**NO$_x$**	**Median**	**NO$_x$**

	Influent Load 70 min.	70 min.	Influent Load 140 min.	140 min.
BR1	4.51	-4.42	1.86	1.42
BG1	2.23	1.46	2.60	0.86
BR4	4.74	-7.64	1.39	-1.72
BG4	3.71	0.54	1.36	0.28

Table K-12: Median reduction of NO_x loads (g) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow load significantly different from outflow load. Negative values represent greater outflow than inflow.

Swale ID	NO_x	p-value
BR1	**-2.52**	0.0313
BG1	**1.35**	0.0313
BR4	**-3.44**	0.0313
BG4	0.41	0.1563

<u>TN</u>

Bioswales on a 1% slope generally reduced TN loads better than those on a 4% slope (Table K-13). No crossed interactions between lining type, storm size, and slope were statistically significant (Table K-14). No load changes were statistically significant unless storm sizes were pooled. Then, BG1 significantly reduced TN loads (Table K-15). It is likely flatter slopes had greater removal because of the increased HRT.

Table K-13: Median reduction of TN loads (g) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. Negative values represent greater outflow load than that of inflow. No results were significant.

Swale ID	Median Influent Load 70 min.	TN 70 min.	Median Influent Load 140 min.	TN 140 min.

BR1	28.47	2.61	17.64	7.02
BG1	17.75	11.69	32.90	6.30
BR4	34.49	-4.94	15.16	3.21
BG4	31.59	8.59	16.08	1.97

Table K-14: TN load reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	TN p-value
Lining	0.3771
Slope	**0.0143**
Storm Size	0.8400
Influent	0.9923
Lining*Storm Size*Slope	0.3349
Lining*Slope	0.9021
Lining*Storm Size	0.1925
Storm Size*Slope	0.8624

Table K-15: Median reduction of TN loads (g) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow load significantly different from outflow load. Negative values represent greater outflow than inflow.

Swale ID	TN	p-value
BR1	4.81	0.2188
BG1	**10.06**	0.0313
BR4	-0.86	0.5625
BG4	4.11	0.1563

TP

Slope was the significant factor for TP load change (Table K-16). No crossed interactions between lining type, storm size, and slope were statistically significant. No load changes were statistically significant (Table K-17), until data across storm sizes were pooled. Then, BG1 significantly reduced TP loads (Table K-18). It is likely that the better stability of the flatter slopes had greater TP load removal because they were less likely to encounter particle (re)suspension.

Table K-16: TP load reduction Rank ANCOVA results.

Factor	**TP p-value**
Lining	0.3999
Slope	**0.0229**
Storm Size	0.9030
Influent	0.3325
Lining*Storm Size*Slope	0.2586
Lining*Slope	0.5884
Lining*Storm Size	0.5347
Storm Size*Slope	0.9512

Table K-17: Median reduction of TP loads (g) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. Negative values represent greater outflow load than that of inflow. No results were significant.

Swale ID	**Median Influent Load 70 min.**	**TP 70 min.**	**Median Influent Load 140 min.**	**TP 140 min.**
BR1	2.92	1.49	2.54	1.54
BG1	1.64	1.01	2.27	0.21

BR4	3.63	0.15	1.40	-1.10
BG4	3.03	0.78	1.53	0.33

Table K-18: Median reduction of TP loads (g) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow load significantly different from outflow load.

Swale ID	TP	p-value
BR1	1.52	0.0938
BG1	**0.85**	0.0313
BR4	0.02	1.0000
BG4	0.54	0.3125

OP

Slope and storm size appear to be important predictors of how well a swale removes OP load (Table K-19). Lining*slope the only significant crossed interaction for OP. No load changes were statistically significant (Table K-20). Some riprap-lined bioswales had insignificant export, while native grass-lined bioswales were more likely to sequester OP than release it.

Table K-19: OP load reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	OP p-value
Lining	0.8672
Slope	**0.0009**
Storm Size	**0.0109**
Influent	0.4787
Lining*Storm Size*Slope	0.0581
Lining*Slope	**0.0006**

Lining*Storm Size	0.1012
Storm Size*Slope	0.5819

Table K-20: Median reduction of OP loads (g) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. Negative values represent greater outflow load than that of inflow. No results were significant.

Swale ID	Median Influent Load 70 min.	OP 70 min.	Median Influent Load 140 min.	OP 140 min.
BR1	1.42	0.81	0.76	0.58
BG1	0.75	0.56	0.40	-0.04
BR4	1.54	-0.16	0.50	-1.25
BG4	0.82	5.44	0.43	0.18

Dissolved Metals

Cd

Lining type did not appear to impact Cd load removal. While slope was shown to have a significant impact, no load changes were statistically significant (Table K-21, K-22). No crossed interactions between lining type, storm size, and slope were statistically significant. When storm size data were pooled, all bioswales significantly reduced Cd loads (Table K-23). Bioswales likely succeeded in removing Cd loads because of Cd's ability to bind to DOC (Sparks, 2003).

Table K-21: Dissolved Cd load reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	Cd p-value
Lining	0.4415
Slope	**0.0005**
Storm Size	0.5421
Influent	0.0746

Lining*Storm Size*Slope	0.1868
Lining*Slope	0.2260
Lining*Storm Size	0.0944
Storm Size*Slope	0.4329

Table K-22: Median reduction of dissolved Cd loads (g) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. No results were significant.

Swale ID	Median Influent Load 70 min.	Cd 70 min.	Median Influent Load 140 min.	Cd 140 min.
BR1	0.11	0.10	0.04	0.04
BG1	0.04	0.04	0.05	0.02
BR4	0.09	0.05	0.04	0.02
BG4	0.08	0.06	0.04	0.02

Table K-23: Median reduction of dissolved Cd loads (g) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow load significantly different from outflow load.

Swale ID	Cd	p-value
BR1	**0.07**	0.0313
BG1	**0.03**	0.0313
BR4	**0.04**	0.0313
BG4	**0.03**	0.0313

Cu

No load changes were statistically significant (Table K-24). Nearly all riprap and native grass-lined bioswales had insignificant export. Influent concentration was the only significant factor to Cu load changes (Table K-25). Because the Rank ANCOVA displayed an insignificant interaction for storm size, the medium and large storm data were then analyzed together (pooled). When storm size data were pooled, BG4 significantly exported Cu loads (Table K-26). It is possible that changes in soil pH, ion exchange, aeration and agitation, or metal binding had an effect on Cu exports (Borne and Tanner, 2013; Sansalone and Ying, 2008).

Table K-24: Median reduction of dissolved Cu loads (g) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. Negative values represent greater outflow load than that of inflow. No results were significant.

Swale ID	Median Influent Load 70 min.	Cu 70 min.	Median Influent Load 140 min.	Cu 140 min.
BR1	0.45	-0.06	0.20	0.05
BG1	0.25	0.10	0.34	-0.05
BR4	0.31	-0.06	0.24	-0.26
BG4	0.47	-0.10	0.18	-0.10

Table K-25: Dissolved Cu load reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	Cu p-value
Lining	0.3459
Slope	0.0652
Storm Size	0.9043
Influent	**0.0449**
Lining*Storm Size*Slope	0.0731
Lining*Slope	0.8511
Lining*Storm Size	0.5909
Storm Size*Slope	0.6558

Table K-26: Median reduction of dissolved Cu loads (g) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow load significantly different from outflow load. Negative values represent greater outflow than inflow.

Swale ID	Cu	p-value
BR1	-0.003	0.8438

BG1	0.94	0.5625
BR4	-0.12	0.2188
BG4	**-0.11**	0.0313

Pb

Riprap-lined bioswales appear to provide more Pb load removal than native grass-lined bioswales (Table K-27). Even so, slope was the only significant factor for Pb (Table K-28). No crossed interactions between lining type, storm size, and slope were statistically significant. No load reductions were statistically significant when data were not pooled (Table K-29). The generally higher rates of sedimentation in the riprap bioswales herein may have contributed to their significant reductions.

Table K-27: Median reduction of dissolved Pb loads (g) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow load significantly different from outflow load.

Swale ID	Pb	p-value
BR1	**0.09**	0.0313
BG1	0.03	0.0625
BR4	**0.05**	0.0313
BG4	0.03	0.0625

Table K-28: Dissolved Pb load reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	Pb p-value
Lining	0.1051
Slope	**0.0056**
Storm Size	0.2383
Influent	0.5490
Lining*Storm Size*Slope	0.1701
Lining*Slope	0.5697

Lining*Storm Size	0.6082
Storm Size*Slope	0.3720

Table K-29: Median reduction of dissolved Pb loads (g) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. No results were significant.

Swale ID	Median Influent Load 70 min.	Pb 70 min.	Median Influent Load 140 min.	Pb 140 min.
BR1	0.13	0.11	0.06	0.04
BG1	0.09	0.06	0.08	0.02
BR4	0.19	0.08	0.04	0.02
BG4	0.10	0.04	0.05	0.02

Zn

Three of the four bioswales significantly reduced Zn loads, when storm data were pooled (Table K-30). When data were not pooled, no load changes were statistically significant (Table K-31). Slope was the only significant factor for Zn (Table K-32). No crossed interactions between lining type, storm size, and slope were statistically significant. Because dissolved portions of zinc are primarily removed by binding to particulate and organic matter and then trapping particulate matter via filtration, these reductions are consistent with TSS load reduction (Legret and Pagotto, 1999).

Table K-30: Median reduction of dissolved Zn loads (g) for each bioswale as taken from Wilcoxon Signed-Rank, pooled across storm size. Bolded values represent inflow load significantly different from outflow load.

Swale ID	Zn	p-value
BR1	**1.20**	0.0313
BG1	0.52	0.0625
BR4	**0.66**	0.0313

BG4	**0.68**	0.0313

Table K-31: Median reduction of dissolved Zn loads (g) for each bioswale and storm size, as taken from Wilcoxon Signed-Rank. No results were significant.

Swale ID	Median Influent Load 70 min.	Zn 70 min.	Median Influent Load 140 min.	Zn 140 min.
BR1	1.82	1.71	0.80	0.69
BG1	0.93	0.83	0.85	0.43
BR4	1.67	0.82	0.64	0.37
BG4	1.58	1.09	0.71	0.39

Table K-32: Dissolved Zn load reduction Rank ANCOVA results. Bolded values are statistically significant.

Factor	Zn p-value
Lining	0.2477
Slope	**0.0007**
Storm Size	0.2529
Influent	0.1696
Lining*Storm Size*Slope	0.5684
Lining*Slope	0.0969
Lining*Storm Size	0.0861
Storm Size*Slope	0.4157

Load Reduction Conclusions

Moderate load reductions were expected because they were highly dependent on volume reduction, which had reductions comparable to these found in literature. Both native grass-lined bioswales had significant TSS load reductions. BG1 had generally higher nutrient load reductions than the other three bioswales, with significant reductions of TKN, NO_x, TN, and TP. Filtration and biological processes, enhanced by the presence of vegetation, could explain higher load reductions in BG1. Flatter slopes would increase contact time, which should likewise benefit pollutant removal. While all four bioswales produced some significant reductions in dissolved metal loads, riprap swales generally were best at reducing Cd and Pb loads. The generally higher rates of sedimentation in the riprap bioswales herein may have contributed to these significant reductions.

Appendix L – Bioswale Native Grass Riprap Combination Analysis

While not an initial consideration for this study, the blending of riprap and native grasses as an alternative lining became of interest when one of the riprap-lined bioswales, BR1, became overgrown with native grasses. Starting 25-AUG-2022, one month after all other experiments were completed, three more large storms were simulated to test the effect that riprap blended with native grasses had on swale hydrology and water quality treatment.

Volume Reduction

Lining was the only significant factor when comparing all three swale liner types for overflow volume reduction (Tables L-1 through L-3). The statistics could not differentiate performance of the three liner types among underdrain infiltration and volumes. While not significant, the combination-lined bioswale reduced total volumes slightly better than native grass-lined bioswales but worse than riprap-lined bioswales. The insignificant p-value may be due to the range in volume reductions observed. For instance, total volume reductions in riprap ranged from 7 to 71%.

Table L-1: Median reduction of overflow volumes, as taken from Wilcoxon Signed-Rank, and corresponding Rank ANCOVA p-values riprap, native grass, and riprap + native grass bioswales on a 1% slope. Bolded values are statistically significant.

Lining	Inflow Volume (L)	Overflow Volume (L)	Percentage of Inflow Volume as Overflow (%)	ANCOVA Lining p-value
Riprap	28,031	190	< 1	
Native Grass	32,220	6,411	20	**0.0409**
Riprap + Native Grass	33,509	8,338	25	

Table L-2: Median reduction of underdrain volumes, as taken from Wilcoxon Signed-Rank, and corresponding Rank ANCOVA p-values riprap, native grass, and riprap + native grass bioswales on a 1% slope.

Lining	Inflow Volume (L)	Underdrain Volume (L)	Percent of Inflow Volume as Underdrain Flow (%)	ANCOVA Lining p-value
Riprap	28,031	10,638	38	
Native Grass	32,220	19,594	61	0.3970
Riprap + Native Grass	33,509	15,137	45	

Table L-3: Median reduction of total volumes, as taken from Wilcoxon Signed-Rank, and corresponding Rank ANCOVA p-values riprap, native grass, and riprap + native grass bioswales on a 1% slope.

Lining	Inflow Volume (L)	Total Volume (L)	Percent of Volume Infiltrated (%)	ANCOVA Lining p-value
Riprap	28,031	10,829	61	
Native Grass	32,220	26,005	19	0.2774
Riprap + Native Grass	33,509	23,475	30	

Peak Flow Reduction

Lining did not significantly impact peak flow reduction (Table L-4). The riprap + native grass combination appeared to have the highest (but insignificantly so) peak flow reduction of the three lining types compared. Peak flow reduction for the riprap + native grass-lined swale was within range and higher than those observed from literature. Stagge (2006) observed vegetated swale peak flow reductions between 50 - 53% while Ainan et al. (203) and Wu et al. (1998) noted reductions of 28.9 - 55.9% and 10 - 20%, respectively. This may be due to sediment accumulation.

Table L-4: Median reduction of combined peak flows (L/s), as taken from Wilcoxon Signed-Rank, and corresponding Rank ANCOVA p-value for riprap, native grass, and riprap + native grass bioswales on a 1% slope.

Lining	Peak Inflow (L/s)	Outflow (L/s)	Outflow Reduction (%)	ANCOVA Combined Lining p-value
Riprap	9.1	6.2	31	
Native Grass	9.1	7.1	22	0.0630
Riprap + Native Grass	9.1	4.5	50	

Changes in Concentration

All pollutants concentration changes (Tables L-5 through L-7) were compared against three lining types: riprap, native grass, and the riprap + native grass combination. TKN, NH_3, NO_x, TN, TP, and Cu concentrations were all insignificantly higher in the overflow and the underdrain of the riprap + native grass-lined swale than in the inflow. TSS, Cd, Pb, and Zn were all insignificantly lower in the overflow and the underdrain than in the inflow. OP in the underdrain was the only pollutant where lining type proved significant. The combination yielded the highest concentration reductions.

Which among the riprap, native grass, and riprap + native grass-lined bioswales best reduced concentrations vary. The riprap + native grass liner was not distinguishably better or worse than the other two swale liner types with regard to pollutant reduction. No results proved significant.

Table L-5: Median reductions of sediment concentrations (mg/L), as taken from Wilcoxon Signed-Rank, and corresponding Rank ANCOVA p-value for riprap, native grass, and riprap + native grass bioswales on a 1% slope. No results were significant.

Pollutant	Lining	Median Influent Concentration	Overflow	ANCOVA Overflow Lining p-value	Underdrain	ANCOVA Underdrain Lining p-value
TSS	Riprap	25.4	5.50	0.7188	11.53	0.5904
	Native Grass	11.6	3.08		7.36	

Riprap + Native Grass	21.4	8.99		12.20

Table L-6: Median reductions of nutrient concentrations (µg/L), as taken from Wilcoxon Signed-Rank, and corresponding Rank ANCOVA p-values for riprap, native grass, and riprap + native grass bioswales on a 1% slope. Bolded values are statistically significant. Negative values represent greater outflow concentration than inflow.

Pollutant	Lining	Median Influent Concentration	Overflow	ANCOVA Overflow Lining p-value	Underdrain	ANCOVA Underdrain Lining p-value
TKN	Riprap	982.2	-249.04	0.0718	13.21	0.7525
	Native Grass	890.1	-63.13		163.13	
	Riprap + Native Grass	797.1	-13.70		-7.55	
NH_3	Riprap	19.8	-0.13	0.6634	-29.89	0.0768
	Native Grass	20.2	-12.57		-5.24	
	Riprap + Native Grass	20.5	-14.26		-30.68	
NO_x	Riprap	100.8	-15.09	0.1610	-461.83	0.0530
	Native Grass	76.4	8.25		34.40	
	Riprap + Native Grass	79.6	-59.38		-70.86	
TN	Riprap	1083.0	-264.13	0.3241	-448.62	0.2171
	Native Grass	966.6	-56.85		197.53	
	Riprap + Native Grass	885.5	-100.28		-89.57	
TP	Riprap	112.4	33.54	0.7358	-19.69	0.3082
	Native Grass	66.7	-5.34		11.93	
	Riprap + Native Grass	77.1	-13.21		-15.44	
OP	Riprap	41.4	20.87	0.3535	3.39	**0.0315**
	Native Grass	16.4	1.70		-6.80	
	Riprap + Native Grass	21.2	-0.64		6.51	

Table L-7: Median reductions of dissolved metal concentrations (µg/L), as taken from Wilcoxon Signed-Rank, and corresponding Rank ANCOVA p-values for riprap, native grass, and riprap + native grass bioswales on a 1% slope. Negative values represent greater outflow concentration than inflow. No results were significant.

Pollutant	Lining	Median Influent Concentration	Overflow	ANCOVA Overflow Lining p-value	Underdrain	ANCOVA Underdrain Lining p-value
Cd	Riprap	2.4	1.1	0.8406	1.9	0.3915
	Native Grass	1.7	0.69		1.2	
	Riprap + Native Grass	1.3	0.48		0.80	
Cu	Riprap	11.0	-9.0	0.9266	-12.0	0.9803
	Native Grass	10.0	-6.0		-7.0	
	Riprap + Native Grass	14.0	-6.00		-6.00	
Pb	Riprap	3.3	0.5	0.5470	1.3	0.3621
	Native Grass	3.1	0.0		0.4	
	Riprap + Native Grass	2.3	0.30		0.30	
Zn	Riprap	45.0	14.0	0.7720	29.0	0.1478
	Native Grass	35.0	10.0		15.0	
	Riprap + Native Grass	90.0	31.00		40.00	

Load Reduction

Results for outflow load reductions provided by the bioswale lined with the riprap + native grass combination are provided in Tables L-8 through L-10. All pollutant loads, excluding NO_x and NH_3, were insignificantly reduced from the inlet to the outlet. Lining had no significant effect on sediment, nutrient, or dissolved metal load reduction.

Due to volume reduction, riprap-lined bioswales had the best load reduction rates for all nutrients and dissolved metals. The riprap + native grass-lined bioswale had the highest TSS load reduction.

Table L-8: Median reductions of sediment loads (g), as taken from Wilcoxon Signed-Rank, and corresponding Rank ANCOVA p-value for riprap, native grass, and riprap + native grass bioswales. No results were significant.

Pollutant	Lining	Median Influent Load	Cumulative Outflow	ANCOVA Lining p-value
TSS	Riprap	420.4	206.5	0.6261
	Native Grass	379.2	208.3	
	Riprap + Native Grass	724.88	396.56	

Table L-9: Median reductions of nutrient loads (g), as taken from Wilcoxon Signed-Rank, and corresponding Rank ANCOVA p-values for riprap, native grass, and riprap + native grass bioswales. Negative values represent greater outflow load than that of inflow. No results were significant.

Pollutant	Lining	Median Influent Load	Cumulative Outflow	ANCOVA Lining p-value
TKN	Riprap	16.00	8.44	0.7206
	Native Grass	30.30	5.65	
	Riprap + Native Grass	27.04	6.77	
NH_3	Riprap	0.44	-0.02	0.2917
	Native Grass	0.69	-0.11	
	Riprap + Native Grass	0.69	-0.35	
NO_x	Riprap	1.86	1.42	0.0921
	Native Grass	2.60	0.86	
	Riprap + Native Grass	2.95	-1.49	
TN	Riprap	17.64	7.02	0.9963
	Native Grass	32.90	6.30	
	Riprap + Native Grass	30.04	5.90	
TP	Riprap	2.54	1.54	0.9620
	Native Grass	2.27	0.21	
	Riprap + Native Grass	2.62	0.31	
OP	Riprap	0.76	0.58	0.1632

	Native Grass	0.40	-0.04	
	Riprap + Native Grass	0.72	0.22	

Table L-10: Median reductions of dissolved metal loads (g), as taken from Wilcoxon Signed-Rank, and corresponding Rank ANCOVA p-values for riprap, native grass, and riprap + native grass bioswales. Negative values represent greater outflow load than that of inflow. No results were significant.

Pollutant	**Lining**	**Median Influent Load**	**Cumulative Outflow**	**ANCOVA Lining p-value**
	Riprap	0.04	0.04	
Cd	Native Grass	0.05	0.02	0.3368
	Riprap + Native Grass	0.04	0.03	
	Riprap	0.20	0.05	
Cu	Native Grass	0.34	-0.05	0.5090
	Riprap + Native Grass	0.48	0.04	
	Riprap	0.06	0.04	
Pb	Native Grass	0.08	0.02	0.4331
	Riprap + Native Grass	0.09	0.03	
	Riprap	0.80	0.69	
Zn	Native Grass	0.85	0.43	0.0620
	Riprap + Native Grass	3.02	1.20	

Appendix M – Bioswale Alternative Linings Turfgrass Comparison Analysis

Purvis (2018) conducted a study to optimize bioswale design in various turf grass-lined bioswales. This study utilized some of the same swales herein, prior to the installation of the alternative linings. Purvis's (2018) storm sizes (inflow ranging from 527 - 1174 cf) were not the same as herein (inflow ranging from 527 - 644 cf) but were most similar to the medium storm event size. Results for both the riprap and native grass bioswales during medium storm events were compared to those of the turf-lined bioswales. Additionally, Purvis (2018) conducted ten and nine trials for the bioswales on 1% and 4% slope, respectively, rather than the three that were conducted herein. Data on the 4% slope herein were not compared to the bioswales on the 4% slope in Purvis's study due to the inclusion of an IWS zone.

Total Volume Reduction

No factors were significant to total volume reduction (Table M-1). Native grass-lined bioswales had modestly higher total volume reduction than those of riprap and turf (Table M-2).

Table M-1: Total volume reduction Rank ANCOVA results for bioswales lined with riprap, native grass, and turf. Bolded values are statistically significant.

Factor	Total Volume Reduction p-value
Lining	0.6336
Inflow Volume	0.2979

Table M-2: Median volume reduction for bioswales lined with riprap, native grass, and turf.

Lining	Median Inflow Volume (L)	Total Volume Reduction (%)

Riprap	16,582	41
Native Grass	15,064	53
Turf	15,836	49

Peak Flow Reduction

No factors were significant to combined peak flow reduction (Table M-3). Native grasses provided (non-significantly) highest combined peak flow reduction (Table M-4). This may be due to an increased HRT caused by greater resistance to flow associated with deep-rooted grasses.

Table M-3: Peak flow reduction Rank ANCOVA results for bioswales lined with riprap, native grass, and turf.

Factor	Combined PFR
Lining	0.2553
Peak Inflow	0.9993

Table M-4: Median peak flow reduction for bioswales lined with riprap, native grass, and turf.

Lining	Median Peak Inflow (L/s)	Combined PFR (%)
Riprap	9.1	25
Native Grass	9.1	59
Turf	8.2	36

Concentration Change

Only concentration changes were statistically analyzed among the three bioswale types. Ranges of both inflow and outflow concentrations for riprap and native grass-lined bioswales were larger than what was expected by the research team (Appendix J). Wide ranges are likely due to the inaccurate inlet flow rate and an over-estimation of the cumulative inflow. Because there appeared to be a discrepancy, a Rank ANCOVA was conducted to compare inlet concentrations to outflow concentrations, in addition to the RE Rank ANCOVA analysis (Tian et al., 2014; personal communication, NC State Data & Visualization Services, May 5, 2023).

Sediment

Turf-lined bioswales reduced TSS concentrations the most in the overflow while riprap-lined bioswales removed the most in the underdrain (Table M-5). The underdrain released the lowest TSS concentrations in the majority of bioswales, likely a result of the additional filtration through the bioswales' engineered media. Lining was not a significant factor to TSS concentration change in the RE or effluent Rank analyses (Tables M-6, M-7). Differences in influent concentrations were only significant to TSS concentration changes in the effluent Rank analysis. Influent concentration appeared to impact TSS removals only in the overflow. The lower influent (16 mg/L) concentration limited the native grass bioswales' ability to reduce TSS, although these bioswales did yield the lowest concentrations of TSS. The small sample size likely influences significance (Tian et al., 2014; personal communication, NC State Data & Visualization Services, May 5, 2023).

Table M-5: TSS concentration reduction (mg/L) for bioswales lined with riprap, native grass, and turf according to median influent concentration. Negative values represent greater outflow concentration than that of inflow.

Lining	Influent Concentration	TSS Overflow	TSS Underdrain
Riprap	24.00	-85.40	17.80
Native Grass	16.05	0.20	9.00
Turf	40.58	12.24	15.74

Table M-6: TSS RE Rank ANCOVA results for bioswales lined with riprap, native grass, and turf.

Factor	TSS Overflow p-value	TSS Underdrain p-value
Lining	0.2327	0.9819
Influent Concentration	0.9964	0.6013

Table M7: TSS effluent Rank ANCOVA results for bioswales lined with riprap, native grass, and turf.

Factor	TSS Overflow p-value	TSS Underdrain p-value
Lining	0.1347	0.6613
Influent Concentration	**0.0287**	0.6518

Nutrients

Lining significantly impacted reduction of overflow concentrations for NO_x, TN, and OP (Table M-8). Lining was also a significant factor for the TKN, NO_x, TN, and OP effluent analysis (Table M-9). Influent concentration significantly impacted TP effluent from the overflow. Results varied between bioswales lined with native grasses and turf (Table M-10). Full tables with inlet, overflow, and underdrain concentrations can be found in Appendix J.

Table M-8: Overflow nutrient RE Rank ANCOVA results for bioswales lined with riprap, native grass, and turf. Bolded values are statistically significant.

Factor	TKN p-value	NO_x p-value	TN p-value	TP p-value	OP p-value
Lining	0.2327	**0.0051**	**0.0035**	0.0802	**0.0056**
Influent Concentration	0.9964	0.8538	0.0628	0.3987	0.8351

Table M-9: Overflow nutrient effluent Rank ANCOVA results for bioswales lined with riprap, native grass, and turf. Bolded values are statistically significant.

Factor	TKN p-value	NO_x p-value	TN p-value	TP p-value	OP p-value
Lining	**0.0044**	**0.0249**	**0.0044**	0.0514	**0.0056**
Influent Concentration	0.7432	0.6898	0.9601	**0.0032**	0.8351

Table M-10: Median overflow nutrient influent concentration and concentration reduction (µg/L) for bioswales lined with riprap, native grass, and turf during medium storm events. Negative values represent greater outflow concentration than that of inflow.

Lining		TKN	NO_x	TN	TP	OP
Riprap	Influent	867	161	1016	105	51
	Reduction	-603	-218	-427	-75	-58
Native Grass	Influent	857	149	1010	110	47
	Reduction	-55	18	-69	-22	2
Turf	Influent	660	130	790	1810	1740
	Reduction	-20	-20	-10	10	-200

External organic nitrogen inputs could result in TKN and TN exports. Assimilation is more likely to occur in turf and native grass-lined bioswales where plant roots are available for fixation (Figure M-1). Perhaps the turf-lined bioswales had more organic matter for nutrients to bind to, resulting in greater removals of nutrient concentrations (Collins et al., 2010). Both native grasses employed herein are considered deep rooted. The tall fescue (turf) grass has a potential rooting depth of 0.46 - 1.52 m (1.5 - 5 ft), yet may only reach approximately 0.91 m (3 ft) when mowed weekly (Lin, 1985). Comparatively, river oats and big bluestem reach root depths of 0.76 m (2.5 ft) and 1.52 - 2.44 m (5 - 8 ft), respectively (University of Maryland Extension, 2023 and USDA, 2000). Root distribution, as well as greater root length and weight, is a crucial factor in how the soil acquires nutrients (Tajima, 2021). Although the native grass-lined bioswales were given a year to establish before experimentation, it is likely their root depths were not fully established. It is possible the turf had deeper roots during Purvis' (2018) experimentation than that of the native grasses herein, resulting in them contributing to the greater removals of nutrient concentrations (Tajima, 2021).

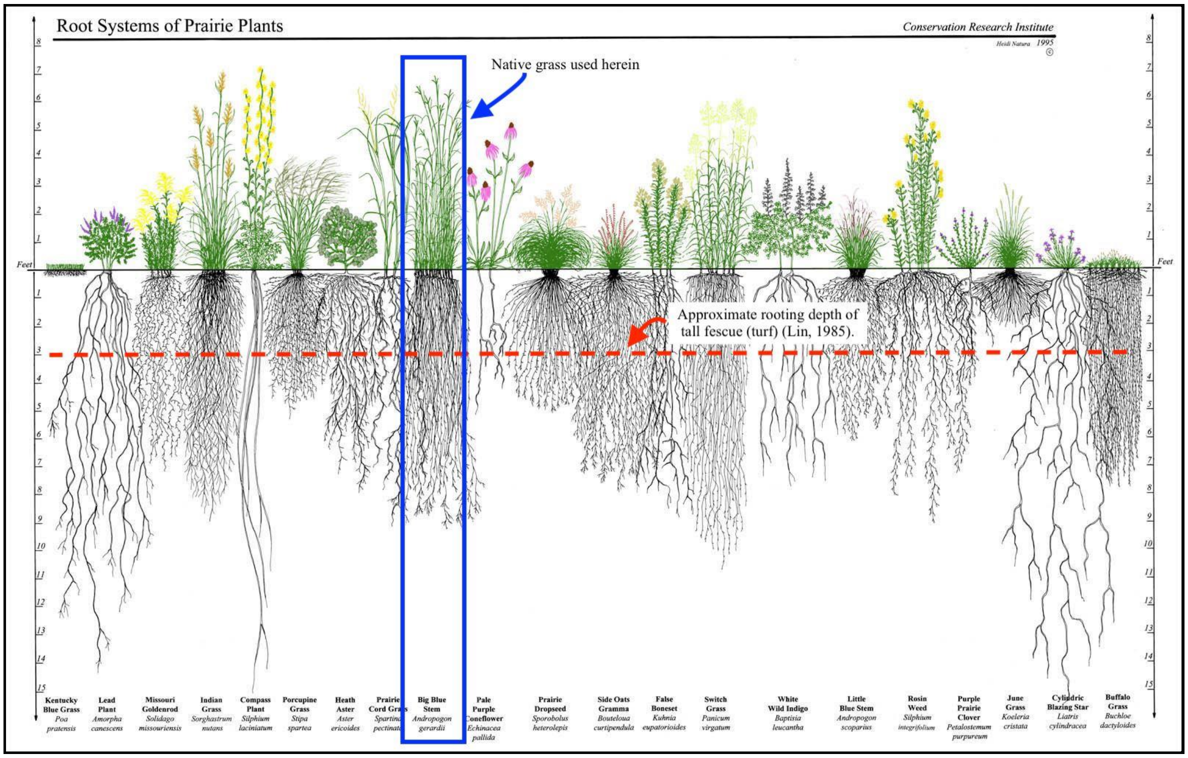


Figure M-1: Illustration of prairie plant roots and surface growth (taken from NPS, 2021).

Native grass-lined bioswales lowered TN concentrations to a greater extent than observed in the riprap and turf-lined bioswales (Table M-11). Concentration reductions for TP and OP were greater for turf-lined bioswales because the inlet concentrations were substantially higher than those of riprap and native grasses. Lining significantly impacted changes in underdrain concentration for NO_x, TN, and OP (Table M-12). Influent concentration significantly impacted TN and OP RE from the underdrain. Similar to the RE ANCOVA, lining was a significant factor for NO_x, TN, and OP when evaluating effluent concentrations (Table M-13). Influent concentration was significant for TKN, TN, and OP.

Table M-11: Median underdrain nutrient influent concentration and concentration reduction (µg/L) for bioswales lined with riprap, native grass, and turf during medium storm events. Negative values represent greater outflow concentration than that of inflow.

Lining		TKN	NO_x	TN	TP	OP
Riprap	Influent	867	161	1016	105	51
	Reduction	-543	-312	-341	-324	12
Native Grass	Influent	857	149	1010	110	47
	Reduction	78	24	99	-19	20
Turf	Influent	660	130	790	1810	1740
	Reduction	-110	10	-30	510	425

Table M-12: Underdrain nutrient RE Rank ANCOVA results for bioswales lined with riprap, native grass, and turf. Bolded values are statistically significant.

Factor	TKN p-value	NO_x p-value	TN p-value	TP p-value	OP p-value
Lining	0.9819	**0.0032**	**0.0196**	0.5548	**0.0087**
Influent Concentration	0.6013	0.1068	**0.0416**	0.1400	**0.0141**

Table M-13: Underdrain nutrient effluent Rank ANCOVA results for bioswales lined with riprap, native grass, and turf. Bolded values are statistically significant.

Factor	TKN p-value	NO_x p-value	TN p-value	TP p-value	OP p-value
Lining	0.0635	**0.0257**	**0.0164**	0.9908	**0.0087**
Influent Concentration	**0.0002**	0.9333	**0.0006**	0.1803	**0.0141**

It is likely the turf-lined bioswales had deeper and more established roots, resulting in greater removals of nutrient concentrations. It is also possible turf-lined bioswales had greater organic matter content for TN, TP and OP to bind to (Collins et al., 2010). Yet, TP and OP likely had greater removals in turf-lined bioswales because of the substantial difference in influent concentrations.

Pollutant Loads

Pollutant loads are highly dependent on volume reduction. Riprap-lined bioswales removed the greatest TSS loads (Table M-14). Native grass-lined bioswales tended to reduce the most nutrient loads. Turf-lined bioswales removed more TP, but this observation is complicated by its high influent load. It is likely native grass-lined bioswales had better load reductions than those of turf because of greater volume reduction.

Table M-14: Median sediment and nutrient influent loads and load reductions (g) for turf-lined bioswales. Negative values represent greater outflow load than that of inflow.

Lining		TSS	TKN	NO_x	TN	TP	OP
Riprap	Influent	694.80	28.34	5.10	33.43	4.27	1.67
	Reduction	480.98	7.04	-4.43	2.61	1.49	0.81
Native Grass	Influent	292.91	15.64	2.10	17.75	1.61	0.75
	Reduction	236.36	9.82	1.46	11.69	1.01	0.56
Turf	Influent	698.83	10.30	2.04	12.89	30.91	26.79
	Reduction	473.87	6.18	-0.10	2.63	16.68	-34.64

Turf Lining Comparison Conclusions

Riprap and native grass-lined bioswales tended to better reduce nutrient concentrations in the overflow and the underdrain than the turf-lined bioswales. Concentration reductions for TP and OP were greater for turf-lined bioswales because the inlet concentrations were substantially higher than those of riprap and native grasses.

Native grasses had higher TKN, NO_x, and TN load reductions than both riprap and turf. Native grasses also had higher volume reduction than turf. Alternative liners herein may be a competitive option to turf because of their simpler, or less frequent, maintenance needs. Turf-lined swales require routine mowing, whereas riprap and native grass-lined swales may only require minimal weed management. The number of mowing cycles in a given season is regulated by the amount of turf growth, but is, on average, five cycles per year (Trogdon et al., 2017). Weed management includes the use of a non-selective herbicide for postemergence control and is careful to avoid undesired residual effects, such as damage from drainage runoff (Connect NCDOT, 2023). This maintenance task can be performed throughout the year, as necessary.

Ideally, three side-by-side plot trials would have been conducted with turf grass and the alternative liners in bioswales to make confident recommendations. Additionally, data should be compared to a turf-lined bioswale on a 4% slope to have a sufficient comparison of the data herein.

Appendix N - Manning’s Roughness Coefficient Determination for Deep Rooted Native Grasses

Manning’s equation was originally introduced by Robert Manning in his paper, “On the Flow of Water in Open Channel and Pipes,” published by *Transaction of the Institution of Civil Engineers of Ireland* in 1891 (Manning, 1891; Fischenich, 2000).

Manning's equation relates flow rate to a channel's dimensions and a unitless “roughness coefficient,” n, that is specific to the channel lining. Roughness values impact swale design, notably the length, as current design criteria specify a minimum hydraulic retention time (HRT) that dictates length. Other design criteria, such as cross-section, are impacted by roughness (NCDEQ, 2020). Determining “n” values for native grasses will provide future design guidance for swales.

Roughness values for turf-lined channels range from 0.035 - 0.112, varying with depth of flow, as well as density and height of vegetation. Grass submergence may decrease values to 0.025 - 0.035 (Arcement and Schneider, 1989; Chow, 1959). NCDA&CS (2023) assigns “n” for grass channels to range from 0.033 - 0.038, for unsubmerged grasses maintained at 0.10 - 0.15 m (4 - 6 in). Mustaffa et al. (2016) observed that the roughness varies with flow depth in grass swales. Dividing the swales into three longitudinal segments, roughness values were determined for each segment. Roughness values were 0.756, 0.462, and 0.110 from inlet to outlet, respectively. Other studies (Ahmad et al., 2011; Arcement and Schneider, 1989) observed a decrease in roughness as flow depth increased; however, Mustaffa et al. (2016) recorded the opposite, with the lowest roughness coefficients being associated with the lowest flow depths. Authors theorized this irregular finding is a result of severe erosion that may have increased “n” values by as much as 0.020 (Mustaffa et al., 2016). This study completed experiments to determine roughness coefficients for swales lined with native grasses. To account for the relationship between roughness and flow depth, two flow depths were considered.

Methods

Manning's roughness experiments were conducted on 11-OCT-2022 (CG1) and 17-OCT-2022 (CG4). Low and high flow measurements were taken for each swale, which were distinguished by 1% and 4% slopes. Low flow rates were approximately 9 x 10^{-4} cms (0.0322 cfs), and high flow rates were approximately 3.8 x 10^{-3} cms (0.1336 cfs).

Before releasing flow, survey flags were stationed at 0.9, 3.7, 6.4, and 9 m (3, 12, 21, and 30 ft) along the longitudinal length of each swale, beginning at the inlet. Stations were indicated as 1 (inlet), 2, 3, and 4 (outlet) (Figure N-1). Water depth measurements were taken at flag locations. Steady flow conditions were reached at both the inlet and outlet of the swale, for "low flow" conditions, then additional flags were placed to indicate extent of water surface of "low flow" (Figure N-1). The flow rate was then increased until steady flow conditions were reached for "high flow." Flags were likewise placed to indicate the extent of "high flow". The experiment was duplicated at each swale.

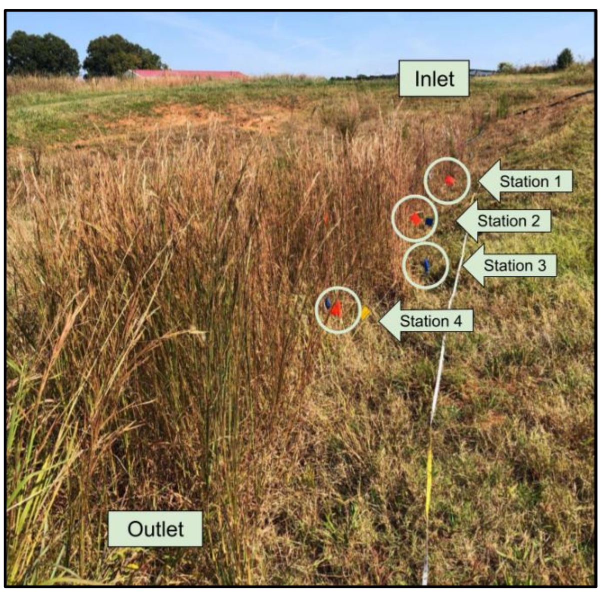


Figure N-1: Flags (circled) placed according to depth of flow.

Elevation points at each flag were recorded using a Sokkia SET530R prismless surveying total station and Carlson Explorer data collector. Multiple elevation points were also taken across the wetted perimeter at each measurement station along the swale.

Elevation data were imported into AUTODESK Civil 3D where surfaces were created for each swale at each flow level. Alignments and section views were then created, and sample lines used to measure the wetted perimeter and area of flow according to each flow depth. Civil 3D drawings of the swales (aerial view and cross-section) can be viewed in Figures N-2 through N-4. Red "X"s indicate surveyed elevation points.

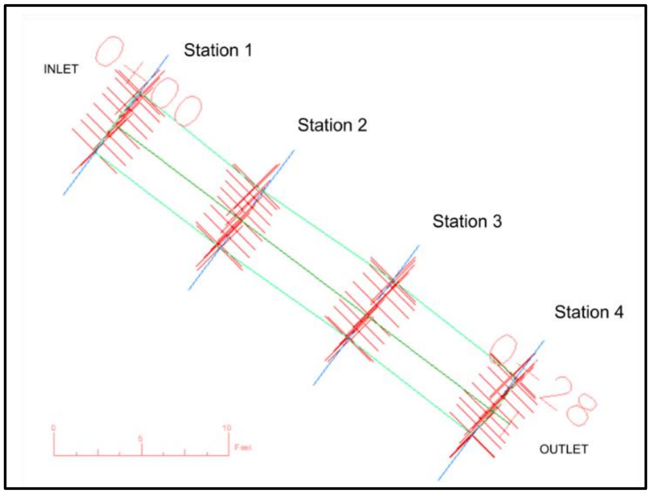


Figure N-2: Civil 3D drawing of CG1 (aerial view).

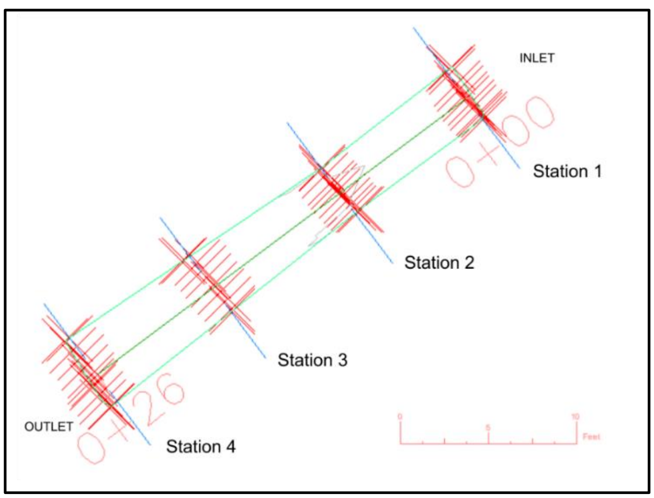


Figure N-3: Civil 3D drawing of CG4 (aerial view).

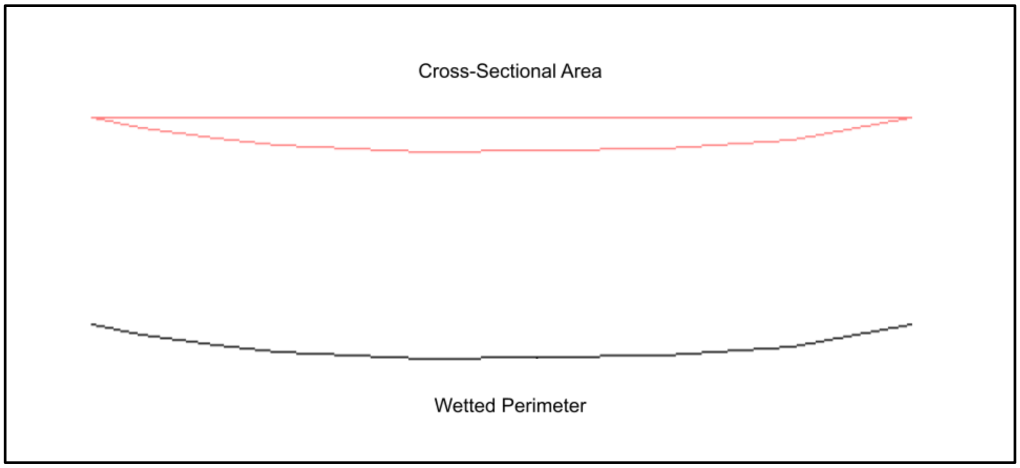


Figure N-4: Example Civil 3D drawing of CG1, Station 1 inlet cross-sectional area and wetted perimeter.

Flow rate (Q) was recorded by the ISCO 6712 sampler and ISCO 730 bubble module at the outlet (Station 4). A 60° V-notch weir was installed in the outlet to measure flow. Flow rate is calculated with equation N-1.

$$Q = 1.443 * H^{2.5} \tag{N-1}$$

Where:

- Q is the flow rate (cfs), and
- h is depth of flow (ft)

The data collected were then input into Manning's equation (equation 5-2) to solve for the roughness "n" of each swale at both low and high flow rates. Manning's equation inputs herein for low and high flows are given in Table N-1.

$$Q = \left(\frac{1.49}{n}\right) AR^{2/3}\sqrt{S} \tag{N-2}$$

Where:

- Q is the flow rate (cfs),
- n is Manning's roughness coefficient (unitless),
- A is the cross-sectional area (ft^2),
- R is the hydraulic radius (ft), and
- S is the slope (ft/ft)

Table N-1: Manning's equation inputs.

Swale ID	Flow Level	Q (cfs)	A (ft^2)	R (ft)	S (ft/ft)
CG1	Low	0.0305	0.1910	0.0520	0.01
CG1	High	0.1309	0.2281	0.0750	0.01
CG4	Low	0.0338	0.1957	0.0482	0.04
CG4	High	0.1363	0.2700	0.0593	0.04

Researchers noticed the area of flow for CG1 high flow rate was less than that of the low flow rate, contradictory to what was measured in the field. It is likely elevation points for high and low flow were transposed during survey collection. Only corrected equation inputs are viewed in Table 5-1.

Results

Results for Manning's roughness values are found in Tables N-2. Average Manning's "n" values were 0.187 and 0.078 for the low and high flows, respectively. Flow rate had a more substantial impact on roughness than slope. In accordance with expectations (based on Chow, 1959; Lau & Afshar, 2013), the shallower slopes exhibited lower roughness than steeper slopes.

Table N-2: Manning's "n" values for native grass lined swales.

Swale ID	Flow Level	Calculated n
CG1	Low	0.146
CG1	High	0.066
CG4	Low	0.227
CG4	High	0.089

Discussions and Conclusions

North Carolina Department of Agriculture and Consumer Services (NCDA&CS) provides roughness coefficients for swales lined with turf grass, riprap, and turf reinforcement matting (Table N-3). It is likely these values are associated with submerged grasses maintained at 0.10 - 0.15 m (4 - 6 in). Roughness values for native grasses were found to be higher than the established values for turf grass, riprap, and turf reinforcement matting, as could be expected with an unsubmerged, deep-rooted, native grass.

Table N-3: Manning's "n" values for various channels (NCDA&CS, 2023).

Channel Lining	Design n
Turf Grass	0.033
Riprap	0.035
Turf Reinforcement Matting	0.038
Mean Native Grass Low Flow, herein	0.187
Mean Native Grass High Flow, herein	0.078

The decrease in "n" from low to high flow depths herein was consistent with Ahmad et al. (2011) and Arcement and Schneider (1989). Arcement and Schneider (1989) report base "n" values for bed material to which adjustment factors for irregularity, variation in channel cross-section, obstruction, and amount of vegetation are added (Equation N-3). Degree of irregularity accounts for the width to depth ratio of a channel. Where the ratio is small, roughness increases with eroded banks, projecting points, and exposed tree roots along the bank (Arcement and Schneider, 1959). Effect of obstruction describes objects - such as logs, stumps, boulders, and debris - that may disturb the flow pattern in a channel and, thus, increase roughness (Arcement and Schneider, 1959). The amount of vegetation is categorized as "very large" when the average depth of flow is half the height of the vegetation. Input values for swales herein were assumed and solved according to Arcement and Schneider (1989), resulting in a range of calculated "n" values from 0.062 to 0.116 (Table N-4). The "low flow" "n" values were greater than calculated values according to Arcement and Schneider's (1989) methodology.

$$n = n_b + n_1 + n_2 + n_3 + n_4 \qquad \text{(N5-3)}$$

Where:

- n is the channel roughness coefficient,
- n_b is a base value of *n* for a straight, uniform, smooth channel in natural materials,
- n_1 is a correction factor for the effect of surface irregularities,
- n_2 is a value for variations in shape and size of the channel cross-section,

- n_3 is a value for obstructions, and
- n_4 is a value for vegetation and flow conditions

Table N-4: Equation inputs for calculating Manning's roughness coefficient, according to Arcement and Schneider (1989).

Bed Material	Median Size of Bed Material (mm)	Base n Value
n_b: Sandy loam	0.2	0.012
Adjustment Factor	**Channel Condition**	**n Value Adjustment**
n_1: Degree of Irregularity	Smooth	0.000
n_2: Variation in Channel Cross-Section	Gradual	0.000
n_3: Effect of Obstruction	Negligible	0.000 - 0.004
n_4: Amount of Vegetation	Very Large	0.050 - 0.100
		Sum: 0.062 - 0.116

NCDOT (2022) does not assign discrete "n" values, rather, they recommend referencing the Arcement and Schneider (1989) report for selection. Further research is necessary to determine roughness variations throughout the entire swale, rather than just the outlet, and also for a wider range of flows.

Design Impacts

NCDA&CS (2023) "n" values for turf grass and riprap as well as native grass herein have been included in sample calculations to demonstrate how a native grass lining impacts the required hydraulic radius (R) and cross-sectional area (A) that is necessary to accommodate a consistent flow rate (Table N-5). A and R are dependent on the constant, geometric characteristics of the swale, such as bottom width (B) and side slopes (M), as well as the variable depth of flow (y) (Figure N-5). Relationships between R, A, and y have been developed by NCDEQ (2017) (Equations N-4 through N-6). The flow rate was calculated for a typical turf grass swale using the dimensions of the experimental swales used herein, a standard design flow depth of y = 0.5 ft (NCDEQ, 2020), and a turf grass "n" value of 0.033 (NCDA&CS, 2023). This flow rate was then used to calculate the necessary depth of flow, y, for a swale with the same dimensions but retrofitted with a native grass lining. Calculations indicate an increase of 0.056 in roughness from turf to native grass will increase the necessary cross-sectional area by 2.8 ft^2.

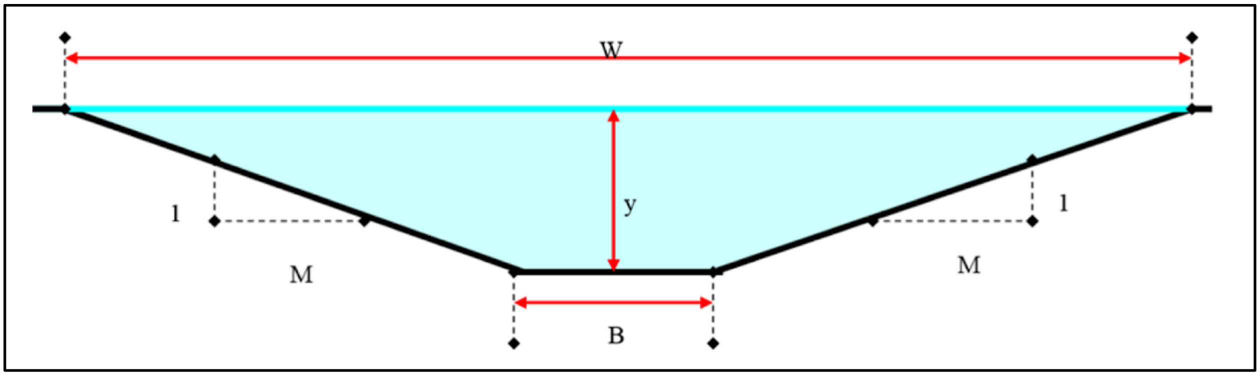


Figure N-5: Schematic of swale cross-section (taken from NCDEQ, 2017).

$$A = By + My^2 \quad \text{(N-4)}$$

Where:

- A is the cross-sectional area (ft^2),
- B is the bottom width of the channel (assumed to be 4ft),
- y is the depth of flow (ft), and
- M is the side slope ratio (ft horizontal/ft vertical; assumed to be 3)

$$P = B + 2y(1 + M^2)^{0.5} \quad \text{(N-5)}$$

Where:

- P is the wetted perimeter, the distance along the cross-section against which water is flowing (ft)

$$R = \frac{A}{P} \quad \text{(N-6)}$$

Where:

- R is the hydraulic radius (ft)

TableN-5: Manning's n impact on hydraulic radius (R) and cross-sectional area (A).

Lining	**Q (cfs)**	**n**	**y (ft)**	**R (ft)**	**S (ft/ft)**	**A (ft^2)**
Turf	13.12	0.033	0.50	0.38	0.04	2.75
Riprap	13.12	0.035	0.52	0.29	0.04	2.87
Native Grass, herein	13.12	0.089*	0.85	0.59	0.04	5.55

*"n" for native grass swale on 4% slope during high flow

Furthermore, the Aberdeen and particle fall number equations (N-7 and N-8) (Deletic, 2005) may be solved to determine the length necessary for swales to remove the same quantity of sediment. Trapping efficiency for grassed swales in the Aberdeen equation was assumed to be 35%. This is considered NCDEQ's (2009) trapping efficiency in swales meeting pollutant credit requirements. Nf was calculated to be 4.15.

$$Tr_s = \frac{N_f^{0.69}}{N_f^{0.69}+4.95} \tag{N-7}$$

Where:

- Tr_s is the trapping efficiency (%), and
- N_f is the particle fall number (dimensionless)

$$N_f = \frac{L_{swale}V_s}{yV} \tag{N-8}$$

Where:

- L_{swale} is the length of the swale (ft),
- V_s is the velocity at which the particle falls, calculated by Stokes Law (Maidment, 1993) (ft/s),
- y is the flow depth (ft), and
- V is the flow velocity (ft/s)
-

Inputs for the particle fall number equation are listed in Table N-6 to solve for Lswale, the necessary swale length. Velocity was calculated from Q and A values in Table N-5 (Equation N-9). Calculations indicate a 70-foot long native grass swale is capable of removing the same quantity of sediment as swales lined with turf or riprap that are 14 and 13 feet longer, respectively. As a reminder, although shorter, native grass swales did require a larger cross-sectional area.

$$V = \frac{Q}{A} \tag{N-9}$$

Where:

- V is the flow velocity (ft/s),
- Q is the flow rate (cfs), and
- A is the cross-sectional area (ft^2)

Table N-6: Particle fall number equation inputs.

Lining	N_f	h (ft)	V_s (ft/s)	V (ft/s)	L_{swale} (ft)
Turf	4.15	0.50	0.12	4.77	84
Riprap	4.15	0.52	0.12	4.58	83
Native Grass, herein	4.15	0.85	0.12	2.36	70

Variations in roughness values will impact swale design. Sample calculations were completed to demonstrate how a native grass lining impacts the required swale cross-sectional area and length. Results indicate native grasses require shorter lengths but larger cross-sections to accommodate the same flow rates and sediment trapping efficiencies as turf or riprap-lined swales.