Long-Term Monitoring and Evaluation of Multiple Green Infrastructure Designs for Stormwater Quality Performance, Effects of Vegetation, and Maintenance

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This

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Author: Wuhuan Zhang

Advisor: Dr. James A. Smith

Advisor:

Committee Member: Dr. Jonathan L. Goodall

Committee Member: Dr. James A. Smith

Committee Member: Dr. Garrick E. Louis

Committee Member: Dr. Venkataraman Lakshmi

Committee Member: Dr. Patricia L. Wiberg

Committee Member:

Accepted for the School of Engineering and Applied Science:

Jennifer L. West, School of Engineering and Applied Science

May 2023

Abstract

Concerns regarding non-point source pollution have been steadily increasing over recent decades around the world. Sudden discharges of stormwater runoff from paved surfaces, which cannot soak into the ground, lead to flooding, and water pollution into aquatic ecosystems. Green infrastructure (GI) systems have been employed as an environmentally sustainable alternative to treat stormwater in urban areas since the late 1990s in the hope of mitigating impervious surface hydrology effects. GI could protect aquatic ecosystems from stormwater quantity and quality pollution due to land development and human activities. There have been many short-term studies that document the performance of individual GI systems and their ability to protect waterways from the detrimental effects of urban stormwater. However, few studies exist comparing the long-term performance of different types of GI designs in the same location, and the removal mechanism of salt by GI vegetation is poorly understood. The potential of different vegetation types for mitigating deicing salt has not been documented significantly, and little is known about the effects of maintenance on GI performance.

This dissertation uses the flow and composite flow-weighted sampling to compare water quality improvements of four typical GI practices (bioretention, grass channel, compost-amended grass channel, and bioswale) along a road in Lorton, Fairfax County, Virginia. The three objectives of this dissertation include: (1) compare long-term monitoring of the water-quality performance of four GI practices receiving similar influent pollutant loadings; (2) explore the potential of different vegetation types to reduce deicing salt released from a bioretention by transpiration; (3) evaluate the economic and environmental maintenance costs and benefits of GI based on water-quality performance.

For the first part of this dissertation, approximately 60 storm events have been monitored and sampled since 2018, and 24 relatively complete storms are selected for comparison and evaluation. The performance of these four monitored GI designs ranges significantly. Grass channel performed best on both runoff and pollutant load reductions, serving a relatively small contributing drainage area, while the bioretention, which has the second highest volume and mass load reduction for pollutants, serves the biggest contributing drainage area, and its performance is considerably more consistent than most of the other types of GI systems monitored.

The second part of this dissertation investigates the attenuated transport of salts by vegetation in the bioretention basin (BR). BR is a typical GI system wherein stormwater runoff is routed to a soil basin planted with vegetation and has been shown to reduce deicing salt loads in surface runoff, but the removal mechanism of salt is poorly understood. This work explores the potential of different vegetation types to reduce deicing salt released from a BR by transpiration. Six engineered soil media columns were built in a laboratory greenhouse to simulate a 1012 m^2 BR basin along Lorton Road, Fairfax County, Virginia. The effect of vegetation types (Blue Wild Indigo and Broadleaf Cattail) and influent salt concentration on flow volume and salt mass reduction were quantified for multiple storm events. For all storm events, inflow concentrations, and vegetation types, Cl^{-} load reduction ranged from 26.1% to 33.5%, Na^{+} load reduction ranged from 38.2% to 47.4%, and volume reductions ranged from 11.4% to 41.9%. Different inflow salt concentrations yielded different removal rates of deicing salt, and for a given column, salt removal decreased over

sequential storm events. For each influent salt concentration, columns planted with Broadleaf Cattail (BC) performed better for volume and salt mass reductions than columns planted with Blue Wild Indigo (BWI), which in turn performed better than the controls.

The third part of this dissertation addresses the effects of long-term maintenance on GI performance. Seven maintenance events with a forebay restoration are monitored from 2018 to 2022 to evaluate the efficiency of maintenance activities. Stormwater quality performance among these four GI practices before and after the seven in-field maintenance activities was assessed according to pollutant load on dissolved organic carbon (DOC), total dissolved nitrogen (TDN), total suspended solids (TSS), and runoff reductions for the 14 storm events over four years. The average runoff reductions over all monitored storms were 74%, 85%,63%, and 68% for bioretention, grass channel, compost-amended grass channel, and bioswale, respectively. Over the seven maintenance events, the mean runoff reduction of all monitored GI designs improved by 3% after maintenance, DOC mass load reduction increased by 41%, TDN mass load reduction improved by 25%, and TSS mass load reduction increased by 2%. All the pollutant and runoff reduction for swales improved after spring maintenance events, and all monitored GI systems performed better after spring maintenance events compared with their performance after fall maintenance activities, which is potentially due more to the vegetation growth than the maintenance work.

This dissertation will help researchers, engineers, and policymakers better understand how GI practices are functioning and identify ways to optimize their effectiveness. It can also help determine the capacity of different types of GI systems to store and treat stormwater, track changes in water quality over time, and evaluate the effectiveness of their maintenance activities.

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Related Publications

This dissertation has directly resulted in the following publications:

- **Chapter 2: Zhang, W.**, Burgis, C.R., Hayes, G.M., Henderson, D.A., Smith, J.A. (2023) "Long-term monitoring of the water-quality performance of four green infrastructure types receiving similar influent pollutant loadings" (manuscript in preparation)

- **Chapter 3: Zhang, W.**, Burgis, C.R., Hayes, G.M., Henderson, D.A., Smith, J.A., 2022. Mitigation of Deicing Salt Loading to Water Resources by Transpiration from Green Infrastructure Vegetation. Land 11, 907. https://doi.org/10.3390/land11060907

- **Chapter 4: Zhang, W.**, Burgis, C.R., Hayes, G.M., Henderson, D.A., Smith, J.A. (2023) "Evaluation of maintenance efficiency for multiple green infrastructure designs based on water-quality performance and economic costs" (manuscript in preparation)

Other related publications from this research:

- Burgis, C.R., Henderson, D.H., Hayes, G.M., **Zhang, W.**, Smith. J.A. (2023) "In-field evaluation of green infrastructure design performance for transportation water quality improvement" (under review)

- Hayes, G.M., Burgis, C., **Zhang, W.**, Henderson, D., Smith, J.A., 2023. Evaluation of the Export of Fecal Contamination from Roadside Green Infrastructure. Journal of Sustainable Water in the Built Environment 9, 04022016. https://doi.org/10.1061/JSWBAY.0001002

- Hayes, G.M., Burgis, C., **Zhang, W.**, Henderson, D., Smith, J.A., 2021. Runoff Reduction by Four Green Stormwater Infrastructure Systems in a Shared Environment. J. Sustainable Water Built Environ. 7, 04021004. https://doi.org/10.1061/JSWBAY.0000932

- Burgis, C.R., Hayes, G.M., Henderson, D.A., **Zhang, W**., Smith, J.A., 2020. Green stormwater infrastructure redirects deicing salt from surface water to groundwater. Science of The Total Environment 729, 138736. https://doi.org/10.1016/j.scitotenv.2020.138736

- Burgis, C.R., Hayes, G.M., **Zhang, W.**, Henderson, D.A., Macko, S.A., Smith, J.A., 2020. Tracking denitrification in green stormwater infrastructure with dual nitrate stable isotopes. Science of The Total Environment 747, 141281. https://doi.org/10.1016/j.scitotenv.2020.141281

Related Presentations

This dissertation has resulted in the following presentations:

- **Zhang, W.**, Burgis, C.R., "Using green infrastructure to manage transportation deicing salt loading to water resources: monitoring salt fate and transport in the field and the potential use of vegetation for management" Lectern presentation at the 2023 Transportation Research Board. Washington D.C. January 2023.

- **Zhang, W.**, Burgis, C.R., Hayes, G. M., Henderson, D.A., Smith, J.A., "Potential of Vegetation to Mitigate Deicing Salt Loading in Green Infrastructure Designs." Poster presentation (abstract submission) at the American Water Resources Association's Annual Water Resources Conference. Seattle, WA, November 2022.

- **Zhang, W.**, Smith, J.A. "Assessment of Low Impact Development Strategies for Lorton Road Widening Project." Lectern presentation at the VDOT Virginia Transportation Research Council: Environmental Research Advisory Committee Meeting. Charlottesville, VA, May 2022.

- **Zhang, W.**, Burgis, C.R., Hayes, G. M., Henderson, D.A., Smith, J.A., "Long-Term Monitoring of Water-Quality Performance of Four Green Infrastructures Receiving Similar Influent Pollutant Loadings." Virtual lectern presentation (abstract submission) at the 2021 World Environmental & Water Resources Congress. June 2021.

- **Zhang, W.**, Burgis, C.R., Hayes, G. M., Henderson, D.A., Smith, J.A., "Potential of Vegetation to Mitigate Deicing Salt Loading in Green Infrastructure." Virtual poster presentation (abstract submission) at the 2021 World Environmental & Water Resources Congress. June 2021.

- Hayes, G.M., Burgis, C.R., **Zhang, W.**, Henderson, D.A., Smith. J.A. "Green Infrastructure Demonstrates Variable Mitigation of Fecal Contamination in Stormwater." Virtual poster presentation (abstract submission) at WaterJAM (VA AWWA and VWEA). September 2020.

- Burgis, C.R., Hayes, G.M., **Zhang, W.**, Smith, J.A. "Tracking Denitrification in Green Stormwater Infrastructure with Nitrogen and Oxygen Stable Isotopes." Lectern presentation (abstract submission) at ASCE International Low Impact Development Conference. Bethesda, MD. July 19-22, 2020.

- Burgis, C.R., Hayes, G., Henderson, D.A., **Zhang, W.**, Smith, J.A. "Green Stormwater Infrastructure Buffers Surface Water from Deicing Salt Loading." Lectern presentation (abstract submission) at ASCE International Low Impact Development Conference. Bethesda, MD. July 19-22, 2020.

- **Zhang, W.**, Burgis, C.R., Hayes, G. M., Henderson, D.A., Smith, J.A., "Water Quality Performance of Green Stormwater Infrastructure along Lorton Road." Poster presentation (abstract submission) at the American Water Resources Association's Annual Water Resources Conference. Salt Lake City, Utah, November 2019. (Student Poster Runner-up Award)

- Hayes, G. M., Burgis, C.R., **Zhang, W.**, Henderson, D.A., Smith, J.A. "Comparing flow reductions of four green infrastructure systems in a roadside environment and early results from groundwater monitoring receiving infiltrated runoff." Lectern presentation (abstract submission) at the Annual Water Resources Conference. Salt Lake City, Utah, November 2019.

- Burgis, C. R., Hayes, G.R., **Zhang, W.**, Smith, J.A., "Tracking Denitrification in Green Stormwater Infrastructure with Nitrate Stable Isotopes." Lectern presentation (abstract submission) at the University of Virginia Global Water Initiative Graduate Research Symposium. Charlottesville, VA, November 2019. (Best presentation winner)

- Hayes, G. M., **Zhang, W.**, Burgis, C.R., Henderson, D.A., Smith, J.A. "Low Impact Development Performance on Lorton Road." Lectern presentation at the VDOT Virginia Transportation Research Council: Environmental Research Advisory Committee Meeting. Charlottesville, VA, May 2019.

Chapter 1: Introduction

1.1 Introduction

Over recent years, urbanization has transformed how land is used in the United States[1]. This process has a significant hydrologic consequence, particularly in the form of non-point pollution, such as stormwater runoff. Due to the prevalence of impervious surfaces in urban areas, stormwater cannot infiltrate and evaporate as it would in natural environments, leading to sudden and intense releases of water [2]. These events can result in flooding and carry various pollutants, including trash, heavy metals, and other harmful contaminants, into nearby water sources. The impact on ecosystems and human health can be significant. As urbanization continues to increase impervious surfaces, the natural flow of stormwater runoff is altered, exacerbating non-point source pollution and causing damage to the environment [3]. To ensure the preservation of public health and the environment, effective stormwater management is crucial to reducing runoff and associated pollutants[4,5].

Linear transportation systems, particularly highways, are a significant concern in urban areas with respect to stormwater runoff[6,7]. Due to the presence of large impervious road surfaces, highways are a major contributor to stormwater runoff, which can lead to a decrease in water runoff quality. In addition, the increased vehicle miles traveled on highways can serve as a potential source of pollutants, further exacerbating the issue. Common contaminants potentially found in highway stormwater runoff include sediment, nutrients, salt, total organic carbon (TOC), bacteria, and metals[6,8–11]. Consequently, managing stormwater runoff from highways has emerged as a primary objective for many state departments of transportation, given its significant impact on water quality degradation. Thus, stormwater management is essential to mitigate the potential effects of highway runoff on receiving waters.

Traditional stormwater management techniques, like gray infrastructure practice, which is a system of pipes, gutters, and tunnels, tend to move stormwater runoff away directly from communities to local surface waters without any treatment, and its capacity to manage large runoff volumes and address multiple environmental challenges at the same time is limited[12]. Thus, improvements are needed in existing stormwater management methods to control flows and protect water resources[13]. Green infrastructure (GI) design, also known as green stormwater infrastructure (GSI) or low impact development (LID), has been employed as an environmentally sustainable alternative to traditional gray infrastructure practices in the United States since the 1990s[14,15]. GI design is a collection of techniques that involve the utilization of vegetation soil systems and other natural landscape features for the purpose of retaining, infiltrating, or evapotranspiring stormwater, thereby mitigating flows to both sewer systems and surface waters[12]. It could simulate natural landscape hydrology, such as slowing, spreading, and infiltrating stormwater runoff prior to discharge into receiving waters. GI practices have proven highly effective in mitigating the adverse impacts of urban stormwater[5,16]. Numerous green infrastructure strategies have been employed to manage stormwater runoff, including green roofs, bioretention basins, and swales[17].

Evaluation of the performance of GI practices in managing stormwater is crucial in determining its feasibility of meeting new regulatory requirements and protecting ecosystems. It is hypothesized that different individual GI designs will have statistically significant differences in performance and economic efficiency and vary with different storm conditions. However, the long-term monitoring and maintenance evaluation for multiple types of GI designs receiving similar influent pollutant loadings in a shared linear transportation environment has not been documented significantly. Therefore, this dissertation aims to explore the performance and evaluate the maintenance efficiency of four types of GI practices (bioretention, grass channel, compost-amended grass channel, and bioswale) over a multi-year range at Lorton Road, Fairfax County, VA, USA. GI performance is assessed based on stormwater quantity and quality improvements, and maintenance efficiency assessments are made by comparing the performance and costs. The monitored water quality parameters in this research include total suspended solids (TSS), total organic carbon (TOC), nutrients (total dissolved nitrogen (TDN), nitrate, nitrite, and phosphate), salt, and trace metals (Cd, Cr, Cu, Fe, Pb, and Zn). The potential of different vegetation types to reduce deicing salt released from the bioretention by transpiration is also explored in this study.

1.2 Green Infrastructure Systems Monitored

1.2.1 Bioretention

The bioretention (BR) system, also recognized as a biofilter, has become widespread in the United States as a form of GI practice. It consists of a soil bed equipped with appropriate vegetation, serving as a filtering medium for stormwater runoff [18]. The stormwater runoff entering the bioretention is filtrated into an underlying layer of engineered soil media before being conveyed downstream by an underdrain system or infiltrated into the existing subsoil below the soil bed. Infiltration through the engineered soil media provides uptake of pollutants and runoff through physical, chemical, and biological mechanisms. When combined with an underdrain system, bioretention systems are commonly referred to as bioretention filters. Through the mechanisms of infiltration, evaporation, and storage, a BR system is capable of achieving substantial reductions of both peak flow and runoff volume, resulting in a considerable decrease in the transportation of pollutant loads to receiving waters [19,20]. They have played a vital role in the implementation of green infrastructure to achieve a number of sustainable stormwater management objectives.

1.2.2 Swale

Swale is another frequently encountered category of green infrastructure design, encompassing a range of components such as grass channels, compost-amended grass channels, bioswales, etc., consisting of a diverse array of soil materials and vegetation types to serve varying treatment objectives. Grass channel (GC), also referred as grassy swales, is a vegetated, open channel stormwater management practice and can provide a relatively modest level of runoff filtering and volume attenuation, within the stormwater conveyance system resulting in the delivery of less runoff and pollutants than a traditional system of curb and gutter, storm drain inlets and pipes[15]. The grass channel equipped with compost-amended soil media is known as a compost-amended grass channel (CAGC) and is another type of swale. Bioswale (BS), also referred to as a dry swale, is a category of swales that is similar in appearance to a grassed swale but employs engineering soil media, similar to the bioretention, below the vegetation and is often accompanied by an underdrain. This unique combination of features endows the BS with the potential to perform the dual function of conveyance, traditionally associated with a grass swale, and filtration and biological treatment, characteristics typically associated with bioretention[21].

1.3 Research Objectives

The goal of this dissertation is to quantify the performance of four types of green infrastructure designs along Lorton Road, Fairfax County, VA, USA., based on their stormwater quantity and quality performance. The three primary objectives of this research are (1) to evaluate the water-quality performance of four GI practices receiving similar influent pollutant loadings in long-term monitoring (Chapter 2); (2) to explore the potential of different vegetation types to reduce deicing salt released from bioretention through transpiration (Chapter 3); and (3) to evaluate the maintenance efficiency for the four monitored green infrastructure designs based on water-quality performance and economic costs (Chapter 4). All data collected and conclusions gained from this study will be utilized to aid engineers in selecting current GI practices and improving future GI designs, to ensure the preservation of public health and the environment.

1.4 References

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Chapter 2: Long-term Monitoring for Water-quality Performance of Four Green Infrastructure Practices Receiving Similar Influent Pollutant Loadings

This study will result in three publications. The first manuscript is focused on a short-term evaluation of green infrastructure design performance for water quality improvement and is under review. The second manuscript focuses on the long-term monitoring for the water-quality performance of green infrastructure practices receiving similar influent pollutant loadings and is in preparation. The third manuscript focuses on the runoff reduction for monitored GI practices and had been published by the Journal of Sustainable Water Built Environment.

- Burgis, C.R., Henderson, D.H., Hayes, G.M., **Zhang, W.**, Smith. J.A. (2023) "In-field evaluation of green infrastructure design performance for transportation water quality improvement" (under review)

- **Zhang, W.**, Burgis, C.R., Hayes, G.M., Henderson, D.A., Smith, J.A. (2023) "Long-term monitoring of the water-quality performance of four green infrastructure types receiving similar influent pollutant loadings" (manuscript in preparation)

- Hayes, G.M., Burgis, C., **Zhang, W.**, Henderson, D., Smith, J.A., 2021. Runoff Reduction by Four Green Stormwater Infrastructure Systems in a Shared Environment. J. Sustainable Water Built Environ. 7, 04021004. https://doi.org/10.1061/JSWBAY.0000932

2.1 Introduction

The sudden discharge of stormwater can result in significant degradation of aquatic ecosystems. As natural land is replaced by impervious surfaces because of urbanization, the amount of stormwater that can be absorbed into the ground decreases significantly. Increasing stormwater runoff traveling into surface receiving water carries lots of pollutants such as trash, oil, bacteria, and heavy metals, particularly along the highway[1,2]. It leads to a range of problems, such as water quality degradation, flooding, erosion, and habitat destruction for aquatic plants and animals [3–5]. Therefore, the management of stormwater runoff in urban areas is an essential issue that requires careful planning and implementation of appropriate measures to mitigate its impacts on the environment and public health[4].

The conventional techniques employed for stormwater management, commonly referred to as gray infrastructure, consist of a network of water retention and purification systems, including pipes, culverts, and retention ponds to move the flow of stormwater during rain events without any treatment[6]. While their efficacy in managing large runoff volumes and addressing multiple environmental challenges at the same time is limited[5]. Therefore, improvements are needed in existing stormwater management approaches in order to better control flows and protect valuable water resources[7]. Gray infrastructure tends to incur environmental costs by degrading the natural landscape and disrupting ecosystems, while green infrastructure typically yields environmental benefits by enhancing the landscape and promoting biodiversity[8].

Green infrastructure (GI), distinct from gray infrastructure, refers to natural or semi-natural systems, such as bioretention, green roofs, and swales, which are designed or managed to provide ecological, social, or economic benefits[9–11]. It is an improved and cost-effective approach using natural features to capture, retain, treat, and release stormwater runoff, to reduce the amount of runoff entering receiving waters, thereby protecting water quality [1,12–14]. GI systems have garnered significant attention and have been increasingly employed as an environmentally sustainable alternative to traditional gray infrastructure practices in the United States since the 1990s[15]. Prior studies have suggested that GI practices are effective in reducing stormwater runoff and improving water quality[16,17]. Burgis et al. (2020) found the cumulative Cl^- surface water effluent load reduction in a BR in Northern Virginia was 80%, and Na^+ effluent load reduction was 82%.

Long-term monitoring and comparison of water quality performance are essential to evaluate the effectiveness of green infrastructure practices that receive similar influent pollutant loadings, but it has not been significantly documented. In this study, four types of green infrastructure practices were monitored from 2018 to 2022 with the aim of assessing their long-term performance in enhancing water quality. The water quality parameters monitored in this study include trace metals and salt ions. The hypotheses of this chapter are that different GI designs result in different pollutant removals and that the performance of bioretention is more stable than swales.

2.2 Materials and Methods

Four types of GI designs are monitored in this study, which were installed in spring 2017 by the Virginia Department of Transportation (VDOT) along Lorton Road in Fairfax County, VA, USA, and are within 0.8 km of each other (as shown in **Figure 2.1**). They are a bioretention (BR), a grass channel (GC), a compost-amended grass channel (CAGC), and a bioswale (BS), which are four distinctly different designs that are commonly used in transportation stormwater management. They were selected based on specific characteristics such as climate, soil quality, watershed area, and expected pollutants. The design specifications and features of these four GI systems are presented in **Table 2.1**. Each GI system consists of a different design, receiving runoff directly from the highway. Regular bi-annual maintenance events for the monitored GI systems are performed by VDOT twice every year (once in spring and once in fall).

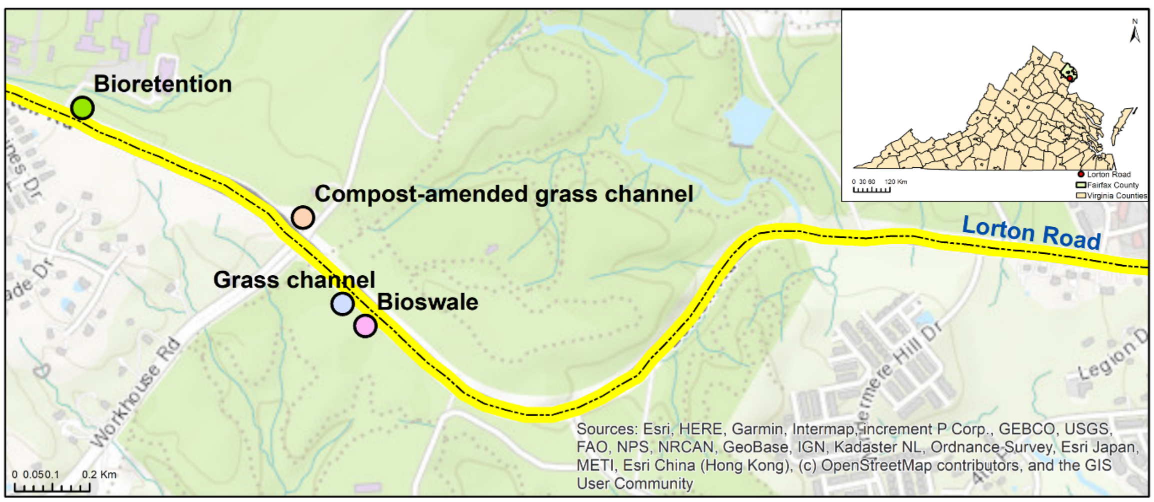

Figure 2.1 Lorton Road stormwater research site and positioning of four LID types. (Created with ArcGIS)

The bioretention (BR), located north of Lorton Road, includes a forebay for the pre-treatment of runoff and a basin for the treatment of stormwater (**Figure 2.2,** top). The elevation of the BR basin is around 77 m above the mean sea level, and the average depth to groundwater from BR basin is approximately 2.3 m during the monitoring period. The BR serves a 47,753 m^2 contributing drainage area (CDA). The forebay and BR basin are connected by a 0.6 m concrete culvert through an earthen berm. Concentrated stormwater from the road travels into the forebay as inflow before flowing into the BR basin, where various vegetation is grown in the engineered soil media (ESM) (3.2% clay, 5.6% silt, 91.2% sand) on top of underlying gravel (VDOT #8 stone with the outlet and VDOT #57 stone). After treatment, the stormwater flows out through an underdrain installed at the top of the gravel layer there and then into the Giles Run watershed, within the Chesapeake Bay watershed[1]. A bypass, connected with the forebay on the other side, has also been installed to allow for overflow during large storm events. The design specifications and plant species used in the BR basin are listed in **Table 2.1**. Monitoring sites have been established at the inlet, outlet, and bypass of the BR to collect stormwater samples and measure flow information during monitored events.

The grass channel (GC), serving a 2,533 m^2 contributing drainage area, is located south of Lorton Road, approximately 0.8 km east of the BR. It's an 85 m swale with a 1:20 slope, consisting of native soils where grass and wildflowers grow, as depicted in **Figure 2.2,** bottom **left**. The GC features three wooden check dams to intercept runoff and facilitate infiltration. More details of GC design specifications are presented in **Table 2.1**.

The compost-amended grass channel (CAGC) has a 6,874 m^2 contributing drainage area and is 0.4 km east of the BR on the north side of Lorton Road (**Figure 2.2,** middle). The CAGC is a 232-m-long and 1:60 linear sloped swale with 6 wood check dams, consisting of 30 cm compost-amended native soils and native soils where trees, shrubs, grasses, and wildflowers grow. More details for GC design characters are shown in **Table 2.1**.

The bioswale (BS) is a 65 m linear swale with a 1:27 linear slope and 6 wood check dams serving a contributing drainage area of 2,772 m^2 (**Figure 2.2**, bottom right). It is constructed with the same engineered soil media as bioretention and features an underdrain at the top of the gravel layer beneath the engineered soil media. Further specifications of BS can be found in **Table 2.1**.

In contrast to the BR, which receives concentrated inflow, the three types of swales in this study receive unconcentrated inflow from Lorton Road. A 9.1-m-long sheet flow collector (as shown in **Figure 2.2,** bottom) receiving direct inflow from the road was set as the inflow from the impervious drainage area (adjacent to the CDAs of swales) for the three swales. This sheet flow collector has a contributing drainage area of 88 m^2 and is situated along the sidewalk of Lorton Road. The inflow from pervious drainage areas of the three monitored swales is calculated with the curve number (CN) method, described by Hayes et al. (2021).

Monitoring sites were established at the bottom of the three swales (CAGC, GC, and BS) to collect the treated outflow. The contributing drainage areas for the CAGC, GC, and BS were determined using a 2018 lidar-derived digital elevation model with a 1-m spatial resolution) of the site and ArcMap software (ESRI 2022)[18].

Table 2.1 Design specifications and characteristics of GI at Lorton Road. (CDA: contributing drainage area. The swale CDAs were determined using a 1-m spatial resolution lidar-derived digital elevation model of the sites from 2018 and ArcMap software (ESRI 2022).)

Design Specification	Bioretention (BR)	Grass Channel (GC)	Compost-Amended Grass Channel (CAGC)	Bioswale (BS)
CDA (m^2)	47,753	2,533	6,874	2,772
% Impervious CDA	35	29	16	32
CDA land use	residential grass, roadway, woods	grass, sidewalk, roadway	grass, roadway	grass, sidewalk, roadway
GI Footprint (m^2)	1,012	337	891	196
CDA: Loading ratio	47.2	7.5	7.7	14.1
Engineered Storage (m^3)	447	2.2	8	55
Inflow type	curb and gutter sewer	sheetflow	sheetflow	sheetflow
Outflow type	10cm diameter underdrain + bypass channel	swale channel	swale channel	10cm diameter underdrain
Subsurface layers (surface → down)	76 cm engineered soil media, 10 cm #8 stone (+underdrain), 31 cm #57 stone	Native soils	30 cm compost-amended native soils, native soils	46 cm engineered soil media
Mulch depth (cm)	5	-	-	-
Engineered soil depth (cm)	76	-	-	46
Underlying gravel depth	40	-	-	40
Vegetation type	trees, shrubs, sedges, wildflowers	grasses, wildflowers	trees, shrubs, grasses, wildflowers	trees, shrubs, grasses, sedges wildflowers
Length (m)	-	85	232	65
Base-width (m)	-	1.5	1.5	1.5

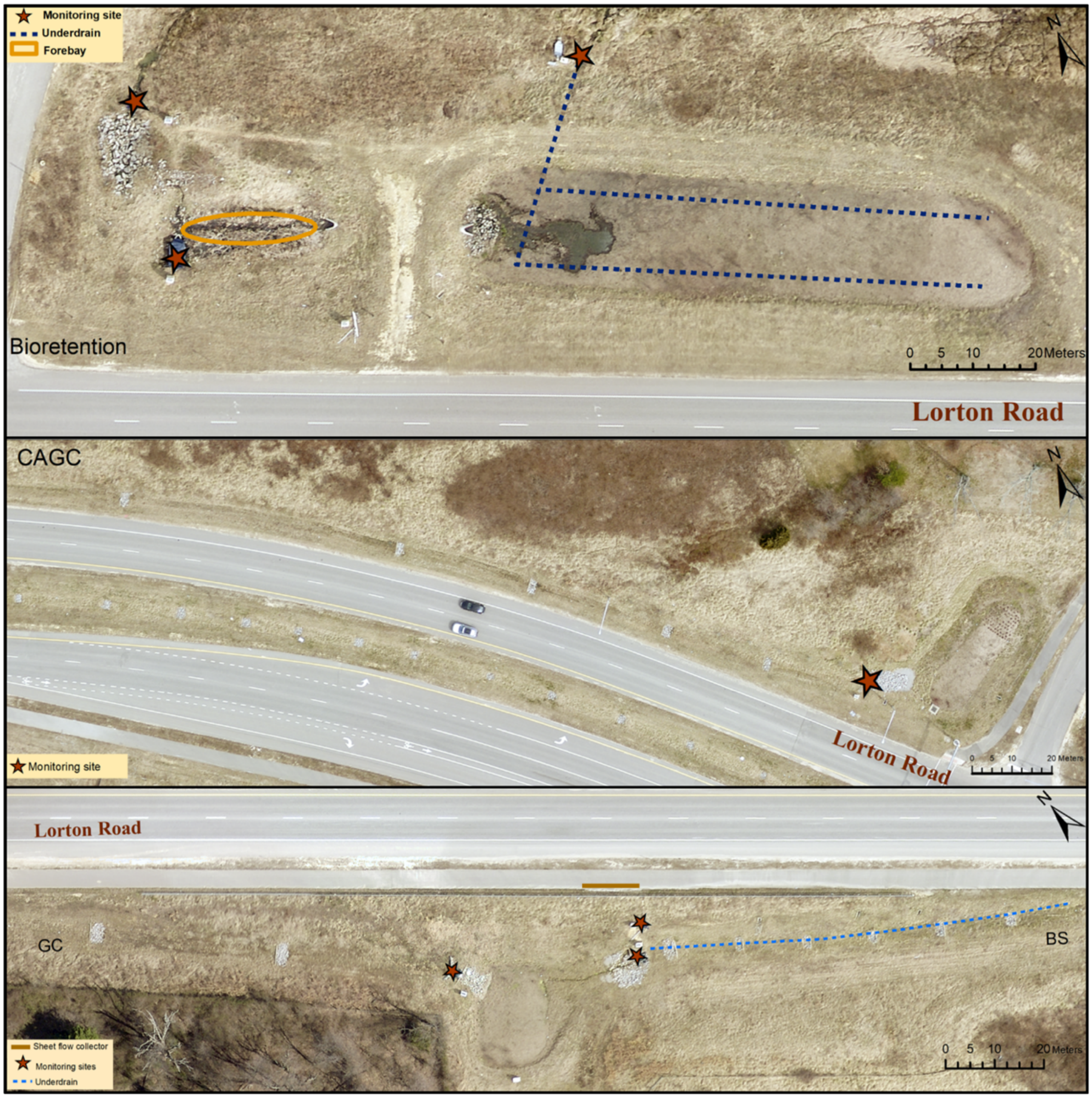

Figure 2.2 Stormwater monitoring site and positioning of four GI designs at Lorton Road. (Created using ArcGIS) (Top: Bioretention. Red stars represent stormwater monitoring sites established (from left to right: bypass, inlet, outlet). The orange circle indicates the forebay. The blue dashed line signifies the underdrain in the BR basin. Middle: Compost-amended grass channel (CAGC). The red star indicates stormwater monitoring sites installed. Bottom: Grass channel (GC) (left) and Bioswale (BS) (right). Red stars indicate stormwater monitoring sites installed. The light blue dashed line indicates underdrain in BS, and the solid brown line shows the sheet flow collector for the inflow of swales.)

Seven monitoring sites were installed in the field to track stormwater runoff quantity, and quality parameters for the four monitored GI systems. There are three monitoring sites located in BR (inflow, bypass, and outflow), and four are for the swales (one for inflow and three for outflow of each swale) (**Figure 2.2**). Each monitoring site includes a Hach AS950 solar-powered programmable auto-sampler to collect flow-weighted composite samples of stormwater, and an

H or HS flume equipped with a US9001 ultrasonic sensor to measure the water level and flowrate of the runoff and calculate the discharge of stormwater, as described by Hayes et al. (2021)[19]. A Hach tipping bucket rain gauge paired to Hach AS900 is set in the bioretention to monitor the parameters of each storm event (e.g., duration time and rain depth). When the rain gauge fails to work due to power off, precipitation data collected by Weather Underground Station in Washington Reagan National Airport (nearby monitored location) is used as the alternative. Flow-weighted composite stormwater samples for each monitored storm were collected automatically into a 9.5 L glass bottle in each auto-sampler for water quality analysis. The pollutant concentration of the flow-weighted composite sample is known as the event mean concentration (EMC), which is used to represent the concentration of each monitoring site and compare the performance of multiple GI designs in one storm or a single GI practices performance in multiple storm events[1]. The EMC could be calculated using Equation (2.1).

$$EMC = Total\ mass\ of\ pollutant/Total\ runoff\ volume \qquad (2.1)$$

In this study, the effectiveness of various Green Infrastructure (GI) practices is evaluated and compared based on their ability to reduce the mass load of pollutants for multiple water quality parameters and stormwater runoff. Flow rates of each monitored storm are measured using H or HS flumes from Open Channel Flow equipped with ultrasonic sensors. The sizing of each established flume is determined based on the estimated stormwater flow rate of each monitored site. Stormwater flow rate can be calculated based on Equation (2.2), which considers the specific flume size and geometry, and the height of flowing water within it[20].

$$Q = a + b * h^{e} + c * h^{1.5} + d * h^{2.5} \qquad (2.2)$$

In Equation (2.2), Q=flowrate, h=stormwater height, a, b, c, d , and e are empirically derived constants specific to each flume size.

Stormwater runoff reductions are calculated using Equation (2.3) and total mass load reductions for each type of water quality parameters are calculated using Equation (2.4).

$$VLR = \frac{(Inlet-Outlet)}{Inlet} * 100 \qquad (2.3)$$

In Equation (2.3), *VLR*=volume load reduction, *Inlet*=inflow volume (L), and *Outlet*=outflow volume (L).

$$MLR = \frac{(Con_{In} * Inlet - Con_{out} * Outlet)}{Con_{In} * Inlet} * 100 \qquad (2.4)$$

In Equation (2.4), *MLR*=mass load reduction, Con_{In}=chemical concentrations of inflow (mg/L), Inlet=inflow volume (L), Con_{out}=chemical concentrations of outflow (mg/L), and *Outlet*=outflow volume (L).

Between March 2018 and December 2022, around 60 storm events have been monitored and sampled. 24 events of them got a relatively complete and significant volume of samples for all four types of GI systems for a variety of stormwater quality analyses, which are used for this objective. Flow-weighted composite samples are collected from H flumes by the autosamplers and stored in 9.5 L gallon glass bottles on ice in the field during each monitored storm event. They are carried back to the water quality lab at the University of Virginia for analysis. The samples are analyzed for a range of parameters in this study, including salt ions and trace metals. Samples filtered through 0.45 µm are analyzed for chloride using a Thermo Scientific Dionex ICS 5000 DP-5 ion chromatography (IC). Samples are preserved with 2% HNO_3 and filtered through 0.45 µm before metals analysis using an Agilent 7900 ICP-MS inductively coupled plasma mass spectrometry (ICP-MS). Concentration, volume, and mass loads of chloride, sodium, calcium, copper, and lead are used to determine the monitored GI practices' performance in this chapter.

2.3 Results and Discussion

Figure 2.3 is an example of the hydrograph of Bioretention for the 1.6 in storm sampling event happening from 10/16/2019 to 10/17/2019, which presents the rain depth, sampling time, and flow rate for all three monitoring sites in bioretention. The figure indicates that bioretention performed well on flow rate and runoff reduction. There are high flow rates for the bioretention Inlet, but the flow rate of the bypass after the pretreatment of the forebay and the flow rate of the outlet after treatment of the bioretention basin are both much lower, which indicates that the bioretention performs well in reducing the flow rate and volume during a stormwater treatment. This greatly benefits nearby receiving waters. The results are consistent with the study reported by Davis (2008), who monitored the performance of two bioretention cells for 49 storm events during a two-year period and found that discharge flow peaks reduced by over 50% after treatment[21]. We sample as much of the storm as possible during a storm for water quality analysis.

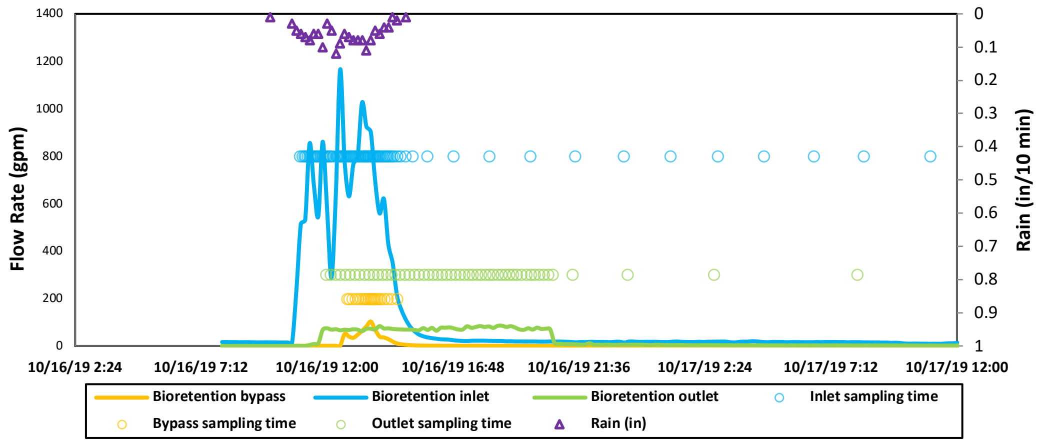

Figure 2.3 Hydrograph of Bioretention for 10/16/2019 – 10/17/2019, 1.6 in. Storm

Runoff reduction for the 24 monitored storm events since March 2018 of the four types of GI practices is displayed in **Figure 2.4**. The bioretention has the most consistent stormwater volume reduction, compared with the other three types of GI systems. The GC has the highest average runoff reduction among these four GI designs. The mean runoff reductions are 73%, 84%, 59%, and 67% for bioretention, GC, CAGC, and BS, respectively. The performance of runoff reduction of CAGC is more unstable and relatively lower than the other three types of GI practices. It potentially results in a larger percentage of surface area of vegetation in its contributing drainage area, compared with other types of GI systems, which leads to it being affected more due to climate changes and vegetation growth.

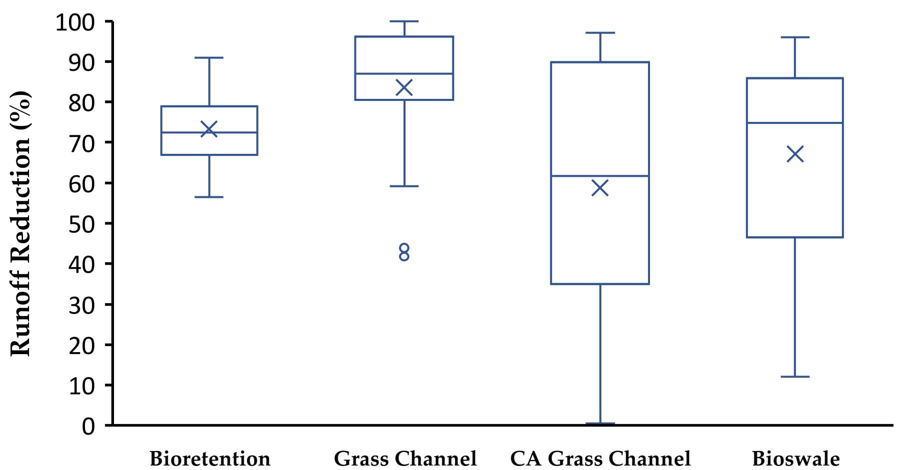

Figure 2.4 Runoff reduction of 24 monitored stormwater events since 2018 for four GI types. Boxplots depict median values (line in box), mean values (×), 25th to 75th percentiles (colored boxes), and outlier values (points).

Deicing salt is employed for every winter snow event by VDOT to ensure the safety of transportation. This increases the concentration of NaCl on Lorton Road. The inflow and outflow concentrations of chloride and sodium for the four monitored GI practices are presented in **Figure 2.5**. The highest inflow chloride concentration is 1056 mg/L for bioretention and 630 mg/L for swales. The highest inflow sodium concentration is 599 mg/L for bioretention and 266 mg/L for swales. The bioretention mean inlet chloride concentration is 123 mg/L (24 sampled events), and the swales' mean inlet chloride concentration is 99 mg/L for GC (22 sampled events) and 96 mg/L CAGC (23 sampled events), and 93 mg/L for BS (24 sampled events). The bioretention mean outlet chloride concentration is 142 mg/L, and the swales' mean outlet chloride concentrations are 22 mg/L, 96 mg/L, and 192 mg/L for GC, CAGC, and BS, respectively.

The mean inlet sodium concentration for bioretention is 78 mg/L (24 sampled events), and the swales' mean inlet sodium concentration is 45 mg/L,44 mg/L, and 40 mg/L for GC (18 sampled events), CAGC (19 sampled events), and BS (23 sampled events), respectively. The bioretention mean outlet sodium concentration is 126 mg/L, and the swales' mean out sodium concentrations are 14 mg/L, 66 mg/L, and 109 mg/L for GC, CAGC, and BS, respectively.

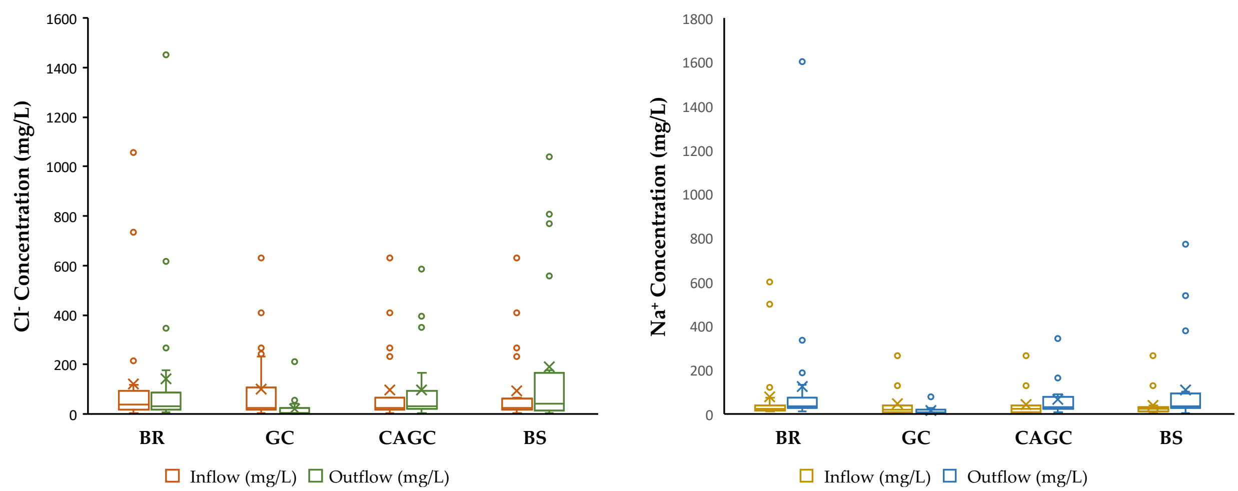

Figure 2.5 GI inlet and outlet concentrations for monitored events. Left: chloride, and right: sodium. Outlet concentrations for the bioretention are from the underdrain outlet. **(**BR: bioretention, GC: grass channel, CAGC: compost-amended grass channel, BS: Bioswale)

Pollutant mass load reduction is used to evaluate and compare the performance of GI practices, since a GI system may show high pollutant load reduction, even with a higher outflow concentration when runoff volume reduction is high during the events. **Figure 2.6** indicates the overall mass load reduction for five water quality parameters (chloride, sodium, calcium, copper, and lead) during monitored storm events, which shows the monitored GI chloride load reduction ranges from 65% to 97%, sodium load reduction ranges from 30% to 95%, calcium load reduction ranges from -19% to 81%, copper load reduction ranges from 44% to 90%, and lead load reduction, between 64% and 85%.

In general, GI systems performed well in monitoring improvements in stormwater flow and water quality along Lorton Road. Compost-amended grass channel and bioswale have negative results for calcium, which potentially are attributed to the compost material applied to the channel, providing the water quality parameter for export.

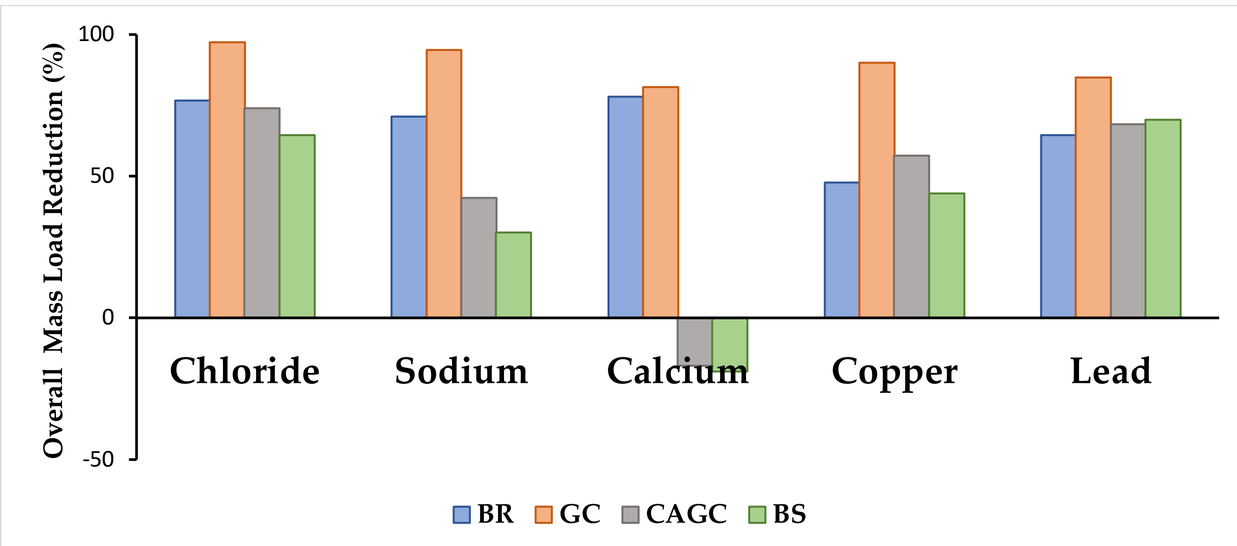

Figure 2.6 Overall mass load reduction for monitored pollutants for four types of GI practices. (BR: bioretention, GC: grass channel, CAGC: compost-amended grass channel, BS: Bioswale)

The mean mass load reduction as water quality performance of four monitored GI practices for monitored storm events is presented in **Figure 2.7**. The mean chloride load reduction ranges from 38% to 96%, sodium load reduction ranges from 18% to 93%, calcium mean load reductions are between -41% and 79%, copper mean load reduction ranges from -46% to 77% and lead load ruction between 39% and 72%.

The performance of BR and GC for all pollutants indicates considerably more consistency than the CAGC and BS. The GC always has the highest load reduction for all the monitored pollutant parameters, compared with others, and the bioretention has the second highest reduction, but the bioretention could treat more runoff than GC for each storm event because of its biggest contributing drainage area. Additionally, the mean calcium and copper reductions of BS and the performance of CAGC in calcium treatment experience a pronounced decline and negative reduction, compared with other monitored GI practices. The compost in CAGC and engineering soil media or design in BS are found to be potentially causing the low reduction of pollutants. In this study, results indicate that more complex GI designs don't necessarily mean better performance on stormwater treatment, compared to simple GI, and that slight differences in design or construction martial (e.g., compost amendment, and engineering soil media) may significantly modify or even decrease GI performance.

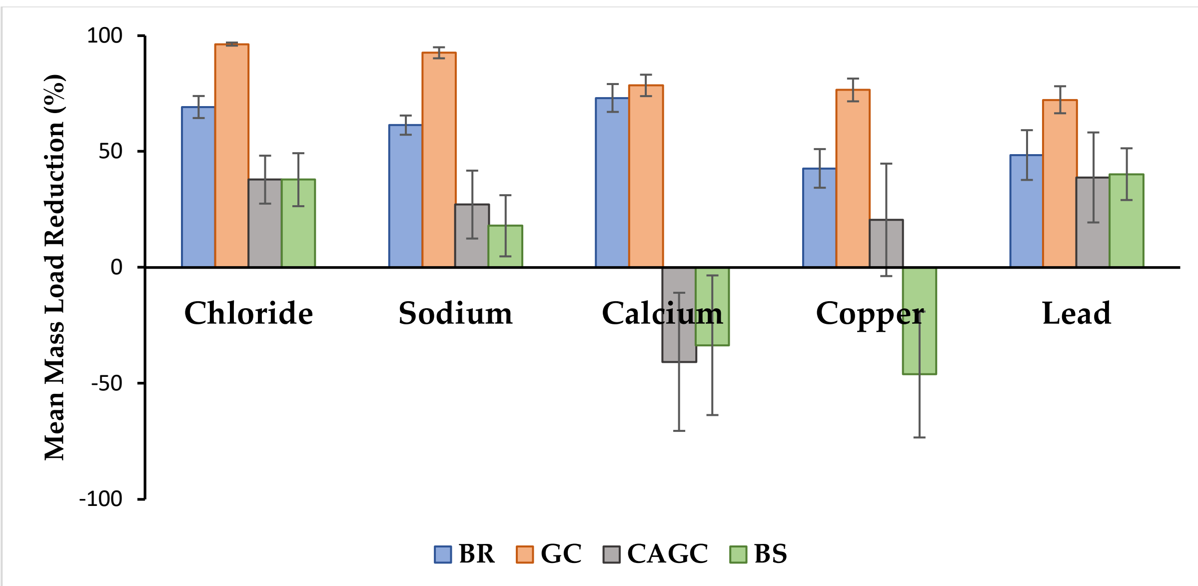

Figure 2.7 Mean mass load reduction for monitored pollutants for four types of GI practices. (BR: bioretention, GC: grass channel, CAGC: compost-amended grass channel, BS: Bioswale)

2.4 Conclusion

In this study, stormwater quantity and quality performance of four types of GI practices that received the same storm event conditions over five years are compared and analyzed. Approximately 60 storm events have been monitored and sampled during these multiple years, and 24 relatively complete storms of them are selected for comparison and evaluation. The performance of different GI designs ranges variously, some acting as pollutant sinks, while others as pollutant sources for some pollutant parameters. Grass channel, the simplest-design swale, performed best on both runoff and pollutant load reductions, but it serves a relatively small contributing drainage area, while the bioretention, which has the second highest volume and mass load reduction for pollutants, serves the biggest contributing drainage area and its performance is considerably more consistent than other types of GI systems monitored. Results also indicate that more complex GI designs don't necessarily mean better performance in stormwater treatment, compared to simple GI, and that slight differences in design or construction martial (e.g., compost amendment, and engineering soil media) may significantly change the GI performance. A series of performance trends of monitored GI designs over time will be included in the forthcoming manuscript for this chapter.

Supplementary Data: Appendix A

2.5 References

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Chapter 3: The Potential of Vegetation to Mitigate Deicing Salt Loading in Green Infrastructure System

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3.1 Introduction

Sudden discharges of stormwater have become a leading threat to aquatic ecosystems [1,2], creating water pollution, soil erosion, flooding, and combined sewer overflows into receiving waters [3,4]. Land-use modifications with urbanization, including removal of vegetation and increasing impervious surfaces, are changing how water flows in urban landscapes and lead to stormwater runoff risks, such as decreasing waterbody health, impairing aquatic habitats, and contributing to nonpoint source pollution [5–7].

The use of deicing salts in winter on highways represents one of a number of different sources of associated salt ions released into receiving waters, others being commercial parking lots, sidewalks, and residential application [8,9]. Chloride-based salts are used worldwide for deicing purposes, and sodium chloride (NaCl) is most commonly employed in North America [10,11]. In the winter of 2018, the estimated amount of deicing salt used in the U.S. for highways was 25 million metric tons [12]. Na^+ and Cl^- ions can easily travel with stormwater runoff from impervious surfaces to plants, receiving waters and soil, which stresses plants and animals, as it impacts water quality [8]. Chloride from deicing salt can be stored in shallow groundwater in winter and released into surface water bodies slowly [13,14], contributing to the impairment of the aquatic life and health of waterbodies with time [15,16]. Cl^- is a relatively conservative constituent and its U.S. EPA acute and chronic freshwater aquatic life ambient water quality criteria are 860 mg/L and 230 mg/L, respectively.

The effects of urbanization and climate change on freshwater ecology have increased the demand for new stormwater management techniques to alleviate hydrologic impact and water quality problems due to urbanization. Roadside stormwater management systems are also being employed to mitigate the potential effects of highway runoff on receiving waters [17]. Conventional stormwater management techniques tend to use curb–gutter–pipe networks to delay the adverse impacts of high-volume stormwater, without treatment [1]. Green infrastructure (GI), also known as green stormwater infrastructure (GSI) or low-impact development (LID), could mimic natural landscape hydrology by slowing, spreading, and infiltrating stormwater runoff before discharging it into receiving waters [8]. Different from gray infrastructure, GI uses vegetation, soils, and other natural landscape features to manage wet weather impacts, reduce and treat stormwater at its source, and create sustainable and healthy communities in a cost-effective and sustainable way [5]. With rapid urbanization in the last few decades, GI has become an effective design in protecting waterways from various detrimental effects of urban stormwater through reducing flow volume and improving water quality[18].

A typical GI stormwater management technique is a bioretention (BR) system, which has received increasing interest for its performance in mitigating runoff risks in recent years [19–21]. A BR consists of a soil bed planted with suitable (preferably native) vegetation to control the quality, quantity, and flow rates of stormwater runoff in urban areas [22]. Stormwater runoff entering the BR system is filtered into an underlying layer of engineered soil media before being either conveyed downstream by an underdrain system or infiltrated into the existing subsoil below the soil bed. Infiltration through the engineered soil media provides uptake of pollutants and runoff through physical, chemical, and biological means. A BR design with an underdrain is known as a BR filter, which could achieve moderate to high levels of runoff and peak flow reduction through infiltration, evaporation, and storage, which further decrease pollutant load transport to receiving waters [23,24]. Plants are introduced for pollutant reduction and soil stability in BR [25]. Previous studies indicate that plants in BR systems maintain soil porosity and contribute to the removal of nutrients, metals, total suspended solids, and some other pollutants [26,27]. However, very few experimental studies exist exploring the potential of vegetation in BR to attenuate the transport of deicing salt (NaCl), which is a threat to aquatic ecosystems along highways in urban areas during winter. Some vegetation types, such as Broadleaf Cattail, can survive in brackish soil water and can store large amounts of salt. This kind of plant could be employed to treat road runoff containing deicing salts before it flows into receiving water [28]. Burgis et al. (2020) monitored the fate and transport of deicing salt through an operational infiltration-based GI systems in Northern Virginia, finding that infiltration GI has the ability to buffer surface waters from salt, but the primary mechanism for doing so was salt transfer from surface water to groundwater, with legacy environmental consequences. That study suggested that vegetation may play a role in salt transport, but the authors were not able to directly determine the contribution of vegetation on salt load reduction.

The purpose of this study is to quantify the flow reduction and salt mass reduction caused by vegetation and to explore the potential of vegetation in green infrastructure to mitigate deicing salt (NaCl). This is accomplished by conducting one-dimensional greenhouse-scale experiments with two plant types and associated controls. Experiments were performed using different salt loadings and multiple simulated storm events for each control and vegetation type. The hypotheses of this chapter are that transpiration by vegetation can reduce the load of deicing salt to groundwater and that the ability of different types of vegetation varies in improving the GI performance to reduce deicing salt.

3.2 Materials and Methods

Lorton Road in Fairfax County, Virginia is a part of the Giles Run watershed, within the Chesapeake Bay watershed. The Virginia Department of Transportation (VDOT) expanded it from an approximately 4 km two-lane undivided road to a four-lane divided road with an average daily traffic volume of 100,000 vehicles/day [29,30]. Fairfax County funded the design and construction for 47 different GI systems to manage the additional stormwater runoff in the spring of 2017. A bioretention basin (BR) was selected and monitored for this study along this road. It is in the north of Lorton Road, consisting of a pretreatment forebay and a basin for treatment connected by a 0.6 m concrete culvert through an earthen berm (approximately 1.5 m in height and 5 m in width) (**Figure 3.1**). The vegetation in the basin was planted as “plugs” instead of seeds. Concentrated stormwater from Lorton Road flows into the bioretention via curb and gutter sewers. The outflow from the bioretention basin after treatment flows into the Giles Run watershed, within the Chesapeake Bay watershed. Stormwater travels into the forebay for pretreatment before flowing into the basin (**Figure 3.2**). For storm events larger than design size, a channel in the forebay allows overflow stormwater to the bypass, which is connected to the forebay. The design specifications, monitoring station characteristics, and plant species of the bioretention design are given in **Table B1**. Inflow, bypass flow, and outflow were monitored using solar-powered programmable samplers for stormwater runoff and H-flumes with ultrasonic sensors to quantify discharge of the runoff at the field site described in Chapter 2. All of the three monitoring locations were used to calculate runoff and salt load reductions (load reduction = (inlet−outlet−bypass)/ inlet). **Appendix B Figure B1** indicates the annual precipitation information from the Washington Reagan National Airport Weather Station in Northern Virginia (nearby Lorton Road) between 2011 and 2021[31].

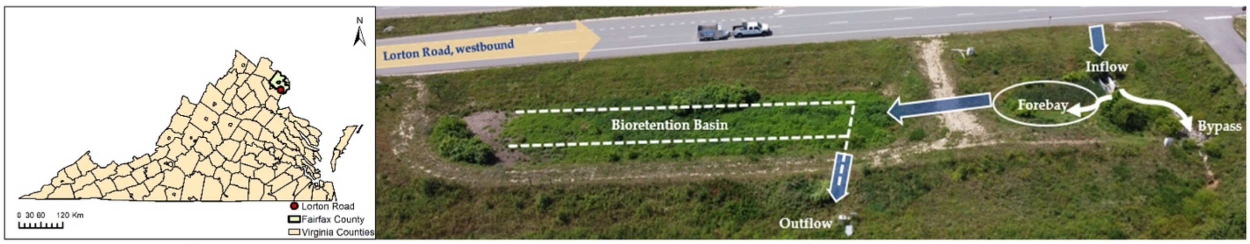

Figure 3.1 Lorton Road bioretention research site and positioning: (**a**) Map of the analyzed bioretention location (created with ArcGIS). (**b**) Aerial image of bioretention with piped/culvert flow represented by blue arrows, surface flow represented by solid white arrows, and perforated underdrain represented by dotted lines (images by authors).

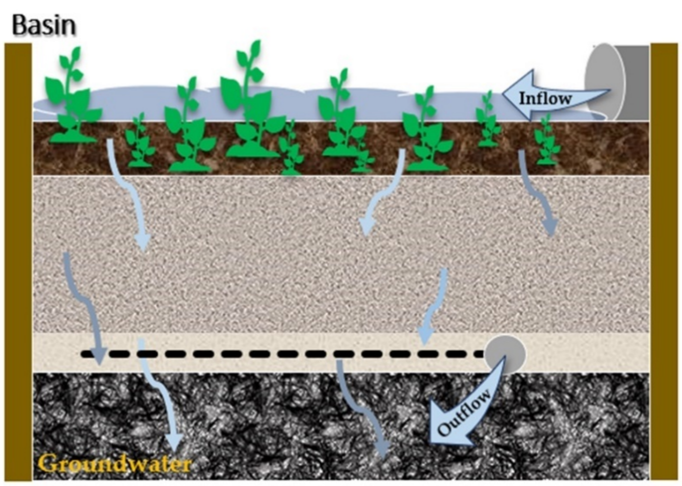

Figure 3.2 Bioretention basin design schematic (created with Microsoft PowerPoint).

Automated stormwater monitoring equipment was installed to measure flow rate and volume. Sampling work started in March of 2018 in the BR, and more than 30 storm events were monitored by 2021. Flow-weighted composite stormwater samples were collected for each storm event for lab analysis by autosamplers. Concentrations of collected samples were used as event mean concentrations (EMCs) for each monitoring station. Ion loads through each monitoring location were determined by multiplying EMC values by total stormwater volume [8]. The cumulative Cl^- surface water effluent load reduction in the BR was 80% and Na^+ effluent load reduction was 82%, as described by Burgis et al. (2020).

The BR basin was simulated in proportion for depth using six engineered soil media columns in the greenhouse laboratory with constant illumination (approximately 16 h for daytime and 8 h for nighttime) and climate (approximately 24 °C during daytime and 20 °C during nighttime). The variability of weather outside the greenhouse at times influenced the internal greenhouse temperature, leading to slight deviations from the set temperatures. The depth of subsurface layers in the field is 1.37 times the column depth. Each column is 0.2 m^2 in surface area, 0.5 m in diameter, and 0.97 m in depth (**Figure 3.3**). They consist of cylindrical plastic containers filled with engineered soil media and drainage gravel of similar specifications to what is used at the Lorton Road bioretention. The columns contain 11.1 cm ponding depths, 55.6 cm of engineered soil media (ESM) (3.2% clay, 5.6% silt, 91.2% sand) on top of 29.7 cm of underlying gravel (7.4 cm VDOT #8 stone with the outlet and 22.3 cm VDOT #57 stone). The ESM was purchased from "Quail Ridge Products" in Fredericksburg, VA, and all of the gravel was triple washed with tap water before installation. Two of the columns had no vegetation (Blank) as control samples, two had native BR vegetation, established Blue Wild Indigo (BWI), to explore the ability of native plants in the BR basin for reducing the loading of deicing salt in the field, and another two columns had salt-tolerant vegetation, Broadleaf Cattail (BC), which is not in the BR basin (**Figure 3.4**), so that each Blank, BWI, and BC had a duplicate column to compare. All of the plants were planted with optimum density of 20 plugs per square meter based on field observation to insure satisfactory growth.

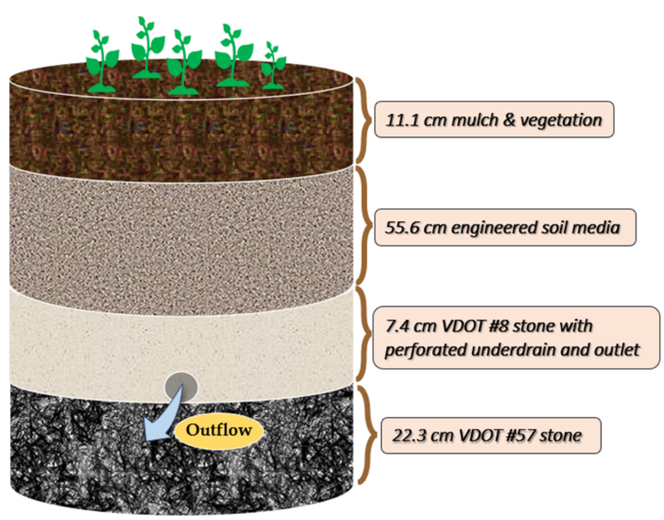

Figure 3.3 Engineered soil media column schematic in laboratory.

Figure 3.4 Six soil columns in laboratory.

Synthetic stormwater, with sodium chloride concentrations matched with observed field samples, was filtered through each soil column at a constant rate and sampled at the outlet at the bottom of each column. Synthetic stormwater was sprayed by the irrigation system into soil columns, and the discharge rate for each column was consistent and designed based on the observed field rain data in proportion. Composite outflow samples were collected in 118 mL Nasco Whirl-Pak™ Stand-Up Sample Bags at column outlets for analysis during every storm event, and then the overflow water from sample bags traveled into buckets for volume measurement.

For each column, five storm events sizes were simulated at three deicing salt (NaCl) concentration ranges. Concentration ranges (low, medium, and high) were selected based on observed field concentrations reported previously by Burgis et al. (2020). Samples of these 15 synthetic stormwater events before and after column filtration was analyzed for chloride by ion chromatography and for sodium using inductively coupled plasma mass spectrometry. The specifications and characteristics for field rain and flow data used to inform the greenhouse column experiments are given in **Table B2**. The design specifications and other characteristics of the soil columns and synthetic storm events are included in **Table B3**.

According to the observed field data in the BR at Lorton Road, the Cl^- and Na^+ concentrations of representative storm events before winter were fewer than 40 ppm, which was set as the low-level deicing salt concentration. Ion concentrations were between 40 ppm and 200 ppm for the first few light snow events during one year, which was set as the medium-level of deicing salt concentration. The highest level of deicing salt concentration could reach up to approximately 2000 ppm in the coldest climate during the winter. The specific concentration and proportion for Cl^- and Na^+ of each inflow concentration level were designed based on the approximate average concentration of the field data in the same range, and other synthetic stormwater specifications were designed based on observed field rain data, which are given in **Table B3**.

Tap water served as a base to generate the synthetic stormwater used for testing. Before each storm event, tap water was stored in tanks and air was bubbled through the water to remove chlorine from the tap water. Due to the variety of experiments, the inflow concentration for each storm was measured as the real inflow concentration (**Table B3**). Water samples were collected as they flowed in and out of each column and volumes of inflow and outflow for each storm event were recorded. Composite outflow samples were collected in sample bags at column outlets for analysis during every storm event, and then the overflow water from sample bags traveled into buckets for volume measurement. Sample bags were new for each storm event and all of the buckets were cleaned between storms. Laboratory blanks were taken to ensure no salt cross-contamination occurred before sampling events. Concentrations of inlet and outlet samples were used as event mean concentrations (EMCs) for each monitoring container. Ion loads through each outlet point were determined by multiplying EMC values by total stormwater inflow or outflow volume over the monitoring period.

Collected water samples were filtered using syringes filters (0.45 μm polytetrafluoroethylene (PTFE)) and analyzed for sodium and chloride ions. All of the analyses included synthetic stormwater samples and column blanks. When a sample had an ion concentration higher than the upper range of calibration, they were diluted and re-run within the calibration range. Volume reductions were calculated using Equation (3.1) and total mass load reductions of deicing salt were calculated using Equation (3.2).

$$VLR = \frac{(Inlet - Outlet)}{Inlet} * 100 \qquad (3.1)$$

In Equation (3.1), VLR = volume load reduction, Inlet = inflow volume (L), and Outlet = outflow volume (L).

$$MLR = \frac{(Con_{In} * Inlet - Con_{out} * Outlet)}{Con_{In} * Inlet} * 100 \qquad (3.2)$$

In Equation (3.2), MLR = mass load reduction, Con_{In} = chemical concentrations of inflow (mg/L), Inlet = inflow volume (L), Con_{out} = chemical concentrations of outflow (mg/L), and Outlet = outflow volume (L).

Before planting vegetation and beginning synthetic stormwater experiments, blank samples for each established column were collected using tap water as inflow to test whether all of the columns had similar nondetectable levels of sodium and chloride ions in the effluent. Blank samples were analyzed, and they are all below designed lowest inflow deicing salt concentrations (**Figure 3.5**), which indicated that all of the six columns were in satisfactory condition to begin the experiments.

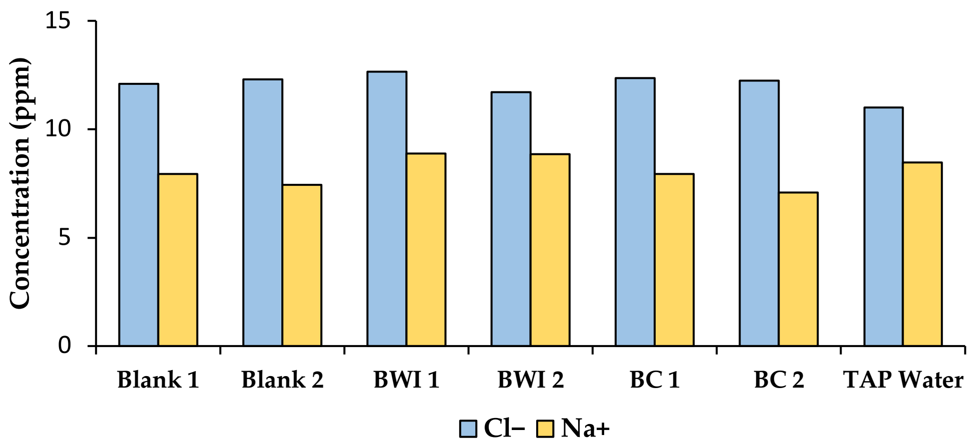

Figure 3.5 Concentration of sodium and chloride ions in tap water for all columns prior to the introduction of plants (blank: no plants; BWI: Blue Wild Indigo; BC: Broadleaf Cattail).

Statistical analysis was performed using the software R (version 4.0.3). An analysis of variance (ANOVA) was used to assess the effect of greenhouse columns and salt levels on Cl^- and Na^+ load reductions. Data normality was confirmed using the Shapiro-Wilk test. The criteria of 95% confidence (significance level, $\alpha = 0.05$) was used for all tests. Tukey's range test, a multiple comparison test, was conducted to determine significant differences between experimental column groups.

3.3 Results

Water quality and quantity data of inflow and outflow for each stormwater event are given in **Tables B4–6**. Three levels of inflow concentrations were used (low, medium, and high). The mean low-concentration inflow solution had Cl^- and Na^+ concentrations of 33.0 mg/L and

23.6 mg/L. The mean medium inflow solution had Cl^- and Na^+ concentrations of 154.0 mg/L and 71.3 mg/L, respectively. The mean high-concentration inflow solution had Cl^- and Na^+ concentrations of 1751.9 mg/L and 649.0 mg/L, respectively.

For flow reduction experiments, the effluent volume of water from the control columns was compared with the effluent volume from the plant columns. In this way, we were able to separate the effects of flow reduction caused by pore filling and evaporation with flow reduction caused by plant transpiration. The water quantity results indicate all three types of columns reduce flow volumes during the experiments. The mean volume reductions for all 15 synthetic storms for each type of column are 11.4% for blank, 21.4% for BWI, and 41.9% for BC, respectively (**Figure 3.6**). BC showed a significantly higher volume reduction than the blank columns ($p = 0.011$).

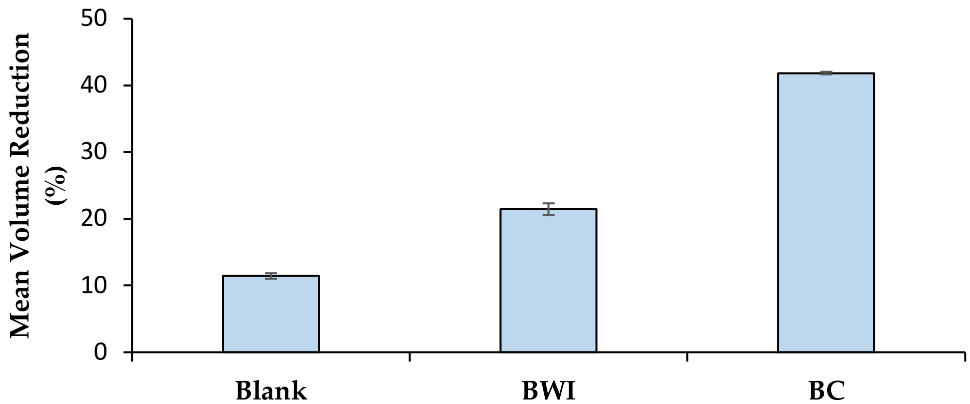

Figure 3.6 Mean volume reduction for all storm events and salt concentration for each column type. Error bars indicate standard error of duplicate measurements (blank: no plants; BWI: Blue Wild Indigo; BC: Broadleaf Cattail).

The mean mass load reductions for all 15 synthetic storm events for both Cl^- and Na^+ were calculated for each of the three types of columns. The results indicate the Cl^- mean mass load reductions are 26.1% for blank, 30.1% for BWI, and 33.5% for BC, respectively, and the mean mass load reductions for Na^+ are 38.2% for blank, 41.7% for BWI, and 47.4% for BC, respectively (**Figure 3.7**).

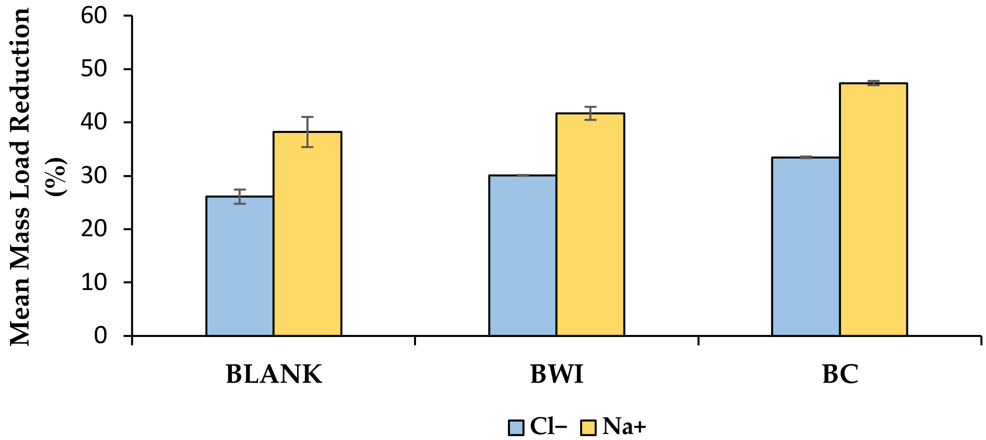

Figure 3.7 Mean mass load reduction for all storm events and salt concentrations for each column type. Error bars indicate standard error of duplicate measurements (blank: no plants; BWI: Blue Wild Indigo; BC: Broadleaf Cattail).

For both volume and mass load reduction, the addition of plants to the columns improved system performance, and BC performed better than BWI (**Figures 3.6 and 3.7**).

Figure 3.8 presents flow-volume reductions for each column type and each deicing salt concentration. The volume reduction ranges from 7.9% to 21.0% for low-level deicing salt concentrations, 14.8% to 73.6% for medium-level deicing salt concentrations, and 11.6% to 31.1% for high-concentration deicing salt concentrations. For the low- and high-concentration levels, each type of column had similar volume reductions, and BC had a larger volume reduction than BWI and blank. BWI performed better than blank for each concentration level, which is consistent with the result of the overall total volume reduction above.

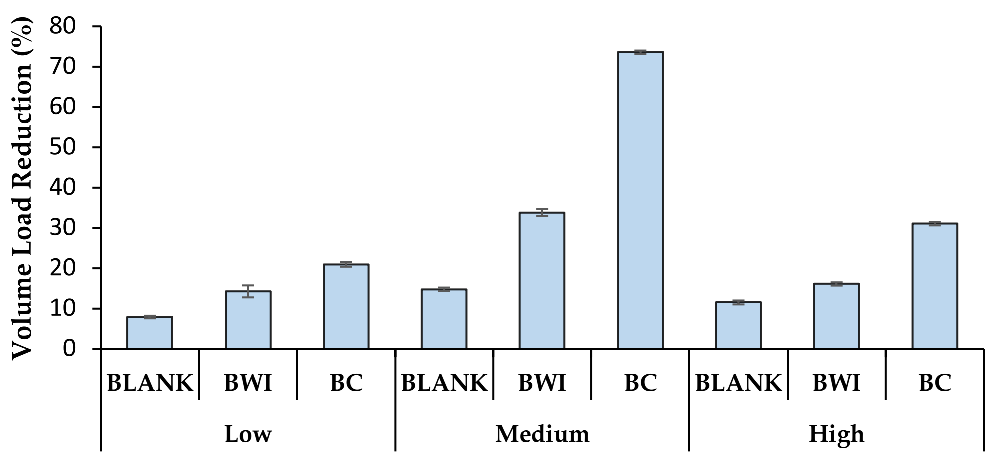

Figure 3.8 Volume reduction for different levels of deicing salt inflow concentration (blank: no plants; BWI: Blue Wild Indigo; BC: Broadleaf Cattail).

Figure 3.9 indicates the mass load reduction for Cl^- ranges from 11.3% to 42.5% for the low-level deicing salt concentrations, 34.5% to 71.2% for the medium-level deicing salt concentrations, and 25.7% to 30.2% for the high-concentration level. The Na^+ mass load reduction ranges from 39.2% to 52.1% for the low-level deicing salt concentrations, 48.8% to 74.3% for the medium-level deicing salt concentrations, and 37.1% to 44.5% for the high-concentration level. For each influent salt concentration, BC and BWI performed better than the blank, and BC performed the best overall. It also indicates that the overall salt removal ability was the best for the medium-concentration level, and worse for high-level salt concentrations. The mass load reductions were similar for all three types of vegetation at the high-level salt concentrations.

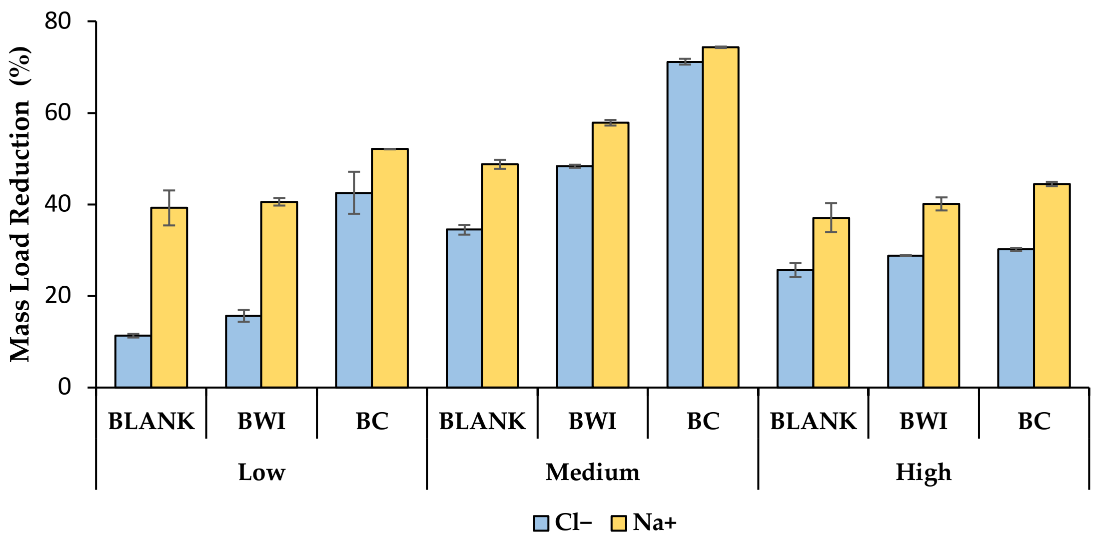

Figure 3.9 Mass load reduction for different inflow salt concentrations (blank: no plants; BWI: Blue Wild Indigo; BC: Broadleaf Cattail).

The mass load reduction trends for ions are shown in **Figure 3.10** for each inflow concentration level. The water quality load reduction for both Cl^- and Na^+ decreased over multiple synthetic storm events. The performance of BC generally was better than BWI and blank, and the ability of BR with vegetation to reduce deicing salt was always better than BR without vegetation.

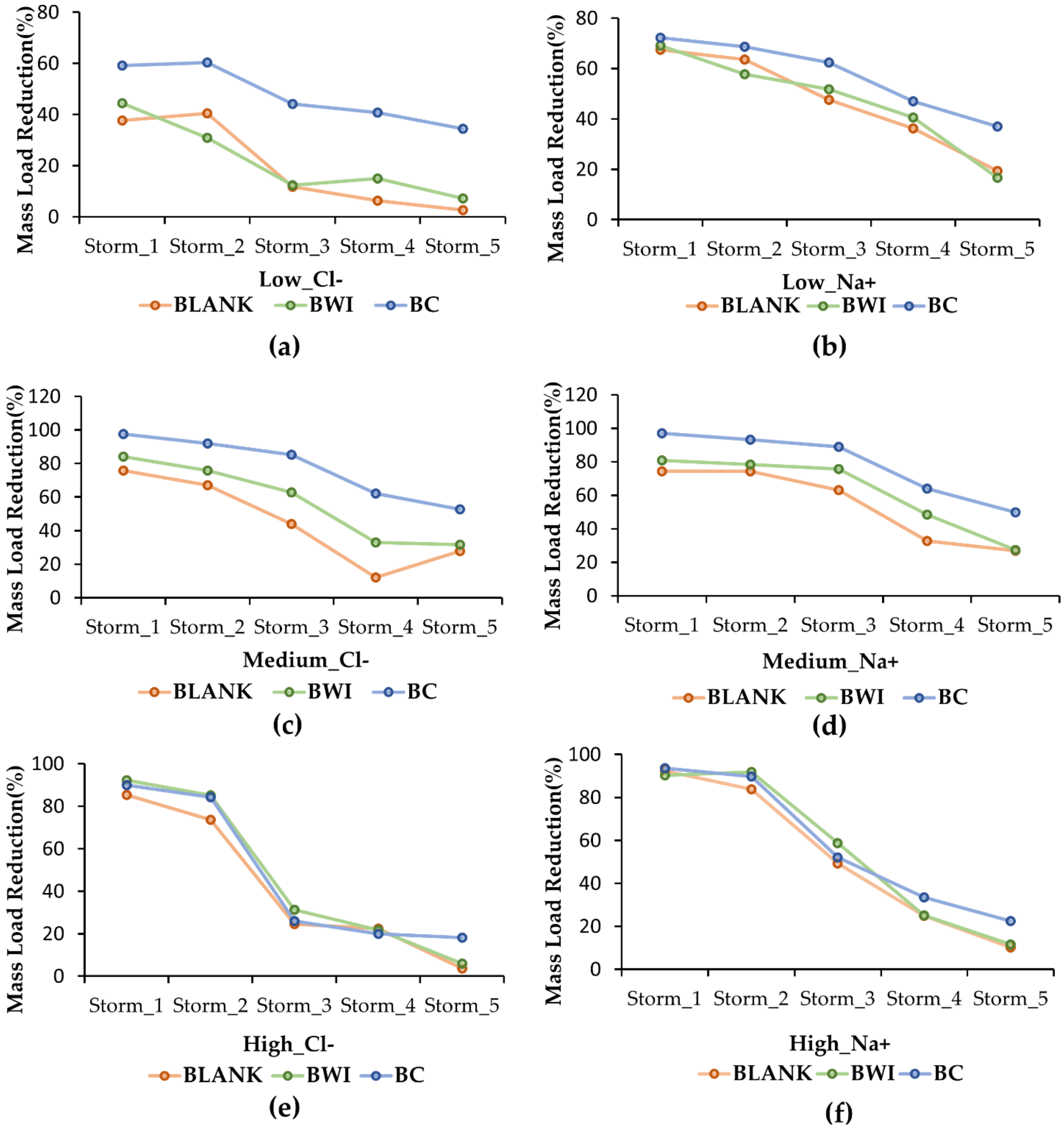

Figure 3.10 Mass load reduction trends for chloride and sodium ions for each of five storms. The flow volumes for each storm are given in **Appendix B** and are based on loadings observed at the Lorton Road BR field site (blank: no plants; BWI: Blue Wild Indigo; BC: Broadleaf Cattail). (a)–(f) depict different Cl^- or Na^+ concentrations.

3.4 Discussion

Vegetated columns generally performed better than non-vegetated columns for salt load and flow reduction. Relative to the blank columns, BWI increased Cl^- and Na^+ load reductions by 4% and 3.5%, respectively, while BC increased Cl^- and Na^+ load reductions by 7.4% and 9.2%, respectively. Overall, while both BWI and BC had higher Cl^- and Na^+ load reductions relative to blank columns (**Figure 3.7**), only BC columns had statistically ($p = 0.037$) higher Cl^- load reduction than blank columns. However, both types of vegetation showed significant increases in Cl^- load reduction with medium inlet salt levels relative to blank columns ($p = 0.047$ for BWI and $p = 0.000045$ for BC). BC also had significantly ($p = 0.00017$) higher Cl^- load reduction than blank for low salt concentrations, but neither vegetation types significantly increased Cl^- load reduction for high inlet salt loads (**Figure 3.9**). Since plants are typically dormant in the winter when salt is applied, they likely have lower load reduction potential at that time. Vegetation may be best used to uptake residual stormwater salt in the spring, summer, and fall seasons. Salt-tolerant plants may also be used to remediate GI soils from salt build up in the warmer seasons of the year.

This experiment was conducted in a heated greenhouse (an ideal environment for vegetation) and infield vegetation performance may be different. However, the results indicate a "best case potential" for vegetation salt uptake. Future greenhouse soil column experiments should consider varying temperature to determine the effects of seasonal temperature change on plant performance. Due to limitations in the greenhouse experimental setup, infiltration of stormwater beneath the columns was not simulated in the experimental columns. Burgis et al. (2020) reported infield bioretention annual load reductions of 80% and 82% for Cl^- and Na^+, respectively, and estimated that the majority of reduced salt in bioretention ends up in groundwater. If infiltration was simulated in the greenhouse columns, stormwater volume reduction and overall salt load reduction would be higher in all experimental scenarios. The limited improvement in Cl^- and Na^+ reduction performance of the native BWI vegetation relative to the blank columns under the favorable greenhouse conditions of this experiment supports the conclusion of Burgis et al. (2020) that the majority of infield bioretention-reduced deicing salt ends up infiltrating into groundwater.

BWI and BC both outperformed the blank (unvegetated) columns in terms of overall salt load reduction, and the BC outperformed the BWI columns (**Figure 3.7**). The BC columns had higher stormwater volume reduction than the BWI and blank columns in all scenarios (**Figure 3.8**), implying that the BC's salt removal mechanism is driven by elevated water volume uptake. The BC in this experiment were larger biomass plants (approximately 1.5 m tall) and known to have high water use [32]. The BWI are smaller biomass plants (approximately 0.3 m tall) and known to have medium water use. While the BWI columns displayed lower volume reduction than the BC, they typically had lower outlet Cl^- and Na+ concentrations than BC columns for medium and high salt events (**Tables B5 and B6**). BWI is commonly used in bioretention and BC is known to be a salt-tolerant plant [28]. The results confirm that they can withstand elevated wintertime salt concentrations similar to infield levels.

Vegetation health was not directly measured in this study, but all plants survived during the 15 storm experiments. With the inflow concentration increasing to more than 1500 ppm for Cl^- and 500 ppm for Na^+, both the BWI and BC plants were observed to have slower growth rates and displayed some visible damage. Limited plant growth under high salt concentrations may have contributed to lower salt load reduction performance of the planted columns.

The low-level salt inlet concentrations were similar to background levels exiting the columns. The high-level inlet salt concentrations appeared to saturate the soil and plants, as indicated by the sharp reduction in performance after the first two storms (**Figure 3.10e, f**). The highest load reduction was observed for the intermediate salt concentration level for all columns. One possible explanation for this observation is the season. These experiments were performed during the summer season, compared with the low-salt (before summer) and high-salt (after summer) inflow concentration experiments. These conditions likely led to faster growth of the plants and more transpiration, which in turn led to greater salt uptake. Another possibility is that residual salt from the medium salt concentration experiment affected the column's salt reduction ability for the high salt concentration storms.

The results on a storm-by-storm basis (**Figure 3.10**) indicate that salt reduction performance decreases with each subsequent storm and at increasing rates for the highest salt inlet concentration scenario. This observation may be due to prior salt stored in columns from previous storms exhausting the salt storage potential for later storms. The experimental columns have internal water storage capacity in soil and gravel pore space, and stored water could be flushed out by subsequent storms, releasing more salt than the first storm. These results are in agreement with field observations by Burgis et al. (2020), where bioretention was observed to initially have higher salt load reductions following the first salt application of a season and then lower reductions for subsequent runoff events as stored salty water was flushed out of the system. These data indicate that bioretention systems, with and without vegetation, have a temporary salt-holding capacity.

Na^+ reductions of these three types of BR with different plant conditions were consistently higher than Cl^- across all experimental columns (**Figure 3.9**), suggesting cation exchange of Na^+ with other soil cations (Ca^{2+}, Mg^{2+}, K^+). Eventually, all the exchange sites will be saturated by sodium ions, and they will not be removed by that mechanism. Due to its negative charge, Cl^- is less reactive with soil particles that typically have a negative surface charge.

3.5 Conclusion

As shown in this research, BR has been confirmed to have beneficial effects on reducing deicing salt from highway stormwater runoff, and vegetation has shown the potential in improving load reduction. Specific conclusions on performance in this research are summarized below:

- The potential of vegetation to mitigate deicing salt loading in BR for all inflow salt concentration levels is BC > BWI > blank.
- Vegetated columns reduced stormwater volume loading for all experimental salt levels in the order: BC > BWI > blank.
- The highest salt removal of all columns was observed for the intermediate salt concentration inflow.
- For all columns, the best salt load reduction was observed for the first storm event, with performance decreasing with repeated salt loadings.
- Additional study is encouraged to simulate the bioretention and explore the potential of vegetation in green infrastructure to mitigate deicing salt (NaCl) under winter conditions. It is also recommended to study the mitigation of other kinds of salt ions (e.g., K^+, SO_4^{2-}) to water resources by green infrastructure.

Supplementary Data: Appendix B

3.6 References

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Chapter 4: Evaluation of Maintenance Efficiency for Multiple Green Infrastructure Designs Based on Water-quality Performance and Economic Costs

One publication for this study has been created and is ready for submission.

- **Zhang, W.**, Burgis, C.R., Hayes, G.M., Henderson, D.A., Smith, J.A. (2023) "Evaluation of maintenance efficiency for multiple green infrastructure designs based on water-quality performance and economic costs" (manuscript in preparation)

4.1 Introduction

The sudden release of stormwater from urban areas can lead to flooding and carry pollutants such as trash, heavy metals, and other contaminants into nearby water sources, which can have a detrimental effect on ecosystems and human health[1–3]. The increase of impervious surface caused by urbanization results in changes in the natural flow of stormwater runoff and contributes to non-point source pollution and damage[4,5]. To ensure the preservation of public health and the environment, effective stormwater management is crucial to reducing runoff and associated pollutants[2].

Traditional stormwater management techniques, like gray infrastructure practices, which is a system of pipes, gutters, and tunnels, used to be installed to move stormwater runoff away directly from communities to local surface waters without any treatment, and its capacity to manage large runoff volumes and address multiple environmental challenges at the same time is limited[3]. Thus, improvements are needed in existing stormwater management methods to control flows and protect water resources[6].

Green infrastructure (GI), also known as green stormwater infrastructure (GSI), or low impact development (LID), is an improved, and economical approach using natural features to capture, retain, treat, and release runoff, resulting in reducing the amount of runoff entering the receiving waters and protecting water quality[4,7]. It can potentially provide a wide range of benefits to ecosystems and society. GI systems have gained significant attention and have been employed as an environmentally sustainable alternative to traditional gray infrastructure practices in the United States in recent years[8]. There have been numerous popular types of GI designs, such as green roofs, bioretention (BR), and swales, installed to treat stormwater in the U.S. since the late 1990s in the hope of mitigating the impervious surface hydrology effects. Previous studies have documented that GI practices worked effectively in stormwater runoff reduction and water quality enhancement[9]. Liu et al. (2015) evaluated multiple GI designs in the Crooked Creek watershed. They found that GI practices could potentially reduce runoff volume by 26.5%, total phosphorus (TP) by 47.4%, total nitrogen (TN) by 34.2%, and total suspended solids (TSS) by 53.6%[10]. Another study found the cumulative Cl^- surface water effluent load reduction in a BR in Northern Virginia was 80%, and Na^+ effluent load reduction was 82%, as described by Burgis et al. (2020), which indicated GI practice is a significantly effective strategy employed on stormwater management for more than one water quality pollutant parameters.

As GI systems become more prevalent, their maintenance has become an increasingly critical topic to ensure the water quantity and quality performance and sustainability of the GI designs over time[11,12]. If GI practices are maintained properly, they can continue to benefit communities and ecosystems for many years. Several previous studies have indicated that it is important to assess the effects of GI maintenance on the performance[13–15]. Proper construction and subsequent maintenance have significant implications on the long-term functioning of GI practices[16]. Previous studies have also indicated that inadequate maintenance for individual GI practice could lead to reduced facility performance and longevity[13,17]. However, the comparison of efficiency for maintenance activities of different types of GI practices based on water-quality performance and economic costs at the same location has not been documented significantly and effectively.

The objective of this research is to evaluate the cost-effectiveness of multiple green infrastructure systems at the same location by comparing their maintenance expenses and environmental benefits in terms of water quantity and quality performance. Four types of GI practices (bioretention, grass channel, compost-amended grass channel, and bioswale) receiving the same rain conditions along Lorton Road in Fairfax County, VA, USA, were selected to compare and evaluate in this study. Bi-annual maintenance (once in spring and once in fall) has been performed in the field from 2018 to 2022 to remove the trash, mow roadside grass slopes, remove debris, and add mulch to maintain its levels (where applicable) for the monitored GI systems. Stormwater quality performance among these four types of GI practices before and after seven selected in-field maintenance activities with a forebay restoration was assessed according to pollutant load reductions and flow reductions. The water quality parameters include dissolved organic carbon (DOC), total dissolved nitrogen (TDN), and total suspended solids (TSS), for the 14 storm events over four years. The hypotheses of this chapter are that maintenance practices can change GI performance and that the effects of maintenance events vary based on the seasons they're performed.

4.2 Materials and Methods

In this study, we considered four types of GI designs, which are the same as in the Chapter 2. These GI practices were installed by the Virginia Department of Transportation (VDOT). They are a bioretention (BR), a grass channel (GC), a compost-amended grass channel (CAGC), and a bioswale (BS). These GI practices are located along Lorton Road in Fairfax County, VA, USA, and are within 0.8 km of each other (as shown in **Figure 2.1**). They were selected based on specific characteristics such as climate, soil quality, watershed area, and expected pollutants. The design specifications and features of these four GI systems are presented in **Table 2.1**. Each GI system consists of a different design, receiving runoff directly from the road, rather than as the outflow from another GI practice. VDOT has performed normal maintenance activities for the monitored GI systems twice a year (once in spring and once in fall) since 2018 to keep systems in working order. In October 2021, a special restoration maintenance event was conducted to dredge the forebay in bioretention.

The constructions of the four GI designs were completed in the spring of 2017, and they were all designed for 1-year, 24-hr frequency storm events. Regular bi-annual maintenance activities (once in spring and once in fall), consisting of removing the trash, mowing roadside grass slopes, removing debris, and adding mulch to maintain its levels (where applicable), have been carried out by Apex Companies, LLC, hired by the Virginia Department of Transportation since 2018. The cost of each BR maintenance activity is $3000, including $2000 for labor costs, $500 for added mulch (up to 7.7 m^3), and $500 for trucks, fuel, equipment, and debris disposal. Each maintenance event for swales costs $491, with labor costs and equipment costs included. **Figure 4.1** (left) shows a maintenance event in the bioretention basin during the spring of 2021. Grass mowed was carried out by maintenance laborers.

An additional restoration maintenance event (**Figure 4.1** right) to remove unwanted vegetation and dredge soil and sediment from the BR forebay was conducted in October 2021. The soil and sand from the inlet of bioretention accumulated in the forebay over time and raised its elevation. This was in-part due to a construction project along Lorton Road, within the drainage area of the BR. This forebay restoration event costs $4,363 for labor, excavator, fuel, and materials (seed, EC matting). Maintenance activities aimed to ensure the sustainability of the GI systems and reduce stormwater runoff and associated pollutants.

From 2018 to 2022, eleven maintenance events (2 regular activities each year and 1 forebay restoration in 2021) have been completed for the four monitored GI practices in this study. Based on the stormwater sampling condition, eight events (7 regular events and the forebay restoration) were selected to analyze the efficiency. The seven studied regular maintenance happened in the 2018 fall (7/9/2018 to 7/10/2018), 2019 spring (3/25/2019 to 3/29/2019) and fall (10/18/2019), 2020 fall (9/30/2020 for bioretention, and 9/8/2020 to 9/9/2020 for swales), 2021 spring (4/29/2021) and fall (10/18/2021 for bioretention, and 9/16/2021 to 9/17/2021 for swales, and the spring of 2022 (4/8/2022 to 4/10/2022). The maintenance work happening in July 2018 is considered as the fall maintenance event in this study since it was the second maintenance event happening that year, following the first one that happened in March. The bioretention forebay restoration in 2021 happened at the same time as the regular maintenance activity for the 2021 fall season.

This research analyzed the impact of maintenance activities on stormwater quantity and quality by comparing performance before and after each selected maintenance event. Stormwater samples were collected at all seven monitoring sites as closely as possible to the maintenance dates to observe the direct effects caused by the maintenance work. This study focused on collecting samples during storm events within two months before or after the maintenance activities at most of the analyzed sampling events (**Table C1**). In this study, 14 stormwater event samples were obtained and analyzed over four years (6/2/2018, 8/31/2018; 3/21/2019, 6/18/2019;10/17/2019, 11/23/2019; 8/3/2020,12/4/2020; 4/1/2021, 5/28/2021;9/1/2021, 10/29/2021; 3/23/2022, 4/18/2022).

Table 4.1 Economic specifications for Lorton Road GI designs maintenance events. (CDA: contributing drainage area. The specific costs of each event on each site were given by Apex Companies, LLC.)

GI	Footprint (m^2)	CDA (m^2)	Cost per regular maintenance event ($)	Maintenance cost per Footprint area per year ($/$m^2$)	Maintenance cost per CDA area per year ($/$m^2$)	Forebay restoration ($)	Average total maintenance costs for GI per year ($) (including forebay restoration)
BR	1,012	47,753	3,000	7.01	0.15	4,363	7,091
GC	337	2,533	491	2.91	0.39	-	982
CAGC	891	6,874	491	1.10	0.14	-	982
BS	196	2,772	491	5.01	0.35	-	982

Figure 4.1 Maintenance event in Bioretention (Left: Regular maintenance activity in April 2021; Right: Forebay Restoration in Fall 2021)

Seven monitoring sites were set up in the field to track stormwater runoff quantity and quality parameters. Three are located in the bioretention (inflow, bypass, and outflow), and four are for swales (one inflow and three outflows) (**Figure 4.1**). Each site includes a Hach AS950 solar-powered programmable auto-sampler and an H or HS flume equipped with an ultrasonic sensor to measure the level and flowrate of the runoff and calculate the discharge of stormwater, as described by Hayes et al. (2021). Composite stormwater samples for each monitored storm were collected automatically into a 9.5-L glass bottle sitting in each auto-sampler for water quality analysis. The event mean concentrations (EMCs) of collected samples were used to represent the concentration of each monitoring station[4]. The total pollutant mass loads at each monitoring location were calculated as EMC × total storm volume. In bioretention, a Hach rain gauge connected to American Sigma 900 (Hach) obtained rain information every 10 minutes to represent the rain information of the four monitoring sites. When the rain gauge failed to work due to power off, we used the precipitation data collected by Weather Underground Station in Washington Reagan National Airport (nearby monitored location). In BR, all three monitoring locations were used to quantify runoff volume, and water quality pollutants load reductions (load reduction = (inlet − outlet − bypass)/inlet). In GC, CAGC, and BS, pollutants load reductions were calculated as (inlet − outlet)/inlet[1,19].

The performance of these four monitored GI designs was analyzed based on the pollutant load reductions, including dissolved organic carbon (DOC), total dissolved nitrogen (TDN), and total suspended solids (TSS) (US EPA, 2010). Stormwater composite samples were carried back from Northern Virginia to the water quality lab at the University of Virginia. Samples for DOC and TDN analysis were acidified to 2% HCl and filtered (0.45 µm PTFE) before being measured by a Shimadsu TOC-L with a coupled TNM-L analyzer. TSS was quantified through filtration using Whatman 1.5 µm glass microfiber and gravimetric determination based on USEPA method 160.2. Concentration, volume, and mass loads of these three water quality parameters were used to determine the relations between GI practices' performance and maintenance work. Based on the results, recommendations are made for future research on the optimal frequency and efficiency of maintenance procedures.

Statistical analysis was conducted using the software R (version 4.2.1). The Shapiro-Wilk test was used to determine data normality. Paired t-tests were used to calculate *p-values* for normally distributed data and the Wilcoxon signed rank test was used to calculate *p-values* for non-normally distributed data. A 95% confidence criterion (significance level, $\alpha = 0.05$) was used for all tests.

4.3 Results

14 stormwater events (with an average depth of 3.7 cm) between June 2018 and April 2022 were sampled and monitored to evaluate seven maintenance activities in the field, and the 2021 fall maintenance event included the forebay restoration. The seven regular maintenance events happened in the 2018 fall, 2019 spring, 2019 fall, 2020 fall, 2021 spring, 2021 fall, and 2022 spring. Storm events before and after each maintenance activity were sampled and analyzed in this study. Each pair of monitored storms for each maintenance work were in a time window of fewer than two months to catch the immediate and direct effects caused by maintenance work, except for the one in the fall of 2020, which is around four months between the two monitored storm events because of the equipment issues, limited precipitation, and Covid.

Flow rates and water levels every 10 min were measured and collected successfully for all 14 storm events from all 7 monitored sites of all 4 GI designs. Mean volume reductions for all

14 monitored stormwater events for the 4 types of GI practices are displayed in **Figure 4.2.** The average runoff reductions over the monitored storms are 74%, 85%,63%, and 68% for bioretention, GC, CAGC, and BS, respectively. In bioretention, an average of 17% of the surface outflow exited through the bypass after the pre-treatment of the forebay.

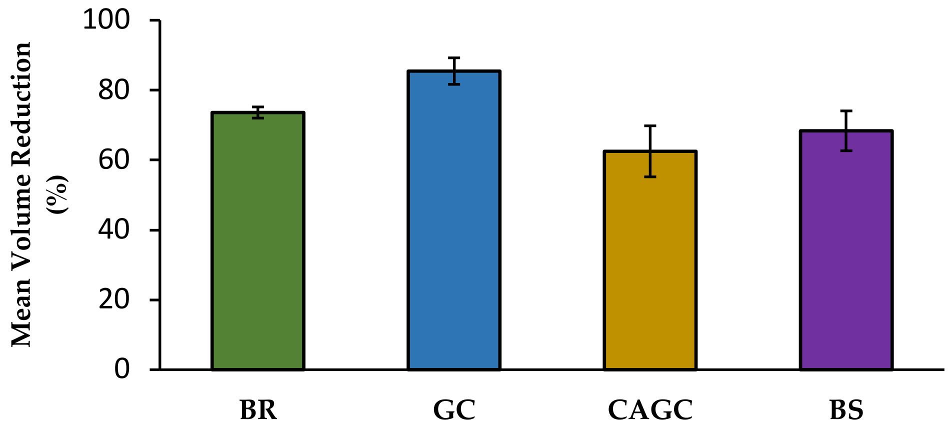


Figure 4.2 Mean volume reduction for all four GI types **(**BR: bioretention, GC: grass channel CAGC: compost-amended grass channel, BS: Bioswale)

Runoff reduction before and after the 7 maintenance activities for the four GI designs are displayed in **Figure 4.3**. The bioretention has the most consistent runoff reduction performance compared with the other 3 types of GI systems. GC has the highest runoff reduction among these 4 GI types. For bioretention, GC, and BS, their volume reduction performance after maintenance work is more consistent than their performance before maintenance. The mean volume reductions before all 7 monitored maintenance events are 73%, 88%, 61%, and 62% for BR, GC, CAGC, and BS, respectively, and their mean runoff reductions after the 7 monitored maintenance activities are 74%, 83%, 64 and 75% respectively. Bioretention, CAGC, and BS have a mean runoff reduction improvement after maintenance activities are performed. There is no significant difference in mean volume reduction of all four GI before and after maintenance events (p = 0.39).

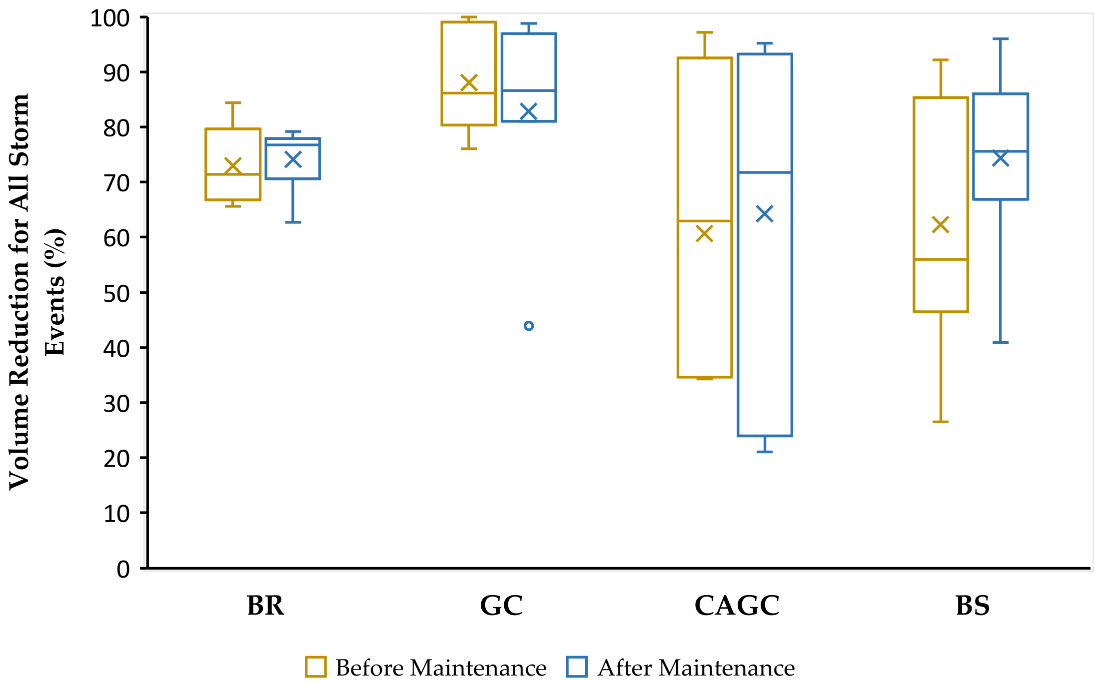


Figure 4.3 Volume reduction of all 14 stormwater events for four GI types (7 before maintenance, 7 after maintenance). Boxplots depict median values (line in box), mean values (×), 25th to 75th percentiles (colored boxes), and outlier values (points). **(**BR: bioretention, GC: grass channel CAGC: compost-amended grass channel, BS: Bioswale)

Figure 4.4 presents the runoff performance of each monitored storm event in bioretention before and after the forebay restoration happened in the fall of 2021, through the proportion of the surface outflow volume exiting through the bypass. 11 storm events happened before the maintenance work, and the highest runoff proportion through the bypass was 49%. Three monitored storm events happened after maintenance. There is a considerable decrease in the outflow proportion flowing through the bypass compared with the performance before the forebay restoration. Before forebay restoration, a mean of 21% of the outflow exited through the bypass without treatment by the bioretention basin, but after the forebay restoration, there is a statistically significant decrease in mean outflow bypass percent to 3% ($p < 0.001$), which indicated a greater percentage of incoming runoff was treated by the bioretention basin after the restoration, and the performance of bioretention was considerably more consistent after the forebay restoration.

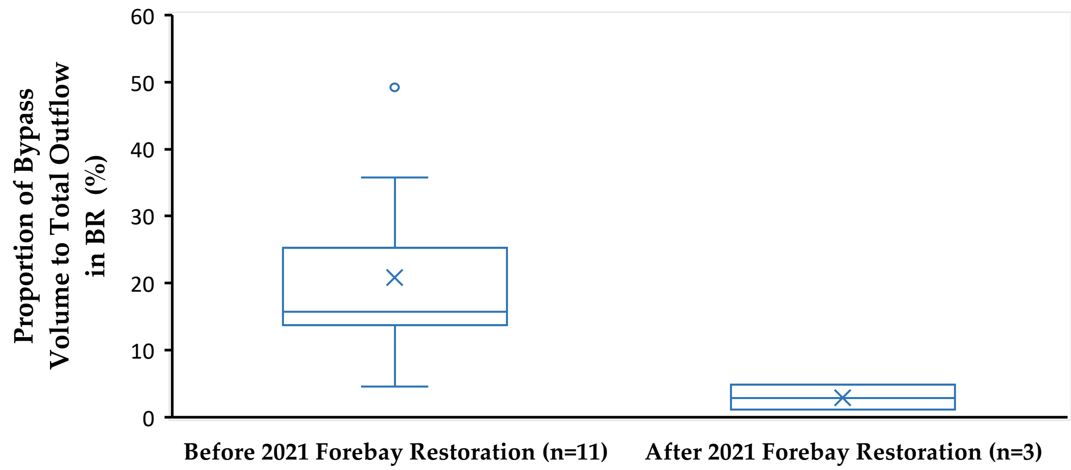


Figure 4.4 Proportion of the surface outflow volume exiting through the bypass before and after the forebay restoration

The runoff reductions of monitored storm events before and after each maintenance activity for the four types of GI designs are displayed in **Figure 4.5**. There are three spring maintenance events evaluated (2019, 2021, and 2022) and four fall maintenance events evaluated (2018, 2019, 2020, and 2021) for water quantity performance.

Before spring maintenance events (**Figure 4.5**, top), the flow volume reduction ranges from 66% to 84% for bioretention, 76% to 91% for GC, 34% to 63% for CAGC, and 56% to 83% for BS. After spring maintenance events, the flow volume reduction for the monitored storms ranges from 63% to 78% for bioretention, 87% to 99% for GC, 65% to 95% for CAGC, and 74% to 96% for BS. All the 3 monitored swales perform better on the runoff reduction after the spring maintenance activities during these 3 monitored years. For bioretention, its performance on the water quantity is stable and similar before and after the maintenance (less than a 7% difference in volume reduction). GC has the highest mean runoff reduction regardless of before or after the maintenance work. CAGC gets the biggest improvement in the runoff reduction after each spring maintenance work (31% improvement in 2019, 53% improvement in 2021, and 32% improvement in 2022, respectively), which potentially is because it has the biggest area of vegetation in its CDA, which helps with the runoff reduction in coming growing seasons after the maintenance is performed.

For the four monitored maintenance activities that happened in the fall of 2018, 2019, 2020, and 2021 (**Figure 4.5**, middle), the volume reduction before the maintenance ranges from 67% to 80% for bioretention, 80% to 100% for GC, 35% to 97% for CAGC, and 27% to 92% for

BS, respectively. The runoff reduction after the maintenance events ranges from 71% to 79% for bioretention, 44% to 87% for GC, 21% to 80% for CAGC, and 41% to 81% for BS, respectively. The mean runoff reduction performance of all 4 GI practices for all monitored spring or fall maintenance activities is displayed at the bottom of **Figure 4.5**. For the maintenance events that happened in the three swales in all monitored spring seasons (2019, 2021, 2022), their mean volume reduction improves by 10% for GC, 39% for CAGC, and 23% for BS, respectively, after maintenance work (**Figure 4.5**, bottom left), and GC volume reduction shows a considerable consistency, compared with CAGC and BS. This suggests that regular maintenance is crucial in preparing swales for the upcoming growing season and the warmer climate conditions necessary for native vegetation growth, thereby improving volume reduction. The mean volume reductions of BR before and after monitored spring maintenance events are similar and stable (74% before maintenance and 73% after maintenance), which indicates that BR demonstrates a greater degree of resilience to the impacts of climate and weather variations during the spring season. The mean runoff reduction of all GI systems increases by 17% after spring maintenance work.

For the maintenance events that happened in all monitored fall seasons (2018, 2019, 2020, 2021), the mean volume reductions before the fall maintenance events are 72%, 91%, 72%, and 63% for BR, GC, CAGC, and BS, respectively (**Figure 4.5**, bottom right). The volume reductions after fall maintenance activities are 75% for BR, 74% for GC, 49% for CAGC, and 66% for BS, respectively. The performance of BR for fall maintenance events indicates considerably more consistency than the other 3 types of swales. Additionally, the mean runoff reductions of CAGC experience a more pronounced decline following maintenance activities, compared with other monitored GI practices. It is plausible that this disparity may be attributable to the fact that CAGC boasts the largest vegetated area, including grass, and the mowing activity when processing the maintenance may have contributed to a reduced runoff reduction post-maintenance work in fall seasons.

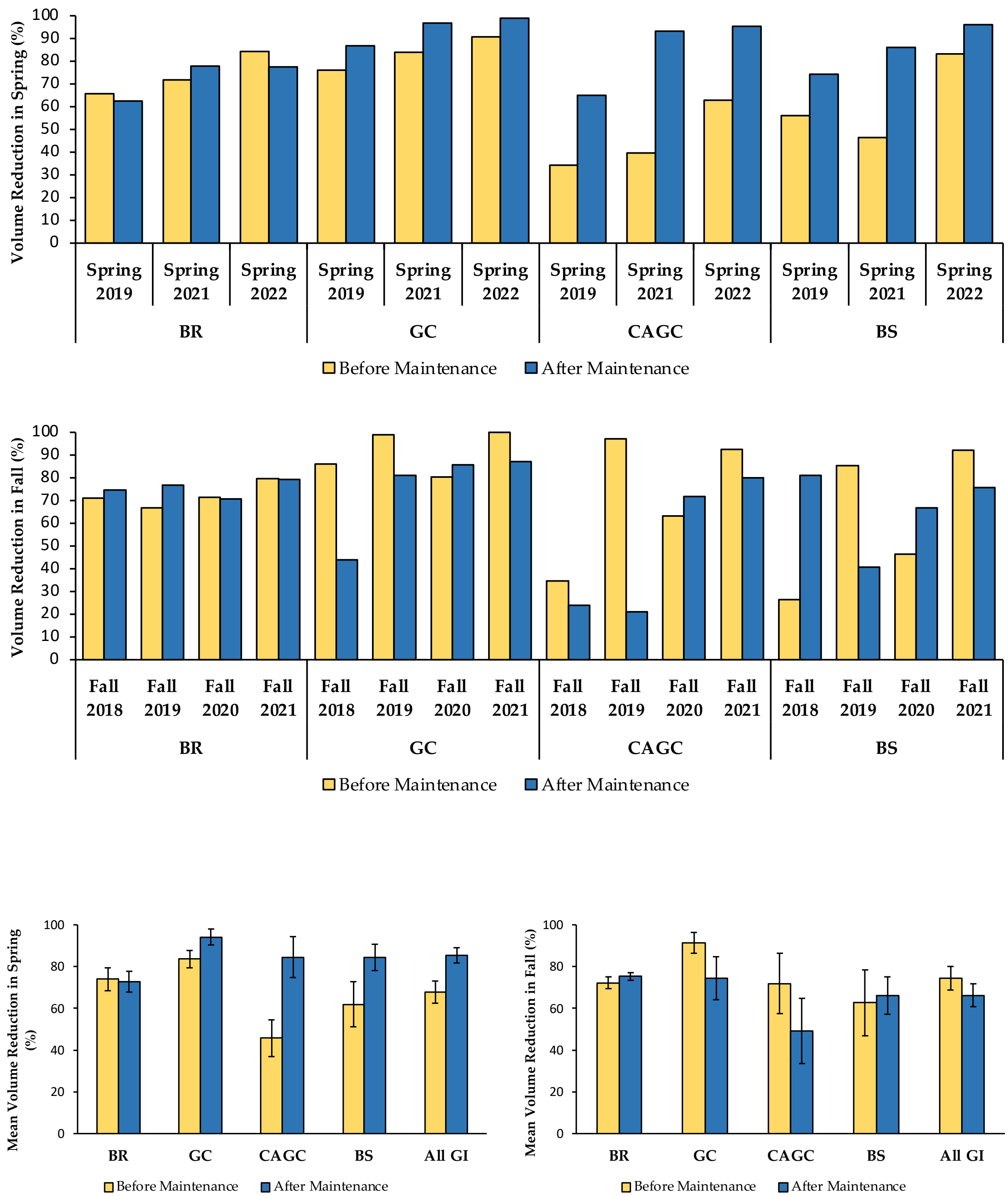


Figure 4.5 Runoff reduction of monitored storm events before and after the maintenance activities for all 4 monitored GI practices. (Top: GI performance on runoff reduction for all spring maintenance events. Middle: GI performance on runoff reduction for all fall maintenance events. Bottom left: Mean runoff reduction for spring monitored maintenance events. Bottom right: Mean runoff reduction for fall monitored maintenance events) **(**BR: bioretention, GC: grass channel CAGC: compost-amended grass channel, BS: Bioswale) (The bottom two figures used the average of the data at the top two figures.)

Figure 4.6 highlights the efficacy of monitored maintenance events in reducing the mean dissolved organic carbon (DOC) mass load for various GI practices. The DOC concentrations for all 4 types of GI designs were monitored successfully for all 3 monitored spring maintenance events (2019, 2021, and 2022). For the 4 monitored fall maintenance events (2018, 2019, 2020, and 2021), the DOC concentrations in bioretention and BS before and after the maintenance were analyzed successfully, but the DOC concentrations for GC before and after the maintenance in 2021 and for CAGC in 2019 were not able to test due to the limited sample volumes from the field.

Before the monitored spring maintenance events, the DOC mass load reductions ranges from 40% to 84% for bioretention, 48% to 76% for GC, -111% to -10% for CAGC, -22% to 69% for BS, respectively (**Figure 4.6**, top). There is some negative DOC mass load reduction in CAGC and BS, possibly because of their construction materials, like the compost in CAGC and engineering soil media in BS. The DOC mass load reduction after the monitored spring maintenance activities ranges from 61 to 66 for bioretention, 73% to 99% for GC, 28% to 94% for CAGC, and 57% to 99% for BS, respectively. Like the runoff reduction shown in **Figure 4.5**, the performance of all the 3 types of swales improves after each maintenance work in the spring seasons, and CAGC improves the most (137% improvement for the 2019 spring, 184% improvement for the 2021 spring, and 104% improvement for the 2022 spring). The DOC mass load reduction for bioretention is considerably more consistent after each maintenance event in the spring seasons (62% for 2019, 66% for 2021, and 61% for 2022).

For the monitored maintenance activities that happened in the fall seasons (**Figure 4.6**, middle), the DOC mass load reduction before then ranges from -21% to 57% for bioretention, 33% to 97% for GC, -161% to 49% for CAGC, and -106% to 76% for BS respectively. The negative DOC mass load reduction in bioretention and BS is potentially caused by their construction material like the compost and engineering soil media. The DOC mass load reductions after fall maintenance events range from 47% to 81% for bioretention, 18% to 74% for GC, -138% to 30% for CAGC, and -47% to 64% for BS, respectively. DOC mass load reduction of bioretention improves by 2% to 68% after each fall maintenance event.

The mean DOC mass load reductions of 4 GI designs for all monitored maintenance events are displayed at the bottom of **Figure 4.6**. For all maintenance events monitored in the spring seasons, the mean DOC mass load reduction increases by 2% for bioretention, 28% for

GC, 142% for CAGC, and 52% for BS, respectively (**Figure 4.6**, bottom left). A substantial improvement of 57% is observed in the mean DOC mass load reduction for all monitored GI practices after spring maintenance events. Bioretention displays the most consistent performance in DOC mass load reduction, indicating its resilience to climate change and other weather condition changes in the upcoming growing seasons. The results also suggest that CAGC exhibited the most significant improvement in DOC reduction performance before and after the monitored spring maintenance work, owing to its high percentage of vegetation area. This contributes to the enhancement of performance during the spring seasons. Prior to the fall maintenance events, the monitored GI designs show mean DOC mass load reductions of 33% for bioretention, 68% for GC, -90% for CAGC, and -12% for BS, respectively (**Figure 4.6**, bottom right). However, after the fall maintenance events, the mean DOC mass load reductions for the same GI designs change to 63% for bioretention, 46% for GC, -34% for CAGC, and 26% for BS, respectively.

These results further reveal that the compost in CAGC and engineering soil media in BR and BS potentially caused the leakage of DOC. However, overall, the mean DOC mass load reduction of all GI designs for all monitored maintenance activities improved from 1% before maintenance to 28% after maintenance. In summary, the findings of this study highlight the effectiveness of monitored maintenance events in improving the performance of various GI practices in reducing the mean DOC mass load. Additionally, the study provides insights into the factors influencing the efficacy of different GI designs and the potential challenges associated with them.

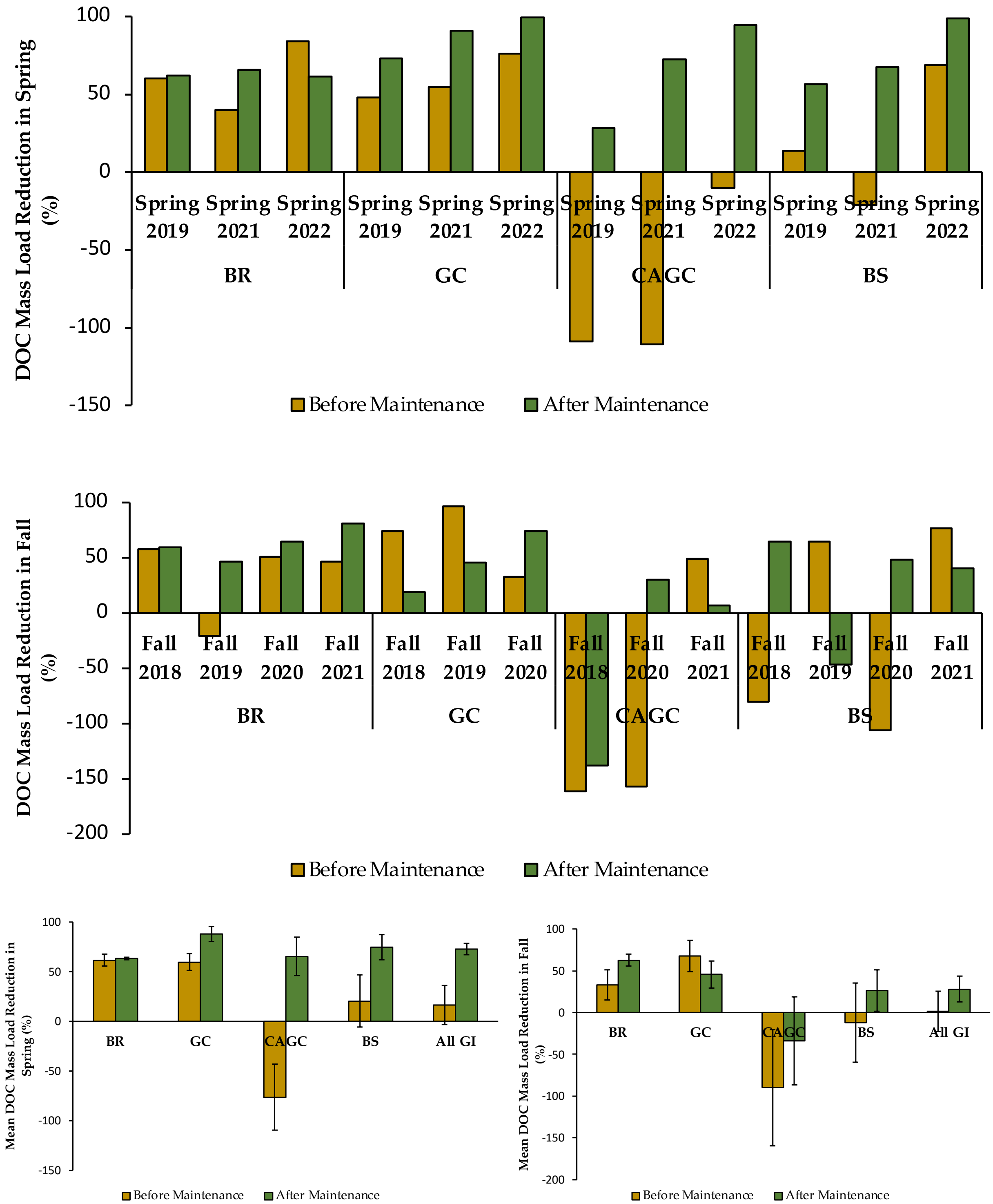


Figure 4.6 DOC mass load reduction of monitored storm events before and after the monitored maintenance activities for all 4 monitored GI practices. (Top: GI performance on DOC reduction for all spring maintenance events. Middle: GI performance on DOC reduction for all fall maintenance events. Bottom left: Mean DOC reduction for spring monitored maintenance events. Bottom right: Mean DOC reduction for fall monitored maintenance events) **(**DOC: dissolved organic carbon, BR: bioretention, GC:

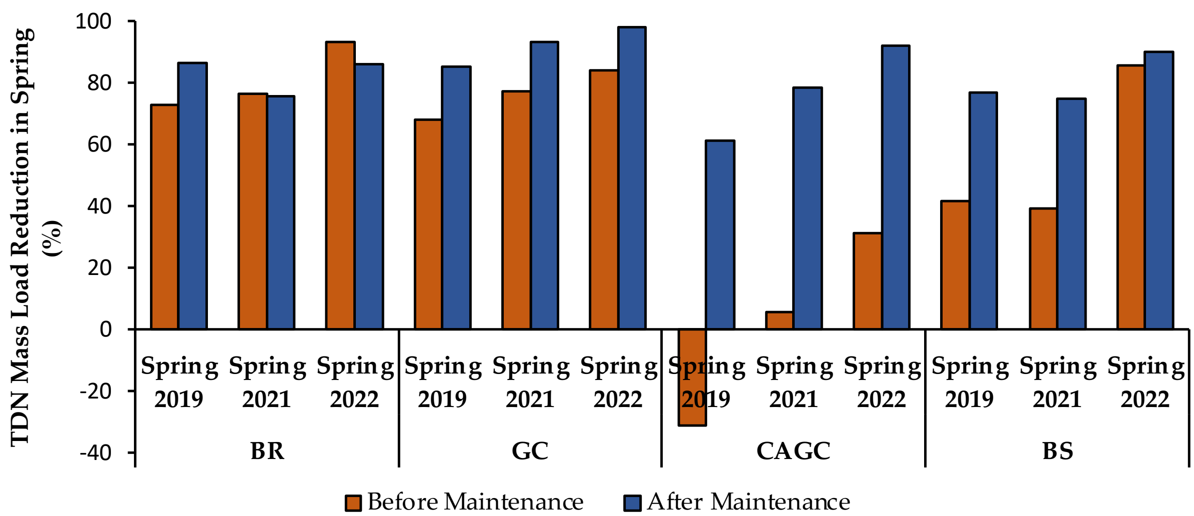
grass channel CAGC: compost-amended grass channel, BS: Bioswale) (The bottom two figures used the average of the data at the top two figures.)

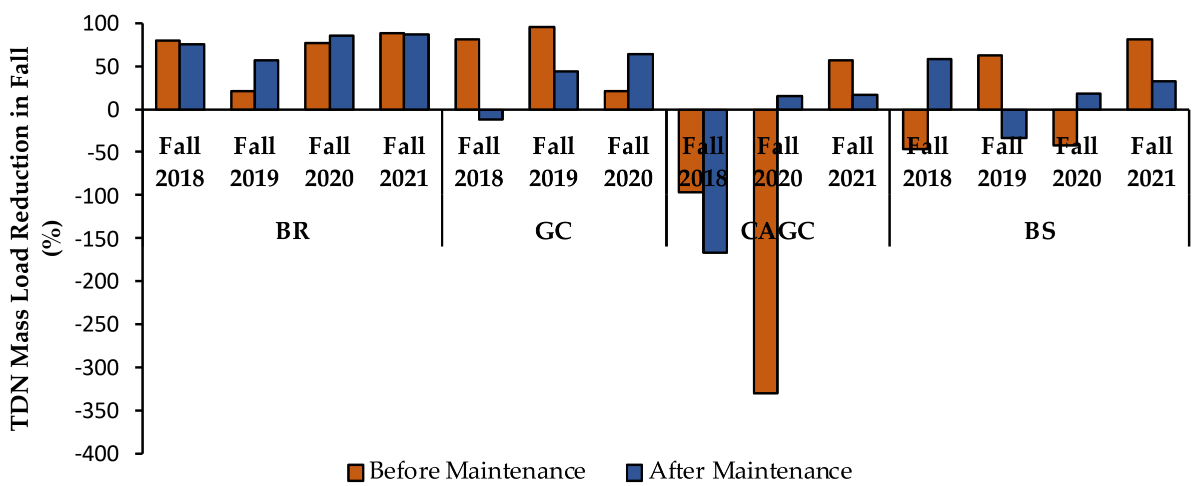
The water quality performance of GI systems on total dissolved nitrogen (TDN) mass load reduction before and after monitored maintenance work is displayed in **Figure 4.7**. The TDN concentrations for all monitored GI designs were analyzed successfully for all 3 monitored spring maintenance events (2019, 2021, and 2022). For the 4 monitored fall maintenance events (2018, 2019, 2020, and 2021), the TDN concentrations in bioretention and BS before and after the maintenance were monitored successfully, but concentrations of TDN for GC in 2021 and CAGC in 2019 were not able to test due to limited sample volumes from the field.

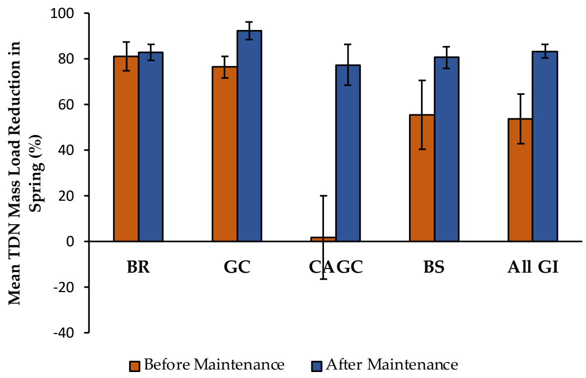
The TDN mass load reduction before the monitored spring maintenance events varies from 73% to 93%, 68% to 84%, -31% to 31%, and 39% to 86% for bioretention, GC, CAGC, and BS, respectively (**Figure 4.7**, top). The TDN reduction performance after monitored spring maintenance work ranges from 76% to 87% for bioretention, 85% to 98% for GC, 61% to 92% for CAGC, and 75% to 90% for BS, separately. All monitored swales show an improvement in the TDN mass load reduction after each spring maintenance event, and the reduction of CAGC improves the most every year. The performance of bioretention is found to be more consistent than the three types of swales.

Regarding the monitored maintenance events in fall seasons, the TDN mass load reduction before then ranges from 21% to 88% for bioretention, 21% to 95% for GC, -331% to 57% for CAGC, and -47% to 81% for BS, respectively (**Figure 4.7**, middle). The TND mass load reduction after the fall maintenance work ranges from 56% to 87% for bioretention, -12% to 64% for GC, -166% to 16% for CAGC, and -33% to 57% for BS, respectively.

The bottom of **Figure 4.7** indicates the mean TDN mass load reductions before and after spring or fall maintenance events. For all maintenance events monitored in the spring seasons, the mean TDN mass load reduction increases by 2% for bioretention, 16% for GC, 75% for CAGC, and 26% for BS, respectively (**Figure 4.7**, bottom left). The mean TDN mass load reduction for all monitored GI practices improves by 29% after monitored spring maintenance events. The performance of bioretention is found to be most consistent in TDN mass load reduction, indicating its resilience to climate and other weather condition changes in the coming growing seasons. The performance of CAGC on mean TDN mass load reduction shows the highest increment after spring maintenance work. The mean TDN mass load reductions before monitored fall maintenance seasons are 66% for bioretention, 66% for GC, -123% for CAGC, and 13% for BS, respectively, and are 76% for bioretention, 32% for GC, -45% for CAGC, and 18% for BS, respectively after then (**Figure 4.7**, bottom right). The compost in CAGC and engineering soil media in BS are found to be potentially causing the leakage of TDN. The overall mean TDN mass load reduction for all monitored GI practices improves to 24% after monitored fall maintenance events.







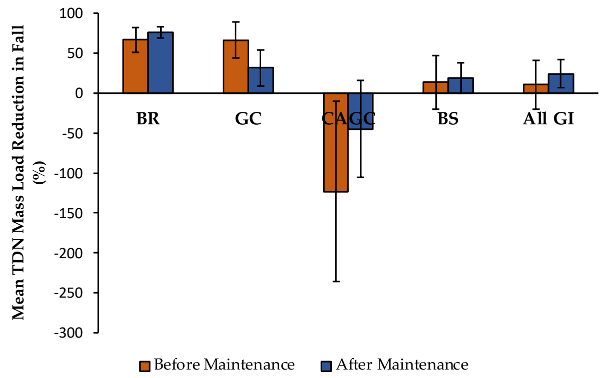
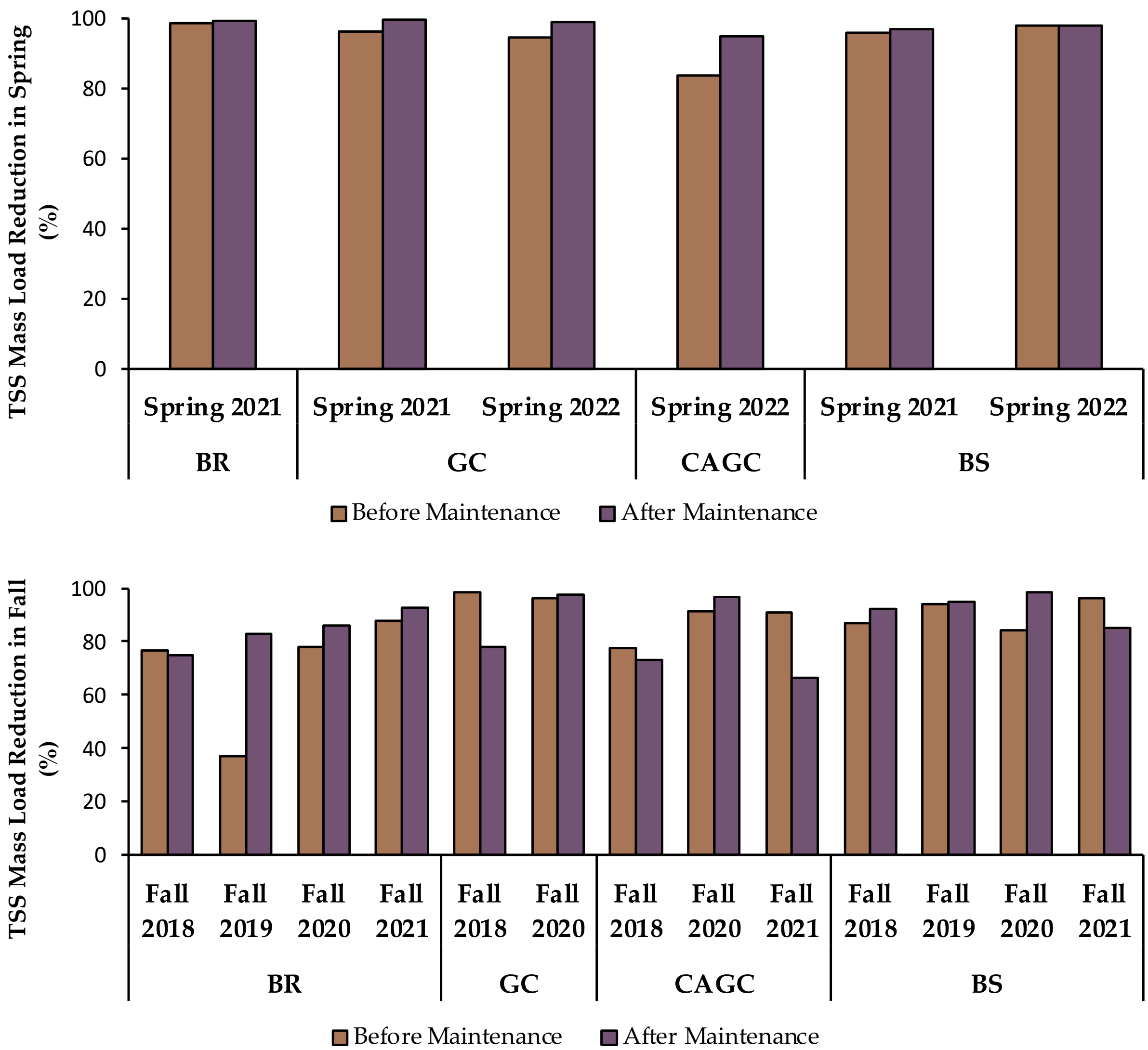


Figure 4.7 TDN mass load reduction of monitored storm events before and after the monitored maintenance activities for all 4 monitored GI practices. (Top: GI performance on TDN reduction for all spring maintenance events. Middle: GI performance on TDN reduction for all fall maintenance events. Bottom left: Mean TDN reduction for spring monitored maintenance events. Bottom right: Mean TDN reduction for fall monitored maintenance events) (TDN: total dissolved nitrogen, BR: bioretention, GC: grass channel CAGC: compost-amended grass channel, BS: Bioswale) (The bottom two figures used the average of the data at the top two figures.)

Figure 4.8 presents the performance of monitored GI systems in terms of total suspended solids (TSS) before and after maintenance events. Due to the high sample volume required for the TSS test and the limited sample volume collected in the field, one spring maintenance (in 2021) and four fall maintenance activities (between 2018-2021) were monitored and compared for bioretention systems. Two spring maintenance activities (in 2021 and 2022) and two fall maintenance activities (in 2018 and 2020) were analyzed for GC for TSS performance. One spring maintenance (in 2022) and three fall maintenance activities (in 2018, 2020, and 2021) were monitored for CAGC for TSS performance. Two spring maintenance activities (in 2021 and 2022) and four fall maintenance activities (between 2018-2022) were analyzed for TSS mass load reduction in BS.

The TSS mass load reduction of bioretention and BS before and after spring maintenance events remains consistent (> 95%) and shows a slight improvement after maintenance (**Figure 4.8**, top). The TSS mass load reduction in GC increases by approximately 4%, and CAGC shows an 11% improvement. For the monitored fall maintenance activities, the TSS mass load reduction before maintenance ranges from 37% to 88% for bioretention, 96% to 99% for GC, 78% to 91% for CAGC, and 84% to 96% for BS, respectively (**Figure 4.8**, middle). The TSS mass load reduction after monitored fall maintenance events ranges from 75% to 93% for bioretention, 78% to 98% for GC, 66% to 97% for CAGC, and 85% to 98% for BS, respectively.

The mean TSS mass load reduction before and after spring or fall maintenance events is presented at the bottom of **Figure 4.8**. The overall mean TSS mass load reduction for all monitored GI systems increased by 3% from 95% after spring maintenance activities (**Figure 4.8**, bottom left). The mean TSS mass load reduction before monitored fall maintenance activities was 70% for bioretention, 97% for GC, 87% for CAGC, and 90% for BS, respectively, and 84% for bioretention, 88% for GC, 79% for CAGC, and 93% for BS, respectively, after maintenance (**Figure 4.8**, bottom right). The overall mean TSS mass load reduction for all monitored GI practices improved by 2% from 84% after monitored fall maintenance events.



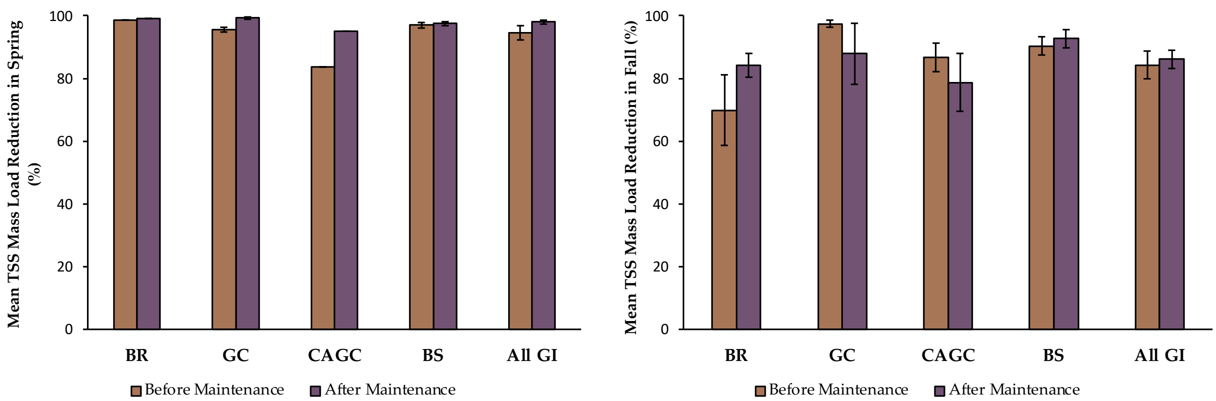


Figure 4.8 TSS mass load reduction of monitored storm events before and after the monitored maintenance activities for all 4 monitored GI practices. (Top: GI performance on TSS reduction for all spring maintenance events. Middle: GI performance on TSS reduction for all fall maintenance events. Bottom left: Mean TSS reduction for spring monitored maintenance events. Bottom right: Mean TSS reduction for fall monitored maintenance events) (TSS: total suspended solids, BR: bioretention, GC: grass channel CAGC: compost-amended grass channel, BS: Bioswale)

Figure 4.9 illustrates the water quality performance of all four green infrastructure (GI) systems by presenting the mean mass load reductions of monitored pollutants, including dissolved organic carbon (DOC), total dissolved nitrogen (TDN), and total suspended solids (TSS), as well as the mean volume reduction for all monitored maintenance activities during both spring and fall seasons. Results demonstrate that runoff reduction improved by 3% for all monitored GI designs, and DOC mass load reduction increases by 41% after monitored maintenance work. TDN mass load reduction after monitored maintenance events increases by 25%, and TSS mass load reduction improves by 2%. The overall mean DOC load reduction from before to after maintenance events for all four GI systems shows a statistically significant increase ($p = 0.019$). However, mean reductions of runoff volume and loads of TDN and TSS before and after maintenance events don't show significant differences for all four GI systems ($p = 0.39$, 0.22, and 0.23, respectively). The flow volume and TSS reduction performance of the studied GI practices are more consistent than their performance on DOC and TDN load reduction. These findings indicate that maintenance work has a positive and effective impact on monitored pollutants and runoff for all four types of GI systems.

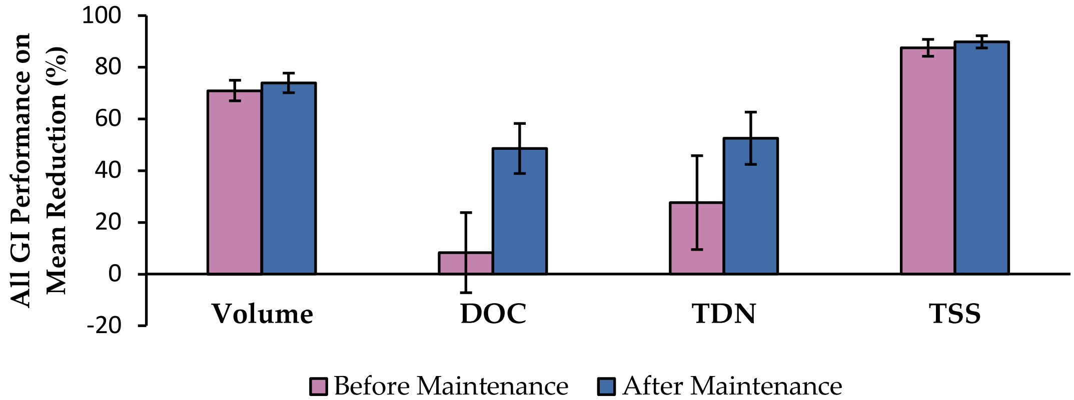


Figure 4.9 Mean reduction on runoff, DOC, TDN, and TSS before and after monitored maintenance events for all 4 monitored GI practices. (DOC: dissolved organic carbon, TDN: total dissolved nitrogen, TSS: total suspended solids, BR: bioretention, GC: grass channel CAGC: compost-amended grass channel, BS: Bioswale)

The costs associated with the maintenance of different types of swales are consistently affordable and comparable when compared to the maintenance costs of bioretention. The cost of maintaining bioretention is around \$3,055 higher per event than swales, including the average cost for forebay restoration. It should be noted, however, that bioretention covers a much larger area, with a CDA of 47,753 m^2, in contrast to the swales, which have a CDA of 2,533 m^2, 6,874m^2, and 2,772 m^2, respectively.

The average maintenance costs per CDA area per year for the 4 monitored GI designs are \$0.15/m^2, \$0.39/m^2, \$0.14/m^2, and \$0.35/m^2 for bioretention, GC, CAGC, and BS, respectively. Overall, for all monitored storms in this study, the economic efficiency for maintenance was \$0.0041, \$0.0016, \$0.0016, and \$0.0017 per liter of runoff reduced for bioretention, GC, CAGC, and BS, respectively. In terms of the reduction of dissolved organic carbon (DOC) mass, the overall maintenance economic efficiency was \$0.0009/mg, \$0.0004/mg, and \$0.0005/mg for bioretention, GC, and BS, respectively. Meanwhile, the reduction of total dissolved nitrogen (TDN) mass was achieved at a maintenance efficiency of \$0.0040/mg, \$0.0048/mg, and \$0.0056/mg for bioretention, GC, and BS, respectively. CAGC experienced an increase in the mean total mass of DOC and TDN at the effluent for all monitored storms, possibly due to its compost construction materials. However, **Figures 4.6** and **Figure 4.7** indicate that maintenance activities have contributed to improving the percentage of DOC and TDN mass load reductions.

4.4 Discussion

Before the forebay restoration in October 2021, an average of 21% of outflow exited through the bypass without undergoing treatment by the bioretention basin. The highest proportion of runoff that passed through the bypass was 49%, indicating that unwanted vegetation, dredge soil, and sediment buildup over the years had elevated the forebay's elevation, changing the direction of flow and discouraging water flow into the bioretention basin. However, after the forebay restoration, the mean proportion of runoff that passed through the bypass significantly decreased to 3%, which is a testament to the effectiveness of the restoration. The restoration process involved removing the unwanted vegetation, dredging the soil, and removing sediment buildup, which helped to lower the forebay's elevation and improve the flow rate through that area.

The forebay restoration is a crucial step in ensuring the sustainability of this type of green infrastructure system, as it helps to recover the bioretention basin's ability to treat runoff effectively. By restoring the forebay, the flow rate to the bioretention basin is improved, thus ensuring that the bioretention basin can perform its intended function of treating runoff effectively.

In this study, various water quality and quantity parameters were monitored and analyzed to assess the performance of four types of GI practices before and after spring maintenance activities. The results showed that all three types of swales demonstrated an improvement in their performance after the maintenance work, which helped them prepare for the growing season and facilitated vegetation growth. The growing vegetation likely contributed to reducing pollutants in the swale effluent.

The grass channel (GC) showed a relatively lower increase in the reduction of runoff, dissolved organic carbon, and total dissolved nitrogen after the spring maintenance work, but it consistently performed better compared to the other two types of swales (CAGC and BS). GC had the highest load reduction for the three monitored parameters, both before and after the maintenance activities during the spring season.

On the other hand, the compost-amended grass channel (CAGC) demonstrated a significant improvement in volume, DOC, and TDN reduction after the spring maintenance events, particularly for DOC and TDN mass load reduction. Before the maintenance work, CAGC had issues with leaking DOC and TDN, but its performance improved significantly after the maintenance work (**Figure 4.6** and **Figure 4.7**). The compost in the CAGC construction material potentially contributed to the DOC and TDN leaking. One possible explanation for the significant improvement in CAGC's performance after maintenance is that the maintenance work put the swale in optimal condition for the upcoming growing season. CAGC has a relatively high percentage of grass and vegetation in its CDA, which played a critical role in its improved performance. As the climate warmed up following the spring maintenance events, there was more biomass to absorb runoff. Additionally, the roots of the vegetation helped with infiltration and retention of the water flow.

The bioswale (BS) exhibits the most consistent performance on total suspended solids (TSS) mass load reduction, showing similar performance before and after the maintenance work (**Figure 4.8**). This may be due to the stable growth of the vegetation in BS.

The bioretention consistently achieves a high mean reduction for the monitored parameters, including runoff, DOC, TDN, and TSS, before and after the spring maintenance activities. The result on TSS supports the conclusions of other observations, as bioretention typically performs a high reduction on TSS[20]. Research reported by Line and Hunt (2009) in North Carolina indicated monitored bioretention cells mean pollutant reduction efficiencies for the bioretention cells of 79% reduction for TSS with an increase in NO_3 and NO_2, resulting from a combination of N additions within the cell and conversion, and insufficient maintenance activities could also contribute to nitrogen losses[21]. Thus, regular maintenance is encouraged to maintain its effective performance.

Following maintenance events during the fall seasons, bioretention system displayed remarkable resilience to the environment, as it can maintain similar levels of runoff reduction compared to those observed during the spring seasons. Conversely, the three types of monitored swales demonstrated substantially different performances regarding runoff reduction. Specifically, GC and CAGC showed decreased runoff reductions of 17% and 23%, respectively, while BS displayed a modest 3% improvement.

With respect to the mean mass load reduction of DOC and TDN, the performance of GC decreased after fall maintenance, as the mowed grass during the maintenance work may have impeded the infiltration of pollutants. Conversely, the mean mass load reduction of DOC and TDN of CAGC and BS increased after maintenance, suggesting that the maintenance procedures reduced the leaching of DOC and TDN from the compost and engineered soil media. In particular, bioretention systems consistently improved performance in reducing these two pollutants after maintenance activities.

Regarding total suspended solids (TSS) reduction, bioretention and BS demonstrated stable performance with slight improvements, while GC and CAGC displayed a decrease in TSS reduction after maintenance due to the removal of blooming grass and other plants. These findings are consistent with those observed during the spring seasons, with CAGC showing the most significant change before and after maintenance, possibly due to its larger CDA with vegetation compared to other swales.

Despite the occurrence of decreased results following fall maintenance events, it remains imperative to conduct maintenance work during this season, as it aids in preparing GI practices for the impending winter seasons. Neglecting to mow grass or wild vegetation during fall seasons could lead to the release of sorbed pollutants into the soil in winter. Thus, performing necessary maintenance tasks during this period can help mitigate potential environmental hazards and preserve the integrity of local ecosystems.

The present study highlights the effectiveness of bioretention as a green infrastructure (GI) practice in mitigating the negative impacts of urban stormwater runoff. While bioretention may be perceived as a costly intervention, the results indicate its efficacy in managing the largest contributing drainage area (47,753 m^2) and accommodating greater flow volumes compared to other types of swales studied.

In addition, incorporating forebay restoration in the bioretention system maintenance appears to be essential in facilitating the efficient transfer of runoff. The implementation of a forebay maintenance event in the field experiment produced promising results in terms of reducing the volume of untreated runoff escaping through the bypass. This underscores the importance of routine forebay restoration to optimize the performance of bioretention systems.

Despite the costs associated with forebay restoration, the study suggests that conducting maintenance every four years may prove to be a sound investment in preserving the functionality and longevity of the bioretention system. Such periodic maintenance interventions are recommended to sustain the effectiveness of GI practices and support the overall management of urban stormwater runoff.

Regular maintenance is necessary to ensure the functionality and effectiveness of green infrastructure systems[22]. This includes pruning, weeding, litter removal, removing debris, and adding mulch to maintain its original levels. Failure to maintain green infrastructure systems can lead to negative consequences such as reduced habitat quality, increased risk of flooding, and decreased aesthetic appeal. Maintenance of green infrastructure systems is essential for ensuring that they continue to provide benefits to people and the environment. By implementing regular monitoring and maintenance activities, securing adequate funding, and promoting community involvement, green infrastructure systems can continue to function effectively and provide benefits for years.

4.5 Conclusion

The bi-annual maintenance of four types of green infrastructure (GI) practices along Lorton Road was conducted in both spring and fall of 2018 to 2022. This study evaluated seven maintenance events, including a forebay restoration for bioretention that occurred in the fall of 2021. The study measured and sampled storm events before and after maintenance activities to assess the performance of monitored GI systems in reducing runoff, dissolved organic carbon (DOC), total dissolved nitrogen (TDN), and total suspended solids (TSS). The study found that different types of GI systems exhibited a wide range of performance in terms of water quantity and quality.

Specifically, the bioretention system exhibited higher resilience to climate and weather conditions when subjected to proper maintenance activities, and the forebay restoration significantly improved the potential for inflow to be treated by the bioretention basin. In monitored spring seasons, the performance of three types of swales increased after maintenance work for all pollutants, and the grass channel (GC) was more consistent than CAGC and bioswale (BS) in reducing flow volume, DOC, and TDN. Moreover, the performance of CAGC in this study showed the most improvement compared to other GI practices, indicating that maintenance work was most necessary for this type of swale.

The overall performance of all GI practices improved after monitored maintenance events, regardless of season or GI type, suggesting that these practices performed well in reducing pollutants and controlling flow when adequately maintained. Suitable construction and subsequent maintenance of GI practices have significant implications for their long-term functioning, and monitoring results, including maintenance costs, can help improve GI designs in the future.

The results of this study provide valuable insights into the performance of different types of GI practices in reducing various types of pollutants under different environmental conditions. These findings may inform the design and maintenance of future GI systems, with the aim of maximizing their environmental benefits.

Supplementary Data: Appendix C

4.6 References

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Chapter 5: Dissertation Conclusions

This dissertation explores the performance of four types of green infrastructure designs along Lorton Road, Fairfax County, VA, USA., over multiple years based on their stormwater quantity and quality performance. The performance of four monitored GI practices (bioretention, grass channel, compost-amended grass channel, and bioswale) receiving similar influent pollutant loadings during 24 storm events are evaluated. The potential of different vegetation types to reduce deicing salt released from bioretention through transpiration is explored, and the maintenance efficiency for the four monitored green infrastructure designs based on water-quality performance and economic costs are also evaluated. All data collected and conclusions gained from this study will be utilized to aid engineers in selecting current GI practices and improving future GI designs, to ensure the preservation of public health and the environment.

Approximately 60 storm events have been monitored and sampled since 2018, and 24 relatively complete storms were selected for comparison and evaluation. The performance of different GI designs ranges variously, some acting as pollutant sinks, while others as pollutant sources for specific constituents. Grass channel performed best on both runoff and pollutant load reductions, serving a relatively small contributing drainage area, while the bioretention, which has the second highest volume and mass load reduction for pollutants, serves the biggest contributing drainage area, and its performance is considerably more consistent than other types of GI systems monitored. More complex GI designs don't necessarily mean better performance in stormwater treatment.

Vegetation in bioretention has shown the potential to improve load reduction. The potential of vegetation to mitigate deicing salt loading in bioretention for all simulated inflow salt concentration levels is Broadleaf Cattail (BC) performing better than Blue Wild Indigo (BWI), and BWI is better than no plants (blank). Vegetated columns reduced stormwater volume loading for all experimental salt levels in the order: BC > BWI > blank. The highest salt removal of all columns was observed for the intermediate salt concentration inflow. For all simulated bioretention, the best salt load reduction was observed for the first storm event, with performance decreasing with repeated salt loadings.

For the maintenance study, the bioretention system exhibited higher resilience to climate and weather conditions when subjected to proper maintenance activities, and the forebay restoration significantly improved the potential for inflow to be treated by the bioretention basin.

In monitored spring seasons, the performance of three types of swales increased after maintenance work for all pollutants, and the grass channel is more consistent than CAGC and bioswale in reducing flow volume, DOC, and TDN. Moreover, the performance of CAGC in this study showed the most improvement compared to other GI practices, indicating that maintenance work was most effective for this type of swale. The overall performance of all GI practices improved after monitored maintenance events, regardless of season or GI type, suggesting that these practices performed well in reducing pollutants and controlling flow when adequately maintained. Suitable construction and subsequent maintenance of GI practices have significant implications for their long-term functioning, and monitoring results, including maintenance costs, can help improve GI designs in the future. The results of this study provide valuable insights into the performance of different types of GI practices in reducing various types of pollutants under different environmental conditions.

These results indicate that the monitored GI practices are effective technologies for reducing runoff and a series of pollutants. These findings may inform the design and maintenance of future GI systems, with the aim of maximizing their environmental benefits. This research can help other researchers, engineers, and policymakers better understand how GI systems are functioning and identify ways to optimize their effectiveness. It would also be able to help determine the capacity of different types of GI systems to store and treat stormwater, track changes in water quality over time, and evaluate the effectiveness of their maintenance activities.

Among all the four types of GI designs monitored and evaluated, the bioretention works considerably most consistently, compared with the other three types of swales, and it serves the largest contributing drainage area and can treat high volumes and flow rates of stormwater. The grass channel, which is the simplest designed one, always gets the highest reduction in runoff and pollutant mass load, compared with other GI practices monitored, but it serves a relatively smaller CDA and costs more than other GI designs on the average maintenance costs per CDA each year. The CAGC costs more to build but performed worse than other swales.

The advantage of this study is that all the GI systems experience the same storms and the same environmental conditions along the same highway, although they get inflow from the different contributing drainage areas, which could cause slight differences in the inflow water quality. This creates a unique opportunity to make the best possible comparison of the performance of different types of GI designs. When extrapolating these practices to other sites or other locations within different weather conditions, there might be some differences in their performance caused by specific hydrogeology conditions and different resource water. However, unlike previous studies, this research is the first one that monitors and evaluates multiple types of GI systems within almost the same inflow and environment conditions, during such a long period.

Future study is encouraged to explore the potential of vegetation in green infrastructure to mitigate deicing salt (NaCl) under winter conditions and simulate the GI performance using a rainfall-runoff model. It is also recommended to study the mitigation of other kinds of salt ions (e.g., K^+, SO_4^{2-}) to water resources by green infrastructure. Further studies about microplastics from tire wear or netting used to sustain new grass growth and to explore how GI designs affect groundwater during the long term by encouraging stormwater infiltration to grounds would also be suggested.

Chapter 6: Appendices

6.1 Appendix A

Table A1 Stormwater runoff volumes for all monitoring sites

	Bioretention			Grass Channel		CA Grass Channel		Bioswale	
Event Date	Inflow Volume (L)	Outlet Underdrain Volume (L)	Outlet Bypass Volume (L)	Inflow Volume (L)	Outlet Underdrain Volume (L)	Inflow Volume (L)	Outlet Underdrain Volume (L)	Inflow Volume (L)	Outlet Underdrain Volume (L)
6/2/18	536065	117315	37704	173996	24150	209919	137119	207014	152112
8/31/18	854638	182464	34127	156163	87617	189725	144306	185699	35156
9/28/18	551727	204304	36197	117792	48172	182655	116901	119161	64634
11/10/18	247456	50005	16287	26038	15155	32283	15103	30529	14040
1/25/19	419692	134092	19122	173465	16462	209279	82459	206382	78464
2/12/19	528110	97907	20771	74691	13144	90112	80870	88864	47527
3/21/19	1201655	265087	147918	246345	59096	297294	195285	293087	128846
6/18/19	376315	71293	69077	38385	5116	50996	17777	43244	11183
10/17/19	499847	140005	25909	156102	1492	188331	5338	185724	27134
11/23/19	401100	69554	23554	37460	7120	45194	35676	44568	26344
2/7/20	830630	226619	52588	87329	32087	105360	104868	103901	91301
8/3/20	1020679	223370	67811	214403	42154	260399	96098	254961	136395
12/4/20	666951	168937	26803	345568	49798	440057	124353	399167	132161
2/10/21	145715	21871	1611	158920	3958	191731	25114	189078	18357
3/18/21	189487	16763	409	65746	0	79320	35700	78222	10632
4/1/21	568002	152727	7303	103358	16615	126465	76109	122057	65121
5/28/21	386667	79260	5925	187237	5814	253971	17174	208237	29080
8/13/21	743178	116940	13222	214573	13741	258874	23843	255291	46076
9/1/21	284531	49544	8262	182031	133	219613	16407	216574	16935
10/29/21	865738	175275	5096	292237	37146	373374	74568	336928	82131
1/16/22	195216	48035	14162	368287	47046	444324	230166	438175	78079
2/3/22	468451	148925	5652	641134	36899	773504	30471	762799	61358
3/23/22	518656	76751	3916	118723	10996	143235	53101	141253	23878
4/18/22	194615	43438	478	251063	3053	302898	14425	298705	11994

Table A2 Concentration of chloride for all monitoring sites

	Bioretention			Grass Channel		CA Grass Channel		Bioswale	
Event Date	Inflow (mg/L)	Outflow Underdrain (mg/L)	Outflow Bypass (mg/L)	Inflow (mg/L)	Outflow (mg/L)	Inflow (mg/L)	Outflow (mg/L)	Inflow (mg/L)	Outflow (mg/L)
6/2/18	51	38	29	25	4	25	30	25	29
8/31/18	4	20	6	11	2	11	20	11	9
9/28/18	23	25	20	18	4	18	15	18	15
11/10/18	45	32	22	21	3	21	23	21	13
1/25/19	216	345	215	241	42	241	167	241	808
2/12/19	1056	618	274	231	61	231	396	231	1041
3/21/19	46	75	56	65	17	65	62	65	141

6/18/19	26	19	4	49	4	49	32	49	52
10/17/19	8	11	12	20	5	20	-	20	52
11/23/19	11	10	27	35	6	35	75	35	76
2/7/20	18	30	9	22	1	22	20	22	21
8/3/20	6	6	3	8	3	8	15	8	8
12/4/20	20	9	3	5	3	5	5	5	6
2/10/21	733	1452	393	409	42	409	585	409	769
3/18/21	50	92	154	30	0	30	101	30	118
4/1/21	56	43	69	28	4	28	39	28	55
5/28/21	15	27	11	16	4	16	54	16	31
8/13/21	36	19	5	3	2	3	25	3	11
9/1/21	32	18	7	9	-	9	28	9	18
10/29/21	19	10	11	21	4	21	37	21	18
1/16/22	119	178	132	630	210	630	350	630	567
2/3/22	217	266	121	268	57	268	95	268	557
3/23/22	105	40	8	21	8	21	22	21	177
4/18/22	43	33	9	38	3	38	19	38	4

Table A3 Concentration of sodium for all monitoring sites

	Bioretention			**Grass Channel**		**CA Grass Channel**		**Bioswale**	
Event Date	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**	**Outflow Bypass (mg/L)**	**Inflow (mg/L)**	**Outflow (mg/L)**	**Inflow (mg/L)**	**Outflow (mg/L)**	**Inflow (mg/L)**	**Outflow (mg/L)**
6/2/18	41	55	41	30	-	30	-	30	103
8/31/18	15	37	15	20	-	20	-	20	35
9/28/18	28	38	28	24	-	24	-	24	33
11/10/18	38	36	28	24	15	24	30	24	27
1/25/19	129	186	123	143	18	143	78	143	379
2/12/19	599	334	144	129	26	129	178	129	539
3/21/19	30	58	35	40	12	40	42	40	92
6/18/19	19	34	3	26	5	26	29	26	50
10/17/19	10	32	13	15	10	15	-	15	49
11/23/19	12	31	22	-	11	-	45	-	52
2/7/20	22	36	15	22	8	22	30	22	32
8/3/20	12	21	9	10	8	10	27	10	21
12/4/20	17	13	4	6	3	6	9	6	14
2/10/21	498	1602	278	266	26	266	345	266	772
3/18/21	36	79	110	25	0	25	89	25	93
4/1/21	40	43	49	20	4	20	44	20	54
5/28/21	13	36	10	11	2	11	43	11	41
8/13/21	25	28	4	3	1	3	14	3	21
9/1/21	22	26	6	6	-	6	28	6	31
10/29/21	12	11	6	8	1	8	20	8	15
1/16/22	75	132	76	33	80	33	163	33	33
2/3/22	121	125	63	14	26	14	61	14	28
3/23/22	25	14	3	6	2	6	9	6	40
4/18/22	23	25	10	41	4	41	22	41	4

Table A4 Concentration of calcium for all monitoring sites

	Bioretention			Grass Channel		CA Grass Channel		Bioswale	
Event Date	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**	**Outflow Bypass (mg/L)**	**Inflow (mg/L)**	**Outflow (mg/L)**	**Inflow (mg/L)**	**Outflow (mg/L)**	**Inflow (mg/L)**	**Outflow (mg/L)**
6/2/18	12.9	11.7	2.0	4.9	-	4.9	-	4.9	41.3
8/31/18	2.4	13.3	0.7	3.1	-	3.1	-	3.1	12.4
9/28/18	15.2	14.6	2.7	9.3	-	9.3	-	9.3	25.6
11/10/18	15.1	11.8	2.3	6.6	9.6	6.6	19.4	6.6	16.8
1/25/19	14.9	25.5	3.4	8.0	9.2	8.0	21.1	8.0	69.7
2/12/19	22.4	27.5	4.0	7.2	10.4	7.2	44.0	7.2	58.5
3/21/19	6.6	5.5	0.9	3.0	5.4	3.0	9.1	3.0	10.1
6/18/19	8.0	5.6	0.4	3.7	8.1	3.7	11.9	3.7	15.3
10/17/19	3.6	6.9	4.4	2.0	4.0	2.0	-	2.0	6.4
11/23/19	4.6	7.7	6.7	4.6	5.1	4.6	13.6	4.6	14.0
2/7/20	5.8	4.4	3.1	3.3	4.1	3.3	12.3	3.3	9.1
8/3/20	6.6	4.8	4.7	3.3	5.5	3.3	13.2	3.3	10.0
12/4/20	11.6	4.8	3.8	2.4	3.7	2.4	7.2	2.4	11.7
2/10/21	30.5	197.6	12.9	12.1	7.9	12.1	74.7	12.1	77.5
3/18/21	6.0	3.6	5.5	3.8	0	3.8	16.2	3.8	7.9
4/1/21	11.4	1.9	2.6	3.3	2.8	3.3	11.2	3.3	6.8
5/28/21	6.0	4.1	2.0	3.8	4.1	3.8	7.6	3.8	6.6
8/13/21	16.2	7.7	1.8	1.7	2.5	1.7	3.3	1.7	3.8
9/1/21	15.9	6.5	3.1	1.7	-	1.7	9.5	1.7	9.1
10/29/21	8.6	2.1	2.1	3.4	3.1	3.4	7.1	3.4	5.9
1/16/22	35.3	14.5	5.5	8.0	22.7	8.0	29.2	8.0	6.4
2/3/22	27.6	16.4	6.3	1.6	7.8	1.6	16.0	1.6	2.5
3/23/22	20.4	3.6	3.1	3.6	3.1	3.6	5.1	3.6	11.3
4/18/22	11.6	3.9	1.8	8.0	2.2	8.0	4.6	8.0	2.1

Table A5 Concentration of copper for all monitoring sites

	Bioretention			Grass Channel		CA Grass Channel		Bioswale	
Event Date	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**	**Outflow Bypass (mg/L)**	**Inflow (mg/L)**	**Outflow (mg/L)**	**Inflow (mg/L)**	**Outflow (mg/L)**	**Inflow (mg/L)**	**Outflow (mg/L)**
6/2/18	0.0083	0.0228	0.0067	0.0069	0.0076	0.0069	0.0125	0.0069	0.0337
8/31/18	0.0062	0.0290	0.0094	0.0113	0.0072	0.0113	0.0799	0.0113	0.0136
9/28/18	0.0073	0.0111	0.0054	0.0069	0.0110	0.0069	0.0091	0.0069	0.0255
11/10/18	0.0088	0.0137	0.0066	0.0080	0.0117	0.0080	0.0097	0.0080	0.0299
1/25/19	0.0147	0.0054	0.0048	0.0091	0.0060	0.0091	0.0070	0.0091	0.0108
2/12/19	0.0129	0.0069	0.0036	0.0090	0.0054	0.0090	0.0058	0.0090	0.0090
3/21/19	0.0121	0.0177	0.0066	0.0095	0.0077	0.0095	0.0072	0.0095	0.0176
6/18/19	0.0108	0.0289	0.0060	0.0103	0.0150	0.0103	0.0114	0.0103	0.0549
10/17/19	0.0104	0.0449	0.0079	0.0088	0.0088	0.0088	-	0.0088	0.0619
11/23/19	0.0076	0.0073	0.0358	0.0075	0.0090	0.0075	0.0116	0.0075	0.0362
2/7/20	0.0119	0.0182	0.0116	0.0096	0.0082	0.0096	0.0082	0.0096	0.0273
8/3/20	0.0105	0.0389	0.0083	0.0075	0.0118	0.0075	0.0166	0.0075	0.0482
12/4/20	0.0022	0.0097	0.0015	0.0017	0.0050	0.0017	0.0037	0.0017	0.0198
2/10/21	0.0270	0.0316	0.0306	0.0259	0.0242	0.0259	0.0217	0.0259	0.0284
3/18/21	0.0227	0.0102	0.0053	0.0072	0.0000	0.0072	0.0109	0.0072	0.0267
5/28/21	0.0000	0.0027	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0659
8/13/21	0.0047	0.0406	0.0024	0.0048	0.0078	0.0048	0.0104	0.0048	0.0630
9/1/21	0.0041	0.0251	0.0033	0.0029	-	0.0029	0.0232	0.0029	0.0611
10/29/21	0.0069	0.0120	0.0044	0.0033	0.0118	0.0033	0.0199	0.0033	0.0366
1/16/22	0.0068	0.0094	0.0116	0.0430	0.0137	0.0430	0.0108	0.0430	0.0120
2/3/22	0.0091	0.0089	0.0088	0.0075	0.0137	0.0075	0.0180	0.0075	0.0147
3/23/22	0.0161	0.0263	0.0227	0.0174	0.0190	0.0174	0.0193	0.0174	0.0223
4/18/22	0.0136	0.0245	0.0114	0.0446	0.0104	0.0446	0.0138	0.0446	0.0076

Table A6 Concentration of lead for all monitoring sites

	Bioretention			Grass Channel		CA Grass Channel		Bioswale	
Event Date	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**	**Outflow Bypass (mg/L)**	**Inflow (mg/L)**	**Outflow (mg/L)**	**Inflow (mg/L)**	**Outflow (mg/L)**	**Inflow (mg/L)**	**Outflow (mg/L)**
6/2/18	0.0021	0.0066	0.0022	0.0064	0.0040	0.0064	0.0047	0.0064	0.0102
8/31/18	0.0008	0.0044	0.0019	0.0024	0.0036	0.0024	0.0143	0.0024	0.0034
9/28/18	0.0024	0.0015	0.0012	0.0019	0.0017	0.0019	0.0036	0.0019	0.0034
11/10/18	0.0019	0.0024	0.0014	0.0023	0.0030	0.0023	0.0042	0.0023	0.0055
1/25/19	0.0047	0.0013	0.0022	0.0027	0.0062	0.0027	0.0030	0.0027	0.0013
2/12/19	0.0025	0.0005	0.0010	0.0041	0.0059	0.0041	0.0026	0.0041	0.0017
3/21/19	0.0035	0.0020	0.0017	0.0036	0.0060	0.0036	0.0045	0.0036	0.0031
6/18/19	0.0025	0.0057	0.0021	0.0053	0.0054	0.0053	0.0039	0.0053	0.0119

10/17/19	0.0012	0.0067	0.0006	0.0024	0.0012	0.0024	-	0.0024	0.0088
11/23/19	0.0010	0.0009	0.0060	0.0027	0.0017	0.0027	0.0020	0.0027	0.0076
2/7/20	0.0037	0.0022	0.0032	0.0049	0.0065	0.0049	0.0034	0.0049	0.0047
8/3/20	0.0009	0.0047	0.0008	0.0021	0.0021	0.0021	0.0016	0.0021	0.0058
12/4/20	0.0010	0.0016	0.0012	0.0041	0.0091	0.0041	0.0030	0.0041	0.0040
2/10/21	0.0029	0.0009	0.0028	0.0106	0.0070	0.0106	0.0016	0.0106	0.0012
3/18/21	0.0058	0.0009	0.0013	0.0038	0.0000	0.0038	0.0030	0.0038	0.0028
4/1/21	0.0030	0.0019	0.0014	0.0017	0.0093	0.0017	0.0034	0.0017	0.0033
5/28/21	0.0036	0.0033	0.0004	0.0025	0.0013	0.0025	0.0020	0.0025	0.0110
8/13/21	0.0004	0.0048	0.0003	0.0038	0.0023	0.0038	0.0014	0.0038	0.0090
9/1/21	0.0004	0.0027	0.0003	0.0016	-	0.0016	0.0031	0.0016	0.0068
10/29/21	0.0002	0.0004	0.0001	0.0005	0.0025	0.0005	0.0023	0.0005	0.0038
1/16/22	0.0018	0.0013	0.0016	0.0159	0.0056	0.0159	0.0018	0.0159	0.0013
2/3/22	0.0013	0.0009	0.0017	0.0007	0.0051	0.0007	0.0031	0.0007	0.0017
3/23/22	0.0016	0.0017	0.0051	0.0094	0.0099	0.0094	0.0037	0.0094	0.0014
4/18/22	0.0016	0.0018	0.0018	0.0029	0.0052	0.0029	0.0019	0.0029	0.0009

6.2 Appendix B

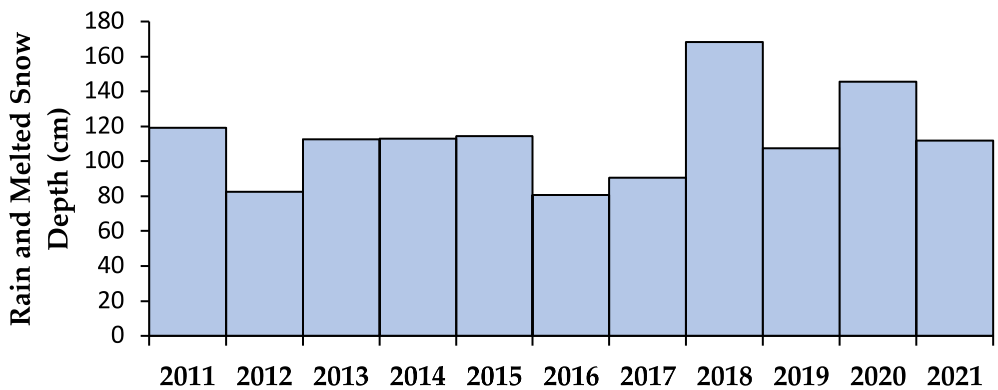

Figure B1 Diagram of the annual precipitation from the Washington Reagan National Airport Weather Station (nearby Lorton Road) between 2011 and 2021.

Table B1 Design specifications and other characteristics for monitored BR (CDA: contributing drainage area; ESM: engineered soil media).

CDA (m^2)	Impervious%	Footprint (m^2)	Engineered Storage (m^3)	InflowType	Outflow Type	Subsurface Layers (Surface → Down)	Mulch Depth (cm)	Engineered Soil Depth (cm)	Underlying Gravel Depth (cm)	Vegetation
47,753	35	1012	447	curb and gutter sewer	10.2 cm diameter underdrain + bypass channel	15.2 cm ponding with mulch and vegetation, 76.2 cm ESM (3.2% clay, 5.6% silt, 91.2% sand), 10.2 cm VDOT #8 stone (+ underdrain), 30.5 cm VDOT #57 stone	5	76.2	40.7	Blue Wild Indigo Marsh Marigold Fox Sedge Buttonbush Winterberry Sweetbay Rough Avens Cardinal flower

Table B2 Bioretention (BR) field rain and flow information of five representative monitored storm events.

Storm No.	Rain Depth (cm)	Duration Time (h)	Area of BR Basin (m^2)	Inflow Volume to BR Basin (L)	Area of Each Soil Column (m^2)	Proportional Inflow Volume for Each Soil Column (L)
1	0.74	3.3		78,101.0		16.6
2	1.01	4.3		57,532.7		12.2
3	2.29	6.0	862.4	214,782.2	0.183	45.6
4	1.91	5.5		307,237.3		65.2
5	2.44	8.7		261,833.0		55.6

Table B3 Design specifications and other characteristics for synthetic storm events (C_{In}: concentration of inflow).

Deicing Salt Concentration Level (ppm)	Storm No.	Duration Time (h)	Inflow Volume (L)	Inflow Cl^- Concentration (ppm)	Inflow Na^+ Concentration (ppm)
	1	3.3	16.6	34.1	26.0
	2	4.3	12.2	31.5	23.3
Low (0< C_{In}< 40)	3	6.0	45.6	33.0	26.1
	4	5.5	65.2	33.1	20.1
	5	8.7	55.6	33.2	22.7
	1	3.3	16.6	149.5	76.2
	2	4.3	12.2	183.5	93.2
Medium (40< C_{In}< 200)	3	6.0	45.6	167.9	84.2
	4	5.5	65.2	133.9	49.6
	5	8.7	55.6	135.4	53.3
	1	3.3	16.6	1545.8	689.7
	2	4.3	12.2	1863.6	697.7
High (500 < C_{In} < 2000)	3	6.0	45.6	1698.6	627.0
	4	5.5	65.2	1906.5	668.8
	5	8.7	55.6	1744.8	561.8

Table B4 Inflow and outflow characteristics for low-level deicing salt concentration of synthetic stormwater runoff (Blank: no plants; BWI: Blue Wild Indigo; BC: Broadleaf Cattail).

Inflow (L)	Inflow Concentration (mg/L)	Inflow Mass (mg)	Column	Outflow (L)	OUT_ Cl^- Concentration (mg/L)	OUT_ Cl^- Mass (mg)	OUT_ Na^+ Concentration (mg/L)	OUT_ Na^+ Mass (mg)
	Cl^-	Cl^-	Blank 1	15.6	23.1	360	9.3	145
	34.1	566	Blank 2	15.6	22.1	345	8.8	137
			BWI 1	14.2	22.0	312	9.4	133
16.6	Na^+	Na^+	BWI 2	14.6	21.7	317	9.2	134
	26.0	432	BC 1	14.0	14.5	203	8.6	120
			BC 2	14.0	18.5	259	8.5	119
	Cl^-	Cl^-	Blank 1	9.4	24.3	228	11.1	104
	31.5	384	Blank 2	9.8	23.5	230	10.6	104
			BWI 1	10.6	25.4	269	11.5	122
12.2	Na^+	Na^+	BWI 2	11.0	23.8	262	10.9	120
	23.3	284	BC 1	8.2	15.0	123	10.3	84
			BC 2	9.4	19.4	182	9.9	93
	Cl^-	Cl^-	Blank 1	41.5	32.0	1328	16.0	664
	33.0	1505	Blank 2	42.9	30.9	1326	13.6	583
			BWI 1	43.1	32.4	1396	13.9	599
45.6	Na^+	Na^+	BWI 2	39.9	31.2	1245	13.8	551
	26.1	1190	BC 1	35.8	19.7	705	11.7	419
			BC 2	38.0	25.7	977	12.6	479
	Cl^-	Cl^-	Blank 1	60.5	33.9	2051	16.1	974
	33.1	2158	Blank 2	60.3	33.0	1990	11.6	699
			BWI 1	49.2	34.8	1712	14.2	699
65.2	Na^+	Na^+	BWI 2	56.2	34.8	1956	15.3	860
	20.1	1311	BC 1	50.7	23.8	1207	14.8	750
			BC 2	48.4	27.8	1346	13.2	639
	Cl^-	Cl^-	Blank 1	51.8	34.7	1797	20.8	1077
	33.2	1846	Blank 2	52.0	34.6	1799	18.4	957
			BWI 1	46.1	35.6	1641	22.9	1056

55.6	Na^+	Na^+	BWI 2	49.7	35.9	1784	21.1	1049
	22.7	1262	BC 1	43.9	24.0	1054	17.7	777
			BC 2	46.0	29.7	1366	17.7	814

Table B5 Inflow and outflow water characteristics for medium-level deicing salt concentration of synthetic stormwater runoff (Blank: no plants; BWI: Blue Wild Indigo; BC: Broadleaf Cattail).

Inflow (L)	Inflow Concentration (mg/L)	Inflow Mass (mg)	Column	Outflow (L)	OUT_ Cl^- Concentration (mg/L)	OUT_ Cl^- Mass (mg)	OUT_ Na^+ Concentration (mg/L)	OUT_ Na^+ Mass (mg)
	Cl^-	Cl^-	Blank 1	13.0	45.2	588	24.2	315
	149.5	2482	Blank 2	13.9	44.6	620	24.0	334
			BWI 1	9.1	45.2	411	29.4	268
16.6	Na^+	Na^+	BWI 2	9.4	40.5	381	22.8	214
	76.2	1265	BC 1	3.0	36.9	111	24.6	74
			BC 2	0.1	75.1	8	28.6	3
	Cl^-	Cl^-	Blank 1	10.3	72.4	746	29.1	300
	183.5	2239	Blank 2	10.5	69.7	732	27.3	287
			BWI 1	8.2	65.7	539	30.0	246
12.2	Na^+	Na^+	BWI 2	9.8	56.0	549	25.1	246
	93.2	1137	BC 1	1.5	60.9	91	24.3	36
			BC 2	4.1	65.9	270	29.4	121
	Cl^-	Cl^-	Blank 1	37.2	112.9	4200	37.7	1402
	167.9	7656	Blank 2	37.6	116.7	4388	38.0	1429
			BWI 1	23.0	111.1	2555	37.6	865
45.6	Na^+	Na^+	BWI 2	27.2	115.7	3147	37.1	1009
	84.2	3840	BC 1	6.8	137.4	934	47.7	324
			BC 2	8.2	163.8	1343	63.1	517
	Cl^-	Cl^-	Blank 1	57.5	133.7	7688	36.8	2116
	133.9	8730	Blank 2	57.6	133.4	7684	38.8	2235
			BWI 1	41.8	141.4	5911	39.7	1659
65.2	Na^+	Na^+	BWI 2	41.4	139.7	5784	40.4	1673
	49.6	3234	BC 1	19.0	158.1	3004	60.7	1153
			BC 2	22.0	164.9	3628	53.7	1181
	Cl^-	Cl^-	Blank 1	47.1	108.5	5110	43.9	2068
	135.4	7528	Blank 2	47.8	120.8	5774	47.3	2261
			BWI 1	44.7	117.3	5243	51.8	2315
55.6	Na^+	Na^+	BWI 2	43.6	116.2	5066	45.7	1993
	53.3	2963	BC 1	20.1	192.0	3859	78.6	1580
			BC 2	18.3	178.3	3263	76.5	1400

Table B6 Inflow and outflow water characteristics for high-level deicing salt concentration of synthetic stormwater runoff (Blank: no plants; BWI: Blue Wild Indigo; BC: Broadleaf Cattail).

Inflow (L)	Inflow Concentration (mg/L)	Inflow Mass (mg)	Column	Outflow (L)	OUT_ Cl^- Concentration (mg/L)	OUT_ Cl^- Mass (mg)	OUT_ Na^+ Concentration (mg/L)	OUT_ Na^+ Mass (mg)
	Cl^-	Cl^-	Blank 1	15.1	229.1	3459	53.4	806
	1545.8	25,660	Blank 2	15.6	260.8	4068	60.1	938
			BWI 1	11.4	141.8	1617	40.4	461
16.6	Na+	Na+	BWI 2	13.9	171.7	2387	128.0	1779
	689.7	11,449	BC 1	9.0	256.8	2311	75.1	676
			BC 2	9.5	296.1	2813	83.4	792
	Cl^-	Cl^-	Blank 1	11.4	516.3	5886	112.3	1280
	1863.6	22,736	Blank 2	10.7	571.5	6115	139.9	1497
			BWI 1	10.6	288.3	3056	59.3	629
12.2	Na+	Na+	BWI 2	10.6	346.7	3675	72.3	766
	697.7	8512	BC 1	5.8	494.4	2868	118.3	686
			BC 2	7.4	579.3	4287	145.0	1073
	Cl^-	Cl^-	Blank 1	40.1	1458.0	58,466	362.3	14,528
	1698.6	77,456	Blank 2	40.5	1440.8	58,352	358.4	14,515
			BWI 1	36.9	1389.1	51,258	292.9	10,808
45.6	Na+	Na+	BWI 2	38.1	1446.1	55,096	334.2	12,733
	627.0	28,591	BC 1	35.3	1682.3	59,385	410.8	14,501
			BC 2	31.1	1780.9	55,386	416.5	12,953
	Cl^-	Cl^-	Blank 1	53.8	1939.2	104,329	704.5	37,902
	1906.5	124,304	Blank 2	54.2	1632.5	88,482	508.9	27,582
			BWI 1	52.5	1917.3	100,658	615.5	32,314

65.2	Na+	Na+	BWI 2	52.1	1803.0	93,936	633.9	33,026
	668.8	43,606	BC 1	42.7	2314.6	98,833	682.0	29,121
			BC 2	43.3	2317.2	100,335	666.7	28,868
	Cl^-	Cl^-	Blank 1	50.9	1836.4	93,473	562.5	28,631
	1744.8	97,011	Blank 2	53.0	1763.1	93,444	519.9	27,555
			BWI 1	51.2	1763.9	90,312	531.4	27,208
55.6	Na+	Na+	BWI 2	50.1	1838.4	92,104	560.7	28,091
	561.8	31,236	BC 1	42.9	1876.9	80,519	568.5	24,389
			BC 2	42.1	1855.2	78,104	570.3	24,010

6.3 Appendix C

Table C1 Stormwater runoff volumes for all monitoring sites

	Bioretention			Grass Channel		CA Grass Channel		Bioswale	
Event Date	**Inflow Volume (L)**	**Outlet Underdrain Volume (L)**	**Outlet Bypass Volume (L)**	**Inflow Volume (L)**	**Outlet Underdrain Volume (L)**	**Inflow Volume (L)**	**Outlet Underdrain Volume (L)**	**Inflow Volume (L)**	**Outlet Underdrain Volume (L)**
6/2/18	536065	117315	37704	173996	24150	209919	137119	207014	152112
8/31/18	854638	182464	34127	156163	87617	189725	144306	185699	35156
3/21/19	1201655	265087	147918	246345	59096	297294	195285	293087	128846
6/18/19	376315	71293	69077	38385	5116	50996	17777	43244	11183
10/17/19	499847	140005	25909	156102	1492	188331	5338	185724	27134
11/23/19	401100	69554	23554	37460	7120	45194	35676	44568	26344
8/3/20	1020679	223370	67811	214403	42154	260399	96098	254961	136395
12/4/20	666951	168937	26803	345568	49798	440057	124353	399167	132161
4/1/21	568002	152727	7303	103358	16615	126465	76109	122057	65121
5/28/21	386667	79260	5925	187237	5814	253971	17174	208237	29080
9/1/21	284531	49544	8262	182031	133	219613	16407	216574	16935
10/29/21	865738	175275	5096	292237	37146	373374	74568	336928	82131
3/23/22	518656	76751	3916	118723	10996	143235	53101	141253	23878
4/18/22	194615	43438	478	251063	3053	302898	14425	298705	11994

Table C2 Concentration of DOC for all monitoring sites

	Bioretention			Grass Channel		CA Grass Channel		Bioswale	
Date	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**	**Outflow Bypass (mg/L)**	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**
6/2/18	5.6	8.3	8.2	5.1	9.6	5.1	20.4	5.1	12.5
8/31/18	4.8	8.0	6.4	6.8	9.9	6.8	21.3	6.8	12.8
3/21/19	5.1	6.1	5.6	3.3	7.2	3.3	10.5	3.3	6.5
6/18/19	9.6	11.1	8.3	9.6	19.5	9.6	19.7	9.6	16.1
10/17/19	4.4	17.8	6.6	6.4	23.0	6.4	-	6.4	15.5

11/23/19	4.0	9.5	8.3	3.7	10.7	3.7	18.9	3.7	9.2
8/3/20	6.0	11.6	6.3	3.5	12	3.5	24.4	3.5	13.5
12/4/20	3.4	4.2	3.5	3.8	6.9	3.8	9.4	3.8	6.0
4/1/21	4.5	9.7	7.7	5.4	15.2	5.4	18.9	5.4	12.3
5/28/21	5.4	8.6	5.0	5.9	18.1	5.9	23.9	5.9	13.7
9/1/21	4.6	13.4	5.3	5.6	-	5.6	38	5.6	17.1
10/29/21	8.4	7.7	9.5	6.4	18.8	6.4	29.8	6.4	15.7
3/23/22	7.8	8.1	3.5	3.9	10.1	3.9	11.6	3.9	7.2
4/18/22	4.0	6.9	5.5	9.3	7.4	9.3	10.8	9.3	3.4

Table C3 Concentration of TDN for all monitoring sites

	Bioretention			Grass Channel		CA Grass Channel		Bioswale	
Date	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**	**Outflow Bypass (mg/L)**	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**
6/2/18	0.6	0.4	0.5	0.3	0.4	0.3	0.9	0.3	0.6
8/31/18	0.4	0.4	0.4	0.4	0.8	0.4	1.4	0.4	0.9
3/21/19	0.8	0.7	0.5	0.3	0.4	0.3	0.6	0.3	0.4
6/18/19	1.1	0.0	0.8	0.9	1.0	0.9	1.0	0.9	0.8
10/17/19	0.4	0.9	1.2	0.5	2.5	0.5	-	0.5	1.3
11/23/19	0.5	1.1	0.5	0.4	1.2	0.4	1.0	0.4	0.9
8/3/20	0.6	0.5	0.5	0.3	1.2	0.3	3.5	0.3	0.8
12/4/20	1.1	0.6	0.4	0.2	0.5	0.2	0.6	0.2	0.5
4/1/21	1.3	1.1	0.7	0.7	1.0	0.7	1.1	0.7	0.8
5/28/21	0.8	0.9	0.7	0.5	1.1	0.5	1.6	0.5	0.9
9/1/21	1.5	0.9	0.6	0.5	-	0.5	2.9	0.5	1.2
10/29/21	1.3	0.8	0.7	0.5	1.5	0.5	2.1	0.5	1.4
3/23/22	2.1	0.9	0.7	0.7	1.2	0.7	1.3	0.7	0.6
4/18/22	1.1	0.7	0.9	0.6	0.9	0.6	1.0	0.6	1.5

Table C4 Concentration of TSS for all monitoring sites

	Bioretention			Grass Channel		CA Grass Channel		Bioswale	
Date	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**	**Outflow Bypass (mg/L)**	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**	**Inflow (mg/L)**	**Outflow Underdrain (mg/L)**
6/2/18	17	10	25	105	11	105	36	105	19
8/31/18	22	23	15	128	50	128	45	128	52

10/17/19	20	43	10	78	-	78	-	78	31
11/23/19	19	15	11	94	14	94	20	94	8
8/3/20	24	20	14	78	15	78	18	78	23
12/4/20	17	7	15	246	41	246	30	246	12
4/1/21	253	10	54	355	81	355	*	355	26
5/28/21	773	28	32	171	18	171	50	171	39
9/1/21	23	14	14	49	-	49	59	49	24
10/29/21	23	7	39	13	32	13	22	13	8
3/23/22	47	13	51	275	156	275	121	275	35
4/18/22	103	11	-	72	62	72	74	72	33