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Evaluating the Effectiveness and Maintenance of Low Impact Development Designs for Stormwater Management: A Case Study Along Lorton Road in Fairfax County

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Abstract:

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This research assesses the effectiveness of four LID systems, which include a bioretention basin, a grass channel, a compost-amended grass channel, and a bioswale, along Lorton Road in Fairfax County, over an extended monitoring period spanning multiple years. The primary objective is to investigate the stormwater quantity and quality performance of these LID systems. This study also evaluates their maintenance efficiency, factoring in various water quality parameters and economic costs, primarily emphasizing safeguarding public health and environmental preservation.

Results of this study indicate that the grass channel emerged as the most effective in terms of runoff and pollutant load reductions, despite serving a modest contributing drainage area and incurring higher average maintenance costs per catchment drainage area annually. In contrast, bioretention, which ranked second in volume and mass load reduction for pollutants, effectively serves the largest contributing drainage area and maintained consistent performance over time. Maintenance efforts enhanced the performance of the swales, with the compost-amended grass channel showing the most significant improvement, emphasizing the effectiveness of maintenance for this specific type of swale.

Three notable changes in practice are recommended. First, use multiple performance metrics to evaluate LID performance, such as considering contributing drainage area, footprint, and maintenance procedures. Second, consider other pollutants in addition to phosphorous. Third, exercise caution when employing compost amendments in swale soils to avoid nutrient losses, as evidenced by the negative impact observed in the compost-amended grass channel. Because the Department of Environmental Quality draft *Stormwater Management Handbook* is presently being updated, VDOT has an opportunity, through participation in the Stormwater Advisory Group, to advocate for these changes in practice.

FINAL REPORT

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ABSTRACT

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INTRODUCTION

The development of urbanization has transformed land use in the United States, resulting in more impervious surfaces overlaying natural landscapes. During storm events, these impervious surfaces accumulate rainwater and channel it to storm sewers, thereby disrupting the natural hydrologic cycle. Sudden release of stormwater from impervious surfaces can precipitate a range of adverse effects, including inundation, increased runoff volumes and peak flow rates, erosion, and the introduction of pollutants into receiving bodies of water (Ahiablame et al., 2013, 2013; Wardynski et al., 2014). In addition, high stormwater flows can trigger combined sewer overflows in urban areas. The impact of urban stormwater runoff on ecosystem health has been well-documented. Non-point source pollution has become the leading threat to aquatic ecosystem habitats in the United States and other highly developed countries over recent years (Spromberg et al., 2016; Walsh et al., 2005). Effective stormwater management is vital to reduce runoff and associated pollutants to preserve public health and the environment (Barbosa et al., 2012; Henderson et al., 2019).

In urban environments, particularly within the context of linear transportation systems such as highways, the issue of stormwater runoff is a significant concern (Kim et al., 2005; Rotaru et al., 2012). Highways, characterized by extensive impervious road surfaces, stand as a main source of stormwater runoff, leading to a discernible deterioration in the water runoff quality. The runoff from highways typically contains a spectrum of common contaminants, including sediment, nutrients, total organic carbon, and metals (Barrett et al., 1998; Li et al., 2008; Rotaru et al., 2012; Walsh et al., 1998; Yu et al., 1993). Consequently, the effective management of stormwater runoff from highways has been a primary objective for many state departments of transportation, driven by its substantial impact on water quality degradation. Thus, the imperative for stormwater management remains essential to mitigate the potential effects of highway runoff on the quality of receiving waters.

Conventional stormwater management approaches, typified by the employment of gray infrastructure systems consisting of pipes, gutters, and tunnels, often direct stormwater runoff away from communities and discharge it directly into local surface waters without undergoing any treatment. However, the efficacy of such methods in handling substantial runoff volumes and concurrently addressing diverse environmental challenges remains limited. Thus, enhancements in existing stormwater management methodologies are needed to control flows and protect water resources (McFarland et al., 2019). In response to this imperative, Low impact development (LID), also known as green infrastructure (GI) or green stormwater infrastructure (GSI), has emerged as an ecologically sustainable alternative to traditional gray infrastructure practices within the United States since the 1990s (Al Bakri et al., 2008). LID practice is a combination of techniques that involve the use of vegetated soil and other natural landscape features to achieve the retention, infiltration, or evapotranspiration of stormwater. This, in turn, reduces stormwater discharges into both sewer systems and surface waters, mimicking the hydrological processes of natural landscapes, which encompass the slowing, spreading, and infiltration of stormwater runoff prior to its discharge into receiving waters. The efficacy of LID practices in ameliorating the adverse impacts of urban stormwater is well-documented (Al Bakri et al., 2008; Henderson et al., 2019; McFarland et al., 2019; Russo et al., 2017). Numerous LID strategies have been employed to efficiently manage stormwater runoff. Prominent examples of these strategies include the implementation of green roofs, the establishment of bioretention basins, and the incorporation of swales into urban design (Burgis, 2020; Hayes, 2021; Zhang, 2023).

Bioretention

Bioretention, a low impact development (LID) technique, involves the temporary retention of stormwater runoff within a shallow vegetated depression, followed by its swift infiltration into an underlying engineered soil media layer (Li et al., 2016). These bioretention systems are designed to permit controlled water ponding above the topsoil layer. The infiltration process through the engineered soil media creates an environment conducive to the removal of pollutants through a combination of filtration, sorption to soil, plant uptake, and biological activity. In addition to effectively reducing the concentration of suspended solids, metals, and nutrients, bioretention filters yield substantial runoff reduction, thereby diminishing the transportation of pollutants to receiving waters (Yu et al., 2013). Similar to other LID approaches, the engineered soil media in bioretention systems may include the incorporation of compost.

Bioretention filters have played a critical role in the implementation of green infrastructure to achieve a number of sustainable stormwater management objectives. According to the stormwater design specifications outlined by the Virginia Department of Environmental Quality, bioretention is recognized for its capability to achieve a 40% reduction in runoff, a 64% reduction in total nitrogen load, and a 55% reduction in total phosphorus load in the context of a level one design, and 80% runoff volume reduction, 90% total nitrogen load reduction, and 90% target total phosphorus load reduction for a level two design (Eger et al., 2017; Maniquiz et al., 2010; Tedoldi et al., 2016; Yu et al., 2013). Bioretention runoff volume reductions have been reported as high as 98%. Performance depends on hydrologic conditions such as rainfall intensity, duration, season, and antecedent moisture conditions (Jenkins et al., 2010; Line and Hunt, 2009; Shrestha et al., 2018).

Swales

Swales represent another frequently encountered category of LID design. This category encompasses a variety of components, including grass channels, compost-amended grass channels, bioswales, etc. Swale designs include a variety of soil materials and vegetation types to serve varying treatment objectives.

Grass channels (GC), or vegetated swales, represent an open-channel management practice characterized by vegetation, expressly designed to address and mitigate runoff for a predetermined water quality volume. Their role in enhancing water quality includes the removal of pollutants through sedimentation and filtration of particulate matter. The presence of a high-density vegetative cover introduces resistance to flow, thereby reducing flow velocity and consequently enhancing the efficiency of sedimentation. Grass channels are particularly well suited for highways and rural road implementation due to their linear configuration (Burgis, 2020). Grass channels may incorporate check dams for increased water retention and compost-amended soils for improved soil structure and stormwater infiltration rates (Burgis, 2020).

The grass channel equipped with compost-amended soil media is known as a compost-amended grass channel (CAGC) and is another type of swale. In a research investigation on grass channels conducted in Texas, notable removal efficiencies were observed, with a 35% reduction in total nitrogen and a 37% reduction in total phosphorus noted (Walsh et al., 1998). Furthermore, Davis et al. (2012) found that vegetated swales, including check dams, significantly reduced runoff volume during rain events with a precipitation depth of less than 3 cm (Davis et al., 2012). A study by Stagge et al. (2012) reported event mean concentration (EMC) removal efficiency of 65-71% for total suspended solids and 30-60% for zinc (Stagge et al., 2012).

Bioswales (BS), also called dry swales, are a category of swales distinguished by the incorporation of engineered soil media beneath the vegetative layer with an underdrain, like the approach employed in bioretention systems. An underdrain system accompanies bioswales to enhance drainage, especially when the native soils or construction fill lack the requisite infiltration capacity. This underdrain system typically comprises perforated pipes within a gravel sump, ensuring adequate drainage. The effluent from the underdrain typically discharges directly into a storm sewer system or receiving waters. Notably, the engineered soil media may be supplemented with compost amendments. Bioswales have demonstrated remarkable effectiveness, yielding total runoff reductions ranging from 78% to 98% and concentration reductions of 73% to 88% for total suspended solids (TSS), 61% to 77% for total nitrogen (TN), and 61% to 79% for total phosphorus (TP) (Jiang et al., 2017; Xiao and McPherson, 2011).

Research on runoff reduction performance of swales has found sufficient volume reduction for smaller rain events, less reduction in larger events, perforated underdrains assisting in volume reduction, and antecedent moisture conditions influencing water storage capacity (Ellis et al., 1994; Kim et al., 2005; Vogel et al., 2015). Davis, et al (2011) observed runoff reductions ranging from 27% to 63% in swales that incorporated check dams.

PURPOSE AND SCOPE

Evaluation of LID performance for highway stormwater management is necessary to determine the feasibility of LID systems to meet new regulatory guidelines effectively. A knowledge gap currently exists regarding both long-term performance and maintenance requirements associated with LIDs for linear transportation systems. The objectives of this study are to develop a plan to assess both the performance and to determine the maintenance requirements, procedures, and costs associated with LIDs used in the highway settings that have been implemented as part of the Lorton Road widening project. The scope of this study is limited to a single location where extensive monitoring has been conducted for a bioretention basin and three swales with different characteristics. This is advantageous for comparison because each LID responds to the same storm event, so direct comparisons between LID efficiency can be made.

METHODS

This study aims to explore the performance and evaluate the efficiency of four types of LID practices, a bioretention (BR), a grass channel (GC), a compost-amended grass channel (CAGC), and a bioswale (BS), over a multi-year range at Lorton Road, located within Fairfax County, Virginia. LID 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), and trace metals.

The GC, CAGC, and BS are all swales for linear stormwater management, while the BR is non-linear. They were installed in spring 2017 by the Virginia Department of Transportation (VDOT) along Lorton Road, and are within 0.8 km of each other (as shown in Figure 1). These four designs are commonly used in transportation stormwater management, receiving relatively similar pollutant inputs along the same highway. They were selected based on specific features, including climate, soil quality, watershed area, and expected pollutants (Hayes et al., 2023). The design specifications and characteristics of these four LID designs are presented in Table 1. Each LID system has a different design, receiving runoff directly from Lorton Road. The four LID systems are maintained by a VDOT contractor twice per year (once in spring and once in fall) by trimming the vegetation to 10 – 15 cm, redistributing mulch, and removing trash and other debris. Trimmings from each LID design are removed and disposed of at a landfill (Hayes et al., 2023).

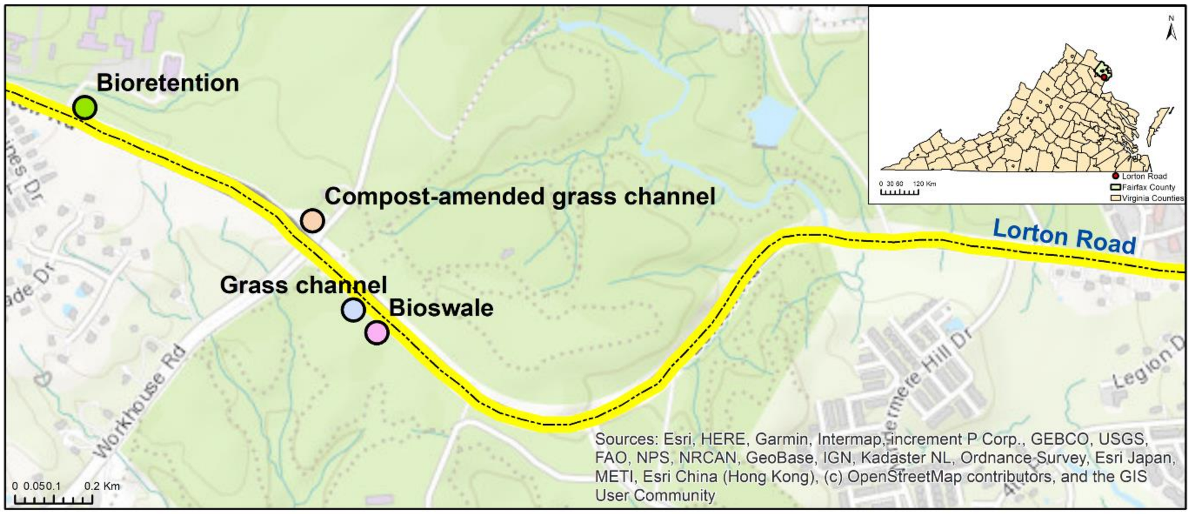

Figure 1. Lorton Road stormwater research site and positioning of four types of LIDs.

The bioretention system (BR), located north of Lorton Road, comprises a two-part structure designed for stormwater management. It incorporates a forebay for pretreatment and a vegetated basin for further treatment, which includes engineered soil media (ESM), an underdrain system, and a gravel sump. The BR basin is approximately 77 m above mean sea level, with the groundwater depth averaging around 2.3 m during the monitoring period. This BR serves a 47,753 m^2 contributing drainage area. A 0.6 m concrete culvert through an earthen berm is installed to connect the forebay to the BR basin. Stormwater runoff from the road is channeled into the forebay, serving as the initial inflow before progressing into the BR basin, where a variety of vegetation is cultivated in the engineered soil media (comprising 3.2% clay, 5.6% silt, and 91.2% sand) layered atop a bed of underlying gravel (VDOT #8 stone with the outlet and VDOT #57 stone). Following treatment, the stormwater is directed out through an underdrain system positioned at the upper level of the gravel layer, ultimately entering the Giles Run watershed, which is part of the larger Chesapeake Bay watershed (Burgis et al., 2020a; Zhang et al., 2022). To handle the excessive runoff during substantial storm events, a bypass system has been installed, interconnected with the forebay. This bypass system provides an overflow mechanism. The specific design specifications and plant species employed in the BR basin are listed in Table 1. To gather essential data during monitored events, monitoring sites have been strategically installed at the inlet, outlet, and bypass of the bioretention system to collect stormwater samples and measure flow parameters during monitored events (Figure 2, top).

Table 1. Design Specifications and Characteristics of LIDs at Lorton Road

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

The grass channel (GC), having a 2,533 m^2 contributing drainage area, is located to the south of Lorton Road, around 0.8 km to the east of the BR. This straight grass-lined channel comprises native soils where wildflowers grow and lacks an underdrain system. It is 85-m-long with a slope ratio of 1:20. To intercept runoff and facilitate infiltration, the GC features three wooden check dams (Figure 2, bottom left). More details of GC design specifications are presented in Table 1.

The compost-amended grass channel (CAGC) is a grass channel that incorporates compost-amended soils, serving a 6,874 m^2 contributing drainage area, and is approximately 0.4 km to the east of the BR on the north side of Lorton Road. The CAGC is characterized by a linear slope with a length of 232 m and a ratio of 1:60, with 6 wood check dams, consisting of 30 cm compost-amended native soils and native soils where trees, shrubs, grasses, and wildflowers grow (Figure 2, Middle). More details for CAGC design characters are provided in Table 1.

The bioswale (BS) is a 65-m-long linear swale incorporating engineered soil media (ESM) and an underdrain system. It has a 1:27 linear slope and is equipped with 6 wood check dams, serving a contributing drainage area of 2,772 m^2. It shares the same engineered soil media as the bioretention system and incorporates an underdrain situated at the upper level of the gravel layer beneath the engineered soil media (refer to Figure 2, bottom right). Further specifications of the BS can be found in Table 1.

In contrast to the BR receiving concentrated inflow, the three monitored swales receive unconcentrated inflow from Lorton Road. The inflow to these swales comprises non-concentrated, overland flow originating from the adjacent roadway, naturally emanating from the road surface. A 9.1-m-long sheet flow collector, positioned to directly receive runoff from the road, serves as the point of entry for impervious drainage area runoff (adjacent to the contributing drainage areas of the swales). This sheet flow collector serves a contributing drainage area of 88 m^2 and is along the sidewalk of Lorton Road. The inflow from pervious drainage areas for these three monitored swales was estimated using the curve number (CN) method, as described by Hayes et al. (2021). Monitoring sites were installed at the downstream end of each monitored swale (CAGC, GC, and BS) to collect the treated outflow.

Seven monitoring stations were strategically positioned in the field to comprehensively monitor both the quantity and quality performance of stormwater runoff for the four monitored LID systems. The bioretention has three monitoring sites (inflow, bypass, and outflow). Additionally, four monitoring sites are dedicated to the swales (one for inflow and three for outflow of each swale). Each monitoring station is equipped with 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, as depicted in Figure 3. To monitor key parameters of each storm event, such as duration and rainfall depth, a Hach tipping bucket rain gauge, paired with a Hach AS900, is incorporated into the BR. In cases where the rain gauge experiences a power outage, precipitation data sourced from the Weather Underground Station at Washington Reagan National Airport (located near the monitoring area) is employed as an alternative data source. For water quality analysis, flow-weighted composite stormwater samples at each monitored station were collected automatically into a 9.5 L glass bottle in the auto-sampler during each storm event. They are stored on ice in the field, collected within 24 hours of a storm event, and carried back to the lab for analysis. Each autosampler is powered by solar panels, which store power in batteries. Figure 3 presents an example of the stormwater sampling setup at the sheet flow collector.

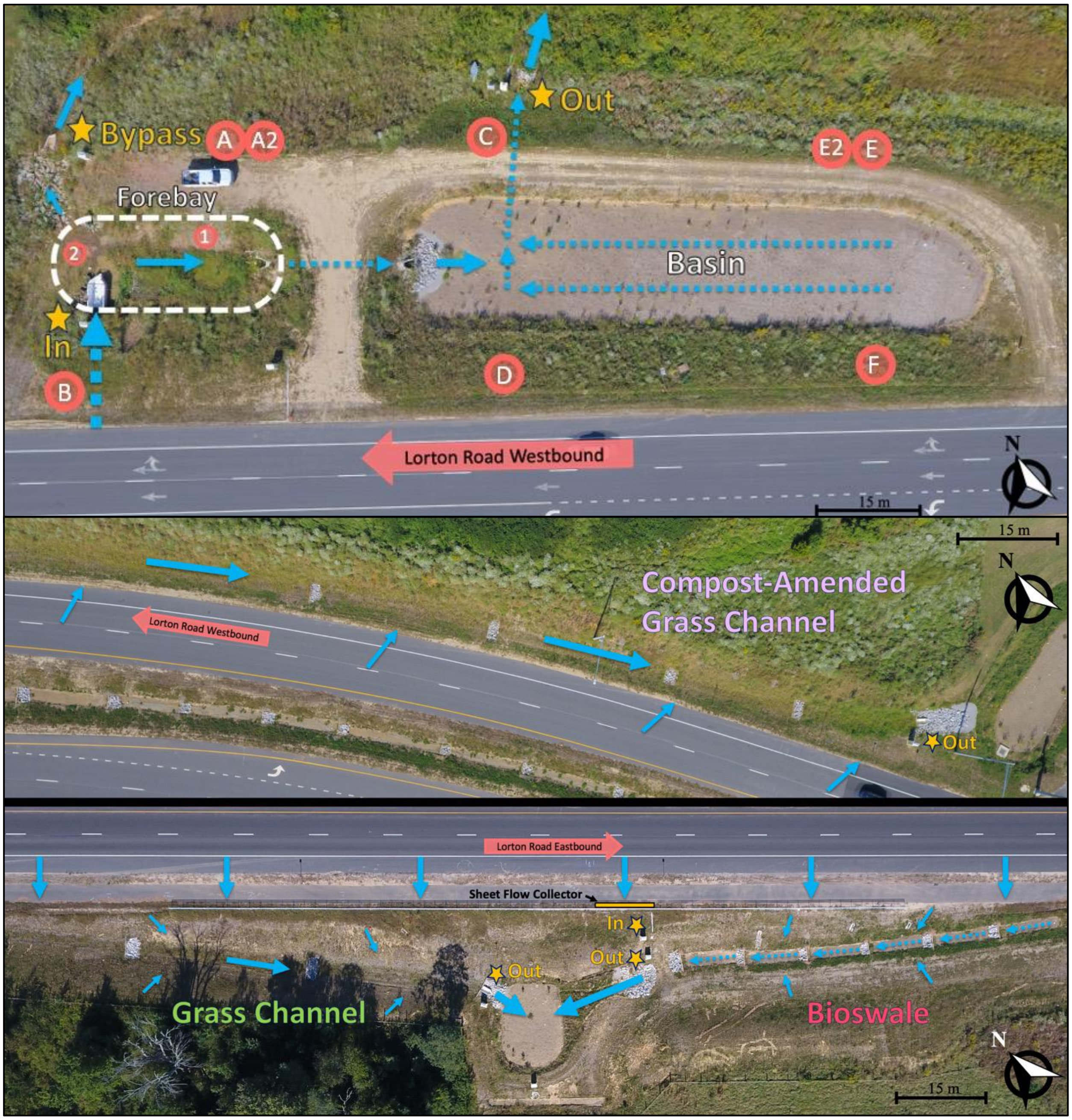

Figure 2. Stormwater monitoring site and positioning of four LID designs at Lorton Road. Solid blue lines indicate surface stormwater flow direction, while dotted blue lines show underground drains. Yellow stars indicate stormwater monitoring locations and red circles show groundwater monitoring wells, and the orange rectangle shows the position of the sheet flow collector. (Top: Bioretention; Middle: Compost-amended grass channel (CAGC); Bottom: Grass channel (GC) (left) and Bioswale (BS) (right).)

Figure 3. Stormwater sampling setup at the roadside sheet flow collector along Lorton Road

Between March 2018 and December 2022, approximately 60 storm events were monitored and sampled for analysis. During the initial 14 months of mutual monitoring, 9 relatively completed sampling events were conducted, providing a basis for assessing the short-term performance of the four types of LID systems. Subsequently, over the entire duration of the project, a total of 24 relatively completed storm events were comprehensively sampled, yielding a substantial and representative volume of data across all four LID system types. Stormwater samples were collected from all 7 monitoring sites during these events. These datasets are instrumental for the long-term performance evaluation undertaken in this study.

The collected field samples are analyzed for a range of parameters in this study, encompassing measurements of runoff volume, ion concentrations, total suspended solids (TSS), nutrients, and trace metals. Samples filtered through 0.45 µm filters are analyzed for ion concentrations employing a Thermo Scientific Dionex ICS 5000 DP-5 ion chromatography (IC). All samples were preserved with a 2% HNO_3 solution and filtered through 0.45 µm filters prior to metals analysis using an Agilent 7900 ICP-MS inductively coupled plasma mass spectrometry (ICP-MS). TSS was quantified through filtration using Whatman 1.5 µm glass microfiber and gravimetric determination based on USEPA method 160.2. Samples for dissolved organic carbon (DOC) and total dissolved nitrogen (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.

Between the years of 2018 and 2022, a total of eleven maintenance events were carried out for the four LID practices under investigation in this study. These maintenance activities consisted of two regular maintenance events each year (once in spring, once in fall), along with a forebay restoration conducted in 2021. Regular bi-annual maintenance activities, consisting of removing the trash, mowing roadside grass slopes, removing debris, and adding mulch to maintain its levels (where applicable), are carried out by Apex Companies, LLC, hired by the Virginia Department of Transportation. To assess the effectiveness of these maintenance efforts, eight specific events were chosen for analysis based on the specific stormwater sampling condition. Seven regular maintenance events occurred during the fall season of 2018, spring and fall of 2019, fall of 2020, spring and fall of 2021 (as shown in Figure 4), and spring of 2022, in addition to the 2021 forebay restoration, which occurred at the same time with the regular fall maintenance of BR that year.

Figure 4. Four monitored LID designs along Lorton Road (BR: bioretention; CAGC: compost-amended grass channel; GC: grass channel and BS: bioswale)

In October 2021, an additional maintenance event aimed at restoring the bioretention (BR) forebay was conducted, as illustrated in Figure 5. The forebay had experienced an accumulation of soil and sediment over time, primarily due to a construction project along Lorton Road, within the drainage area of the BR. This accumulation resulted in a gradual elevation increase in the forebay. The restoration efforts involved the removal of unwanted vegetation and the dredging of soil and sediment.

Figure 5. Forebay restoration maintenance in October 2021

The concentration of pollutants in the flow-weighted composite sample is referred to as the event mean concentration (EMC). EMC serves as a representative measure of pollutant concentration at each monitoring site, and compares the performance of multiple LID designs during a single storm event or the evaluation of a single LID practices performance across multiple storm events (Burgis, 2020). The calculation of EMC is typically performed using Equation (1).

$$EMC = Total\ pollutant\ mass\ / Total\ runoff\ volume \qquad (1)$$

This study assesses and compares the efficacy of different LID practices with regard to their capacity to diminish the mass load of pollutants across various water quality parameters and stormwater runoff events. To quantify the flow rates for each monitored storm event, H or HS flumes from Open Channel Flow, equipped with ultrasonic sensors, are utilized. The selection of the appropriate flume size for each monitoring site is guided by an estimation of the stormwater flow rate for that specific location. Stormwater flow rate can be calculated based on Equation (2), which considers the specific flume size and geometry, as well as the height of flowing water within it (Hayes, 2021).

$$Q = a + b * h^{e} + c * h^{1.5} + d * h^{2.5} \qquad (2)$$

In Equation (2), Q=flowrate, h=stormwater height, a, b, c, d , and e are empirically derived constants specific to each flume size.

Stormwater runoff volume reductions are calculated employing Equation (3), while the total mass load reductions for each category of water quality parameters are determined using Equation (4).

$$VR = \frac{(In - Out)}{In} * 100 \qquad (3)$$

In Equation (3), *VR*=volume load reduction, *In*=inflow volume (L), and *Out*=outflow volume (L).

$$MR = \frac{(Con_{In} * In - Con_{out} * Out)}{Con_{In} * In} * 100 \qquad (4)$$

In Equation (4), *MR*=mass load reduction, Con_{In}= water quality parameter concentrations of inflow (mg/L), *In*=inflow volume (L), Con_{out}= water quality parameter concentrations of outflow (mg/L), and *Out*=outflow volume (L).

The software R (version 4.2.0) was used for statistical analysis. Analysis of variance (ANOVA) was used to assess the effect of LID and reductions of water quality parameters. Data normality was confirmed using the Shapiro-Wilk test. A criterion 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 LID groups.

RESULTS AND DISCUSSION

Figure 6 presents an example of the hydrograph of the bioretention for a storm event on July 30, 2018, with a rainfall depth of 0.96 inches. The graph visually represents rainfall depth, sampling timestamps, and flow rates at all three measurement points within the bioretention system. Notably, the figure indicates that the flow rates at the bioretention inlet exhibit significant peaks, while the flow rates at the outlet are consistently much lower. This observation underscores the commendable effectiveness of the bioretention system in mitigating both flow rate and volume during stormwater treatment. Such performance is notably beneficial for the protection of nearby receiving waters.

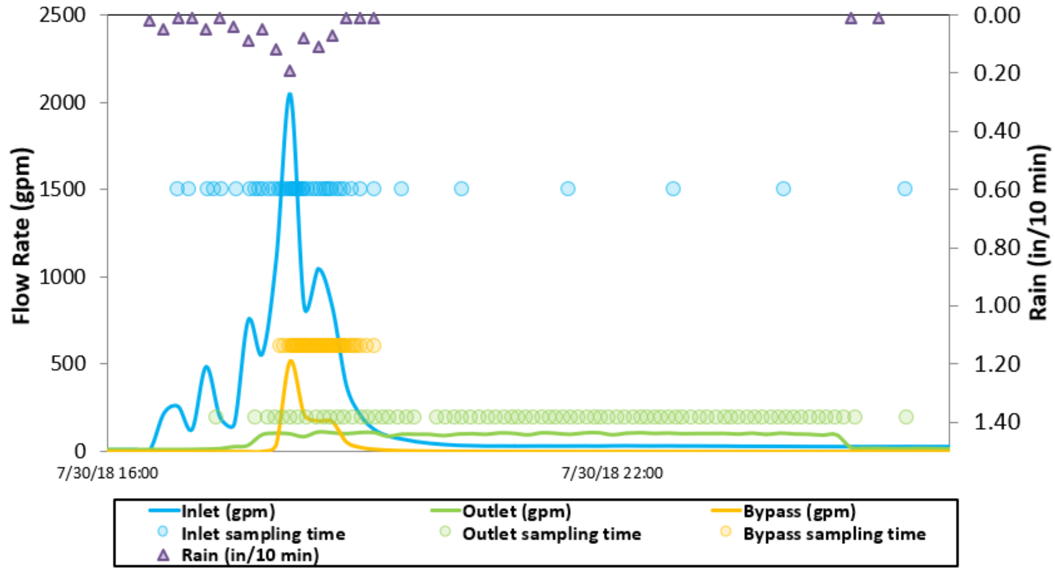

Figure 6. Hydrograph of Bioretention for July 30, 2018, 0.96-in. storm

Short-term monitoring

Between March 2018 and June 2019, an integrated assessment of stormwater pollutant concentrations and runoff volumes was conducted, resulting in the determination of total surface water influent and effluent loads for each LID system across the initial 14 months of mutual monitoring (refer to Figure 7). Notably, the bioretention system exhibited substantially larger influent loads compared to the swales across all water quality parameters, primarily attributable to its considerably larger contributing drainage area.

The effluent loads from the bioretention system are comprised of cumulative underdrain outlet loads and bypass channel loads. For various water quality parameters, including nitrate, TDN, phosphate, TP, DOC, and TSS, a proportion of the bioretention surface effluent loads was bypassed, which are 3%, 8%, 14%, 19%, 13%, and 32% of nitrate, TDN, phosphate, TP, DOC, and TSS, respectively, with the remaining surface effluent loads exiting through the underdrain outlet.

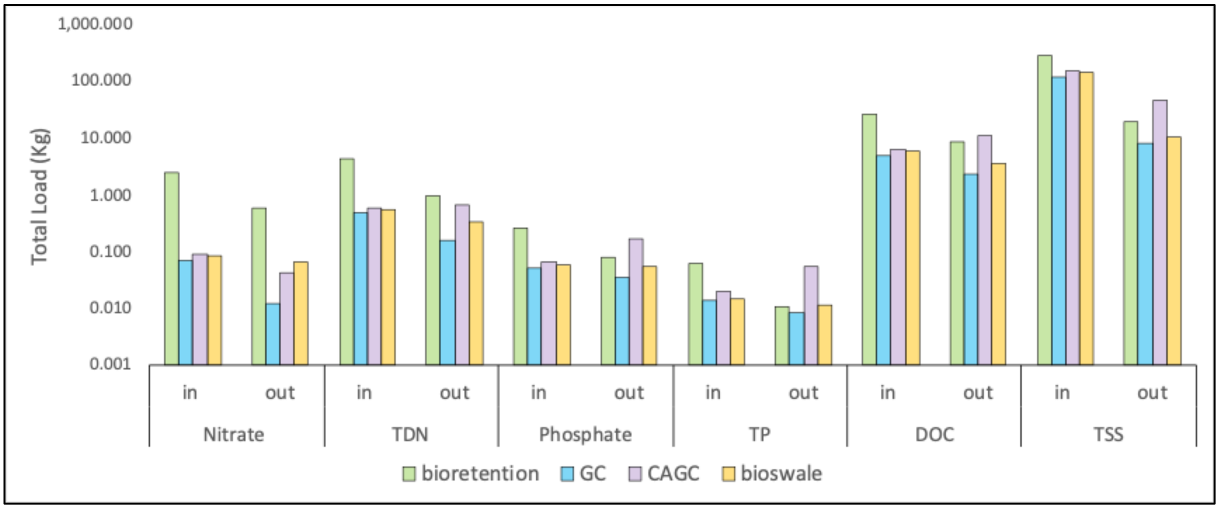

Figure 7. LID surface water inlet and outlet water quality parameter total loads from mutually monitored events during March 2018 and June 2019. From left to right: nitrate as nitrogen (N) (9 events), total dissolved nitrogen (TDN) (9 events), phosphate as phosphorous (P) (7 events), total phosphorous (TP) (2 events), dissolved organic carbon (DOC) (9 events), and total suspended solids (TSS) (6 events). Outlet loads for the bioretention are a sum of the underdrain outlet and bypass channel. The vertical total load axis is log-scaled. (GC: grass channel, CAGC: compost-amended grass channel)

Effluent surface load reductions for the monitored LID systems varied across different parameters. Nitrate average concentration reductions were 20%, 63%, 55%, and -53% for the bioretention, GC, CAGC, and bioswale, respectively. TDN average concentration reductions were 30%, -6%, -69%, and -28% for the bioretention, GC, CAGC, and bioswale, respectively. Phosphate average concentration reductions were 6%, -31%, -224%, and -65% for the bioretention, GC, CAGC, and bioswale, respectively. TP average concentration reductions were 48%, -3%, -234%, and -34% for the bioretention, GC, CAGC, and bioswale, respectively. DOC average concentration reductions were -6%, -69%, -178%, and -67% for the bioretention, GC, CAGC, and bioswale, respectively. TSS average concentration reductions were 85%, 82%, 56%, and 84% for the bioretention, GC, CAGC, and bioswale, respectively, highlighting the variability in their performance across these water quality parameters.

Figure 8 provides a comprehensive overview of the overall performance of the four LID types, focusing on total stormwater runoff, average concentrations, and total loads of nitrate, TDN, phosphate, TP, DOC, and TSS, as well as six metals (chromium, nickel, copper, zinc, cadmium, lead). This analysis reveals notable variations in stormwater management performance criteria across the four LID systems and for different water quality parameters.

The bioretention and GC consistently exhibited positive load reductions across all water quality parameters. In contrast, the bioswale demonstrated a single instance of pollutant load export (phosphate), while the CAGC experienced pollutant load exports in four parameters (TDN, phosphate, TP, and DOC). Among the four GI systems, the bioretention consistently achieved the most robust load reduction performance across all water quality parameters, while the GC showcased the highest level of consistency among the three swales.

Nitrate total surface load reductions were 76%, 83%, 54%, and 21% for the bioretention, GC, CAGC, and bioswale, respectively. TDN total surface load reductions were 77%, 68%, -

15%, and 42% for the bioretention, GC, CAGC, and bioswale, respectively. Phosphate total effluent surface load reductions were 71%, 32%, -156%, and 3% for the bioretention, GC, CAGC, and bioswale, respectively. TP total effluent surface load reductions were 83%, 41%, -162%, and 24% for the bioretention, GC, CAGC, and bioswale, respectively. DOC total effluent surface load reductions were 66%, 53%, -71%, and 39% for the bioretention, GC, CAGC, and bioswale, respectively. TSS total effluent surface load reductions were 93%, 93%, 68%, and 93% for the bioretention, GC, CAGC, and bioswale, respectively. Metals total effluent surface load reductions for Cr were 78%, 80%, 25%, and 68%, for Ni were 42%, 82%, -22%, and -36%, for Cu were 55%, 75%, -53%, and -13%, for Zn were 67%, 74%, 36%, and 57%, for Cd were 84%, 70%, 13%, and -33%, and for Pb were 68%, 70%, -3%, and 37%, all for the bioretention, GC, CAGC, and bioswale, respectively.

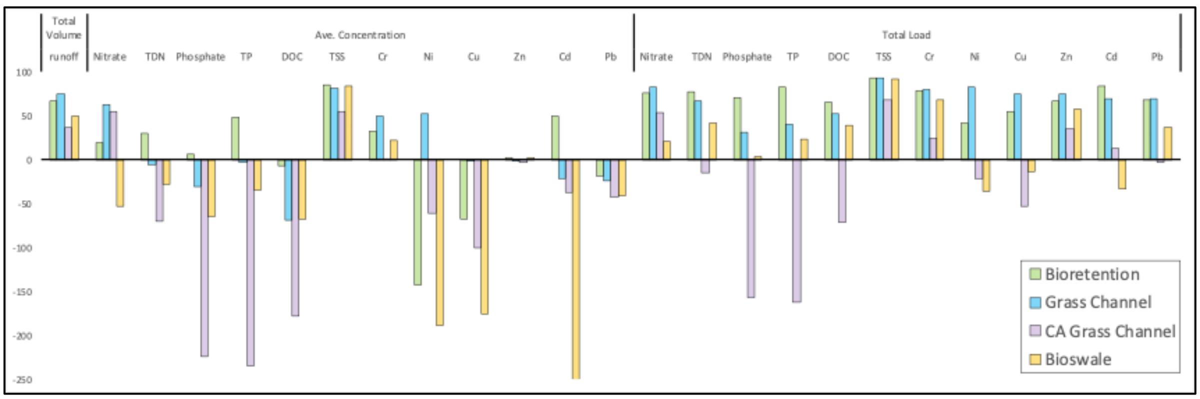

Figure 8. LID stormwater management performance over the first 14-month mutual monitoring period. From left to right: total stormwater runoff reductions, average concentration reductions (in vs. out), and total load reductions. Outlet concentrations for the bioretention are the underdrain outlet, while outlet loads are a sum of the underdrain outlet and bypass channel.

The bioretention system exhibited the lowest total LID effluent loads per unit contributing drainage area across all water quality parameters, with the exception of nitrate, for which the GC achieved the lowest value (refer to Figure 9). Specifically, the sum of the six water quality parameters' total effluent loads per unit contributing drainage area were 1104 kg/km^2, 4801 kg/km^2, 9434 kg/km^2, and 7566 kg/km^2 for the bioretention, GC, CAGC, and bioswale, respectively.

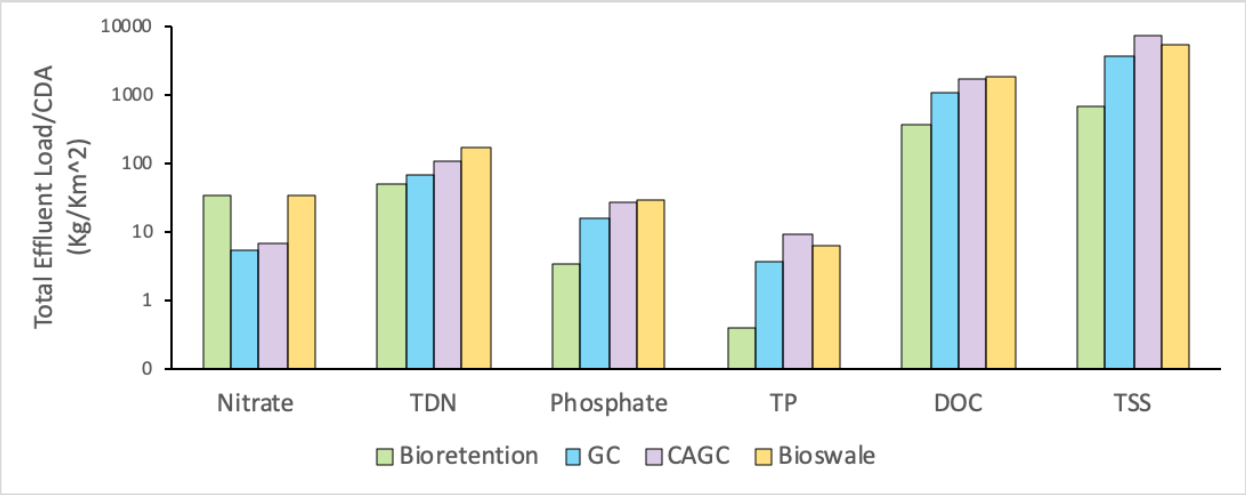

Figure 9. LID stormwater quality parameter effluent loads per unit contributing drainage area over the first 14-month mutual monitoring period. Bioretention outlet loads are a sum of the underdrain outlet and bypass channel. (GC: grass channel, CAGC: compost-amended grass channel)

Figure 10 provides a comprehensive summary of the overall performance of the four LID types concerning the average total load reduction across all 12 stormwater quality parameters. These parameters encompass nitrate, TDN, phosphate, TP, DOC, TSS, as well as six metals (Cr, Ni, Cu, Zn, Cd, Pb) over the initial 14-month mutual monitoring period for all four LID types. Notably, there exists a significant degree of variability in the performance metrics for stormwater management across the four LID systems and among different water quality parameters.

The bioretention and grass channel (GC) consistently demonstrated positive load reductions across all water quality parameters. In contrast, the compost-amended grass channel (CAGC) exhibited seven instances of load export (TDN, phosphate, TP, DOC, Ni, Cu, Pb), while the bioswale recorded four instances of load export (phosphate, Ni, Cu, Cd). Among the four LIDs, the bioretention exhibited the most consistent load reduction performance across all water quality parameters, while the GC showcased the highest level of consistency among the three swales.

The average load across all 12 water quality parameters was 72 ± 4 (standard error) for bioretention, 69 ± 5 for GC, -24 ± 22 for CAGC, and 25 ± 11 for bioswale (as depicted in Figure 10). Statistical analyses revealed that the bioretention's average load reduction across all water quality parameters was significantly higher than that of the CAGC ($p < 0.0001$) and nearly significantly higher than the bioswale's ($p = 0.059$) but not significantly different from the GC's ($p = 0.998$). The GC's average load reduction of all water quality parameters was also significantly higher than that of the CAGC ($p < 0.0001$), but not quite the bioswale's ($p = 0.089$). The bioswale's average load reduction of all water quality parameters was significantly higher than the CAGC's ($p = 0.043$).

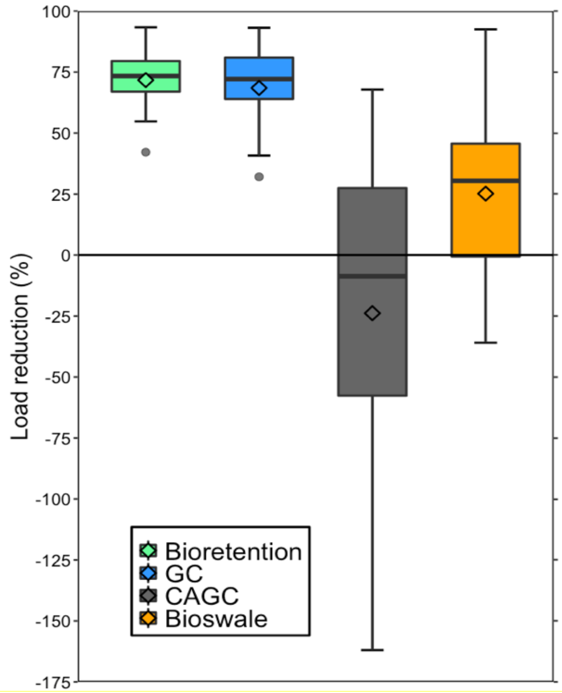

Figure 10. Average total load reduction of all 12 stormwater quality parameters over the first 14-month mutual monitoring period for all four LID types. Boxplots depict median values (thick black line), mean values (diamond), 25th to 75th percentiles (colored boxes), 1.5 times the interquartile range (whiskers), and outlier values (points). (GC: grass channel, CAGC: compost-amended grass channel)

Long-term monitoring

Figure 11 presents the runoff reduction data for the 24 monitored storm events that occurred between March 2018 and December 2022 across the four types of LID practices. Notably, bioretention consistently demonstrates the most stable stormwater volume reduction when compared to the other three LID systems. Among these four LID designs, the GC recorded the highest average runoff reduction. It is important to highlight that the runoff reduction performance of CAGC appears to be less stable and relatively lower than that of the other three LID practices. This variability could be attributed to a larger proportion of vegetated surface area within its contributing drainage area compared to the other types of LID systems. This increased vegetation exposure makes CAGC more susceptible to the influence of climate fluctuations and the growth of vegetation, resulting in the observed variability in its runoff reduction performance.

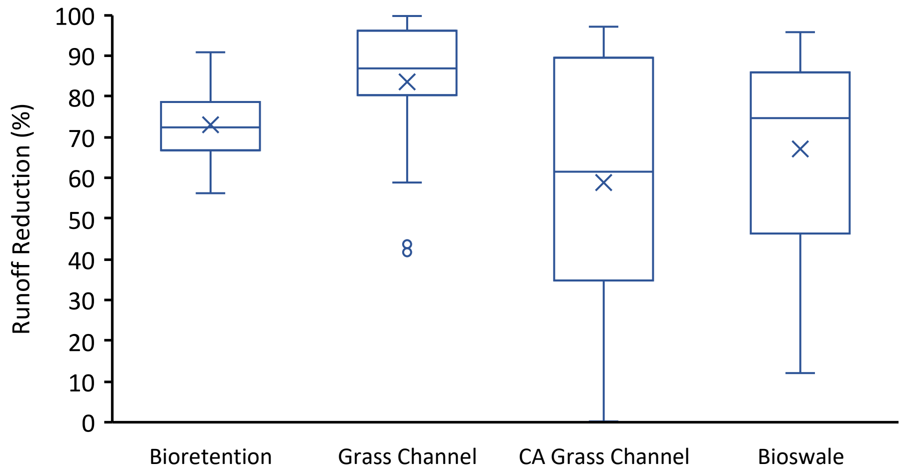

Figure 11. Runoff reduction of 24 monitored stormwater events between 2018 and 2022 for four LID types. Boxplots depict median values (line in box), mean values (×), 25th to 75th percentiles (colored boxes), and outlier values (points).

The assessment of pollutant mass load reduction serves as a valuable means to evaluate and compare the efficacy of monitored LID practices. This allows for the evaluation of LID systems even when they exhibit higher outflow concentrations, particularly in cases where there is significant runoff volume reduction during storm events. Figure 12 provides an overview of the overall mass load reduction for five water quality parameters (chloride, sodium, calcium, copper, and lead) during monitored storm events. The monitored LID systems demonstrated substantial chloride load reductions ranging from 65% to 97%, sodium load reductions ranging from 30% to 95%, calcium load reductions spanning from -19% to 81%, copper load reductions ranging from 44% to 90%, and lead load reductions between 64% and 85%.

In general, the LID systems exhibited commendable performance in enhancing both stormwater flow management and water quality along Lorton Road. Notably, the compost-amended grass channel and bioswale displayed negative results for calcium, which may be attributed to the compost material applied within the channel, potentially leaching out this specific water quality parameter.

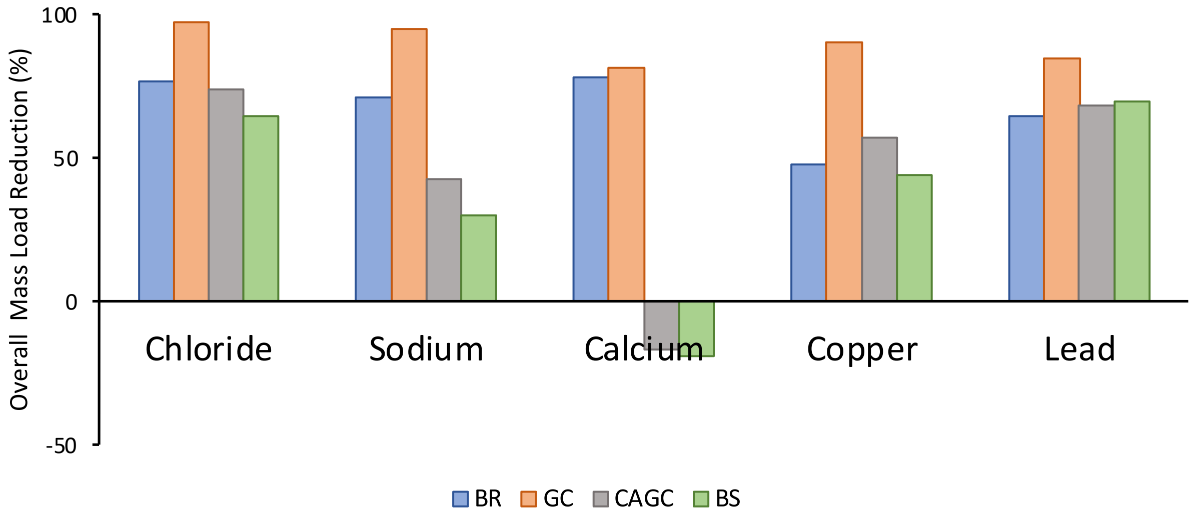

Figure 12. Overall mass load reduction for monitored pollutants for four types of LID practices between 2018 and 2022 (BR: bioretention, GC: grass channel, CAGC: compost-amended grass channel, BS: bioswale)

Figure 13 offers a comprehensive view of the mean mass load reduction as an indicator of water quality performance for the four monitored LID practices across the monitored storm events. The mean load reduction for chloride ranges from 38% to 96%, sodium load reduction ranges from 18% to 93%, mean calcium load reductions span from -41% to 79%, copper exhibits a mean load reduction ranging from -46% to 77%, and lead load reduction is observed to be between 39% and 72%.

The performance of the BR and GC consistently displayed a higher degree of consistency across all pollutant parameters compared to the compost-amended grass channel (CAGC) and bioswale (BS). The GC consistently achieved the highest load reduction for all monitored pollutant parameters when compared to the other LID practices. While bioretention secured the second-highest reduction, it should be noted that bioretention treated a larger volume of runoff than GC for each storm event due to its large contributing drainage area.

Additionally, the mean reductions in calcium and copper for the bioswale (BS) and the calcium treatment performance of the compost-amended grass channel (CAGC) experienced a notable decline, resulting in negative reductions, different from the other monitored LID practices. These findings suggest that the compost used in CAGC and the engineering soil media or design in BS may be potential factors contributing to the lower pollutant reduction. This study underscores the notion that more intricate LID designs do not necessarily translate into superior stormwater treatment performance when compared to simpler LID systems. Furthermore, slight variations in design or construction materials, such as compost amendments and engineering soil media, may significantly modify or even decrease LID performance.

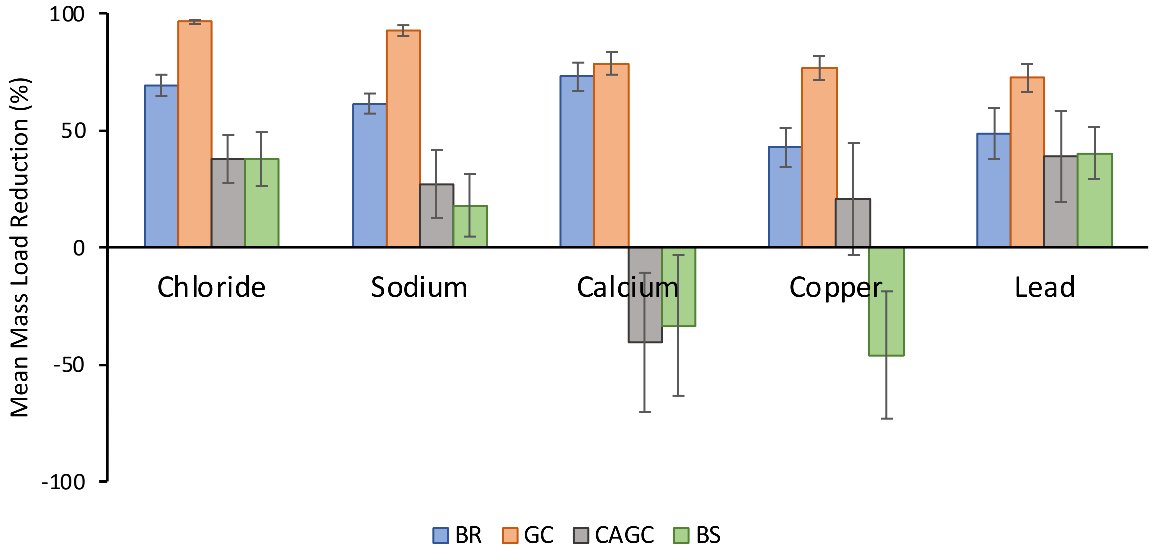

Figure 13. Mean mass load reduction for monitored pollutants for four types of LID practices between 2018 and 2022 (BR: bioretention, GC: grass channel, CAGC: compost-amended grass channel, BS: bioswale)

Figure 14 provides a comprehensive overview of pollutant mass load reduction trends in CAGC concerning several key water quality parameters, chloride, sodium, calcium, copper, and lead, between 2018 and 2022. During the initial two years of monitoring, it was observed that some pollutant effluent from CAGC exhibited higher pollutant levels compared to the influent, potentially attributable to the application of compost amendments. However, as time progressed and diligent maintenance practices were implemented, the performance of CAGC demonstrated a notable and consistent enhancement in pollutant mass load reduction over the study period.

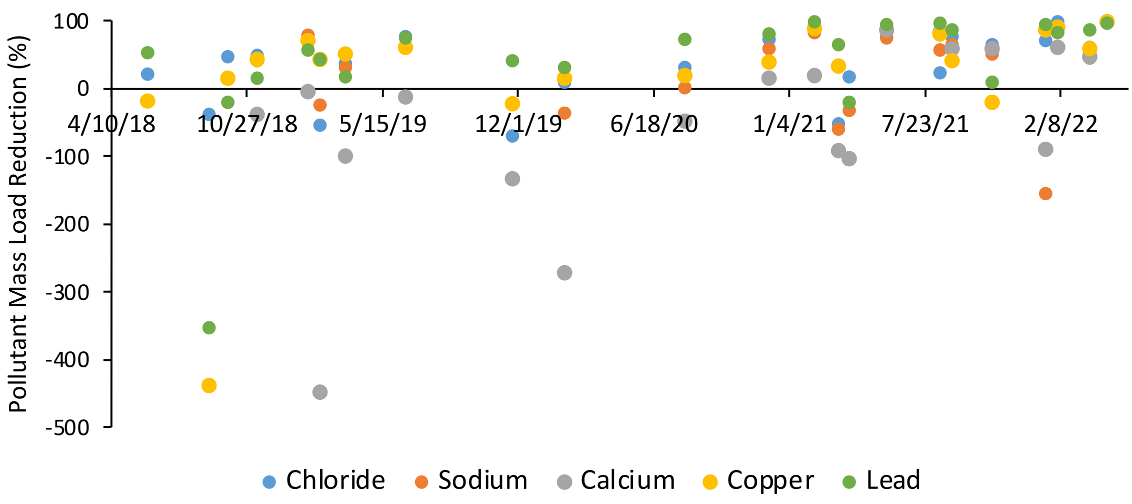

Figure 14. Pollutant mass load reduction in CAGC between 2018 and 2022 (CAGC: compost-amended grass channel)

Maintenance Assessment

Figure 15 presents the runoff reduction before and after the seven monitored maintenance activities for the four LID designs. Among these events, bioretention has the most stable and consistent runoff reduction performance compared to the other 3 types of LID systems. The GC consistently records the highest runoff reduction among these four LID types.

For bioretention, GC, and BS, their runoff reduction performance after maintenance work displays a higher level of consistency compared to their performance before maintenance activities. The mean volume reductions before all seven monitored maintenance events were 88%, 61%, 62%, and 73% for GC, CAGC, bioswale, and bioretention, respectively. Following the completion of the seven monitored maintenance activities, their mean runoff reductions changed to 83%, 64%,74%, and 74%, respectively. Notably, bioretention, CAGC, and bioswale exhibit an enhanced mean runoff reduction after the implementation of maintenance activities. Furthermore, no significant differences were observed in the mean volume reduction among all four LID practices before and after the maintenance events ($p = 0.39$).

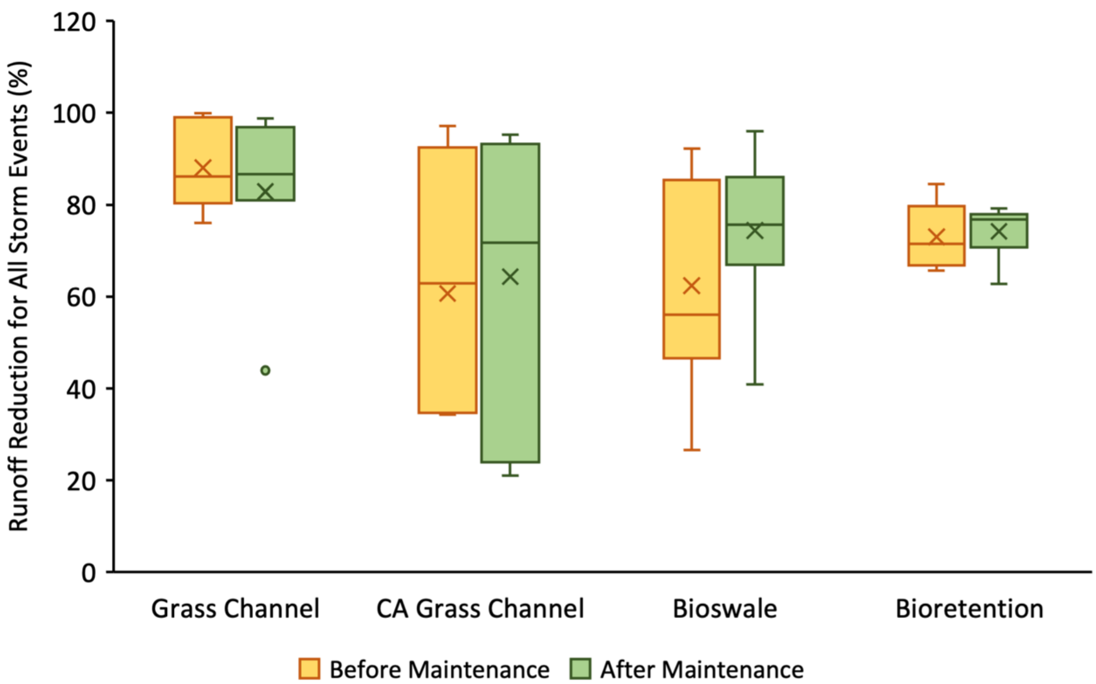

Figure 15. Runoff reduction of all fourteen stormwater events for four LID types (seven before maintenance, seven after maintenance). Boxplots depict median values (line in box), mean values (×), 25th to 75th percentiles (colored boxes), and outlier values (points).

Prior to the forebay restoration carried out in October 2021, a total of 11 storm events occurred, with the highest runoff proportion flowing through the bypass reaching 49%. Following the completion of the forebay restoration maintenance activities, three monitored storm events took place. It is noteworthy that there was a substantial decrease in the outflow proportion passing through the bypass channel in comparison to the system's performance before the forebay restoration. Before then, on average, 21% of the outflow exited through the bypass without undergoing treatment by the bioretention basin. However, after the forebay restoration, a statistically significant reduction in the mean outflow bypass percentage to 3% ($p < 0.001$) was observed. This significant decrease in the mean outflow bypass percentage indicates that more incoming runoff is effectively treated by the bioretention basin following the forebay restoration. Consequently, the performance of the bioretention system exhibits a notably higher level of consistency after the forebay restoration.

After all maintenance events monitored in the spring seasons, the mean mass load reduction for dissolved organic carbon (DOC) increases by 2% for bioretention, 28% for GC, 142% for CAGC, and 52% for BS. Collectively, there is a significant enhancement of 57% in the mean DOC mass load reduction for all monitored LID practices following the completion of monitored spring maintenance events. Bioretention is the most consistent LID design in DOC mass load reduction, indicating its resilience to changes in weather conditions during the upcoming growing seasons. Notably, CAGC exhibits the most significant improvement in DOC reduction performance when comparing the results before and after the monitored spring maintenance work, which is potentially attributed to both maintenance work and its substantial percentage of vegetated area in its contributing drainage area.

The mean mass load reduction for total dissolved nitrogen (TDN) increases by 2% for bioretention, 16% for GC, 75% for CAGC, and 26% for BS, during all maintenance events monitored in the spring seasons. A notable improvement of 29% is indicated in the mean TDN mass load reduction for all monitored LID practices following the completion of spring maintenance events. Like the performance trends on DOC reduction, the performance of bioretention is found to be most consistent in TDN mass load reduction, indicating its resilience to climate and other changes in weather conditions. The performance of CAGC on mean TDN mass load reduction still increases most after spring maintenance work.

Figure 16 provides an overview of the water quality performance exhibited by all four LID systems, including the mean mass load reductions of monitored pollutants (dissolved organic carbon (DOC), total dissolved nitrogen (TDN), and total suspended solids (TSS)) and the mean runoff reduction for all monitored maintenance activities. Results indicate that there is a significant increase in DOC mass load reduction, with a 41% improvement following the completion of monitored maintenance activities. Furthermore, TDN mass load reduction demonstrates a 25% increase after these maintenance events, and TSS mass load reduction experiences a 2% improvement. Additionally, a notable improvement in runoff reduction, with a 3% enhancement, was observed across all monitored LID designs. Specifically, the change in the mean DOC load reduction before and after maintenance events for all four LID systems shows a statistically significant increase ($p = 0.019$). It is worth noting that the flow volume and TSS reduction performance of the studied LID practices are more consistent than their performance in terms of DOC and TDN load reduction. These findings collectively indicate that maintenance work has a positive and effective impact on mitigating pollutants and runoff for all four types of LID systems.

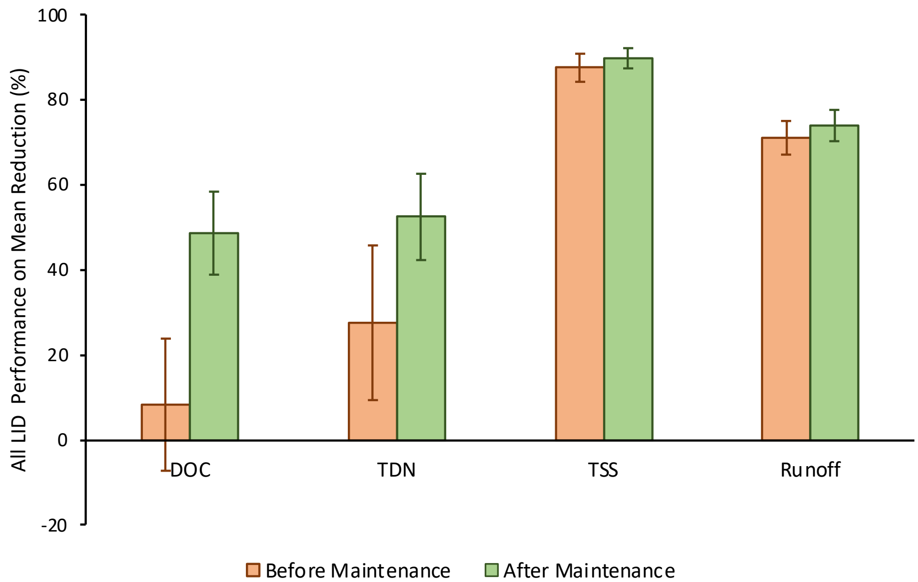

Figure 16. Mean reduction on DOC, TDN, TSS, and runoff before and after monitored maintenance events for all four monitored LID practices. (DOC: dissolved organic carbon, TDN: total dissolved nitrogen, TSS: total suspended solids)

These maintenance activities were undertaken with the overarching goal of ensuring the long-term sustainability of the LID systems, aiming to reduce stormwater runoff and associated pollutants. Economic specifications of the Lorton Road LID designs' maintenance events are in Table 2. The total cost of the 2021 forebay restoration event, including expenses for labor, excavator usage, fuel, and materials such as seed and erosion control matting (EC matting), amounted to $4,363.

Table 2. Economic Specifications for Lorton Road LID Maintenance Events, 2018-2022

LID	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 LID per year ($) (including forebay restoration)
GC	337	2,533	491	2.91	0.39	N/A	982
CAGC	891	6,874	491	1.10	0.14	N/A	982
BS	196	2,772	491	5.01	0.35	N/A	982
BR	1,012	47,753	3,000	7.01	0.15	4,363	7,091

CDA = contributing drainage area

The maintenance costs of the three types of monitored swales are consistently affordable and comparable when contrasted with the maintenance costs of bioretention, as detailed in Table 2. The maintenance expenses for bioretention are approximately $3,055 higher per event than for swales, including the average forebay restoration cost conducted between 2018 and 2022. It is worth noting, however, that bioretention covers a significantly larger area, with a contributing drainage area of 47,753 m^2.

The average annual maintenance costs per unit of contributing drainage area for the four monitored LID designs are \$0.39/m^2, \$0.14/m^2, \$0.35/m^2, and \$0.15/m^2 for GC, CAGC, BS, and bioretention, respectively. Overall, when considering all monitored 14 storms in this objective, the economic efficiency for maintenance was \$0.0016, \$0.0016, \$0.0017, and \$0.0041 per liter of stormwater runoff reduced for GC, CAGC, BS, and bioretention, respectively.

In terms of the reduction of dissolved organic carbon (DOC) mass for the monitored 14 storm events, the overall maintenance economic efficiency was around \$408/lbm, \$181/lbm, and \$227/lbm for bioretention, GC, and BS, respectively, and the reduction of total dissolved nitrogen (TDN) mass was achieved with a maintenance efficiency of \$1814/lbm, \$2177/lbm, and \$2540/lbm 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, potentially due to its compost construction materials.

Future research endeavors could explore the potential of vegetation in LID designs to mitigate pollutants and employ rainfall-runoff models to simulate LID performance. Future research could also investigate microplastics originating from tire wear or netting used to promote new grass growth. Studies could also explore how LID designs impact groundwater dynamics over the long term by encouraging stormwater infiltration into the ground. Research could also study more frequent forebay restoration for bioretention.

CONCLUSIONS

- *The performance of the studied LID designs displayed a wide range of outcomes, with some effectively acting as efficient pollutant sinks with others emerging as sources for specific constituents.* Notably, the grass channel, the simplest design swale, performed best on both runoff and pollutant load reductions, serving a modest contributing drainage area, costing more than other LID designs on the average maintenance costs per contributing drainage area each year. By contrast, bioretention, which ranks second in volume and mass load reduction for pollutants, serves the largest contributing drainage area and maintains a notably consistent performance compared to other monitored LID systems. Bioretention can treat high volumes and flow rates of stormwater relative to the other designs studied.

- *More complex swale designs do not necessarily mean better performance in stormwater treatment*. The grass channel swale, which had the simplest design, was more effective with respect to flow and pollutant load reduction than the more complex swale designs studied.

- *Maintenance matters for all four systems*. During the monitored spring seasons, the performance of three types of swales improved after maintenance work for all pollutants, and the grass channel displayed greater consistency in reducing flow volume, DOC, and TDN compared to the CAGC and bioswale. Moreover, the performance of CAGC indicated the most improvement compared to other LIDs in this study, highlighting the efficacy of maintenance work for this swale type. Overall, the performance of all LID practices exhibited improvement following monitored maintenance events, regardless of season or LID type, suggesting that these practices performed better in reducing pollutants and controlling flow when properly maintained.

- *The bioretention system has demonstrated a higher degree of resilience to climate and weather conditions when subjected to proper maintenance activities, and the forebay restoration significantly enhanced the potential for inflow to undergo treatment within the bioretention basin.*

RECOMMENDATION

1. *Three practices suggested by this study should be considered for the next revision of the stormwater handbook (VDEQ, 2013a).* First, multiple performance metrics should be used to evaluate LID performance, including contributing drainage area, footprint, and maintenance practices for selecting an LID for a given site. Second, instead of using phosphorous as a "keystone" pollutant, (VDEQ, 2013a) multiple pollutants should be considered to assess the performance of LID designs. Third, compost amendment in swale soils should also be considered sparingly to avoid nutrient losses. These three practices should be communicated by the VDOT point of contact on the stormwater stakeholder advisory group (SAG) which is providing comments on proposed revisions to the handbook.

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project work together to craft a plan to implement the study recommendations and to determine the benefits of doing so. This ensures that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

Regarding Recommendation 1, there are multiple locations in the existing handbook (VDEQ, 2013a) where results from this study can inform revisions being made by the stormwater handbook committee. Table 3 shows, for each study finding, an appropriate modification that can be considered. Communication of this information from the VDOT point of contact on the stormwater stakeholder advisory group regarding the items in Table 3 should occur by February 1, 2025.

Table 3. Blueprint for Updating the Stormwater Handbook (VDEQ, 2013a)

Candidate practice from the recommendation	Potential location for updating the stormwater handbook (VDEQ, 2013a)
"Multiple performance metrics should be calculated by taking into consideration contributing drainage areas, LID footprints, and influent and effluent concentrations and loads for multiple pollutants."	Chapter 6, on page 6-D-6, emphasizes low impact development and mentions a forthcoming refinement of guidelines and performance benchmarks related specifically to low impact development. Thus, this sentence can be included at that location.
"Considering multiple performance metrics revealed that bioretention performance was the most consistent LID system, and its design is space efficient, the grass channel also performed well in terms of flow reduction and pollutant load reduction."	The above location (page 6-D-6) appears to be the most appropriate location for this statement. However, LID also figures prominently in several other places in Chapter 6, notably pages 6-9, 6-17, and 6-18. A cost comparison between LID and conventional approaches appears on page 6-D-14. Thus, this sentence may be incorporated into any of these locations.
"Instead of using phosphorous as a 'keystone' pollutant, multiple pollutants should be considered to assess the performance of LID designs."	Chapter 9, page 9-B-12 includes a sample maintenance plan stating that the plan is "designed to ensure that the amount of phosphorus (a 'keystone' pollutant) leaving the site in runoff water was not increased by construction…" This example could thus be modified to refer to multiple pollutants rather than just phosphorous.
"The use of compost amendment in swale soils should also be considered sparingly to avoid nutrient losses."	Chapter 7, page 7-69, refers to compost amendments for grass channels. (There are several other locations in the handbook where compost amendments are discussed.) Thus, any of these locations would be a suitable location to include this concept.

Implementation of this recommendation should also take the form of an update to at least two other documents. Information needed to consider these updates should be communicated by February 1, 2025.

- Chapter 11, Section 7 of the VDOT Drainage Manual (VDOT, 2023), where the update should distinguish between grass channel (GC) and compost amended grass channel (CAGC). The update should make the reader aware of the potential for nutrient release by CAGC. The paragraph spanning pages 11-117 through 11-118 of that chapter is an appropriate location for this discussion, as that paragraph encourages the use of LID.

- BMP specification 3 (VDEQ, 2013b) which mentions compost amendments on pages 1, 2, 6, 10, 14, 16, and 17. At this point, when VDOT's Location and Design Division shares the results of this study with VDEQ, VDOT should request DEQ's feedback regarding potential updates to relevant BMP specification such as number 3.

Benefits

Implementation of the recommendation will better capture the performance of LID designs. This information will allow engineers to better select and design practices given specific site conditions and may allow these LID practices to be implemented in areas where space is constrained. This information may also lower out-of-pocket costs through up to two different mechanisms: a reduction in the expenditure for right of way and a lower cost per acre drained. This latter mechanism—a lower cost per acre drained—is estimated to be roughly \$50,000 at a site like that described in Table 1, subject to the uncertainty and approach described here.

Uncertainty Associated with Estimation of Cost Reductions

Because costs are highly dependent on local conditions, contractor availability, and time of procurement, and because performance is dependent on design parameters and construction material (as discussed in conclusion 2), an estimate of the reduction in the out-of-pocket expenditures attributed to the use of LID is subject to a considerable degree of uncertainty. For example, Clark and Acomb (2008) suggested that the costs of bioretention basins varied by a factor of 2 for large areas (i.e., \$5,000 to \$10,000 per acre of development) and by a factor of 5 for small areas (i.e., \$3 to \$15 per square foot). As another example, Joksimovic and Alam (2014) suggested that at one 75-acre site, bioretention cells had a higher cost per cubic unit of runoff reduced than that of a vegetated swale, which would negate any cost savings. Given that state departments of transportation have a fairly detailed process for estimating construction costs (see, for example, California Department of Transportation (2021)), pinpointing exact costs and monetized benefits that are generalizable to all sites is not feasible.

Approach for Estimating Cost Reductions

That said, a rough estimate of cost savings attributed to well-designed LID may be estimated for planning purposes based on sites where, like this study, the bioretention basin, although having a higher construction cost than a grassy swale, serves a much larger contributing drainage area than the swale. Joksimovic and Alam (2014) suggested that a bioretention cell had a capital cost of approximately 3.86 times that of a vegetated swale (i.e., \$2,024,786 for the former compared to \$523,985 for the latter). Table 1 of this report suggested that the contributing drainage area for a bioretention basin is 18.85 times larger than for a grass channel (i.e., 47,753 m^2 for the former and 2,533 m^2 for the latter). Based on these two sources, one would expect the cost per acre served by a bioretention basin to be about a fifth of the cost had a grass swale been used (i.e., 3.86/18.85 = 0.20). However, Clark and Acomb (2008), when comparing bioretention basins to "conventional systems" suggest a cost savings of only about 0.50.

The aforementioned cost of \$5,000 - \$10,000 per acre drained is described by Axler et al. (2009) as being "dated-2000." Conversion of the lower end of this cost of \$5,000 per acre drained in year 2000 dollars yields roughly \$9,000 in year 2023 dollars (U.S. Bureau of Labor Statistics, 2023). For a bioretention basin at a 12 acre site (similar to the size of the site used in Table 1), the cost would be (\$9,000)(12) = \$108,000 in year 2023 dollars. Using the more conservative cost savings estimate of Clark and Acomb (50%), this suggests that a well-designed LID could yield a cost savings of 50% of \$108,000 or about \$54,000. Because reporting this figure of \$54,000 conveys a false sense of precision in light of conclusion 2, it is appropriate to report the potential cost savings as \$50,000.

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