Assessment of a Bioretention Basin Treating Highway Runoff: A Five-Year Performance Evaluation

by

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(Under the Direction of Gary L. Hawkins and Ernest W. Tollner)

ABSTRACT

Bioretention is a common stormwater management practice that mimics natural hydrology. This study evaluated the long-term performance of a bioretention basin in South Downtown Atlanta, Georgia, treating highway runoff over five years. Between November 2024 and April 2025, 14 storm events were monitored. Removal efficiencies were 94% for total nitrogen, 96% for total Kjeldahl nitrogen, 95% for orthophosphate, 95% for total solids, and 88% for nitrate-nitrogen. Compared to year one (82% TN, 88% TKN, 86% orthophosphate, 100% TSS), results show sustained or improved pollutant removal despite gradual media changes. High treatment performance was maintained through biological uptake and denitrification. These results support the long-term effectiveness of bioretention and highlight the importance of ongoing monitoring for optimizing urban green infrastructure design and maintenance.

Keywords: stormwater runoff, nitrogen, phosphorus, pollutant, long-term performance.

ASSESSMENT OF A BIORETENTION BASIN TREATING HIGHWAY RUNOFF: A FIVE-YEAR PERFORMANCE EVALUATION

by

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CHAPTER 1

INTRODUCTION

Urbanization has led to an increase in impervious surfaces and associated runoff, exacerbating flooding and water pollution. Cities with inadequate stormwater management face growing challenges because stormwater runoff from roads, rooftops, and other hard surfaces collects pollutants such as nutrients, heavy metals, oils, sediments, and pathogens, which are then carried into local water bodies (Barbu et al., 2009; Paul & Meyer, 2001). Furthermore, in areas with Combined Sewer Systems (CSS), large storm events can overwhelm the system's capacity, causing Combined Sewer Overflows (CSO) that discharge untreated stormwater and sewage directly into the environment, increasing pollutant loads in surface waters and placing additional strain on Publicly Owned Treatment Works (POTWs) (Davis et al., 2001). Even in cities with separate storm sewer systems, stormwater can infiltrate aging or damaged sanitary sewers, indirectly increasing the flow to wastewater treatment plants and contributing to operational challenges and higher treatment demands (U.S. EPA, 2004). As a result, both water quality and wastewater infrastructure are increasingly impacted in urban environments without effective stormwater management.

Bioretention basins are a sustainable stormwater management practice that use vegetation, soil, and engineered filter media to capture, filter, and treat stormwater runoff, removing pollutants and reducing flow volumes before the water enters storm drains or receiving waters (US EPA, 1999; Davis et al., 2009). Unlike traditional stormwater infrastructure — commonly referred to as gray infrastructure — which moves water quickly through pipes and channels, green infrastructure solutions such as bioretention systems are designed to mimic natural hydrological processes. These green infrastructure systems enhance infiltration, reduce runoff volumes, and improve water quality (EPA, 2023; Davis et al., 2009; Liu et al., 2019). Many cities are increasingly adopting green infrastructure approaches to improve urban resilience to climate-driven flooding while providing additional benefits such as urban cooling, habitat creation, and enhanced public spaces (Zhou et al., 2021; Chatzimentor et al., 2021). Biological, chemical and physical processes in the soil and root zone work together to remove pollutants such as heavy metals, nutrients, sediments and hydrocarbons from stormwater runoff. Physical processes such as filtration and sedimentation trap particle-bound pollutants, while chemical processes such as sorption and precipitation remove dissolved metals and phosphorus. At the same time, biological processes, including plant uptake and microbial degradation, act on nutrients and organic pollutants (Davis et al., 2003; Hsieh & Davis, 2005; LeFevre et al., 2015; Blecken et al., 2017). These synergistic mechanisms contribute to the high pollutant removal efficiency observed in well-designed bioretention systems (US EPA, 2023). Vegetation supports evapotranspiration, regulates the water balance and contributes to the urban water cycle (Hunt et al., 2014; Zhang et al., 2023).

Bioretention basins promote on-site water retention, reduce runoff peaks and mitigate climate-related impacts such as extreme precipitation and the urban heat island effect (Hathaway et al., 2014; Takaijudin, 2016). Their integration into urban landscapes brings additional environmental and social benefits, including better air quality, more green spaces and greater biodiversity (Van der Meulen et al., 2022; Kim et al., 2003). Given the impact of climate change on the frequency and intensity of storms of extreme precipitation events in many regions of the United States, shown in Figures 1.1, 1.2, and 1.3. (Kunkel et al., 2013; USGCRP, 2018), bioretention supports urban sustainability by reducing flood risks and protecting water resources (Dickey et al., 2025)

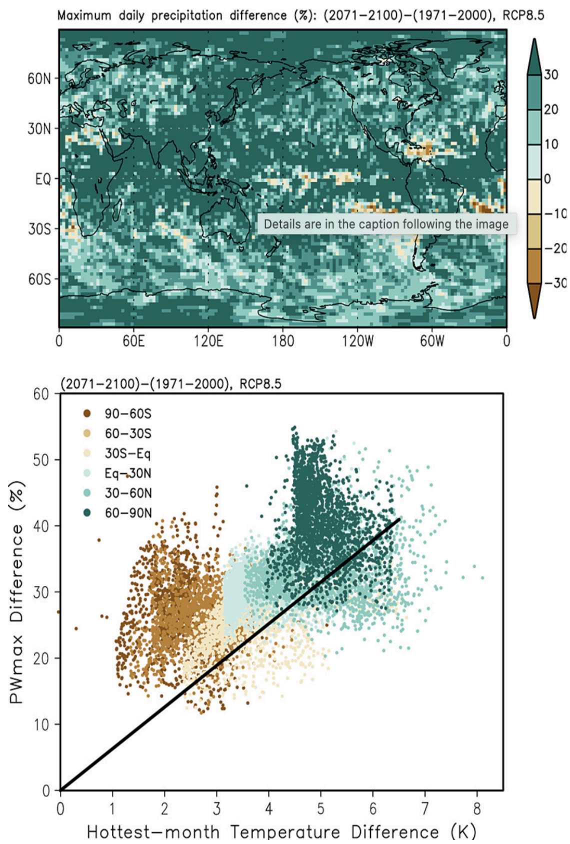


Figure 1.1. Fractional changes (%) of precipitation and PWmax projected by seven CMIP5 climate models. (top) These are multimodal mean differences (future minus present) in the 30-year period maximum daily precipitation for 2071–2100 under the RCP8.5 scenario, relative to the 1971–2000 reference value. (bottom) A scatterplot of grid points differences (future minus present) of the 30-year maximum precipitable water versus 30-year average temperature of the climatologically. The straight line represents a slope of 6.3% K−1, the approximate value of the derivative of the saturation vapor pressure with respect to temperature at 288 K. (Kunkel et al. 2013)

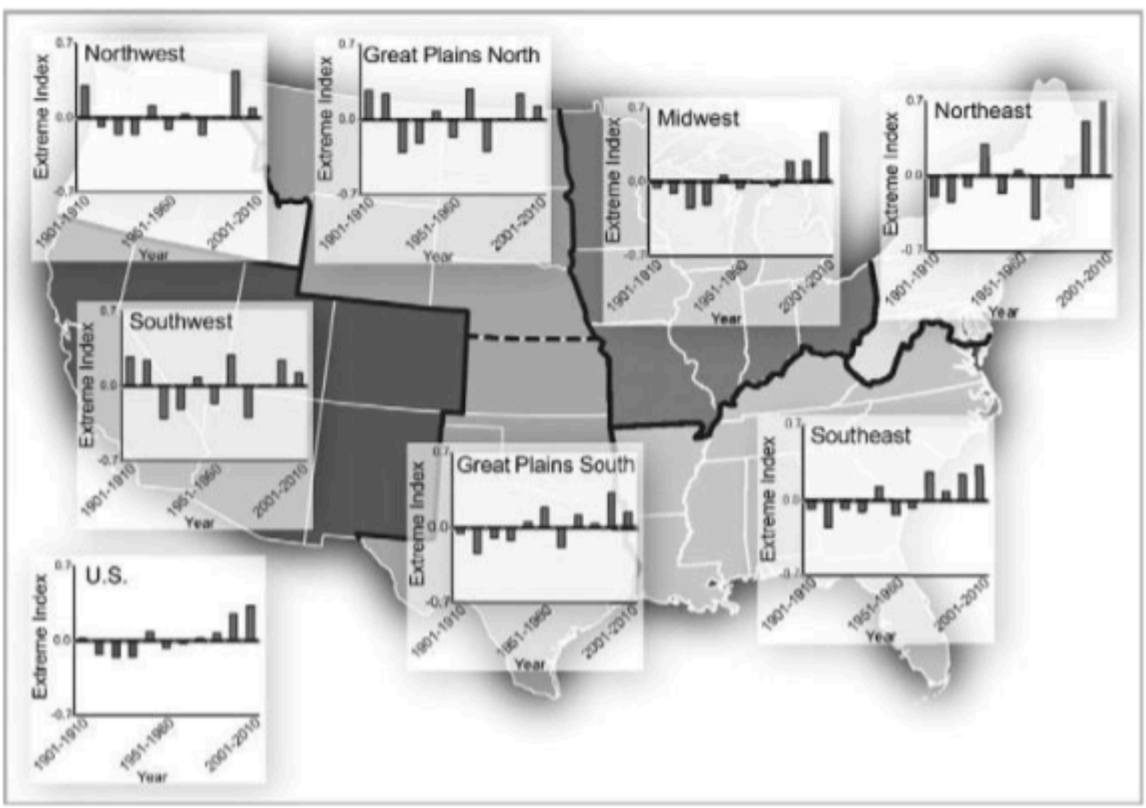


Figure 1.2. Trends in extreme 2-day precipitation events (1-in-5-year threshold) across seven U.S. regions and the contiguous United States, based on decadal averages from 1901 to 2010. Adapted from Kunkel et al. (2013), Bulletin of the American Meteorological Society, 94(4), 499–514.

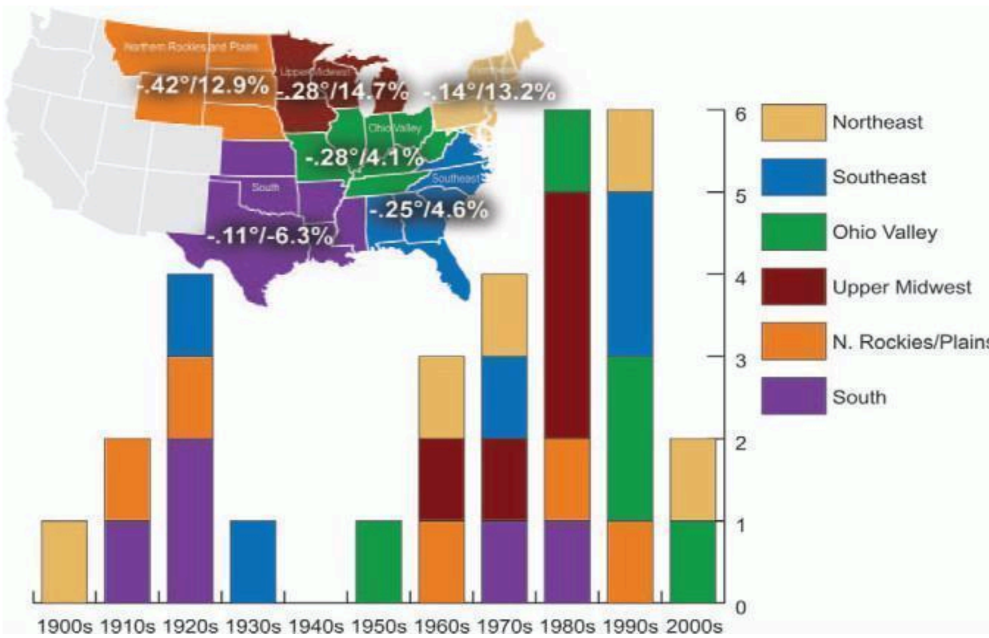


Figure 1.3. Number of extreme snowstorms (upper 10th percentile) per decade in six U.S. climate regions of the eastern two-thirds of the contiguous United States (1900–2010), with associated temperature and precipitation anomalies. Adapted from Kunkel et al. (2013), Bulletin of the American Meteorological Society, 94(4), 499–514.

Bioretention in Urban Planning and Stormwater Regulation

Bioretention is a cost-effective alternative to traditional stormwater infrastructure, including underground detention systems, storm sewers, and centralized treatment plants (Davis et al., 2009; Hunt et al., 2008). By decentralizing stormwater treatment, bioretention systems reduce both installation and maintenance costs while improving water quality and reducing runoff peaks

(Li & Davis, 2008; Brown & Hunt, 2010). Unlike large-scale drainage infrastructure, which requires significant financial investment and ongoing maintenance, bioretention utilizes natural processes with minimal intervention (Hathaway et al., 2014). Cities that use bioretention can relieve drainage networks, reduce flooding risks and increase property values by integrating green spaces (Van der Meulen et al., 2022; Kim et al., 2003). However, to achieve long-term performance, key design, maintenance and regulatory compliance challenges must be overcome (Davis et al., 2006; Shrestha et al., 2018).

Stormwater ordinances are increasingly requiring the integration of bioretention basins into urban design to manage runoff and improve water quality. More cities across the United States are enacting stormwater and green infrastructure ordinances that require or strongly encourage the integration of bioretention basins into urban development and redevelopment projects. Philadelphia's Green Stormwater Infrastructure Manual, for example, requires bioretention as a key component of its comprehensive stormwater management strategy (Philadelphia Water Department, 2018). Atlanta's Post-Development Stormwater Ordinance mandates the use of green infrastructure, including bioretention, on new and redeveloped properties (City of Atlanta, 2020). Similarly, the Minnesota Stormwater Manual provides detailed standards for bioretention design used in Minneapolis–St. Paul and throughout the region (Minnesota Pollution Control Agency, 2021). Other cities with established bioretention policies include Orlando (City of Orlando, 2021), San Francisco (SFPUC, 2016), Los Angeles (City of Los Angeles, 2019), New York City (NYC DEP, 2021), Seattle (City of Seattle, 2021) and Portland (City of Portland, 2020). This growing trend reflects a nationwide shift toward decentralized stormwater management strategies that increase resilience to climate change, improve water quality, and support urban sustainability.

The Georgia Stormwater Management Manual (Atlanta Regional Comission, 2016) provides design criteria and best management practices (BMPs) for bioretention facilities. Maryland also emphasizes nutrient and sediment reduction to protect the Chesapeake Bay (MDE, 2009), while California incorporates bioretention into Low Impact Development (LID) strategies (CASQA, 2014). The U.S. Environmental Protection Agency (EPA)'s National Pollutant Discharge Elimination System (NPDES) program requires communities to implement stormwater control measures, with bioretention being one, to reduce nonpoint source pollution and improve water quality (EPA, 2017). The Clean Water Act mandates stormwater management programs for urban areas, especially those with municipal separate storm sewer systems (MS4s). Phase I and Phase II MS4 permits require stormwater plans that incorporate green infrastructure, and many cities have included bioretention as part of compliance (EPA, 2023).

At the international level, the European Union's Sustainable Urban Drainage Systems (SUDS) framework is in line with the Water Framework Directive to maintain ecological balance and prevent flooding (Duan & Wang, 2024). In Australia and Canada, bioretention is integrated into urban stormwater strategies through comprehensive green infrastructure policies (Spraakman et al., 2020; Macedo et al., 2017). Differences in adoption are influenced by local regulations, funding mechanisms and public awareness, which vary greatly from region to region. For example, Melbourne offers stormwater offset credits to encourage the installation of green infrastructure (Wang et al., 2021), Toronto requires bioretention as part of mandatory building plan approval for new developments (Li et al., 2021), and Singapore mandates bioretention as part of its national ABC Waters program (PUB, 2023). Understanding these policy differences — from incentive-based models to regulatory requirements — is critical to improving the implementation and long-term effectiveness of bioretention basins (Fan et al., 2021; Berland et al., 2023; Carter & Fowler, 2022).

In alignment with the guidelines provided by the ARC Blue Book, recent studies emphasize the importance of evaluating bioretention systems over extended operational periods. Addressing this need, the present thesis assesses the effectiveness of the bioretention basin in managing highway runoff after five years of operation. Through comprehensive field investigation and analysis, this study contributes valuable insights into the long-term performance of a bioretention basin, helping to bridge the gap between theoretical knowledge and practical application of such systems.

CHAPTER 2

LITERATURE REVIEW

1. Importance of Water Quality

Water quality is a fundamental aspect of environmental health. It affects ecosystems, the safety of drinking water and economic activities such as agriculture, fishing and industry. As populations grow and cities expand, pressure on water resources increases, leading to concerns about pollution, scarcity and climate resilience. Clean water is vital for public health, biodiversity and habitat conservation. However, its degradation is largely due to anthropogenic impacts such as urbanization, agricultural runoff, industrial discharges and climate change (Hunt et al., 2006; Wang et al., 2018; Zhang et al., 2023).

Urbanization significantly alters hydrological processes through the expansion of impervious surfaces, which inhibit infiltration and lead to increased surface runoff. This runoff facilitates the accumulation and transport of pollutants into stormwater infrastructure and ultimately into receiving water bodies, posing risks to water quality. The increased volume and velocity of stormwater runoff leads to higher erosive forces in downstream watercourses, causing bank erosion, channel incision and habitat degradation (Kong et al., 2017; Walsh et al., 2022; Jefferson et al., 2021). In addition, pollutants such as heavy metals, oils, fertilizers and sediments further degrade water quality. Climate change exacerbates these problems by altering precipitation patterns and increasing extreme weather events (Figures 1.1, 1.2 and 1.3), contributing to variable runoff volumes and pollutant loads (Huang et al., 2016; Kundzewicz et al., 2014). To mitigate these impacts, sustainable stormwater management practices and regulatory frameworks have been introduced to control pollution, improve retention and protect watersheds.

Bioretention basins are used to effectively manage stormwater by mimicking natural processes such as infiltration, evapotranspiration, and pollutant filtration (Davis et al., 2009; Champagne et al., 2010). These systems typically include a vegetated surface layer, a layer of mulch, and an engineered soil media designed to absorb water, filter pollutants, and promote biological treatment. (Chu et al., 2020; Shrestha et al., 2018). A typical configuration is shown in Figure 2.1 (U.S. EPA, 2015). The choice of vegetation influences nutrient uptake, evapotranspiration, and landscape aesthetics. Additionally, soil composition, plant selection, and basin size significantly affect system efficiency (Takaijudin, 2016; Bodus et al., 2024). Larger basins provide greater hydraulic residence time and surface area, which enhance pollutant removal and allow for more effective management of high-volume storm events (LeFevre et al., 2020). In contrast, undersized basins may experience short-circuiting or overflow during heavy rainfall, limiting their treatment performance. Given these factors, careful consideration of bioretention system design parameters — including sizing, media composition, and vegetation selection — is essential to optimize performance across varying site conditions.

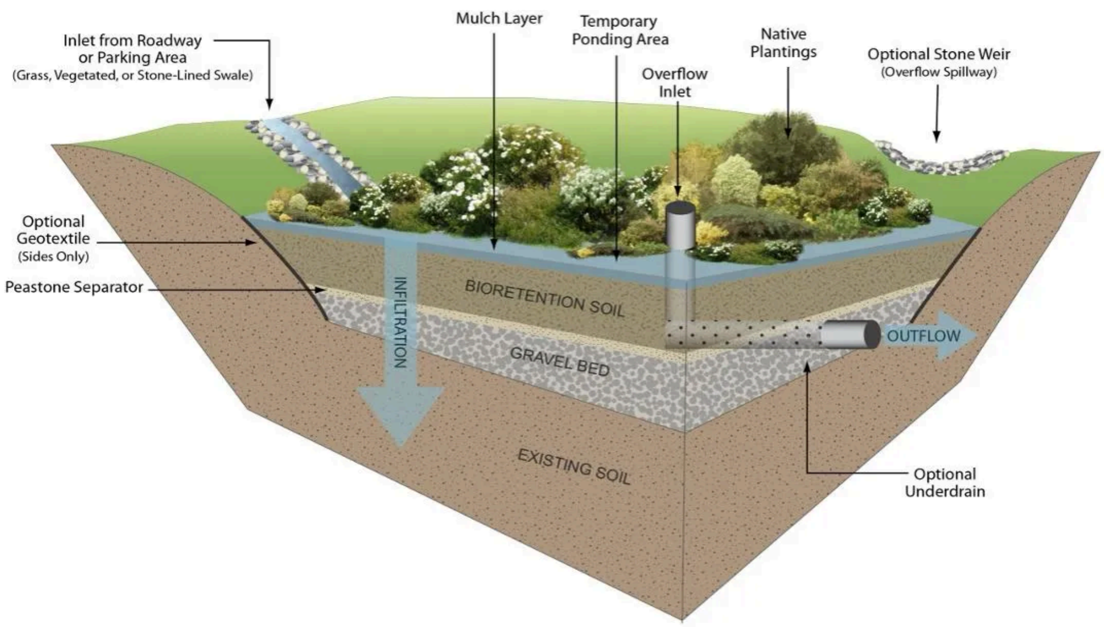


Figure 2.1. Image takes from Geosyntec Consultants provide detailed technical guidance on the design and function of bioretention systems within the broader stormwater management framework. "Bioretention Areas and Rain Gardens." Minnesota Stormwater Manual (MECA, 2021)

In accordance with ARC Blue Book guidelines (Atlanta Regional Commission, 2016), bioretention systems are typically required to capture and treat the first 1 inch (25 mm) of rainfall from contributing impervious surfaces. This design criterion ensures effective treatment of most annual storm events, which are generally small in volume but frequent. Undersized systems may fail to adequately detain stormwater, leading to increased runoff, reduced pollutant removal efficiency, and a higher likelihood of overflow even during minor precipitation events, while oversized basins may enhance hydrologic and pollutant control but introduce inefficiencies, including increased construction costs, potential for prolonged saturation, and anaerobic conditions that can trigger nutrient release. Accordingly, proper sizing requires careful estimation of contributing drainage areas, anticipated runoff volumes, and localized rainfall patterns to ensure system functionality and cost-effectiveness. Properly designed basins can reduce peak stormwater runoff by 30–90%, depending on climate, soil permeability and maintenance (Davis et al., 2009; Olszewski & Davis, 2013). They also contribute to groundwater recharge, biodiversity and mitigation of the urban heat island (Vijayaraghavan et al., 2021).

Long-term effectiveness depends on routine maintenance, including sediment removal, plant health monitoring and engineered soil replenishment to maintain pollutant removal (Chu et al., 2020; Davis et al., 2008). Excess sediment accumulation can clog the surface or pore spaces of the bioretention media, thereby reducing infiltration capacity and limiting the system's ability to effectively treat stormwater (Kim et al., 2003). Although bioretention basins are designed to reduce nutrient loads, under certain hydrological conditions — particularly in systems with high infiltration rates or unlined designs — nitrogen leaching may occur. In such cases, nitrate-rich water can percolate into underlying groundwater aquifers or discharge into adjacent surface waters, posing a potential risk to water quality (Kim et al., 2003; Wang et al., 2021; Liu et al., 2020). This risk is particularly significant in areas with shallow groundwater tables or in unlined bioretention systems where infiltration rates are high (Liu et al., 2020). Strategic planning and regular maintenance help to mitigate these challenges (Brown & Hunt, 2010). Plant selection is critical for the removal of pollutants, as different species absorb different amounts of nitrogen and phosphorus, which are major contributors to eutrophication, algal blooms and oxygen depletion in water bodies (Davis et al., 2009; Hsieh & Davis, 2005). Vegetated bioretention systems can remove at least 50% of heavy metals, nutrients, and suspended solids from urban runoff (Hsieh & Davis, 2005; Li & Davis, 2014). Li and Davis (2014) found that bioretention basins can remove up to 99% of heavy metals such as zinc, copper, and lead. This makes bioretention systems essential components of urban stormwater management, as they provide source control — treating polluted runoff before it enters downstream water bodies. In doing so, bioretention improves urban water quality by reducing heavy metals, nutrients, suspended solids, and pathogens, while also lowering runoff volumes and peak flows that can trigger combined sewer overflows (Paus et al., 2021; Rolla et al., 2023). These improvements help reduce risks to public health by limiting human exposure to toxic metals, preventing harmful algal blooms, and decreasing the incidence of waterborne diseases linked to contaminated urban waters (Miller et al., 2022).

The efficiency of nitrogen and phosphorus removal depends on the organic content of the soil and the hydraulic load. Some systems achieve nitrogen removal rates of up to 82% and phosphorus removal rates of up to 85% (Hsieh & Davis, 2005; Cavalcante, 2021). Cavalcante (2021) confirmed 85% phosphorus and 82% nitrogen removal in a highway bioretention system, highlighting their role as best management practices (BMPs). According to the ARC Blue Book (Atlanta Regional Commission, 2016), bioretention systems are expected to remove at least 75–80% of total suspended solids (TSS) and achieve substantial reductions in total nitrogen (TN) and total phosphorus (TP) to meet stormwater treatment objectives. However, under certain site or maintenance conditions, efficiency can decrease by at least 20% due to clogging, soil compaction, or fluctuations in pollutant loads (Bratieres et al., 2008). Brown and Hunt (2010) found that bioretention basins perform best in permeable soils, whereas compacted or clayey soils require specific design modifications — such as underdrains or amended media — to maintain treatment efficiency. To address stormwater challenges, regulatory frameworks and pollution prevention programs have been enacted to control pollution sources, improve stormwater management, and protect watersheds. The U.S. Environmental Protection Agency (USEPA) implemented the National Pollutant Discharge Elimination System (NPDES) in 1990 and promoted BMPs such as green roofs, bioswales, and bioretention systems. These practices improve urban stormwater management through retention, infiltration and biological treatment.

Performance standards for bioretention systems vary by region due to climate, soil conditions and regulations. Georgia mandates treatment during rainfall events of at least 1 inches in a 24-hour period to manage storms in the Southeast (Georgia Stormwater Management Manual, 2016). Minnesota has more stringent requirements due to its cold climate, which impairs infiltration and nutrient decomposition (Hunt et al., 2008). California emphasizes water conservation and groundwater recharge to manage seasonal droughts and extreme storms (Li et al., 2009).

The effectiveness of sediment and nutrient reduction in bioretention systems depends on soil characteristics, maintenance frequency, and site-specific design adjustments. Runoff volume reductions typically range from 30% to 50%, with optimal results achieved in permeable soils supported by well-established vegetation (Chapman et al., 2010; Hunt et al., 2008). In Atlanta, Georgia, bioretention basins have been shown to reduce stormwater runoff volumes by approximately 40% to 70%, significantly contributing to flood risk mitigation in the urban environment (City of Atlanta Department of Watershed Management, 2020).

A highway bioretention system analyzed in Atlanta between 2020 and 2021 achieved complete removal of total suspended solids (TSS), along with reductions of 82% in total nitrogen (TN) and 86% in total Kjeldahl nitrogen (TKN) (Cavalcante, 2021). These results underscore the importance of region-specific design strategies in optimizing stormwater treatment performance and maximizing ecological benefits across diverse climate zones.

2. Regulatory and Implementation Programs Incorporating Green Infrastructure

2.1 Georgia Department of Natural Resources – Environmental Protection Division (EPD)

The Georgia Environmental Protection Division (EPD) manages a variety of programs designed to protect water quality across the state. These include the Total Maximum Daily Load (TMDL) program, which identifies impaired waters, sets pollutant limits, and regulates industrial, agricultural, and municipal discharges to restore water quality. EPD also administers the EPA's Section 319 Nonpoint Source (NPS) Management Program, which provides funding and guidance to reduce nonpoint source pollution in vulnerable watersheds (Georgia Department of Natural Resources, 2019).

The Water Quality Control Act (Georgia Environmental Protection Division, 2016) regulates industrial discharges, wastewater treatment, and large-scale agricultural operations. EPD also enforces the Safe Drinking Water Act (SDWA) to ensure a safe public water supply by requiring compliance with federal Maximum Contaminant Levels (MCLs).

Together, these programs form a comprehensive regulatory and voluntary framework that supports state and federal water quality goals and promotes the adoption of best management practices (BMPs). Many of the BMPs promoted through the Georgia Stormwater Management Manual (GSMM), developed by the Atlanta Regional Commission (ARC), support the goals of the TMDL and Section 319 NPS programs by providing effective stormwater control at the local level.

2.2. Atlanta Regional Commission (ARC)

The Atlanta Regional Commission (ARC) developed and manages the Georgia Stormwater Management Manual (GSMM) or "Blue Book" (Atlanta Regional Commission & Georgia Environmental Protection Division, 2016). The GSMM provides detailed stormwater control measures and promotes low-impact development (LID) practices such as bioretention basins, green roofs, permeable pavements, and rain gardens to manage stormwater at the source.

The GSMM serves as a key technical resource for local governments, developers, and property owners, supporting implementation of BMPs that align with EPD programs such as the TMDL and Section 319 NPS programs. The practices outlined in the GSMM are widely used by local governments and developers to meet water quality objectives established under EPD-administered programs.

2.3. Georgia Department of Transportation (GDOT)

The Georgia Department of Transportation (GDOT) recognizes the significant impact of highway stormwater runoff on water quality. GDOT addresses this issue through its Stormwater Design Manual (Georgia Department of Transportation, 2020), which provides guidance for managing transportation-related runoff.

GDOT integrates green infrastructure practices such as bioretention basins, planted filter strips, and detention systems into highway drainage plans. These practices have been shown to significantly reduce total suspended solids (TSS), nitrogen (TN), and phosphorus (TP) in highway runoff (Cavalcante, 2021). GDOT's Stormwater Design Manual aligns with the principles of the GSMM and supports statewide efforts led by EPD to reduce nonpoint source pollution from transportation corridors.

2.4. Local Government Initiatives and Incentives

Many Georgia communities are expanding green infrastructure as part of local watershed protection and stormwater management initiatives. Cities such as Atlanta and Savannah, along with counties such as Gwinnett County incorporate bioretention, stormwater collection, and wetland restoration into municipal plans to reduce urban stormwater runoff (Georgia Environmental Protection Division, 2016).

For example, Gwinnett County has successfully implemented bioretention systems in commercial areas, schools, and public parks to mitigate runoff from impervious surfaces and improve local water quality (Gwinnett County Department of Water Resources, 2020). To support these efforts, EPD and local governments offer a combination of tax credits, grants, and technical assistance (Georgia Environmental Protection Division, 2019; Georgia Environmental Finance Authority, 2023). GDOT also provides technical guidance to assist local governments in incorporating green infrastructure into transportation-related stormwater projects.

Local green infrastructure initiatives are often guided by state-level frameworks such as the GSMM and are designed to help communities comply with EPD's TMDL and NPDES permit requirements.

2.5. Alignment with State and Federal Guidelines

Georgia's stormwater management strategy is guided by a convergence of state and federal regulatory programs—including the Nonpoint Source Management Plan (Georgia Department of Natural Resources, 2019), the Georgia Stormwater Management Manual (GSMM), NPDES permits, and the Total Maximum Daily Load (TMDL) program. Within this framework, bioretention systems have emerged as a core component in efforts to reduce urban stormwater pollution, particularly when applied to transportation infrastructure where impervious surfaces and high runoff volumes present persistent challenges.

As part of these broader state and local initiatives, transportation infrastructure has emerged as a key focus area for green stormwater management, with bioretention systems increasingly integrated into highway design and maintenance strategies. One approach to achieving this integration involves applying Novotny's framework (Novotny, 2003).

2.6. Integration of Nonpoint Source Pollution Modeling: The Role of Novotny's Framework

Nonpoint source (NPS) pollution has been recognized as a primary contributor to water quality degradation in urban environments. Unlike point source discharges, which originate from discrete locations such as pipes or treatment plants, nonpoint sources are diffuse and result from surface runoff across wide areas. This includes pollutants such as heavy metals, nutrients, oil and grease, and suspended solids washed off roads, rooftops, and other impervious surfaces during storm events.

Among the most influential scholars in the field of diffuse pollution is Vladimir Novotny, whose foundational research in the late 20th and early 21st centuries significantly advanced both the theoretical and practical understanding of urban runoff dynamics. Novotny (2003) emphasized that the "first flush" phenomenon—where a large proportion of pollutant mass is mobilized during the early stages of a storm—is especially problematic in dense urban areas. His work highlights the need for systemic land use changes and decentralized infrastructure to effectively manage urban runoff.

Novotny's contributions have shaped pollutant loading estimation methods that are still widely used in modern watershed planning. Specifically, he introduced a simplified empirical approach that links stormwater runoff volume (Q) with pollutant concentration (C) to estimate total pollutant loads (L) in kilograms per hectare (kg/ha). The empirical formula for pollutant concentration $C_{Element}$ is given by:

$$L = 0.01 \, x \, Q \, x \, C$$

where Q is runoff in mm and C is pollutant concentration in mg/L. These equations allow for first-order estimations of pollutant loads (kg/ha) from urban stormwater runoff, based on curve number (CN) methodology and statistical values of typical urban pollutants (Novotny et al., 1995; Novotny, 2003).

Pollutant concentrations can be derived from event mean concentrations (EMC) adjusted by coefficients of variation (CV) using the empirical formulation:

$$Celement = 10^{(log10(EMC)x(1+1.28xCV))}$$

This modeling approach allows researchers and engineers to make first order estimates of pollutant loadings, particularly useful in watersheds with limited monitoring data. It enables comparative evaluations across sites, and the prioritization of areas for stormwater intervention. These formulas have been central to water quality management decisions involving lead, zinc, TSS, nitrogen, phosphorus, and other common stormwater pollutants.

Novotny's work has informed the development and implementation of Best Management Practices (BMPs), including bioretention basins, green roofs, bioswales, and permeable pavements. These strategies align with contemporary green infrastructure paradigms, which focus on source control and low-impact development to restore more natural hydrologic conditions. Bioretention systems operate on principles consistent with Novotny's modeling logic—capturing, filtering, and treating the "first flush" of runoff where pollutant loads are most concentrated.

3. Highway Water Quality Management

Building on Georgia's regulatory framework for green infrastructure, highway water quality management increasingly incorporates bioretention systems to address the unique challenges of transportation-related stormwater runoff.

Highway stormwater runoff is a major source of pollution, carrying heavy metals, hydrocarbons, and sediments from road surfaces into nearby water bodies. These pollutants threaten water quality and aquatic ecosystems. To address this, bioretention basins are widely used to capture, filter, and treat road runoff before it enters streams and rivers (Davis et al., 2019).

Bioretention systems have shown high effectiveness in removing pollutants. Studies from Davis et al., (2009); Hunt et al., (2008) and Cavalcante, (2021) report removal of up to 90% of suspended solids, 80% of nitrogen and 85% of phosphorus. These systems also mitigate runoff peaks and thus reduce the risk of flooding in cities. They are particularly effective at removing pollutants from vehicle emissions, such as hydrocarbons, lead, zinc and copper (Trowsdale & Simcock, 2011).

While bioretention systems are effective, they require regular maintenance to ensure their long-term performance. Over time, sediment accumulation, clogging and vegetation changes can reduce infiltration capacity and treatment efficiency (LeFevre et al., 2012; Hatt et al., 2009). Seasonal fluctuations and the use of road salt also affect system performance, especially in colder regions (Li & Davis, 2014; LeFevre et al., 2012). Best management practices include routine sediment removal, vegetation maintenance and regular replacement of filter media (Hunt et al., 2008; Davis et al., 2012).

Design enhancements such as layered filter materials, underdrain systems, and engineered soil amendments can improve bioretention performance (Brown & Hunt, 2011). Materials such as biochar and iron filings improve nutrient retention and microbial activity (Lucas & Greenway, 2008), while aeration and optimized filter configurations help maintain infiltration rates (Hatt et al., 2009).

Georgia is expanding the use of bioretention systems as part of its highway stormwater management strategy. A study by Cavalcante (2021) at the I-75/I-85 and I-20 interchange in

Atlanta showed strong pollutant removal: 100% of total suspended solids (TSS), 88% of total Kjeldahl nitrogen (TKN), 82% of total nitrogen (TN), and 86% of ortho-phosphorus (ortho-P) were removed. However, nitrate removal is still limited. To improve denitrification, design adjustments such as internal water storage zones are recommended.

Cavalcante, 2021 also found that bioretention facilities are most effective during frequent, smaller rain events, while larger storms reduce treatment efficiency due to media saturation and bypass flows (Wang et al., 2023). Seasonal trends influence bioretention performance, with nitrogen removal typically lower during warmer months due to increased microbial activity and nitrification challenges (Zhang & Hunt, 2013). Adaptive design approaches, including internal storage, optimized inlets and outlets, and climate-aware maintenance, are critical to maintaining long-term performance (Wang et al., 2023; Larsen et al., 2022).

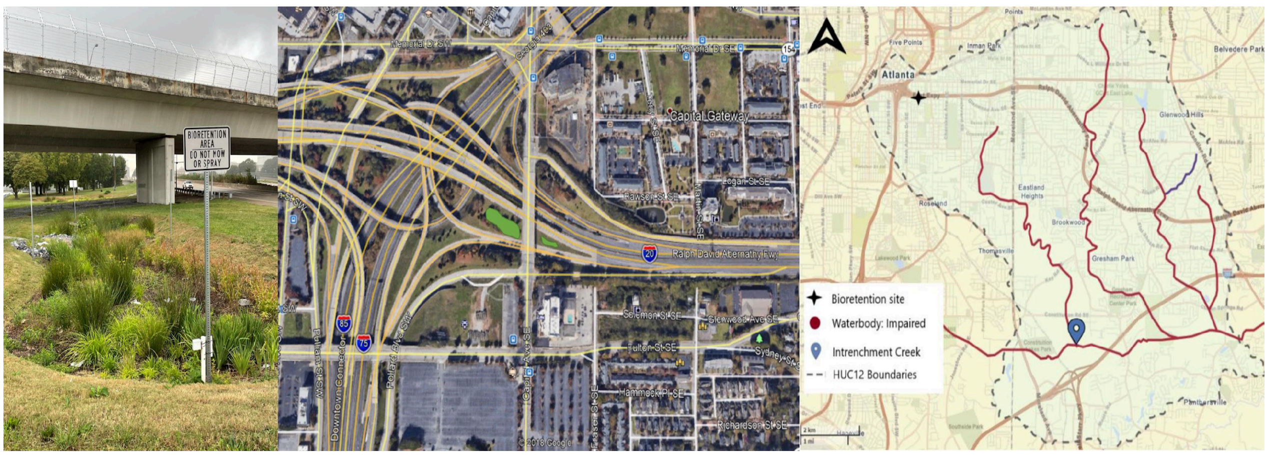
These findings support the integration of bioretention into transportation infrastructure and municipal stormwater programs. For transportation authorities and urban planners, bioretention offers a sustainable solution to mitigate the impacts of highway runoff and improve water quality in urban watersheds (Wang et al., 2023; Larsen et al., 2022).

4. Project Background and Site Description

Urban expansion in south-central Atlanta has led to persistent stormwater management problems, particularly in neighborhoods near the headwaters of Intrenchment Creek, a tributary of the South River. Due to extensive development, portions of the Intrenchment Creek watershed, including Peoples town and Summerhill, contain up to 90% impervious surfaces, such as roads, parking lots, and buildings, which prevent natural infiltration of water (City of Atlanta Department of Watershed Management, 2014). As a result, rainwater accumulates rapidly, contributing to excessive runoff, water pollution, and combined sewer overflows. This problem is particularly severe in densely built areas with large transportation networks and commercial structures. Following major flooding events in Peoples town and Summerhill in 2012, the City of Atlanta, in collaboration with local organizations, developed more effective stormwater management strategies to mitigate impacts on Intrenchment Creek (City of Atlanta Department of Watershed Management, 2015).

A study conducted by American Rivers recommended the implementation of stormwater control measures, commonly known as Best Management Practices (BMPs), along major highway corridors to improve water infiltration and filtration. The results showed that such measures could mitigate up to 95% of stormwater-related problems in the area. Based on these recommendations, the GDOT initiated a stormwater management project in 2020 that included the construction of a bioretention basin at the intersection of I-75/I-85 and I-20. This system was designed to handle runoff from a 606 m^2 drainage area, and a pond area of 156 m^2 while complying with local stormwater regulations and design. Key design features of the bioretention basin include a 45.7 cm (18-inch) filter layer to remove pollutants and a 22.9 cm (9-inch) ponding zone to temporarily store excess water, allowing for gradual infiltration.

In 2016, Intrenchment Creek was listed as an impaired water body in the Georgia EPD's 305(b)/303(d) Integrated Report, due to high levels of fecal coliform, indicating the need for improved water quality management in the region (Georgia EPD, 2016). This study examines the role of bioretention systems in addressing stormwater issues and evaluates their effectiveness in controlling runoff, improving water quality, and contributing to sustainable urban water management in Atlanta's rapidly evolving landscape. Figure 2.2 shows the project site along with impaired water bodies within the Sugar Creek-South River watershed (HUC 030701030102), including Intrenchment Creek. It also provides an overview of the bioretention system and shows its placement.



a) b) c)

Figure 2.2) a) An overview of the bioretention cell; b) project site location highlighted in green, and the project site is only the Right green section; c) Project location and Sugar Creek-South River watershed waterbody impairment map.

The studied bioretention basin is located adjacent to Interstate 20 (I-20) in southeast Atlanta, an area characterized by dense transportation infrastructure and high impervious surface coverage. The site regularly experiences storm events ranging from 1.3 to over 5 cm (0.5 to over 2 inches), contributing to significant runoff volumes. The basin was constructed in 2019 as part of Georgia Department of Transportation's (GDOT) green infrastructure initiative and is designed to treat highway runoff before it enters the Intrenchment Creek watershed. The drainage area includes multiple highway lanes with average daily traffic volumes exceeding 100,000 vehicles, making it a hotspot for pollutants such as total suspended solids (TSS), heavy metals, hydrocarbons, and nutrients. No prior studies had evaluated the long-term performance of this basin before this research, making it a critical case study for understanding pollutant load reduction in high-traffic urban environments.

As bioretention basins are increasingly adopted throughout the City of Atlanta to manage urban stormwater. This study was developed to evaluate the long-term performance of a bioretention system located at the I-75/I-85 and I-20 interchange after five years of operation. Specifically, the study assesses the basin's effectiveness in reducing pollutant loads from highway runoff by analyzing total solids (TS), total nitrogen (TN), total Kjeldahl nitrogen (TKN), and ortho-phosphorus (ortho-P) concentrations during eight paired storm events. This was achieved by (1) quantifying pollutant loading during storms, and (2) comparing pollutant removal efficiencies and event mean concentrations (EMCs) between influent and effluent samples. The results contribute to a deeper understanding of the long-term functionality of bioretention systems in highway contexts and offer practical insights to inform future maintenance, design improvements, and urban stormwater policy planning in Atlanta and similar urban environments.

CHAPTER 3

METHODS AND MATERIALS

1. Location and description of Bioretention Basin

The project site was a bioretention basin located in Atlanta, Georgia, between the ramp from I-85/I-75 to I-20 and I-20 itself, immediately east of Capitol Avenue (Latitude: 33.73930° N, Longitude: -84.38483° W). The bioretention basin was constructed in 2020 to capture runoff from approximately 606 m^2 (6,524 square feet) of the on-ramp to I-20. The design of the filtering media and ponding area aligns with current local engineering standards, which specify a preferred bioretention soil media depth of 45.7 cm (18 in.) and a maximum surface ponding depth of 22.9 cm (9 in.). Underdrain flow and any excess water exceeding the basin's storage capacity exit through a drop inlet box connected to the existing Combined Sewer Outfall (CSO) system.

2. Sample Collection

A discrete, time-based sampling technique was used to collect water samples at the inflow and outflow points every five minutes based on presence of water at a specified height in the inlet flume and outlet upturned elbow. An ISCO 6712 automated water sampler with 24 one-liter bottles facilitated sampling. Ten water samples of 800 ml were collected per event and provided consistent water quality monitoring during storm events. The inflow rates to the bioretention basin for each sampled storm were determined by multiplying the cross-sectional area of the inlet channel by the flow velocity, which was measured using an area-velocity flow sensor (e.g., ISCO 2150) installed at the inlet point.

Stormwater runoff entered the bioretention basin through a trapezoidal concrete flume which was 61 cm wide at the base and 122 cm wide at the top and had a length of 12 meters with side slopes of 5:1. Before the water reached the filter materials, it was passed through a forebay, which helped to regulate the flow intensity and distribute the water evenly. Sampling was initiated using a Doppler ultrasonic area velocity sensor (ISCO-2150 Area Velocity Module) installed in the flume to track depth of water and flow velocity at one-minute intervals. Once initiated, the ISCO took samples through a 7.6m (25-foot) suction tube connected to a screen in the inlet flume.

The bioretention system also had an outflow control structure that regulated both overflow and discharge from the perforated drainage system embedded in gravel on the bottom of the bioretention basin. To facilitate the collection of discharge samples, a second ISCO 6712 was used and equipped with a pressure transducer for measuring depth in the upturned elbow to start the collection and a strainer attached to collection tubing. The transducer and tubing with strainer attached was inserted in a hole drilled in the top of the unturned elbow and placed on the bottom of the pipe to measure water depth. Figure 3.1 shows the author in the drop inlet bay collecting samples from the ISCO 6712.

Figure 3.1. Interior view of the drop inlet box used for stormwater sampling. An automated sampler is installed to collect flow-proportional water quality samples during storm events. This location captures runoff from surrounding impervious areas before entering the bioretention system. The image shows *the author* retrieving a sample bottle from the autosampler setup.

The inflow volumes were determined by direct field measurements using area–velocity methods, where the cross-sectional area of the channel was multiplied by the observed flow velocity. Outflow volume was estimated by applying the standard geometric formula for the volume of a cylinder. This method is commonly used in hydrology and hydraulic engineering (Chin, et. al., 2013). Outflow volume was estimated by applying the standard volume formula for a cylinder,

$$Volume = \pi r^2 h$$

$$Qout = \frac{Volume}{\Delta t}$$

where Q_{out} is the outflow rate (L m^{-1}), Q_{in} is the inflow rate (L m^{-1}), r is the inner radius of the column (m), h is the water height (m), V is the volume (m^3), and Δt is the time interval (min). This geometric approach was necessary as there were no direct velocity measurements at the outflow. By treating the column as a vertical cylinder, changes in water height over time were converted to changes in volume, allowing an approximation of discharge. This method eliminates the need for velocity data while still providing a reliable estimate of discharge.

An ECRN-100 tipping bucket rain gauge (METER Group, formerly Decagon Devices) was connected to a ZL6 data logger (METER Group) to measure cumulative precipitation, while a TEROS 12 sensor (METER Group) continuously monitored soil temperature. To quantify runoff volumes and pollutant loads, a subset of 5 bottles was selected at uniform time intervals from the 12 collected per inflow and outflow event. This time-distributed sampling method allowed for representative coverage of each storm's hydrograph.

Water samples were analyzed in the laboratory for total solids (TS), ortho-phosphorus (Ortho-P), and total Kjeldahl nitrogen (TKN). TS was analyzed according to Standard Methods 2540 B (APHA, AWWA, & WEF, 2023), using the gravimetric method. Ortho-P was analyzed using Hach TNT843 vials, and TN and TKN using Hach TNT880 vials. This methodical approach ensured accurate data collection and provided valuable insight into the system's ability to manage stormwater runoff and effectively remove pollutants over time.

3. Water Quality Analysis

Water samples were collected during 14 storm events and analyzed for concentrations of total solids (TS), total nitrogen (TN), total Kjeldahl nitrogen (TKN), and ortho-phosphorus (Ortho-P). Storm events where only discharge samples were available—due to sensor blockage from sediment deposition, a common issue in similar studies—were excluded from the analysis. Only events with both inflow and outflow samples were used to calculate the pollutant removal efficiencies of the bioretention system. Of the 14 sampled storm events, only 8 events had complete paired inflow and outflow water quality data suitable for determining performance of the basins. Therefore, this study focused on these 8 storm events sampled between November 2024 and April 2025.

Total solids (TS) were measured gravimetrically following Standard Methods 2540 B (APHA, AWWA, & WEF, 2023). A known volume of each sample was poured onto a pre-weighed drying dish, oven-dried at 103–105°C to remove moisture and then reweighed. The TS concentration (g/L^{-1}) was calculated based on the difference in mass and the initial sample volume.

Total nitrogen (TN), total Kjeldahl nitrogen (TKN), and ortho-phosphorus (Ortho-P) were analyzed using Hach TNT plus vials according to manufacturer test procedures: Hach Test TNT 880 for TN and TKN, and Hach Tests TNT 843 for Ortho-P (ascorbic acid method). A Hach DR3900 spectrophotometer was used to measure absorbance and determine nutrient concentrations for all Hach tests.

4. Pollutant Loads and Mass Removal Efficiency

The cumulative pollutant mass at the inflow and outflow was determined using the USEPA National Nonpoint Source Monitoring Program methodology (USEPA, 1997). For each storm event, the pollutant load was estimated by calculating the product of pollutant concentration and flow rate at each time interval, and then summing these values over the duration of the runoff event (i.e., integrating over time) to obtain the total mass of pollutant transported. This process is mathematically represented as follows:

$$Total\ Pollutant\ Mass = \int_{0}^{tr} C(t)Q(t)dt$$

Where: C(t) denotes the pollutant concentration (mg/L^{-1}) recorded at specific time intervals, Q(t) stands for the runoff rate (L/min^{-1}) measured every five minutes and the integration limits range from t_0 (start of runoff) to t_r (end of runoff).

To quantify pollutant concentrations over an entire storm event, the Event Mean Concentration (EMC) was calculated by dividing the total pollutant mass by the total volume of runoff collected during the event:

$$EMC \frac{Total\ Pollutant\ Mass}{Total\ Runoff\ Volume} = \frac{\int_{o}^{tr} C(t)Q(t)dt}{\int_{0}^{tr} Q\ (t)dt}$$

The effectiveness of the system in removing pollutants was evaluated by calculating the removal efficiency (RE), which determines whether the system retains (positive values) or releases (negative values) pollutants. The RE for each individual storm event was calculated using the following equation, as recommended in the USEPA National Nonpoint Source Monitoring Program guidance (USEPA, 1997). The RE for each individual storm event was calculated using the following equation:

$$RE(\%) = \frac{Pollutant\ Mass\ in - Pollutant\ Mass\ out}{Pollutant\ Mass\ in}\ x100$$

To determine whether there was a statistically significant difference in pollutant concentrations between inflow and outflow, hypothesis tests were conducted for all water quality parameters. Because the data did not meet normality assumptions, the non-parametric Wilcoxon signed-rank test for paired samples was used. For each parameter, the null hypothesis (H_0) stated that there was no significant difference between inflow and outflow concentrations. The alternative hypothesis (H_1) stated that a significant difference existed. A p-value was calculated for each comparison; if the p-value was less than 0.05, the null hypothesis was rejected, indicating that the observed difference was statistically significant at the 95% confidence level.

CHAPTER 4

RESULTS AND DISCUSSION

1. Monitored Events

Fourteen monitored storm events were sampled from November 2024 to April 2025 (Table 4.1) with eight of them having both inflow and measurable water in the drain line and upturned elbow. These eight events were used for detailed analysis of pollutant loading and treatment performance. All fourteen storm events recorded during this period had precipitation depths ranging from 3 millimeters to 31 millimeters. To distinguish between small and large storm events, a threshold of 30.48 millimeters (1.2 inches) was applied — a value widely used in urban stormwater management (GWMM, 2016; USEPA, 2009). This threshold reflects the sizing and design criteria for stormwater controls such as bioretention systems, which are typically optimized to treat frequent, small rainfall events that contribute disproportionately to annual pollutant loads in urban runoff. Since none of the monitored storms exceeded this threshold except one, all others were classified as small storms.

The duration of these storms ranged from fifteen minutes to just over two hours. This pattern of short, low-intensity rainfall events is commonly observed in urban catchments with extensive impervious surfaces such as roads, parking lots, and rooftops. In such environments, even small precipitation events can generate substantial runoff due to the lack of infiltration and rapid surface flow over sealed surfaces. Impervious cover reduces lag time and increases peak discharge rates, amplifying the hydrologic response to rainfall regardless of intensity. As a result, these frequent, low-intensity events can cumulatively contribute a significant pollutant load to receiving waters (Ongaga et al., 2024; Kelleher et al., 2024). Studying bioretention system performance under these conditions provides critical insight into how well such infrastructure can manage runoff in highly urbanized areas.

Table 4.1. Event date, size (mm), and type of samples collected.

Event Date	Precipitation Depth (mm)	Precipitation Depth (inches)	Inflow	Outflow
11/14/24	22	0.87	x	x
11/26/24	6	0.24	x	x
12/11/24	12	0.47		x
12/27/24	8	0.31	x	
1/18/25	20	0.79	x	x
1/31/25	9	0.35	x	
2/11/25	10	0.39	x	x
2/13/25	37	1.46		x
2/15/25	1	0.04	x	x
3/20/25	1	0.04	x	
3/24/25	6	0.24	x	
3/31/25	10	0.39	x	x
4/10/25	21	0.83	x	x
4/22/25	1	0.04	x	x

2. <u>Pollutant Analysis</u>

Based on cumulative data from the inflow and outflow samples, the average removal efficiency for total nitrogen (TN) was 94%, with concentrations decreasing from 81 grams in the influent to

6 grams in the effluent. Total Kjeldahl nitrogen (TKN) was reduced by 96%, from 48.2 grams to 1.3 grams. Orthophosphate (Ortho-P) decreased by 95%, from 15 grams to 0.9 grams. Total solids (TS) showed a 98% reduction, from 8,185 grams/L to 144 grams/L. Nitrate-nitrogen was reduced by 88%, from 33 grams to 5 grams. Despite the modest size and intensity of these storm events, the treatment system demonstrated consistently high pollutant removal performance.

Among all monitored events presented in Table 4.1, four events (12/27/2024, 01/31/2025, 03/20/2025, and 03/24/2025) were only monitored for inflow. Due to the absence of corresponding outflow data, cumulative pollutant loadings for these storms were not computed. The absence of outflow sampling was due to battery-related equipment issues for the first few events prior to November 2024. For later events, the lack of outflow was attributed to insufficient runoff generation, likely due to high infiltration and storage within the bioretention system. Two storm events—occurring on 11/26/2024 and 01/18/2025— produced measurable inflow but no outflow, indicating 100% retention of both volume and pollutant loads. These fully retained events were classified as small storms, based on precipitation depths of 6 mm (0.24 in) and 20 mm (0.79 in), respectively. Estimated cumulative pollutant loads for these retention events were TN = 119 g, TKN = 111 g, Ortho-P = 40 g, and TS = 81,000 g.

Eight storm events were successfully monitored for both inflow and outflow and were used to calculate pollutant removal efficiencies and event mean concentrations (EMCs, mg L^{-1}). These are referred to throughout the analysis as Sampled Storms #1 through #8 in chronological order.

Storms that produced both inflow and outflow samples were further analyzed for pollutant loadings, removal efficiency (%), and event mean concentrations (EMC, mg L^{-1}). These events are referred to in subsequent sections of this thesis as sampled storms #1 through #8, in chronological order.

To evaluate the influence of storm size on inflow loads and runoff volumes, storms were categorized as “large” if total precipitation exceeded 25.4 mm (1.0 in), consistent with the ARC Blue Book's standard for design capture. Based on this criterion, one storm (February 13, 2025) was classified as large, while the remaining 13 were considered small. The large storm contributed TN = 13.5 g, TKN = 8.0 g, Ortho-P = 2.5 g, and TS = 1,364,000 g, with a total inflow volume of 22,422 liters**.** In contrast, the small storms collectively contributed TN = 67.5 g, TKN = 40.2 g, Ortho-P = 12.5 g, and TS = 6,821,000 g, with an estimated inflow volume of 76,962 liters. As shown in Table 4.2, the large storm accounted for approximately 17% of the total observed pollutant load and inflow volume, while the small storms contributed the remaining 83%. These results highlight the importance of treating frequent, smaller storm events, which represent the dominant contributor to pollutant loads in urban runoff during the monitoring period.

Table 4. 2. Cumulative inflow pollutant loadings and volume, and percentage of loadings and volume contribution accounted for by large and small sampled storms in the monitoring period from November 2024 to April 2025.

		TN (g)	**TKN (g)**	**Ortho-P (g)**	**TS (g)**	**Volume (L)**
Cumulative inflow load and volume	Large Storms (1 event)	13.5	8	2.5	1364000	22422
	Small Storms (13 events)	67.5	40.2	12.5	6821000	76962
Load and volume contribution (%)	Large	17%	17%	17%	17%	23%
	Small	83%	83%	83%	83%	77%

3. Storm Pollutant Load and Removal Efficiency

The number of pollutants that the bioretention basin handles during each storm event depends on both the type of pollutant and the strength of the storm. Table 4.3 shows a breakdown of the amounts of pollutants that ran in and out of the system during each storm, along with the corresponding removal efficiencies (% RE). By and large, there was a consistent decrease in pollutant loading from inflow to outflow, indicating a significant improvement in water quality as the runoff passed through the basin.

Table 4.3. Pollutant load reduction from inflow to outflow (In (g) and Out (g)), and calculated removal efficiency (% RE) for the storm events sampled spanning November 2024 to April 2025.

		TN			TKN			PO4			TS	
Event	In (g)	Out (g)	% RE	In (g)	Out (g)	% RE	In (g)	Out (g)	% RE	In (g)	Out (g)	% RE
#1	81	6	93%	48.2	1.3	97%	15	0.9	94%	8185	144	98%
#2	24.4	2.76	88%	11	0.51	95%	4	0.25	94%	2996	103	97%
#3	142	2	98%	127	0.91	99%	15	0.2	99%	77680	113	100%
#4	109	0.16	100%	57	0.1	100%	9	0.012	100%	17280	31	100%
#5	27	0.2	100%	14	0.1	100%	2	0.04	97%	1816	8	99%
#6	75	0.3	99%	71	0.3	99%	14.1	0.001	100%	3954	20.1	99%
#7	59	14	73%	50	10	79%	2.64	0.7	73%	1357	451	66%
#8	72	1.18	98%	61	1	98%	5.2	0.03	99%	2264	43	98%

To take a closer look at how specific pollutants behaved during these events, Figure 4.3 shows loading profiles for total nitrogen (TN), total Kjeldahl nitrogen (TKN) and orthophosphate (Ortho-P) across all nine storms sampled.

The removal efficiency observed during the eight storm events varied depending on the pollutant being monitored. Total nitrogen (TN) removal ranged from 68% to 98%, while total Kjeldahl nitrogen (TKN) showed consistently high performance with values between 90% and 100%.

Orthophosphate (Ortho-P) showed greater variation, with removal efficiencies ranging from 59% to 94%. Nitrate-N (NO_3^--N) followed a similar trend, with reductions between 63% and 93%. Total suspended solids (TS) were treated effectively, with removal rates ranging from 74% to 100%.

To evaluate the statistical significance of pollutant reductions, a Wilcoxon signed-rank test was applied to paired influent and effluent concentrations across eight storm events. The results indicated statistically significant differences for all parameters analyzed, including total nitrogen (TN), total Kjeldahl nitrogen (TKN), orthophosphate (Ortho-P), and total solids (TS), with p-values of 0.0078. These findings affirm the overall effectiveness of the bioretention basin in reducing pollutant loads under field conditions (Figures 4.1- 4.4).

Notably, Event #7 exhibited lower removal efficiencies across several pollutants—particularly nitrate, Ortho-P, and total solids. In contrast, TN and TKN removal remained above target, suggesting the system still performed well for certain nitrogen forms. This selective underperformance likely reflects a combination of storm-specific and seasonal factors. For example, high antecedent soil moisture, reduced microbial activity in cooler months, and diminished plant uptake can reduce treatment efficiency. Additionally, a high-volume or intense storm may have exceeded the system's storage or infiltration capacity, leading to runoff bypass or short-circuiting.

These results highlight the bioretention system's general robustness but also its sensitivity to individual storm conditions. Although seasonal influences were likely at play, this study did not include a dedicated seasonal analysis. Future research should incorporate multi-seasonal or long-term monitoring to better understand climate-related effects on pollutant removal.

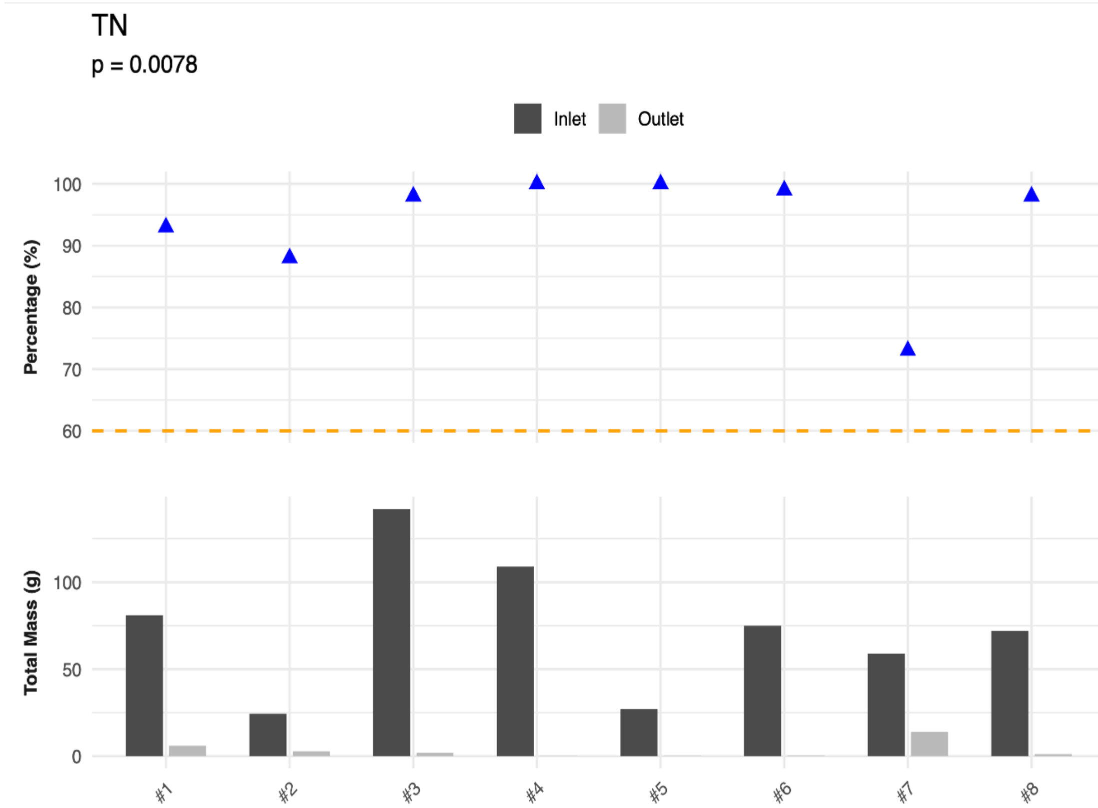


Figure 4.1. Pollutant load (g) at the inlet and outlet and removal efficiency (%) of each of the eight sampled storms for TN.

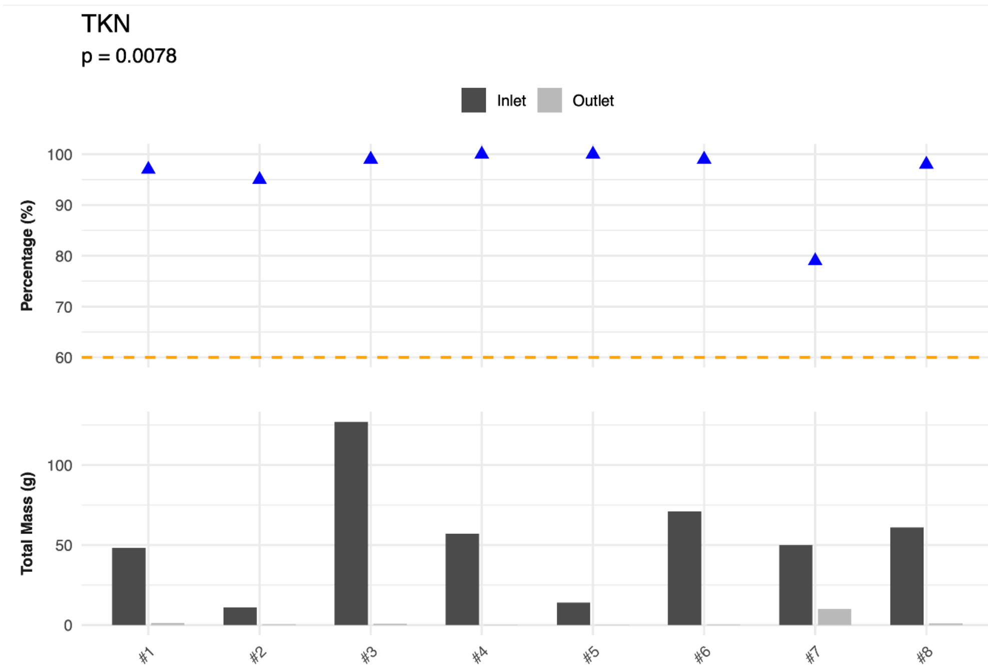


Figure 4.2. Pollutant load (g) at the inlet and outlet and removal efficiency (%) of each of the eight sampled storms for TKN.

Figure 4.3. Pollutant load (g) at the inlet and outlet and removal efficiency (%) of each of the eight sampled storms for Ortho-P.

Figure 4.4. Pollutant load (g) at the inlet and outlet and removal efficiency (%) of each of the eight sampled storms for TS.

The TS laboratory analysis showed a significant reduction in total solids between influent and effluent samples, as shown in Figure 4.2. The most detailed comparison was performed for the largest storm event in the dataset (Event #3, February 15, 2025), where the total solids (TS) load was 77,680 g in the influent and 113 g in the effluent, corresponding to a removal efficiency of 100%. Smaller storm events also showed similar or even higher removal rates, with events no. 4, 5 and 6 achieving 100% and 99% TS removal respectively. These results confirm that the bioretention basin consistently retains solids across a range of events. The cumulative retained TS mass across all eight sampled events was 132,805 g, based on a total influent load of 144,278 g and an effluent load of 11,473 g, giving an average removal efficiency of over 95%. These values confirm the strong and consistent performance of the system in reducing solids from road runoff.

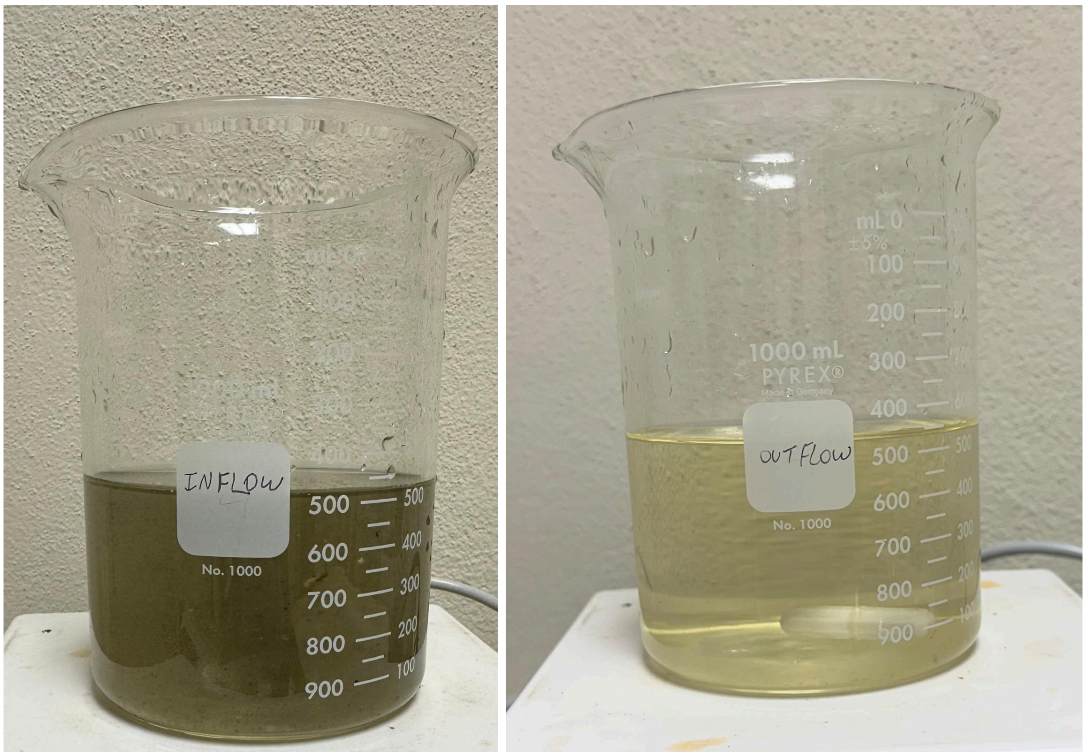


Figure 4.5. Comparison between inflow and outflow total solids samples during laboratory analysis.

4. <u>Event Mean Concentration</u>

The event means concentrations (EMCs) for TN, TKN and Ortho-P in the inflow and outflow were analyzed for eight storm events and are shown in Figure 4.6 – 4.9. For TN, inflow concentrations ranged from 11 to 34 mg L^{-1}, with outflow values consistently reduced to 11mgL^{-1} for all events, indicating a decreasing trend, although variability was high. TKN levels showed a more pronounced treatment effect with concentrations ranging from 6 to 18 mg L^{-1} in influent and 2 to 6 mg L^{-1} in effluent, reflecting a significant reduction in organic nitrogen and ammonia levels. Ortho-P concentrations in the influent samples were generally lower than the nitrogen species and ranged from 1 to 6.3 mg L^{-1} and were further reduced to levels as low as 0.6 mg L^{-1} in the effluent. These reductions in all events indicate that the treatment system is consistently retaining phosphorus species. For total solids (TS), the mean concentration in the influent was 2,285 mg L^{-1} with a median of 1,674 mg L^{-1}, while the mean and median concentrations in the effluent were significantly lower at 1,407 mg L^{-1} and 1,154 mg L^{-1} respectively.

The corresponding box plot analysis, shown in Figure 4.6-4.9, confirms statistically significant reductions in pollutant concentrations for all three analytes. A Wilcoxon signed-rank test, a non-parametric test used to assess differences between paired samples, was applied to compare influent and effluent event mean concentrations (EMCs). The resulting p-values were 0.0225 for total nitrogen (TN), 0.0078 for total Kjeldahl nitrogen (TKN), and 0.0207 for orthophosphate (PO_4), indicating that the observed reductions were statistically significant and unlikely due to random variation. These findings support the conclusion that the bioretention system provided effective nutrient removal under the monitored conditions, particularly for nitrogen and phosphorus species commonly present in urban stormwater runoff.

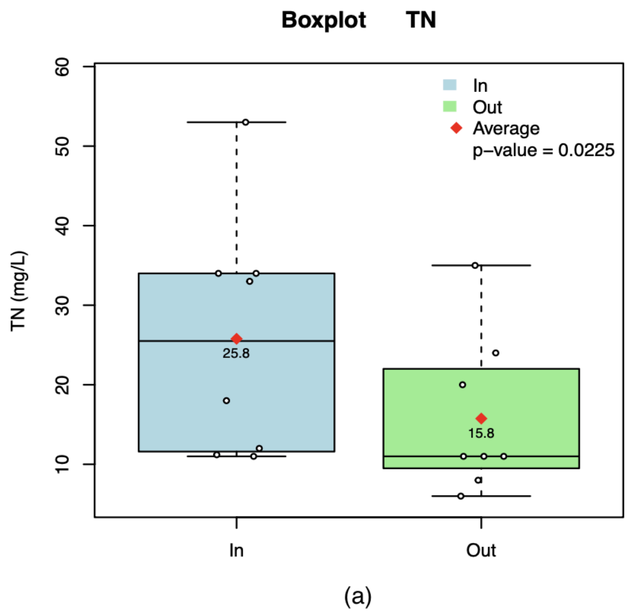


Figure 4.6. Comparison between inflow and outflow event mean concentration (EMC) for TN. Wilcoxon Rank Signed test p-values are indicated.

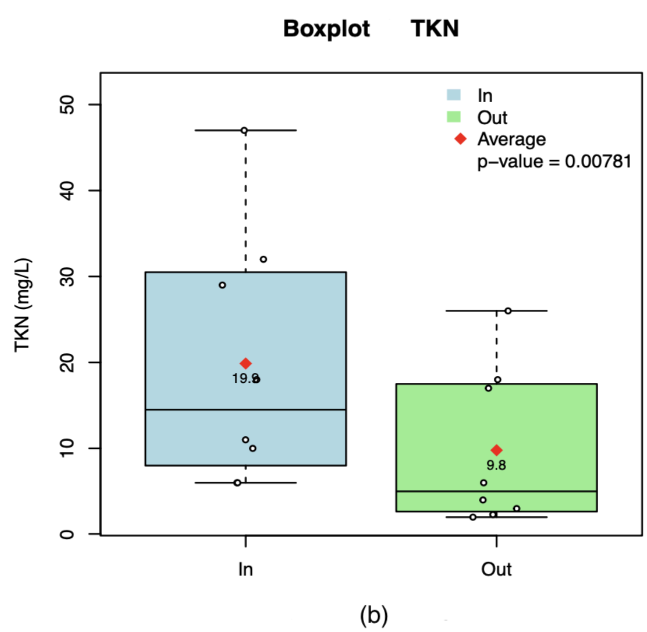
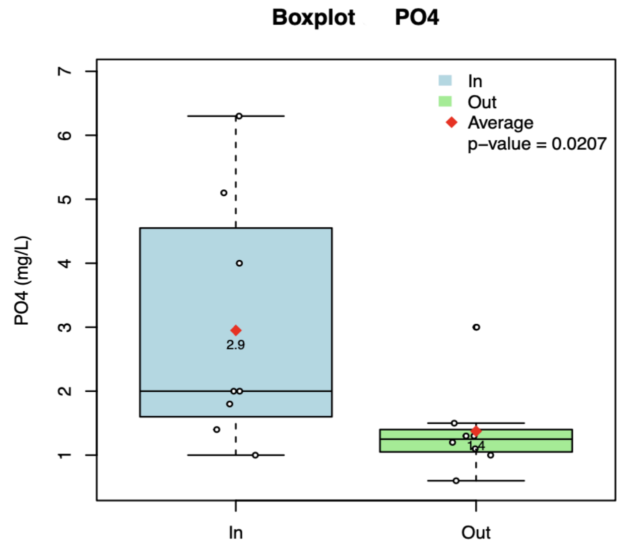
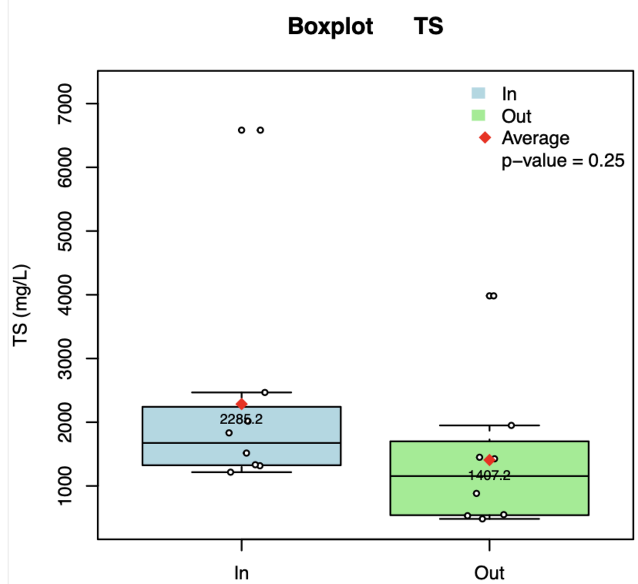


Figure 4.7. Comparison between inflow and outflow event mean concentration (EMC) for TKN. Wilcoxon Rank Signed test p-values are indicated.



(c)

Figure 4.8. Comparison between inflow and outflow event mean concentration (EMC) for PO4. Wilcoxon Rank Signed test p-values are indicated.



(d)

Figure 4.9. Comparison between inflow and outflow event mean concentration (EMC) for TS. Wilcoxon Rank Signed test p-values are indicated.

5. Treatment Efficiency

Fourteen storm events were recorded between November 2024 and April 2025 and were used to characterize rainfall patterns, event size, and sampling conditions. All events had precipitation depths ranging from 1 to 31 mm, with only one event exceeding the 30.48 mm threshold commonly used to distinguish between small and large storms. Most were therefore classified as small and were characterized by short durations between fifteen minutes and two hours. These low-intensity events are typical of urban runoff patterns. However, pollutant removal efficiency was assessed using a subset of eight events for which both inflow and outflow data were available. This subset allowed for quantification of bioretention treatment performance under representative storm conditions.

Despite the relatively modest size and intensity of the monitored storm events, the bioretention system consistently demonstrated high pollutant removal efficiencies. Across the eight events with paired inflow and outflow data, total nitrogen (TN) concentrations were reduced by 94%, from 81 grams to 6 grams. Total Kjeldahl nitrogen (TKN) decreased by 96%, from 48.2 grams to 1.3 grams, while orthophosphate (Ortho-P) concentrations declined by 95%**,** from 15 grams to 0.9 grams. The removal of total solids (TS) was particularly notable, with a reduction of 95%, from 8,185 grams to 144 grams. These results underscore the system's robust treatment performance under small storm conditions, highlighting its effectiveness in reducing nutrient and solid pollutant loads even when runoff volumes are low.

Analysis of pollutant loading by storm size revealed that the single large storm event (February 13, 2025) accounted for only 17% of the total cumulative inflow pollutant load, while the remaining 83% originated from smaller storms. This highlights the critical importance of designing bioretention systems to effectively manage frequent, lower-intensity events—particularly given that ARC (Atlanta Regional Commission, 2016) guidelines recommend sizing basins to capture up to 1.2 inches (30.48 mm) of rainfall. The large storm produced an estimated inflow volume of 22,422 liters and contributed 13.5 grams of total nitrogen (TN), 8.0 grams of total Kjeldahl nitrogen (TKN), 2.5 grams of orthophosphate (Ortho-P), and 1,364 grams of total solids (TS). In contrast, the aggregate contribution from the 13 smaller storms was substantially higher, comprising 67.5 grams of TN, 40.2 grams of TKN, 12.5 grams of Ortho-P, and 6,821 grams of TS from a combined estimated inflow volume of 833 liters. These findings underscore that although large storms deliver considerable volume per event, the cumulative impact of small, recurring storms is more substantial in terms of both pollutant mass and hydraulic loading—supporting the rationale for treatment designs that prioritize high-frequency, small-volume events in urban runoff management.

The mean concentrations of the events (EMCs) also reflect the strong performance of the bioretention system. TN concentrations in the influent ranged from 11 to 34 mg L^{-1} and steadily decreased to 11 mg/L^{-1} in the effluent. TKN concentrations decreased even more significantly, with values between 6 and 18 mg/L^{-1} in the influent and 2 to 6 mg/L^{-1} in the effluent. The orthophosphate concentration fell from 1 to 6.3 mg/L^{-1} to as low as 0.6 mg/L^{-1} in the outflow. The TS showed a mean concentration of 2,285 mg/L^{-1} in the inflow and a reduced mean value of 1,407 mg/L^{-1} in the outflow. Statistical analysis using the Wilcoxon signed-rank test for paired non-parametric data showed significant differences between the values for TN ($p = 0.0225$), TKN (p = 0.00781), and Ortho-P (p = 0.0207) in the influent and effluent, indicating that these reductions were unlikely to be due to random variation.

Overall, these results demonstrate the effectiveness of the bioretention basin in reducing pollutants from stormwater runoff. The system was particularly efficient at removing nitrogen and phosphorus species as well as total solids. Although most of the monitored storms were relatively small, their contribution to the total pollutant load was significant, emphasizing the need for systems that can handle frequent, low-volume runoff events. The data suggest that bioretention systems, when properly designed and maintained, can play a critical role in improving urban water quality as can be seen in Table 4.4.

Table 4.4. Comparison of pollutant removal rates in this study to literature values.

Study	Total Nitrogen (TN)	Ortho-Phosphorus (Ortho-P)	Total Suspended Solids (TSS)
This study	**94%**	**95%**	**98%**
Hsieh & Davis	up to 82%	up to 85%	
Cavalcante	82%	86%	100%
Wang et al.	25%	46%	53%
Davis et al.	55–65%	80–85%	96–99%
Brown & Hunt	88%	85%	95%
Shrestha et al. [21]	45–57%	-470 to 94	89–99%

The efficiency of pollutant removal observed in this study corresponds to or even exceeds the values reported in the literature. In particular, the bioretention system located at the interstate interchange in Atlanta, Georgia, achieved removal efficiencies of 94% for total nitrogen (TN), 95% for orthophosphate (Ortho-P), and 98% for total solids (TS). These results agree well with those of Cavalcante (2021), who reported 82% for TN, 86% for ortho-P and 100% for TSS for a similar urban highway. Studies by Hsieh & Davis (2005) reported TN and ortho-P removal of up to 82% and 85%, respectively, further confirming the effectiveness of bioretention systems for nutrient management. Shrestha et al., (2018) documented a TSS removal efficiency of 89% to 99%, although ortho-P removal was highly variable and, in some cases, even negative. The phosphorus removal in the present study (95%) therefore represents a remarkable improvement. Compared to Davis et al. (2009), where TN removal was 55–65% and ortho-P removal was 80–85%, the results of this study demonstrate the effectiveness of the system design and media selection. Brown & Hunt (2010) observed a slightly lower TN and ortho-P reduction (88% and 85% respectively), but a similarly high TSS removal (95%). Overall, the high efficiency of this system, particularly for TN and phosphorus, underscores the value of bioretention systems for improving stormwater quality in urban street networks.

CHAPTER 5

A COMPARATIVE ANALYSIS OF BIORETENTION EFFICIENCY THEN AND NOW: PERFORMANCE SHIFTS OVER FIVE YEARS

Over the past five years, increasing urbanization and growing awareness of environmental sustainability have led to greater focus on stormwater management strategies. Bioretention systems have proven to be a particularly promising solution, as they combine hydrologic control with pollutant removal. These systems use engineered soil media and vegetation to treat stormwater runoff, reducing the transport of pollutants to surface waters.

This chapter evaluates the long-term performance of a single bioretention basin located in Atlanta, Georgia, originally constructed in 2020. The basin was monitored during an initial study period (2020–2021) and again five years later during the 2024–2025 monitoring period, providing an opportunity to assess how system performance may have changed over time. The pollutants of interest include total nitrogen (TN), total Kjeldahl nitrogen (TKN), and orthophosphate (PO_4).

The baseline study conducted by Cavalcante (2021) involved the monitoring of 17 storm events, during which paired inflow and outflow samples were collected to evaluate pollutant removal efficiency. The results demonstrated substantial reductions in nutrient concentrations, with removal efficiencies of 82% for total nitrogen (TN), 88% for total Kjeldahl nitrogen (TKN), and 86% for orthophosphate (PO_4). These findings underscore the effectiveness of bioretention systems as best management practices (BMPs) for mitigating urban stormwater pollution. However, as with all natural systems, performance can change over time due to factors such as soil media saturation, seasonal biological variability, and sediment accumulation. Long-term assessments are therefore essential to understand how operational longevity influences treatment effectiveness.

The basis for this comparative analysis is a bioretention basin constructed in 2020 in Atlanta, Georgia, designed to treat roadway stormwater runoff from a nearby highway interchange. During the initial study period (2020–2021), the inflow and outflow of the system were monitored across 17 storm events. That baseline monitoring showed strong pollutant removal efficiencies: 82% for total nitrogen (TN), 88% for total Kjeldahl nitrogen (TKN), and 86% for orthophosphate (PO_4).

These results demonstrated the system's potential as an effective best management practice (BMP) for urban runoff treatment. However, because system performance can vary over time due to factors such as soil media aging, seasonal biological changes, and sediment accumulation, long-term monitoring is critical to fully assess the durability of treatment performance.

During the 2024–2025 monitoring period, eight storm events were sampled, with paired inflow and outflow samples collected for each event. The objective of this comparative analysis is to determine whether the basin's treatment performance has remained consistent, improved, or declined relative to the 2020–2021 baseline.

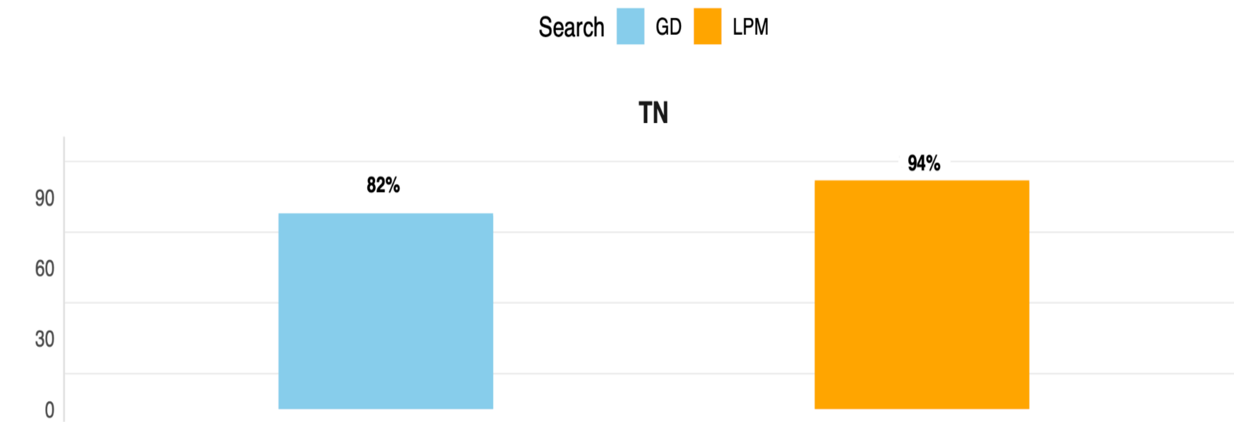


Figure 5.1. Comparison of pollutant removal efficiencies (RE%) between previous study (2021) and actual study (2025) TN.

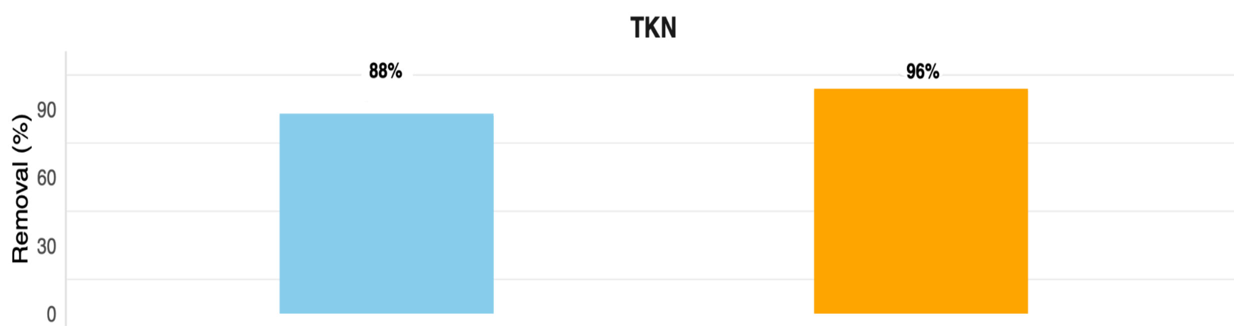


Figure 5.2. Comparison of pollutant removal efficiencies (RE%) between previous study (2021) and actual study (2025) TKN.

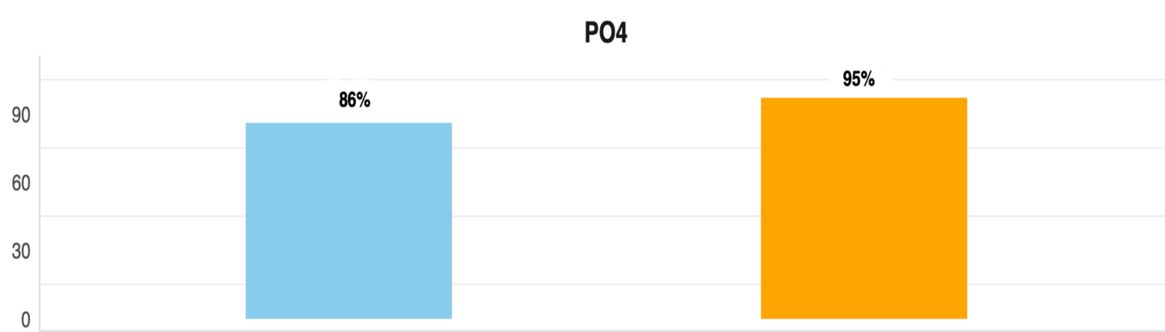


Figure 5.3. Comparison of pollutant removal efficiencies (RE%) between previous study (2021) and actual study (2025) PO4.

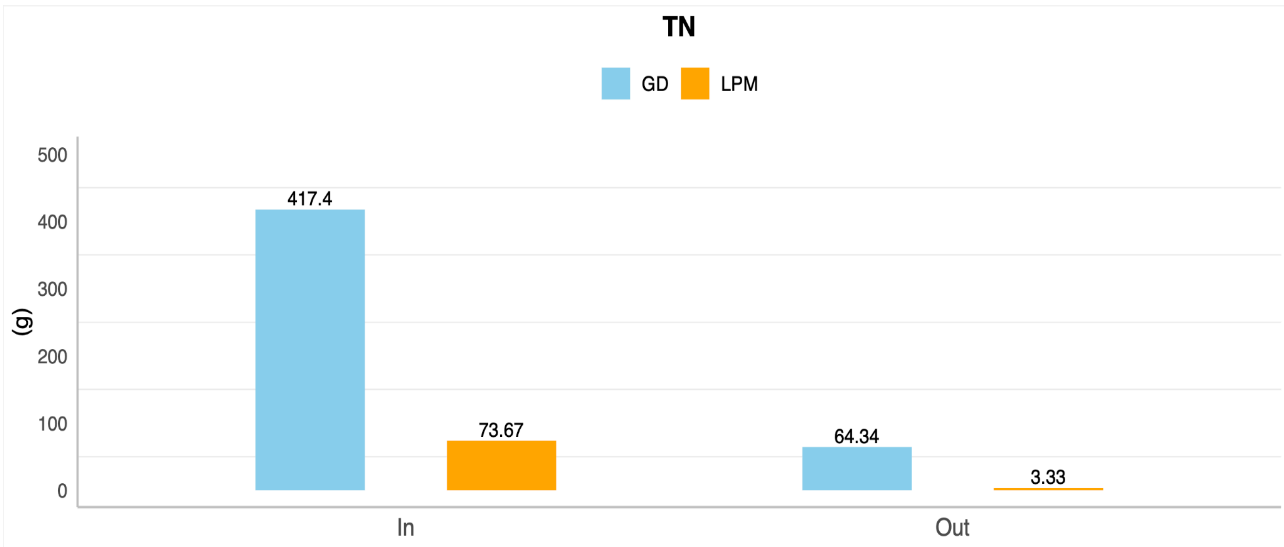


Figure 5.4. Comparison of Total pollutant mass (g) at inflow and outflow for previous study (2021) and actual study (2025) across TN.

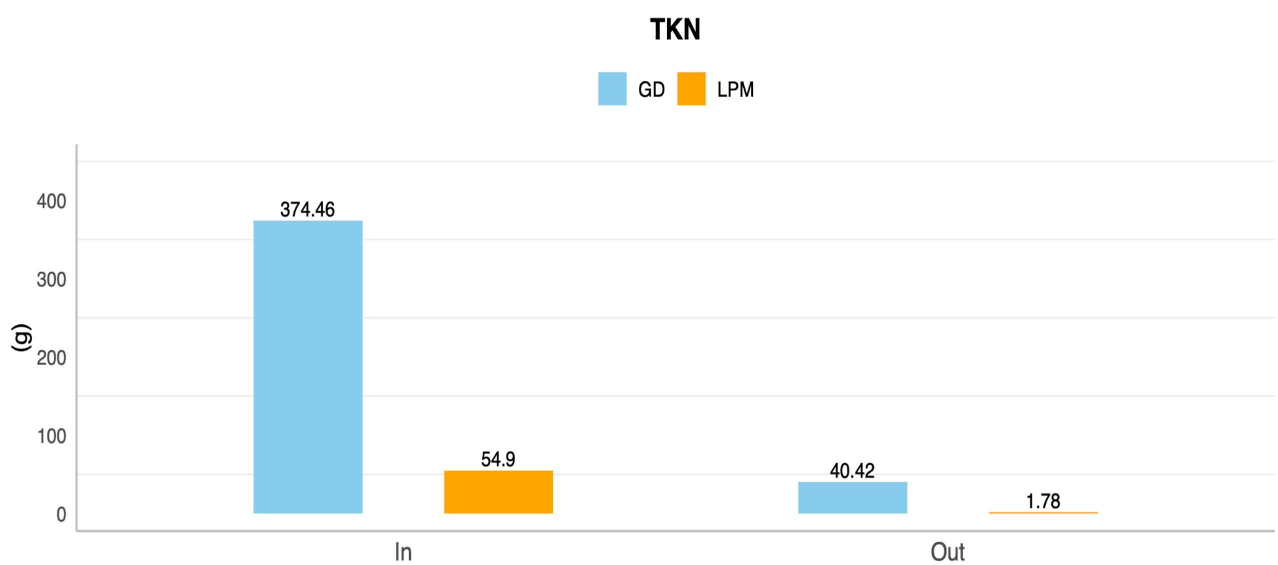


Figure 5.5. Comparison of Total pollutant mass (g) at inflow and outflow for previous study (2021) and actual study (2025) across TKN.

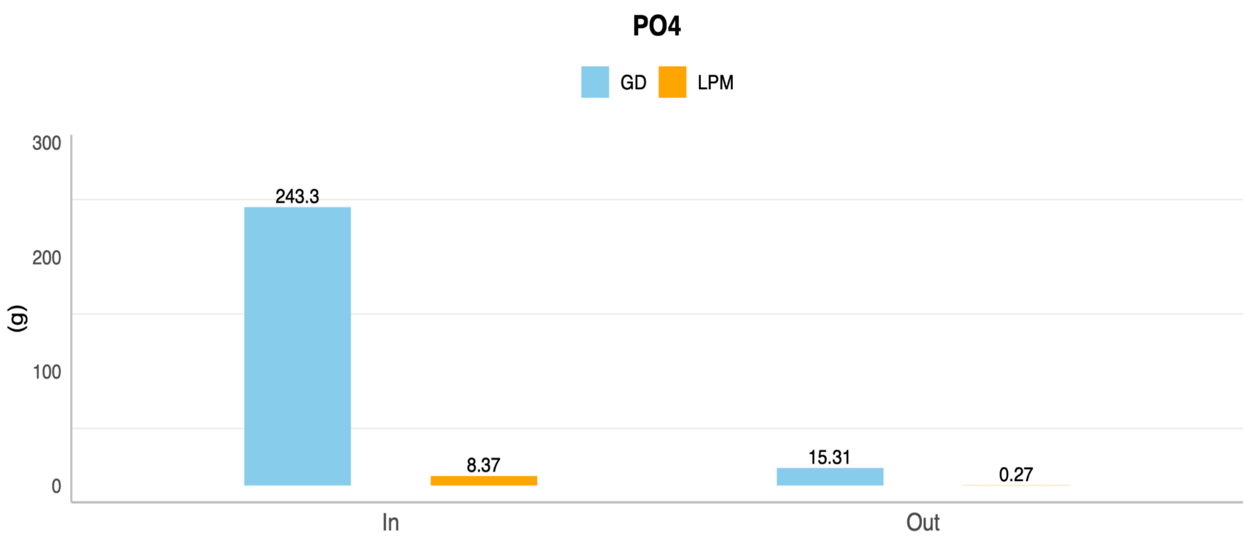


Figure 5.6. Comparison of Total pollutant mass (g) at inflow and outflow for previous study (2021) and actual study (2025) across PO4.

A two-stage statistical approach was used to assess potential shifts in the bioretention system's pollutant removal performance over time. First, the Shapiro-Wilk test was applied to test the normality of the removal efficiency data (RE%). The results indicated that at least one group's data was not normally distributed ($p < 0.05$), which ruled out the use of parametric tests such as the independent t-test. Therefore, the Mann-Whitney U-test — a non-parametric test suitable for comparing median values — was employed. This approach is well-suited for environmental datasets, which often deviate from normal distribution. All tests were conducted at a significance level of $\alpha = 0.05$.

To explore potential changes in system performance, the removal efficiency (RE%) data from the current monitoring period (2024–2025), were compared to baseline results reported by a previous researcher (2020–2021). Table 5.1 summarizes the mean and standard deviation of RE% for total nitrogen (TN), total Kjeldahl nitrogen (TKN), and orthophosphate (PO_4) across both monitoring periods, providing a basis for evaluating long-term treatment consistency.

Table 5.1. Comparison of means and standard deviations of RE% by pollutant for previous study (2021) and actual study (2025).

Pollutant	Method	Mean_RE	SD_RE
PO4	GD	89.5	9.9
PO4	LPM	94.5	9
TKN	GD	88	14
TKN	LPM	95.9	7
TN	GD	85.6	12.5
TN	LPM	93.6	9.3

The statistical results indicate that while removal efficiencies during 2024–2025 were consistently higher than those reported in 2020–2021 for all three pollutants (TN, TKN, and PO_4), the differences were not statistically significant at $p < 0.05$. This suggests that while some performance improvement is evident, it cannot be conclusively attributed to system design changes or maintenance interventions alone and may also reflect natural variation.

To complement the statistical tests, visual comparisons were created using bar charts and boxplots to illustrate pollutant removal trends across the two periods. As shown in Figure 5.1, the bioretention system maintained a consistently high level of pollutant reduction across all analytes in both the baseline (2020–2021) and current (2024–2025) monitoring. Moreover, a Mann-Whitney U-test comparing influent vs. effluent concentrations for the 2024–2025 data showed statistically significant reductions for all pollutants studied ($p = 0.0078$ for TN, TKN,

PO_4, NO_3–N, and Total Suspended Solids), confirming that the system continues to provide effective stormwater treatment.

The comparative analysis demonstrates that the same bioretention system evaluated in this study continues to perform at a high level of efficiency over time, with no statistically significant degradation or decline in removal performance compared to the initial baseline monitoring. This result underscores the robustness and resilience of the bioretention design in long-term urban stormwater applications.

The broader implications of these results emphasize the resilience and reliability of bioretention systems as a key component of urban stormwater management. Despite the lack of statistically significant differences between the 2020–2021 and 2024–2025 datasets, the consistently high treatment performance observed in both periods underscore the suitability of bioretention systems for urban applications.

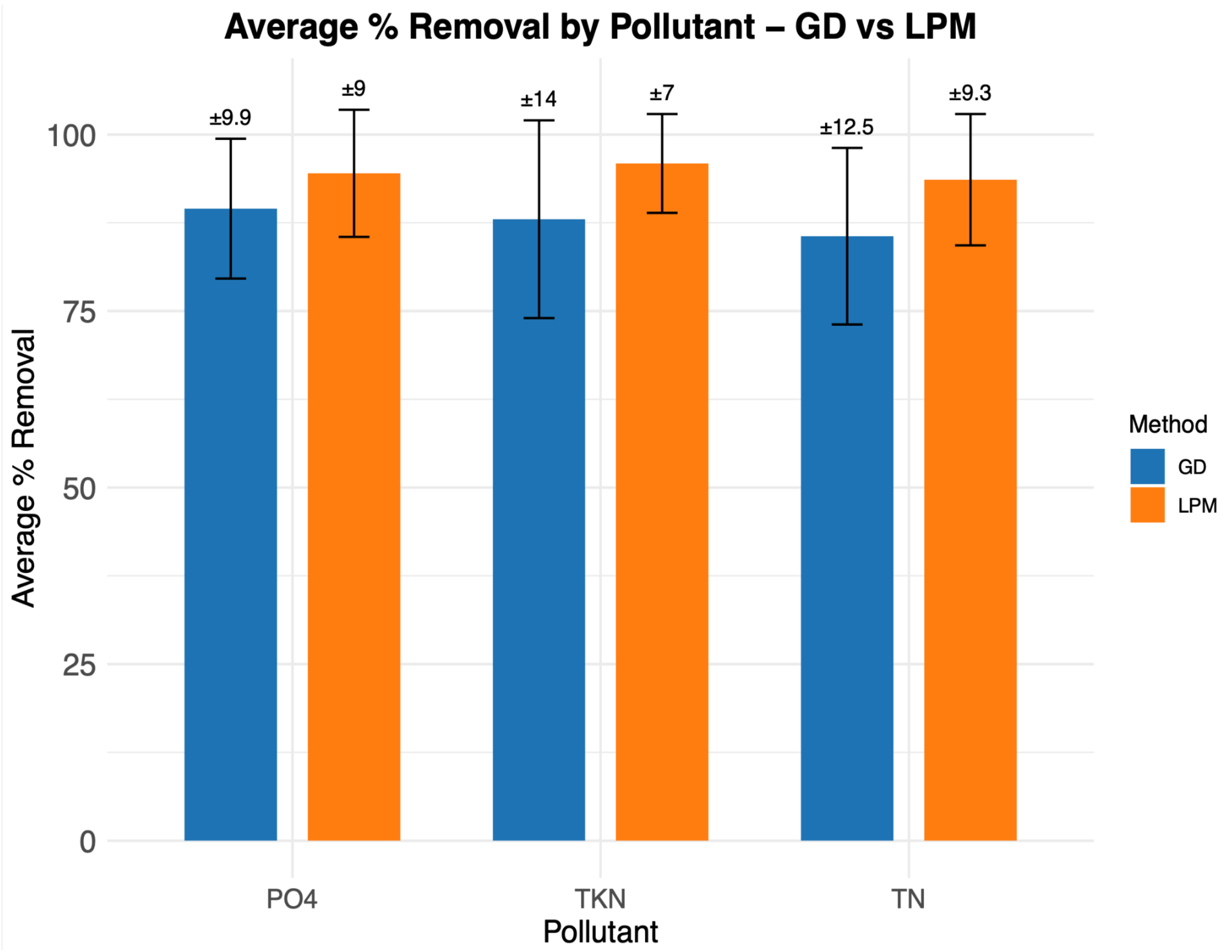


Figure 5.7. Comparison of mean removal efficiencies (RE%) for TN, TKN, and PO_4 between the current (2024–2025) and baseline (2020–2021) monitoring periods.

The slight improvements in performance over time suggest that, when properly maintained, bioretention systems can sustain or even enhance their pollutant removal capabilities. This is particularly encouraging in the context of aging urban infrastructure and the increasing intensity of storm events linked to climate change.

It is also important to note that while this study focused on pollutants—total nitrogen (TN), total Kjeldahl nitrogen (TKN), orthophosphate (PO_4), and sediments—stormwater runoff contains a complex mixture of additional contaminants, including heavy metals, hydrocarbons, pathogens, microplastics, and pharmaceutical residues. Future research should adopt a more holistic approach by incorporating these emerging pollutants. In addition, long-term, seasonal monitoring over multiple years would provide deeper insight into how environmental variables such as temperature, precipitation patterns, and vegetation dynamics influence system performance.

In summary, this study confirms that the bioretention system monitored in 2024–2025 remains an effective and reliable tool for improving urban stormwater quality. The comparison with the 2020–2021 baseline highlights the importance of long-term monitoring to assess the durability and sustained performance of bioretention best management practices (BMPs). The system consistently demonstrated high removal efficiencies for nitrogen, phosphorus, and total solids, with performance that was either maintained or slightly improved over time. These findings reinforce the role of bioretention systems as a sustainable stormwater management strategy and underscore the need for ongoing research and design optimization to ensure their continued effectiveness under evolving environmental conditions.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

The water quality performance of a bioretention basin located at the I-75/I-85 and I-20 interchange in Atlanta, Georgia, was evaluated during the 2024–2025 monitoring period, using pollutant loading data and event mean concentrations (EMCs) from 14 storm events. Of these, 8 storm events included paired inflow and outflow samples, enabling detailed analysis of the basin’s treatment performance under real-world urban highway runoff conditions. The following conclusions and recommendations are drawn from this study:

- The bioretention basin demonstrated excellent water quality treatment performance during the monitoring period. Average removal efficiencies were consistently high across all monitored storms, with total suspended solids (TSS) achieving the highest average removal rate (98%), followed by total nitrogen (TN, 94%), total Kjeldahl nitrogen (TKN, 96%), orthophosphate (PO_4, 95%), and nitrate-nitrogen (NO_3-N, 88%). These results reflect an improvement or sustained performance when compared to the first-year monitoring by Cavalcante (2021), which reported 82% TN, 88% TKN, 86% PO_4, and 100% TSS removal.
- High pollutant removal was observed across both small and larger storms, with no significant influence of storm size on overall treatment efficiency. However, small storms

accounted for most cumulative pollutant loading, contributing approximately 85–91% of the total TN, TKN, PO_4, and TS loads. This underscores the importance of designing bioretention systems to effectively treat frequent, small-volume storm events typical of urban runoff.

- While this study did not conduct a comprehensive seasonal analysis, some variation in pollutant removal was observed during specific events (e.g., Storm #7), potentially linked to seasonal factors such as temperature, pollen inputs, and biological activity. Future studies should incorporate multi-season monitoring to better understand the effects of seasonal dynamics on treatment performance.
- The bioretention system maintained high performance throughout the monitoring period without evidence of media saturation or significant decline in treatment efficiency. However, long-term sustainability requires regular maintenance. Gradual clogging of filter media and vegetative overgrowth can reduce infiltration rates and pollutant removal effectiveness. A proactive maintenance strategy should include periodic sediment removal and vegetation management to sustain optimal system function.
- Continued long-term monitoring is recommended to track potential performance shifts as the system ages and to guide adaptive maintenance strategies. Additionally, future studies should broaden the scope of monitored contaminants to include emerging pollutants such as microplastics, pharmaceuticals, heavy metals, and hydrocarbons, providing a more comprehensive assessment of bioretention effectiveness.

In summary, this study confirms that the bioretention basin consistently provided high levels of pollutant removal under challenging urban highway runoff conditions. The system's ability to maintain or even improve performance over time highlights the resilience of bioretention as a best management practice (BMP) for stormwater treatment. Ongoing monitoring and maintenance will be critical to ensuring continued effectiveness, especially as climate change and urbanization drive increasing runoff volumes and pollutant loads in urban environments.

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