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(Review Article)

Bioswales in Urban Stormwater Management: A literature review on design principles and performance assessment

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Abstract

As urbanization intensifies across global regions, the demand for resilient, sustainable stormwater management solutions has never been greater. Bioswales, a cornerstone of green infrastructure, have gained prominence for their ability to mitigate urban runoff by combining hydrologic control with water quality treatment. This literature review critically examines the evolution of bioswale design and performance, synthesizing findings from peer-reviewed studies, modeling frameworks, and engineering manuals published between 2015 and 2020.

The review highlights key design parameters—vegetation selection, soil media composition, hydraulic geometry, and drainage configurations—that collectively govern bioswale functionality. Empirical evidence demonstrates that, when properly implemented and maintained, bioswales can achieve total suspended solids (TSS) removal rates exceeding 90%, nutrient and heavy metal reduction, and runoff volume reductions ranging from 50% to 80%. Moreover, advances in computational modeling have enabled more precise simulations of infiltration dynamics, pollutant fate, and long-term system behavior under variable climatic conditions.

Despite these advantages, bioswales are subject to several limitations, including media clogging, climatic performance constraints, space limitations in dense urban contexts, and variability in municipal design standards. The review identifies emerging trends that seek to overcome these challenges, including the deployment of smart bioswales with real-time monitoring, integration into multi-element treatment trains, and adoption of nature-based multifunctional designs.

To optimize the role of bioswales in next-generation stormwater management, future research must prioritize site-specific adaptability, maintenance-informed lifecycle modeling, and policy frameworks that support widespread implementation. When strategically integrated, bioswales offer a compelling pathway toward achieving climate-resilient, ecologically enhanced urban hydrologic systems.

Keywords: Bioswales; Green Stormwater Infrastructure (GSI); Urban Runoff Management; Pollutant Removal Efficiency; Climate-Resilient Design

1. Introduction

The rapid pace of urbanization has fundamentally disrupted natural hydrological cycles, replacing vegetated landscapes with impervious surfaces such as roads, rooftops, and parking lots (EPA, 2014). This transformation leads to increased stormwater runoff volumes, accelerated flow velocities, and diminished infiltration and evapotranspiration. As a result, urban runoff becomes a primary vector for transporting a wide array of pollutants—such as sediments, heavy metals,

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nutrients, hydrocarbons, and pathogens—into receiving water bodies, thereby degrading water quality and aquatic ecosystem health.

Traditional gray infrastructure systems, including curb-and-gutter conveyance networks and centralized detention basins, have historically been engineered to move stormwater away from built environments quickly. While effective for flood mitigation, these systems largely neglect the water quality treatment and groundwater recharge functions essential to long-term watershed health. Furthermore, their reliance on large-scale, centralized control often lacks flexibility and adaptability, especially under changing climatic conditions and increasing storm intensities.

In response to these limitations, the paradigm of green stormwater infrastructure (GSI) has gained prominence. GSI emphasizes decentralized, nature-based solutions that restore hydrological functions at or near the source of runoff. Among these, bioswales have emerged as a versatile and scalable best management practice (BMP). These shallow, vegetated channels are designed not only to convey stormwater but also to filter, infiltrate, and treat it through a combination of physical, chemical, and biological processes.

Bioswales mimic the hydrologic behavior of natural systems, offering benefits such as:

- **Pollutant removal** through sedimentation, adsorption, and plant uptake,
- **Runoff volume and peak flow reduction** via infiltration and storage,
- **Aesthetic and ecological enhancement** of urban landscapes.

This paper explores design principles, performance metrics, limitations, and emerging bioswale innovations, emphasizing their critical role in advancing sustainable and climate-resilient urban water management.

2. Design Principles of Bioswales

The effectiveness of bioswales in stormwater management is inherently tied to their design, which integrates biological, hydraulic, and geotechnical elements. A well-conceived bioswale enhances water quality, reduces runoff volume, and contributes to ecological and infrastructural resilience. This section synthesizes key design elements — vegetation, media, geometry, and drainage — that underpin optimal performance.

2.1. Vegetation Selection and Functionality

Vegetation is a foundational component of bioswales, serving both hydrological and ecological functions. Native and deep-rooted species such as sedges, rushes, and switchgrass outperform conventional turfgrass by improving sediment retention, nutrient uptake, and evapotranspiration rates (Li et al., 2020). Moreover, vegetative cover stabilizes the soil, mitigates erosion, and fosters microbial communities that enhance biodegradation of organic pollutants. Species selection must align with climate, water regime, and maintenance goals, with emphasis on resilience to drought, inundation, and seasonal variation.

2.2. Soil Media Composition and Amendment Strategies

The media composition in a bioswale serves as both a filtration matrix and an infiltration substrate, directly influencing pollutant attenuation and hydrologic performance. Standardized soil media typically consist of a blend of sand, compost, and loamy topsoil, engineered to balance infiltration rates—often ranging from 1.3 to 5.1 in/hr—and maximize adsorptive capacity for nutrients and metals. These engineered mixes also support vegetation growth and maintain structural stability over time.

Research conducted by the Bay Area Stormwater Management Agencies Association (BASMAA) found that loamy sand mixtures demonstrated not only adequate infiltration capacity but also minimized nutrient export, making them favorable for urban biotreatment systems. While the vegetative cover in these media was somewhat less vigorous compared to higher-organic mixes, plant health and pollutant removal efficiency remained within acceptable performance thresholds (BASMAA, 2016).

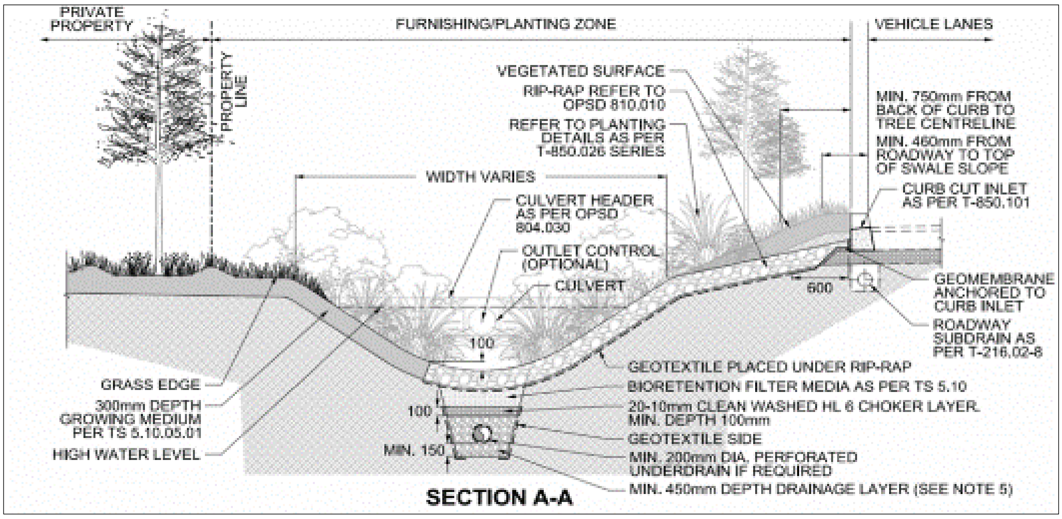
Amendments such as biochar, zeolites, and composted organic matter can significantly enhance phosphorus sorption capacity and microbial activity, particularly in nutrient-sensitive watersheds (Hua et al., 2018). The choice and layering of media must consider local soil properties, target pollutants, and long-term maintenance viability.

2.3. Geometry, Hydraulics, and Flow Control

Bioswale geometry directly governs hydraulic residence time and flow attenuation. Optimal designs incorporate shallow slopes (1–5%), bottom widths of 2–10 feet, and parabolic or trapezoidal cross-sections to slow velocities and maximize infiltration surface area. Strategic inclusion of check dams and berms helps maintain ponding depth, promoting sedimentation and enhancing infiltration during low-intensity storm events. Performance is strongly influenced by surface roughness, detention volume, and flow path length, all of which must be tailored to local rainfall characteristics and runoff volumes (Filtrexx International, 2019).

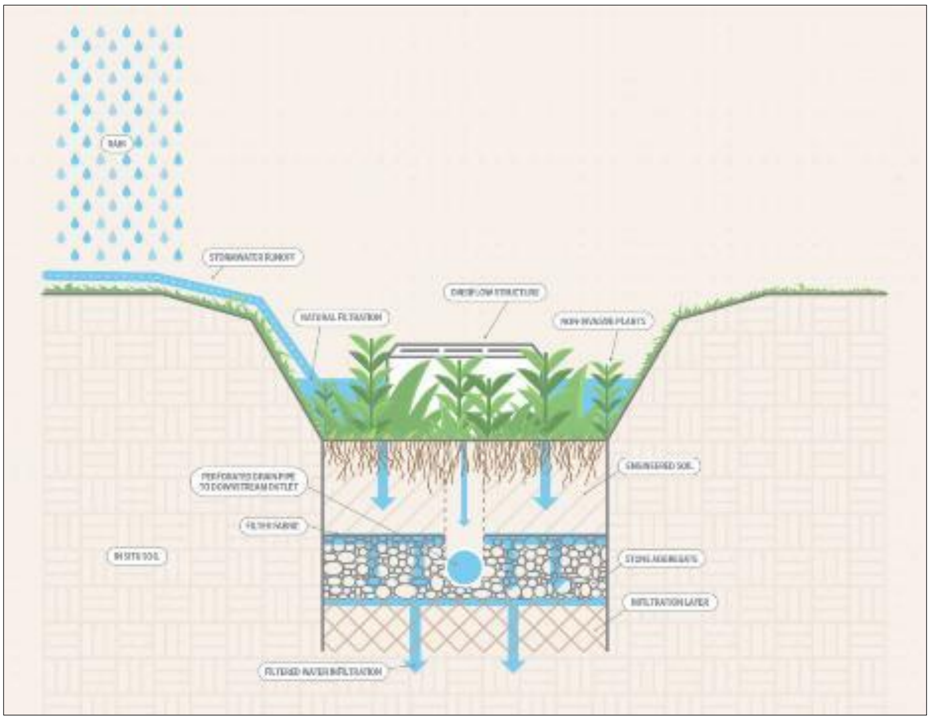
2.4. Subsurface Drainage and Overflow Management

In areas with low-permeability soils or shallow groundwater, bioswales may include underdrain systems composed of perforated pipes surrounded by gravel and geotextile fabric. These systems expedite drainage during high-flow conditions while allowing partial infiltration. Overflow structures, such as weirs and curb cuts, serve as safety valves during design exceedance storms, preventing erosion and structural failure. Integrating redundant drainage pathways ensures bioswale functionality under both design storms and extreme weather events, a critical feature in climate-resilient infrastructure.



Source: Sustainable Technologies Evaluation Program (STEP). “Drawings.” Available at: https://wiki.sustainabletechnologies.ca/wiki/Drawings

Figure 1 A cross-sectional diagram of a typical bioswale, detailing its structural components



Source: Florida Department of Environmental Protection, Green Stormwater Infrastructure Basics – What is GSI? Available at: https://gsi.floridadep.gov/gsi-basics/what-is-gsi/

Figure 2 A flow path diagram demonstrating how stormwater moves through a bioswale system

3. Performance Evaluation Metrics

The functional performance of bioswales is evaluated through both water quality improvement and hydrologic regulation. These systems are increasingly recognized for their dual capacity to mitigate urban runoff impacts and enhance stormwater quality. However, their effectiveness is influenced by design variables, site-specific conditions, and long-term maintenance regimes. This section reviews empirical findings related to pollutant removal, hydrologic attenuation, and maintenance implications, drawing from peer-reviewed field studies and performance audits.

3.1. Pollutant Removal Efficiency

Bioswales act as biogeochemical filters that trap, transform, and remove contaminants from stormwater. The effectiveness of pollutant removal depends on factors such as vegetation type, media composition, detention time, and microbial activity. Field studies have reported:

- Total Suspended Solids (TSS): Removal efficiencies of up to 90%, particularly in systems with dense vegetation and appropriate pretreatment structures (Liu et al., 2019). TSS removal is largely governed by sedimentation and filtration within the root zone.
- Total Nitrogen (TN): Removal ranges from 30–60%, often enhanced by incorporating carbon-rich amendments (e.g., compost, biochar) and deep-rooted vegetation that supports denitrification processes (Bratieres et al., 2008). Nitrogen transformation depends heavily on redox conditions and residence time.
- Heavy Metals (Zn, Cu, Pb): Reported removal efficiencies range between 50–85% (Davis et al., 2017), with mechanisms including adsorption to soil particles, precipitation, and plant uptake. Performance is highest in bioswales with amended soils and high cation exchange capacity.

These results underscore bioswales' role as cost-effective tools for meeting regulatory limits on nonpoint source pollution in urban catchments.

3.2. Hydrologic Performance

Bioswales contribute significantly to hydrograph moderation by reducing both peak discharge and total runoff volume. Their hydrologic performance is especially critical in urban areas prone to flash flooding and combined sewer overflows (CSOs).

- Peak Flow Reduction: Field-monitored bioswales have demonstrated reductions in peak flows ranging from 20% to 70%, with higher efficiencies in sandy or loamy soils and when bioswales are deployed in series along flow paths (Barrett et al., 2020).
- Runoff Volume Reduction: Bioswales optimized for infiltration (through amended media and minimal compaction) can reduce runoff volumes by up to 80%, thereby alleviating the burden on downstream conveyance systems and improving groundwater recharge (Liu et al., 2019).

The variability in performance is linked to storm event size, antecedent soil moisture, and the degree of underdrain implementation.

3.3. Maintenance Impact

While bioswales are often praised for their low life-cycle costs, their performance is highly dependent on routine maintenance. Studies reveal that pollutant removal and infiltration rates decline noticeably after 3 to 5 years if sediment, debris, and invasive vegetation are not actively managed (Luo et al., 2025).

- Sediment Accumulation: Reduces storage volume and infiltration, necessitating periodic excavation or vacuuming.
- Vegetation Decline: Leads to reduced evapotranspiration and pollutant uptake; replanting and invasive species control are often required.
- Clogging of Underdrains: Affects hydraulic conductivity and can convert bioswales into ineffective conveyance features.

As documented by Brown & Hunt (2017), bioswales subject to proactive maintenance schedules (e.g., biannual inspections and interventions) retain significantly higher hydraulic and pollutant-removal performance compared to neglected installations.

4. Modeling Tools and Approaches

The application of hydrologic and water quality models is fundamental to the design, optimization, and performance assessment of bioswales. These tools allow engineers and researchers to simulate complex interactions between surface runoff, infiltration, and contaminant transport under a range of climatic and land use conditions. Advanced modeling frameworks are increasingly integrated into stormwater planning to reduce uncertainty, support regulatory compliance, and guide evidence-based decision-making.

4.1. EPA SWMM (Storm Water Management Model)

The EPA SWMM is a dynamic, semi-distributed model widely used for urban hydrologic and hydraulic simulation. It facilitates the analysis of rainfall-runoff processes, infiltration, storage, and pollutant buildup/wash-off. For bioswale applications, SWMM enables users to:

- Simulate stormwater flows through vegetated swales as **low impact development (LID) controls**.
- Evaluate **detention time, overflow frequency**, and **runoff volume reduction**.
- Calibrate performance against **design storms**, providing a basis for sizing and layout.

Its LID module supports parameterization of infiltration media, underdrains, and vegetation—making it particularly well-suited for performance modeling under various maintenance and loading conditions.

4.2. Hydrus-1D and Hydrus-2D

The Hydrus suite, developed for variably saturated flow and solute transport, is instrumental in modeling the vertical and lateral movement of water and pollutants through the unsaturated vadose zone. In bioswale systems, these models have been employed to:

- Predict **percolation rates** and **nutrient leaching** through layered soil profiles.
- Assess the influence of **root zone dynamics** on nitrate and phosphorus migration.
- Simulate **non-uniform infiltration**, especially relevant for systems with complex soil structures or variable vegetation.

Hydrus models are particularly valuable for evaluating long-term pollutant fate, optimizing media composition, and investigating potential groundwater impacts.

4.3. WEPP (Water Erosion Prediction Project)

Developed by the USDA, the WEPP model provides a physically based approach to soil erosion and sediment transport under different land management and vegetation regimes. Though originally developed for agricultural settings, its use in bioswale studies has expanded to:

- Estimate **soil loss** and **sediment deposition** along swale profiles.
- Evaluate how **vegetative cover and slope geometry** affect erosion control effectiveness.
- Model **storm event-based sediment delivery**, particularly useful for bioswales located in high-runoff or sloped urban areas.

When used alongside SWMM or GIS-based hydrologic models, WEPP enhances the understanding of **long-term geomorphic stability** and sediment trapping functions of bioswales.

5. Challenges and Limitations

Despite their demonstrated efficacy, bioswales face a range of implementation and operational challenges that can compromise performance, particularly under non-ideal site conditions, extreme weather events, or insufficient maintenance regimes. Recognizing these limitations is essential for ensuring realistic expectations in planning, as well as for informing adaptive designs and long-term management strategies.

5.1. Clogging and Reduced Infiltration Capacity

A primary constraint in bioswale performance is clogging of the surface and media layers due to accumulation of fine sediments, organic debris, and hydrocarbons. This phenomenon significantly impairs infiltration rates and can lead to surface ponding and flow bypass. Studies show that bioswales located near construction sites or unpaved areas are especially prone to rapid clogging if pretreatment features (e.g., sediment forebays, rock inlets) are absent. Regular sediment removal is critical to sustaining long-term functionality.

5.2. Climatic Constraints in Cold Regions

Bioswale effectiveness is highly sensitive to seasonal variability, particularly in cold climates where frozen soils inhibit infiltration and dormant vegetation reduces evapotranspiration. Under such conditions, snowmelt runoff can overwhelm swales, reducing residence time and increasing pollutant wash-through (Fassman-Beck et al., 2016). Freeze-thaw cycles may also degrade soil structure and media porosity over time. Design modifications, such as subsurface warming layers or insulated media, are being explored to mitigate these effects.

5.3. Land Use and Spatial Constraints

In dense urban environments, limited right-of-way and land availability pose significant constraints on bioswale implementation. Large-scale bioswales require considerable footprint to achieve meaningful hydrologic impact, which is often infeasible in retrofitted streetscapes. This spatial limitation often necessitates modular or linear bioswale designs, or co-location with other green infrastructure elements (e.g., permeable pavements) to optimize available space.

5.4. Design inconsistency and Regulatory Fragmentation

A lack of standardized design criteria across jurisdictions leads to variability in bioswale performance. Municipal guidelines differ in specifications for media composition, vegetation types, hydraulic loading rates, and inspection intervals. This fragmentation undermines reproducibility and limits scalability. Inconsistent permitting and enforcement mechanisms further hinder uniform adoption and long-term stewardship, especially where inter-agency collaboration is weak.

6. Emerging Trends in Bioswale Innovation

As urban environments confront escalating challenges from climate change, water quality degradation, and infrastructure strain, bioswales are increasingly evolving beyond conventional design paradigms. Recent advancements emphasize technological integration, hybrid system approaches, and ecosystem-based design, positioning bioswales at the forefront of next-generation stormwater management strategies. This section highlights three key emerging trends that are redefining the functionality and strategic value of bioswales in modern civil and environmental engineering practice.

6.1. Smart Bioswales and Real-Time Monitoring

The integration of Internet of Things (IoT) technologies and remote sensing into bioswale systems marks a shift toward data-driven stormwater infrastructure. Smart bioswales leverage embedded sensors to monitor parameters such as soil moisture, water level, infiltration rate, and pollutant concentration in real-time. This capability enables:

- **Adaptive flow control** through automated valves or actuated weirs based on storm intensity or system saturation.
- **Predictive maintenance scheduling**, reducing downtime and extending system lifespan.
- **Performance benchmarking and regulatory reporting**, using cloud-based platforms to visualize trends over time.

These advancements enhance operational reliability, support decision-making under uncertain conditions, and align bioswales with broader smart city and climate adaptation frameworks.

6.2. Co-treatment systems and Hybrid Green Infrastructure Systems

Modern stormwater strategies increasingly favor treatment trains, where bioswales are integrated with complementary infrastructure such as permeable pavements, rain gardens, green roofs, and detention basins. These co-treatment systems:

- Enhance **hydrologic performance** by reducing peak flows and increasing detention time.
- Improve **pollutant removal synergy**, with upstream BMPs pre-treating stormwater to prevent bioswale overloading.
- Allow for **flexible retrofitting**, particularly in space-constrained or previously developed urban areas.

Such integrated systems provide redundancy and resilience, ensuring consistent treatment under varying inflow conditions and operational stressors.

6.3. Nature-based solutions and Ecological Multifunctionality

Beyond water treatment, bioswales are increasingly recognized as multifunctional landscape features that deliver a range of ecosystem services. Nature-based design principles emphasize:

- **Habitat creation** through native plant palettes that support pollinators and urban biodiversity.
- **Carbon sequestration and heat island mitigation**, via increased vegetation and soil carbon storage.
- **Community engagement and aesthetic value**, by transforming grey infrastructure into green public space.

This broader ecological framing aligns with international movements such as the UN Sustainable Development Goals (SDGs) and EU Green Infrastructure Strategy, reinforcing the role of bioswales as tools not only for stormwater management but for enhancing urban sustainability and social resilience

7. Conclusion

Bioswales represent a cornerstone of nature-based solutions in urban stormwater management, offering a cost-effective, multifunctional, and ecologically sound alternative to conventional gray infrastructure. When thoughtfully designed and systematically maintained, bioswales provide substantial benefits, including peak flow attenuation, pollutant load reduction, groundwater recharge, and habitat creation—all of which contribute to more resilient and sustainable urban environments.

However, their performance is not universally guaranteed and is contingent upon a suite of site-specific factors such as soil type, vegetation, hydraulic design, and climate conditions. Moreover, long-term functionality can be compromised by maintenance neglect, seasonal variability, and design inconsistencies. These realities underscore the importance of holistic planning, adaptive design, and institutional support in scaling up bioswale implementation.

Recent advancements in smart monitoring technologies, integrated green infrastructure networks, and ecologically multifunctional design paradigms are redefining the role of bioswales from isolated treatment units to dynamic components of urban sustainability strategies. These emerging approaches enhance the reliability, scalability, and public value of bioswales, particularly when integrated with policy, planning, and community engagement frameworks.

To fully realize their potential, further interdisciplinary research is needed in the areas of:

- Long-term performance across diverse climatic zones,
- Soil-media and vegetation optimization, and
- Data-informed maintenance and operation strategies.

As urban centers face increasing hydrological stress due to climate change and densification, bioswales offer a promising, adaptable tool for stormwater resilience. Embedding them within broader **green-blue infrastructure systems** will be critical to achieving future-ready, climate-adaptive cities.

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