



(REVIEW ARTICLE)



Long-term performance and maintenance of bioswales: A review of aging, clogging, and lifecycle costs

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Abstract

Bioswales have increasingly been adopted as sustainable stormwater management practices, providing ecological benefits by reducing runoff volumes and improving water quality in urban environments. Despite their growing popularity, long-term performance issues such as aging, clogging, and associated maintenance challenges have emerged, affecting their effectiveness and reliability. This review critically evaluates the current literature regarding the long-term performance of bioswales, focusing specifically on aging processes affecting hydraulic conductivity, vegetation health, and media integrity. It examines primary clogging mechanisms, their impacts on pollutant removal efficiencies, and practical mitigation measures. A comprehensive lifecycle cost analysis underscores the economic implications, contrasting bioswales with traditional stormwater systems. Case studies from diverse geographical locations highlight practical insights and adaptive management practices, demonstrating effective maintenance strategies under various environmental conditions. The paper concludes by identifying gaps in current research, proposing essential future studies aimed at optimizing bioswale design, maintenance, and economic sustainability.

Keywords: Bioswales; Aging; Clogging; Lifecycle Costs; Stormwater Management

1. Introduction

Urbanization significantly alters natural hydrological processes, increasing stormwater runoff volumes, peak flows, and pollutant loads, thereby threatening water resources and aquatic ecosystems. Traditional stormwater infrastructure frequently struggles with managing increased volumes and quality of runoff, prompting the adoption of sustainable stormwater management practices such as bioswales. Bioswales—shallow vegetated channels designed to capture, infiltrate, and treat stormwater runoff—offer multiple environmental and ecological benefits, including pollutant removal, runoff reduction, groundwater recharge, and enhanced urban biodiversity. However, the long-term effectiveness of bioswales is compromised by aging-related deterioration, media clogging, and increasing maintenance demands, posing challenges to their widespread implementation and sustainability. Given their critical role in urban stormwater management, understanding the long-term performance, maintenance strategies, and lifecycle costs associated with bioswales is essential. This paper systematically reviews recent literature, synthesizing insights on aging processes, clogging mechanisms, maintenance requirements, economic implications, and practical adaptive management practices to guide future implementation and research.

2. Aging Performance of Bioswales

The aging of bioswales is a critical aspect affecting their long-term effectiveness in stormwater management. Over time, bioswales inevitably experience declining performance due to factors such as decreased hydraulic conductivity, deterioration in vegetation health, media compaction, and sediment accumulation. Understanding these aging

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mechanisms and their implications on functionality is essential to improving maintenance practices and ensuring sustained bioswale efficiency. This section explores the impacts of aging on bioswale components, highlighting specific processes that compromise their long-term performance and effectiveness.

2.1. Impact of Aging on Hydraulic Conductivity

Hydraulic conductivity, a key measure of bioswale effectiveness, generally decreases with age due to progressive clogging from sedimentation and organic matter accumulation. Research indicates a direct relationship between aging and reduced infiltration capacity, primarily caused by sediment deposition, microbial growth, and root decay. Over time, these factors diminish pore space within the media, significantly reducing infiltration rates and the bioswale’s stormwater management efficiency.

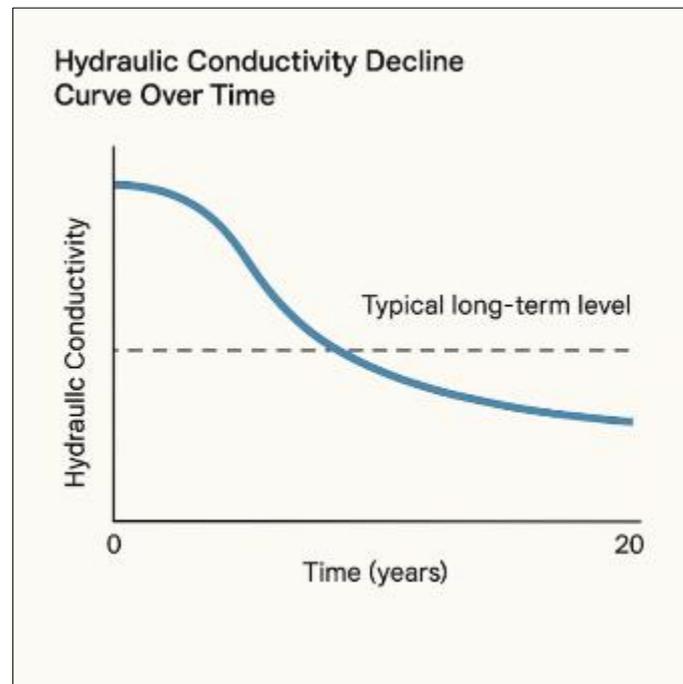


Figure 1 Hydraulic Conductivity Decline Curve Over Time

2.2. Vegetation Degradation and Management

Vegetation plays a critical role in maintaining bioswale performance by enhancing infiltration rates, stabilizing soil structure, and facilitating pollutant removal through biological processes. Aging vegetation often suffers from reduced vigor and increased susceptibility to diseases, pests, and invasive species. Factors such as extreme weather events, nutrient deficiencies, and lack of adequate maintenance further exacerbate vegetation degradation. Effective management strategies, including regular pruning, replanting, and monitoring of plant health, are essential to mitigate the negative impacts of vegetation aging.

Table 1 Common Vegetation Species Used in Bioswales and Their Environmental Adaptability

Species	Climate Adaptability	Pollutant Uptake Efficiency	Maintenance Intensity
Species A	Cold climates	High (Nitrogen, Phosphorus)	Medium
Species B	Temperate climates	Moderate (Heavy metals)	Low
Species C	Arid climates	High (Sediments, Oils)	Low

2.3. Effects of Media Compaction and Sediment Accumulation

Media compaction occurs due to physical pressure from foot traffic, equipment usage, and sediment accumulation, leading to a reduction in pore space and diminished infiltration capacity. Accumulated sediments, primarily from stormwater runoff, fill voids within the media, exacerbating compaction and clogging issues. Compaction reduces the

effective life span of the bioswale, increasing the need for periodic interventions such as media replacement, aeration, or addition of amendments like biochar to enhance porosity and maintain infiltration capacity.

Table 2 Summary of Aging Effects on Bioswale Performance Components

Component	Aging Factor	Impact on Performance	Suggested Maintenance
Media	Compaction, sedimentation	Reduced infiltration capacity	Periodic media rejuvenation
Vegetation	Climate stress, invasive species	Reduced pollutant uptake and aesthetics	Regular vegetation inspection and replacement
Drainage layer	Sediment accumulation, clogging	Poor drainage performance	Regular cleaning, inspection, and repair

2.4. Monitoring and Adaptive Management Strategies

Continuous monitoring and adaptive management are crucial to addressing aging impacts proactively. Effective monitoring includes regular inspections and hydraulic conductivity testing, assessment of vegetation health, and periodic soil analysis. Adaptive management strategies entail timely maintenance actions such as sediment removal, vegetation replacement, and media rejuvenation. Advanced approaches incorporating real-time monitoring technologies and predictive maintenance schedules are increasingly recommended to optimize long-term bioswale performance and sustainability.

3. Clogging Mechanisms and Maintenance Strategies

Clogging significantly hampers the operational efficiency and effectiveness of bioswales, ultimately limiting their capacity to manage and treat stormwater runoff. Various clogging mechanisms, including sediment deposition, accumulation of organic matter, and biological growth, pose persistent challenges to bioswale functionality. Addressing these issues requires a detailed understanding of clogging processes and proactive implementation of appropriate mitigation strategies. This section discusses key clogging mechanisms, their detrimental effects on pollutant removal performance, and effective preventative measures to maintain the functional longevity of bioswales.

3.1. Primary Causes of Clogging

Clogging significantly impairs the long-term functionality of bioswales, leading to reductions in infiltration capacity and pollutant removal effectiveness. The primary clogging mechanisms include sediment deposition, organic matter accumulation, biological growth (e.g., algae and microbial films), and debris accumulation from vegetative matter (Lucke & Nichols, 2015). Urban runoff typically contains high concentrations of suspended solids, oil, grease, and leaf litter, which accelerate clogging in bioswales, particularly those receiving runoff from high-traffic roadways or construction areas (LeFevre et al., 2015).

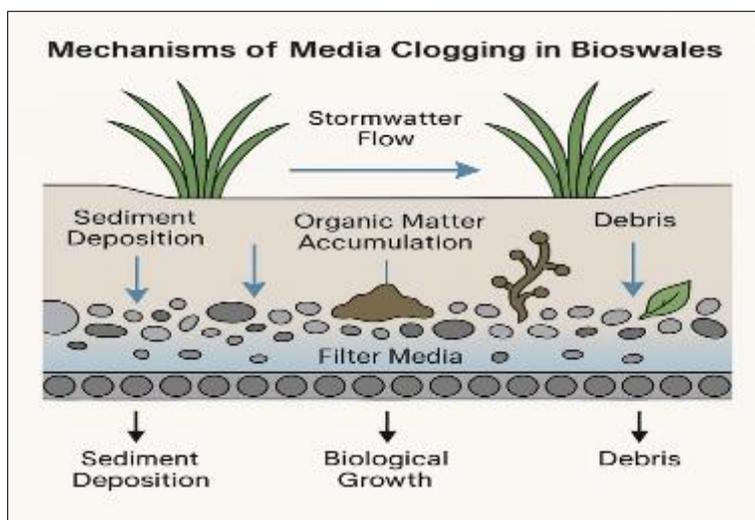


Figure 2 Mechanisms of Media Clogging in Bioswales

3.2. Impact of Clogging on Pollutant Removal Efficiency

Clogging adversely affects pollutant removal efficiency, diminishing the bioswale's ability to treat stormwater effectively. Accumulated sediments and organic matter obstruct the filtration media pores, reducing residence time and limiting the interaction between runoff and filter media, thus lowering pollutant capture rates (Hatt et al., 2011; Li et al., 2018). Nutrient removal, particularly for phosphorus and nitrogen, significantly declines when clogging occurs, thereby reducing the effectiveness of bioswales in urban water quality management (Hua et al., 2018).

3.3. Clogging Mitigation and Preventative Measures

To maintain long-term functionality, clogging must be proactively managed. Common preventive strategies include pre-treatment systems such as sediment forebays, vegetative filter strips, and catch basin inserts designed to trap larger sediment particles before they reach the bioswale (Lucke et al., 2018). Regular removal of debris, organic matter, and sediments is crucial. Media rejuvenation techniques, such as tilling, surface scraping, and periodic replacement of surface media layers, also effectively restore permeability and extend bioswale life spans (Brown & Hunt, 2017).

Table 3 Effectiveness of Clogging Mitigation Measures

Mitigation Measure	Clogging Reduction (%)	Recommended Frequency
Sediment Forebays	60–80%	Quarterly inspection, annual cleaning
Surface Tilling and Media Replacement	70–90%	Every 3–5 years
Vegetation Pruning and Removal of Organic Debris	40–60%	Monthly to quarterly

4. Lifecycle Costs Analysis of Bioswales

Evaluating the economic feasibility of bioswales necessitates a comprehensive understanding of lifecycle costs, encompassing initial capital investments, ongoing maintenance expenditures, and comparative cost-benefit analyses with traditional stormwater systems. While bioswales are frequently promoted for their environmental advantages, an in-depth economic assessment is critical to guide stakeholder decision-making and adoption. This section provides a systematic examination of lifecycle costs associated with bioswales, highlighting essential economic considerations from initial construction through sustained operational phases, and contextualizes these within broader stormwater management economics.

4.1. Initial Capital Costs

Initial capital costs of bioswales encompass expenses related to site preparation, construction labor, materials (media, drainage layers, vegetation), and any pre-treatment structures (EPA, 2019). The cost typically varies based on scale, location, design complexity, and local regulatory requirements. Proper initial investment in design and construction quality significantly impacts long-term maintenance needs and overall lifecycle costs (Flynn & Traver, 2013).

Table 4 Lifecycle Cost Breakdown for Typical Bioswale Installation

Lifecycle Stage	Cost Component	Estimated % of Total Lifecycle Cost
Initial Capital Investment	Design and construction	50–65%
Operational Stage	Routine maintenance (vegetation & media)	20–30%
Long-term Maintenance	Media replacement, structural repairs	10–20%
End-of-Life or Major Rehabilitation	Reconstruction or major rehabilitation	5–10%

4.2. Operation and Maintenance Costs

Operational costs mainly involve routine inspections, vegetation management, sediment removal, and media replenishment. Davis & McCuen (2005) emphasized that routine maintenance is crucial for maintaining bioswale

performance. Maintenance practices typically account for 5–10% of total lifecycle costs, underscoring their significance for long-term functionality (Flynn & Davidson, 2016).

4.3. Comparative Cost Analysis with Traditional Systems

Lifecycle cost comparisons highlight that bioswales, despite potentially higher upfront costs compared to traditional stormwater infrastructure, often provide long-term economic advantages. Reduced reliance on conventional gray infrastructure (pipes, pumps, drainage basins) and reduced pollutant load on downstream water bodies offer indirect cost savings through minimized regulatory penalties and environmental remediation expenditures (Clary & Jones, 2017).

5. Case Studies on Long-term Performance and Maintenance

Empirical evidence from real-world applications of bioswales provides valuable insights into their long-term performance and maintenance challenges. Case studies enable practitioners and researchers to evaluate bioswale effectiveness across various climatic conditions, urban environments, and maintenance strategies. By examining practical examples from diverse geographical regions, this section illustrates the successes, common issues, and adaptive management solutions implemented to maintain bioswale performance, contributing essential practical knowledge for future installations and management practices.

5.1. Case Study 1: Portland, Oregon, USA

In Portland, Oregon—a city with a temperate climate—bioswales have been implemented extensively as part of the city's green infrastructure program. Over a 10-year monitoring period, bioswales installed along streets and parking areas demonstrated effective reductions in stormwater runoff and pollutant loads. However, as these systems aged, key issues such as media clogging, vegetation thinning, and sediment buildup at inflow points began to impair performance. To counter these effects, the City of Portland implemented an effective maintenance regime. This included annual removal of accumulated sediment, regular replanting of native species to maintain vegetative cover, and media tilling every 5 to 7 years to restore infiltration capacity. These practices have proven essential in sustaining long-term bioswale functionality across the city (City of Portland, 2016; EPA, 2014).

5.2. Case Study 2: Melbourne, Australia

A comprehensive 15-year evaluation of Melbourne's bioswale systems demonstrated significant vegetation degradation due to drought conditions and irregular maintenance. Adaptive management, including enhanced plant selection, irrigation during drought periods, and regular maintenance schedules, successfully restored hydraulic and pollutant removal performance (Bratieres et al., 2008).

5.3. Case Study 3: Toronto, Canada

Toronto's bioswales, monitored over eight years, showed notable clogging from road salts and winter sediments. Systematic adoption of pre-treatment forebays and regular maintenance significantly mitigated these challenges, sustaining high pollutant removal performance even under cold climate stresses (Toronto Water, 2019; Fassman-Beck et al., 2016).

5.4. Case Study 4: Auckland, New Zealand

In Auckland, New Zealand's humid subtropical climate, bioswales were evaluated over a five-year period as part of a long-term biofilter performance study. Installed in parking lots and roadside applications, the systems demonstrated strong retention of nutrients and heavy metals, with 60–90% nitrogen and 70–95% heavy metal removal efficiency. However, performance gradually declined due to media compaction and localized clogging, particularly near inflow areas. In response, the city implemented an annual maintenance schedule involving removal of surface mulch and biomass, replanting with drought- and flood-resilient species, and refurbishment of the media every five years. These interventions effectively prolonged the lifespan and pollutant removal capabilities of Auckland's bioswales, illustrating the importance of adaptive maintenance in preserving treatment efficiency (Fassman-Beck et al., 2013).

Table 5 Case Studies Summary: Long-term Bioswale Performance and Maintenance Insights

Location	Climate	Monitoring Duration	Key Issues Identified	Effective Maintenance Actions
Portland, USA	Temperate	10 years	Media clogging, vegetation thinning, sediment buildup	Annual sediment removal, media tilling every 5-7 years, replanting
Melbourne, Australia	Dry/temperate	15 years	Vegetation stress, media compaction	Adaptive vegetation selection, irrigation, media tilling
Toronto, Canada	Cold climate	8 years	Winter salt, sediment accumulation	Pre-treatment forebays, frequent inspections
Auckland, New Zealand	Humid subtropical	5+ years	Media compaction, localized clogging	Annual mulch/biomass removal, vegetation replacement, media refurbishment every 5 years

6. Future Research Needs and Recommendations

Despite the significant advances in understanding bioswale performance, substantial research gaps remain, particularly concerning long-term monitoring, media optimization, vegetation management, and comprehensive lifecycle cost evaluations. Addressing these gaps is crucial for enhancing the functionality, economic viability, and environmental sustainability of bioswales. This section outlines the critical research areas and recommended strategies that will enhance future bioswale designs, management practices, and overall effectiveness, guiding continued innovation and informed decision-making in stormwater infrastructure management.

6.1. Enhanced Long-term Monitoring Programs

Future research should prioritize establishing robust long-term monitoring protocols to better quantify performance deterioration rates, specifically focusing on clogging, vegetation sustainability, and hydraulic performance under diverse environmental conditions. Enhanced monitoring systems, incorporating remote sensing technologies and smart sensors, offer opportunities for real-time performance tracking and adaptive management (Shafique & Kim, 2017).

6.2. Optimization of Media Composition

Further research into novel and optimized filter media compositions, such as incorporating biochar, engineered soils, and mineral additives, can enhance long-term permeability and pollutant removal performance. Understanding the longevity and cost-effectiveness of these advanced media types warrants detailed investigation (Hua et al., 2018; Davis et al., 2017).

6.3. Adaptive Vegetation Selection and Management

Improving bioswale sustainability through adaptive vegetation management remains crucial. Research is required to identify plant species and cultivars resilient to climatic extremes (drought, flooding, freeze-thaw), suitable for varying geographic locations. Optimal vegetation management practices, including adaptive irrigation and nutrient management, are critical areas of further investigation (Dagenais et al., 2018).

6.4. Comprehensive Lifecycle Cost Studies

There is a pronounced need for detailed lifecycle cost analyses incorporating both direct and indirect economic impacts, long-term maintenance schedules, and comparative analyses with traditional stormwater systems. Comprehensive lifecycle assessments (LCAs) can provide critical data supporting policy-making and adoption of sustainable infrastructure practices at municipal levels (Clary & Jones, 2017).

7. Conclusion

Bioswales present valuable ecological solutions for sustainable urban stormwater management; however, their effectiveness is critically dependent upon long-term performance and diligent maintenance. Aging significantly impacts hydraulic conductivity, vegetation health, and filter media integrity, necessitating proactive and systematic maintenance interventions. Clogging, primarily resulting from sediment deposition, organic matter accumulation, and

biological growth, presents major operational challenges, adversely affecting pollutant removal efficiencies. Lifecycle cost analyses indicate that despite potentially higher initial investment, bioswales offer long-term economic advantages through reduced maintenance and environmental remediation costs compared to conventional stormwater systems. Case studies from diverse climates underline the importance of adaptive management practices, including robust monitoring programs, preventive clogging mitigation, and strategic vegetation selection. Further research into optimized media composition, advanced vegetation management, comprehensive lifecycle cost assessment, and enhanced monitoring methods is vital. Addressing these research areas will enable sustained performance, economic viability, and broader acceptance of bioswales as integral components of urban stormwater infrastructure.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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