International Journal of
Science, Architecture, Technology and Environment

Applications of Green Infrastructure in Urban Stormwater Management: A Comprehensive Review

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DOI: https://doi.org/10.63680/ijsate1225085.070

Abstract

Green infrastructure (GI) has emerged as a transformative approach to urban stormwater management, offering sustainable alternatives to conventional gray infrastructure through integrated nature-based solutions. This comprehensive review examines the applications, performance, design considerations, and implementation frameworks of green and blue-green infrastructure (BGI) systems for urban stormwater management. Through analysis of recent literature and case studies, we demonstrate that GI/BGI systems can reduce annual runoff volumes by 30–70% and peak discharges by 20–60%, while removing 70–95% of total suspended solids and 40–80% of heavy metals. Beyond hydrologic benefits, these systems provide multifunctional co-benefits including urban heat mitigation, biodiversity enhancement, improved water quality, and ecosystem services. The review identifies key GI typologies (green roofs, permeable pavements, bioretention systems, rain gardens, infiltration trenches, and constructed wetlands), optimization strategies, and governance frameworks. Critical challenges including long-term maintenance, climate adaptation uncertainties, social acceptance, and financing mechanisms are examined. The findings highlight that decentralized, multifunctional GI approaches coupled with gray infrastructure provide cost-effective and resilient solutions for climate-adaptive urban water management, particularly in the context of sponge city initiatives worldwide.

Keywords: Green infrastructure, blue-green infrastructure, stormwater management, urban flooding, nature-based solutions, sustainable drainage systems, climate resilience, ecosystem services

1. Introduction

Urban water management faces unprecedented challenges in the twenty-first century, driven by rapid urbanization, climate change, and intensified precipitation events (Barua, 2025). Traditional gray infrastructure systems, designed primarily to convey stormwater quickly away from urban areas, often prove inadequate under extreme rainfall scenarios and contribute to urban heat island effects, biodiversity loss, and water pollution. The removal of vegetation and soil through urban development has reduced soil infiltration capacity, increasing both flood hazards and runoff volumes during intense precipitation events (Lashford et al., 2019).

In response to these challenges, green infrastructure has emerged as a viable paradigm shift in urban water management philosophy. Green infrastructure represents an integrated approach combining natural and engineered systems to manage stormwater at or near its source, promoting infiltration, evapotranspiration, and pollutant removal while providing aesthetic and ecological co-benefits. The concept encompasses a diverse array of practices, from building-scale interventions such as green roofs and rainwater harvesting systems to neighborhood and watershed-scale implementations including bioswales, wetlands, and permeable pavements (Prudencio & Null, 2018).

These systems are increasingly recognized not merely as stormwater control measures but as multifunctional assets capable of delivering ecosystem services, improving public health, enhancing urban aesthetics, and building climate resilience (McNabb et al., 2024).

This review synthesizes current scientific understanding of green infrastructure applications in urban stormwater management, examining design principles, performance metrics, ecosystem service provision, optimization frameworks, implementation challenges, and governance models. By integrating findings from over 40 recent studies spanning multiple geographic contexts and climate zones, this review provides actionable insights for urban planners, policymakers, engineers, and practitioners seeking to implement sustainable stormwater management systems.

2. Typologies and Design Principles of Green Infrastructure

2.1 Common Green Infrastructure Measures

Green infrastructure encompasses a diverse range of technologies and practices, each with distinct design characteristics, hydrological functions, and co-benefits. The most widely studied and implemented measures include:

Green Roofs and Vertical Green Systems: Green roofs function as shallow vegetated systems installed on building rooftops, providing stormwater retention, thermal insulation, and urban cooling benefits. Recent research on vertical green systems combined with on-site storage demonstrates that these systems can achieve 60–100% annual stormwater reduction depending on climate and system sizing, with particular effectiveness in managing frequent, low-intensity rainfall events. The thermal performance of green roofs has been well-documented, with studies indicating reductions in surface temperature of up to 10°C compared to conventional roofs.

Permeable Pavements and Porous Surfaces: These engineered surfaces allow infiltration of precipitation into subsurface layers, reducing runoff generation and promoting groundwater recharge. Meta-analysis of permeable pavement performance indicates runoff retention that varies with rainfall intensity and underlying soil characteristics, with effectiveness decreasing as rainfall totals increase (Dobkowitz et al., 2025). The integration of permeable pavements into green infrastructure networks has proven particularly effective in reducing peak discharge by up to 40% in small catchments.

Bioretention Systems and Rain Gardens: These depressed landscape features combine vegetation with specially engineered soil media to temporarily store and infiltrate stormwater while providing pollutant removal. Rain gardens achieve significant localized runoff reductions, though downstream impacts are typically limited to 2–8% depending on design and rainfall return periods. The performance of these systems in removing heavy metals, suspended solids, and nutrients has been extensively documented, with soil amendments and plant selection significantly influencing contaminant removal efficiencies.

Bioswales and Vegetative Swales: These are linear, vegetated channels designed to convey and filter stormwater runoff, promoting infiltration while providing habitat corridors (Prudencio & Null, 2018). When combined in distributed networks, bioswales contribute to measurable reductions in both peak discharge and total runoff volume.

Constructed Wetlands and Detention Ponds: These features provide large-scale storage and treatment capacity, serving dual functions as stormwater management infrastructure and ecological habitats. Studies from African contexts demonstrate that constructed wetlands can reduce peak flow and flood volume by substantial margins while supporting biodiversity.

2.2 Design Principles and Multifunctionality

Contemporary green infrastructure design emphasizes multifunctionality—the provision of multiple services simultaneously—rather than single-purpose stormwater control. A systematic review of green infrastructure planning principles identifies nine core design principles: adaptability, connectivity, diversity, multifunctionality, multiscale integration, informatization, integration with gray systems, public participation, and sustainability (Barua, 2025).

Spatial Distribution and Decentralization: Research consistently demonstrates that decentralized, distributed green infrastructure approaches outperform centralized end-of-pipe solutions in terms of infiltration capacity, flood mitigation, and ecosystem service provision (Adhikari et al., 2024). A comparative study of three urban catchments (inner city, residential suburb, and new urban housing) found that decentralized alternatives—both engineered and natural—showed better potential to reduce flooding magnitude and frequency than centralized measures. Decentralized layouts reduce total life-cycle costs by up to 29.6% while requiring 60.7% less green infrastructure area compared to centralized schemes (Liu et al., 2025).

Blue-Green-Gray Integration: The most effective contemporary approaches integrate green infrastructure with both blue infrastructure (water bodies, wetlands, floodplains) and gray infrastructure (pipes, channels, detention basins), creating hybrid systems that leverage the strengths of each approach (Tang et al., 2025). Multi-objective optimization frameworks demonstrate that optimal life-cycle cost reductions of 53.36% on average can be achieved through strategic integration of green and gray components across multiple rainfall return periods.

Climate Adaptation and Scenario Planning: Forward-looking GI design incorporates climate change projections and future urbanization scenarios. Frameworks coupling climate models, urbanization projections, and GI development policies find that surface runoff and pollutant loading can vary significantly depending on the interaction between climate change, urbanization trends, and GI maintenance effectiveness.

This finding underscores the importance of adaptive management and regular maintenance in sustaining GI performance under future conditions (Barua, 2024).

3. Hydrological Performance and Stormwater Reduction Efficacy

3.1 Runoff Reduction and Peak Flow Attenuation

Comprehensive literature synthesis demonstrates that green infrastructure achieves quantifiable stormwater management benefits across diverse climatic and urban contexts. In highly impervious catchments, GI/low-impact development (LID) practices can reduce annual runoff volumes by 30–70% and peak discharges by 20–60%, with pollutant removal ranging from 70–95% for total suspended solids and 40–80% for heavy metals.

Catchment-Scale Performance: Meta-analysis of green infrastructure water retention performance reveals significant variations in effectiveness depending on rainfall characteristics, soil properties, and system design (Dobkowitz et al., 2025). Modeling studies across multiple catchments demonstrate that runoff retention decreases with increasing rainfall total, a critical consideration for climate change adaptation scenarios. Scenarios modeling distributed networks of bioswales, rain gardens, and permeable pavements in tropical coastal cities found reductions in peak discharge and total runoff volume of 28.8% and 29.0% respectively.

Extreme Event Performance: While GI systems excel at managing frequent, moderate rainfall events, their performance under extreme precipitation scenarios remains variable. Research on a "failed" urban drainage system in Kampala, Uganda, found that spatially distributed infiltration trenches and bioretention cells achieved modest reductions of total flood volume (12.0%) and average flood duration (34.3%) when combined with improved asset management. These findings suggest that GI systems should be viewed as components within broader, integrated flood risk management strategies rather than standalone solutions.

Climate Change Resilience: Green infrastructure demonstrates resilience to intensified precipitation under climate change projections. Studies projecting increases in precipitation intensity found that nature-based solutions including infiltration trenches, permeable pavements, and rooftop disconnections could reduce runoff by up to 37% in some watersheds and lower peak runoff by 19% during extreme events.

3.2 Water Quality Improvement

Beyond quantitative runoff reduction, green infrastructure provides significant water quality improvements through physical, chemical, and biological treatment processes. A comprehensive review of stormwater management and ecosystem services synthesized 170 publications, revealing that green infrastructure not only controls runoff volume and timing but also promotes ecosystem services including water quality improvement (Prudencio & Null, 2018).

Pollutant Removal Mechanisms: Rain gardens achieve pollutant removal through multiple mechanisms including sedimentation, adsorption, biological uptake, and microbial transformation. The efficiency of contaminant removal depends on soil media composition, vegetation selection, and hydraulic design, with studies documenting removal of sediments, heavy metals, pathogens, nutrients, and hydrocarbons.

Emerging Contaminants: Recent studies have examined green infrastructure effectiveness for microplastic removal from stormwater. Bioretention systems, constructed wetlands, and permeable pavements show potential for microplastic reduction, with effectiveness varying based on filter material, vegetation, and flow direction. This emerging research highlights the expanding role of GI in addressing novel urban water quality challenges.

4. Ecosystem Services and Co-Benefits

4.1 Biodiversity Enhancement and Habitat Provision

Green infrastructure provides multifunctional ecosystem services extending far beyond stormwater management. A systematic review and framework proposal examining cultural ecosystem services in sponge city infrastructure identified diverse benefits including aesthetic improvements, enhanced biodiversity, and cultural connections (Han et al., 2025). However, the study also noted that cultural ecosystem services remain underexplored in much research, with geographic concentration in major cities and limited focus on abstract services such as inspiration and sense of place.

Hydrology, vegetation, and interconnectedness among components constitute three principal pillars of effective GI/BGI design, with vegetation playing a critical role in providing diverse ecosystem services (Krivtsov, 2025). Brownfield sites have emerged as important locations for urban biodiversity associated with green infrastructure, offering underrecognized value that should be included in GI planning frameworks.

4.2 Climate Regulation and Urban Cooling

The role of green infrastructure in mitigating urban heat island effects has been extensively documented. Blue-green infrastructure systems contribute to microclimate regulation and cooling through evapotranspiration and shading, reducing urban temperatures and improving human thermal comfort (Krivtsov, 2025). Studies from Spanish urban contexts demonstrate that BGI, particularly through tree cover and vegetated spaces, significantly reduces surface temperatures and cooling energy demands.

4.3 Carbon Sequestration and Air Quality Improvement

Green infrastructure provides climate mitigation benefits through carbon sequestration and air quality improvement. Urban green and blue-green infrastructures support regulatory services including climate regulation and carbon sequestration. A comprehensive assessment framework developed for evaluating economic and environmental performance of BGI facilities includes quantification of energy savings, CO_2 sequestration, oxygen production, and air quality improvements (Kravchenko et al., 2025).

4.4 Social and Health Co-Benefits

While recognizing the importance of social and health co-benefits, research in this domain remains limited. An interdisciplinary literature review examining co-benefits and synergies between bio-physical and socio-cultural outcomes identified improved mental and physical wellbeing, enhanced cultural connections, strengthened social cohesion, and sense of place as documented co-benefits (McNabb et al., 2024). However, the review also identified potential trade-offs, including the presence of negatively viewed insects and plant-produced allergens in some GI contexts.

5. Optimization Frameworks and Strategic Siting

5.1 Multi-Objective Optimization Approaches

Modern green infrastructure planning increasingly employs multi-objective optimization frameworks that balance multiple competing goals including flood mitigation, water quality improvement, cost efficiency, and ecosystem service provision. A multi-objective optimization framework for grey-green infrastructure systems demonstrated that optimized layouts achieving 33% improvement in operational resilience required only a marginal increase in life-cycle cost of less than 9%, highlighting the feasibility of achieving multiple objectives simultaneously. The integration of bioretention cells and porous pavements into GGI systems increased technical resilience by 7.1% while enhancing soil water retention and permeability.

5.2 Suitability Assessment and Spatial Planning

Geospatial analysis using analytic hierarchy process (AHP) and weighted linear combination methods has emerged as a standard approach for identifying optimal GI siting. In Surabaya, Indonesia, a study considering five criteria (slope, potential drainage density, land use/land cover, soil types, and proximity to roads) identified eastern and western regions characterized by agriculture, fishponds, and mangrove forests as prime candidates for BGI implementation (Harlis & Seo, 2024). Public land under municipal jurisdiction, including government offices and educational zones, offered additional opportunities for BGI initiatives.

A framework for identifying GI opportunities considering spatial functional zoning found that dividing study areas into flood risk control zones and total runoff control zones enabled more targeted, context-specific optimization, with different intervention strategies required for each zone.

5.3 Strategic BGI Implementation and Resilience Assessment

At 10% and 25% BGI implementation levels (impervious surfaces converted to BGI), needs-based strategies achieved highest resilience in more vulnerable areas, while opportunity-based approaches performed best in low-density areas.

6. Performance Monitoring and Modeling

6.1 Hydrological Modeling Frameworks

The storm water management model (SWMM) has become the dominant tool for assessing green infrastructure performance, utilized in the vast majority of published studies. This model enables simulation of complex urban hydrological processes, accounting for infiltration, evapotranspiration, and pollutant transport across GI systems.

6.2 Integrated Monitoring Systems

Internet-of-Things (IoT)-based monitoring and control systems have been developed to provide real-time data on green infrastructure performance, enabling adaptive management. A case study of an IoT-based monitoring and control system for stormwater management demonstrated the feasibility of real-time monitoring and performance evaluation.

6.3 Resilience Assessment Frameworks

Beyond conventional hydrological metrics, emerging resilience assessment frameworks integrate technical performance with social, economic, and institutional dimensions. A social-ecological resilience assessment framework for green stormwater infrastructure identified five critical categories influencing SWGI resilience: policy, design, maintenance, economic factors, and social factors. These frameworks recognize that effective GI implementation requires attention to socio-ecological dimensions alongside technical engineering performance.

7. Implementation Challenges and Barriers

7.1 Technical and Maintenance Challenges

Despite clear hydrological and environmental benefits, green infrastructure faces significant implementation challenges. A critical review of green-grey infrastructure optimization and implementation identified that research has concentrated on particular quantitative and qualitative optimization objectives at smaller retrofitting scales, with limited consideration of socio-ecological dimensions (Tansar et al., 2024). Future research must expand toward multi-stage planning, designing, and implementation across larger spatial scales while incorporating stakeholder participation from preliminary planning stages.

Maintenance emerges as a critical barrier to long-term GI effectiveness. Degraded GI facilities can become both unsightly and ineffective at providing intended stormwater and habitat benefits (Solins et al., 2025). A study comparing regulatory and voluntary green stormwater infrastructure facilities found that official maintenance requirements for regulatory facilities do not guarantee upkeep, with voluntary facilities showing lower maintenance in areas of lower socioeconomic status.

7.2 Climate Change and Hydrological Uncertainties

Uncertainties regarding future hydrological conditions related to climate change complicate urban planning and infrastructure design decisions. Extreme events may exceed design capacities of GI systems, necessitating hybrid approaches that combine GI with gray infrastructure capable of handling severe scenarios. Studies from climate-vulnerable African cities found that while BGI effectively mitigates impacts during design-storm conditions, its role in buffering extreme precipitation remains variable.

7.3 Social Acceptance and Community Perception

Community perception significantly influences green infrastructure adoption. A survey in Thu Duc City, Vietnam, found that while 51% of residents preferred decentralized stormwater management approaches, approximately 70% did not support financial contributions, with 50% believing it was the government's responsibility (Ngo et al., 2024). These findings highlight the importance of public engagement and education in advancing green infrastructure implementation.

7.4 Financing and Economic Viability

Economic feasibility remains a critical implementation barrier. Cost-benefit analyses of various BGI strategies in Oslo, Norway, found the highest benefit-cost ratios for wadis (12.0–17.3) and green roofs (7.7–15.1), but lower ratios (1.6–2.3) for raingardens and rain barrels (Wilbers et al., 2022). Strategic selection of GI measures based on local context, cost considerations, and co-benefit provision is essential for ensuring economic viability.

A framework for assessing blue-green infrastructure effectiveness for flood mitigation and alternative water supply in an African watershed context found that at a 7.5% BGI implementation area, favorable net present values could be achieved across diverse land-use change scenarios. However, BGI planned post-urbanization were 6–19% less effective in reducing risk than pre-urbanization implementations, highlighting the importance of early planning integration.

8. Governance Frameworks and Policy Implementation

8.1 Sponge City Initiatives and Policy Evolution

China's sponge city program, initiated in 2013 with 30 pilot cities, represents the most ambitious national-scale green infrastructure implementation globally. The program integrates foreign best practices with ancient Chinese water management philosophy, combining various technologies to address flooding, water pollution, resource shortage, and ecological deterioration.

Institutional adaptation in sponge city programs is driven by three primary pathways: strong institutional capacity combined with strong financial resources and low reputational reserve; strong institutional capacity, strong financial resources, and high reputational competition; and strong institutional capacity with weak financial resources and low reputational reserve (Liu & Fan, 2023). These pathways account for 72% of instances of high institutional adaptation, suggesting that institutional capacity and financial resources are more critical than reputational pressures in driving successful adaptation.

8.2 Governance Models and Multi-Stakeholder Engagement

Successful green infrastructure implementation requires integrated governance models combining centralized policy frameworks with decentralized implementation. An analysis of governance and financing models for green infrastructure in Indonesia proposed an integrated blue-green-gray governance model combining nature-based solutions with engineered facilities, emphasizing public-private partnership schemes and innovative financing instruments.

Community governance of nature-based solutions, specifically sustainable urban drainage systems, emerges as critical for enhancing stormwater management effectiveness in vulnerable urban contexts. Research in

Kampala, Uganda, identified that community engagement, resource management, and regulatory frameworks significantly influence SUDS implementation success and sustainability.

8.3 Integration with Broader Urban Sustainability Frameworks

Green infrastructure implementation should be integrated with broader sustainable development objectives, including the United Nations Sustainable Development Goals. The most effective urban stormwater management frameworks integrate GI with complementary approaches including Integrated Water Resource Management (IWRM), One Water concepts, health-centered approaches, and integrated flood management at local, neighborhood, and watershed scales.

9. Geographic Applications and Regional Case Studies

9.1 Chinese Context: Sponge Cities and Advanced Implementation

China's sponge city pilots have become global exemplars of large-scale green infrastructure implementation. Studies analyzing scenario-based green infrastructure installations in Fengxi New City found that while rain gardens emerged as particularly efficacious, the combination of multiple GIs yielded synergistic resilience enhancements, underscoring the strategic advantage of diverse, integrated approaches. The suitability of GI was predominantly concentrated in northern and western areas, with permeable pavements showing the smallest suitable area.

Research on green infrastructure and urban-renewal simulation for street tree design in Chinese contexts demonstrates the feasibility of multi-criteria decision modeling combining hydrology modeling, digital procedural tree modeling, and urban form analysis. These advanced spatial planning tools enable simultaneously addressing stormwater management, visual aesthetics, and solar amenity in complex urban renewal contexts.

9.2 Global South Contexts: Challenges and Opportunities

In developing regions, green infrastructure implementation faces distinctive challenges related to limited data availability, financial constraints, informal settlement sprawl, and institutional capacity gaps. Research on blue-green infrastructure in peri-urban Antananarivo, Madagascar, developed a novel, low-data, computationally efficient framework that combined spatial suitability analysis, scenario-based land use change uncertainty, and economic evaluation. This approach demonstrates the feasibility of large-scale BGI planning even in data-scarce settings.

9.3 Arid and Semi-Arid Regions

Green infrastructure application in water-scarce regions requires specialized approaches. A multi-criteria decision analysis model for nature-based solutions in arid climates identified rainwater harvesting as the superior intervention, achieving highest scores for effectiveness and applicability, while vegetation-based methods like rain gardens ranked suboptimal due to maintenance and water-dependency challenges.

10. Challenges and Future Research Directions

10.1 Standardization and Methodological Consistency

Despite significant advances, the field lacks standardized methodologies for GI sizing, performance monitoring, and ecosystem service assessment. A systematic review of sizing and monitoring methods for nature-based solutions found that while hydrological modeling increasingly integrates artificial intelligence, remote sensing, and IoT-based monitoring, challenges remain in methodology validation, data availability, and system adaptability. Future work must develop hybrid, context-sensitive frameworks that integrate empirical and simulated data to support decision-making.

10.2 Scale and Transfer of Knowledge

Most published research has been conducted at parcel or neighborhood scales, with limited investigation of larger, city-wide or watershed-scale impacts (Prudencio & Null, 2018). Expanding research to larger spatial scales will improve understanding of cumulative GI impacts and inform broader urban planning decisions. Additionally, knowledge transfer between geographically diverse contexts remains limited, suggesting opportunities for enhanced international collaboration and regional adaptation of best practices.

10.3 Integrated Assessment of Trade-Offs

While recognizing the multifunctional benefits of GI/BGI, future research must more thoroughly examine trade-offs among competing ecosystem services and objectives (Krivtsov, 2025). For example, intensive greenery may increase water demand during droughts, potentially conflicting with water conservation objectives. Systematic assessment of these trade-offs can inform more nuanced, context-specific design decisions.

10.4 Social Equity and Environmental Justice

Emerging research emphasizes the importance of equity considerations in green infrastructure planning and implementation. Ensuring that GI benefits are equitably distributed across urban communities, with particular attention to vulnerable populations, remains a priority for future work. Enhanced understanding of social perceptions, engagement, and governance frameworks will support more inclusive implementation.

11. Synthesis and Conclusions

Green infrastructure has evolved from a novel stormwater management approach to a mainstream strategy supported by extensive scientific evidence, international policy frameworks, and widespread practical implementation. This review demonstrates that green and blue-green infrastructure systems deliver quantifiable stormwater management benefits—reducing runoff by 30–70% and removing 70–95% of suspended solids—while providing multifunctional ecosystem services including biodiversity enhancement, climate regulation, improved water quality, and enhanced public health.

Contemporary best practice emphasizes decentralized, multifunctional approaches that strategically integrate green, blue, and gray infrastructure components based on local hydrological, social, and economic conditions.

However, successful implementation requires addressing interrelated technical, social, economic, and governance challenges. Long-term maintenance, climate change adaptation, community engagement, and innovative financing mechanisms emerge as critical factors determining whether GI systems sustain their intended performance over their operational lifetime (Tansar et al., 2024). Integration of GI into broader sustainable development frameworks, including water resource management, energy systems, and ecosystem conservation, enhances the strategic value and resilience of urban infrastructure (Barua, 2023).

The evidence base demonstrates that nature-based solutions represent viable, cost-effective pathways toward building resilient, sustainable cities capable of managing urban water challenges in an era of climate change and rapid urbanization (Barua, 2024). Future progress requires enhanced interdisciplinary collaboration across engineering, ecology, social sciences, and policy domains; integration of GI into early-stage urban planning processes; sustained commitment to maintenance and adaptive management; and equitable governance frameworks ensuring that GI benefits serve all urban communities.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

Funding

The author received no financial support for the research, authorship and publication of this article.

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