

The Impact of Landscape Design on Surface Runoff and Stormwater Management

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Abstract - Urban expansion has significantly changed the natural water cycle by replacing permeable natural surfaces with hard, non-absorbent infrastructure. This has led to water flowing quickly and in large amount across the surface. In the past, urban planning focused mainly on removing water instead of managing it properly. By prioritizing fast drainage through concrete channels, we overlooked the volume of water and how fast it reaches river, causing lasting harm to the environment. This approach is clearly not sufficient, especially with the increase pace of urban development and more intense rainfall cause by climate change, as noted by IPCC in 2021. This paper critically explores how landscape design specially organization of vegetation layer, soil system, landforms and permeable surface can be key tool for reducing these hydrological issues.

This paper uses the Rational Method equation $Q = CIA$ as a key framework for analysis. It investigates three main factors: Mannings coefficient (n), which determines the speed of water movement over a surface, the soil infiltration Rate (f), which is based on Horton's infiltration model and shows the amount of water ground can take in, and the Total impervious Area (A). Through a review of international and national literature, this paper evaluates the performance of several types of green infrastructure, such as bioswales, rain gardens, green roofs, constructed wetlands, and permeable pavements. Particularly how different layers of the landscape- such as tree canopies, shrubs and grass contributes to process like interception, infiltration, evaporation and groundwater recharge. The finding backup recommendation for the policies suburban growth, as referenced by Fletcher et al. (2015) and Davis et al. (2009).

Key Words: Urban Hydrology; Stormwater Management; Green Infrastructure (GI); Landscape-Based Water Management; Surface Runoff Reduction; Horton Infiltration Model; Manning's Coefficient; Impervious Surface Area;

Vegetation Interception; Groundwater Recharge; Nature-Based Solutions (NbS); Climate-Resilient Urban Design; Sustainable Drainage Systems (SuDS); Low Impact Development (LID); Urban Sustainability.

1. INTRODUCTION

Water, the basic element which supports urban life, is becoming a greater threat and a diminishing resource in present day. As urban areas grow across the globe we see an unequalled rate of change to the hydrological environment. Natural vegetated surfaces which absorb, filters and slowly releases rainfall are giving way to manmade elements like concrete, asphalt, and compacted soils. These man-made elements cause water to run off quickly and do not provide the environmental benefits that natural systems do.

Urban flooding events have multiplied in frequency and intensity. Groundwater tables are declining. Combined sewer systems are overwhelmed during storm events, releasing untreated waste into rivers and lakes. Heat island effects are intensifying, further modifying evapotranspiration patterns. Cities such as Chennai (2015), Mumbai (2005), and Indore have all experienced catastrophic flooding events that exposed deep vulnerabilities in conventional grey drainage infrastructure.

In response, the global planning and design community has turned towards landscape-based and nature-based solutions. Concepts such as Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID), Water-Sensitive Urban Design (WSUD), and the Sponge City model represent a paradigm shift — from the rapid conveyance of stormwater to its on-site retention, infiltration, and beneficial reuse. At the center of these frameworks lies the discipline of landscape architecture, which, far from being merely aesthetic, functions as a precision hydrological engineering tool.

This paper investigates the mechanisms by which landscape design — particularly the composition and structure of vegetation layers, soil configurations, grading decisions, and surface material choices — affects the quantity, quality, velocity, and timing of surface runoff. It also synthesizes design guidance, performance data, and policy implications for practitioners and researchers working in the Indian urban context.

2. THEORETICAL FRAMEWORK AND HYDROLOGICAL CONCEPTS

2.1 The Urban Hydrological Cycle

In a natural, forested watershed, rainfall is distributed through a several interconnecting processes before any water reaches a stream channel. Canopy interception removes 10–40% of gross rainfall. The water that reaches the ground is significantly infiltrated into the soil, recharging groundwater and maintain base flow in rivers. Evapotranspiration — the loss of water through soil evaporation and plant transpiration — returns 50–70% of annual rainfall to the atmosphere in tropical and subtropical regions. As a result, only a limited amount of rainfall generates surface runoff under normal conditions.

Urbanization has disturbed this natural water cycle significantly. Research show that even urbanization with 30–50% impervious cover can increase storm water runoff volumes by 200–400% compared to conditions before development. It results Peak water discharge rises rapidly, floodwater reaches drainage channels much faster, and base flow in urban streams decreases or disappears totally. These changes collectively constitute

what hydrologists call the "urban hydrological signature."

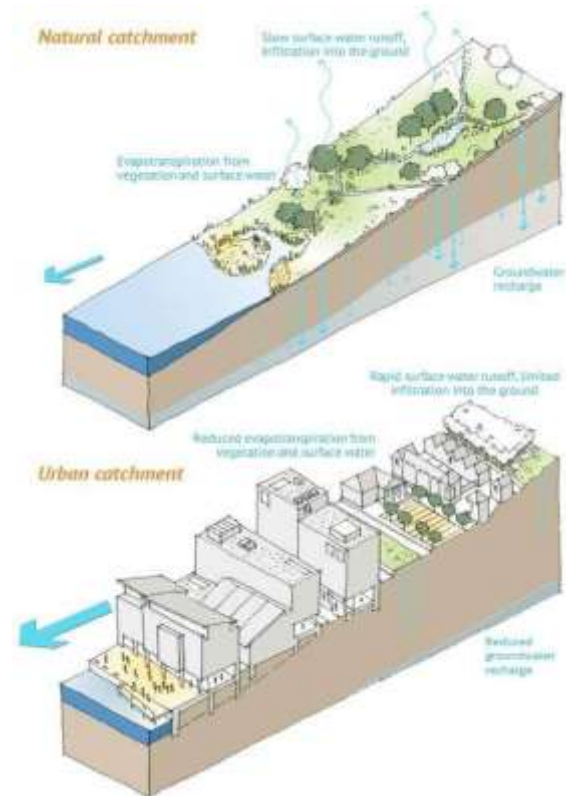


Fig -1: URBAN HYDROLOGICAL CYCLE

2.2 Runoff Generation Mechanisms

Hortonian (Infiltration Excess) Flow: As described by Robert Horton in 1933, it is the flow of water over the ground surface that occurs when rainfall intensity exceeds the rate at which soil can absorb it. In cities where large areas are covered by impervious pavements and compacted soil, the natural absorption of rainwater is greatly reduced, and Hortonian flow is the dominant even during moderate rainfall.

Saturation Excess Flow: This mechanism occurs when soil is completely filled with water and incapable of absorbing any additional rainfall water. It is more common in areas with porous soil, high water tables, or clay-rich soils with low permeability. Both mechanisms are relevant in designing landscape-based interventions.

2.3 Green Infrastructure vs. Grey Infrastructure

Over the centuries, the grey infrastructure — pipes, culverts, drains, retention tanks — has been the

backbone of urban storm water management. They are designed to quickly collect and transport runoff away from urban areas as soon as possible. Although this system is dependable, it is expensive, inflexible to changing rainfall patterns, and provides no co-benefits beyond drainage.

Green infrastructure, works with natural hydrological processes. It slows down, disturbs, absorbs, and stores water within the landscape. The United States Environmental Protection Agency defines green infrastructure as "a cost-effective, resilient approach to managing wet weather impacts that provides many community benefits." While well-designed, green infrastructure can match or exceed the performance of grey systems while also supporting biodiversity enhancement, reducing urban heat, capturing carbon, air quality improvement, and enhancing overall quality of life.

3. The Hydrological Role of Individual Landscape Layers

The major contribution of this paper is the detailed analysis of how different vertical layers within the urban landscape — trees, shrubs, and ground covers — individually and collectively modulates the stormwater cycle. Understanding this contribution of each layer enables designers and planners to make more informed, performance-based planting decisions.

3.1 Trees and the Tree Canopy Layer

Trees represent the most hydrologically significant component of the urban plant community. Their influence operates across multiple mechanisms simultaneously:

Canopy Interception: Tree canopies capture rainfall on leaf and branch surfaces, where it either evaporates directly (wet canopy evaporation) or drips as throughfall and stemflow. Interception rates differ significantly by trees species, canopy density, and storm characteristics. Broadleaf deciduous trees intercept 15–40% of annual precipitation, while conifers intercepts by 20–50% owing to their year-round foliage retention. A single oak

tree may intercept up to 100,000 liters of rainfall annually.

Root Zone Infiltration Enhancement: Tree root systems substantially enhance soil microporosity, creating preferential flow channels that increases infiltration rates by 30–100% compared to compacted, rootless soils. Root-induced bio pores persist even after root decay, providing long-term benefits.

Evapotranspiration: Mature trees transpire large volumes of water. A single large deciduous tree may transpire 150–400 liters per day during the growing season, contributing significantly to local atmospheric moisture and reduces soil water content available for runoff generation.

Stemflow and Throughfall Regulation: While trees redirect some intercepted water down stems and through the canopy to the ground, this process generally delivers water at lower intensities than direct rainfall, giving the soil more time to absorb it.

Urban forests and street tree networks therefore serve as distributed hydrological infrastructure. Research in London demonstrated that increasing urban tree canopy cover from 22% to 28% could reduce annual stormwater runoff volumes by approximately 4%. In denser urban canopy scenarios, reductions of 10–15% in runoff volume have been recorded.

3.2 Shrubs and the Mid-Story Layer

The shrubs occupy the vertical space between the tree canopy and ground level, serves a complementary but distinct role in hydrological cycle:

Secondary Interception: Shrubs intercept throughfall from the upper canopy, they create a layer or cascading interception effect. Depending on factors such as leaf area index and branching density, shrubs can capture an additional 5–20% of rainfall that passes through the trees.

Litter and Organic Matter Accumulation: Shrub understories and maintain higher levels of organic matter like— decaying leaves, root exudates, and fungal networks. This enriched soil environment enhances soil water-holding capacity and increases infiltration rates.

Flow Retardation: Shrub stems and foliage increase surface roughness, reducing the velocity of overland flow and extending the time water remains on-site. This delay promotes greater infiltration and decreases rapid surface runoff.

Erosion Prevention: By breaking the kinetic energy of raindrops and binding soil particles with root networks, shrubs significantly reduce soil erosion and the sediment load of stormwater runoff.

Native and adapted shrub species are particularly great effective in bioswale and rain garden designs, as their deep root systems and drought tolerance allow them to function effectively in alternately wet and dry conditions.

3.3 Grasses and Groundcover Layer

Ground-level vegetation includes grasses, sedges, forbs, and low-growing groundcovers, forms critical hydrological interface between precipitation and soil. These vegetation layers play a major role in regulating runoff, infiltration, and soil erosion processes.

Surface Roughness and Manning's n: Dense grass cover increases surface hydraulic roughness, which slows overland flow velocities from typical values of 0.3–1.5 m/s on bare soil to 0.05–0.3 m/s on established turf. The results in increase in hydraulic residence time promotes infiltration and minimizing erosive forces.

Raindrop Splash Erosion Prevention: On bare soil the direct impact of rainfall creates splash erosion and surface sealing, forming compacted crust that reduces infiltration capacity. Even a sparse grass cover of 30–40% can reduce splash erosion by 50–70% and prevent surface sealing.

Root Density and Soil Structure: Grass root systems are generally shallower than those of trees and shrubs, are extremely dense. The grassland may contain root lengths of 600–1,000 km per cubic meter of soil. This root density maintains soil microporosity and supports the microbial activity essential for maintaining soil structure.

Infiltration Performance: Well-established turf on loamy soils can achieve infiltration rates of 25–75

mm/hour, where compacted bare soil exhibit rate of only 5–15 mm/hour. Native prairie grasses with deep root systems can achieve rates exceeding 100 mm/hour.

3.4 Comparative Hydrological Performance by Layer

Landscape Layer	Interception (%)	Infiltration Enhancement	ET Rate	Flow Velocity Reduction	Sediment Retention
Mature Tree Canopy	15–40%	30–100% above bare soil	High (150–400 L/day)	Moderate	High
Dense Shrub Layer	5–20%	20–50% above bare soil	Moderate	High	Very High
Grass / Groundcover	2–10%	10–60% above bare soil	Moderate	Very High	High
Combined multi-layer	25–60%	50–200% above bare soil	Very High	Very High	Very High
Impervious Surface	0%	Near zero	Negligible	None (accelerates)	None

Table 1: Comparative hydrological performance of landscape layers

4. Landscape-Based Stormwater Management Techniques

4.1 Bioswales

Bioswales are vegetated, engineered drainage channels designed to convey, filter, and partially infiltrate stormwater runoff. Unlike conventional drains, bioswales incorporate a designed soil profile, selected plant communities, and a controlled longitudinal slope (typically 0.5–4%) to maximize hydraulic residence time and enhance both physical and biological treatment processes.

The vegetation in a bioswale serves several hydrological and ecological functions. Root system maintains soil permeability and improves infiltration capacity; stems and foliage reduce flow velocity and promote sedimentation. The plant surfaces support microbial biofilm that contributes for nutrient and pollutant degradation. Well-designed bioswales with appropriate plant communities and engineered soil can remove 70–95% of total suspended solids (TSS), 40–80% of total phosphorus, and 30–70% of heavy metals from stormwater.

4.4 Permeable Paving Systems

Permeable pavements — including permeable interlocking concrete pavers (PICP), porous asphalt, porous concrete, and grass-concrete grid systems are used to allow rainfall to infiltrate through the pavement surface into a stone reservoir layer. The stored water infiltrates into the subgrade or is collected by underdrains for controlled discharge. Well-maintained permeable pavements can achieve infiltration rate from 500 to 5,000 mm/hour, far exceeding typical rainfall intensities.

In Indian cities, permeable paving is particularly suitable for parking areas, pedestrian pathways, low-volume roads, and public plazas. This all collectively represent a significant fraction of urban impervious area. Lifecycle studies show that the marginally higher capital cost of permeable pavements relative to conventional materials (typically 10–30% premium) is offset by savings in conventional drainage infrastructure, reduced road maintenance costs, and avoided flood damage.



5. Design Parameters and Performance Factors

5.1 Soil Hydraulic Properties

Soil texture and structure play a crucial role in determining the hydrological performance of landscape system. The hydraulic conductivity (K_{sat}) of soils varies across several order depending on soil composition ranging from less than 1 mm/hour for heavy clays to more than 500 mm/hour for coarse sands and gravels. In GI design, engineered soil media are commonly specified with target K_{sat} values of 25–75 mm/hour to

ensure effective stormwater infiltration while avoiding excessive rapid drainage that would affect plant health.

In Indore and the broader Malwa region, native soils include black cotton soils with high clay content and low K_{sat} , making low permeability and limited infiltration. GI (green infrastructure) designs in this context typically incorporate engineered filter media within lined bioretention cells with underdrains directing filtered water to storage or reuse systems rather than relying on native soil infiltration.

5.2 Rainfall-Runoff Modelling

Accurate hydrological design depends on the application of established runoff estimation techniques. The Rational Method ($Q = CiA$, where C is the runoff coefficient, i is rainfall intensity, and A is catchment area) remains commonly used approaches for small catchment design ($< 0.5 \text{ km}^2$). However, this method is often considered limited because it oversimplifies the complex and continuous hydrological processes.

The SCS Curve Number method, developed by the United States Soil Conservation Service. This method incorporates the values such as antecedent soil moisture, land cover, and hydrological soil group, making it particularly appropriate for the runoff reduction potential of green infrastructure.

Advanced continuous simulation modelling uses tools such as SWMM (Storm Water Management Model) and HEC-HMS enables designers to evaluate green infrastructure performance across wide range of rainfall and antecedent conditions. These modelling tools provide more robust estimates of annual runoff volume reduction and peak flow attenuation for design storms of specific return periods.

5.3 Vegetation Selection Criteria

Plant selection for stormwater landscape systems must balance hydrological performance requirements and long-term horticultural realities. Species must be chosen not only for their ecological performance but also for their adaptability to local environmental and maintenance conditions. Key selection criteria include:

Tolerance of alternating moisture conditions — Green infrastructure systems cycle between inundation (during and after storm events) and drought (during dry seasons or prolonged inter-storm periods).

Root depth and architecture — Deep-rooting species are preferred as they enhance infiltration and access deeper soil moisture, reducing irrigation dependency.

Native species preference — Locally indigenous species are better as they are adapted to regional climate variability, support local biodiversity and typically require less maintenance once established.

Leaf area index (LAI) and seasonal variation — Species with high, year-round LAI maximize rainfall interception throughout year. Conversely, deciduous species provide reduced winter interception that may be desirable or undesirable depending on design intent.

Maintenance requirements — Stormwater landscapes must be designed according to the maintenance capacity of the managing authority or organization with preference for species requiring minimal irrigation, pruning, and replacement.

6. Quantitative Performance Assessment

6.1 Key Performance Metrics

GI Typology	Peak Flow Reduction	Annual Volume Reduction	TSS Removal	Nutrient Removal
Bioswale	30–65%	25–50%	70–95%	40–80%
Rain Garden / Bioretention	40–90%	30–80%	80–95%	50–85%
Extensive Green Roof	50–85%	40–75%	60–85%	20–50%
Constructed Wetland	50–80%	30–60%	70–90%	40–70%
Permeable Pavement	70–95%	50–90%	70–85%	25–60%
Urban Forest (high density)	20–40%	15–35%	50–70%	20–40%

Table 2: Performance summary of major green infrastructure typologies (compiled from international literature)

6.2 Cost-Benefit Considerations

Economic analysis of green infrastructure consistently demonstrates favorable cost-benefit ratios when co-

benefits are properly accounted. While initial capital costs of GI can range from US\$15–80 per square meter depending on typology and site conditions, conventional grey drainage infrastructure designed to achieve similar hydraulic performance typically costs 2–5 times more. When ecosystem services including urban cooling (reduced air conditioning costs), property value uplift (5–15% premium for nearby green space), public health benefits, and avoided flood damage are monetized, GI benefit-cost ratios of 1.5:1 to 3:1 are commonly reported.

A study of Philadelphia's Green City, Clean Waters programmed — one of the world's most ambitious GI investment programmed — found that investing US\$1.67 billion in GI rather than conventional grey infrastructure delivered US\$3.3 billion in present value net benefits over a 45-year period.

7. Environmental, Social, and Economic Co-Benefits

7.1 Environmental Co-Benefits

Landscape-based stormwater Management systems provide various environmental benefits that extend well beyond their primary role in drainage and runoff control. Urban biodiversity is enhanced as vegetated green infrastructure systems provide habitat corridors for birds, insects, and small mammals in otherwise hostile urban environments. Green roofs, in particular, have been shown to support diverse invertebrate species and native plant communities.

Improvement in Urban microclimate is a significant environmental co-benefit in the Indian context. Indore's summer temperatures routinely exceed 40°C, and the urban heat island effect adds a further 2–5°C in dense built areas. Trees and vegetated green infrastructure systems moderate this condition through shading and evapotranspiration cooling, with studies reports in reductions of 2–8°C in air temperatures within and around to well-vegetated urban spaces.

Carbon sequestration, while modest relative to the scale of urban emissions, contributes meaningfully to municipal sustainability targets. Urban trees sequester an

average of 2–10 kg of CO₂ per tree per year, with large, mature specimens sequestering considerably more. Bioretention soils with high organic matter content also serve as carbon sinks.

7.2 Social Co-Benefits

The psychological and public health benefits of urban green space are well documented in the research. When stormwater management features are well designed in multifunctional landscapes like parks, greenways, and community gardens rather than purely as drainage infrastructure — reduces stress, encourages physical activity, and improves mental health outcomes. Research conducted in the Netherlands found that residents living within 1 km of green space had lower rates of depression and anxiety than those without access.

Stormwater green infrastructure also provides valuable educational opportunities. Rain gardens and bioswales designed with interpretive signage and visible hydrological processes create tangible connections between community members and the water cycle, building environmental literacy and increasing public support for continued investment in sustainable infrastructure.

7.3 Economic Co-Benefits

Beyond direct drainage cost savings, green infrastructure (GI) investments generate significant economic benefit through property value enhancement, reduced urban heat, lower public health costs associated with improved air and water quality, and the development of a skilled green workforce. Indian Smart City initiatives increasingly recognize these multiple returns in their infrastructure investment calculus, though more rigorous economic studies in the Indian urban context are needed to establish locally calibrated benefit-cost relationships.

8. Case Studies

8.1 Sponge Cities Initiative, China

Sponge City programmed, launched in 2015 across 30 pilot cities, represents the world's most ambitious deployment of urban green infrastructure. The

programmed aims to ensure that 70% of rainfall from 80% of urban land area be captured, stored, infiltrated and reused by 2030. Cities including Wuhan, Xiamen, and Nanjing have invested billions of yuan in bioswales, permeable pavements, constructed wetlands, and urban parks designed as multi-functional stormwater landscapes. Preliminary monitoring data from areas of Xiamen showed a 38% reduction in surface runoff volume and a 30% reduction in peak discharge rates across pilot demonstration areas.

8.2 Indian Context — Ahmedabad and Delhi

Indian cities have begun adopting green infrastructure GI principles in urban development projects although implementation remains largely pilot-scale. In Ahmedabad several initiatives under smart city have been incorporated like- bioretention planters and permeable footpaths, with early performance data suggesting peak flow reductions of 40–60% in instrumented catchments.

Similarly, Delhi's Yamuna floodplain rejuvenation efforts have incorporated constructed wetlands and riparian buffer planting to improve treatment of agricultural and urban runoff before it reaches the river. However, India-specific long-term performance data, maintenance experience, and lifecycle cost data remain sparse, representing a significant research gap.

8.3 Indore: Context and Opportunities

Indore, with a population over 3.5 million and growing rapidly, faces significant stormwater management challenges. The city experiences a monsoon-dominated rainfall regime, with 70–80% of its annual average rainfall of approximately 900 mm arriving in the June–September monsoon period. This intense seasonal concentration creates extreme hydrological variability — severe flooding during monsoon months and water scarcity for the remaining eight months.

The existing drainage infrastructure in Indore consists of combination of open nallahs and underground drains, is widely acknowledged to be undersized relative to current urban extent and rainfall intensities that are trending higher due to climate change. Rapid

development along the urban periphery, particularly over former agricultural and natural landscapes, has substantially increased impervious surface cover within upstream catchments, thereby intensifying runoff volumes and placing additional pressure on downstream drainage systems.

The city's Smart City Mission investments and the development of new residential and commercial zones provide significant opportunities to integrate green infrastructure GI from the outset rather than retrofitting it at greater cost later. Priority interventions identified for the Indore context include: bioswale networks along arterial road medians and footpaths; rain garden installations in residential colonies and institutional campuses; mandatory permeable paving requirements for parking areas; retention pond networks in open spaces; and urban reforestation with native Malwa region tree species.

9. Policy, Governance, and Implementation Framework

The effectiveness of landscape-based stormwater management systems depends not only on design but also on the policy and governance structure within which they operate. Even efficiently designed bioswale and rain garden fails if it is poorly maintained; even well-maintained green infrastructure GI delivers sub-optimal results if it is implemented in isolation rather than as a coordinated catchment-scale network.

In the Indian context, stormwater management responsibilities are divided across multiple agencies — Urban Local Bodies (ULBs), State Urban Development Agencies, Public Works Departments, and Housing Boards — with limited coordination and unclear accountability. A major governance reform priority is the establishment of unified stormwater management authorities with clear jurisdiction, technical capacity, and maintenance budgets.

International experience has shown that several regulatory instruments can significantly improve the implementation of green infrastructure. These include development regulations requiring that post-

development runoff levels do not exceed pre-development conditions for specified storm events, stormwater utility fees that encourage on-site runoff management, and mandatory GI compliance standards as part of development approval processes. Such policy mechanisms help mainstream sustainable stormwater practices within urban planning frameworks.

In India, national programmes such as the Smart Cities Mission, Atal Mission for Rejuvenation and Urban Transformation, and emerging urban flood management policies provide important opportunities to promote wider adoption of green infrastructure. However, achieving large-scale implementation will require stronger policy integration, clearly defined performance standards, and dedicated financial mechanisms to move beyond isolated pilot projects toward comprehensive urban-scale transformation.

10. Future Scope and Innovation

10.1 Smart Stormwater Systems

The integration of Internet of things IoT sensor networks, real-time monitoring system, and predictive analytics is emerging as advancement of stormwater management. Smart green infrastructure GI systems can adjust their operation in anticipation of incoming storm events — for example, drawing down the water level in a retention pond before a heavy rainfall to maximize storage capacity. Through well-developed Soil moisture sensors and rain gauge networks feeding machine, it can enable adaptive, catchment-scale management that optimizes the performance of green infrastructure GI networks in ways that static, design-standard-based systems cannot.

10.2 Nature-Based Solutions and Biomimicry

Nature-Based Solutions (NbS) — defined by the International Union for Conservation of Nature IUCN as actions that protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively — offer a conceptual framework that elevates landscape-based stormwater management from a technical practice to a philosophy of urban design. Biomimetic design

principles, which draw inspiration from natural hydrological systems such as wetlands, floodplains, and riparian corridors, are increasingly shaping the development of urban stormwater landscapes. Rather than relying solely on conventional engineered solutions, these approaches aim to create urban environments that replicate the structure and functioning of natural ecosystems. As a result, contemporary stormwater landscapes are evolving into multifunctional ecological systems that support hydrological regulation, biodiversity enhancement, and urban resilience simultaneously.

10.3 Climate Adaptation

Climate projections for central India consistently indicate increasing rainfall variability, characterized by more intense rainfall during wet season events with more severe dry periods. As a result, green infrastructure GI systems designed to current standards may require recalibration to remain effective under future climate conditions. This underscores the need for research into climate-adaptive GI design incorporating larger storage volumes, more drought resilient plants, and greater infrastructural redundancy. This adaptive approach is urgently needed to ensure that today's investments remain functional across the 50–100 year service lives of urban infrastructure.

11. Challenges and Limitations

Despite their substantial potential, landscape-based stormwater management systems are subject to face real constraints that must be considered in planning and design:

- **Space requirements:** High-performance GI typically requires 3–8% of the contributing catchment area to be allocated as managed landscape. In dense urban environments with competing land use pressures, finding and securing this space is often a major obstacle to GI implementation.
- **Maintenance intensity:** GI systems require ongoing maintenance including vegetation management, sediment removal, inlet clearance, soil replacement, that exceeds the maintenance

demands of conventional pipe systems. Without adequate maintenance budgets and skilled workforce, GI performance degrades significantly over time.

- **Performance variability:** GI performance is inherently more variable than grey infrastructure, responding dynamically to antecedent soil moisture conditions, seasonal plant growth cycles, and storm characteristics. This variability must be accounted for in design through conservative performance assumptions and system redundancy.
- **Large storm limitations:** Most GI typologies are designed to manage frequent, smaller storm events (the 1–2-year return period) rather than large, infrequent floods (the 50–100 year event). For major flood protection, GI must be complemented by conventional structural measures.
- **Initial cost barriers:** While lifecycle costs of GI compare favourably with grey alternatives, higher upfront capital costs can be a barrier in budget-constrained municipal environments without specific GI funding mechanisms.

12. Conclusion

This paper has demonstrated that landscape design is not merely a visual or aesthetic discipline when applied to the urban hydrological system — it is a precision engineering science with quantifiable, measurable hydrological outcomes. The disaggregated analysis of landscape vertical strata (trees, shrubs, grasses) reveals that each layer makes distinct and complementary contributions to the stormwater management system: canopy interception, root-zone infiltration enhancement, surface flow retardation, evapotranspiration, and erosion prevention. When these layers are combined in a structurally diverse, ecologically coherent planting design, their collective hydrological performance substantially exceeds what any single layer or engineered grey alternative can achieve.

The evidence base from international practice — Portland's Green Streets, China's Sponge Cities, Singapore's ABC Waters programmed — consistently

demonstrates that cities that have committed to landscape-based, catchment-scale stormwater management have achieved dramatic reductions in flood risk, significant improvements in water quality, and measurable enhancement of urban live ability and biodiversity. These outcomes are achievable at a fraction of the equivalent grey infrastructure cost when GI is integrated systematically from the urban planning stage rather than retrofitted after development.

For Indore and similar rapidly urbanizing Indian cities, the window of opportunity to embed GI into the fabric of urban expansion is now. New development areas, Smart City investments, road upgrades, and public space improvements all represent integration opportunities that, if seized, can establish the hydrological and ecological foundations of a genuinely water-sensitive city. This will require coordinated action across disciplines — landscape architects and urban designers specifying performance-based GI systems, civil engineers integrating them within broader drainage networks, planners embedding GI requirements in development controls, and municipal managers establishing the maintenance systems and monitoring frameworks needed to ensure enduring performance.

Future research priorities for the Indian context include: long-term monitored performance databases for locally deployed GI typologies; development of Indian-context Curve Number and Manning's n values for native vegetation communities; economic valuation studies for co-benefits in Indian urban settings; and investigation of hybrid GI-grey systems optimized for the monsoon-dominated rainfall regime. With this research foundation in place, India can move from isolated GI pilots to a genuine transformation of the urban water landscape.

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