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Green Infrastructure / LID for Urban Stormwater Management

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Abstract:

Green Infrastructure (GI) and Low Impact Development (LID) have emerged as essential strategies to mitigate urban stormwater quantity and quality challenges caused by rapid urbanization. Recent surveys show that in highly impervious catchments GI/LID practices 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 from stormwater. Beyond hydrologic and water-quality benefits, GI/LID offers co-benefits such as urban heat mitigation, biodiversity enhancement, and improved public amenities. This paper reviews international terminology and policy evolution, hydrologic and pollutant-removal mechanisms, and the performance of common measures such as green roofs, bioretention, and permeable pavements. We also discuss modeling and decision frameworks (with emphasis on SWMM-based workflows), Sponge City practices in China, and challenges in long-term maintenance, regional adaptation, and climate resilience.

Keywords: Green infrastructure; Low impact development; Sponge City; Stormwater; SWMM; Bioretention; Green roof; Permeable pavement

1. Introduction

1.1 Background and motivation

Rapid urbanization increases impervious cover and shortens hydrologic response times, resulting in higher peaks, more frequent combined sewer overflows, and pollutant pulses to receiving waters. GI/LID emphasizes source control and on-site retention to reduce runoff generation and pollutant loads [1,2].

1.2 Scope and contributions

This review clarifies terminology and policy targets used internationally [1]; summarizes mechanisms at facility and catchment scales and connects them to design parameters and acceptance criteria [2,3]; synthesizes performance evidence and practical strengths/limitations of common measures [6]; and consolidates guidance useful for planning and implementation [4,5]. We also outline modeling workflows based on SWMM [3] and distill governance and programmatic lessons for practice.

2. Concepts and System Framework

2.1 Terminology and evolution

The nomenclature of sustainable stormwater management has diversified across regions. In the U.K., "Sustainable Drainage Systems (SUDS)" arose from the 1990s CIRIA guidance; in the U.S., "Low Impact Development (LID)" and "Best Management Practices (BMPs)" were popularized by EPA; in Australia, "Water Sensitive Urban Design (WSUD)" integrates urban planning and stormwater reuse; and more recently, "Nature-Based Solutions (NbS)" appears in EU policy documents. Despite these differences, all converge on distributed, vegetated systems that infiltrate, detain, store, and treat runoff before discharge [1]. Table 1 compares key terms, origin years, and policy drivers.

2.2 Measure types and design elements

EPA classifies GI/LID measures as green roofs, bioretention/rain gardens, permeable pavements, bioswales/vegetated swales, depressed green spaces, and rainwater harvesting systems [4,5]. Each measure includes common design elements such as layered media, pretreatment (forebays, filter strips), hydraulic connectivity between cells, overflow/bypass routing for extreme storms, and maintainability considerations. Typical parameter ranges include: green roof substrate depth 80–150 mm, bioretention surface infiltration rates 25–150 mm/h, and permeable pavement surface void ratios 15–20 %. Figures illustrating cross-sections can help convey these elements.

2.3 Policy targets and performance objectives

Typical objectives include controlling a specified design storm depth (e.g., first 25–38 mm in U.S. MS4 permits), achieving annual runoff control ratios (≥70 % in China's Sponge City pilots), reducing pollutant loads by specified percentages (e.g., 60 % TSS), and attenuating peak flows to pre-development levels. Program success can be tracked by indicators such as capture ratio, pollutant mass reduction, and receiving-water biological health. Increasingly, multi-criteria decision-making integrates hydrologic metrics with cost, constructability, equity, and co-benefits such as heat mitigation and biodiversity [4].

3. Mechanisms of Action

3.1 Hydrologic regulation

Infiltration, storage, and evapotranspiration reduce effective runoff volume, attenuate peaks, and delay time to peak [2]. At catchment scale, placement density, hydraulic connectivity, and synchronization of outflows govern aggregate effects [3].

3.2 Water-quality improvement

Filtration removes suspended solids; adsorption/ion exchange and redox transformations address metals and nutrients; microbial denitrification lowers nitrate under anoxic conditions with sufficient carbon [6]. Media recipes balance hydraulic conductivity, sorption capacity, and plant health.

3.3 From mechanisms to design parameters

Design parameters translate mechanisms into specifications: design capture depth, media hydraulic conductivity, available storage, drawdown time, bypass stage, and under-drain orifice coefficients. Acceptance criteria often require dewatering within 24–48 h while maintaining sufficient residence time for treatment [3,5].

4. Performance Evidence of Typical Measures

4.1 Bioretention (rain gardens)

Laboratory and field studies demonstrate significant removal of Cu, Pb, Zn, and nutrients, as well as attenuation of runoff peaks in impervious catchments [7,8]. Media gradation and organic content govern infiltration rates and nutrient dynamics; under-drains with internal water storage can improve nitrate removal where permissible [8].

4.2 Green roofs

Green roofs reduce roof runoff volume and peak flow; performance depends on substrate depth, vegetation, antecedent moisture, and storm size. Typical layers include vegetation, growth medium, filter fabric, drainage, insulation, waterproof membrane, and roof deck (Figure 1) [9].

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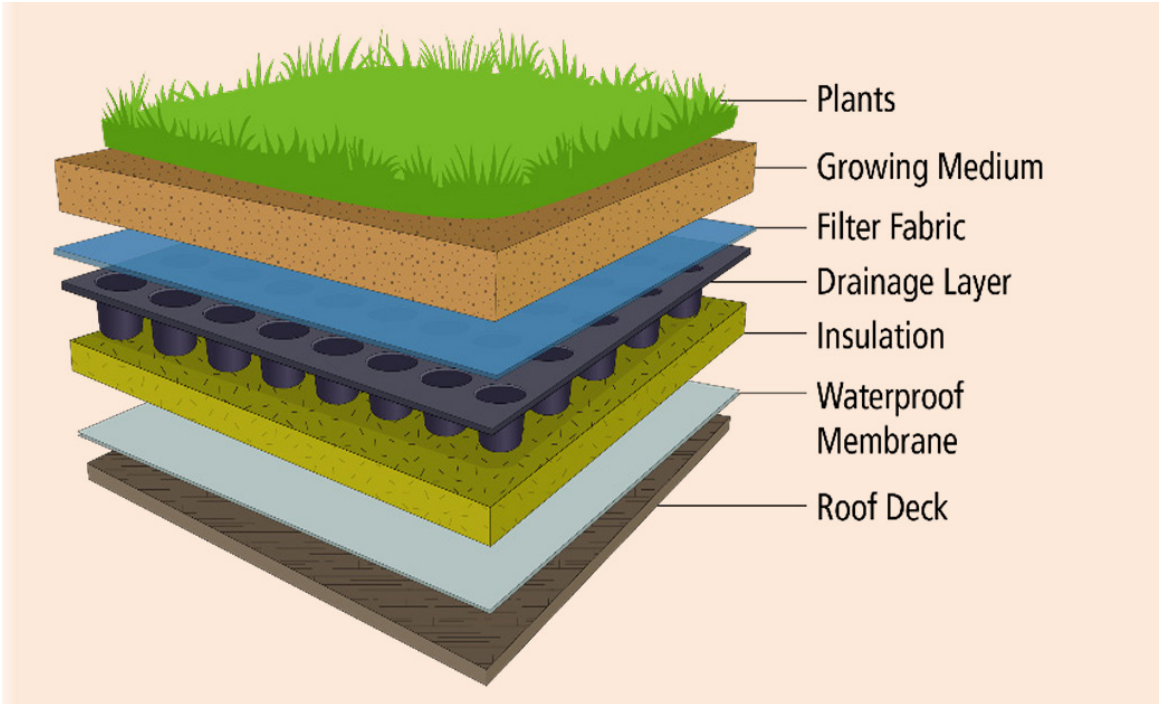

Figure 1. Typical green roof material layers. Source: US EPA, "Green Roofs" BMP Fact Sheet (2021) [9].

4.3 Permeable pavements

Field surveys and long-term monitoring indicate robust reduction in surface runoff and metals under suitable subgrade and groundwater conditions [10,11]. Regular vacuum sweeping maintains infiltration capacity in sediment-laden settings.

4.4 Compiled evidence and design details

EPA fact sheets synthesize cross-project performance and design details, including event-scale inflow–outflow relationships for bioretention (Figure 2) and pollutant removal ranges for permeable pavement surface types (Figure 3) [12,13].

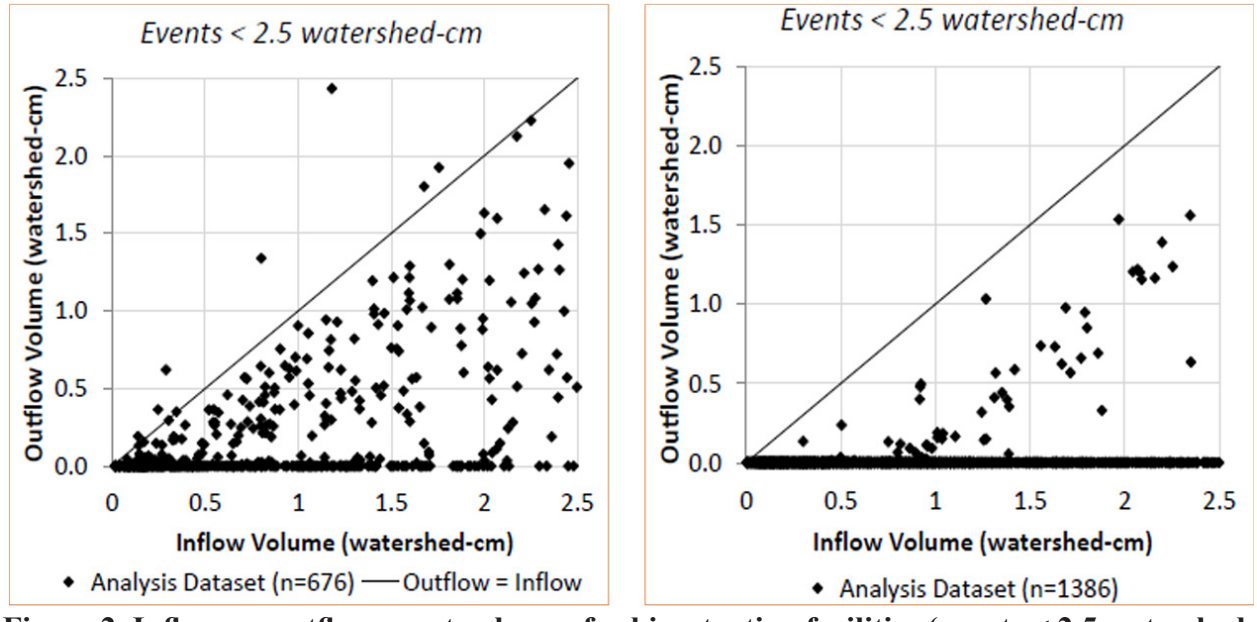

Figure 2. Inflow vs. outflow event volumes for bioretention facilities (events < 2.5 watershed-cm). Source: US EPA, "Bioretention (Rain Gardens)" BMP (2021) [12].

Table 1. Pollutant removal ranges for permeable pavement surface types (porous asphalt, pervious concrete, PICP). Source: US EPA, "Permeable Pavements" BMP (2021) [13].

Surface Type	Total Suspended Solids	Metals	Nutrients
Porous asphalt	94–99%	76–97%	42–43%
Pervious concrete	91%	75–92%	N/A
PICP	67–81%	13–88%	34–72%

4.5 Comparative strengths and limitations

Green roofs excel where land is scarce and provide thermal co-benefits but offer limited storage per unit cost; bioretention delivers strong pollutant removal and flexible siting but needs diligent O&M and pretreatment; permeable pavements suit parking and low-speed corridors but require strict sweeping regimes and careful base/subgrade design [4,6,10,13].

5. Modeling and Assessment

5.1 Tools and parameterization

SWMM represents LID controls with parameters for storage, conductivity, and under-drain controls and supports planning, sizing, and scenario analysis [5].

5.2 Uncertainty and verification

Uncertainty analysis (e.g., Monte Carlo or GLUE) clarifies predictive ranges and robust designs; monitoring networks with gauges and samplers support verification and model updating [6].

5.3 Resilience-oriented decision frameworks

Resilience thinking—from fail-safe to safe-to-fail—advocates distributed, sacrificial storage and controlled inundation at low-consequence sites, which can be evaluated with multi-criteria decision analysis alongside hydrologic metrics and co-benefits [14].

6. Sponge City Practices

6.1 Policy framework and targets

China's Sponge City strategy emphasizes the sequence of infiltration–detention–storage–purification–use–discharge, with pilots adopting annual runoff control targets and performance-based assessments [15].

6.2 Case evidence and lessons

Projects report total runoff control and pollutant reduction alongside public-realm enhancements; remaining challenges include retrofitting dense built areas, ensuring maintenance, and localizing models to soils and rainfall regimes [16].

7. Key Issues and Frontiers

7.1 O&M and life-cycle management

Asset registers should record media specifications and inspection points; routine tasks include trash removal, vegetation care, and infiltration maintenance. Trigger levels for rehabilitation might include loss of surface infiltration rate or standing water beyond 48 h [5,6,13].

7.2 Regional adaptation and scale coupling

Arid, cold, and coastal settings require differentiated designs and parameter localization; scaling from lot to sub-catchment needs attention to spatial placement and interactions among controls to avoid hydraulic conflicts [1,2,3].

7.3 Digitalization and smart control

Sensorized under-drains and controllable outlets enable pre-storm drawdown and adaptive operation; digital twins link real-time data to operating rules [3].

8. Conclusions

GI/LID measures—green roofs, bioretention, and permeable pavements—provide proven dual control of runoff quantity and quality while delivering co-benefits. In practice, these measures have also shown positive effects on urban heat mitigation, biodiversity enhancement, and public amenity, which strengthen the case for their adoption in dense urban areas. Advancing practice requires life-cycle O&M, data-informed parameterization and uncertainty analysis, and integrated blue–green–grey planning tailored to local climate and morphology [1–6,14–16]. Future research should further document long-term performance, co-benefits, and cost-effectiveness to support wider implementation.

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