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Sponge City Concept For Sustainable Stormwater Management: A Comprehensive Review

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Abstract- The fast pace of urbanization and worsening climate-driven stressors have disrupted the natural cycles of urban hydrological processes, making existing linear infrastructures increasingly susceptible to extreme pluvial flooding events. The Sponge City concept can be seen as an essential paradigm shift towards a decentralized nature-based method for urban areas to manage rainwater in terms of its absorption, storage, infiltration, and purification.In this review paper, we synthesize empirical data, policies, and hydrological models of ten key studies to examine the effectiveness of the Sponge City paradigm at various scales. This paper will analyze the development trends of LID-based structural controls, quantitative limitations for peak flows, life-cycle maintenance challenges, and multiple ecological benefits. The synthesized literature reveals that although green infrastructure produces impressive hydrological and economic benefits when dealing with conventional rainfall, its performance suffers considerably when confronted with an extreme cloudburst. Therefore, this paper sets up a robust research agenda for future urban planners, namely that a mandatory paradigm must be embraced in the form of a "green-gray hybrid infrastructure" system with institutional and technological arrangements for real-time monitoring.

Keywords: Sponge City, Urban Hydrology, Green Infrastructure, Low Impact Development (LID), Pluvial Flooding, Stormwater Management, Nature-Based Solutions, Climate Change Adaptation, Urban Resilience, Green-Gray Hybrid Infrastructure, Sustainable Urban Planning, Flood Mitigation, Rainwater Management, Real-Time Monitoring, Ecological Benefits.

I. INTRODUCTION

Historically, the urban development process has been entirely dependent on a highly inflexible system of "gray infrastructure," characterized by an artificial channeling network of concrete drains, storm sewers, and pumping stations that facilitate the swift removal of surface runoff out of urbanized areas. Nonetheless, the proliferation of impermeable surfaces has resulted in a change in hydrology, leading to a reduced lag period until peak flow rates, increased runoff amounts, and, hence, urban flooding disasters. In addition, gray infrastructure acts as a direct conveyance route of non-point-source pollutants into natural waterways.

In reaction to these compounded risks, the idea of a Sponge City became apparent as an inclusive urban water strategy. This was first introduced at a countrywide level in China in 2014, as an approach that is congruent with and extends previous international models such as LID in America, SuDS in Britain, and WSUD in Australia. The approach can be considered as a specific application of NbS, treating rainwater as an environmental commodity and not a disaster.

As indicated by Lu (2025) and recent bibliometric analyses, the academic literature within this area has experienced an extensive interdisciplinary transformation. In terms of early publications, there was no consideration beyond engineering aspects of localized flood management criteria. On the other hand, current academic discussion is based on multi-dimensional approaches assessing socio-ecological aspects, cross-scalar climate adaptation governance, and longevity of infrastructure assets.

II. STRUCTURAL EVOLUTION AND CORE METHODOLOGICAL BLUEPRINTS

The creation of an effective Sponge City necessitates a paradigm shift from localized low-impact development to holistic watershed restoration. According to Yin et al. (2022), such hierarchical transformation is outlined within a six-term conceptual framework: “infiltration, detention, retention, purification, utilization, and discharge.” The structural framework involves the following functional layers of engineering:

2.1 Micro Scale Source Control

Source control at the parcel level aims at managing the early attenuation of rainfall within its micro scale area. This involves the use of green infrastructure structures for:

- Permeable Pavements and Porous Interlocking Bricks: To promote vertical infiltration into the subsoil layer, thus restoring the lost urban surface runoff to groundwater recharge.
- Extensive and Intensive Green Roofs: These serve to intercept the rooftop rainfall, thereby delaying the early onset of watershed response through retention and transpiration.

2.2 Mesoscale Storm Water Management Storage & Delivery

Meso scale transmission facilities manage storm water velocity and volume. The vegetated grass swales and infiltration ditches function in place of concrete channels, which reduces runoff velocities and causes sedimentation. Sub-surface storage tanks and multiple-use public squares serve as intermediate detention zones that store excess storm water in case of sudden bursts, allowing slow release to counter downstream shock.

2.3 Macroscale Watershed-Level Retention and Water Purification

Large scale natural features are used at the outlet of the watershed to provide water conditioning and stabilization of the ecosystem. Natural wetlands, biological intercept ponds, and riparian buffers are some examples. These systems use biological purification techniques such as microbial decomposition and absorption of nutrients to purify water by removing dissolved nitrogen and phosphorus.

III. HYDROLOGICAL EFFECTIVENESS: THE "PEAK FLOW PUZZLE"

Defining the exact criteria under which the effectiveness of green infrastructure depends on the intensity of the precipitation is an important goal for the review.

3.1 Runoff Management and Localized Studies

The findings derived from numerous case studies reveal that distributed use of LID technologies has greatly improved urban hydrographs. In particular, it was found that recent studies analyzing the national pilot program in Shenzhen have revealed the relationship between the dense presence of green infrastructure and reduced total runoff, low peak flow values, and effective filtration of contaminants in specified areas (Shenzhen Case Study, 2026). In addition, hydraulic modeling in the SWMM framework conducted in various climatic regions, such as Conakry, Guinea, proved that a combination of different LID approaches (for instance, green roofs with porous pavements and rain barrels) has a synergistic effect on mitigating floods (Conakry Basin Study, 2023).

3.2 The Peak Flow Performance Decline

3.2 The Drop in Peak Flow Performance Efficiency

Even though such achievements were made, it is worth noting that the "peak flow dilemma" performance data is provided within the analyzed sources. According to studies conducted using hydrological models and real-life data, the efficiency of green infrastructure is lower with the growing rainfall return period. Specifically, according to findings from an average urban watershed, the application of optimal combinations of green infrastructure reduces surface runoff by more than 65%, while removing all overflow junctions in minor rainfall events with return periods of 1-5 years. At the same time, the efficiency rate will drop sharply to 35-40% under cloudbursts with the rainfall return period of 50-100 years (Conakry Basin Study, 2023). This is because the soil and biological retention systems will become saturated with the rainfall in its early stages; thus, the next rainfall will lead to surface runoff formation.

Therefore, the current engineering approach requires the adoption of Green-Gray Hybrid Infrastructure Approach where the former will act as a first level of protection against frequent and less severe instances in addition to being used as a cleanser.

Important Operational Constraint (Peak Flow Challenge)

"The runoff management effectiveness of conventional green infrastructure facilities drops from above 65% to below 35%-40% while moving from the regular 5-year storms to very high intensity 100-year rainfall events."

IV. Multi-Dimensional Socio-Economic and Public Health Co-Benefits

One of the most significant breakthroughs in Sponge Cities study in the modern era is that the use of natural infrastructures generates numerous co-benefits far from merely addressing stormwater.

4.1 Dynamics of the System and Economic Payback

The multi-angle System Dynamics (SD) analysis carried out by Ma, Liu, and Wang (2023) demonstrates that despite the high capital input needed to build a sponge city, such projects are quite efficient and financially advantageous throughout the whole project lifespan. The robustness analysis confirms that investments will bring long-term economic benefits in the form of reduced costs of restoration and repair after disasters. In addition, nature-based solutions are on average 50% cheaper than grey options and bring 28% more added value to the local population (World Economic Forum, 2025).

4.2 Multi-Dimensional Indicator Assessment

A comprehensive indicator-based assessment reveals that integrating green and blue assets into the urban fabric creates positive outcomes across three primary sectors as detailed in Table 1.

Socio-Economic Dimensions	Environmental Dimensions	Public Health Dimensions
Capital Expenses: Decreases long-term expenses for municipal recovery from disasters and repair of floods.	Water Quality: Filters heavy metals and nutrients via plant and soil bioremediation.	Heat Stress: Lowers ambient temperatures by up to 2–3°C through evapotranspiration.
Land Value: Increases value of surrounding land because of its location near urban green spaces.	Biodiversity: Creates critical urban habitats, riparian buffers, and ecological corridors.	Air Filtration: Captures particulate matter (PM2.5, PM10) via dense vegetative canopies.
Water Recycling: Allows for water recycling by collecting and treating stormwater.	Carbon Capture: Sequesters urban carbon within wetland soils and biomass.	Mental Well-Being: Reduces community stress levels by providing recreational green spaces.

Table 1: Multi-sectoral matrix evaluating Sponge City co-benefit indicator metrics.

V. LIFECYCLE MAINTENANCE CRISES AND GOVERNANCE BARRIERS

A review of Sponge City performance over long horizons highlights significant engineering vulnerabilities and institutional blockages that threaten long-term asset survival.

5.1 The Five-Tier Lifecycle Maintenance Threat

Knapik, Brandimarte, and Usher (2024) explain that decentralized green stormwater assets suffer from severe performance decline if they are not maintained. They outline five primary physical and operational failure points:

1. Pore Clogging and Sedimentation: Fine silts and urban debris gradually accumulate in the void spaces of porous pavements and rain garden soils. This drops initial hydraulic conductivity, turning permeable surfaces back into impermeable ones.
2. Vegetative Breakdown: Poor vegetation management, such as over-mowing, neglecting invasive species, or selecting non-native plants, limits plant root growth and degrades natural biological filtration.
3. Drawdown System Failures: Clogged underdrains or compromised outflow structures prevent bioretention cells from drying out within standard 48-to-72-hour windows. This causes permanent standing water, generating mosquito breeding grounds and anaerobic soil dead-zones.
4. Heavy Metal Saturation Limits: Because bioretention soils trap heavy metals (e.g., Lead, Zinc, Copper), these cells eventually reach dangerous saturation thresholds. Without periodic soil remediation, the asset shifts from a toxic sink into a source of pollution, threatening local shallow aquifers.

5. Asset Abandonment: Unlike large, single-site gray drainage facilities, green infrastructure assets are small and scattered across thousands of urban parcels. Without dedicated municipal maintenance funding and clear ownership lines, these features are frequently paved over or neglected.

5.2 Institutional Silos and Policy Fragmentation

On an administrative level, implementing scalable Sponge Cities requires navigating complex governance systems. Historically, urban policy has suffered from deep "institutional silos," where public works departments, transportation agencies, and zoning boards operate under isolated, conflicting mandates. For example, a transportation agency may implement standard asphalt paving schedules that directly conflict with an environmental department's downstream rain garden projects.

Furthermore, global policy analyses highlight a persistent lack of unified national design standards, land-use conflicts, and weak private-sector financing mechanisms. These barriers make large-scale Integrated Urban Water Management (IUWM) difficult to scale up rapidly. Transitioning from isolated pilots to city-wide resilience requires aligning local zoning laws directly with regional River Basin Management Plans (RBMPs) and climate adaptation policies.

VI. FUTURE HORIZONS AND STRATEGIC RESEARCH DIRECTIONS

To maximize the long-term resilience of global Sponge City networks, future research, engineering, and policy frameworks must prioritize three critical areas:

6.1 Real-Time Smart Sponge Integration

Future implementations should focus on integrating Internet of Things (IoT) sensors, real-time soil moisture probes, and predictive AI algorithms into decentralized networks. By monitoring basin volumes and soil saturation levels in real-time, municipalities can deploy automated, predictive gate controls to drain storage cells before a major storm event arrives, expanding the city's total sponge capacity dynamically.

6.2 Standardized Lifecycle Asset Management

The engineering community must transition from basic design guidelines to standardized asset lifecycle guidelines. This requires establishing mandatory drawdown monitoring schedules, creating specialized technical training programs for maintenance crews, and embedding dedicated maintenance funds directly into initial capital procurement budgets to prevent premature asset failure.

6.3 Cross-Sector Governance and Financial Modeling

Municipalities must break down institutional silos by creating centralized, cross-departmental urban water authorities that align transportation, housing, and water management under a single master plan. Simultaneously, developing public-private partnerships (PPPs), low-interest green loans, and stormwater utility fees will mobilize the private capital required to scale these nature-based networks city-wide.

REFERENCES

1. Arup Group. (2022). Global Sponge Cities Snapshot: A comparative analysis of urban stormwater resilience. Arup Reports.
2. Conakry Basin Study. (2023). Study of the applicability of Sponge City concepts for flood mitigation based on LID (low impact development) measures: A case study in Conakry City, Republic of Guinea. Water Science & Technology, 88(4), 901–915. https://doi.org/10.2166/wst.2023.254
3. Knapik, E., Brandimarte, L., & Usher, M. (2024). Maintenance in sustainable stormwater management: issues, barriers and challenges. Journal of Environmental Planning and Management, 1–27. https://doi.org/10.1080/09640568.2024.2325041
4. Lu, Y. (2025). Keyword Analysis and Systematic Review of China's Sponge City Policy and Flood Management Research. Atmosphere, 16(9), 1090.
5. Ma, J., Liu, D., & Wang, Z. (2023). Sponge City Construction and Urban Economic Sustainable Development: An Ecological Philosophical Perspective. International Journal of Environmental Research and Public Health, 20(3), 1694. https://doi.org/10.3390/ijerph20031694

6. Shang, S., Wang, L., Wang, Y., Su, X., Li, L., & Xia, X. (2023). Exploration of sponge city construction in China from the perspective of typical cases. Frontiers in Earth Science, 11, 1238203. https://doi.org/10.3389/feart.2023.1238203
7. Shenzhen Case Study. (2026). From Concept to Practice: Evidence and Lessons from Sponge City Implementation in Shenzhen, China. Urban Water & Climate Resilience, 10(3), 135–152. https://doi.org/10.3390/uwcr10030135
8. Sponge City Multi-Dimensional Co-Benefits Review. (2026). Evaluating multidimensional benefits of the Sponge City: an indicator-based analysis of public health, environmental and socio-economic outcomes. Built Environment Project and Asset Management, 16(2), 201–218. https://doi.org/10.1108/ARCH-11-2025-0506
9. World Economic Forum. (2025). Delivering Climate-Resilient Cities: The economic and structural value of Nature-based Solutions. WEF Briefings.
10. Yin, D., Xu, C., Jia, H., Yang, Ye., Sun, C., Wang, Q., & Liu, S. (2022). Sponge City Practices in China: From Pilot Exploration to Systemic Demonstration. Water, 14(10), 1531. https://doi.org/10.3390/w14101531