Urban Landscape and Surface Runoff Management: A Review

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ABSTRACT

Urban surface runoff has become an increasing concern in rapidly expanding cities, particularly in regions with high rainfall intensity. The present study examines the influence of urban landscape composition and configuration, which includes vegetation type, density, and spatial distribution, on runoff generation and regulation. By synthesizing knowledge from hydrology, urban ecology, environmental engineering, and social sciences, it aims to provide a multidisciplinary perspective on the effectiveness of vegetation-based interventions in mitigating urban runoff. Natural vegetation, especially deep-rooted grasses and tree species, has been observed to enhance soil infiltration, stabilize slopes, and intercept rainfall through canopy processes. These mechanisms collectively contribute to reducing flood risks and improving urban resilience. Comparative evidence from various climatic regions indicates that integrating green infrastructure, such as green roofs, permeable pavements, and vegetated buffers, within urban design frameworks can substantially decrease runoff volumes and enhance water quality. Furthermore, the economic feasibility, scalability, and current research limitations associated with such interventions are addressed. Emphasis is placed on developing cost-effective, inclusive, and adaptive approaches suitable for diverse urban contexts. Overall, the findings underscore the critical role of strategic landscape planning and vegetation management in achieving sustainable, flood-resilient, and climate-adaptive urban environments.

Keywords-urban landscape; surface runoff; rainfall intensity; vegetation management; environmental sustainability

I. INTRODUCTION

Changes in urban landscapes and the intensification of rainfall influence surface runoff within such environments. Urbanization and population growth have transformed permeable land surfaces into impervious materials, such as asphalt and concrete, reducing soil infiltration capacity and increasing the risk of flooding and erosion [1-3]. Impervious surfaces restrict water absorption and accelerate runoff generation, with runoff volumes in densely built-up areas reported to be up to six times higher than those in natural landscapes [4, 5]. These trends underscore the importance of understanding how land surface alterations affect hydrological processes and exacerbate urban vulnerability to extreme rainfall events.

Large metropolitan areas, such as Jakarta and New York, are typical examples of this phenomenon, where rapid urban expansion combined with high rainfall intensity has exceeded the capacity of existing drainage systems [6]. In Jakarta, the proportion of built-up area increased from 42% in 1985 to 68% in 2015, coinciding with a notable rise in flood frequency. The interaction between urban expansion, climate-induced rainfall extremes, and inadequate drainage infrastructure generates compounding effects on runoff generation, waterlogging, and water quality degradation [7-10]. Excessive runoff often transports pollutants from industrial and residential zones into receiving water bodies, resulting in ecosystem degradation and intensified environmental stress [7, 8]. Consequently, the interactions among urban morphology, climatic variability, and drainage capacity are a central concern in sustainable urban water management.

Extreme hydrometeorological events, like Hurricane Harvey in 2017, further demonstrate the vulnerability of urban systems to intense rainfall combined with extensive impervious surface coverage [11]. Such events indicate that urban flood risk is not only governed by rainfall intensity but also by the spatial configuration of land cover and the extent of vegetation presence. Vegetation performs an essential hydrological function by intercepting rainfall, enhancing infiltration, and reducing runoff velocity. Nevertheless, the integration of vegetation structure, land-cover configuration, and rainfall variability remains insufficiently addressed in contemporary urban hydrology research [12]. Therefore, an improved understanding of how green and built-up areas interact to regulate surface runoff dynamics has become a research priority in the context of climate adaptation and urban resilience [1, 4].

To achieve a systematic and transparent synthesis, the present study adopts a semi-systematic review methodology encompassing publications from 2000 to 2024 retrieved from Scopus, Web of Science, and ScienceDirect databases. It specifically focuses on peer-reviewed studies that examine the relationships among urban landscape patterns, vegetation cover, and runoff dynamics. Studies limited to rural contexts or purely engineering-based drainage modeling were excluded, while research integrating hydrological and spatial analyses was prioritized. The inclusion and screening process adhered to the PRISMA protocol to ensure methodological rigor, consistency, and reproducibility. This approach enables an understanding of how urban landscape structure contributes to runoff regulation under high rainfall conditions.

Moreover, the review emphasizes that effective runoff mitigation requires integrating green infrastructure, such as green roofs, bioswales, and permeable pavements, into landscape-oriented urban planning [13-20]. Strategic vegetation management, enhanced green-space connectivity, and optimized impervious surface distribution reduce runoff, promote infiltration, and improve overall urban ecological health. By linking landscape composition, spatial configuration, and vegetation characteristics to hydrological performance, this study establishes a conceptual framework that bridges existing research gaps and supports sustainable urban water management. Ultimately, it aims to contribute to the development of climate-resilient urban environments that harmonize development objectives with long-term environmental sustainability [12, 13, 16–20]. The findings also highlight the necessity of interdisciplinary collaboration among urban planners, hydrologists, and ecologists in designing adaptive and resilient landscape strategies. Strengthening such cross-sectoral connections enables cities to better predict hydrological risks and implement proactive measures that enhance environmental resilience.

II. LANDSCAPE CONFIGURATION AND COMPOSITION

Landscape composition and configuration are fundamental determinants of surface runoff regulation in urban environments, with their hydrological influence varying across multiple spatial scales, ranging from individual plots to neighborhood, city, and watershed contexts. Numerous studies have quantitatively evaluated the role of natural vegetation, particularly grass, in mitigating surface runoff compared with synthetic alternatives such as artificial turf. Empirical evidence consistently indicates that natural grass substantially enhances infiltration and reduces runoff rates at both the plot and neighborhood scales. In [14], it was reported that natural grass surfaces can reduce surface runoff volumes by approximately 45-65% relative to bare or impervious surfaces, primarily due to increased soil infiltration capacity.

Infiltration experiments conducted in [15] revealed that natural grass plots achieved infiltration rates of 25-40 mm/h, whereas artificial turf surfaces exhibited only 3-7 mm/h, producing runoff rates nearly five times higher on synthetic surfaces. These findings suggest that integrating natural grass and vegetated areas can collectively reduce peak discharge, enhance infiltration across urban catchments, and improve overall hydrological performance when scaled to the city or watershed scale. Additional studies have demonstrated that natural grass can lower total suspended solids and nutrient loads in runoff by 30-50%, providing dual benefits for hydrological regulation and water quality improvement [14, 15]. Summarizing the types of grasses, their hydrological performance, and corresponding site conditions (Table I), underscores the necessity of multi-scale consideration in developing effective urban runoff management strategies, from plot-level interventions to landscape-scale integration.

TABLE I. TYPE OF GRASS AND CONDITION

Type of grass / vegetation	Location	Condition / key findings	References
Natural grass	The Combaima River, Colombian Andes	Reduces the volume and speed of surface runoff and mitigates soil erosion	[14]
Natural versus synthetic grass	Agricultural Experimental Station of Northwest A & F University, Shaanxi, China	Natural grass improves water quality through filtration of pollutants; synthetic grass is less effective	[15]
Synthetic grass	Texas A&M University, United States	Synthetic grass generates higher runoff and lacks effective infiltration; ineffective in reducing soil erosion and runoff carrying pollutants	[21-23]
Natural vegetation (buffer strips)	Various catchments, China	High vegetation density reduces surface runoff by up to 30%; dense vegetation increases water infiltration, reducing volume and speed of flow	[16, 20]
Spacious and connected green spaces	Suzhou City, China	Large, unfragmented green spaces reduce runoff by up to 40%; green space connectivity through ecological corridors improves runoff control; fragmentation increases erosion	[17, 18]
Connected green spaces (ecological corridors)	Texas, USA, Europe	Connectivity improves runoff control; fragmentation reduces soil's capacity to absorb water, increasing risk of erosion and runoff	[18, 19]

Although synthetic grass provides a practical alternative for creating green spaces, it remains less effective in controlling surface runoff, since it lacks the ability to filter and does not have root systems capable of stabilizing the soil or promoting water absorption. Authors in [21] found that areas covered with synthetic grass generated 60-80% higher runoff volumes than natural grass plots under similar rainfall intensities, primarily due to compacted subsoil layers that limit infiltration. Similarly, in [22], it was reported that synthetic grass surfaces increased sediment yield by up to 45% and failed to retain pollutants effectively, facilitating the transport of suspended solids and nutrients into nearby water bodies. Despite its aesthetic and low-maintenance advantages, synthetic grass performs poorly in hydrological regulation, making natural vegetation a more sustainable choice for reducing runoff, soil erosion, and pollutant transport.

Vegetation density also plays a crucial role in regulating surface runoff. It has been indicated that even moderate vegetation cover substantially improves infiltration and decreases runoff. Areas with vegetation cover exceeding 25-30% generally exhibit superior hydrological performance compared to sparsely vegetated surfaces. Authors in [16] demonstrated that increasing vegetation density from 10% to 40% reduced runoff by 28-35%, primarily through enhanced canopy interception and improved soil permeability. In [20], it was further observed that densely vegetated plots exhibited infiltration rates of 20-35 mm/h, compared to less than 10 mm/h in low-density areas. These results highlight that maintaining high vegetation density is an effective strategy for enhancing hydrological regulation and mitigating flood risks in urban areas.

Beyond vegetation density, the spatial size and the configuration of green spaces are equally important in controlling surface runoff. Large, contiguous green areas are capable of absorbing greater volumes of water and providing longer infiltration durations than fragmented areas. In [17], it was found that unfragmented green spaces exceeding 1 ha could reduce surface runoff by 35-40%, whereas fragmented areas, smaller than 0.3 ha, achieved only 15-20% reduction. Authors in [18] emphasized that spatial connectivity, which is achieved through ecological corridors or linkages with vegetation, further enhances water distribution efficiency, reducing localized flooding by approximately 25% compared with disconnected green zones. Similar patterns have been documented in European and North American cities, where landscape fragmentation was associated with 20-30% reductions in infiltration capacity and increased uncontrolled runoff [19].

Maintaining large, connected, and densely vegetated green spaces is essential for sustainable surface runoff management. Urban landscape planning that incorporates natural vegetation, spatial continuity, and ecological connectivity enhances infiltration, reduces erosion, and improves stormwater quality. The reviewed evidence demonstrates that when natural vegetation is sufficiently dense and spatially integrated, it provides measurable hydrological benefits that synthetic alternatives cannot replicate. Therefore, urban and regional planning should prioritize the preservation and expansion of natural green spaces as a central strategy for effective runoff mitigation and climate-resilient urban design.

III. RAINFALL INTENSITY AND RUNOFF

Rainfall intensity, vegetation interception, and local environmental characteristics determine the magnitude of surface runoff in both urban and natural landscapes. High-intensity rainfall events exceeding 50 mm/h have been shown to increase runoff coefficients by more than 60%, whereas vegetation interception can reduce these values by approximately 20-40%, depending on canopy density and species composition (Table II). Also, comparative analyses indicate substantial variability among watersheds. For example, the Citarum Hulu–Majalaya watershed exhibits a runoff conversion rate of approximately 65%, which is almost double the 34% of the Arui watershed in Manokwari, a difference attributed to steeper slopes, higher rainfall intensity, and compacted soils [24-27]. These findings emphasize the necessity of incorporating site-specific hydrological and geomorphological characteristics into runoff management strategies, as variations in climate type between tropical and temperate, and the land-cover conditions exert significant influence on runoff behavior.

TABLE II. RAINFALL INTENSITY AND CONVERSION RATE INTO SURFACE RUNOFF.

Location	Rainfall intensity (mm/h)	Conversion rate into surface runoff (%)	Research
Upstream Gajahwong sub-watershed, Sleman	10 – 100	15 – 55	[24]
Upstream Citarum watershed-Majalaya	10 – 150	20 – 65	[25]
Arui watershed, Manokwari	30 – 240	25 – 80	[26, 27]
Laboratory and field studies, Loess Hilly Area, China	10 – 100	20 – 70	[23, 28]
Loess Plateau, China	20 – 150	40 – 80	[29]
East Africa	50 – 200	35 – 75	[30]
Slopes containing rock fragments	30 – 180	50 – 90	[31]

Methodological approaches also contribute to the observed variability in reported runoff rates. Controlled rainfall simulations, such as those conducted in [28], have demonstrated runoff rates of 40-55% under artificial rainfall intensities of 60 mm/h, while field-based observations typically report broader ranges, 45-80%, due to variations in micro topography and soil heterogeneity. These results highlight the importance of integrating laboratory precision with field-based observations to more accurately characterize the complex relationship between rainfall intensity and surface runoff. As rainfall intensity increases, soil infiltration capacity is rapidly exceeded, resulting in a nonlinear or exponential increase in runoff coefficients [32-34].

Soil type and vegetation cover further modulate runoff through their effect on infiltration and water-retention capacities. Low-permeability clay soils exhibit runoff coefficients exceeding 70%, while sandy loam soils generally remain below 35%, illustrating the inverse relationship between infiltration capacity and runoff volume [23, 24, 26-31]. Vegetation cover enhances infiltration and reduces runoff by approximately 25-50% relative to bare soils, with tree canopies playing a particularly significant role through rainfall interception and delayed surface flow. In [35], it was reported that birch trees intercepted up to 45% of rainfall and pine trees up to 23%, effectively reducing the amount of water reaching the ground, while in [36], it was demonstrated that canopy interception can lower stormwater peaks by 15-30%. These findings quantitatively affirm the hydrological significance of vegetation, particularly tree-dominated canopies, in mitigating surface runoff, stabilizing hydrological cycles, and enhancing resilience against urban flooding.

High rainfall intensity has a direct and measurable effect on surface runoff generation, frequently exceeding the infiltration capacity of both natural and urban soils. In [11], it was observed that a rainfall depth of 12.5 mm over 12 h produced runoff coefficients exceeding 0.65 in densely built-up areas, resulting in drainage overflow and localized flooding. Similarly, in [23], it was reported that rainfall intensities above 50 mm/h on slopes steeper than 15° increased soil erosion rates by nearly 70%, primarily due to elevated runoff velocity and sediment transport. Urbanization further enhances these effects, as demonstrated in [21], where it was found that impermeable materials, such as asphalt and concrete, reduce infiltration by 80-90%, leading to a fivefold increase in surface runoff relative to vegetated areas. The results demonstrate a nonlinear escalation in runoff generation as both rainfall intensity and impervious surface coverage increase, underscoring the hydrological vulnerability of urban environments.

Vegetation, particularly tree canopies, provides an effective natural buffer by intercepting rainfall and delaying surface flow, thereby reducing peak runoff and enhancing flood resilience [35, 36].

IV. URBANIZATION AND RUNOFF

Urbanization is associated with the transformation of natural or agricultural landscapes into built environments dominated by infrastructure, buildings, and impervious surfaces such as asphalt and concrete. This transformation fundamentally alters hydrological processes by decreasing soil infiltration capacity and modifying the temporal dynamics of surface runoff. As permeable areas are progressively replaced by impervious materials, rainfall infiltration is impeded, resulting in higher surface runoff volumes that fluctuate with seasonal rainfall intensity and storm frequency [1, 2].

Empirical research has consistently demonstrated a strong positive relationship between urban expansion and increased runoff generation, particularly during wet seasons and extreme precipitation events. In [9], it was reported that a 50% increase in urbanized area may lead to a 13-27% rise in surface runoff, depending on rainfall variability and regional climatic patterns. Similarly, in [2], it was observed that land conversion from natural to urban use reduced soil water absorption capacity by approximately 60-70%, thereby amplifying surface water accumulation and elevating flood risks during high-intensity storms. Even moderate urban expansion can produce substantial hydrological impacts. Authors in [37] found that a 10% increase in impervious surface coverage resulted in a 20% increase in runoff volume, particularly during peak rainfall periods.

The cumulative impact of urbanization on runoff dynamics is affected by multiple interacting factors, including imperviousness, topographic slope, drainage infrastructure, and long-term climatic variability. Shifts in rainfall patterns and the growing frequency of extreme weather events further intensify these effects, challenging conventional urban drainage systems [4, 5]. To address these trends, adaptive and temporally responsive approaches, such as the incorporation of green infrastructure, permeable pavements, and urban vegetation, are essential measures for enhancing infiltration and reducing surface runoff under changing climatic conditions [8, 13].

In summary, urbanization leads to greater surface runoff primarily through the replacement of permeable soils with impervious materials. Yet, runoff behavior is not solely a function of land cover, but it is also shaped by temporal factors such as seasonal variability, storm intensity, and long-term climatic change. Effective runoff management, therefore, requires integrated strategies that consider both spatial and temporal dimensions to ensure sustainable and climate-resilient urban water systems [1, 2, 37].

V. MITIGATION STRATEGY

Effective management of surface runoff in urban environments requires an integrated framework that combines ecological design, spatial planning, and supportive governance mechanisms. Beyond controlling vegetation density, implementing tree planting programs, and regulating impervious surfaces, the success of runoff mitigation largely depends on institutional capacity and the coherence of land-use policies that promote sustainable urban development. Maintaining or increasing vegetation cover within the 0-25% range has been identified as both a cost-effective and policy-relevant measure for reducing surface runoff and mitigating flood risk [16, 20]. However, the implementation of such measures is often constrained by limited urban land availability, weak enforcement of green space regulations, and competing development priorities.

Municipal policy instruments, including stormwater credit systems, green roof incentives, and zoning regulations mandating minimum green coverage, have been shown to effectively address these constraints. For instance, Singapore and Portland demonstrated that integrated landscape planning, supported by coordinated urban policy frameworks, can reduce surface runoff by up to 30% through the combined application of vegetation management and permeable surface zoning [18, 19].

Tree planting initiatives embedded within urban environmental strategies further contribute to long-term hydrological resilience. Tree canopies intercept significant portions of rainfall, reaching up to 45% for birch species and approximately 23% for pine species, while their root systems enhance soil permeability and prevent compaction [35, 36]. Cities, such as Melbourne and Seoul, have incorporated urban forestry into flood mitigation plans by offering tax incentives and community-based grants for tree planting in flood-prone areas. Similarly, optimizing the spatial distribution of impervious surfaces through regulations that limit plot coverage or require the use of pervious pavements has been demonstrated to lower peak runoff and improve urban microclimates [10].

Authors in [19] emphasized that effective runoff reduction depends on policy coherence linking hydrological modeling, climate adaptation, and land-use planning. Despite persistent challenges including fragmented governance structures, limited public participation, and weak integration of scientific data, successful international practices indicate that cross-sectoral collaboration and incentive-based governance can bridge the gap between scientific understanding and practical implementation [10, 16, 18-20, 35].

VI. DISCUSSION

Managing surface runoff in urban environments extends beyond environmental and engineering considerations. It represents a fundamental component of sustainable urban development and climate adaptation that necessitates interdisciplinary integration across hydrology, urban ecology, environmental engineering, and the social sciences. Within the context of the United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 15 (Life on Land), effective runoff management directly contributes to urban resilience, ecological balance, and community well-being. Case studies from Singapore and Copenhagen illustrate that green infrastructure elements, such as bioswales, rain gardens, and green roofs, can significantly improve surface runoff while enhancing biodiversity and urban livability. Similarly, Melbourne's Water Sensitive Urban Design (WSUD) framework demonstrates how integrating hydrology and urban planning can create multifunctional landscapes that improve infiltration and mitigate flood risks. Natural grass and vegetation strengthen infiltration and slope stability, whereas synthetic grass, lacking comparable hydrological and ecological functions, increases surface temperature and erosion susceptibility. These global experiences underscore the importance of ecosystem-based and evidence-driven approaches in achieving hydrological stability, climate adaptability, and biodiversity conservation.

Vegetation density and structural diversity play pivotal roles in linking runoff regulation with broader ecological and social sustainability goals. In Portland, vegetated green streets and urban tree canopies have been shown to reduce stormwater runoff while improving community aesthetics and environmental well-being. Hydrologically, dense vegetation enhances infiltration and water retention, while ecologically, it supports biodiversity and moderates microclimatic variation. Technological innovations, such as Japan's permeable pavements and decentralized drainage systems, complement natural processes by increasing infiltration capacity and moderating runoff peaks. Socially inclusive approaches in Curitiba (Brazil) demonstrate how participatory governance and community engagement ensure equitable access to green infrastructure. Comparative evidence across these cases suggests that successful runoff management depends on institutional commitment, citizen involvement, and sustained maintenance, highlighting the need for environmental effectiveness to align with social inclusivity and governance coherence.

Urbanization and the expansion of impervious surfaces intensify hydrological vulnerabilities, reinforcing the need for globally informed and system-oriented runoff management strategies. Nature-based solutions implemented in Rotterdam and Singapore, including green corridors and water plazas, demonstrate how hybrid infrastructure can simultaneously store excess rainfall and restore ecological functions. Likewise, xeriscaping practices in arid regions, such as Phoenix, promote water conservation and reduce runoff, while vertical gardens in Kuala Lumpur help manage high-intensity tropical rainfall. Technological innovations, such as IoT-based hydrological sensors and AI-assisted flood monitoring systems in Seoul, exemplify how digital tools can enhance adaptive capacity and long-term resilience. Lessons from programs including Singapore's ABC Waters initiative, Rotterdam's Climate Adaptation Strategy, and Nairobi's green corridor projects highlight the benefits of cross-city collaboration and knowledge exchange in developing context-sensitive solutions. Future research should expand interdisciplinary and cross-regional collaborations that integrate hydrology, ecology, engineering, and social sciences to strengthen the global framework for sustainable runoff management and to advance climate-resilient urban development.

Integrating economic and policy dimensions further enhances the sustainability and scalability of urban runoff management strategies. Cost–benefit analyses from cities such as Portland, Singapore, and Copenhagen indicate that investments in green infrastructure, such as bioswales, green roofs, and permeable pavements, provide significant long-term returns through reduced flood damage, lower maintenance expenses, and improved urban livability. For instance, each dollar invested in green infrastructure can yield two to four dollars in avoided flood and health-related costs over its lifecycle. Policy mechanisms, including green credits, tax incentives, and stormwater fee reductions, have proven effective in encouraging private-sector participation and community engagement, thereby aligning ecological objectives with financial and institutional support. Furthermore, integrating ecosystem service valuation into urban planning enables decision-makers to prioritize interventions that deliver the greatest environmental and social benefits relative to their cost. Consequently, the combination of hydrological science, ecological restoration, social inclusion, and economic rationality forms a comprehensive and adaptive framework for managing surface runoff in cities facing the dual challenges of climate change and rapid urbanization.

VII. CONCLUSION

Effective management of surface runoff in urban environments requires an integrated framework that connects vegetation management, spatial planning, and the regulation of impervious surfaces within the broader context of sustainable urban design. Strengthening natural vegetation cover and integrating green spaces with permeable surfaces should remain key priorities to enhance infiltration, reduce flood risks, and support ecological stability. Urban planners and designers are encouraged to adopt nature-based and hybrid infrastructure solutions that optimize hydrological performance while providing social, aesthetic, and economic benefits.

To ensure effective implementation, local governments should establish coherent policy frameworks and long-term maintenance strategies that sustain the functionality of green infrastructure and promote active community participation. For the research community, future studies are encouraged to develop predictive models that integrate hydrological, climatic, and socioeconomic parameters to evaluate the performance of green infrastructure across diverse urban contexts. Additionally, greater attention should be directed toward developing scalable and low-cost solutions, suitable for cities with varying densities, particularly in low-income regions where infrastructure resources are limited.

By combining practical implementation strategies with advanced modeling and cross-disciplinary collaboration, future initiatives can support the creation of urban environments that are not only flood-resilient but also socially equitable, economically viable, and ecologically sustainable.

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