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Sustainable stormwater management for urban waterlogging mitigation: Design and performance evaluation modelling of an integrated stormwater recharge system

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Abstract: Urban waterlogging remains a persistent challenge in rapidly urbanizing cities worldwide, particularly in regions with inadequate drainage infrastructure and declining groundwater levels. This study presents the design and analytical performance evaluation of a compact, decentralized stormwater management system that integrates a bioswale-inspired surface channel, recharge trenches, and vertical borewells to mitigate localized urban flooding while promoting subsurface water retention. The system is designed for high-density built environments and aims to provide a cost-effective, modular, and space-efficient intervention for data-scarce or infrastructure-constrained urban settings. Informed by local topography, catchment hydrodynamics, drainage limitations and implementation constraints, the proposed approach introduces a context-responsive framework for decentralized stormwater management. A case application in a flood-prone, densely built neighborhood in Dhaka, Bangladesh demonstrates design feasibility of the proposed system. System performance is evaluated through analytical computation and modeling to assess its design-level efficiency in managing runoff during peak rainfall scenarios. Under base-case assumptions, the proposed system reduces the estimated waterlogging severity indicator from 176% to approximately 9.7%, suggesting substantial design-level potential for reducing post-rainfall drainage delay while supporting localized groundwater recharge. By integrating surface conveyance with structured subsurface recharge pathways, the study contributes a compact retrofit-oriented stormwater management model that simultaneously mitigates pluvial flood risk and supports long-term groundwater resilience in space-constrained urban environments.

Key words: Urban stormwater management; waterlogging mitigation; urban flood resilience; recharge trench–borewell system; Low Impact Development (LID).

1. INTRODUCTION

The increasing frequency and intensity of extreme rainfall events, exacerbated by climate change, are straining urban drainage systems, resulting in chronic waterlogging and flash flooding around cities worldwide (UN-Habitat, 2020; IPCC, 2022). Urban areas with high impervious surface coverage and inadequate drainage face growing risks of stormwater accumulation, damaging infrastructure, disrupting livelihoods, and threatening public health (Manandhar et al., 2023; Alam & Rabbani 2007). Cities in both developed and developing countries including New York, Jakarta, London, and Nairobi, have reported substantial disruption from pluvial flooding in recent years (Fletcher et al., 2015; Zhou, 2014; Rosenzweig et al., 2011). While the manifestations of urban flooding are often localized, their underlying causes such as reduced infiltration, increased runoff, aging infrastructure, and fragmented governance, are globally pervasive (Alshammari et al., 2023; UNESCO & UN-Water 2020).

Historically, urban stormwater systems were designed to remove excess water quickly using centralized, pipe-based infrastructure. However, these systems are increasingly ill-equipped to handle today's rainfall volumes and intensities, particularly amid changing precipitation patterns (Sharma et al., 2012; Rosenzweig et al., 2018). Moreover, traditional systems often neglected key opportunities for on-site water retention, filtration, and recharge, focusing solely on rapid removal. This reactive approach limits both flood mitigation and long-term water sustainability (Jayasooriya

& Ng 2014; Ahiablame et al., 2012). In response, urban water governance has increasingly embraced sustainable, nature-based solutions (NbS) that align with hydrological processes while providing co-benefits such as groundwater recharge, water quality improvement, urban cooling, and ecological enhancement (Kabisch et al., 2015; Fletcher et al., 2015; WWAP, 2018). Approaches like Low Impact Development (LID) in North America, Sustainable Urban Drainage Systems (SUDS) in the UK, and Water Sensitive Urban Design (WSUD) in Australia emphasize source-level stormwater management through infiltration, evapotranspiration, and localized retention (Woods Ballard et al., 2015; Fletcher et al., 2015). Techniques such as bioswales, rain gardens, permeable pavements, and green roofs have proven effective in diverse urban contexts, including Portland, Melbourne, Singapore, and Copenhagen (Li et al., 2017; Kazmierczak & Carter, 2010). For instance, Singapore's ABC Waters Program integrates bioretention and wetlands into its drainage network (Liao, 2019), while Copenhagen's climate plan employs cloudburst boulevards and permeable corridors to enhance flood resilience (City of Copenhagen, 2012). These models reflect a growing consensus around decentralized infrastructure that provides both technical and ecological benefits. However, implementing NbS in dense urban areas faces practical challenges. Large-scale green infrastructures like wetlands or retention ponds are often unfeasible due to issues such as space constraints, land costs, and competing usage (Brown & Farrelly 2009). This has spurred growing interest in compact, modular solutions suitable for retrofitting in dense urban contexts. Among them, hybrid systems combining bioswales with subsurface recharge trenches have shown practical relevance for runoff detention, filtration, and localized recharge. (Bai et al., 2019). These systems function sequentially capturing, filtering, detaining, and recharging stormwater through deep soil or aquifers, depending on site-specific drainage and subsurface conditions. (Hao et al., 2019; Su et al., 2023).

Existing studies have shown that Low Impact Development (LID), Sustainable Urban Drainage Systems (SUDS), and Water Sensitive Urban Design (WSUD) approaches can reduce runoff volume, attenuate peak flow, and delay runoff response in urban catchments. However, their performance varies depending on rainfall duration, catchment characteristics, storage capacity, infiltration conditions, and maintenance conditions. Recent studies using monitored data and SWMM-based modeling have shown that LID performance can decline during prolonged rainfall when storage layers become saturated or infiltration capacity becomes limiting. Similarly, model-based LID planning studies emphasize that runoff reduction depends not only on the selected technology, but also on location, drainage connectivity, and feasibility of implementation in the built environment (Fletcher et al., 2015; Jayasooriya & Ng, 2014; Baltaci & Kalin, 2024; Chiu et al., 2025).

Most research on LID and hybrid infrastructure focuses on large or flexible environments, overlooking the spatial, institutional, and hydrological constraints of dense urban areas (Brown and Farrelly, 2009; Jayasooriya & Ng, 2014). Many stormwater management models also treat bioswales, trenches, and recharge components as standalone elements, lacking an integrated systems perspective suited for narrow medians or compact neighborhoods (Zhou, 2014; Huo et al., 2019). However, limited attention has been given to how established stormwater components can be spatially integrated into a compact, corridor-based recharge system that simultaneously addresses runoff conveyance, temporary storage, filtration, and vertical groundwater recharge in land-constrained urban settings.This study addresses that gap by proposing a context-responsive, modular LID system that sequentially integrates bioswales, filtering trenches, and borewells to enhance flood mitigation and groundwater recharge. Bioswales, recharge trenches, and vertical borewells are already established stormwater management and recharge practices. Therefore, the contribution of this study lies not in presenting these elements as entirely new technologies, but in integrating them into a compact, median-based system suited to a drainage-constrained urban corridor.

The primary objectives of this research are twofold: first, to conceptualize a decentralized, compact stormwater system that integrates hydrological, infrastructural, and ecological considerations; and second, to analytically evaluate its design-level potential for reducing runoff, enhancing temporary detention, and enabling localized groundwater recharge. The design offers a compact, multi-stage system tailored to the spatial constraints of high-density neighborhoods. As part of the analytical evaluation, this study introduces a simple waterlogging severity indicator to compare pre and post-intervention drainage delay relative to rainfall duration. By aligning LID principles with local constraints and integrating surface and subsurface water management, this study contributes a compact retrofit-oriented framework for decentralized stormwater management in physically and institutionally constrained urban settings. Although this investigation is grounded in the urban morphology of Dhaka, Bangladesh similar patterns of secondary-drainage overload, shallow groundwater stress, and land-use densification are increasingly evident across rapidly urbanizing Asian cities, making the proposed framework regionally transferable. The work is also relevant to urban resilience and integrated water management goals reflected in the UN's New Urban Agenda and Sustainable Development Goals 6.3 and 11.5 (UN-Habitat, 2017; UNDRR, 2017).

2. METHODOLOGY

This study adopts a multi-phase methodological framework to design and evaluate an integrated stormwater mitigation strategy for high-density urban areas, grounded in hydrological modeling, infrastructural diagnostics, and sustainable urban design. The methodology comprises four sequential stages: (1) Study Site Selection; (2) Hydrological Characterization and Existing Drainage Capacity Assessment; (3) Design of the Stormwater Recharge Intervention; (4) Modeling or Evaluation of the Proposed System's Performance.

2.1 Selection of study site

The proposed stormwater intervention was designed and evaluated for Road No. 16 in Dhanmondi, a densely populated residential area in southern Dhaka, Bangladesh. Dhaka, the capital city of Bangladesh, is characterized by rapid and unplanned urban expansion over the last few decades, which has significantly increased the city's impervious surfaces and diminished its natural drainage capacity (Alam & Rabbani, 2007; Dewan et al., 2012). Consequently, the city experiences extensive waterlogging during monsoon (Dasgupta et al., 2015), notably between May and October, when approximately 80 % of the annual ~1850 mm rainfall occurs (Taufiq, 2021). Geographically, the selected drainage corridor along Road No. 16 in Dhanmondi lies near 23.7465° N, 90.3740° E. The contributing sub-catchment delineated for runoff assessment covers approximately 110,000 m², equivalent to 11 ha. Characterized by high-density residential buildings, paved surfaces, and central median, the segment exhibits minimal permeability, exacerbating runoff and local flooding risks. Field observations and local accounts confirm that the area experiences frequent waterlogging during the monsoon months, which disrupts traffic and everyday activities arising from prolonged stagnation of rainwater (Khan & Akhand 2021). With its limited space, high runoff potential, and recurring drainage failures, Road No. 16 appears as a suitable site to evaluate a compact, modular decentralized stormwater management intervention with strong potential for replication in other rapidly urbanizing contexts.

2.2 Hydrological characterization and drainage capacity assessment

A critical first step in designing supplemental stormwater mitigation infrastructure is the comprehensive evaluation of the local hydrological regime and the capacity of existing drainage systems. This stage aims to characterize the local hydrological regime through quantifying the surface runoff generated under extreme rainfall events and then assess the capacity of the current drainage infrastructure to convey this runoff. This evaluation is performed in four sequential steps:

2.2.1 Sub-catchment delineation and land use classification

The sub-catchment contributing to surface runoff along the study site was delineated using a combination of high-resolution satellite imagery from Google Earth and Digital Elevation Model (DEM) analysis. The delineation process was complemented with field surveys and consultation with local water authority experts (from Dhaka Water Supply and Sewerage Authority (DWASA) to enhance spatial accuracy, accounting for the complex flow patterns characteristic of flat urban terrains. The delineated contributing catchment, approximately 110,000 m² in area, was digitized using GIS tools and verified through field observations and consultation with local drainage authority experts. Land cover of the area was categorized into four primary classes: built-up areas (e.g., rooftops, pavement), roadways, green/open spaces, and surface waterbodies (Figure 1). These classifications informed subsequent hydrological computations.

Figure 1. Land use classification map of the study area delineating key urban features including stormwater drains, buildings, roads, impervious cover, and a central waterbody

2.2.2 Peak runoff estimation using the rational method

The next step involves quantifying the volume and intensity of surface runoff generated during peak rainfall events. To estimate this, the Rational Method was employed. The Rational Method offers a widely accepted empirical approach for estimating peak runoff in small urban catchments, particularly those characterized by impervious surfaces and rapid hydrological response times. The formula for the method is illustrated in eq. (1) (Bengtson, 2010)

$$Q_p = CIA/360 \quad (1)$$

where, Q_p is the peak runoff rate (m³/s); C is Runoff Coefficient; I is the rainfall intensity (mm/hr); A is the Catchment area (in hectares). A composite runoff coefficient was derived to reflect the varied land uses using eq. (2):

$$Q_p = I\,(A_1C_1+A_2C_2+A_3C_3+ \ldots + A_nC_n)/360 \quad (2)$$

The runoff coefficient is a dimensionless coefficient relating the amount of surface runoff to the amount of received rainfall by a particular type of land cover or material. Runoff coefficients were determined based on established hydrological references and refined through on-site observations of surface materials and slopes. Final values were validated in consultation with domain experts (Table 1). Design rainfall intensity was determined from 10 years (2014–2024) of hourly rainfall records for Dhaka city, with the maximum observed hourly value selected to represent a locally severe short-duration rainfall scenario. This value is not presented as a formal return-period design storm, but as a conservative local rainfall input suitable for preliminary design-level assessment. Because the selected rainfall intensity directly affects runoff estimation, its influence was also considered in the sensitivity analysis by examining the effect of increased runoff inflow on the waterlogging severity indicator.

Table 1. Runoff coefficient for different land use categories in the study site

Land use category	Type of material	Runoff coefficient (C)
Buildings / Structures	Concrete	0.7
Roadway / Streets	Asphalt	0.8
Impervious urban coverage (in and around buildings and roads, including pavements and walkways)	Predominantly concrete	0.7
Waterbody (lake)	-	-

2.2.3 Drainage infrastructure assessment and hydraulic capacity estimation

To evaluate the sub-catchment's ability to effectively discharge storm-generated runoff, the stormwater drainage network was comprehensively mapped using secondary data from DWASA, supplemented by field inspections. This process documented the structural characteristics of the drainage system, including flow direction, connectivity, material composition, and spatial alignment with adjacent land uses. The principal drainage outlet serving the sub-catchment was identified through visual flow path tracing and expert consultation. To assess whether this primary outlet could accommodate runoff during peak rainfall events, a hydraulic capacity analysis was conducted using Manning's Equation, a standard empirical formula in hydraulic engineering for estimating steady, uniform flow in open channels (Chow, 1959; Brater & King, 1976). Hydraulic capacity refers to the maximum volume of water that a drainage conduit or channel can convey without causing surface overflow. As storm sewer serves as open channels with liquid or rainwater flowing under gravity, flow velocity and discharge rate for storm water outlets can be calculated using Manning's formula (Bengtson, 2022). Manning's formula for uniform open channel flow (eq. 3):

$$Q_{d,\,th} = A_c V = A_c * (1/n)\, R_h^{2/3} S^{1/2} \tag{3}$$

Here, $Q_{d,\,th}$ represents theoretical flow rate or discharge capacity (m^3/s); A_c represents conduit cross sectional area (m^2); V represents flow velocity (m/s); n represents Manning's Roughness coefficient; R_h represents hydraulic radius; S represents channel or conduit slope (m/m). By integrating field-derived measurements, secondary data, and material characteristics observed during site visits, the value for different measures in eq. (3) was determined (Table 2). The analysis provided a quantitative understanding of the discharge potential of the principal outlet. This was essential for identifying capacity shortfalls and guiding the design of any supplemental stormwater management infrastructure.

The use of simplified analytical methods in this study is consistent with the design-level objective of the analysis. The purpose of the study is not to simulate the full dynamic behaviour of the urban drainage network, but to estimate whether a compact recharge-based intervention can reduce the runoff exceedance gap under a locally severe rainfall condition. The Rational Method was selected because it provides a practical first-order estimate of peak runoff for urban catchments with high impervious cover and rapid hydrological response. Manning's equation was used to estimate the theoretical conveyance capacity of the principal drainage outlet based on available conduit geometry, slope, and roughness information. These methods are suitable for preliminary evaluation in data-constrained urban settings where detailed drainage-network geometry, inlet-level flow data, continuous rainfall-runoff records, and calibration datasets are limited. However, they do not fully capture unsteady runoff routing, inlet surcharge, backwater effects, sediment blockage, groundwater mounding, or spatially variable infiltration processes. Therefore, the results are interpreted as analytical design estimates rather than field-validated operational performance.

Table 2. Principal drainage outlet characteristics in the study location

Parameter	Value
Conduit ID	DSW1967
Length (m)	900
Diameter(m)	0.75
Cross sectional Area (m^2)	0.44
Slope (average)	0.0015 m/m
Material	Concrete
Manning’s roughness coefficient	0.012

Note: Data collected manually from DWASA internal records (February 2025 – unpublished)

2.3 Design of the stormwater recharge intervention

Following the hydrological and infrastructural assessment, an integrated stormwater recharge system was systematically designed using a data-driven research methodology grounded in applied hydrological engineering, urban environmental planning, and expert consultation. The intervention was shaped through a contextually informed approach that translated diagnostic findings (including runoff volume estimates, drainage limitations, and infiltration potential) into a technically viable and physically implementable solution. The design process incorporated both the best international practices and localized engineering constraints that ensure adaptability to hyper-urbanized environments. Consultations with engineers, hydrologists, and local municipal authorities played a pivotal role in validating assumptions, refining design dimensions, and ensuring the system's feasibility under real-world constraints.

2.3.1 Conceptual overview

The main concept of the proposed intervention system involves rainwater harvesting through lateral recharge structures (trenches or chambers) on the road, with recharge shafts or borewells drilled down to the subsurface aquifer or permeable strata. The core design strategy centers around retrofitting the central median of Road No. 16 into a multifunctional rainwater harvesting infrastructure (Figure 2). More specifically, the proposed system replaces the existing raised divider with a bioswale-inspired depressed channel, intermittently embedded with recharge trenches connected to vertical borewell shafts. This transformation ensures passive collection, filtration, and vertical infiltration of stormwater runoff from adjacent road surfaces.

2.3.2 Design components and functional specifications

Channel configuration: The proposed stormwater harvesting channel is a linear structure replacing the existing 1m wide road divider. Its bottom is set below road crest level to promote gravitational inflow of stormwater runoff from adjacent lanes. To prevent erosion and enhance stability, both side slopes are inclined and lined with concrete. Functioning partially as a bioswale, the channel features a natural subsoil base to support vegetation that reduces erosion and improves aesthetics. Vegetation suitable to resist heat and water stress is recommended. A gravel layer over the soil base prevents scouring (see Figure 3). The channel is segmented by recharge trenches at regular intervals, with each segment having a slightly inclined base (~5°) to direct water toward the trenches. Metal wire nets placed at trench junctions prevent gravel migration while ensuring water flow. For public safety, reinforced concrete footings with metallic railings line the channel, acting as vehicle guide walls with openings that serve as runoff ports. Streetlight pedestals are integrated within channel segments to maintain utility services.

Figure 2. Schematic 3D illustration of the proposed stormwater recharge system integrated within the median of a roadway

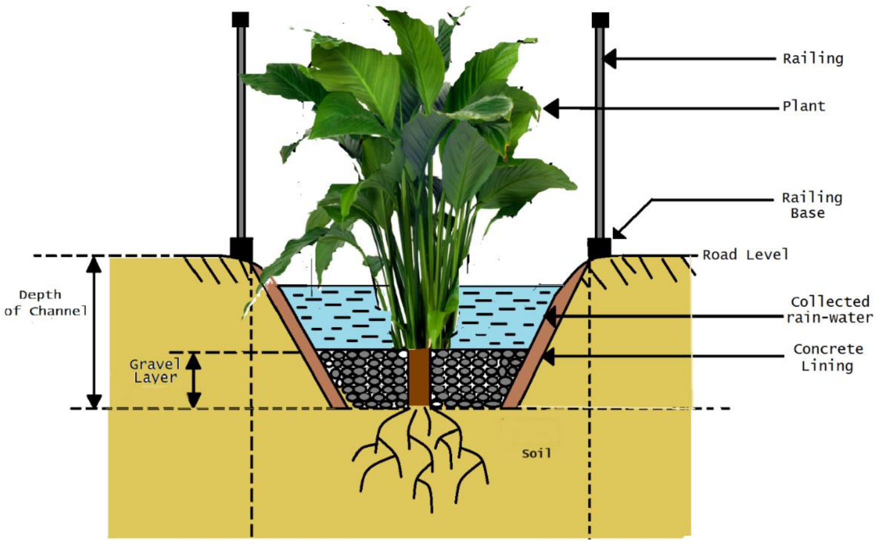

Figure 3. Schematic cross-section of the stormwater collection channel

Recharge Trenches (Filtering Chambers and Vertical Borewells): A series of strategically placed recharge trenches with integrated borewells forms a core component of the proposed stormwater recharge system. These structures are designed to collect, filter, and convey runoff into the underlying aquifer while minimizing contamination risks. Each trench is embedded beneath the central channel and functions as a multi-layered treatment and infiltration unit. Built with brick sidewalls and reinforced bases, the trenches ensure durability and ease of maintenance in high-traffic urban areas. For pedestrian safety, concrete bridges are intermittently placed over the trenches to allow uninterrupted foot traffic. Each trench comprises two main parts: the filtering chamber and the vertical recharge shafts (borewells). The filtering chamber purifies surface runoff before infiltration. It is vertically divided into two main segments - one half filled with porous media and the other half left void for temporary water storage (see Figure 4). This dual structure enables both filtration and detention. In addition to the metal wire nets at channel junctions, the chamber has a second mesh barrier to block larger debris such as leaves, plastics, and stones. Within the chamber, four stratified layers (sand, gravel, charcoal, and pebbles) are arranged from top to bottom to progressively remove fine sediments, coarse particles, dissolved pollutants, and pathogens, preparing water for infiltration. Below the filtering chamber, each recharge trench includes two borewells fitted with perforated PVC (Poly Vinyl Chloride) pipes that allow filtered stormwater to percolate into the underlying aquifer. The pipes include two sets of perforations, one near the chamber inlet and the other at the bottom. Both are wrapped in jute or synthetic coir for added filtration. Water enters through these openings and percolates into permeable subsurface layers. The top of each pipe is sealed to prevent entry of unfiltered surface water.

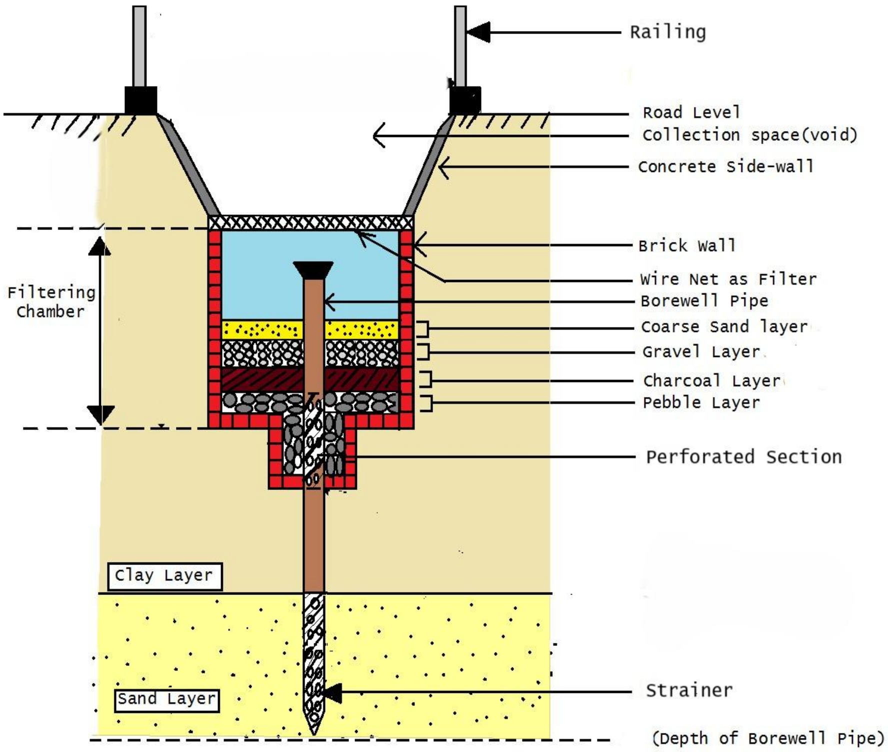

Figure 4. Cross-sectional view of a proposed recharge trench with borewell pipe, illustrating the infiltration pathway, and vertical connection to the deep aquifer for groundwater recharge

2.4 Performance evaluation of the proposed system

This section outlines a methodology to evaluate the potential effectiveness of the proposed stormwater recharge system in mitigating waterlogging at the investigation site. The assessment is structured around two key processes: (1) defining the system's physical design parameters and (2) evaluating its efficiency in managing runoff from a design rainfall event.

2.4.1 Determination of design dimensions

The dimensions of different components of the stormwater intervention system were finalized using a combination of expert advice, field observations, and contextual engineering considerations. While some parameters were derived based on infrastructural constraints (e.g., available space for the channel), others were designed to meet performance requirements for infiltration, groundwater recharge, and stormwater detention. A schematic longitudinal cross-section of the integrated system layout is presented in Figure 5. Key design specifications include:

Channel Geometry: The central channel consists of inclined segments with 60° side slopes. It measures 1 meter wide and 0.6 meters deep (with 0.1m gravel layer), sufficient to collect runoff without obstructing traffic. The full channel spans ~700 meters (m), aligned with the existing road median.

Recharge Trenches: A total of 55 recharge trenches (3 m×1 m each) are spaced along the channel, each housing two vertical borewells. This configuration complies with the Dhaka City Building (Construction, Development, Maintenance and Demolition) Rules 2011 under the Building Construction Act 1952 (Act No-II of 1953), which recommend one borewell per 1,000 m² of impervious area. Each trench includes a 1 m-deep filtering chamber serving as both pretreatment and temporary storage. Filtration media are arranged in layers: 0.1 m each of sand, gravel, and charcoal, topped by a 0.2 m pebble base.

Borewell depth was set at 25 m, based on subsurface geological considerations and the need to extend below the low-permeability clay layer toward the target permeable aquifer zone in the study location (Sultana et al., 2010). This unconfined aquifer provides high recharge potential. The depth ensures efficient delivery of filtered stormwater without incurring excess drilling costs. A 4-inch borewell pipe diameter was chosen for optimal flow and maintenance in compact urban settings, consistent with best practices in similar recharge systems.

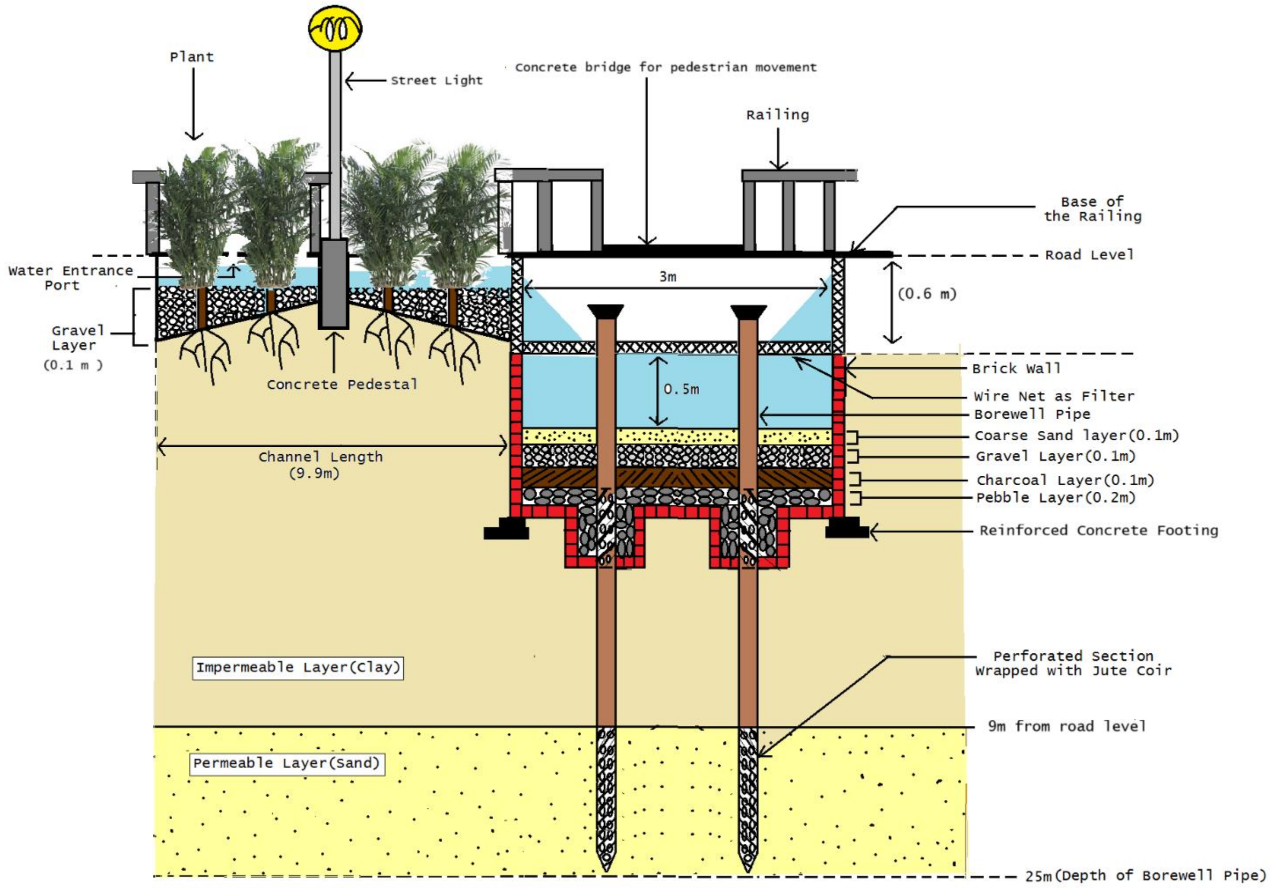

Figure 5. Schematic longitudinal cross-section of the proposed stormwater recharge system, illustrating key components such as the vegetated channel, recharge trench, filtering chamber, and borewells along with their proposed dimensions.

2.4.2 Evaluation of the system efficiency

To estimate the design-level performance of the proposed stormwater recharge system, the estimated runoff generated during a design rainfall event (worst-case scenario) is compared against the system's cumulative capacity to manage that runoff, in addition to the existing drainage. This analysis focuses on the system's ability to absorb, infiltrate, and convey stormwater, thereby reducing surface water accumulation and minimizing waterlogging severity during peak rainfall. The assessment is structured around three key performance dimensions: (1) the volume temporarily stored in recharge trenches, based on the void ratio and porosity of filtering materials; (2) infiltration through borewells into the aquifer, assuming gravity-driven percolation through sandy substrata; and (3) storage and conveyance capacity of the artificial channel to ensure collected runoff is transported to recharge points without surface overflow. Together, these measurements determine the system's ability to mitigate waterlogging by capturing, infiltrating, and conveying excess stormwater during peak rainfall events.

To examine the robustness of the deterministic performance evaluation, a brief sensitivity analysis was also conducted. Selected parameters were varied to represent non-ideal operating conditions, including reduced borewell recharge capacity, reduced storage availability due to clogging and sediment accumulation, lower effective drainage capacity, and increased runoff inflow. The resulting changes in the waterlogging severity indicator were used to assess how system performance may vary under reduced operational efficiency.

3. RESULTS

3.1 Stormwater runoff exceedance and drainage limitations

A key finding of the hydrological assessment is the evident inadequacy of the existing stormwater drainage infrastructure to manage peak runoff during intense rainfall events. Using the Rational Method, the peak surface runoff rate for the delineated sub-catchment was estimated at 0.91 m³/s based on a worst-case rainfall intensity of 40.2 mm/h and the area's land use characteristics. In contrast, hydraulic analysis of the principal drainage conduit (an underground circular concrete pipe) revealed a theoretical discharge capacity of 0.47 m³/s, calculated using Manning's Equation for full flow conditions. The Manning-based discharge capacity represents a theoretical full-flow condition. However, field inspection and DWASA expert input indicated sediment accumulation, solid waste blockage, and reduced inlet accessibility in the existing drainage system. Similar studies have shown that inlet clogging, sediment deposition, and solid waste accumulation can substantially reduce effective drainage capacity and increase urban flood risk (Hao et al., 2021; Wang et al., 2025). Therefore, a conservative field-informed drainage efficiency factor of 70% was applied to represent reduced operational performance, lowering the effective discharge capacity (Q_d) from 0.47 m³/s to 0.33 m³/s.The analysis highlights a runoff-exceedance gap of approximately 0.58 m³/s, meaning the existing drainage system can handle only about one-third of the runoff generated during peak storm events. This structural deficiency leads to frequent overflows, localized flooding, and persistent waterlogging, even during moderate rainfall.

3.2 Comparative evaluation of waterlogging severity: pre- and post-implementation

A key performance metric for evaluating the effectiveness of the proposed recharge-based stormwater management system is the reduction in waterlogging duration following peak rainfall events. This section presents a comparative assessment between the prevailing drainage scenario (Scenario A) and the improved condition expected after the supplemental system implementation (Scenario B), based on analytical computations and parametric modeling of runoff, storage, infiltration, and discharge dynamics.

3.2.1 Scenario A - Baseline condition (without recharge infrastructure)

Under existing conditions, the stormwater drainage system in the study area lacks any supplemental recharge or infiltration features. To assess the severity of waterlogging during extreme weather, a worst-case design event is considered (A rainfall intensity of 40.2 mm/h sustained over a 30-minute duration). This scenario reflects the maximum recorded intensity in recent years and serves as a conservative basis for evaluating the system's performance. Based on earlier runoff calculations using the Rational Method, the total volume of surface runoff generated during this event was estimated to produce a peak discharge of 0.91 m³/s. To determine the amount of stormwater that would remain as excess on the road surface after the rainfall event, the following formula (eq. 4) is used:

$$V_b = (Q_p - Q_d)\, t_r \quad (4)$$

where, V_b is the excess runoff volume accumulated under the baseline condition (m^3), Q_p is the peak runoff rate (m^3/s), Q_d is the effective drainage capacity of the principal conduit (m^3/s), and t_r is rainfall duration (s). Substituting values to eq. (4), V_b=1044 m^3. This means that during the event, approximately 1044 cubic meters of water would accumulate on the road surface, since the drainage system alone is incapable of handling the entire runoff in real-time. Next, the time required to evacuate or drain this accumulated water after the rainfall stops is determined using eq. (5):

$$t_d = V_b/Q_d \quad (5)$$

where, t_d is the time required for the discharge of accumulated excess runoff on road surface (after the rainfall has stopped); Substituting the values in eq. (4), t_d =3163.6 seconds = 52.8 minutes. This drainage time indicates that it would take nearly 53 minutes after the rain ends for the area to clear the excess runoff under current infrastructure. To express the severity of this delay, a performance indicator W has been introduced in this study (eq. 6):

$$W = (t_d / t_r) \times 100\% \quad (6)$$

Here, W represents the relative water logging severity indicator (%); t_d indicates the time required for the discharge of accumulated runoff (after the rainfall has stopped) (s); t_r defines the design rainfall period (s). The waterlogging severity indicator W is used here as a simple comparative measure of post-rainfall drainage delay. Existing urban drainage and LID studies commonly evaluate performance using indicators such as runoff-volume reduction, peak-flow attenuation, peak-time delay, flood depth, flood area, and ponding duration (Bai et al., 2019; Al Amin et al., 2024; Chiu et al., 2025). The proposed indicator does not replace these established metrics. Rather, it complements them by expressing the time required to clear accumulated runoff after rainfall as a percentage of rainfall duration. This makes it useful for design-level comparison of pre- and post-intervention conditions in data-constrained urban settings where continuous flood-depth or flow-monitoring data may not be available.

Substituting values to eq. (6), W= 176%. A value of 176% means that the waterlogged condition would persist for approximately 1.76 times the duration of the rainfall itself. This further confirms that the existing drainage system alone is insufficient to prevent prolonged surface flooding during peak storm events, highlighting the urgent need for supplementary mitigation measures.

3.2.2 Scenario B - Post-implementation condition (with recharge intervention)

The proposed intervention system integrates artificial surface channels, subsurface filtering trenches, and deep borewells designed to rapidly drain excess stormwater. Its effectiveness in supplementing the existing drainage is evaluated by quantifying its total storage, infiltration, and discharge capacities and comparing them with the runoff generated during the worst-case rainfall scenario.

The total potential storage volume of the system consists of three components: the stormwater channels, recharge trenches, and borewell pipes. The total water storage in the recharge channel comes from two parts: the void space above the gravel bed and the porous volume within the gravel layer. Using trapezoidal cross-section calculations, the void space per meter of channel is estimated as 0.336 m^3, and the gravel layer adds 0.022 m^3, based on a standard porosity of 37.5%. Thus, the total storage capacity per unit length of the channel is 0.36 m^3/m. Given the total channel length is 700 m, and 165 m is occupied by recharge trenches (3 m × 55) the total channel storage capacity is calculated as, $S_{Channel}$= 0.36m^3/m × 535m =192.6 m^3.

Moreover, each recharge trench is a rectangular structure, providing a void space of 1.5 m^3 above the filter media for temporary stormwater detention. Multiple porous layers add additional storage based on their volume and material porosity. For example, the sand layer (3 m × 1 m × 0.1 m) with a porosity of 42.85% contributes approximately 0.128 m^3 of effective water storage. Similarly, the gravel layer (37.5% porosity) adds 0.1125 m^3, the charcoal layer (40.8% porosity) adds 0.122 m^3, and the pebble layer (49.5% porosity) contributes 0.297 m^3. Summing all components, each trench can store approximately 2.16 m^3 of water. For 55 trenches, the total storage capacity ($S_{trenches}$) becomes 118.8m^3. Besides, each recharge borewell (with an effective pipe length of ~25m and 4 inches diameter) can store about 0.20 m^3 of water. With 110 borewells, total water storage in the borewells ($S_{borewells}$) becomes 22 m^3. Combining all storage ($S_{channel}$+$S_{trenches}$+$S_{borewells}$) the total system storage capacity (S_{total}) becomes 333.4 m^3.

Beyond static storage, the system also facilitates dynamic removal of water through two primary mechanisms: vertical recharge via borewells and natural infiltration through the soil base of the channel. Vertical recharge is enabled by deep borewells connected to each trench. Information regarding the recharge rate of these structures was obtained from DWASA, based on similar rainwater harvesting installations near the study location. The recharge rate for each borewell is 0.003 m^3/s. With a total of 110 borewells, the combined recharge rate (d_r) amounts to 0.33 m^3/s. Besides, infiltration through the soil occurs along the unpaved portions of the stormwater channel base, which consists of a topsoil and gravel interface overlying a low-permeability clay layer. The infiltration rate of the clay, derived from secondary sources, is 5.5 × 10^{-7} m/s. To estimate the total infiltration flow rate (Q_i) in cubic meters per second, the infiltration rate is multiplied by the effective area of the channel base (535m×0.296m) and found to be approximately 0.00009 m^3/s. To determine how much runoff still remains as excess after accounting for the system's drainage, recharge, and infiltration, eq. (7) is used:

$$V_p = (Q_p - Q_d - Q_r - Q_i)\, t_r - S_{total} \quad (7)$$

where, V_p is the remaining excess runoff volume after implementation (m^3), Q_r is borewell recharge capacity (m^3/s), Q_i is soil infiltration capacity (m^3/s), and S_{total} is total system storage capacity (m^3).This equation subtracts the amount of water that can be immediately drained, recharged, or infiltrated over time and the amount that can be held in storage, from the total generated runoff volume. Substituting the values in eq. (7), volume of excess water accumulated on road surface, V_p = (.91- .33 - .33 - .00009) × 1800 – 333.4 = 116.5 m^3. The total rate at which this excess can now be discharged is $(Q_d + Q_r + Q_i)$ 0.66009m^3/s. Hence, the time needed to drain this remaining water t_d = $V_p/(Q_d+Q_r+Q_i)$ = 176.5 seconds or approximately 2.9 minutes. Using the same waterlogging severity formula (eq. 6), W =9.7 %. This indicates that with the proposed system in place, stormwater is expected to clear in just 9.7% of the rainfall duration compared with 176% under the existing drainage conditions. However, this value represents a base-case analytical estimate under the assumed drainage, storage, and borewell recharge conditions, rather than guaranteed field performance. Under actual operating conditions, sediment accumulation, clogging of filtering media, reduced borewell intake, partial blockage of drainage inlets, and variability in subsurface permeability may reduce system performance.

3.3 Sensitivity analysis under reduced system performance

A brief sensitivity analysis was conducted to assess how the estimated waterlogging severity indicator may change under non-ideal operating conditions. The base-case result assumes full storage availability, design borewell recharge capacity, and 70% effective drainage capacity. When borewell recharge capacity is reduced by 25%, the estimated waterlogging severity indicator increases from approximately 9.8% to 25.5%. Under a 50% reduction in borewell recharge capacity, the indicator increases to 46.4%. Similarly, when available storage capacity is reduced by 25% to represent clogging and sediment accumulation, the estimated indicator increases to 16.8%. If the effective drainage capacity is reduced to 50% of the theoretical drainage capacity, the indicator increases to 28.3%. Under a conservative combined case, assuming 25% lower borewell recharge, 25% storage loss, and 50% drainage efficiency, the waterlogging severity indicator increases to 59.8%. Although this value is higher than the base-case estimate, it remains lower than the pre-intervention baseline value of 176%. These results suggest that the proposed system may still reduce post-rainfall drainage delay under non-ideal conditions, but its actual performance would depend strongly on borewell intake capacity, sediment control, clogging prevention, and regular maintenance.

4. DISCUSSION

Based on analytical estimations and performance modeling, the proposed stormwater recharge system shows strong design level potential to mitigate waterlogging in the study area. By decentralizing runoff management and incorporating infiltration pathways, the system can transform an overwhelmed drainage scenario into one capable of managing stormwater during high-intensity events. A key performance indicator is the relative waterlogging severity (W), which was 176% under current conditions, meaning it takes 1.76 times longer than the rainfall duration to drain runoff. Post-implementation, W drops sharply to 9.7%, indicating stormwater would drain shortly after rainfall endsThis represents a reduction of approximately 166 percentage points in the waterlogging severity indicator under base-case assumptions. This result suggests that the combined use of surface conveyance, temporary storage, filtration, existing drainage discharge, and borewell recharge can substantially reduce post-rainfall drainage delay under the assumed design conditions.

However, the magnitude of this improvement should be interpreted cautiously. The base-case result depends on the assumed combined effect of existing drainage capacity, temporary storage in the proposed channel and trenches, and sustained borewell recharge performance. Under actual operating conditions, sediment accumulation, clogging of filtering media, reduced borewell intake, partial blockage of drainage inlets, and variability in subsurface permeability may reduce system performance. The sensitivity analysis shows that under a conservative combined case involving reduced borewell recharge, storage loss, and lower drainage efficiency, the waterlogging severity indicator may increase to approximately 59.8%. Although this value remains below the baseline condition of 176%, it indicates that the very low base-case value is realistic only under maintained operating conditions.

The sensitivity of the estimated performance is consistent with findings from similar LID and urban drainage studies. Previous monitored and model-based studies show that LID benefits vary with rainfall duration, storage capacity, infiltration conditions, drainage connectivity, and implementation configuration (Baltaci & Kalin, 2024; Chiu et al., 2025). In the present study, the base-case reduction in waterlogging severity is mainly driven by the combined storage volume, existing drainage capacity, and assumed borewell recharge rate. Therefore, the result should be interpreted as a design-level estimate under specified assumptions rather than guaranteed field performance.

Sensitivity analysis also highlights the importance of recharge trench configuration. The value of W consistently declines with increasing number of trenches, showing a direct link between infiltration capacity and runoff clearance time (see Figure 6). This insight is valuable for replicating the system in other dense urban settings, where available right-of-way space may determine the feasible number, spacing, and dimensions of recharge structures. Additionally, the performance evaluation equations developed in this study, particularly those estimating runoff exceedance, storage-discharge balance, and waterlogging severity provide a simple analytical framework for preliminary assessment of similar recharge-based drainage interventions under different design and hydrological conditions.

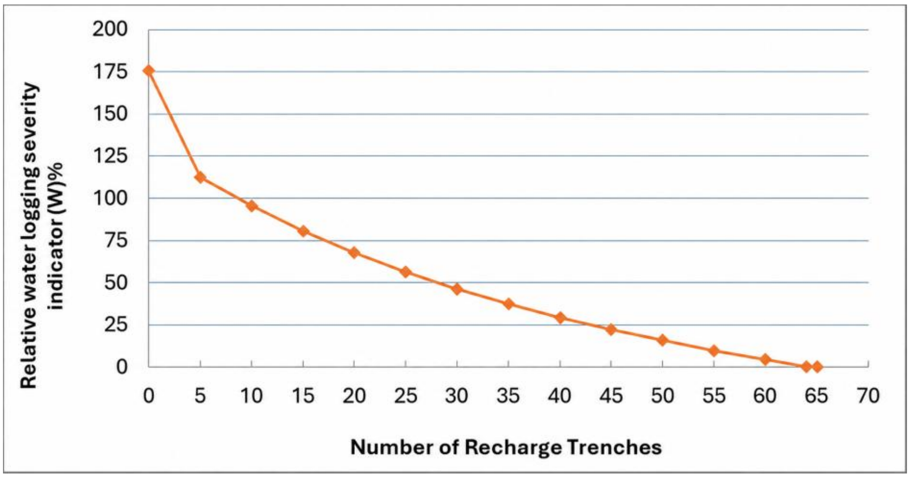

Figure 6. Relationship between the number of recharge trenches and Waterlogging Severity Indicator (W) under constant hydrological and infrastructural conditions.

Beyond immediate runoff management, the designed system also has potential to support localized groundwater sustainability. In highly urbanized contexts with declining groundwater tables, the integration of surface drainage and subsurface recharge can provide a dual function: reducing temporary surface water accumulation while directing part of the runoff toward deeper permeable layers. Also, by offsetting groundwater withdrawals and reducing reliance on centralized supply networks, the design can contribute to enhancing urban water resilience. Nevertheless, the system's modular and decentralized nature enhances its adaptability for replication in other drainage-constrained urban areas. Components like trench dimensions, channel layout, and borewell depth can be adjusted to site-specific conditions including land availability, and subsurface conditions. However, the actual recharge benefit would depend on local hydrogeology, borewell intake capacity, water quality, and long-term maintenance.

Despite these promising outcomes, the proposed design is not without limitations. The number and placement of trenches were constrained by space and land use patterns, which may not represent a hydraulically optimal layout. Infiltration rates and borewell discharge capacities are based on idealized assumptions, which may vary due to clogging, sedimentation, or geological heterogeneity. The Rational Method and Manning's equation also involve simplifying assumptions. In particular, Manning's equation assumes steady and uniform flow, while actual drainage performance during intense rainfall may be affected by inlet blockage, sediment deposition, surcharge, backwater effects, and maintenance conditions. Therefore, the reported performance should be interpreted as an analytical design estimate rather than field-validated operational performance. Future work should apply dynamic hydrological or hydraulic models, supported by field monitoring, to evaluate system performance under variable rainfall and drainage conditions.

Moreover, long-term maintenance and regular desilting will be essential to sustain system performance, and these operational aspects were not modeled in this study. Recharge trenches are vulnerable to sediment deposition and gradual bio-clogging, while borewell inlets require periodic desilting to sustain percolation capacity. Regular inspection, removal of accumulated fines and debris, filter-media maintenance, and monitoring of borewell recharge performance would be necessary to preserve the estimated reduction in waterlogging severity. Municipal guidelines for decentralized stormwater Best Management Practice (BMP) units in dense urban corridors recommend inspection every 6–12 months, with removal of accumulated fines and debris at inlet points. Embedding such maintenance routines into existing right-of-way service schedules would help preserve the observed reduction in waterlogging severity and ensure long-term system reliability.

5. CONCLUSION

This study presents a comprehensive design and performance evaluation of a decentralized stormwater recharge system aimed at mitigating urban waterlogging in a highly urbanized context. The proposed system integrates a bioswale-inspired surface channel, recharge trenches, filtering media, and vertical borewells to combine runoff conveyance, temporary storage, filtration, and subsurface recharge within limited right-of-way space. Under the selected peak rainfall condition, the proposed trench–borewell system reduced the estimated waterlogging severity indicator from 176% to approximately 9.7%, indicating its design-level potential for reducing post-rainfall drainage delay in land-constrained urban corridors. Beyond alleviating surface flooding, the proposed system also offers design-level potential for localized groundwater recharge, which is relevant for rapidly urbanizing areas experiencing drainage overload and declining groundwater levels. Its dual-purpose functionality could help address both immediate drainage challenges and the long-term groundwater stress in dense urban environments. Furthermore, this study contributes to a scalable, adaptable, and context-sensitive approach to urban stormwater management. It provides actionable insights for urban planners, hydrologists, and municipal authorities seeking decentralized interventions that not only address localized flooding but also contribute to groundwater sustainability and climate change adaptation. Although the hydrological parameters and land-use morphology in Dhaka are context-specific, the modular configuration and decentralized storage logic demonstrated here can be adapted to other rapidly urbanizing Asian cities facing drainage overload, shallow groundwater decline, and limited right-of-way space. Future research could focus on integrating smart monitoring technologies, conducting cost–benefit analyses, and incorporating community co-design approaches to improve the technical effectiveness and social acceptance of such integrated stormwater management systems.

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REFERENCES

Ahiablame, L. M., Engel, B. A., & Chaubey, I. (2012). Effectiveness of low impact development practices: Literature review and suggestions for future research. Water, Air, & Soil Pollution, 223(7), 4253–4273.

Al Amin, M. B., Sujono, J., & Triatmadja, R. (2024). Urban flood mitigation by implementing LIDs: Case study: Bendung Watershed in Palembang City. Journal of Water Management Modeling, 32, C526. https://doi.org/10.14796/JWMM.C526

Alam, M., & Rabbani, M. G. (2007). Vulnerabilities and responses to climate change for Dhaka. Environment and Urbanization, 19(1), 81–97.

Alshammari, E., Rahman, A., Rainis, R., Seri, N., & Fuzi, N. (2023). The impacts of land use changes in urban hydrology, runoff and flooding: A review. Current Urban Studies, 11, 120–141. https://doi.org/10.4236/cus.2023.111007

Bai, Y., Zhao, N., Zhang, R., & Zeng, X. (2019). Storm water management of low impact development in urban areas based on SWMM. Water, 11(1), 33. https://doi.org/10.3390/w11010033

Baltaci, E., & Kalin, L. (2024). A low-impact development-based modeling framework for flood mitigation in a coastal community. Water, 16(19), 2772. https://doi.org/10.3390/w16192772

Bengtson, H. H. (2010). The rational method for calculation of peak storm water runoff rate. Bright Hub Engineering. https://www.brighthubengineering.com/hydraulics-civil-engineering/60842-the-rational-method-for-calculation-of-peak-storm-water-runoff-rate/

Bengtson, H. H. (2022). Open channel flow and the Manning equation. PDH Star. https://pdhstar.com/wp-content/uploads/2019/06/CE-089-Manning-Equation-for-Open-Channels.pdf

Brater, E. F., & King, H. W. (1976). Handbook of hydraulics for the solution of hydraulic engineering problems (6th ed.). McGraw-Hill.

Brown, R. R., & Farrelly, M. A. (2009). Delivering sustainable urban water management: A review of the hurdles we face. Water Science and Technology, 59(5), 839–846.

Chiu, Y.-J., Chang, L.-C., Lin, Y.-T., Lin, Y.-T., Liu, C.-W., & Lee, J.-J. (2025). Hydrologic performance assessment of low impact development facilities based on monitoring data and SWMM modeling in an urban catchment in Taiwan. Scientific Reports, 15, 11586. https://doi.org/10.1038/s41598-025-11586-7

Chow, V. T. (1959). Open-channel hydraulics. McGraw-Hill.

City of Copenhagen. (2012). Cloudburst management plan 2012. https://climate-adapt.eea.europa.eu/en/metadata/case-studies/the-economics-of-managing-heavy-rains-and-stormwater-in-copenhagen-2013-the-cloudburst-management-plan/cloudburst_management_plan_2012.pdf

Dasgupta, S., Zaman, A., Roy, S., Huq, M., Jahan, S., & Nishat, A. (2015). Urban flooding of Greater Dhaka in a changing climate: Building local resilience to disaster risk. World Bank.

Dewan, A. M., Yamaguchi, Y., & Rahman, M. Z. (2012). Dynamics of land use/cover changes and the analysis of landscape fragmentation in Dhaka Metropolitan, Bangladesh. GeoJournal, 77(3), 315–330.

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., & Viklander, M. (2015). SUDS, LID, BMPs, WSUD and more: The evolution and application of terminology surrounding urban drainage. Urban Water Journal, 12(7), 525–542. https://doi.org/10.1080/1573062X.2014.916314

Hao, M., Gao, C., Sheng, D., & Qing, D. (2019). Review of the influence of low-impact development practices on mitigation of flood and pollutants in urban areas. Desalination and Water Treatment, 149, 323–328.

Hao, X., Mu, J., & Shi, H. (2021). Experimental study on the inlet discharge capacity under different clogging conditions. Water, 13(6), 826. https://doi.org/10.3390/w13060826

Huo, Y. C., Wu, X., Luan, Q. H., Liu, J. H., & Ma, D. (2019). Effectiveness evaluation of LIDs through SWMM: A case study of typical urban unit in Handan, China. IOP Conference Series: Earth and Environmental Science, 344(1), Article 012056. https://doi.org/10.1088/1755-1315/344/1/012056

Intergovernmental Panel on Climate Change. (2022). Climate change 2022: Impacts, adaptation, and vulnerability. Cambridge University Press. https://doi.org/10.1017/9781009325844

Jayasooriya, V. M., & Ng, A. W. M. (2014). Tools for modeling of stormwater management and economics of green infrastructure practices: A review. Water, Air, & Soil Pollution, 225, 2055.

Kabisch, N., Qureshi, S., & Haase, D. (2015). Human–environment interactions in urban green spaces: A systematic review of contemporary issues and prospects for future research. Environmental Impact Assessment Review, 50, 25–34.

Kazmierczak, A., & Carter, J. (2010). Adaptation to climate change using green and blue infrastructure: A database of case studies. University of Manchester.

Khan, M. Z. H., & Akhand, A. F. M. M. (2021). Study on the drainage system of Dhanmondi residential area in Dhaka city. World Vision Research Journal, 14(1), 45–56.

Li, C., Fletcher, T. D., Duncan, H. P., & Burns, M. J. (2017). Can stormwater control measures restore altered urban flow regimes at the catchment scale? Journal of Hydrology, 575, 631–641.

Liao, K.-H. (2019). The socio-ecological practice of building blue-green infrastructure in high-density cities: What does the ABC Waters Program in Singapore tell us? Socio-Ecological Practice Research, 1(1), 67–81.

Manandhar, B., Cui, S., Wang, L., & Shrestha, S. (2023). Urban flood hazard assessment and management practices in South Asia: A review. Land, 12(3), 627. https://doi.org/10.3390/land12030627

Rosenzweig, C., Solecki, W., Hammer, S. A., & Mehrotra, S. (Eds.). (2011). Climate change and cities: First assessment report of the Urban Climate Change Research Network. Cambridge University Press.

Rosenzweig, C., Solecki, W., Romero-Lankao, P., Mehrotra, S., Dhakal, S., & Ali Ibrahim, S. (Eds.). (2018). Climate change and cities: Second assessment report of the Urban Climate Change Research Network. Cambridge University Press. https://doi.org/10.1017/9781316563878

Sharma, A. K., Cook, S., Tjandraatmadja, G., & Gregory, A. (2012). Impediments and constraints in the uptake of water sensitive urban design measures in greenfield and infill developments. Water Science and Technology, 67(7), 1443–1451.

Su, J., Wang, M., Razi, M. A. M., Dom, N. M., Sulaiman, N., & Tan, L.-W. (2023). A bibliometric review of nature-based solutions for urban stormwater management. Sustainability, 15(9), 7281. https://doi.org/10.3390/su15097281

Sultana, S., Ahmed, K. M., & Mia, M. B. (2010). Prospects of artificial recharge for augmentation of the upper Dupitila aquifer in Dhaka City, Bangladesh. In Proceedings of the 7th International Symposium on Managed Aquifer Recharge (ISMAR7).

Taufiq, H. A. (2021). Dhaka water-logging: Causes, effects and remedial policy options. arXiv. https://arxiv.org/abs/2107.12625

United Nations Educational, Scientific and Cultural Organization, & UN-Water. (2020). United Nations world water development report. UNESCO.

United Nations Human Settlements Programme. (2017). New urban agenda. UN-Habitat.

United Nations Human Settlements Programme. (2020). World cities report 2020: The value of sustainable urbanization. UN-Habitat.

United Nations Office for Disaster Risk Reduction (2017). How to make cities more resilient: A handbook for local government leaders. https://www.undrr.org/publication/how-make-cities-more-resilient-handbook-local-government-leaders-2017

United Nations World Water Assessment Programme. (2018). The United Nations world water development report 2018: Nature-based solutions for water. UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000261424

Wang, X., Xia, J., Feng, J., & Dong, B. (2025). Numerical modelling of the impact of drainage system clogging on urban flood processes. Journal of Environmental Management, 388, 125969. https://doi.org/10.1016/j.jenvman.2025.125969

Woods Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R., & Kellagher, R. (2015). The SuDS manual (C753). CIRIA.

Zhou, Q. (2014). A review of sustainable urban drainage systems considering the climate change and urbanization impacts. Water, 6(4), 976–992.