



# Enhancing Urban Drainage Infrastructure Through Implementation of Low Impact Development Techniques

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## Abstract

The global phenomenon of urban flooding has become a pressing issue for cities worldwide. Conventional strategies to alleviate flooding, such as augmenting the capacity of drainage systems, are incompatible with the principle of sustainable development. In this regard, Low Impact Development (LID) techniques have emerged as a promising and sustainable approach to manage storm water. The objectives of the present study are to determine the enhancement in functional and structural resilience of an UDS after implementation of LIDs and Life Cycle Cost (LCC) analysis of implementation of LIDs. To showcase the role of LIDs in enhancing drainage system resilience, a case study was conducted in Gurugram, India, a city frequently impacted by flooding. The LID Performance Index is designed to measure the improvement in functional resilience and decrease in the number of vulnerable locations aims to quantify the enhancement in structural resilience. The LCC analysis is carried out to determine the Benefit–Cost Ratio (BCR) of implementing the LID. The study determined the optimal percentage of LIDs to incorporate into the urban drainage system through the creation of various scenarios that considered the impacts of urbanization, climate change, and the cost of implementing LIDs. Results indicated that a system incorporating 10% of LIDs (S1) with a Benefit–Cost ratio of 2.05 was the most suitable scenario for the case area. For the scenario S1 the functional resilience is enhanced by 21% and number of vulnerable locations decreases by 8.7%. The study also identifies the barriers to the implementation of LIDs in developing countries like India, categorizing them into planning, implementation, and maintenance stage barriers. Ultimately, the study provides a comprehensive understanding of nature-based solutions for the effective management of urban drainage infrastructure, offering valuable insights for urban planners, design engineers, and policy makers to protect cities from flood hazards.

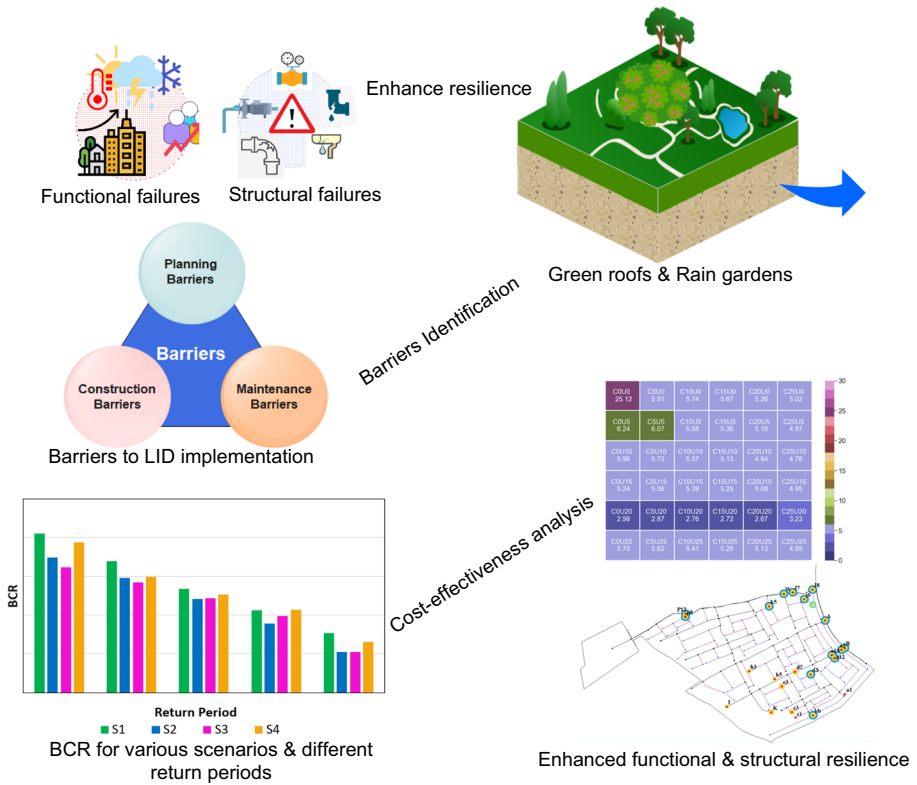
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Graphical Abstract



**Keywords** Urban drainage system · Low impact development · Resilience · Life cycle cost · Barriers

1 Introduction

The swift proliferation of urbanization across the world has resulted in a drastic decline in pervious surfaces, thereby causing a lack of effective infiltration and interception of rainwater in urban regions (Sutton et al. 2009; Locatelli et al. 2017; Zhang et al. 2022). These changes often lead to increased runoff, increased peak flows, and reduced time of concentration, thereby drastically altering the flow regimes and hydrological patterns (Liu et al. 2023; Moazzem et al. 2024) and eventually resulting in a common cause of waterlogging problem (Bisht et al. 2016). To mitigate the detrimental hydrological effects of urbanisation, the Prince George’s County, Maryland in 1990 proposed the concept of nature-based solutions for rainwater control and coined the term ‘Low Impact Development’ (Dietz 2007). The LID practices aimed to reduce runoff pollution, runoff volume and peak flows by controlling stormwater at the source of runoff by using decentralized and small-scale retention and infiltration facilities (Lin et al. 2023; Rong et al. 2024). Beyond hydrological benefits, LID facilities can enable multiple ecosystem benefits such as habitat creation,

climate change mitigation, aesthetic value, recreation, and public education (Prudencio and Null 2018; Wang et al. 2022).

In the past few years, a growing number of research studies have demonstrated the effectiveness of LIDs around the world (Cipolla et al. 2016). In an Italian urban locality, the implementation of green roofs on 30% of buildings and permeable pavement in lieu of 30% of impermeable pavements led to a 25% decrease in stormwater runoff (Palermo et al. 2020). Gao et al. (2021) identified the optimal combination of three LIDs in 15% area of the Shaanxi province in China and observed the runoff reduction by 73.75%. Tansar et al. (2022) evaluates different spatial placement strategies of LIDs and concluded that the placement locations of LID have significant impact on the performance of Urban drainage system. Dadrasajirlou et al. (2023) compared the various combination of LID technique using Analytic Hierarchy Process-Preference Ranking and inferred that highest ranked combination lead to average reduction in total flood volume by 80% and average reduction in peak flow by 90%. Pampaloni et al. (2024) retrofitted an impervious area with different percentages of rain garden and green roofs and observed 15–60% reduction in the peak flow. Furthermore, the majority of computer modeling, sensor monitoring, or experimental studies focusing on retrofit existing UDS with LIDs have been conducted in cities across North America, Europe, China, and Australia (Fu et al. 2023; Mugume et al. 2024). In developing countries like India, the LIDs are not yet frequently used on ground level nonetheless researchers across India are trying to highlight the benefits of implementing nature-based solution for flood management in cities. LIDs have only been extensively studied in very few cities of India, such as Ahmedabad, Delhi, Madurai Mumbai and Pune, with varying results (Gogate et al. 2017; Mell 2018; Tauhid and Zawani 2018; Kumar et al. 2022). Hence, it is essential to develop and test methodologies and frameworks for assessing implementation costs and recuperating ecosystem services across the case area.

An Urban Drainage System (UDS) ought to be functional in present and adaptive in an uncertain future (Butler et al. 2018). This means that the system must be capable of minimizing the duration and magnitude of failures under unprecedented circumstances, in addition to being reliable under standard loading. The concept of resilience perfectly encompasses the aforementioned requisites of the drainage system and has become a key objective for an UDS (Osheen et al. 2022). Studies can be found in the literature depicting nature-based solutions as a prominent way to enhance resilience (Almaaitah et al. 2021; Rodriguez et al. 2021; Mugume et al. 2024). However, the literature presents only a limited number of studies that have quantified the enhancement in resilience of an urban drainage system using LIDs (Dong et al. 2017). This study aims to precisely quantify resilience enhancement by categorizing it into functional and structural resilience. Functional resilience pertains to resilience against external threats such as urbanization and climate change, whereas structural resilience relates to resilience against internal threats such as system and component failures. Retrofitting the UDS with nature-based solutions, while considering the deleterious consequences of functional and structural failures, with the aim of improving resilience, will become increasingly crucial in navigating the inevitable uncertainties ahead. Cost-effectiveness is an important parameter significantly influences the adoption of most resilient LID scenario. Cost is a significant consideration, particularly given the high land requirements associated with LID techniques, which can be prohibitively expensive in urban areas. This study acquires a cost–benefit approach using hydrological performance evaluations and the Life Cycle Cost (LCC) analysis approach for benefit and cost assessment, respectively. Various studies have used LCC techniques to evaluate the cost-effectiveness of LID measures (Montalto et al. 2007; Liao et al. 2014; Mei et al. 2018; Wang et al. 2020; Liu et al. 2023;). It aids in identifying the most cost-effective

scenario of LIDs by considering all the combined costs over the lifespans of LID measures. The hydrological performances of several LID implementation scenarios were evaluated by life cycle costs (LCCs) versus flood mitigation performances. The investment in construction costs significantly influences the widespread adoption of LIDs, therefore evaluating the cost and benefits of LID measures before implementation is necessary (Liu et al. 2023; Sousa et al. 2024).

The necessity to comply with LIDs stormwater focused approaches is highlighted in the Stormwater Management Manual (CPHEEO 2019) by the Government of India (GOI) yet there are no procedures and plans for the design, implementation, and evaluation of LIDs. The adoption of LIDs in cities of developing countries has been constrained by inadequate evidence of their effectiveness, absence of clear policies, standards, and guidelines (Thoms and Köster 2022; Ghosh et al. 2024; Mugume et al. 2024). Therefore, the study analyses the barriers to incorporation of LIDs for stormwater management in the Indian scenario as it is imperative for urban planners, communities and environmental agencies to identify these barriers to efficiently deal with the challenges in formulating policies and guidelines in LIDs procurement.

After studying the extensive literature, the following research gaps have been identified:

- I. Research focusing on assessing the applicability and effectiveness of LID techniques in diverse urban contexts in developing nations is lacking in the literature.
- II. There is a dearth of studies quantifying the enhancement in resilience achieved through LID implementation.
- III. Studies carrying out comprehensive cost–benefit analyses to inform decision-making processes are not extensively explored in the literature.
- IV. Studies analyzing the barriers to the incorporation of LIDs in urban planning and stormwater management strategies in developing country contexts, like India, are rarely found in the literature.

Keeping above gaps in view following objectives were formulated for this study,

- a) Enhancement in resilience of an UDS after implementation of LIDs
- b) Life Cycle cost analysis of implementation of LIDs
- c) Barriers that affect the planning, construction or maintenance of LIDs in a developing country

## 2 Methodology

The overall methodology for the present study is provided in a detailed methodology flowchart (Fig. S.1). The specific components of the flowchart, i.e. determination of potential subcatchment index, LID implementation scenario, enhancement in functional and structural resilience analysis, and benefit–cost ratio estimation, are discussed herein in detail.

### 2.1 Study Area

The study site is located in Gurugram city, a millennium city in the state Haryana and National Capital Region of India. Sector 81 to 97, an area under ‘Hyper development potential Zone’, of the Gurugram city has been used as study site. The location of this

study site i.e., between 28°22'12" to 28°25'48" North latitude and 76°52'30" to 77°59'24" East longitude, was selected as drainage data for entire city limits was not available. Gurugram has witnessed an average yearly rainfall of 773 mm over the last three decades, with most of the precipitation occurring from June to September. The case site is a typical residential area, with an area of 30 km<sup>2</sup> (Fig. 1) and elevation of 219–244 m above mean sea level.

Despite a planned stormwater drainage network, the city has been frequently facing the issue of water logging in the recent years. The most recent occurrence of flooding, as documented, took place on September 22, 2022, when a precipitation of 55 mm resulted in widespread waterlogging and congestion throughout the city. Additional documented instances of acute flooding were recorded in July 2016, August 2018, August 2019, August 2020, and July 2021 (Osheen et al. 2023). Frequently reported flooding during monsoon season reflects the inadequacy of conventional drainage system in handling the stormwater, thereby indicating the need for sustainable drainage practices.

### 2.2 Data Used

Information required for rainfall-runoff modelling vis-à-vis urban hydrology includes rainfall data for design storm estimation, detailed drainage network map for conduits and nodes location, conduits dimensions, land-use type distribution to estimate proportions for percentage imperviousness, soil-type details for infiltration properties, and topographic information. Rainfall intensity dataset, available at 0.1 degree spatial resolution and half-hourly

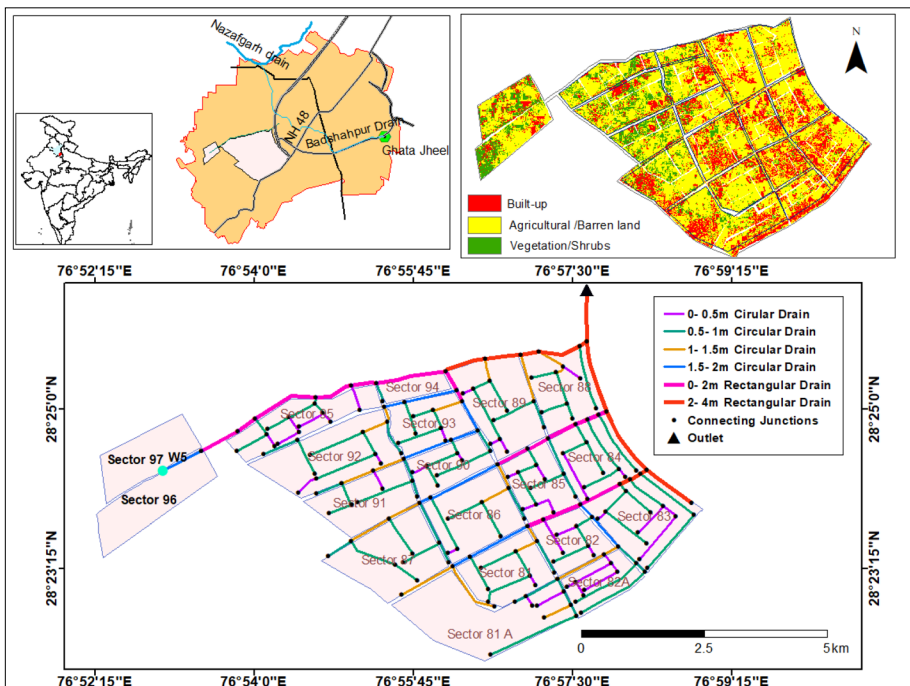


Fig. 1 Study area map

temporal resolution, from June 2000 to December 2019 obtained from the GPM -IMERG Version 06 were used for design storm estimation. The drainage network map (Fig. 1) of Sector 81 to Sector 97 along with the invert level of nodes and drain dimensions used in the present study were provided by Gurugram Metropolitan Development Authority (GMDA). Slope map was prepared using a 12.5 m resolution ALOS PALSAR DEM obtained from the ASF. According to the soil classification map of the NBSS&LUP, the case area's soil type belongs to group 016 (loamy sand). Soil characteristics were ascribed based on the work of Rawls et al. (1983). Random Forest Approach in Google Earth Engine was employed to analyse the Cartosat-3 satellite imagery available at 1.1 m spatial resolution from the National Remote Sensing Centre to determine the land-use type distribution and proportions.

### 2.3 Design Storm Scenarios

Design storm has two important components i.e., return period of storm and duration of storm. To consider different possible future scenarios of extreme events, return period of 5, 10, 25, 50 and 100 years were used for the estimation of six possible storms. The second component, i.e., duration of storm is dependent on time of concentration. To assess the maximum flow from the catchment, it is recommended that the design storm should be at least as long as the time of concentration. (Butler et al. 2018). Time of concentration in the present study is determined using SWDM method suggested by CPHEEO (2019). In the SWDM method, time of concentration has two elements i.e., overland flow duration and time of flow through channel (CPHEEO 2019; Mehta et al. 2022).

The concept of a design storm involves two pivotal factors: the return period of the storm and its duration. To anticipate various potential extreme event scenarios, this study employs return periods spanning 5, 10, 25, 50, and 100 years to estimate six possible storms. The duration of these storms, on the other hand, depends on the time of concentration, a critical variable in assessing maximum flow within a catchment area.

In accordance with (Butler et al. 2018), it is recommended that the design storm's duration should be atleast equal to or greater than the the time of concentration. This time of concentration, is determined in this study, using the SWDM method given by CPHEEO (2019), comprising two key elements: overland flow duration and time of flow through the channel, as detailed in (CPHEEO 2019; Mehta et al. 2022).

Estimated time of concentration was utilized to decide the design storm duration. Thereafter, Intensity–Duration–Frequency (IDF) curves were used to estimate the depth corresponding to a particular storm return period and duration. The hyetographs were plotted employing an alternative block method based on this estimated depth (Chow et al. 1988; CPHEEO 2019; Mehta et al. 2022).

To generate the IDF curves, the study conducted frequency analysis on a 20-year dataset of GPM-IMERG rainfall. An annual maxima time series has been created by determining extreme rainfall intensities for specific durations ranging from 0.5 h to 24 h for each year. The L-moments method was employed to estimate the distribution parameters of Generalized Extreme Value probability distribution. This distribution was fitted to the annual maxima time series data. With the estimated parameters, rainfall intensity was then calculated for each duration and return period. The resulting dataset, comprising rainfall intensities corresponding to various durations and return periods, were used for plotting the IDF curves. These curves offer invaluable insights into the relationship between rainfall

intensity, storm duration, and the likelihood of occurrence, crucial for effective stormwater management and infrastructure design.

## 2.4 LIDs Based Runoff Management

LID refers to systems and practices that either utilize or imitate natural processes such as infiltration, filtering, storing, evaporating, and detaining runoff to decrease the quantity and enhance the quality of stormwater runoff (Mani et al. 2021). The Storm water management model (SWMM) is utilized to model the drainage system along with the LIDs (Rossman 2010). Various LIDs that can be explicitly modeled in SWMM include Vegetative Swales, Bio-retention Cells, Green Roofs, Permeable Pavement, Infiltration Trenches, and Rain Gardens (Montalto et al. 2007). The present study examines two LID practices, namely Green Roofs and Rain Gardens.

Since, Vegetative swales and Infiltration trenches are open ditches, therefore, are usually unsuitable in Indian cities due to space constraints. Besides, regular maintenance of ditches is comparatively difficult. In addition, permeable pavement comprises of hard layers that are filled with gravel and paved with porous concrete, which permits rainfall to seep into the underlying base. For the implementation of this LID measure, the existing pavement are needed to be replaced, which is expensive and not practically feasible in a functioning city.

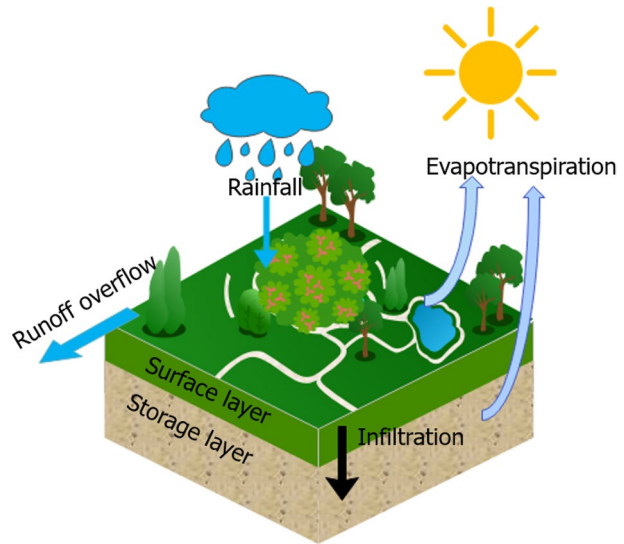
Green roof detention type LID practices and consists of three layers i.e., a vegetation layer, a soil layer, and a storage layer (Qin et al. 2013; Yang and Chui 2018). The only inflow into the green roof is directly from rainfall. It temporarily stores the roof runoff before releasing it into the overflow component to conventional drainage system. Green roof has advantages that its maintenance is carried out by the building owners and reduces load on government authorities. Further, as study area comes under Indian Hot Arid Zone, a green roof would reduce the air-conditioning requirement by keeping the building cool while complementing the aesthetics. It has been also reported that green roofs reduce the urban heat island effect (Dwivedi and Mohan 2018).

Rain gardens are retention-in-filtration type LID practices and consists of landscape depression, planted with native vegetation that receives surface runoff from contributing drainage area (Yang and Chui 2018; Osheen and Singh 2019). Rain garden reduces the runoff volume by using the natural processes of infiltration and evapotranspiration while enhancing the aesthetics of surrounding. Rain garden collects water from roofs, driveway and streets and soaks it into the ground. The added advantage of having a rain gardens is that it helps in removing the pollutant-load from runoff while reducing the runoff volume in the downstream.

The LID controls are designed based on the subcatchments characteristics, viz., area, slope, land use, and impervious area. For urban watershed's hydrologic modelling, combinations of LIDs can also be incorporated using the SWMM. During simulation in SWMM, water balances and movements are computed for each layer of LID practice by considering these as separate vertical layers (Rossman 2010).

During the simulation, the LID practices are represented as vertical layers and the water movements and balances for each layer were computed individually (Rossman 2010). The basic hydrological processes for a green roof and rain garden are shown in Fig. 2 for reference. The parameters for the two LID practices modelled in this study are provided in Table S.1. These parameters were considered following application manual

**Fig. 2** Conceptual model of rain garden in SWMM



of SWMM (Gironás et al. 2010) and relevant literature (Chui et al. 2016; Rossman and Huber 2016; Wu et al. 2018).

To effectively integrate the green roofs and rain gardens in the runoff management, the subcatchments with substantial impervious area and high runoff volume were designated as the potential locations for LIDs' application. To determine the potential subcatchments, a Potential Subcatchment Index (PSI) was computed for each subcatchment using the percentage imperviousness of subcatchment and the total runoff volume.

## 2.5 Potential Subcatchment Identification for the LIDs

Herein, a potential subcatchment is defined as the subcatchment in which if LID practices are implemented, the performance of system improves significantly. Ghodsi et al. (2020) defined an index (termed in the present study as PSI) to identify potential subcatchments for LID's implementation by multiplying the total runoff volume in each subcatchment to the corresponding percentage impervious of the subcatchment.

$$\text{PSI} = \text{Runoff} \times \% \text{Imperviousness} \quad (1)$$

The runoff in each subcatchment is obtained corresponding to the 5 year return period design storm as return period, as suggested by CPHEEO (2019), to layout the drainage network in city with population above 100 thousand. Impervious area and land use type are the prime governing factors for runoff generation from the subcatchments. Since runoff reduction is the main purpose of LIDs, therefore supplementing, the subcatchments having greater value of imperviousness or runoff generated or both, with LIDs will be helpful in reducing runoff volume drastically.



## 2.6 LID Implementation Scenarios and Proportion in Subcatchments

To examine the impact of LID implementation on runoff reduction, the subcatchments are arranged in descending order of PSI. Subcatchments with higher value of PSI are potential subcatchments for LIDs. The value of PSI determines the following four scenarios:

- Scenario 1 (S1): 10% potential subcatchments provided with LIDs
- Scenario 2 (S2): 25% potential subcatchments provided with LIDs
- Scenario 3 (S3): 50% potential subcatchments provided with LIDs
- Scenario 4 (S4): 100% subcatchments provided with LIDs

Resilience improvement was observed in all four scenarios, and a Cost–Benefit analysis was conducted to identify the optimal scenario. The area and total number of green roof units and rain garden practices depends on availability of roof space and bare land in the subcatchment, respectively. Surface area of a green roof unit varies from 75 to 500 m<sup>2</sup> depending on the size of roof. In addition to this, 75% of roofs in a subcatchment were provided with green roof infrastructure to account the uncertainties in owner's opinion and future plans. The size of a rain garden unit varies from 2500 to 10000 m<sup>2</sup> depending upon the availability of bare land in the subcatchment. This range is kept on the basis of bare land available in the subcatchment. Total number of rain garden unit in a subcatchment was determined following the Wisconsin bioretention design guidelines, the recharge benefit is at its highest when the rain garden facility within an area is equivalent to 15% of the contributing impervious area (Ahiablame and Shakya 2016). However, in 16 out of 89 subcatchments, the available open area for raingarden is less than 15%. Therefore, maximum possible area available was used for employing rain garden as LID.

## 2.7 SWMM Setup

SWMM version 5.2, a dynamic rainfall-runoff simulation model developed by USEPA was used in this study. The model contains a LID control module which can simulate hydrological response of eight LID measures (i.e., rain barrels, infiltration trenches, permeable pavement, rooftop disconnection, bio-retention cells, rain gardens, green roofs and vegetative swales). The LID control is represented as vertical layers for computation of water balance and movements. To completely solve the one-dimensional Saint Venant flow equation and obtain theoretically most reliable results, dynamic wave routing method of flow routing has been used. Green-Ampt method was utilized to compute the infiltration whereas runoff velocity was determined using Manning's equation.

In order to simulate the rainfall-runoff response in the SWMM setup, 90 discrete subcatchments ranging from 4 to 178 ha were discretized. The study area's drainage network consisted of 188 nodes and 187 conduits. To achieve the steady state condition the simulation duration has been taken as 6 h. Sensitivity analysis of model parameters has been carried out using One-at-a-time (OAT) technique to overcome calibration and validation limitations. For detailed description of the SWMM model setup in the study area, refer to Osheen et al. (2022). Flood duration and volume, variables required for resilience evaluation, were obtained from the SWMM simulation results.

## 2.8 LID Effectiveness in Resilience Enhancement

Resilience is elucidated as “The degree to which the system minimizes the level of service failure magnitude and duration over its design life when subject to exceptional conditions” (Butler et al. 2014). There are two modes of failure in an UDS i.e., functional failure and structural failure. External threats such as climate change (i.e., change in precipitation) and urbanization can trigger functional failures. Structural failures occur by internal component malfunction or failure such as structural damage of a pipe, blockage of sewers or inlets, pump or sensor failure and bed load sediment deposition, chronic stresses i.e., asset decay/ ageing, and sewer collapse. Therefore, resilience corresponding to these modes of failures is termed as functional and structural failures, respectively.

The resilience is computed using the idea of volumetric severity using Eq. 2 (Mugume et al. 2015b). The resilience index ( $Res_o$ ) is calculated as ‘one minus the volumetric severity’ where volumetric severity ( $Sev_i$ ) is a function of failure duration and maximum failure magnitude (Mugume et al. 2015a). The volumetric severity is a measure of the potential consequences of the simulated failure impacts, including property, and system damage.

$$Res_o = 1 - Sev_i = 1 - \frac{V_{TF}}{V_{TI}} \times \frac{t_f}{t_n} \quad (2)$$

where,  $V_{TI}$  is the total inflow into the system,

$V_{TF}$  is the total flood volume,

$t_n$  is the total simulation time.

$t_f$  is the mean nodal inundation duration.

### 2.8.1 Functional Resilience

The enhancement in functional resilience of system by incorporation of LIDs was evaluated considering 144 scenarios which include (i) variation in percentage of LIDs in system, (ii) by altering the rainfall intensity, and (iii) percentage imperviousness. For a particular scenario or percentage of LID in the system, 36 scenarios were formulated for analysing the consequences of climate change and urbanization. The impact of climate change is simulated by increasing the rainfall intensity by 5%, 10%, 15%, 20% and 25%. On the similar lines, the impact of urbanization is simulated by increasing the impervious cover by 5%, 10%, 15%, 20% and 25%. Corresponding to each scenario S1, S2, S3 and S4, there are 36 scenarios of varying imperviousness and rainfall intensity and hence leads to 144 future functional failure scenarios in total.

To evaluate the effectiveness of LID measure, the LID performance Index (LPI) i.e., the ratio of the system resilience with LID measure under a future scenario to the reference scenarios used as shown in Eq. 3 (Dong et al. 2017).

$$LPI = \frac{Res_{CUI+LID}}{Res_{COU0}} \quad (3)$$

where,  $Res_{CUI+LID}$  represents the system resilience with LID practice under a future scenario and  $Res_{COU0}$  represents system resilience for the reference scenario. If the  $LPI$  is equal to 1, it means that the LID measure can offset the effect of climate change and urbanization

in the future. If the LPI is greater than 1, it represents the LID measure not only mitigates the adverse effects, but can also enhance the performance of the system. If the LPI is less than 1, it indicates that implementation of LIDs has no effect on the performance of the system.

## 2.8.2 Structural Resilience

The enhancement in structural resilience by providing LIDs in the system was evaluated in the four scenarios S1, S2, S3 and S4 as defined in Sect. 2.6. A structural failure is simulated by the removal of a specific component to depict the system's inability to perform its intended function under altered circumstances. One-at-a-time link failure is conducted to assess the effects of link failure on system performance. The link failure, herein, was simulated by scaling down the diameter/depth (in case of rectangular drain) of the conduit to approximately 1 mm while still satisfying the hydraulic connectivity constraints necessary for solving the flow equations.

As the performance of each node affects the resilience of the entire system, simulations were performed to evaluate the performance of each node. During the simulations, links in the system that caused the structural resilience to change by more than 5% were identified. Nodes connected with these conduits were analysed, and among these nodes for which flood volume was greater than the threshold  $\mu + \sigma$ , (where  $\mu$  and  $\sigma$  are the mean and standard deviation of flood volume over each node) were identified as worst affected nodes and designated as vulnerable locations in the present study.

## 2.9 Cost–benefit Analysis

The main concern in capacity augmentation of existing drainage system with LID techniques is the cost of LID implementation. In the present study, the effectiveness of LIDs were quantized in terms of Benefit–Cost Ratio (BCR), as expressed in Eq. 4, using the present value of costs (PVC) and the present value of benefits (PVB). It helps in determining the cost-effectiveness of LID combination or specific LID practices. BCR has a relative attribute, high BCR indicates higher cost effectiveness of the application of LIDs.

$$BCR = \frac{PVB}{PVC} \quad (4)$$

where, PVB infers the effectiveness of the LIDs implementation in flood mitigation. It can be determined using Eq. 5 (Mei et al. 2018) as follows,

$$PVB = \frac{R_f + R_o + R_p}{3} \quad (5)$$

where,  $R_f$ ,  $R_o$  and  $R_p$  are the reduction rates of flood volume, outflow volume, and peak flow, respectively, emerging from the execution of LID techniques. The three indices flood volume, outflow volume, and peak flow are equally important in evaluating the reduction in vulnerability of urban flood therefore, arithmetic mean of these three indices was considered to determine the PVB (unit: %).

### 2.9.1 Cost Calculation

The LCC analysis approach was used to estimate the PVC in Eq. (4), considering all the costs associated with project. The PVC is represented by unit life cycle cost of a specific LID practice following Eq. 6 (Liao et al. 2014) which includes initial case cost (ICC), cost of operation and maintenance (COM), and salvage value (SV).

$$PVC_{x,n} = ICC_{x_i} + \sum_{t=0}^n f_{r,t} g COM_t - f_{r,n} g SV_n \tag{6}$$

where,

- $PVC_{x,n}$  is the PVC of LID practice  $x_i$  in year  $n$ ,
- $ICC_{x_i}$  is the unit initial cost of construction of LID practice  $x_i$ ,
- $COM_t$  is the annual operation and maintenance cost in year  $t$ ,
- $SV_n$  is the salvage value of LID practice  $x$  in the end year  $n$  of the design life,
- $f_{r,t}$  is the present value factor of discount rate  $r$  in year  $t$ , and.
- $f_{r,n}$  is the present value factor of discount rate  $r$  in the end year  $n$  of the design life.

The ICC comprises the construction cost, excavation cost, and design and planning cost etc. The COM includes material, manpower, equipment investment, and energy. This cost is usually estimated in terms of the time unit. When a LID measure attained its design life, its usability can still be above the lowest tolerable threshold value, indicating that there is a residual life. Mei et al. (2018) computed the Salvage Value (SV) or residual life value of a LID measure as the percentage of residual life to life expectancy using Eq. 7

$$SV = \left(1 - \frac{L_A}{L_E}\right) COM \tag{7}$$

where,

- $L_A$  is interval number from last maintenance year to designed life year;
- $L_E$  is design life of a LID measure.

The interval number from the most recent maintenance year to the designed life year has been set to 1, since it is anticipated that all the LID measures require annual maintenance.

By taking into account the time value of money, the present value factor is utilized to ascertain the current worth of money that will be received at a future point in time. The present value factors  $f_{r,t}$  and  $f_{r,n}$  are determined using Eq. 8 where  $r$  in the Eq. 8 is discount rate.

$$f_{r,t} = \frac{1}{(1+r)^t} \tag{8}$$

It was inappropriate to compare the overall PVC since life cycles of different LID practices are different. To indicate the unit annual average cost (UAAC), the PVC in Eq. 2 was employed. The UAACs of single LID practice was calculated using Eq. 9 and UAACs for combination of LIDs was calculated using Eq. 10.

$$P = UAAC_x = PVC_x/n_x \quad (9)$$

$$UAAC^c = \sum_{k=1}^m w_k \cdot P \quad (10)$$

where,

- $x$  represents a specific LID type,
- $n_x$  is the design life of LID practice  $x$ ,
- $w_k$  is area proportion of each LID practice in combination;
- $P$  is the UAAC of each LID practice, and.
- $m$  is the number of different LID practices in a LID combination.

### 3 Results and Discussion

#### 3.1 Potential Subcatchment Identification and Scenario Distribution

The simulations were carried out in SWMM for 5-year design storm without LIDs intervention. The produced runoff in the 89 subcatchments of the case area is multiplied with the corresponding percentage impervious to determine the PSI, as explained in Sect. 2.5. The generated runoff in each subcatchment and percentage imperviousness of each subcatchment is shown in column 2 and 3 of Table S.2 respectively and corresponding value of PSI is shown in column 4 (Fig. 3).

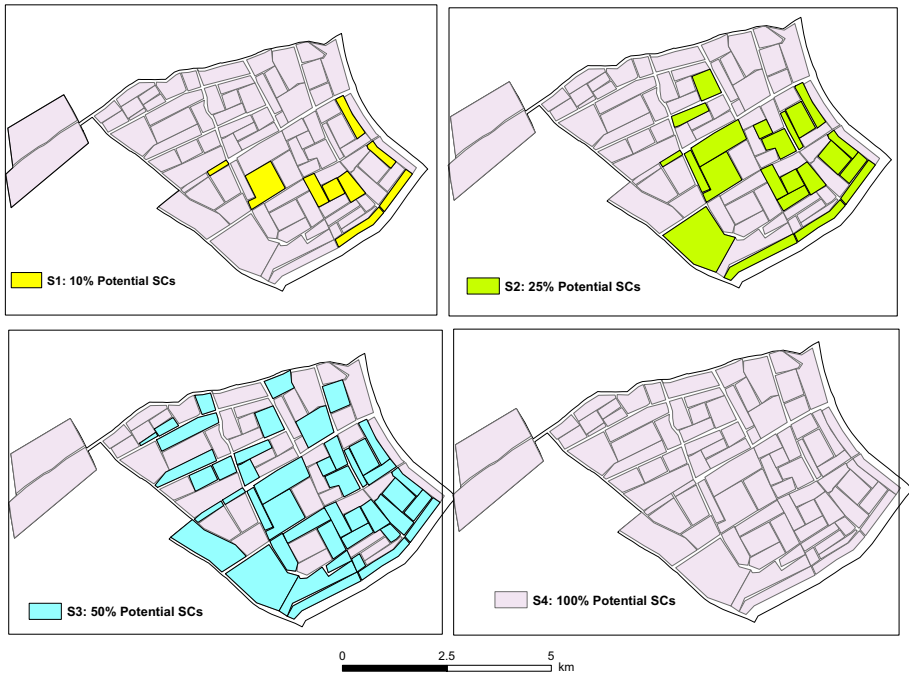
Based on the value of PSI, the four scenarios of LIDs implementation were employed as discussed in Sect. 2.6. After arranging the subcatchments in decreasing order of PSI, subcatchments 4, 10, 13, 18, 19, 20, 29, 34 and 47 (bolded in Table S.2) were found to be top nine subcatchments in the list, hence, classified as the 10% potential subcatchments. The nine subcatchments having highest PSI were used in scenario S1; similarly, 22 subcatchments including the afore-mentioned 9 in S1 were used in scenario S2; 45 subcatchments including the afore-mentioned 22 in S2 were used in scenario S3 and all 89 subcatchments were provided with LIDs in scenario S4. The details of the subcatchment's scenario of LID implementation along with PSI values can be referred from Fig. 3.

#### 3.2 LID Effectiveness in Resilience Enhancement

LID techniques can be effective in enhancing the resilience of an urban drainage system as these are designed to intercept and store rainwater at the source, thus, reducing the total volume of stormwater runoff and the peak flow rates that need to be managed by the drainage system.

##### 3.2.1 Functional Resilience

The enhancement of functional resilience using green roofs and rain gardens were evaluated for 144 future scenarios, considering the increasing urbanization and changing climate. A set of 36 scenarios determine the effect of 10 percent (S1) of potential subcatchments provided with LIDs in witch percentage imperviousness and the rainfall intensity

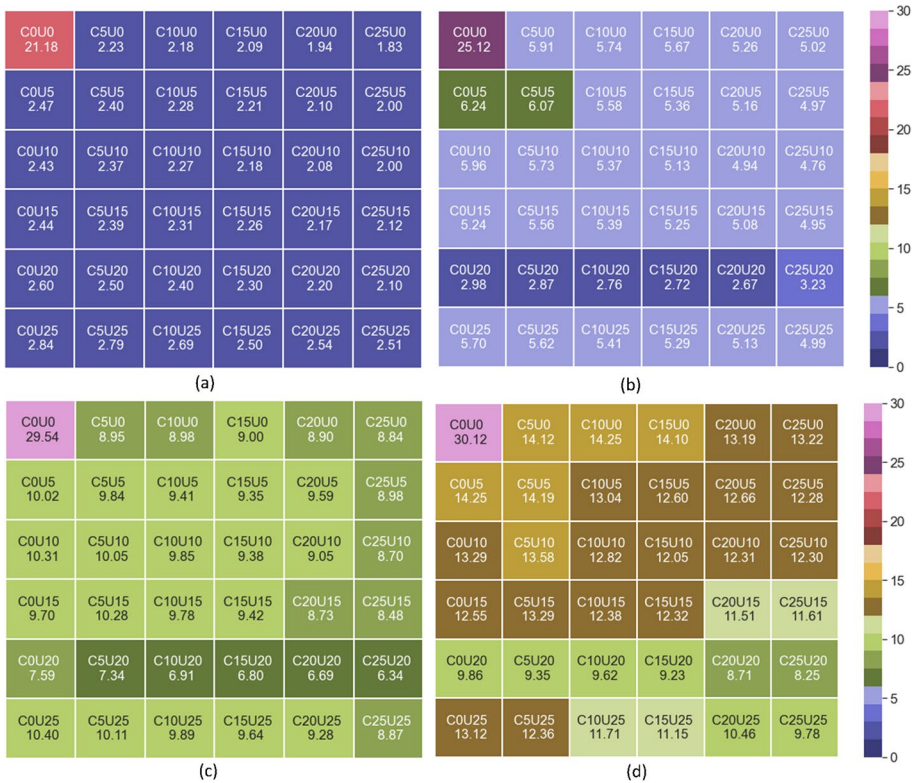


**Fig. 3** Potential Subcatchments under different scenarios for LID implementation

was increased from 5 to 25%. Similarly, other three sets of 36 scenarios considers scenario S2, S3 and S4 of LID implementation on similar axis. As shown in Fig. 4, considering the reference scenario i.e., present scenario of urbanization and climate change, 10% of potential subcatchments provided with rain gardens and green roofs would lead to about 21% increase in functional resilience. Similarly, 25%, 50% and 100% of potential subcatchments provided with rain gardens and green roofs would enhance the function resilience to the tune of 25%, 29% and 30%, respectively.

As discussed in Sect. 2.8.1, LPI is calculated to determine the effectiveness of LIDs in combatting the negative effects of urbanization and climate change in the future scenarios. On determining and assessing the LPI for all the future scenarios (Table S.3) it can be observed that in case of S1, LPI is greater than 1 for scenario C5U0, indicating that LID measures can deal with the climate change. Likewise, in the case of scenario S2, the LID measures are capable of mitigating the effects of climate change in scenarios up to C20, including C5U0, C10U0, C15U0, and C20U0. Alternatively, these measures can address the issue of urbanization in scenario C0U5 or the combined scenario C5U5. In the case of scenario S3, the LID measures are found to counteract the impacts of climate change in most future scenarios, including those involving urbanization up to U10 or the combined scenarios C5U5, C10U5, C15U5, and C5U10. Finally, in the case of scenario S4, the LID measures are capable of mitigating the effects of climate change in nearly all future scenarios or addressing urbanization in scenarios up to U15, or combined scenarios involving C5U5, C10U5, C15U5, C20U5, C25U5, C5U10, C10U10, C15U10, and C5U15.

However, in this case area, it can be observed that though LID measures manifest the distinctive advantages, they cannot deal with the extreme future scenarios and fail to fully retain the volume of runoff that occurs during extreme scenarios. The findings suggest



**Fig. 4** Percentage increase in functional resilience of system w.r.t. reference scenario for scenarios **a** S1 **b** S2 **c** S3 **d** S4

that even when all the potential subcatchments are provided with LID measures, still the extreme combinations of urbanizations and climate change cannot be tackled. Wang et al. (2020) also observed that LIDs retention and storage capacities were exhausted in handling the storm with longer duration and runoff was difficult to control. Wang et al. (2018) inferred that LIDs with limited retention capacities are unable to handle the storm with higher return period.

### 3.2.2 Structural Resilience

The runoff overflow from the nodes reduces the structural resilience of the system. As discussed in Sect. 2.8.2, the nodes having flood volume greater than the threshold ( $\mu + \sigma$ ) were labelled as ‘vulnerable spot’. High value of flood volume over a node reflects the higher vulnerability of the node and weakens the system’s resilience. Thus, to enhance the resilience of the system the performance of vulnerable nodes must be improved.

Inclusion of LIDs can reduce the vulnerability of nodes by decreasing the flood volume over the node. The effect of LIDs in enhancing the system structural resilience under S1, S2, S3 and S4 scenarios was analysed by simulating 748 one-at-a-time link failure scenarios by failing all the 187 links in each of the four scenarios. A total of 23 vulnerable node locations were identified in the study area when no LIDs were

provided. For the scenario S1 i.e., when 10% of potential subcatchments are provided with LIDs the number of vulnerable nodes reduced to 21 (Fig. 5). For scenario S2, the number of vulnerable nodes reduced to 19 and for scenario S3 the number of vulnerable nodes reduced to 15. When 100% of subcatchments are provided with LIDs i.e., scenario S4 the number of vulnerable nodes reduced to 14 (Fig. 5). The decrease in the number of vulnerable nodes represents the increased structural resilience of the system.

The system resilience can be substantially ameliorated if flooding on these nodes are completely prevented. Storage tanks or detention tanks can be provided at these vulnerable spots to further enhance the resilience. It is to be noted, in a real-world system, multiple conduits may fail concurrently, the present study accounts for single link failure scenario.

### 3.3 Cost–benefit Analysis

Cost–Benefit analysis has been carried out using BCR method as discussed in Sect. 2.9. BCR has been evaluated using PVB and PVC to determine the effectiveness of LID combinations in flood reduction. The benefit of LID implementations is interpreted by PVB, which is an integrated indicator and PVC is present value of expenditure incurred during the whole life cycle of a LID measure.

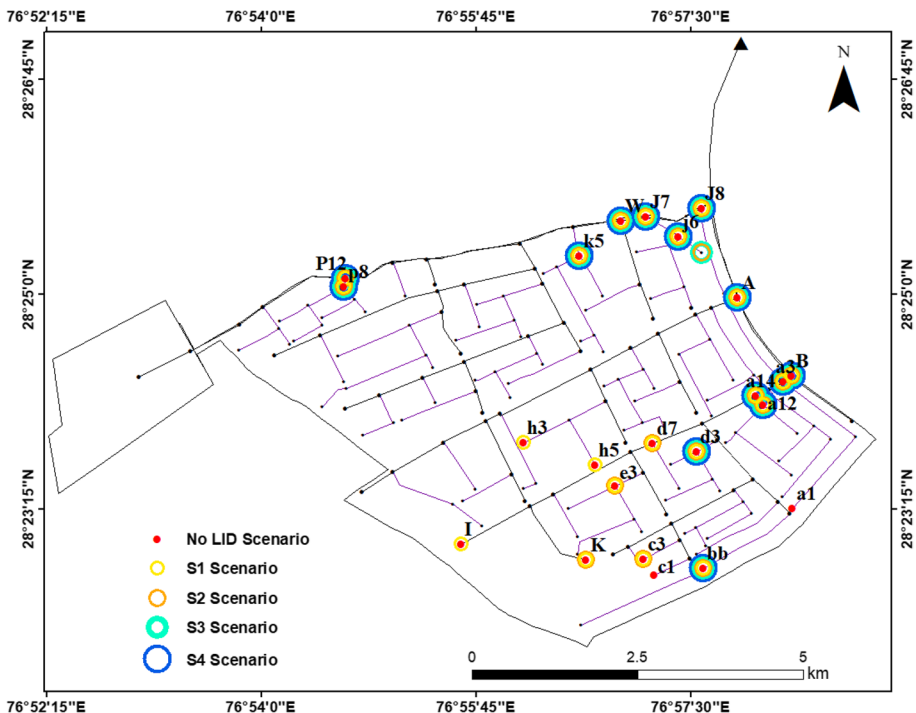


Fig. 5 Vulnerable nodes identified in structural resilience analysis for scenario S1, S2, S3 and S4



### 3.3.1 Present Value of Benefits

As discussed in Sect. 2.9, PVB is an index of hydrological performance of the drainage system. It was calculated using the arithmetic mean of the reduction rates of flood volume, outflow volume, and peak flow for five different design storms of 5, 10, 25, 50 and 100 years return period. The percentage reduction of flood volume, outflow volume, and peak flow for each scenario S1, S2, S3, and S4 were computed with respect to the reference scenario in which no LID was provided in the system.

For the same design storm, the percentage reduction of flood volume, outflow volume, and peak flow increases with the increasing percentage of LID measures as also shown by (Chui et al. 2016; Winston et al. 2016; Wang et al. 2020). From Table 1 it can be observed that percentage reduction in peak flow is greater than flood volume and outflow volume with increasing percentage of LID measures. This illustrates that LIDs are effective in reducing the peak of flow at the source due to its structural retention capacity which establishes them as an important solution for flood mitigation in an urban setup.

For a particular LID scenario (i.e., S1, S2, S3 or S4) the percentage reduction of flood volume, outflow volume, and peak flow decreases with the increasing return period of the rainfall event. The results correspond with the findings of Ayoublu et al. (2024), indicating that the effectiveness of LID practices decreases with an increase in the return period. For scenario S1, the percentage reduction in flood volume varies from 11.43% for a rainfall event of 5-year return period to 5.01% for a storm event of 100-year return period. Similarly, for scenario S4, the percentage reduction in flood volume varies from 51.32% to 28.11% when return period of rainfall event changes from 5-year to 100-year. Greater storm return period generates higher runoff volume and storage and retention capacity of LID practices gets exhausted during heavy storms causing reduced effectiveness of LID practices.

The PVB, as discussed above, is estimated for five different design storms of 5, 10, 25, 50, and 100 years return period using Eq. 5 for each scenario S1, S2, S3, or S4. The PVB increases with the increased percentage of LID in the system. The PVB (in %) for scenario S1; for a flood event of a 5-year return period is 6.1; for S2 is 14.8; for S3 is 22.7; and for S4 is 37.7. In addition to this, it can be inferred from Table 2 that for a particular scenario, PVB decreases with an increasing return period. In the case of scenario S1, for a flood event with a 5-year return period, PVB is 6.1; for a 10-year return period, PVB is 5.0, 25-year return period PVB is 4.0, 50-year return period PVB is 3.2 and 100-year return period PVB is 2.3.

**Table 1** Reduction rate in Flood volume ( $R_f$ ), Outflow volume ( $R_o$ ) and Peak flow ( $R_p$ ) for different return periods in S1, S2, S3 and S4 scenarios

Return period	Scenario S1			Scenario S2			Scenario S3			Scenario S4		
	$R_f$	$R_o$	$R_p$	$R_f$	$R_o$	$R_p$	$R_f$	$R_o$	$R_p$	$R_f$	$R_o$	$R_p$
5 year	11.4	1.6	5.3	25.8	3.7	14.8	38.4	6.2	23.7	51.3	12.2	49.6
10 year	9.5	1.4	4.3	22.2	2.3	13.1	34.2	4.1	21.5	46.2	9.7	31.4
25 year	7.3	1.2	3.5	17.3	1.6	11.8	28.6	2.8	20.0	39.2	7.1	28.0
50 year	6.1	1.1	2.3	14.2	1.3	7.2	24.0	2.1	15.4	33.9	5.7	23.1
100 year	5.0	1.0	0.9	11.4	0.8	1.1	19.2	1.5	1.5	28.1	4.2	5.9

**Table 2** PVB (unit: %) for S1, S2, S3 and S4 scenarios for different return periods

Return period	5 year	10 year	25 year	50 year	100 year
Scenario S1	6.1	5.0	4.0	3.2	2.3
Scenario S2	14.8	12.5	10.2	7.6	4.4
Scenario S3	22.7	19.9	17.1	13.8	7.4
Scenario S4	37.7	29.1	24.8	20.9	12.7

### 3.3.2 Present Value of Costs

PVCs of GR and RG were estimated using Eq. 6, which consists of the unit life-cycle cost including ICC, COM, and SV. The costs of each LID practices used for the LCC estimation in this study are provided in Table 3 (Kumar et al. 2022). The unit LCC of GR and RG practices were estimated as INR 4240.17 and INR 6151.10 (Table 3). The UAAC of combination of GR and RG for each scenario based on the proportion of area under each LID is estimated using Eq. 6 and tabulated in Table 4. It is to be noted that the land costs associated with RG and GR were not taken into account while calculating the LCCs of LIDs assuming that land will be readily available to achieve overarching goals of sustainable development.

**Table 3** Life cycle cost analysis of each LID practice

LID	Unit initial cost	Unit cost of O & M		Unit salvage value		LCC (INR)	UAAC (INR)
		Construction cost (INR/m <sup>2</sup> )	% of Installation cost	Annual O&MC (INR/m <sup>2</sup> )	Projected lifetime (years)		
GR	1678 <sup>a</sup>	6–16%	60–160	20	104.5	4240.17	212.01
RG	3356 <sup>b</sup>	5–7%	100–140	20	114	6151.10	307.55

<sup>a</sup>Kumar et al. 2022 considered the unit implementation cost for GR as INR 1000/- in 2012. Considering the rate of inflation, the unit implementation cost in 2021 is estimated as INR 1678/- using the Consumer Price Index (CPI) formula

<sup>b</sup>For RG construction cost is slightly high therefore, INR 2000/- has been considered as the unit implementation cost for RG and using CPI, the present cost is estimated as INR 3356/-

**Table 4** UAAC of LID combinations for S1, S2, S3 and S4 scenarios for different return periods

	$w_{gr} = \frac{\text{Area under GR}}{\text{Total SC area}}$	$w_{rg} = \frac{\text{Area under RG}}{\text{Total SC area}}$	UAAC <sup>S*</sup> (INR/m <sup>2</sup> )
Scenario S1	0.004	0.007	2.98
Scenario S2	0.017	0.015	8.46
Scenario S3	0.027	0.026	14.03
Scenario S4	0.032	0.041	19.47

\* Unit annual average cost of green roof and rain garden combination in each scenario

### 3.3.3 Benefit—Cost Ratio

The BCR is estimated using Eq. 4 for the combination of GR and RG for five different design storms of 5, 10, 25, 50 and 100 years return period. The BCR for scenario S1, S2, S3 and S4 under rainfall events of different return period are shown in Fig. 6. For all the rainfall events of different return periods, i.e., 5, 10, 25, 50, and 100-year, BCR for scenario S1 is greater than S2, S3, and S4. The reason can be attributed to the lesser area of LIDs under scenario S1, which leads to reduced cost. It can be observed from Fig. 6 that BCR is less than 1 for all the four scenarios under rainfall event of return period 100 years indicating LIDs are uneconomical in dealing with storms of longer return periods. In addition to this, the BCR is less than 1 for scenarios S2 and S3 under rainfall event of return period 50 years. These results are consistent with the results of Wang et al. (2020) that LID measures manifest the distinctive advantages but the BCR decreases with increasing return period of the design storm.

## 4 Barriers in LID

There is a recognized need of nature-based solutions for urban flood risk management yet the uncertainties regarding the public acceptability and hydrological performance, affects the widespread adoption of LIDs. This study identifies the barriers that might be faced by Low Impact Development techniques during the planning, implementation and maintenance stage that creates hinderance in their usage. A wide range of barriers can be found in literature however; the present study demarcates the barriers faced by LIDs in context of developing countries. The identified barriers will aid urban planners, communities and environmental agencies to deal with the challenges that might arise in their respective fields. Also, by exploring the barriers, other LID project planners have experienced, decision makers will be able to anticipate the barriers that their LID projects may face during

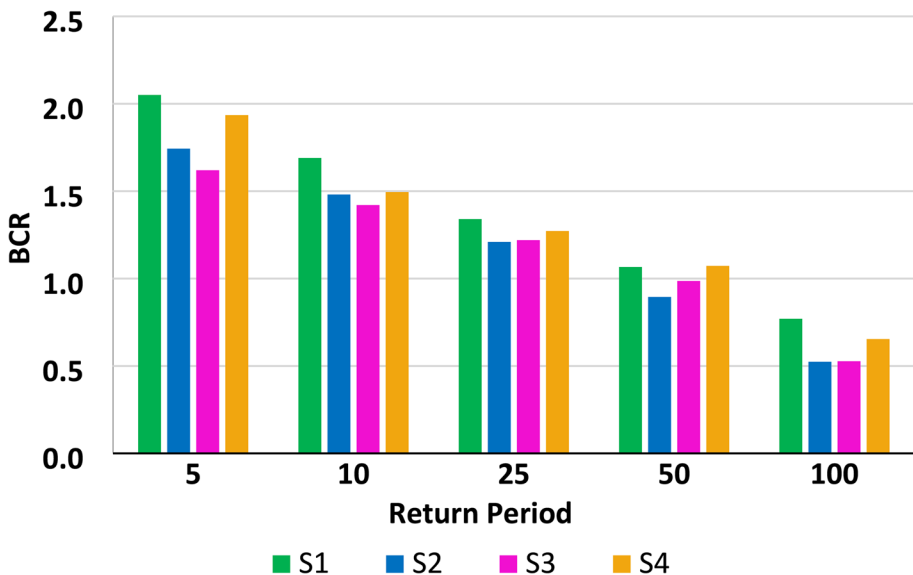
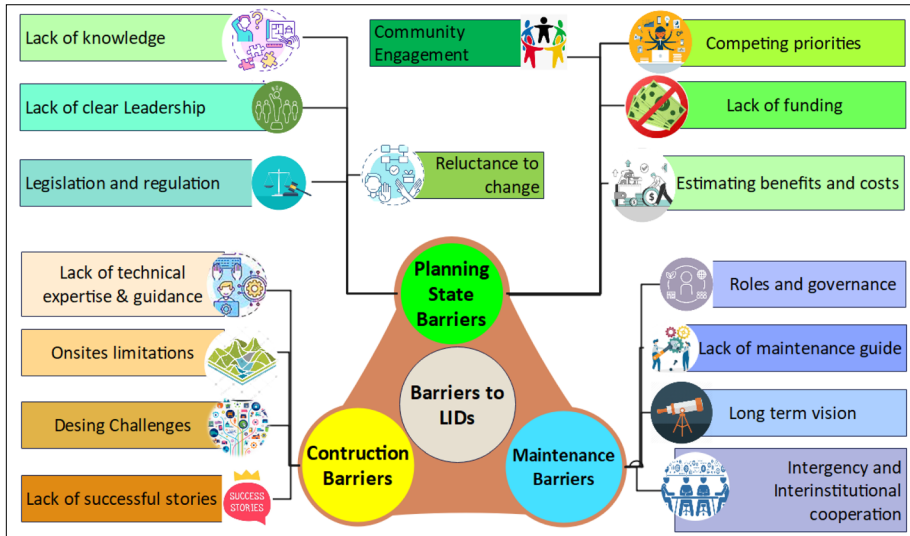


Fig. 6 BCR for scenario S1, S2, S3 and S4 under rainfall events of different return period



**Fig. 7** Barriers to the implementation of LIDs

their lifecycle (Kabisch et al. 2016; Ershad Sarabi et al. 2019). The identified barriers are categorized into three classes i.e. Planning, Maintenance and Construction stage barriers based on the implementation procedure of a LID practice into drainage infrastructure (Fig. 7). Refer Supplementary material for details on further details on this section.

The scientific novelty of the presented work lies in its multifaceted approach to addressing the challenges of urban stormwater management through the implementation of LID techniques. The study quantifies resilience enhancement by categorizing it into functional and structural aspects, providing a detailed understanding of how LIDs mitigate both external threats like urbanization and climate change, as well as internal threats such as system failures. Additionally, the integration of hydrological performance evaluations with a LCC analysis approach offers a comprehensive assessment of the economic viability of LID implementation, aiding in identifying the most cost-effective scenarios. Lastly, by focusing on the Indian context and analyzing the barriers to LID adoption in developing countries, the study contributes to the formulation of efficient policies and guidelines, addressing the challenges faced in implementing nature-based solutions in urban areas. Overall, this holistic approach makes the study scientifically novel and significant in advancing the understanding and implementation of LID techniques for urban stormwater management.

## 5 Conclusion

To support robust decision making regarding the implementation of Low Impact Development (LID) techniques in an urban area to enhance the resilience of a drainage system, the study carries out an integrated assessment to evaluate the enhancement in resilience and determine the cost-effective scenario of LID implementation that can extenuate the urban flooding. Potential subcatchments for green roofs and rain gardens implementation were determined using Potential Subcatchment Index (PSI). Based on the PSI, four scenarios for LID implementation were framed. A comparative analysis among these four scenarios

employing Benefit Cost Ratio (BCR) was carried out to determine the cost-effective solution for resilience enhancement. The enhancement in functional resilience of the drainage system was determined using LID Performance Index (LPI).

- LPI is greater than 1 for 1 scenario when 10% of potential subcatchments are provided with LIDs (i.e., Scenario S1), 6 scenarios when S2, 11 scenarios when S3 and 17 scenarios when 100% of potential subcatchments are provided with LIDs (i.e., Scenario S4).
- For the present scenario of urbanization and climate change 21% functional resilience of the system will get enhanced if S1 is implemented, 25% if S2, 29% if S3 and 30% if S4 will be implemented.
- Structural resilience analysis shows that with the implementation of LIDs the number of vulnerable nodes reduced from 23 (when no LIDs were provided) to 21 for scenario S1, 19 for S2, 15 for S2 and 14 for scenario S4.
- BCR for design storm of 5-year return period has been obtained as 2.05 for S1, 1.74 for S2, 1.62 for S3 and 1.94 for S4.

BCR has been obtained for various return periods it has been observed that BCR decreases with increasing return periods of design storm. It can be concluded from the present study even if all the subcatchments are provided with LIDs the flooding cannot be eliminated completely indicating that LIDs must be provided in combination with conventional drainage infrastructure to mitigate the urban flooding effectively. Further, Planning, Construction and maintenance stage barriers to the implementation of LIDs in developing countries has been identified based on literature. The identified barriers will be useful for various urban planners, communities and environmental agencies to deal with the challenges that might be faced.

Due to lack of detailed drainage network data a part of city is considered for the evaluation, if drainage data for the whole city would be available may lead to few more points which might have been over-sighted. Further, the study limits the use of two LIDs in the present study, multiple LIDs and their combination can be used in the future studies to bring more insight. In addition to this, the benefits obtained due to water quality improvement in LCC analysis of LIDs can be incorporated in future studies.

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**Ethical Approval** The author declares that the manuscript has not been submitted to other journals.

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