Cost-Effective Solutions for Sustainable Urban Flood Mitigation: Comparing LID Practices and Performance Metrics

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Report submitted to
Indian Institute of Technology, Kharagpur
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of

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in

Hydraulics and Water Resources Engineeing

by

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INDIAN INSTITUTE OF TECHNOLOGY KHARAGPUR

April 2025

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DECLARATION

I hereby declare that the work presented in this thesis entitled **Cost-Effective Solutions for Sustainable Urban Flood Mitigation: Comparing LID Practices and Performance Metrics**, submitted to the Indian Institute of Technology Kharagpur for the award of the degree of Master of Technology, is a bona fide record of original research work carried out by me under the supervision of **Dr. Manish Pandey** in the Department of Civil Engineering.
This thesis has been composed solely by me and has been authorized by me for submission. I further declare that the work reported in this thesis has not been submitted, either in part or in full, for the award of any other degree or diploma at this institute or any other institute or university.

Chukka Vinay Kumar
23CE61R06

Place: Kharagpur
Date: April 29, 2025

Department of Civil Engineering
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CERTIFICATE

This is to certify that the Dissertation Report entitled **"Cost-Effective Solutions for Sustainable Urban Flood Mitigation: Comparing LID Practices and Performance Metrics"** submitted by **Mr. Chukka Vinay Kumar (Roll Number: *23CE61R06*)**, a postgraduate student of the **Department of Civil Engineering**, with specialization in **Hydraulic and Water Resources Engineering**, is a record of the bonafide research work carried out by him under my supervision. The Dissertation Report is submitted in partial fulfillment of the requirements for the award of the degree of **Master of Technology**, and I hereby approve the dissertation for submission, having found it to meet the standards and regulations of the Institute.

(Supervisor)
Dr. Manish Pandey
Assistant Professor
Department of Civil Engineering
Indian Institute of Technology,
Kharagpur

Place: Kharagpur
Date:

To

My Father

మత్తః పరతరం నాన్యత్ కిఞ్చిదస్తి ధనఞ్జయ ।
మయి సర్వమిదం ప్రోతం సూత్రే మణిగణా ఇవ ॥

Lord Shree Krishna states about his dominion and his supreme position in this universe. He is the substratum over which this entire creation exists; he is the creator, sustainer, and annihilator. Similar to the beads strung in a thread, which can move in their place, God has given individual souls the free will to act as they wish, yet their existence is bound to him. (***Bhagavad Gita: Chapter 7, Verse 7***)

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This acknowledgment would be incomplete without the mention of my mother (my first teacher) and father, whose constant love and support have given me strength at every step, for which I am forever indebted.

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ABSTRACT

Urban flooding, particularly in fast-urbanized areas, is a key threat that arises from increasing impervious areas paired with poor stormwater management. This study aims to assess the performance of different categories of Low Impact Development (LID) practices, such as Bioretention Cells (BRC), Permeable Pavements (PP), and Rain Barrels (RB), for urban flood mitigation in Bharatpur, India. Results for pre-development, post-development, and LID-fitted situations were simulated with the Storm Water Management Model (SWMM) in association with high-resolution spatial data and long-time rainfall records. New performance metrics, such as the LID Hydrological Restoration Index (LHRI), Hydrological RestorationCost Efficiency Index (HRCEI), and Hydrological Volume Reduction Cost Efficiency Index (HVCEI), were introduced to measure hydrological benefits and economic feasibility. The LID interventions decreased total outfall volume by 73.82% peak runoff by 92.81% and flood volume by 78.59% respectively. Results showed that the combined implementation of LID practices maximized the LHRI value to 83.58% indicating significant hydrological restoration. The BRC was found to be the most cost-effective solution with an HRCEI value of 0.11, while PP and RB had a value of 0.09, respectively. To survive immense flood impacts and sustainable stormwater management, we highlighted the integrationof LID with urban planning. This study underscores the important role of nature-based solutions, in addressing urban flooding and in achievinglong-term hydrological sustainability, especially in the developing world.

Keywords: LID and SWMM, Urban Flooding, Storm Water Management, Bioretention Cell, Permeable Pavement, Rain Barrels, Cost Analysis

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$\%Imperv$	Impervious surface fraction	$[\%]$
$\%Perv$	Pervious surface fraction	$[\%]$
$\bar{n}$	Flow exponent	$[fraction]$
ϕ	Porosity	$[fraction]$
ψ	Suction head	$[mm]$
C	Total cost of each LID case	[₹$Lakhs$]
c	Flow coefficient	$[fraction]$
$C1$	Catchmant 1	$[-]$
C_1	Case 1	$[-]$
C_f	Clogging factor	$[fraction]$
C_s	Conductivity slope	$[fraction]$
D	Drain delay	$[hrs]$
e	Void ratio	$[fraction]$
f	Infiltration rate	$[mmhr]$
FC	Field capacity	$[fraction]$
h	Berm height	$[mm]$
K	Conductivity	$[mmhr]$
n	Surface roughness	$[fraction]$
NSE	Nash - Sutcliffe Efficiency	$[fraction]$

O	Drain offset height	$[mm]$
P	Permeability	$[mmhr]$
R^2	Coefficient of Determination	$[fraction]$
S_o	Surface slope	$[fraction]$
$Seep$	Seepage rate	$[mmhr]$
t	Soil thickness	$[mm]$
t_c	Time of concentration	$[hrs]$
t_s	Storage thickness	$[mm]$
$VegFrac$	Vegetation volume fraction	$[fraction]$
WP	Wilting point	$[fraction]$
X_{Casei}	Processed output from other cases (i = 3 means C_3 (BRC)	$[-]$
X_{Post}	Processed output from C_2 (Post)	$[-]$
X_{Pre}	Processed output from C_1 (Pre)	$[-]$

Chapter 1

Introduction

Urban flooding has emerged as a major problem in rapidly urbanizing regions across the world, primarily due to the spread of impervious surfaces that interfere with natural hydrological cycles (Kumar et al., 2024). Conventional stormwater management systems are often unable to handle extreme precipitation events, resulting in flooding, economic loss, and environmental degradation (Berndtsson, 2010; O'Donnell et al., 2017). Urban hydrology and flood mitigation approaches have been studied widely in previous research, asserting that stormwater management has to be sustainable (Ahmed et al., 2024; Elliott & Trowsdale, 2007). Traditional drainage infrastructure, which consists mainly of storm drains and culverts, aims to rapidly transport runoff away from cities. However, these systems are not necessarily efficient in managing increasingly frequent and intense rainfall occurrences, especially in highly populated areas (Hoang et al., 2024; Xiao et al., 2024). Consequently, Low Impact Development (LID) strategies are gaining traction as sustainable and decentralized solutions to stormwater issues in urban settings (D'ambrosio et al., 2021).

Many studies have evaluated the potential benefits of LID technologies, including Green Roofs (GR), Bioretention Cells (BRC), Rain Barrels (RB), and Permeable Pavements (PP) in regard to managing urban flooding. These methods operate through improved infiltration, decreased surface runoff, and increased groundwater recharge (Ahiablame et al., 2012). Eskandaripour & Soltaninia (2024) showed that peak runoff significantly reduces and improves water retention effects in urban environments using LID techniques. Likewise, the study by Fletcher et al. (2013) underscored green infrastructure's effectiveness in controlling urban stormwater, noting its importance in lowering flood risks and enhancing water quality. Research by Hua et al. (2020) and Khorashadi et al. (2024) assert that LID techniques are effective in increasing flood resilience throughout many other urban scenarios. However, most existing studies tend to concentrate on individual LID practices or strategies rather than holistic, tailored approaches that also consider the wider urban context (Barbaro et al., 2021).

What distinguishes this study from past research is that it assessed a range of LID practices as part of an integrated stormwater management framework tailored to the condition of Bharatpur, India. In contrast to previous studies that frequently focus on qualitative evaluations or employ simplified hydrology models, this work utilizes a rigorous modeling structure with the Storm Water Management Model (SWMM) to objectively evaluate the performance of LID strategies (Eckart et al., 2017; Rossman, 2010). Additionally, although the performance of LID has been evaluated in most studies through conventional hydrological parameters, such as volume and peak flow of runoff, this study applies novel modified metrics for the characterization of flood mitigation efficiency in a more comprehensive way (Tan & Taeihagh, 2020). The LID Hydraulic Restoration Index (LHRI) and Hydrological Restoration Cost Efficiency Index (HRCEI) offer a detailed overview of the extent of LID practice effectiveness while accounting for cost-effectiveness.

These new modified metrics fill an important gap in the literature. Traditional assessments often do not represent the trade-offs between hydrological performance and economic feasibility, which can result in suboptimal decisions in urban planning (Roy et al., 2008). With the inclusion of LHRI, this study presents a common metric that can be used to assess to what degree LID measures and mimics natural hydrological processes. On the other hand, HRCEI enables urban planners to evaluate the cost-effectiveness of LID practices, assisting them in determining which areas are filtered to allocate a budget. This system helps to ensure that flood mitigation strategies are not just hydrologically effective but also economically viable.

As climate change leads to an increase in extreme weather events, the demand for resilient urban stormwater management strategies has become even more pressing (Chae et al., 2024). Conventional flood mitigation schemes like comprehensive drainage networks and detention basins typically need large capital investment and prolonged maintenance (Eckart et al., 2018; Jang et al., 2024). Similarly, because LID practices are cost-effective and environmentally sustainable, they can help to support contemporary urban resilience approaches

This study is also distinguished by its contextual relevance, addressing an issue precipitated by rapid urbanization and regular flooding in the growing city of Bharatpur. Most studies on LID practices are focused on developed countries with more advanced stormwater separation infrastructure, but literature on the applicability of LID practices in developing regions is relatively scarce (Cheng et al., 2024). This study fills this gap as it evaluates the feasibility and effectiveness of LID techniques in an urban landscape with stormwater management challenges due to unplanned development and insufficient drainage infrastructure.

1.1 Aim

This study aims to evaluate the effectiveness of various LID practices, specifically BRC, PP, and RB in mitigating urban flooding in Bharatpur, India, where rapid urbanization and poor stormwater infrastructure have intensified flood risks. Using the SWMM, simulations were carried out for pre-development, post-development, and LID-implemented scenarios by integrating long-term rainfall data and high-resolution spatial inputs. The study further introduces and applies new performance metrics LHRI, HRCEI, and HVCEI to evaluate both hydrological benefits and economic feasibility of the interventions. By identifying the most effective and cost-efficient LID strategies, this study aims to support sustainable stormwater management and promote the integration of nature-based solutions into urban planning, particularly in flood-prone areas of developing countries.

1.2 Objectives

The objectives of this study involve:

1. To evaluate the effectiveness of various LID methods: BRC, PP, and RB in minimizing the total peak runoff, outlet volume, and flood volume, to quantitatively determine their roles in the hydrological recovery to pre-development hydrological conditions with novel modified performance metrics (LHRI, HRCEI, and HVCEI).

2. To evaluate the hydraulic performance of various LID cases involving combinations of LID practices for urban flood control based on conventional hydrological indices and the restoration of natural hydrological conditions.

3. To identify the most effective and economical combination of LID practices to mitigate the adverse effects of urbanization on stormwater management practices and prioritize solutions that most closely replicate pre-development hydrology and are economically viable.

1.3 Scope

To achieve the aforementioned objectives, the study is conducted under the following constraints:

1. The study focuses on the urban catchment of Bharatpur, India, with specific hydrological and land-use characteristics used for model calibration and analysis.

2. Only three types of LID practices are considered: BRC, PP, and RB, either in isolation or in combination.
3. The simulations are performed using the SWMM, assuming consistent soil, rainfall, and infiltration parameters across different LID scenarios.
4. The economic analysis is limited to construction and implementation costs; operation and maintenance costs over the long term are not considered in detail.

Chapter 2

Model Calibration and Validation

Before using the SWMM for result-driven simulations, a rigorous calibration process is necessary to accurately represent runoff at a predefined junction. Statistical metrics such as Nash-Sutcliffe Efficiency (NSE) and the coefficient of determination (R^2) are commonly used to evaluate model consistency and validate its reliability (Gündel & Önac, 2024).

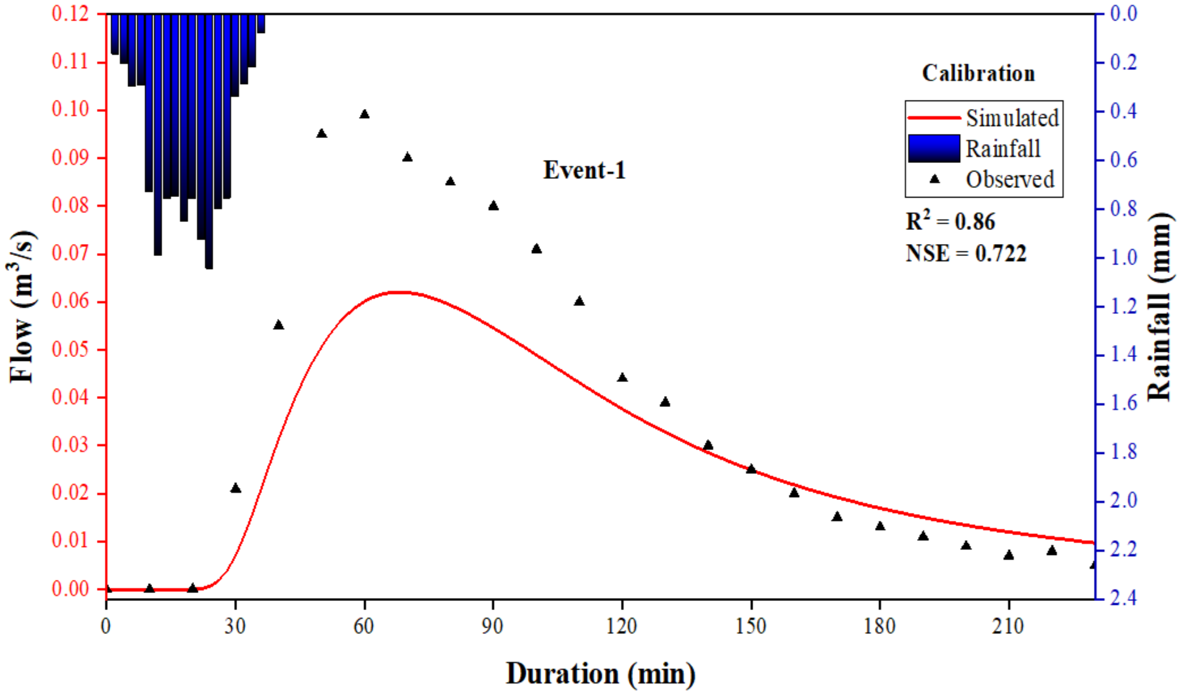

Figure 2.1 Model Calibration with Event-1

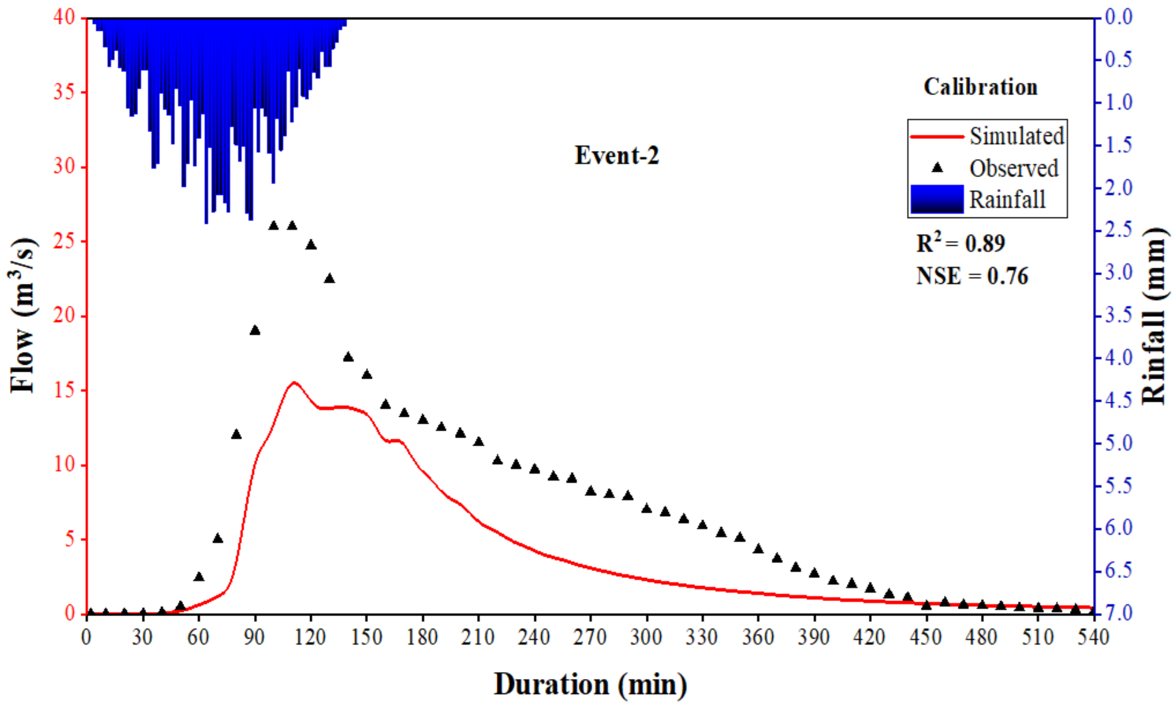

Figure 2.2 Model Calibration with Event-2

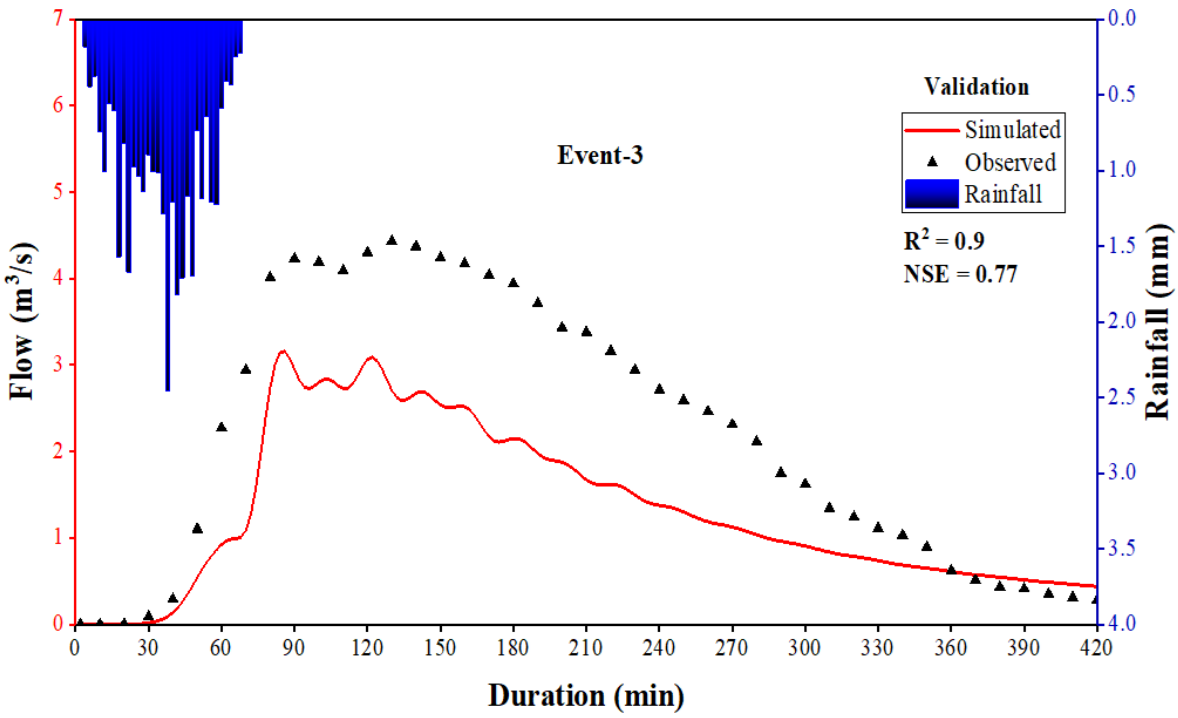

Figure 2.3 Model Validation with Event-3

This study employed SWMM to analyze and predict stormwater runoff, ensuring accuracy through an extensive calibration and validation process (Abdalla et al., 2024; Baltaci & Kalin, 2024). Three rainfall events, representing both low and high rainfall intensities, were used for this purpose. Calibration was performed using two events: low rainfall on September 11, 2024, and high rainfall on September 12, 2024. The model parameters were iteratively adjusted to align simulated runoff with observed data, demonstrating the model's ability to reproduce runoff under varying rainfall conditions (Figure 2.1, Figure 2.2) (Fan et al., 2024). Validation was conducted using the remaining event on September 13, 2024. This step assessed the calibrated model's predictive capability without further parameter adjustments, confirming its robustness and generalizability to new rainfall events (Figure 2.3) (Hasankhan et al., 2024).

The inclusion of both low- and high-intensity rainfall events ensured that the SWMM model was tested across diverse hydrological conditions. Performance metrics were calculated based on observed rainfall and discharge data from the three events (Figure 2.1, Figure 2.2, Figure 2.3). The model exhibited strong efficiency, with NSE values between 0.72 and 0.77. R^2 values ranging from 0.86 to 0.90, indicating a high correlation between observed and simulated data.

This rigorous calibration and validation process ensures that the SWMM model reliably represents stormwater runoff across varying hydrological conditions, making it suitable for further analysis and scenario simulations.

Chapter 3

Materials and Methods

3.1 Study area and data

The study was carried out in Bharatpur, western Rajasthan, India, a famous city that has seen great urban growth in recent years. The population was approximately 3,14,457 as of 2021, reaffirming the city's existence as a prospering urban hub. It is estimated that by 2031, the population of Bharatpur will reach approximately 3,87,475, which justifies the constant development of the city. In the year 2024 (late), the State Government of Rajasthan announced the formation of the Bharatpur Development Authority (BHDA), which will be responsible for the development of urban and rural areas of Bharatpur district. The study area is bounded by the Ranjit Nagar Flood Control Drain (RNFCD) and the Giriraj Canal. This stretch of Bharatpur was chosen because of its perennial flooding problem. The total study area is around 3.1 km^2 (Figure 3.2), and some parts of this study area are prone to flooding, even in moderate rainfall events (Figure 3.1).

Keoladeo National Park, formerly Bharatpur Bird Sanctuary, is a UNESCO World Heritage Site located in Rajasthan, India. A key avian breeding and migratory center, it attracts thousands of birds, including those that are endangered, like the Siberian crane. However, the rapid urbanization is a dire threat to its fragile ecosystem. The few remaining bird habitats are disturbed due to encroachment, pollution, deforestation, and water scarcity which ultimately lead to declining bird populations. Also, the growing human activity disrupts the natural balance and threatening biodiversity. Efforts must be made to conserve this ecological gem.

Figure 3.1 Flooding in (a) Keshav Nagar, 27°12’27.5”N 77°28’13.5”E, (b) Ranjit Nagar, 27°13’53.7”N 77°29’05.1”E, (c) government school, 27°12’58.1”N 77°30’19.5”E, (d) RIICO industrial area, 27°14’07.0”N 77°30’21.1”E, in Bharatpur.

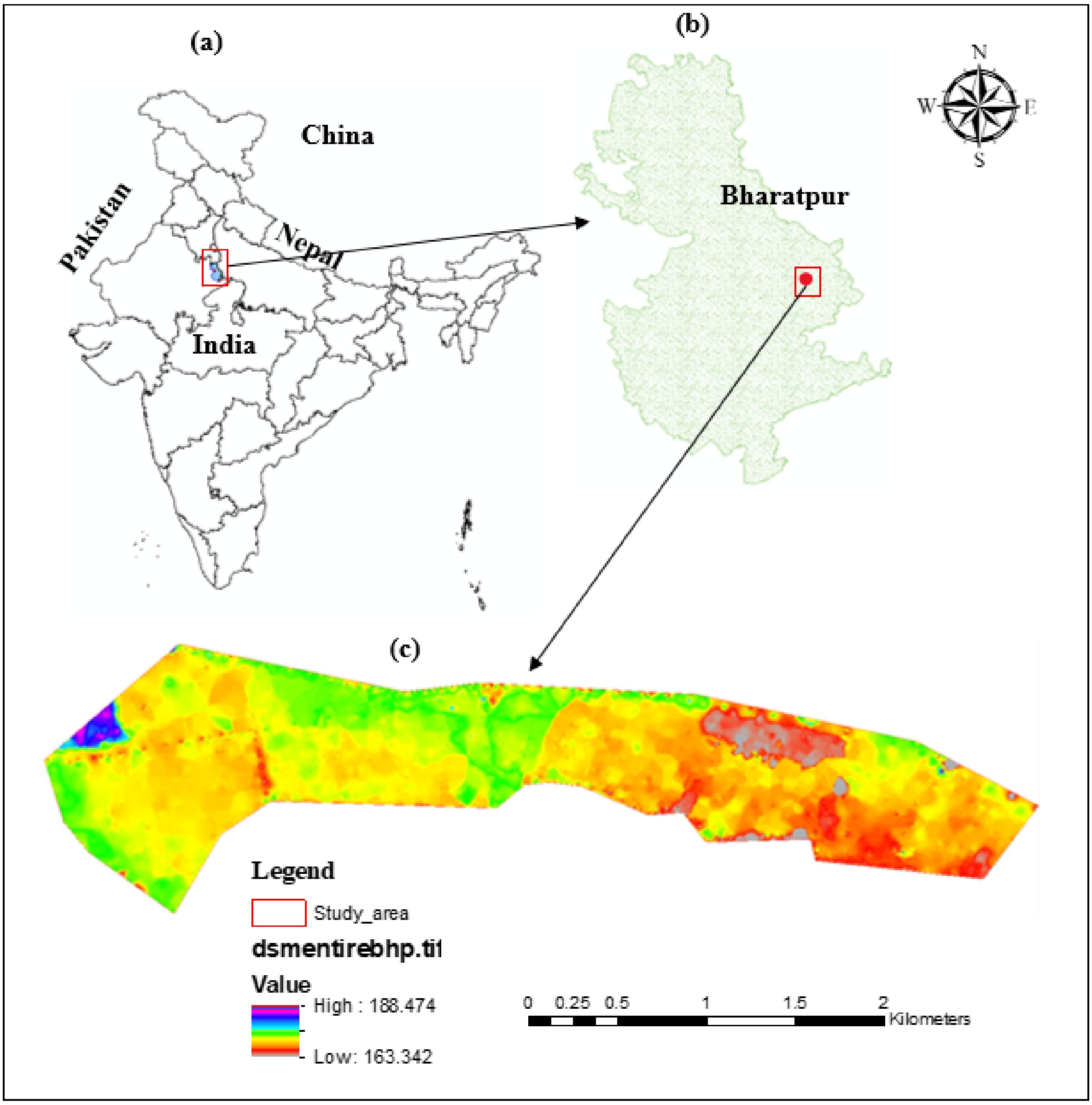

Figure 3.2 Map of India (a), Bharatpur (b), and the study area (c) covered with DEM.

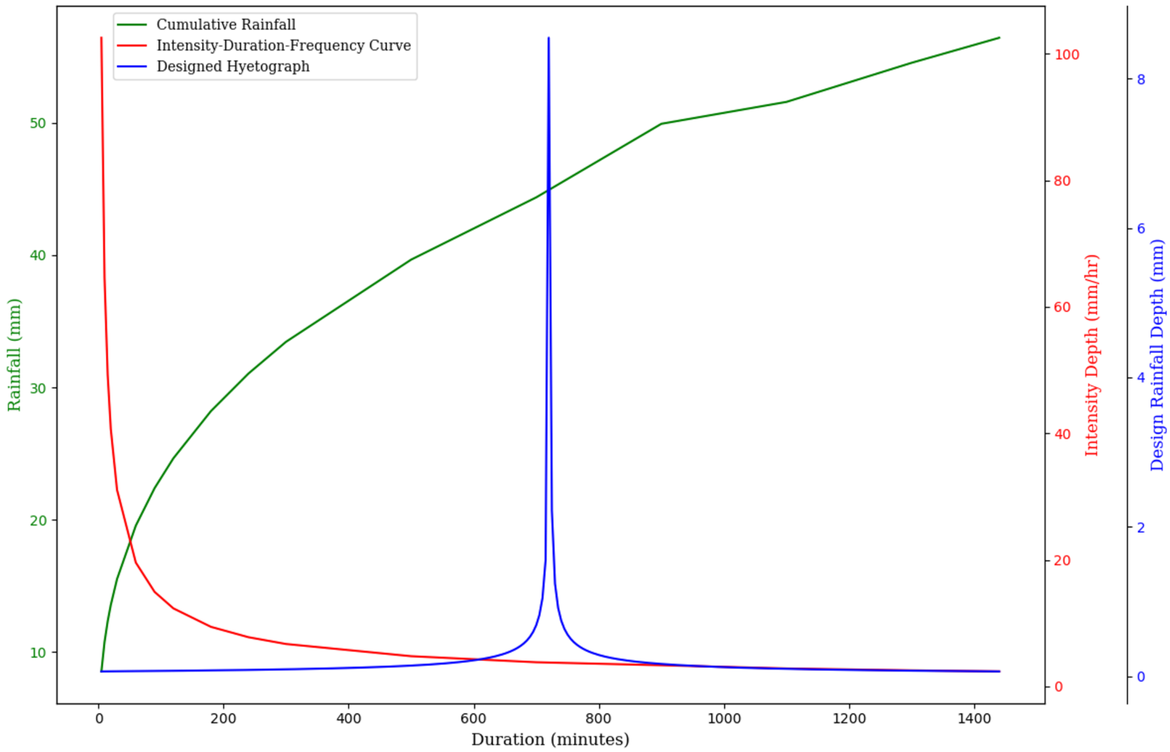

Figure 3.3 Hyetograph generated for a 2-year return period.

A high-resolution Digital Elevation Model (DEM) of 2024 with a cell size of 12.5 m was acquired from ISRO Bhoonidhi Portal. Hourly data on rainfall from the period 2013 to 2023 was used for this study area from the Indian Meteorological Department (IMD) website. The data were then analyzed to interpret historical rainfall trends and produce the design storm hyetograph (Bourque et al., 2005). The Gumbel's Extreme Value distribution was used by the research team to acquire rainfall depth (Figure 3.3) and Intensity-Duration-Frequency curves (IDF) (Figure 3.3) (Jia et al., 2024). These were subsequently used to produce 24-hour design hyetograph that corresponds to the 2-year return period (Figure 3.3) (Table 3.1) (Chitrakar et al., 2023). In the Alternating Block Method (ABM), the rainfall was accurately adjudged temporal distribution (Watt et al., 1986). The time interval for the designed storm event should be less than 16^{th} of the time of concentration (t_c), which is 5 minutes considered for the generation of the design hyetograph (Jin & Fang, 2023).

Table 3.1 Duration, Rainfall Depth, and Intensity by Gumbel Distribution, and Design Rainfall Data by Alternative Block Method for Various Durations.

Duration (min)	**Depth** (mm)	**Intensity** ($mmhr$)	**Design Rainfall** (mm)
5	8.545	102.54	0.066
10	10.766	64.596	0.066
15	12.324	49.296	0.066
20	13.564	40.693	0.066
25	14.612	35.068	0.067
30	15.527	31.055	0.067
35	16.346	28.022	0.067
40	17.09	25.635	0.068
45	17.774	23.699	0.068
50	18.41	22.092	0.068
55	19.004	20.732	0.069
60	19.563	19.563	0.069
65	20.092	18.547	0.069
70	20.595	17.653	0.070
75	21.074	16.859	0.070
80	21.532	16.149	0.071
85	21.972	15.509	0.071
90	22.394	14.930	0.071
95	22.802	14.401	0.072
100	23.195	13.917	0.072
105	23.575	13.471	0.072
110	23.944	13.060	0.073
115	24.301	12.679	0.073
120	24.648	12.324	0.074
125	24.986	11.993	0.074
130	25.315	11.684	0.074
135	25.635	11.393	0.075
140	25.948	11.120	0.075
145	26.253	10.863	0.076
150	26.551	10.621	0.076
155	26.843	10.391	0.077
160	27.129	10.173	0.077
170	27.683	9.770	0.078
180	28.215	9.405	0.079
190	28.728	9.072	0.080
200	29.224	8.767	0.081
210	29.703	8.486	0.082
220	30.167	8.227	0.083
230	30.617	7.987	0.084
240	31.055	7.764	0.085
250	31.480	7.555	0.087
260	31.894	7.360	0.088
270	32.298	7.177	0.089
280	32.692	7.005	0.091
290	33.077	6.843	0.092
300	33.453	6.691	0.093
310	33.820	6.546	0.095
320	34.180	6.409	0.096
330	34.533	6.279	0.098
340	34.878	6.155	0.100
350	35.216	6.037	0.102
360	35.549	5.925	0.103
370	35.875	5.818	0.105
380	36.195	5.715	0.107
390	36.510	5.617	0.110
400	36.819	5.523	0.112
410	37.124	5.433	0.114
420	37.423	5.346	0.117
430	37.718	5.263	0.119
440	38.008	5.183	0.122
450	38.294	5.106	0.125
460	38.575	5.032	0.128
470	38.853	4.960	0.132
480	39.126	4.891	0.135

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Duration (min)	**Depth** (mm)	**Intensity** ($mmhr$)	**Design Rainfall** (mm)
490	39.396	4.824	0.139
500	39.663	4.760	0.143
510	39.925	4.697	0.148
520	40.184	4.637	0.153
530	40.440	4.578	0.158
540	40.693	4.521	0.164
550	40.943	4.466	0.170
560	41.189	4.413	0.177
570	41.433	4.361	0.185
580	41.674	4.311	0.193
590	41.912	4.262	0.203
600	42.148	4.215	0.214
605	42.264	4.192	0.22
610	42.381	4.169	0.227
615	42.496	4.146	0.234
620	42.611	4.124	0.242
625	42.725	4.102	0.25
630	42.839	4.08	0.259
635	42.952	4.058	0.269
640	43.064	4.037	0.28
645	43.176	4.016	0.292
650	43.287	3.996	0.305
655	43.398	3.975	0.32
660	43.508	3.955	0.338
665	43.618	3.935	0.357
670	43.727	3.916	0.38
675	43.835	3.896	0.407
680	43.943	3.877	0.44
685	44.051	3.858	0.479
690	44.158	3.84	0.529
695	44.264	3.821	0.594
700	44.37	3.803	0.684
705	44.475	3.785	0.819
710	44.58	3.767	1.047
715	44.685	3.75	1.558
720	44.789	3.732	8.545
725	44.892	3.715	2.221
730	44.995	3.698	1.24
735	45.098	3.681	0.916
740	45.2	3.665	0.744
745	45.301	3.648	0.635
750	45.402	3.632	0.559
755	45.503	3.616	0.503
760	45.603	3.6	0.458
765	45.703	3.585	0.423
770	45.802	3.569	0.393
775	45.901	3.554	0.368
780	46	3.538	0.347
785	46.098	3.523	0.329
790	46.195	3.509	0.313
795	46.293	3.494	0.298
800	46.39	3.479	0.286
805	46.486	3.465	0.274
810	46.582	3.451	0.264
815	46.678	3.436	0.254
820	46.773	3.422	0.246
825	46.868	3.409	0.238
830	46.962	3.395	0.23
835	47.056	3.381	0.223
840	47.15	3.368	0.217
845	47.244	3.355	0.211
850	47.337	3.341	0.206
855	47.429	3.328	0.201
860	47.521	3.315	0.196
865	47.613	3.303	0.191
870	47.705	3.29	0.187

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Duration (min)	**Depth** (mm)	**Intensity** ($mmhr$)	**Design Rainfall** (mm)
875	47.796	3.277	0.183
880	47.887	3.265	0.179
885	47.978	3.253	0.175
890	48.068	3.241	0.172
895	48.158	3.228	0.169
900	48.247	3.216	0.165
905	48.336	3.205	0.162
910	48.425	3.193	0.159
915	48.514	3.181	0.157
920	48.602	3.17	0.154
925	48.69	3.158	0.152
930	48.777	3.147	0.149
935	48.865	3.136	0.147
940	48.952	3.125	0.145
945	49.038	3.114	0.142
950	49.124	3.103	0.14
955	49.211	3.092	0.138
960	49.296	3.081	0.136
965	49.382	3.07	0.134
970	49.467	3.06	0.133
975	49.552	3.049	0.131
980	49.636	3.039	0.129
985	49.721	3.029	0.128
990	49.804	3.018	0.126
995	49.888	3.008	0.124
1000	49.972	2.998	0.123
1005	50.055	2.988	0.122
1010	50.138	2.978	0.12
1015	50.22	2.969	0.119
1020	50.303	2.959	0.117
1025	50.385	2.949	0.116
1030	50.466	2.94	0.115
1035	50.548	2.93	0.114
1040	50.629	2.921	0.112
1045	50.71	2.912	0.111
1050	50.791	2.902	0.11
1055	50.871	2.893	0.109
1060	50.952	2.884	0.108
1065	51.032	2.875	0.107
1070	51.111	2.866	0.106
1075	51.191	2.857	0.105
1080	51.27	2.848	0.104
1085	51.349	2.84	0.103
1090	51.428	2.831	0.102
1095	51.506	2.822	0.101
1100	51.585	2.814	0.1
1105	51.663	2.805	0.099
1110	51.741	2.797	0.099
1115	51.818	2.788	0.098
1120	51.895	2.78	0.097
1125	51.973	2.772	0.096
1130	52.049	2.764	0.095
1135	52.126	2.756	0.094
1140	52.203	2.748	0.094
1145	52.279	2.739	0.093
1150	52.355	2.732	0.092
1155	52.431	2.724	0.092
1160	52.506	2.716	0.091
1165	52.581	2.708	0.09
1170	52.657	2.7	0.09
1175	52.731	2.693	0.089
1180	52.806	2.685	0.088
1185	52.881	2.677	0.088
1190	52.955	2.67	0.087
1195	53.029	2.663	0.086
1200	53.103	2.655	0.086

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Duration (min)	**Depth** (mm)	**Intensity** ($mmhr$)	**Design Rainfall** (mm)
1205	53.176	2.648	0.085
1210	53.25	2.64	0.085
1215	53.323	2.633	0.084
1220	53.396	2.626	0.083
1225	53.469	2.619	0.083
1230	53.542	2.612	0.082
1235	53.614	2.605	0.082
1240	53.686	2.598	0.081
1245	53.758	2.591	0.081
1250	53.83	2.584	0.08
1255	53.902	2.577	0.08
1260	53.973	2.57	0.079
1265	54.045	2.563	0.079
1270	54.116	2.557	0.078
1275	54.187	2.55	0.078
1280	54.258	2.543	0.077
1285	54.328	2.537	0.077
1290	54.398	2.53	0.076
1295	54.469	2.524	0.076
1300	54.539	2.517	0.076
1305	54.609	2.511	0.075
1310	54.678	2.504	0.075
1315	54.748	2.498	0.074
1320	54.817	2.492	0.074
1325	54.886	2.485	0.073
1330	54.955	2.479	0.073
1335	55.024	2.473	0.073
1340	55.092	2.467	0.072
1345	55.161	2.461	0.072
1350	55.229	2.455	0.071
1355	55.297	2.449	0.071
1360	55.365	2.443	0.071
1365	55.433	2.437	0.07
1370	55.501	2.431	0.07
1375	55.568	2.425	0.07
1380	55.635	2.419	0.069
1385	55.702	2.413	0.069
1390	55.769	2.407	0.069
1395	55.836	2.402	0.068
1400	55.903	2.396	0.068
1405	55.969	2.39	0.068
1410	56.035	2.384	0.067
1415	56.102	2.379	0.067
1420	56.168	2.373	0.067
1425	56.233	2.368	0.066
1430	56.299	2.362	0.066
1435	56.365	2.357	0.066
1440	56.43	2.351	0.065

Some of the important factors taken into account concerning the selection of 24-hour design rainfall event with a return period of 2 years as the baseline design of LID performance evaluation in the SWMM model are as follows. A return period of 2 years is often preferred as it helps to check the resilience of the drainage system to be able to withstand regular storm events. The second reason is that 24-hour representation simulates an extended event that challenges the drainage structure's maximum capacity. Finally, LID practices are often aimed at capturing runoff from the smaller, more frequent storms that constitute a large volume of overall flooding, according to research (Ahmad et al., 2025). As a result, the 24-hour duration storm with a return period of 2 years serves as an appropriate point of comparison for assessing

LID practice effectiveness in the SWMM framework.

3.2 Model

The EPA-SWMM was chosen for this study owing to its ability to model the performance of multiple LID practices integrated into an urban drainage network (Rossman, 2010). One of the well-known software tools for urban hydrology research is SWMM, which is widely used to model the hydrological effects of urbanization and assess stormwater management measures. Given its unique features like built-in LID controls and computational efficiency, the software is ideally suited to conduct this research, which evaluates the convincingness of LIDs in reducing flood hazards in a quickly urbanizing region such as Bharatpur. The SWMM model is developed with the Rainfall-Runoff and Flow Routing process models, Modified Green-Ampt Infiltration method, and Dynamic Wave routing model, which guarantees appropriate hydrologic and hydraulic projections (Greenberg & Langseth, 2015). The detailed soil type characteristics in the studied area were derived from the India Water Resources Information System (WRIS). The infiltration model parameters (suction head, hydraulic conductivity, and Initial deficit) for the Modified Green-Ampt Model were taken from the SWMM user manual for site soil characters. Using SWMM, the study allowed detailed simulation of individual LID cases (PP, BRC, and RB) to assess the effectiveness of such measures towards restoring baseline hydrological conditions during precipitation events and improving stormwater management performance (Khan et al., 2025). We built a hydrologic SWMM-based model that included the study site's topography, land use, and drainage infrastructure of the site.

3.3 LID practices considered

The LID practices analyzed in this study consisted of BRC (Figure 3.4a), PP Figure 3.4b), and RB (Figure 3.4c) (Motovalibashi et al., 2024). BRCs are shallow vegetated depressions that intercept and temporarily store rainfall, encouraging infiltration and evapotranspiration (Davis et al., 2009). PP are pervious surfaces that allow rainwater to infiltrate through them; sometimes, this reduces runoff and encourages groundwater recharge (Abreu & Goncalves, 2020). RB are cisterns that catch runoff from roofs and help store it for non-potable uses like irrigation, decreasing the overall volume of stormwater (Henderson & Demond, 2007).

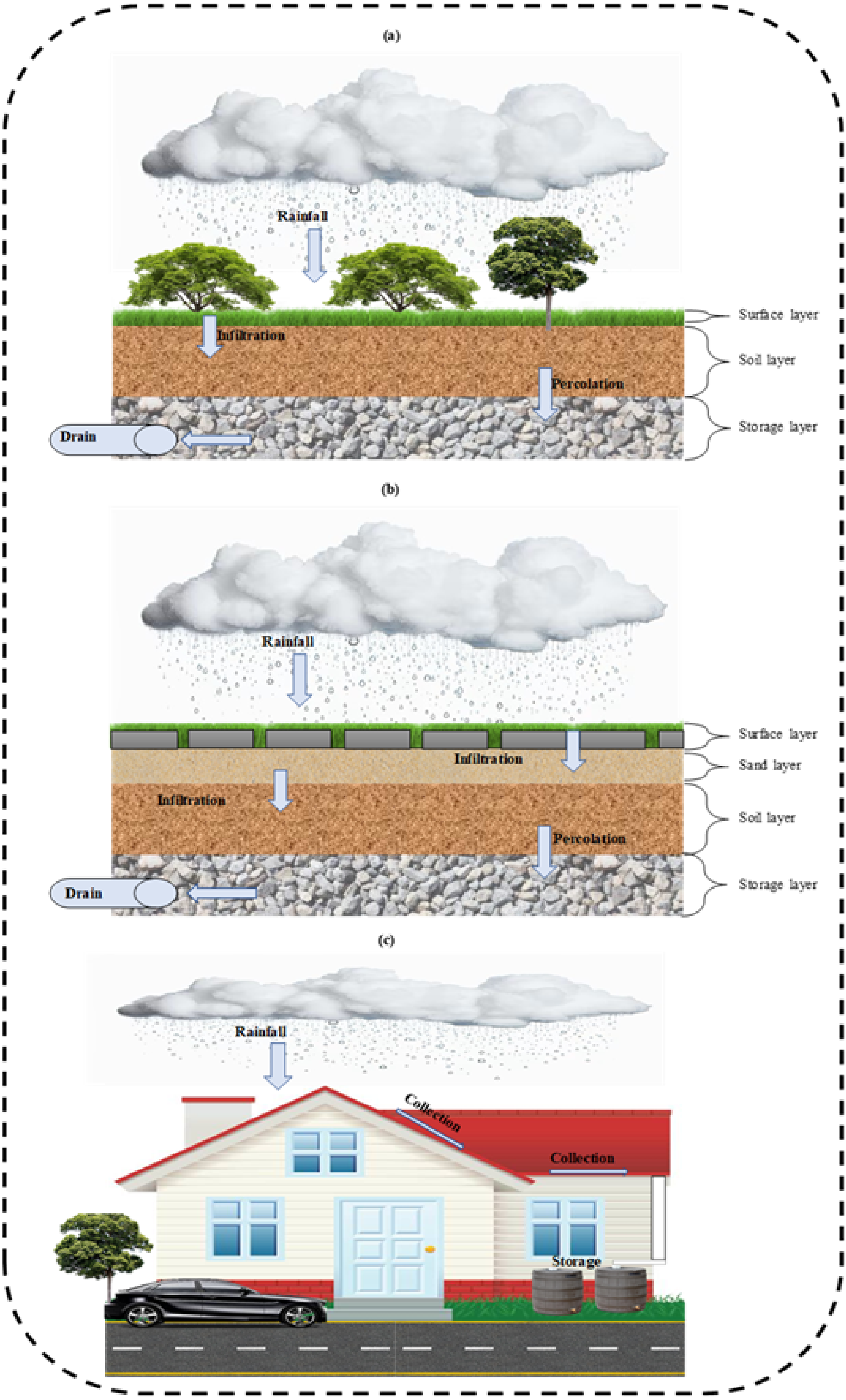

Figure 3.4 Different LID practices: (a) Bioretention cell (BRC), (b) Permeable Pavement (PP), (c) Rain Barrels (RB).

Using the model, the hydrological performance of these LID practices was simulated in terms of peak runoff, flood volume, and total outfall volume. A new performance matrix was modified to assess how efficiently the LID practices restored the pre-development hydrological pattern.

3.4 Development of study cases

Three primary cases were evaluated during the study to find the convincingness of LID practices.

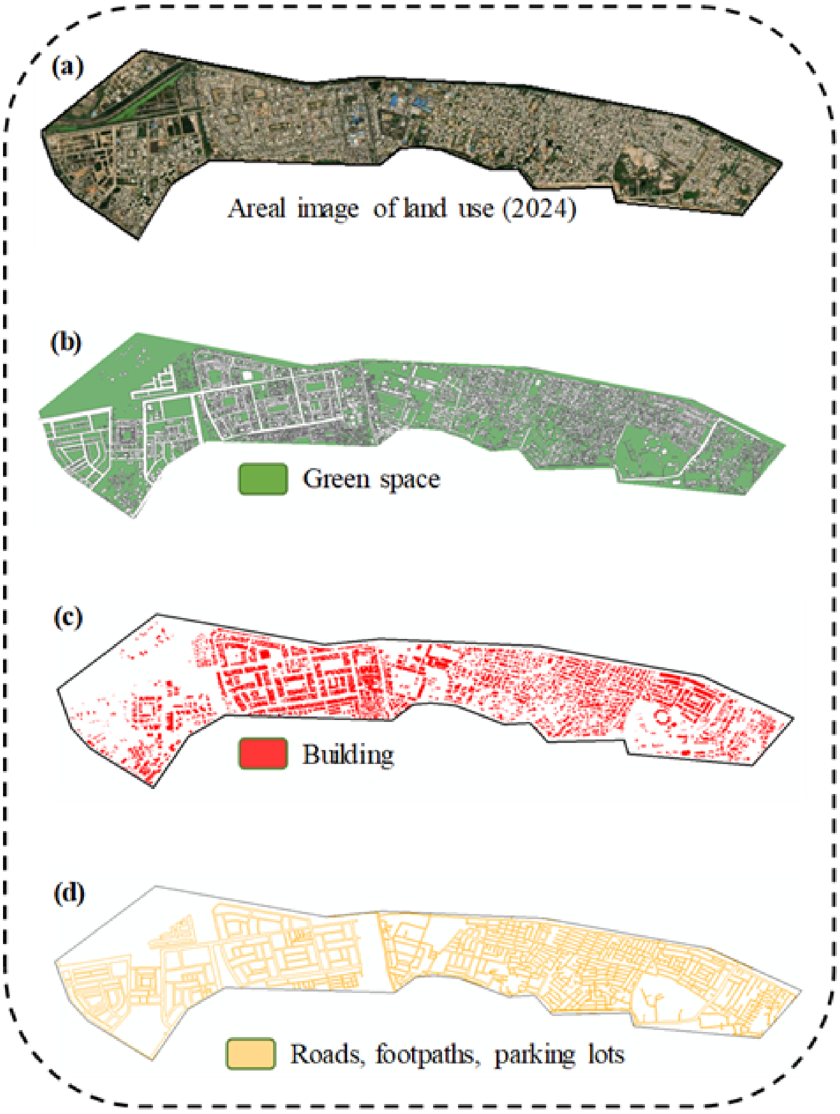

Figure 3.5 Land use analysis for 2024, highlighting the (a) aerial view of the study area, (b) green spaces, (c) buildings, and (d) transportation infrastructure (roads, footpaths, and parking lots).

Pre-development case: SWMM model was created to reflect the inherent hydrological situation of the investigated region before urban development. It enabled us to create a baseline

Table 3.2 Land Use Distribution

Type of Land Use	**Area** (km^2)
Buildings	0.74
Roads, footpaths, parking lots	0.365
Green spaces	1.995
Total Area	**3.1**

for the natural runoff generation, peak flows, and flooding in the study area, which was possible without human intervention. This case was built using detailed data on the site's historical rainfall patterns, as well as its existing land use and topography. This involved specifically using a detailed DEM and hourly rainfall data retrieved between 2013 and 2023 to describe the natural hydrology of the site. Pre-development case conditions were then simulated using a 24-hour design storm with a return period of 2 years. The model outputs were then analyzed to give important baseline data on the study area's natural hydrological behavior (e.g., peak runoff, outfall volume, and flood volume) (Ahmad et al., 2025). This reference point was used to see the impacts of urban development along with the effectiveness of the proposed LID strategies.

Post-development case without the LID implementation: This case represents the hydrologic conditions after development. One of the major drivers of these changes is the increase in impervious surfaces, which can significantly alter the normal hydrologic processes (Babaei et al., 2018). The interplay of antecedent hydrological conditions with impervious land cover has posed challenges to determining the degree of imperviousness, and the current study used a generalized Land Use and Land Cover (LULC) analysis method to quantify the percentage of imperviousness (Banjara et al., 2024; Zha et al., 2024). High-resolution imagery (Figure 3.5a) and advanced geospatial tools were used to map, and classify the variety of land cover in the study site: buildings (Figure 3.5c), roads, parking lots (Figure 3.5d), and formerly green spaces (Figure 3.5b). With such a detailed LULC assessment, impervious surfaces percentage within the sub-catchment of the drainage system was accurately calculated (Basha et al., 2024; Dai et al., 2023). Object-oriented classification methods were used for LULC analysis to accurately delineate the impervious and pervious surfaces. This gave us a strong and most recent representation of the current land cover conditions on the site, which was essential for understanding the hydrological behavior of the site to give an accurate representation of what was happening now. The land use types are divided into three main classes, as in Table 3.2: building, transport infrastructure (roads, footpaths, parking lots), and green land. Using a simple ratio of the total impervious area to the total sub-catchment area, imperviousness values were determined for each of the sub-catchments. Similar to the pre-development, the post-development conditions were modeled with a 24-hour duration, 2-year return period design storm. LULC data was directly used in the SWMM model, which contained a case of development without the application of LID. The hydrological impacts of urbanization were quantified by comparing model outputs for the baseline conditions case with existing development cases.

Post-development case with LID implementation: The emerging technology of LID is a paradigm shift in stormwater management, particularly in high-density urban environments. Unlike traditional methods, LID is an alternate practice that employs decentralized techniques to reduce runoff from impervious surfaces that closely mimic hydrological processes (Wang et al., 2024). It promotes the implementation of green infrastructure stormwater management practices and urban drainage systems. SWMM has been widely used as a simulation framework for assessing best management practices in treating stormwater runoff from different storm types (Qi et al., 2025). LID practices can be modeled in SWMM, including RB, green roofs, PP, vegetative swales, infiltration trenches, BRC, rain gardens, and rooftop disconnections (Li et al., 2021; Lu et al., 2019). These practices, implemented globally, can help reduce peak runoff and protect urban drainage systems. LID practice's effectiveness depends on the proportion of the total catchment area taken up by LID infrastructure (Mallick et al., 2021). The LID practices studied were PP, BRC, and RB. To evaluate the effect of LID, we created and simulated several case scenarios that represented different degrees of LID (Ahmad et al., 2024; Eskandaripour & Soltaninia, 2024; Poirer et al., 2010). For each case, the hydrological benefits of the LID interventions were quantified by comparing LID treatment to a pre-development and to a post-development condition (Shafique et al., 2018).

Table 3.3 The area occupied by each land use type in subcatchments.

Sub-catchment	**Total Area** (m^2)	**Green Spaces** (m^2)	**Roads, Footpaths, Parking** (m^2)	**Buildings** (m^2)
C1	186600	182306	0	4294
C2	147400	112092	29227	6081
C3	170400	89134	32204	49062
C4	185600	100677	76576	8347
C5	192500	95920	55344	41236
C6	176900	97602	42475	36823
C7	119600	44882	26599	48119
C8	222200	77375	61298	83527
C9	163500	61744	30173	71583
C10	213000	123749	32109	57142
C11	260200	128519	59743	71938
C12	157600	66821	39287	51492
C13	350820	259040	73266	18514
C14	297400	137364	48393	111643
C15	256700	138164	46690	71846

Table 3.3 presents the distribution of different land use types within various sub-catchments, including green spaces, roads, footpaths, parking lots, and buildings. The total area of each sub-catchment is divided among these categories to illustrate the extent of urbanization and vegetation coverage. The data highlights significant variations in land use across the sub-catchments. Some areas, such as C1 and C13, are predominantly covered by green spaces,

whereas others, like C8 and C14, exhibit a higher proportion of built-up areas. The distribution of roads and footpaths also varies, influencing surface runoff and drainage characteristics in each sub-catchment. This land use assessment is crucial for evaluating hydrological responses, urban planning, and environmental management. The information can help in designing stormwater management strategies, assessing flood risks, and implementing sustainable urban development plans.

3.5 Placement of LID practices

The study also took into account the placement of LID practices in strategic locations; BRC was implemented in the open green areas to capture and store rainfall and promote infiltration and evapotranspiration (Figure 3.6). The roadways of this facility were built with permeable pavement that allows water from rainstorms to infiltrate, minimizing runoff and enhancing groundwater recharge (Figure 3.6). Installed RB on the buildings catch roof runoff, which is stored for future non-potable uses (irrigation, etc.) to reduce (disperse) the total amount of stormwater (Figure 3.6).

To address runoff and flood risk in the selected neighborhoods, three LID practices were applied: PP, BRC, and RB. These types of measures are standard LID approaches, and they are supported by local drainage planning and require minimum residential areas. The layout design for these practices is based on the following principles: (1) BRC are largely located in green areas; (2) PP can be implemented on roads, parking lots, and squares, displacing traditional surfaces around buildings and sidewalks outside of major roads; and (3) RB can be placed next to the building structure, receiving surface runoff, and potentially be part of a system that encompasses water from neighboring sub-catchments. A tailored approach to LID strategies was implemented according to sub-catchment characteristics as well as land use distribution. Every land use type was surveyed so that a suitable surface area was used to implement LID measures (PP, BRC, and RB) that could be properly applied to the designated sub-catchments.

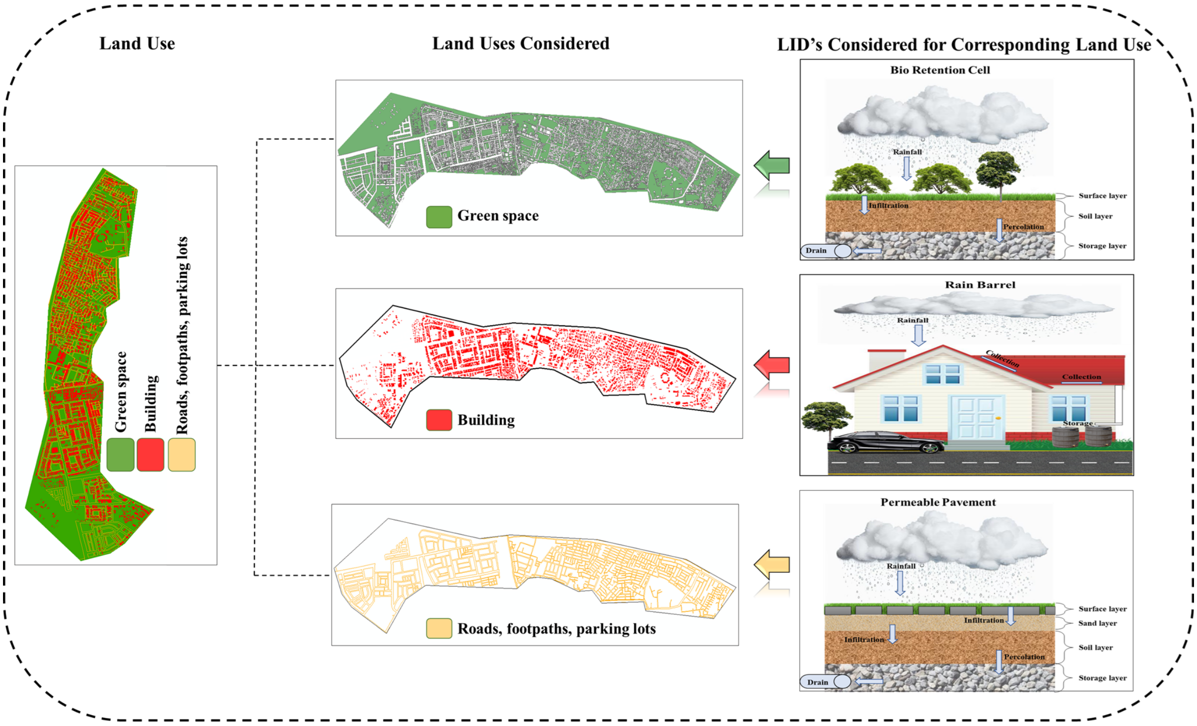

Figure 3.6 Placing of LIDs, BRC in green spaces, RBs in buildings, PP in transportation infrastructure (roads, parking lots, and footpaths).

Six different cases were studied to conclude the results of LID practices. Pre-development case, C_1 (Pre): We could start to know more about what the site would undergo in natural conditions in terms of runoff, peak flows, and flooding. Post-development case without LID, C_2 (Post): This case simulates the hydrological conditions after the development of urban areas, with a focus on the effects of increased impervious surfaces on the natural hydrological processes. Post-development case with BRC, C_3 (BRC), Post-development case with PP, C_4 (PP): These cases will study the effect of BRC and PP on runoff reduction and groundwater recharge. Post-development case with RB, C_5 (RB): Examines the contribution of RB to capture and store rooftop runoff as a method to decrease the total volume of stormwater. Post-development case with combined implementation of LID practices, C_6 (Comb): The effect of multiple LID applications (BRC, PP, and RB) will be analyzed to restore baseline case hydrological conditions.

3.6 LID Parameters Selection

To accurately model and analyze the hydrological performance of various stormwater management systems, specific design parameters were selected for BRC, PP, and RB. These parameters were chosen based on standard design practices, previous research findings, and site-specific considerations. Each system's characteristics, including surface, soil, storage, and drainage properties, were carefully defined to ensure realistic simulation and performance assessment (Wilson et al., 2013).

Table 3.4 BRC parameters

Parameters	Value Selected	Unit
Surface Parameter		
Berm Height (h)	150	mm
Vegetation Volume Fraction ($VegFrac$)	0.5	-
Surface Roughness (n)	0.035	-
Surface Slope (S_o)	3	$\%$
Soil Parameter		
Soil Thickness (t)	200	mm
Porosity (ϕ)	0.35	-
Field Capacity (FC)	0.2	-
Wilting Point (WP)	0.1	-
Conductivity (K)	73	$mmhr$
Conductivity Slope (C_s)	10	-
Suction Head (ψ)	25	mm
Storage Parameter		
Storage Thickness (t_c)	350	mm
Void Ratio (e)	0.4	-
Seepage Rate ($Seep$)	11	$mmhr$
Clogging Factor (C_f)	0	-
Drain Parameter		
Flow Coefficient (c)	10.5	-
Flow Exponent ($\bar{n}$)	0.5	-
Offset (O)	30	mm

Table 3.4 presents the key parameters for the BRC system, detailing surface conditions, soil properties, storage capacity, and drainage characteristics.

Similarly, Table 3.5 outlines the parameters for the PP system, which consists of surface layers, an underlying soil bed, and storage components. Lastly, Table 3.6 provides the selected parameters for the RB system, highlighting its storage height and drainage properties. The chosen values ensure that each system is designed to effectively manage stormwater, enhance infiltration, and mitigate runoff impacts (Purnagusti et al., 2024). The details of these parameters are provided in the following tables (Table 3.4, Table 3.5, Table 3.6).

Table 3.5 PP parameters

Parameters	Value Selected	Unit
Surface Parameter		
Berm Height (h)	150	mm
Vegetation Volume Fraction ($VegFrac$)	0.2	-
Surface Roughness (n)	0.035	-
Surface Slope (S_o)	3	$\%$
Pavement Parameter		
Thickness (t)	100	mm

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Parameters	Value Selected	Unit
Void Ratio (e)	0.15	-
Impervious Surface Fraction (% Imperv)	0.2	-
Permeability (P)	45	$mmhr$
Clogging Factor (C_f)	0	-
Soil Parameter		
Thickness (t)	250	mm
Porosity (ϕ)	0.35	-
Field Capacity (FC)	0.2	-
Wilting Point (WP)	0.1	-
Conductivity (K)	73	$mmhr$
Conductivity Slope (S_o)	10	-
Suction Head (ψ)	25	mm
Storage Parameter		
Thickness (t_s)	350	mm
Void Ratio (e)	0.75	-
Seepage Rate ($Seep$)	0.5	$mmhr$
Clogging Factor (C_f)	0	-
Drain Parameter		
Flow Coefficient (c)	0	-
Flow Exponent ($\bar{n}$)	0.5	-
Offset (O)	0	mm

Table 3.6 RB parameters

Parameters	Value Selected	Unit
Storage Parameter		
Height (h)	1000	mm
Drain Parameter		
Drain Coefficient (C)	2204	-
Drain Exponent ($\bar{n}$)	0.5	-
Drain Offset Height (O)	0	mm
Drain Delay (D)	24	$hours$

3.7 Cost Analysis

Cost for individual component in LID and total cost for different LIDs are comprehensively analysed in Table 3.7. The cost analysis of LID techniques (BRC, PP, and RB) is calculated with the help of local rates obtained from Bharatpur. The cost of BRC per m^2 is ₹1308, PP is ₹1972, and RB is ₹6800 (Table 2). For large regions, the total cost differs significantly between LID implementation cases.

For instance, In case C3 (BRC), BRC for an area size of 42,100 m^2, total construction cost is ₹606.14 Lakhs (Table 3.7). On the other hand, Case C4 (PP), which implements PP cover on 38,500 m^2, costs ₹835.04 lakhs and in case C5 (RB), which uses 5,256 m^2 of RBs, the total cost is ₹393.15 lakhs (Table 3.7). The overall cost worked out for Case C6 (Comb) with the combined implementation of all LIDs is ₹920.38 lakhs (Table 3.7). The costs include a 10% contingency for future maintenance and overall care of the LID practices.

This detailed cost analysis underscores the financial aspects of large-scale implementation of LID strategies and would help those involved in choosing cost-effective solutions for stormwater management and urban flood mitigation. The strengths and costs associated with stormwater funneling methods such as BRC, PP, and RB have been thoroughly assessed by this research on LID practices for urban flood response.

Table 3.7 Parameters of LID construction cost per m^2

LID Type	Component	Volume/m^2	Cost/m^3	Cost/m^2
Bio Retention Cell	Soil layer (0.2 m thick)	0.2 m^3	₹2000	₹400
	Storage layer (0.35 m thick)	0.35 m^3	₹1500	₹525
	Plants for vegetation	4 units	₹75/unit	₹300
	Labor and soil excavation	0.55 m^3	₹152.5	₹83.88
	Total Cost			**₹1308.88**
Permeable Pavement	Soil layer (0.25 m thick)	0.25 m^3	₹2000	₹500
	Storage layer (0.35 m thick)	0.35 m^3	₹1500	₹525
	Pavement (0.1 m thick)	0.1 m^3	₹8400	₹840
	Labor and soil excavation	0.7 m^3	₹152.5	₹106.75
	Total Cost			**₹1971.75**
Rain Barrel	Rain barrel	1 unit	₹5900/unit	₹5900
	Gutter and pipe installation	1 unit	₹900/unit	₹900
	Total Cost			**₹6800**

As such the cost analysis provides a vital consideration for decision-makers during the selection process of the most cost-effective LID strategies. Pervious concrete pavement has the highest price per m^2 but provides structural durability and increased infiltration. BRC is a more cost-effective option that offers great hydrological input. While rain barrels are costly on a per-unit basis, they are very useful in small-scale rainwater harvesting systems. The analysis can employ the local-level construction costs concerning Bharatpur City to the realistic financial measurement of sustainable urban drainage solutions.

3.8 Metrics

The four metrics used for evaluating LID performance in the current study: % Volume Reduction, LHRI, HRCEI, and HVCEI: add to the mix a new and broader assessment of LID strategies for the meaningful performance of peak runoff, outfall volume, and flood volume management. % Volume Reduction, one of the most standard parameters, helps to measure the ability of LID techniques to minimize peak runoff, outfall volume, and flood volume with the help of Equation 3.1, which in turn are critical to flood management and water conservation.

$$VR\% = \frac{X_{\text{Post}} - X_{\text{Case}_i}}{X_{\text{Post}}} \tag{3.1}$$

Where VR is volume reduction in percentage, showing how much volume is reduced in peak runoff, flood volume, and outfall volume for post-development with LID and without LID, having a range ($0\% \leq VR \leq 100\%$). X_{Post}, processed output from C_2 (Post), whereas X_{Pre}, processed output from C_1 (Pre). X_{Case_i}, represents the processed output from the remaining cases, which are implementation of LID in the study area (e.g., i=3 means C_3 (BRC)).

The LHRI is the first novel modified metric utilized in the study, quantifying how well LID methods restore pre-development hydrology through reductions in outfall volume and flood volume by using Equation 3.2, which allows better stormwater infiltration and resilient systems. A higher LHRI value means better restoration. Thus, it serves as a valuable metric to assess various LID techniques.

$$LHRI = 100 \times \left(1 - \frac{|X_{\text{Case}_i} - X_{\text{Pre}}|}{|X_{\text{Post}} - X_{\text{Pre}}|}\right) \tag{3.2}$$

LHRI is the LID Hydrological Restoration Index in %, having a range ($0\% \leq LHRI \leq 100\%$), which indicates how much LID is achieved in restoring pre-development conditions. X_{Case_i} is the value of the hydrological parameter after LID implementation. X_{Post} is the processed output from C_2 (Post), whereas X_{Pre} is the processed output from C_1 (Pre).

HRCEI is a novel metric, Equation Equation 3.3, that evaluates the effectiveness of various solutions based on an investment-cost analysis, providing information regarding cost efficiency and thereby guiding the decision process towards the option with the best peak runoff reduction, flood volume reduction, and total outfall volume reduction per unit cost (in this study, the unit cost is in ₹Lakhs).

$$HRCEI = \frac{LHRI\%}{C\ \text{₹Lakhs}} \tag{3.3}$$

HRCEI is the Hydrological Restoration Cost Efficiency Index, which explains that for every ₹1 lakh spent on LID, it provides a percentage contribution to restoring pre-development conditions. C is the total cost in ₹lakhs required to implement LID in the proposed locations.

HVCEI is a novel metric, Equation Equation 3.4, that evaluates the effectiveness of various solutions based on an investment-cost analysis, providing insights into cost efficiency. It helps guide the decision-making process toward the most effective option by considering flood volume reduction per unit cost.

$$HVCEI = \frac{VR\%}{C\ \text{₹Lakhs}} \tag{3.4}$$

HVCEI is the Hydrological Volume Reduction Cost Efficiency Index, which explains that for every ₹1 lakh spent on LID, it provides a percentage contribution to flood volume reduction. $VR\%$ is the percentage of flood volume reduction achieved. C (₹Lakhs) is the total cost in ₹Lakhs required to implement LID in the proposed locations.

The proposed $LHRI$, $HRCEI$, and $HVCEI$ play a new role in stormwater management practices by integrating quantitative metrics with cost-effectiveness assessment. These indices serve as critical metrics for ensuring sustainable urban water management and optimizing LID implementation.

Chapter 4

Results and Discussion

The LID techniques have a great effect on stormwater management due to the reduction of total peak runoff, outfall volume, and flood volume. The positive performance of BRC, PP, and RB, as well as their mixed configurations, is evident in the comparative analysis of different LID cases. This study's assessments consider the performance of these techniques in terms of key hydrological indicators, i.e., volume reduction percentage, LHRI, HRCEI, and HVCEI as well as their economic feasibility, as shown in Table 4.1.

Table 4.1 Hydrological Performance Metrics for Different LID Cases

Parameters	C_1 **(Pre)**	C_2 **(Post)**	C_3 **(BRC)**	C_4 **(PP)**	C_5 **(RB)**	C_6 **(Comb)**
Total Outfall Volume (m^3)	79	1650	534	627	884	432
% Volume Reduction	-	-	67.64	62.00	46.42	73.82
LHRI (%)	-	-	71.04	65.12	48.76	77.53
HRCEI	-	-	0.12	0.08	0.12	0.08
HVCEI	-	-	0.11	0.07	0.12	0.08
Peak Runoff (m^3/s)	0.022	0.306	0.034	0.025	0.079	0.022
% Volume Reduction	-	-	88.89	91.83	74.18	92.81
LHRI (%)	-	-	95.77	98.94	79.93	100.00
HRCEI	-	-	0.16	0.12	0.20	0.11
HVCEI	-	-	0.15	0.11	0.19	0.10
Total Flood Volume (m^3)	704	11797	4077	3764	7755	2526
% Volume Reduction	-	-	65.44	68.09	34.26	78.59
LHRI (%)	-	-	69.59	72.42	36.44	83.58
HRCEI	-	-	0.11	0.09	0.09	0.09
HVCEI	-	-	0.11	0.08	0.09	0.09

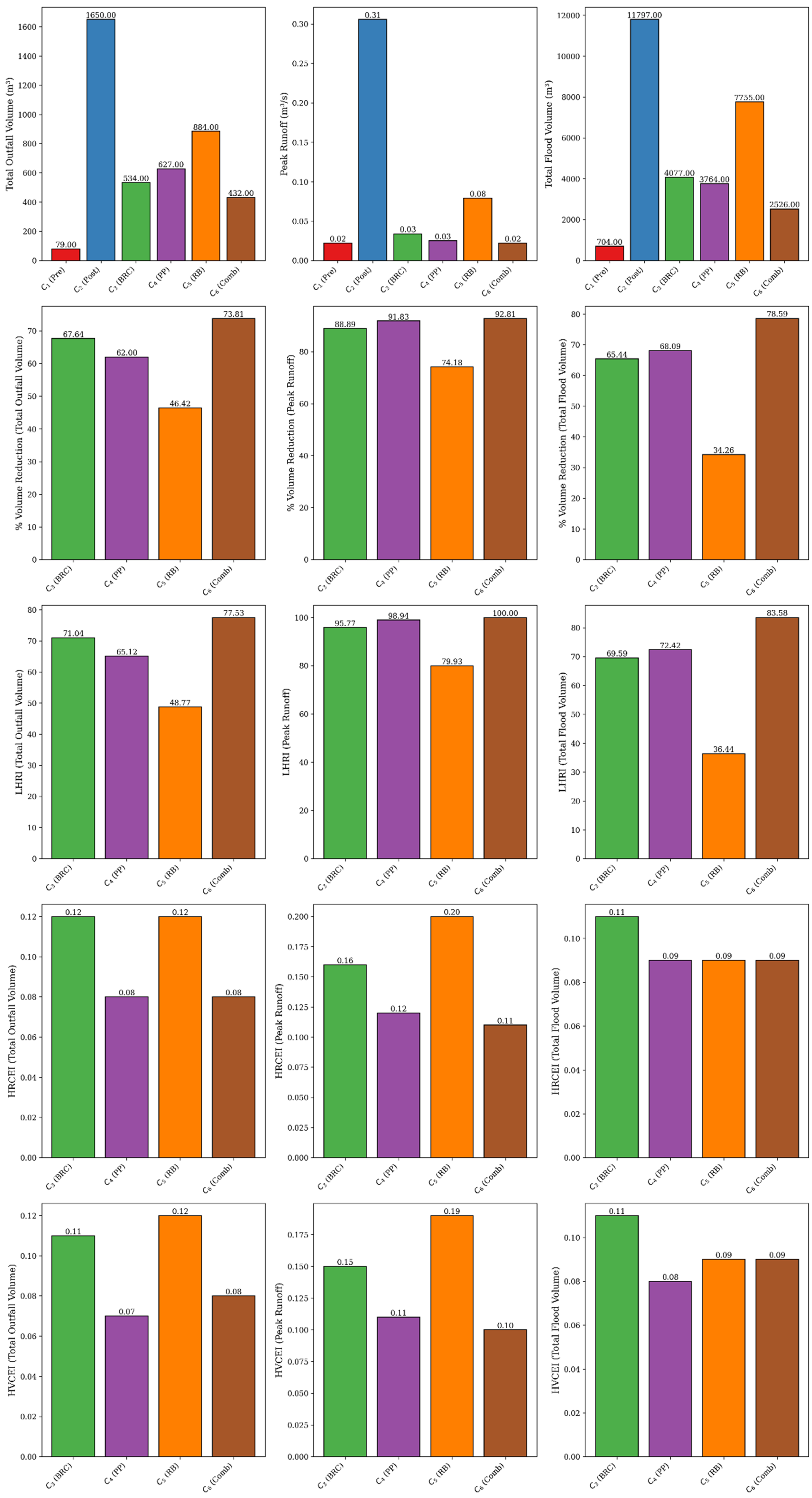

Figure 4.1 Comparative analysis of LID strategies on hydrological performance metrics, including peak runoff, outfall volume, flood volume, volume reduction, LHRI, HRCEI, and HVCEI.

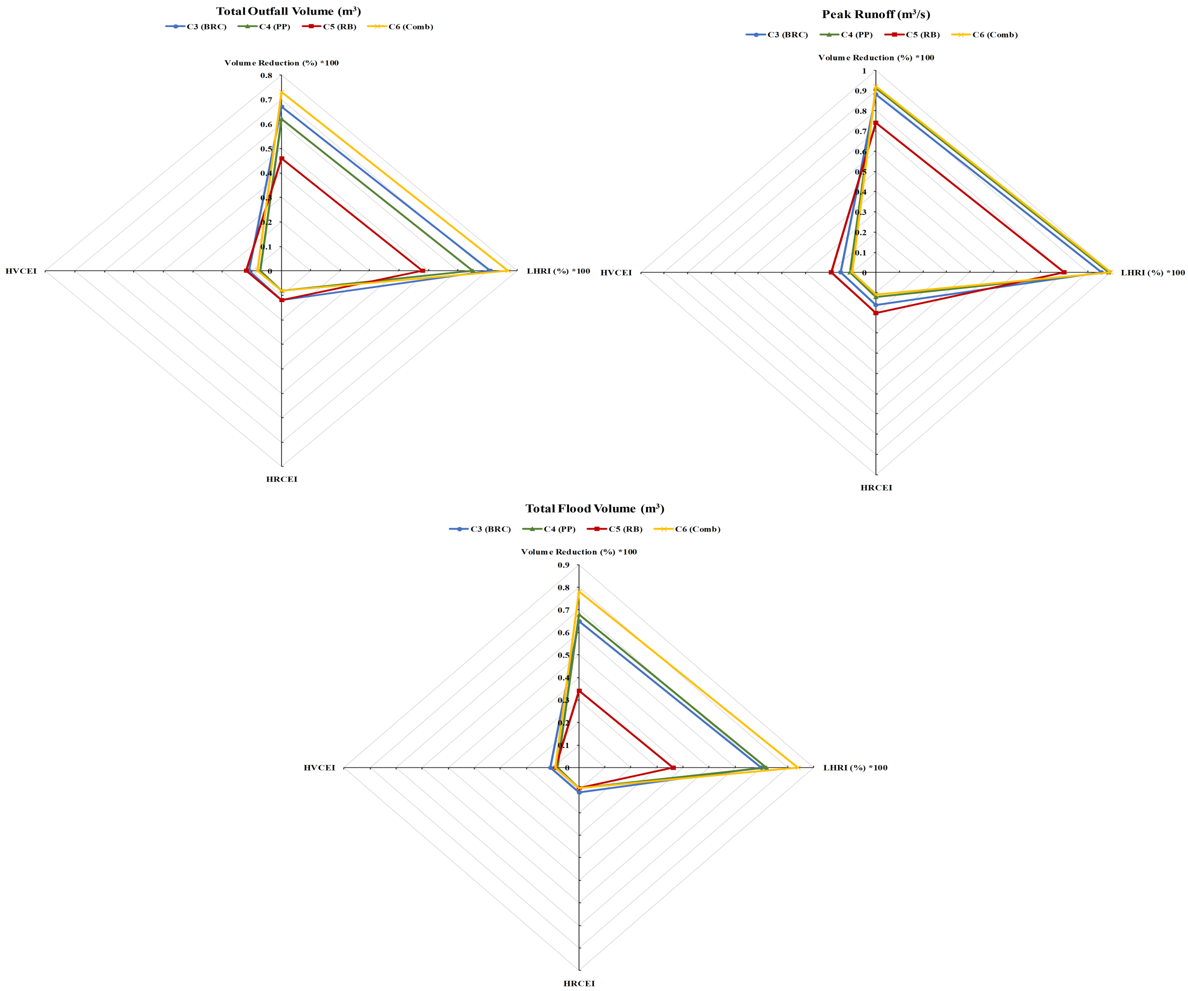

Figure 4.2 Comparative analysis of LID strategies (C_3 (BRC), C_4 (PP), C_5 (RB), C_6 (Comb)) on hydrological performance metrics: volume reduction, LHRI, HRCEI, and HVCEI; alongside indicators like total outfall volume, peak runoff, and total flood volume, highlighting the superior efficiency of the C_6 (Comb) scenario across all parameters.

A thorough analysis of the convincingness of LIDs in different aspects (peak runoff reduction, total outfall volume reduction, and total flood volume reduction) is presented in Table 4.1.

4.1 Total outfall volume reduction

In the evaluation of the effectiveness of various LIDs, total outfall volume is an important parameter. In the pre-development stage C_1 (Pre), the total outfall volume was very small by 79 m^3, 757 times less than the post-deforestation stage, due to natural infiltration. However, in the post-development condition C_2 (Post), this volume increased tremendously to 1650 m^3, which represents the adverse effect of urbanization on stormwater management. From the implemented LID techniques, it could be concluded that Case C_6 (Comb) was the best since, in this case, the total volume of the outfall after the implementation of LID was only 432 m^3, which is a reduction of 73.82%. The drastic drop in C_6 (Comb) indicates that combining LIDs outperforms independent implementations. The findings suggest that while LID techniques individually promote reductions in outfall volume, PP and BRC were the most effective techniques in this respect due to readiness for increased infiltration and reduced runoff. Despite their applicability for water harvesting, RB also offered the weakest volume reduction in outfall because of their limited storage capacity. The combined approach incorporated several techniques for maximum efficiency and produced the best solution.

4.2 Peak runoff reduction

Peak runoff is another important variable since larger peak runoffs can cause urban floods and erosion. The runoff peak value in the post-development case C_2 (Post) increased significantly, with 0.306 m^3s compared to 0.022 m^3s in the pre-development stage C_1 (Pre). It underscores the detrimental effect of paved surfaces on stormwater management. Reports from a cohort of LID strategies showed a diversity of improvement. On the other hand, the integrated approach C_6 (Comb) lowered the peak runoff to 0.022 m^3s, getting it to the pre-development level, thus proving to be the best strategy in mitigating floods. Out of the standalone approaches, the C_4 (PP) scenario recorded the best performance by reducing peak runoff to 0.025 m^3s (91.83% reduction), while C_3 (BRC) recorded a peak runoff of 0.034 m^3s (88.89% reduction) and C_5 (RB) showed moderate performance, reducing peak runoff to 0.079 m^3s (74.18%).

The reduced surface runoff is due to the excellent infiltration attribute of PP, which allows the removal of excess rainwater that the surfaces can only take in, thus reducing peak runoff rates. In the same way, BRC slows down water and absorbs it to reduce peak discharge rates. RB do not help as much in this, as these hold water and do not provide for infiltration. The combination approach C_6 (Comb) integrates all three techniques and ensures both storage and infiltration; therefore, it can be considered as the best solution for reducing peak runoff.

Table 4.2 presents the peak runoff (m^3/s), percentage volume reduction, and LHRI for different sub-catchments under various conditions. The table compares pre-development C_1 (Pre) and post-development C_2 (Post) scenarios with different BMPs, including BRC, PP, RB, and a combined approach C_6 (Comb). The peak runoff values indicate how urbanization and stormwater management techniques affect runoff intensities across sub-catchments. A significant reduction in peak runoff is observed in LID-implemented scenarios compared to post-development conditions. The percentage volume reduction demonstrates the effectiveness of each BMP in controlling runoff volume, with the combined approach generally showing the highest reduction. The LHRI values provide a comparative measure of hydrological improvement, where higher percentages reflect better restoration of natural hydrological conditions.

Table 4.2 Impact of LID Strategies on Peak Runoff, Volume Reduction, and LHRI Across Sub-Catchments

Sub Catchment	**Peak Runoff** (m^3s)						**% Volume Reduction**				**LHRI** (%)			
	C_1 (Pre)	C_2 (Post)	C_3 (BRC)	C_4 (PP)	C_5 (RB)	C_6 (Comb)	C_3 (BRC)	C_4 (PP)	C_5 (RB)	C_6 (Comb)	C_3 (BRC)	C_4 (PP)	C_5 (RB)	C_6 (Comb)
C1	0.01	0.02	0.01	0.01	0.01	0.01	50	50	50	50	100	99	99	99
C2	0.01	0.09	0.01	0.01	0.09	0.01	89	89	0	89	99	99	1	99
C3	0.01	0.16	0.02	0.02	0.11	0.02	88	88	31	88	92	92	32	92
C4	0.02	0.23	0.02	0.01	0.22	0.03	91	96	4	87	99	100	4	94
C5	0.02	0.23	0.07	0.02	0.18	0.01	70	91	22	96	75	99	23	100
C6	0.02	0.19	0.02	0.01	0.14	0.01	89	95	26	95	99	100	28	100
C7	0.01	0.12	0.01	0.03	0.08	0.02	92	75	33	83	99	81	35	90
C8	0.02	0.27	0.02	0.01	0.19	0.01	93	96	30	96	99	100	31	100
C9	0.01	0.24	0.03	0.01	0.16	0.02	88	96	33	92	90	99	34	95
C10	0.02	0.26	0.03	0.02	0.07	0.03	88	92	73	88	95	99	78	95
C11	0.02	0.36	0.05	0.01	0.13	0.02	86	97	64	94	90	100	67	99
C12	0.01	0.29	0.07	0.06	0.10	0.02	76	79	66	93	78	81	67	95
C13	0.03	0.22	0.02	0.02	0.06	0.02	91	91	73	91	100	100	83	100
C14	0.02	0.30	0.01	0.02	0.01	0.04	97	93	97	87	100	99	100	92
C15	0.03	0.45	0.03	0.02	0.08	0.02	93	96	82	96	99	100	87	100

These results emphasize the role of green infrastructure in mitigating urban runoff impacts and improving stormwater management. The findings can support decision-making in urban planning and watershed management to enhance flood resilience and environmental sustainability.

4.3 Total flood volume reduction

Understanding the flood volume is a primary issue in the management of urban water. In the case of post-development C_2 (Post), the volume of flood increased significantly to 11,797 m^3 after the development from 704 m^3 in the pre-development stage, suggesting the need for appropriate flood mitigation options. Of the LID techniques, the combination approach C_6 (Comb) performed best again, with flood volume reduced to 2526 m^3 (78.59% reduction). For a single LID strategy, C_3 (BRC) managed to achieve 4077 m^3 (volume reduction of 65.44%), and C_4 (PP) was able to reduce it to 3764 m^3 (68.09%). The lowest flood volume reduction, 34.26%, was observed at C_5 (RB), producing a flood volume of 7755 m^3, as expected. This shows that green infrastructure such as BRC and PP can greatly aid in reducing flood volumes due to their nature of absorbing water, while RB may not be as effective for large volumes of flooding due to their limited storage capacity. On the other hand, for the combined approach C_6 (Comb), flood mitigation efficiency rose considerably, emphasizing the necessity of integrating LID techniques in urban areas.

4.4 Cost analysis of LID implementation

Comparative analysis of different LID cases on hydrological performance metrics are represented in Figure 4.1. LHRI aids in understanding how different LID strategies affect the local hydrological state. Based on the results of the combined approach C_6 (Comb), it can be seen that for peak runoff, outfall volume, and flood volume, the maximum LHRI values of 77.53%, 100%, and 83.58% are generated, respectively, in all cases. C_3 (BRC) and C_4 (PP) have produced excellent performance (LHRI values: outfall volume: 71.04% and 65.12%; peak runoff: 95.77% and 98.94%). C_5 (RB) exhibited the poorest LHRI performance, especially for flood volume (36.44%), confirming their restricted usage spectrum for flood control and stormwater management.HRCEI is an important factor used to compare the cost-effectiveness and merits of different LID strategies. The C_3 (BRC) has HRCEI of 0.11, and C_4 (PP), C_5 (RB), and C_6 (Comb) have HRCEI values of 0.09. The C_3 (BRC) achieved the maximum hydrological benefits, but with an HRCEI of 0.11. This indicates that, for stormwater management, BRC represents an optimal compromise between cost and performance.

LID techniques are the focus of attention due to their high implementation cost. C_3 (BRC) has a total cost of ₹551.04 lakhs, while C_4 (PP) has the highest total cost of ₹759.12 lakhs and C_5 (RB) has the lowest cost of ₹357.41 lakhs. Of the three separately considered LID techniques, C_6 (comb) seems to perform better, yielding a total construction cost of ₹836.71 lakhs. The total costs include a 10% contingency for future maintenance and overall care of the LID practices. Considering its production costs, this hybrid strategy exhibits excellent hydrological performance and represents a long-term investment in urban stormwater management.

Table 4.3 The cost analysis of various LID cases in terms of applied area, per square meter, and implementation cost.

Case	LID	Area (m^2)	Cost/m^2 (₹)	Total Cost (₹Lacs)
C_3	BRC	42 100	1308.88	606.14
C_4	PP	38 500	1971.75	835.04
C_5	RB	5256	6800	393.15
C_6	BRC	31 100	1308.88	920.38
	PP	15 500	1971.75	
	RB	1824	6800	

4.5 Optimal LID based on HRCEI

In this study optimal LID was selected based on HRCEI values in terms of flood volume. HRCEI plays a crucial role in determining the most efficient LID strategy (Figure 4.1). The combined approach C_6 (Comb) has an HRCEI of 0.09, indicating that it offers hydrological benefits, while its cost-effectiveness is slightly reduced due to the combined implementation costs. Among the analyzed cases, C_3 (BRC) provides the highest cost-effectiveness with an HRCEI of 0.11. This indicates that for every unit cost invested, and yields the most significant reduction in stormwater impacts. C_4 (PP) and C_5 (RB) show lower HRCEI value of 0.09, respectively, suggesting that they are effective in volume and peak runoff reduction, while their cost-effectiveness is relatively lower compared to BRC. This suggests that if budget constraints are a concern, prioritizing BRC can provide the best return on investment.

Chapter 5

Conclusions

The evaluation of various LID solutions shows that, when applied together, BRC, PP, and RB would contribute substantially to decreased volume of stormwater discharged, maximum runoff, and flood volume. Across the different strategies, C_3 (BRC) showed the most balance and high performance with respect to volume reduction, LHRI, HRCEI, and HVCEI while having moderate costs. C_4 (PP) was highly effective in reducing peak runoff and flood volume, but its cost-effectiveness was slightly lower. While C_5 (RB) had low per-unit costs for volume reduction, they would be ineffective for large flooding events. The combined LID approach C_6 (Comb) achieves the highest flood volume reduction but does not necessarily stand out in terms of cost efficiency. The LID selection for the study area must be based on not just environmental makeup but also economic aspects. Individual LID techniques showed a varying cost-effectiveness ratio with BRC, which ended up being a very balanced choice. Of them, PP was the priciest (due to material and installation costs), and RB was the lowest-cost option but relatively ineffective. Considering all stormwater performance, the C_3 (BRC) offered the best performance at a reasonable cost. The findings underscore the importance of integrating BRC into urban planning policies to enhance flood resilience, reduce runoff, and promote long-term hydrological sustainability in rapidly urbanizing regions like Bharatpur. Finally, for large-scale management of urban stormwater, it is advisable to use a BRC as an optimal LID.

Chapter 6

Suggestions for Future Study

This chapter outlines potential directions for future research based on the findings and limitations of the present study. These suggestions aim to guide further exploration and contribute to the ongoing development of knowledge in this field.

1. Future studies can focus on assessing the long-term performance of LID practices under varying climatic conditions, including extreme rainfall and seasonal variations, to better understand their resilience and adaptability.

2. Comparative analysis of additional LID techniques such as green roofs, infiltration trenches, and vegetated swales could further enhance insights into their effectiveness in diverse urban contexts.

3. Integration of socio-economic parameters, such as community acceptance, maintenance costs, and implementation challenges, would provide a more holistic understanding of LID feasibility in developing regions.

4. In addition, the use of real-time monitoring systems and advanced hydrological modeling tools can improve the precision of predictions and support dynamic decision-making for sustainable urban flood management.

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Appendix A

A.1 List of Abbreviations

ABM	Alternating Block Method
BHDA	Bharatpur Development Authority
BRC	Bio Retention Cell
DEM	Digital Elevation Model
GR	Green Roofs
HRCEI	Hydrological Restoration Cost Effeciency Index
HVCEI	Hydrological Volume Reduction Cost Effeciency Index
IDF	Intensity-Duration-Frequency
IMD	Indian Meteorological Department
LHRI	LID Hhdrological Restoration Index
LID	Low Impact Development
LULC	Land Use and Land Cover
NSE	Nash–Sutcliffe Efficiency
PP	Permeable Pavement
RB	Rain Barrel
RNFCD	Ranjit Nagar Flood Control Drain
SWMM	Storm Water Management Model
WRIS	Indian Water Resources Information System

A.2 Reference Tables

Table A.1 Expected Flood Computation by Gumbel frequency factor method

Return Period (T) in years	Probability (P in %)	Reduced variant $Y = -\ln\ln\frac{T}{T-1}$	Frequency Factor $K = \frac{Y-\bar{Y}_n}{\sigma_n}$
2	50	0.366513	-0.16412
5	20	1.49994	0.719641
10	10	2.250367	1.30477
25	4	3.198534	2.044081
50	2	3.901939	2.592545
100	1	4.600149	3.136958
200	1/2	5.295812	3.679386
400	1/4	5.990213	4.220829

Appendix B

B.1 Common Conversion Factors

Table B.1 Unit Conversion Factors

From	To	Conversion Factor
Length Conversion Factors		
1 meter	centimeter (cm)	100
1 meter	kilometer (km)	0.001
1 inch	meter	0.0254
1 foot	meter	0.3048
1 mile	meter	1609
1 angstrom	meter	1×10^{-10}
1 fermi	meter	1×10^{-15}
1 light-year	meter	9.460×10^{15}
1 meter	inch	39.37
1 meter	foot	3.281
1 meter	mile	6.214×10^{-4}
1 centimeter	inch	0.3937
1 kilometer	mile	0.6214
1 inch	foot	0.08333
1 inch	mile	1.578×10^{-5}
1 foot	inch	12
1 mile	feet	5280
Area Conversion Factors		
1 square meter	square centimeter (cm^2)	10,000
1 square meter	square kilometer (km^2)	1×10^{-6}
1 square meter	square inch (in^2)	1550
1 square meter	square foot (ft^2)	10.764
1 square meter	square mile (mi^2)	3.861×10^{-7}
1 square inch	square meter	6.452×10^{-4}
1 square foot	square meter	0.0929
1 square mile	square meter	2.59×10^{6}
1 acre	square meter	4046.86
1 hectare	square meter	10,000
1 square centimeter	square meter	1×10^{-4}
1 square kilometer	square meter	1×10^{6}
1 square foot	square inch	144
1 square yard	square foot	9
1 acre	square foot	43,560
1 square mile	acres	640
1 hectare	acres	2.471

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From	To	Conversion Factor
Volume Conversion Factors		
1 cubic meter	liter (L)	1000
1 liter	milliliter (mL)	1000
1 cubic meter	cubic centimeter (cm^3)	1×10^6
1 cubic meter	cubic foot (ft^3)	35.315
1 cubic meter	cubic inch (in^3)	61023.74
1 liter	cubic meter	0.001
1 liter	cubic inch	61.024
1 gallon (US)	liter	3.785
1 pint (US)	liter	0.473
1 cubic foot	cubic meter	0.0283
1 cubic inch	cubic centimeter	16.387
Time Conversion Factors		
1 second	minute	1.667×10^{-2}
1 second	hour	2.778×10^{-4}
1 second	day	1.157×10^{-5}
1 second	year	3.169×10^{-8}
1 minute	second	60
1 minute	hour	1.667×10^{-2}
1 minute	day	6.944×10^{-4}
1 minute	year	1.901×10^{-6}
1 hour	second	3600
1 hour	minute	60
1 hour	day	4.167×10^{-2}
1 hour	year	1.141×10^{-3}
1 day	second	8.640×10^{4}
1 day	minute	1440
1 day	hour	24
1 day	year	2.738×10^{-3}
1 year	second	3.156×10^{7}
1 year	minute	5.259×10^{5}
1 year	hour	8.766×10^{3}
1 year	day	365.25
Speed Conversion Factors		
1 m/s	cm/s	100
1 m/s	ft/s	3.281
1 m/s	mi/h	2.237
1 cm/s	m/s	0.01
1 cm/s	ft/s	0.03281
1 ft/s	m/s	0.3048
1 ft/s	cm/s	30.48
1 mi/h	ft/s	1.467
Mass Conversion Factors		
1 kg	g	1000
1 slug	kg	14.59
1 u (atomic mass unit)	kg	1.661×10^{-27}
1 metric ton	kg	1000
Force Conversion Factors		
1 newton (N)	dyne	10^5
1 newton (N)	pound (lb)	0.2248
1 dyne	newton (N)	1×10^{-5}
1 pound (lb)	newton (N)	4.448

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From	**To**	**Conversion Factor**
Pressure Conversion Factors		
1 Pa	dyne/cm^2	10
1 Pa	atm	9.869×10^{-6}
1 Pa	cm Hg	7.501×10^{-3}
1 Pa	lb/in^2	1.450×10^{-4}
1 atm	Pa	1.013×10^{5}
1 cm Hg	Pa	1333
1 lb/in^2	Pa	6.895×10^{3}
Energy, Work, and Heat Conversion Factors		
1 joule (J)	erg	10^{7}
1 J	ft•lb	0.7376
1 J	eV	6.242×10^{18}
1 J	cal	0.2389
1 J	Btu	9.481×10^{-4}
1 cal	J	4.186
1 Btu	J	1.055×10^{3}
1 kWh	J	3.600×10^{6}

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