Asian Journal of Science, Engineering and Technology (AJSET)
eISSN: 3006-6980 (online)
https://ideapublishers.org/index.php/ajset
Vol. 4, No. 1 (January-June), 2025, pp. 110-130
https://doi.org/10.47264/idea.ajset/4.1.7
Original Research Article

Investigating the role of green infrastructure for planning flood resilient cities: a case study of Peshawar, Pakistan

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Article History

Received:
17-Mar-2025

Revised:
10-May-2025

Re-revised:
18-Jun-2025

Accepted:
19-Jun-2025

Published:
30-Jun-2025

Abstract:

Rapid urbanisation and the worsening effects of climate change are the primary causes of urban flooding, which is becoming an increasingly serious global issue. Flood risks have increased in developing countries due to deteriorating infrastructure, intensifying precipitation, unchecked urban growth, and ineffective stormwater management. Major Pakistani cities, such as Peshawar, experience urban flooding, which damages infrastructure, disrupts the economy, and negatively affects livelihoods. Using Khamosh Colony as a representative example of one of the urban flooding hotspots, this study explores how Green Infrastructure (GI) can enhance urban flood resilience in Peshawar. The effectiveness of both standalone and combined GI interventions in addressing floods under rainfall events with a 5-year return period was simulated using the Storm Water Management Model (SWMM). While community preferences were gathered through surveys conducted using the Kobo Toolbox platform with over 400 respondents, economic feasibility was evaluated using MRS 2024. The most successful solutions were permeable pavement and a combination of permeable pavement and bioretention. This study provides stakeholders with a clear understanding of flood scenarios, both before and after GI implementation. This method encourages strategic investment in climate-resilient infrastructure and informs participatory planning.

Keywords: SWMM, GIS, Urbanisation, Urban flooding, Green infrastructure, Economic assessment, Social survey, Kobo toolbox, 3D visualisation.

How to Cite: Shah, S. S. A. & Shah, S. S. A. (2025). Investigating the role of green infrastructure for planning flood resilient cities: a case study of Peshawar, Pakistan. *Asian Journal of Science, Engineering and Technology (AJSET), 4*(1), 110-130. https://doi.org/10.47264/idea.ajset/4.1.7

1. Introduction

The rapid growth of the global population continues to drive widespread urbanisation. According to the United Nations Department of Economic and Social Affairs, approximately 2.6 billion more people are expected to migrate to urban areas by 2050 (UNDESA, 2020). This rise exerts intense stress on urban infrastructure and water services. Stormwater runoff rises, groundwater recharge decreases, and water quality is negatively affected due to the conversion of natural land to impervious surfaces (Rahman *et al.*, 2019). Disruption in natural hydrological processes due to factors such as climate change, accompanied by changes in land cover conditions, increases the severity and frequency of urban runoff generation (Akhter & Hewa, 2016).

Urban flooding is considered one of the most catastrophic hazards, resulting from climate change, with negative impacts that include displacing a vast number of people and significantly damaging infrastructure and livelihoods (Khan *et al.*, 2020; Loc *et al.*, 2020, 2023). Traditional stormwater management systems are becoming insufficient for coping with the increasing volume of runoff, as they are typically designed based on past climate data (Hu *et al.*, 2020; Padulano *et al.*, 2021; Xiong *et al.*, 2019). To address the challenges of climate change, particularly urban flooding issues, urban areas around the globe are utilising Green Infrastructure (GI), a nature-based strategy that revitalises the ecological and hydrological systems of the environment, offering environmental and social benefits (IUCN, 2016).

These strategies have been known and successfully implemented using different names like Sustainable Urban Drainage Systems (SUDs) in the United Kingdom, ABC Waters in Singapore, Low-impact Development (LID) in North America, Water Sensitive Urban Design (WSUD) in Australia, Blue-Green Infrastructure in Europe and the Sponge City initiative in China. GI approaches, such as rain gardens, bioretention systems, green roofs, and permeable pavement, simulate natural water cycles to address runoff at its origin effectively (Dagenais *et al.*, 2018; Si *et al.*, 2022; Vijayaraghavan *et al.*, 2021). These strategies prove to be cost-effective and offer various advantages in addition to reducing surface runoff and improving water quality (Arjenaki *et al.*, 2021; Kim *et al.*, 2022; Latifi *et al.*, 2023; Suresh *et al.*, 2023; Ahmed *et al.*, 2024). However, their effective implementation and operation require a comprehensive understanding of their technical efficiency, economic viability and community preference.

Hydrologic and hydraulic modelling play a significant role in simulating and understanding flood behaviour in urban areas. For simulating runoff flows and the performance of the drainage system, the Storm Water Management Model (SWMM) by the US EPA is considered a standard tool (Rossman & Huber, 2017). Although SWMM enhances usability, it still poses challenges for users without a technical background (Elliott & Trowsdale, 2007). Studies integrating SWMM with two-dimensional modelling, such as in PCSWMM, enable visualisation of urban flood scenarios and support informed decision-making (Hsu *et al.*, 2002; Masseroni & Cislaghi, 2016).

In Pakistan, recent weather extremes, such as the 2020 Karachi floods, which caused nearly $1 billion in damages and resulted in 20 deaths (Ali, 2021), and the 2022 Lahore floods, which paralysed urban life for days (Gabol, 2023), underscore the growing vulnerability of Pakistani cities. Peshawar, one of Pakistan's oldest and fastest-growing urban centres, is increasingly prone to urban flooding. The city's inadequate drainage infrastructure, combined with rapid, unplanned urban growth and intense monsoon rainfall, frequently results in flooding of homes, roads, and businesses. Despite the global success of GI strategies, their contextual effectiveness, feasibility, and community acceptance remain under-researched in Peshawar. A comprehensive, localised evaluation integrating hydrologic modelling, economic analysis, and community perception is critically needed to inform climate-resilient and sustainable urban development.

This study aims to bridge this critical gap by evaluating multiple Green Infrastructure (GI) strategies within Khamosh Colony, one of the most flood-vulnerable urban catchments in Peshawar. By integrating high-resolution hydrological modelling using SWMM, market-based cost analysis, and community-level surveys, the research comprehensively assesses the performance of GI interventions from technical, economic, and social perspectives. The study's defined objectives are listed below.

- Assessing the efficacy and contextual applicability of selected GI measures to address urban flooding based on historical rainfall patterns.
- Identifying the most socially acceptable GI measure using household-level surveys to gather insights on community preferences for these measures.
- Developing an integrated, evidence-based decision-making tool that incorporates hydrological modelling, economic assessment, and stakeholder perspective to guide resilient urban flood management approaches.

The study methodology can be more broadly applied to other rapidly urbanising, flood-prone cities in South Asia and beyond, despite being based in Peshawar. By combining hydraulic modelling, economic analysis (CAPEX costs for GI solutions), and community engagement, the research makes a meaningful contribution to the global discourse on sustainable urban water management and the strategic integration of Green Infrastructure for climate adaptation.

2. Materials and methods

The study followed the methodology outlined in Figure 1. Each GI option, both standalone and in combination, was assessed across three key dimensions: technical effectiveness, economic feasibility, and social acceptability. The data to be utilised in the study, along with the corresponding sources and the detailed methodology followed to achieve the outlined objectives, are discussed in this section.

2.1. Study area

Peshawar City is vulnerable to multiple climate hazards, especially urban flooding, due to its rapid urbanisation, making it the focus area of this research. According to the 2017 census, the city had a population of 4,267,198, with a population density of approximately 3,394.75 people per km^2 and an average annual growth rate of 3.99% between 1997 and 2017. As a rapidly urbanising centre, Peshawar frequently experiences recurrent and severe flooding events.

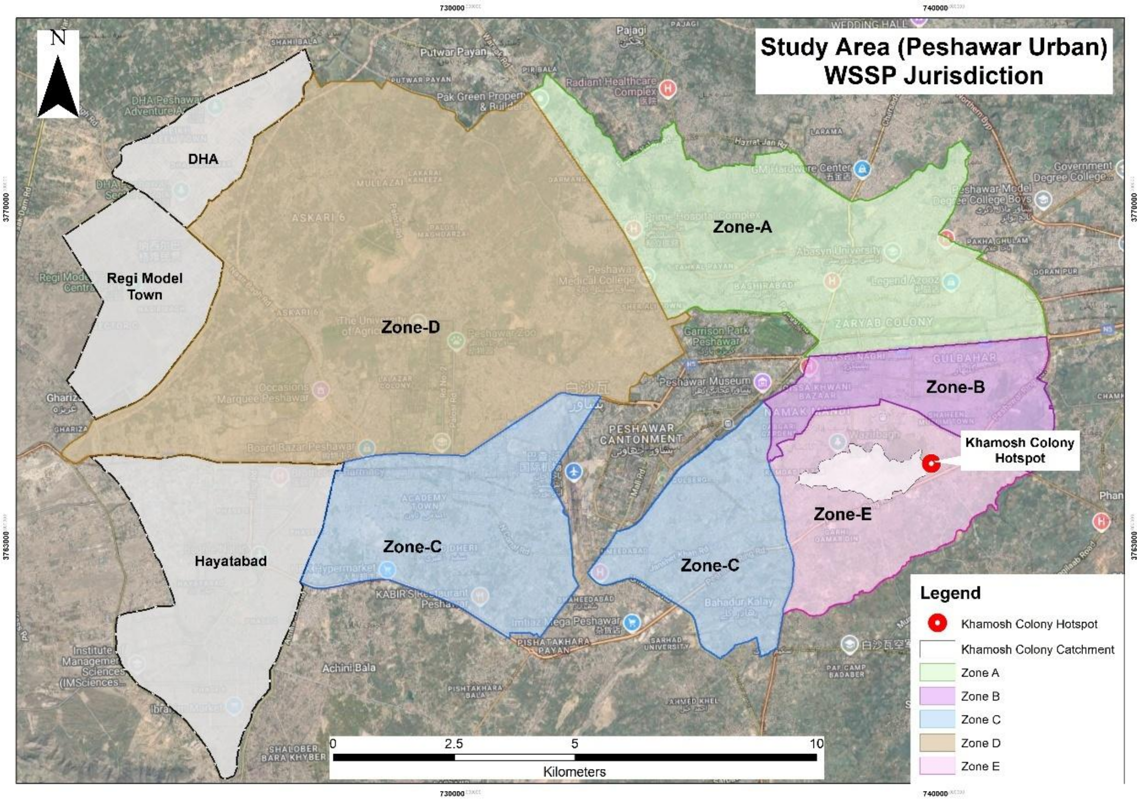
The total area of District Peshawar is approximately 1,215 km^2, of which 176.9 km^2 or 14.6% constitutes the defined study area (Figure 1). This area encompasses the five operational zones of the Water and Sanitation Services Peshawar (WSSP), namely Zones A, B, C, D, and E, which cover 51 Union Councils and mark the urban footprint of the city. Additionally, the study boundary encompasses key planned residential developments, including Hayatabad, Regi Lalma Township, and the Defence Housing Authority (DHA).

Table-1: Data and sources

Sr No	Data	Period	Source
1	Precipitation	1961-2024	Pakistan Meteorological Department (PMD)
2	Digital Elevation Model (DEM)	2020	Project Management Unit (PMU) of Local Government, KPK
3	3D Building Data	2023	Google Open Buildings
4	Drain Sizes	2024	Field Survey
5	Green Infrastructure (GI) Cost	2024	MRS 2024, literature
6	Social Aspects of GI	2025	Data Collection Survey (Kobo Toolbox)

The research specifically focuses on one of the identified urban hotspots, namely Khamosh Colony, situated within the core zones of the city. This hotspot was selected based on its high flood vulnerability, rapid land-use transformation, and the presence of critical urban infrastructure. It is also projected to experience a significant increase in built-up land between 2025 and 2050, which will further exacerbate its exposure to urban flood risks.

Figure 1: Study area map



2.2. Data and sources

The data used in this study were sourced from a range of credible and authoritative institutions to ensure the accuracy and reliability of the urban flood modelling and analysis conducted for Peshawar (Table-1). Historical precipitation data spanning from 1961 to 2024 were obtained from the Pakistan Meteorological Department (PMD), providing a strong foundation for model calibration and simulation.

Topographic and spatial analyses were supported by a high-resolution (1-meter) Digital Elevation Model (DEM) from 2020, acquired from the Project Management Unit (PMU) of the Khyber Pakhtunkhwa Local Government. This dataset was necessary to delineate flow paths and define sub-catchments in the model. Google Open Buildings tool was used to extract the building footprint data for the year 2023, enabling accurate land use classification and improving 3D visualisation capabilities.

To obtain site-specific and existing drainage system details for the use of updated hydraulic modelling inputs, data on the existing drainage network were collected through a field survey conducted in 2024. Community preferences for GI measures were assessed through a systematic household survey using the Kobo Toolbox, with responses collected from over 400 people across the study area.

Finally, for evaluating the economic viability of GI options, the Market Rate System (MRS) 2024 was referenced and supported by relevant academic and industry literature. This thorough data acquisition enabled a comprehensive assessment of GI measures in terms of their technical efficacy, social acceptance, and economic viability.

3. Model

3.1. Rainfall-runoff modelling

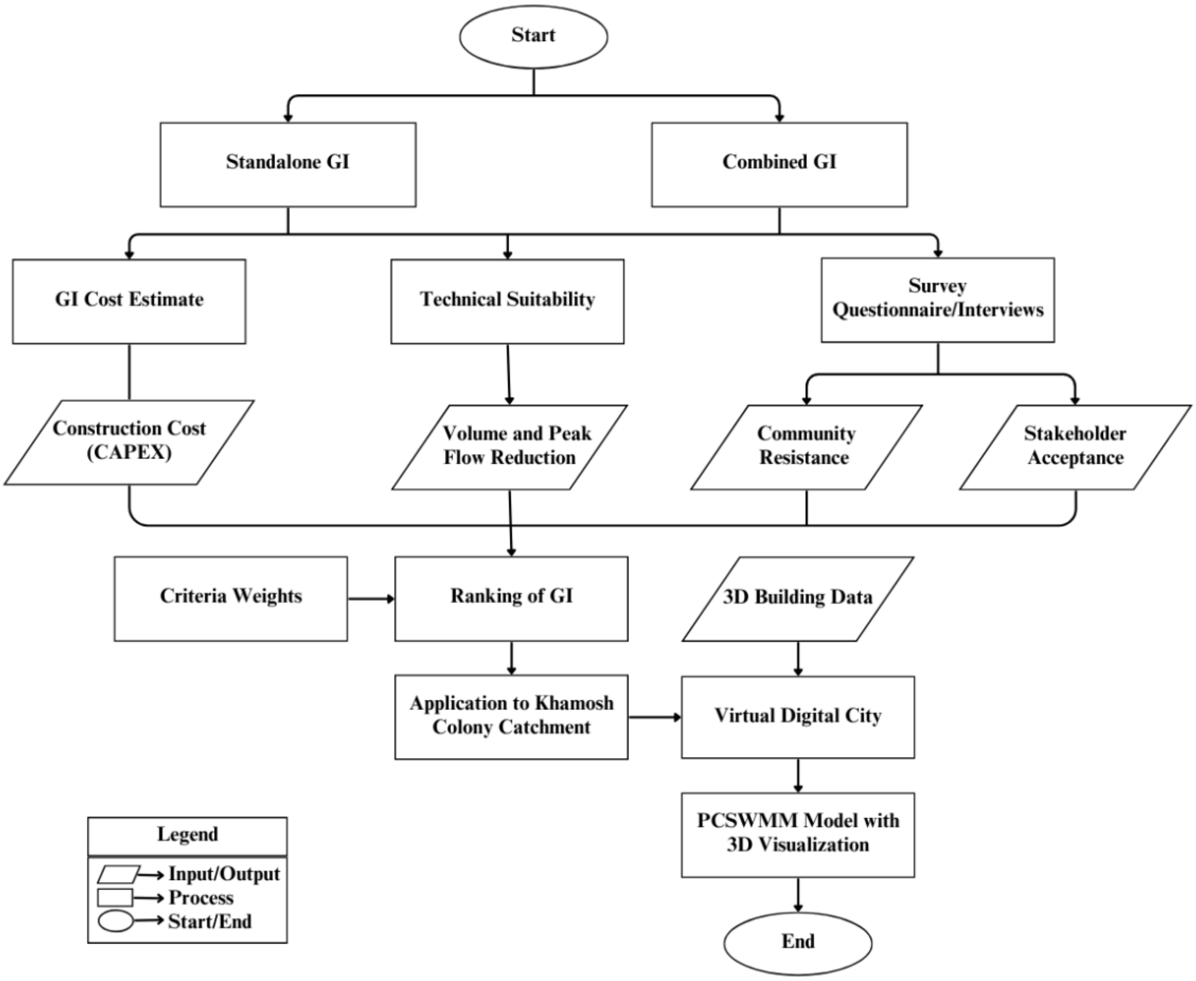
3.1.1. Model development

The rainfall runoff model is based on the frequency analysis of daily rainfall data obtained from the Pakistan Meteorological Department (PMD-KP). The frequency analysis provides peak rainfall values with respect to different return periods. The Log Pearson Type III method has been used to determine peak rainfall values ranging from 2 to 200 years. The Intensity Duration Curve, which distributes the intensity of rainfall over 24 hours, has also been derived from daily rainfall data collected over the period from 1980 to 2024. This extensive data availability helped in determining the Intensity-Duration-Frequency (IDF) curve for Peshawar, which was utilised as one of the key input data sets for the PCSWMM model.

According to the Water and Sanitation Agency (WASA)/Public Health Engineering Department (PHED) Punjab guidelines for the design of drainage systems, primary drains or trunk mains are designed for a 5-year return period, whereas secondary or tertiary drains at street levels are designed for a 2-year return period. Based on frequency analysis, the peak flow values corresponding to the 2- and 5-year return periods and their respective IDF curves were determined using the daily rainfall data.

PCSWMM employs rainfall data (IDF Curve) to simulate hydrological responses and assess the performance of the drainage system. This rainfall data and its respective analysis help in calibrating the PCSWMM model, as explained in the section below.

Figure 2: Methodology flow chart



3.1.2. Model calibration

Model calibration improves the confidence level of model predictions and reliability. The calibration of the SWMM model is governed by a variety of input parameters derived from physical surveys, a high-resolution Digital Elevation Model (DEM), rainfall frequency analysis outputs (i.e., peak flow against return periods and Intensity-Duration Curve), Land cover classification, and catchment/sub catchment analysis.

Since the flow gauges were not available, the calibration of the model has been based on the assumption that the existing drains are designed for a flow of at least a 2-year return period. The model was run for a 2-year return period peak flow and corresponding IDF curve, and the flooding hotspots/flooding nodes were determined. The flooding nodes were observed even at a 2-year RP rainfall, which was optimised by minor adjustments to the hydraulic parameters of the model.

The model parameters that were adjusted primarily include sub catchment land cover, which was derived from land cover analysis using GIS. The adjustment resulted in the removal of flooding nodes, which satisfied the model calibration. This calibration approach (assumption-based) is widely adopted where direct observational data are limited or unavailable in urban flood modelling studies (Leandro *et al.*, 2011).

The simulation for a 5-year return period flow was then carried out on this calibrated model, and the effectiveness of the Green Infrastructure was determined using Standalone and Combined options. This methodology for calibrating an urban stormwater model using sub-catchment parameters under a 5-year design storm scenario was also employed by Rosenberger *et al.* (2021).

3.2. Green infrastructure assessment

Regarding the GI assessment, multiple scenarios were developed and simulated using the calibrated PCSWMM model to assess the impact of GI on reducing surface runoff within the study area, i.e., Khamosh Colony. The scenarios including both standalone and integrated applications of GI interventions, were customised to the specific hydrological and spatial characteristics of each catchment.

The performance of each GI scenario (Standalone and Combined) was evaluated in three dimensions: effectiveness, i.e., reduction in surface runoff; economic viability, i.e., Capital cost for GI interventions; and social acceptance, derived from social surveys. This technical, economic, and social assessment ensures the identification of the most suitable GI, which is not only economically viable and technically sound but also aligned with local stakeholder or community preferences, thereby supporting practical flood resilience planning for urban areas of a city in a developing country.

3.2.1. Economic assessment

The capital cost or construction cost of each GI Intervention, i.e., Green Roof, Permeable Pavement, Bioretention System, and Rain Garden, has been determined to gauge the economic aspect of the solution. References for different GI cross-sections and design specifications were taken from the literature to ensure accuracy and consistency.

The cost of typical sections was then determined using the latest Market Rate System (MRS, 2024). The per-square-meter cost for GIs are given in Table 2.

Table-2: GI cost estimates

Sr No	Green Infrastructure	Level of Intervention	Approx. CAPEX (PKR)	Units
1	Green Roof	House Level	7,000	Per m^2
2	Permeable Pavement	Street Level	4,500	Per m^2
3	Bioretention System	Street Level	18,500	Per m^2
4	Rain Garden	Street Level	12,000	Per m^2

3.2.2. Technical assessment and scenario design

The technical suitability of various GI options was assessed for both standalone and combined GI interventions to mitigate surface flow volumes.

The existing drainage system, which currently lacks any GI measures, has been taken as a baseline scenario, serving as a reference point for the comparative analysis of pre- and post-GI implementation. Standalone GI including Rain Gardens (RG), Bioretention Cells (BR), Green Roofs (GR), and Permeable Pavements (PP) were independently simulated. The combinations, including Green Roof + Bio Retention, Rain Garden + Bio Retention, and Permeable Pavement + Bio Retention, were evaluated.

Each scenario was tested under historical precipitation conditions, using 5-year return period storm events to capture a range of flood intensities. The model outputs, including total flood volume and the number of inundated nodes, were analysed to determine the most technically effective GI in the study area.

Table-3: Standalone and combined GI scenarios

Application	GI Applied	Description	Number of Units	Total area (m^2)
Standalone	GR	50% Houses in each sub catchment with 50% of roof covered with vegetation	2,960	18,451
	BR	5% impervious area in each catchment	664	56,089
	RG	10% pervious area in each catchment	332	49,736
	PP	50% roads and streets	559	75,251
Combination	GR & BR	50% Green Roof + 5% Bioretention		
	BR & PP	5% Bioretention + 50% Porous Pavement		
	RG & BR			

3.2.3. Social assessment

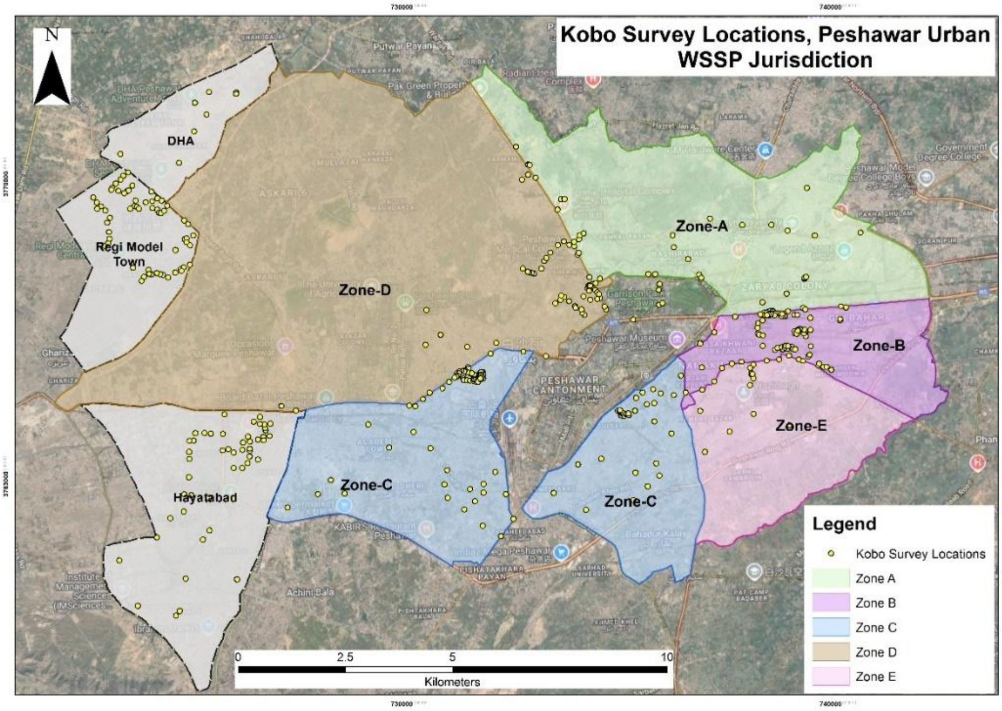
The social assessment of the GI was performed using a questionnaire prepared on the Kobo Toolbox. A variety of data was collected from the respondents in the study area, including frequency, severity and duration of flooding, types and extent of damage caused by flooding, community willingness to adapt GI initiatives both at the house and street levels, and level of satisfaction from the available infrastructure

A minimum sample size of 385 was determined for a population of approximately 2 million, i.e., the urban area of Peshawar, based on a 95% confidence level and a 5% margin of error. The survey successfully yielded 443 valid responses, exceeding the required threshold and providing a strong foundation for meaningful analysis.

The results were analysed to evaluate levels of community support or resistance toward different GI options. These insights were subsequently integrated into the final ranking of GI strategies, giving higher priority to interventions that demonstrated greater public approval. This participatory approach ensures that the recommended GI solutions are not only technically and economically sound but also socially acceptable and aligned with the local population's preferences and priorities.

Figure 3 presents the spatial distribution of survey locations within the study area, encompassing all five operational zones of the Water and Sanitation Services Company (WSSC)—Zones A, B, C, D, and E—as well as planned residential areas such as Regi Model Town, DHA, and Hayatabad Township. Individual survey responses are marked as black dots, illustrating the comprehensive geographic coverage and inclusive nature of social assessment across the entire study area.

Figure 3: Kobo survey data collection points



3.3. Developing an informed decision-making model for policymakers

To develop a comprehensive PCSWMM model integrated with the most effective GI solutions and to enhance understanding through three-dimensional visualisation of urban flooding scenarios, ArcGIS Pro was used in conjunction with PCSWMM. The 3D visualisation drew upon multiple datasets, including a 1-meter resolution Digital Elevation Model (DEM), open-access building footprint data, PCSWMM flood simulation outputs, and a high-quality base map for contextual reference.

The DEM was processed in ArcGIS Pro to extract topographic features and delineate flow directions within the study catchment. Building footprints were extruded into 3D models using available height attributes, effectively creating a realistic digital representation of the urban landscape. Flood simulation data from PCSWMM, particularly the flood depth and spatial distribution at individual junctions, were imported into ArcGIS. The radius of influence for each inundated node was used to map the extent and severity of flooding across the catchment area.

Once the base 3D environment was established, the top-performing GI interventions, evaluated under both standalone and combined configurations, were incorporated into the PCSWMM model. These GI-integrated scenarios were then visualised alongside the 3D urban models, providing an intuitive and spatially enhanced understanding of how GI impacts flood dynamics on the local scale.

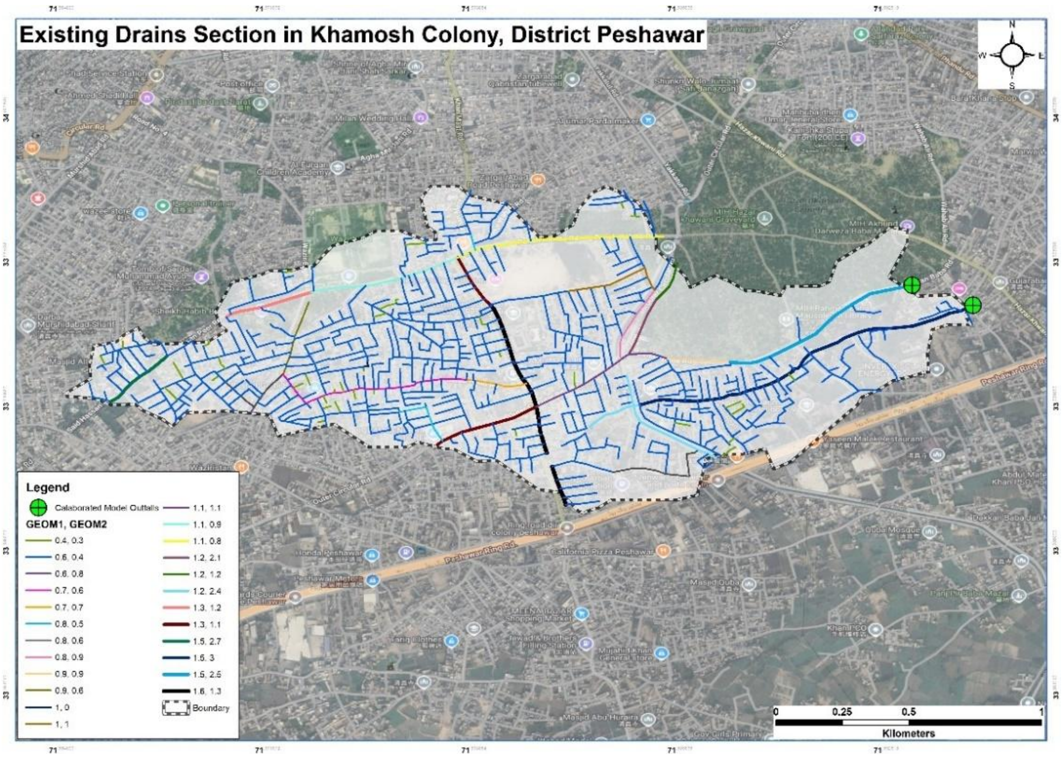
Simulations were carried out for storm events corresponding to a 5-year return period. The resulting outputs are presented in the following section, offering a comparative analysis of flood extent and severity between the baseline (no-GI) and GI-implemented scenarios. This visualisation demonstrates the tangible benefits of GI in mitigating urban flood risks within the study area.

4. Results

4.1. SWMM model

The PCSWMM model developed for this study is illustrated in Figure 4, which depicts the existing drainage network within the Khamosh Colony sub-catchment. Variations in drain width and depth are represented by colour-coded segments, corresponding to specific geometric dimensions as detailed in the legend. Blue markers indicate the location of calibrated outflows within the model.

Figure 4: Calibrated SWMM model

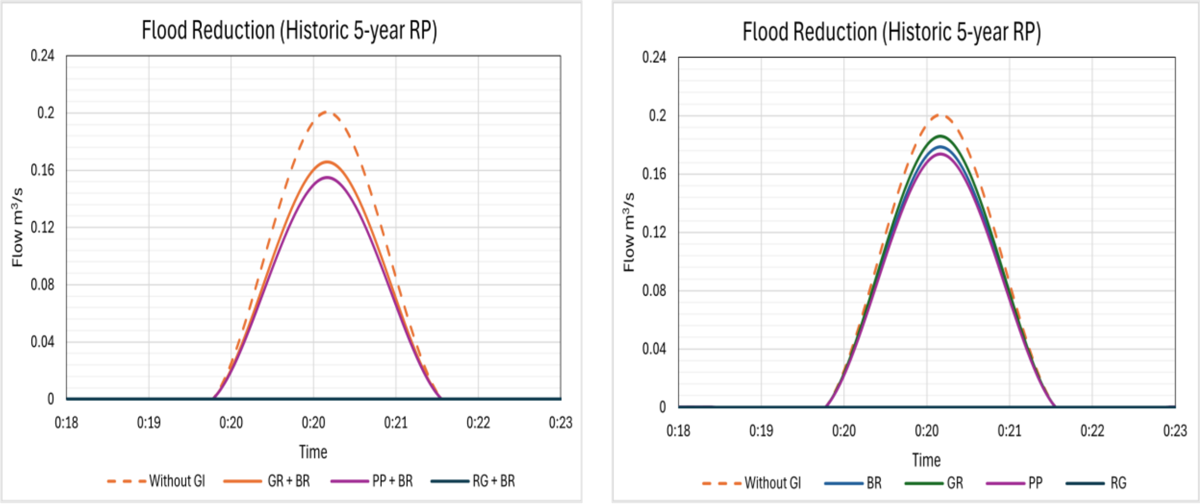


Following the scenarios described in the methodology section, each GI intervention was systematically incorporated into the model for this catchment. The effectiveness of these interventions in reducing flood volumes was subsequently evaluated. For the technical assessment, peak flow rates generated under each GI scenario were simulated and analysed using PCSWMM to assess their capacity for mitigating urban flooding under both current and projected precipitation conditions.

4.2. Performance of Green Infrastructure (GI)

The performance of GI, both as standalone measures and in combination, varies across the different aspects of the assessment. The reduction in peak flow under a 5-year return period event is illustrated in Figure 5 for both standalone and combined scenarios of the GI interventions.

Figure 5: Peak flow reduction with GI interventions



The technical assessment reveals that the scenario without any GI intervention exhibits the highest peak of flooding in the figure above. In contrast, the rain garden and rain garden plus bioretention pavement scenarios reduce the peak to the lowest values (~0 m³/s) in the standalone and combined categories, respectively.

Table-4: Green infrastructure ranking

Sr No	Green Infrastructure	Score			Total Score	Rank
		Economic Aspect	Technical Aspect	Social Aspect		
Standalone GI						
1	Green Roof (GR)	2	4	2	8	3
2	Permeable Pavement (PP)	1	2	1	4	1
3	Bioretention System (BR)	2	3	1	6	2
4	Rain Garden (RG)	2	1	1	4	1
Combined GI						
1	50% GR + 5% BR	2	3	2	7	3
2	5% BR + 50% PP	1	2	1	4	1
3	RG + BR	3	1	1	5	2

The overall evaluation of GI is based on a multi-criteria performance ranking system that considers economic, technical, and social factors. The results presented in the following table indicate that a lower overall score represents a better-performing GI option across these three dimensions.

Among the standalone applications, permeable pavement emerges as the most effective solution due to its cost-effectiveness, social acceptability, ease of implementation, and balanced performance across technical, social, and economic criteria. In terms of combined applications, scenario involving bioretention with permeable pavement demonstrates the best overall performance. Table 4 presents the performance and ranking of standalone and combined GI options, in terms of social, economic, and technical aspects.

4.3. 3D representation of urban flooding

This study integrates the PCSWMM model with 3D visualisation to enhance policymakers' and key stakeholders' understanding of flooding scenarios. The most effective GI options, PP and the combination of BR + PP were identified through a multi-criteria ranking process and applied to the case study area of Khamosh Colony. The resulting 3D maps provide a more intuitive and realistic depiction of buildings and flood inundation, aiding in more transparent communication of flood risks. For the 5-year return period under historical climate conditions, GI performance remains optimal, significantly reducing flood impacts. However, it can be concluded that while GI plays a valuable role in mitigating flood impacts, especially under historical conditions, it may not be sufficient on its own during high-intensity rainfall events driven by climate change. In such cases, GI should be considered a complementary system to traditional grey infrastructure, rather than a standalone solution, particularly in space-constrained urban environments.

4.4. Social assessment of GI acceptance

Multiple questions were asked by the community, covering the study area, from historical flooding events experienced in the region to the community's willingness to support and maintain GI. The results of this social assessment of GI are given next.

4.4.1. Community perceptions of urban flooding: severity, causes, duration, and impacts

According to the survey results, 33.63% of respondents reported severe flooding, 12.40% very severe flooding, and others reported moderate (22.57%), minimal (23.02%), or no flooding (8.38%) after heavy rainfall. Of those impacted, approximately 32% reported experiencing flooding problems for more than ten years, 27.5% for the last five to ten years, and 19% said flooding began in the last two to five years. Due to drainage disruptions caused by projects like the BRT, flooding has gotten worse, particularly along University Road.

Of the 503 responses, 34.91% attributed the flood to unusual rainfall, 57.78% to poor drainage, and only 8.76% to changes in land use, indicating a lack of public awareness. Of the respondents who answered questions about flood damage, 51.84% reported no damage, while others indicated structural damage (31.51%), water in lawns (33.27%), and loss of possessions (10%). Problems such as clogged, undersized, and encroached drains were confirmed through field surveys conducted in Khamosh Colony. These results underscore the need for improved urban planning, effective drainage, efficient waste management, resilient infrastructure, sustainable green solutions, and heightened public awareness.

Figure 3(a): Severity, causes, duration and impacts of urban flooding

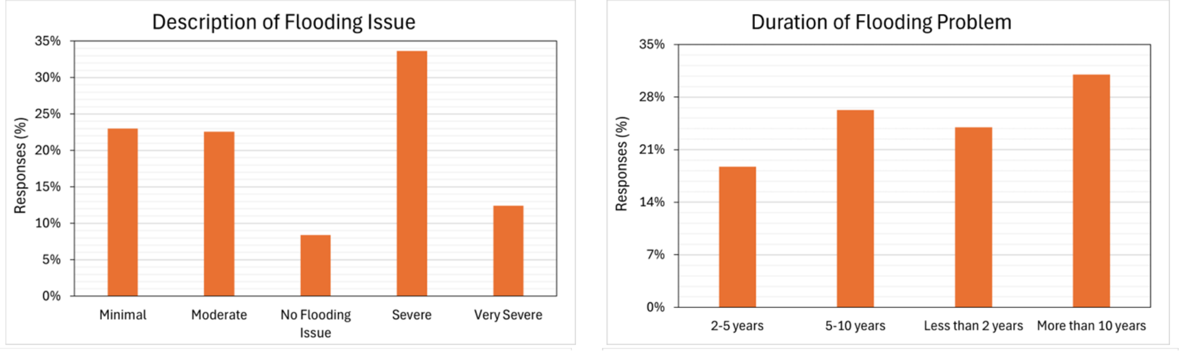
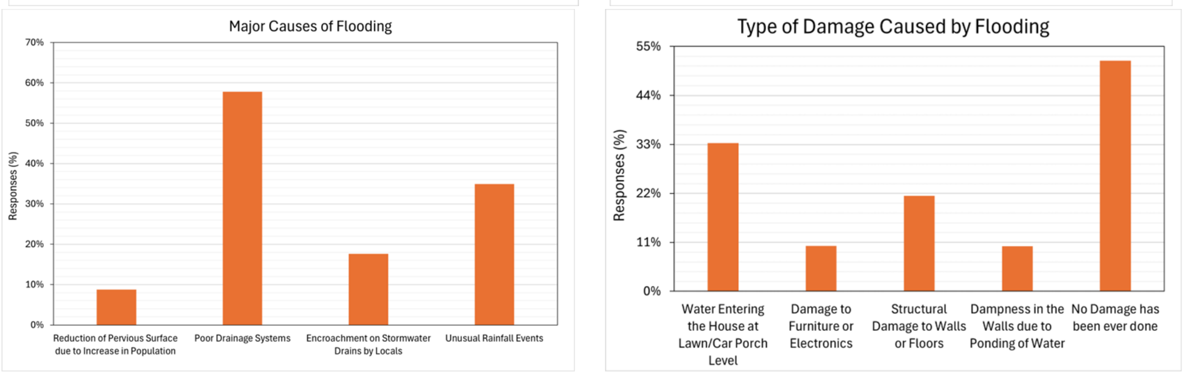


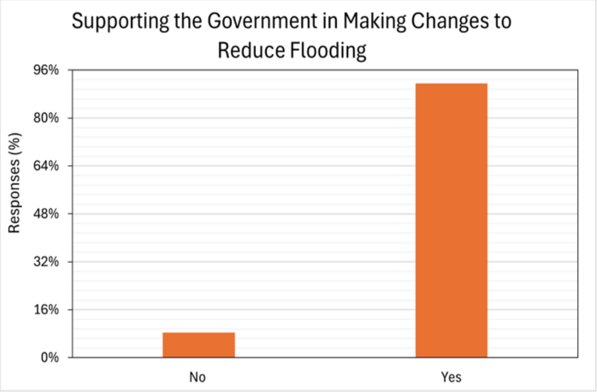
Figure 4(b): Severity, causes, duration and impacts of urban flooding



4.4.2. Community willingness to support green infrastructure

According to the survey's findings, more than 90% of participants are willing to support government initiatives to mitigate urban flooding, demonstrating a high level of public awareness and engagement. This emphasises the urgent need for sustainable urban planning, particularly the incorporation of green infrastructure to mitigate the effects of rapidly increasing urbanisation and the loss of permeable surfaces. Effective government-led programs can improve urban sustainability and resilience if the public supports them.

Figure 7: Respondents' support for the government in reducing floods



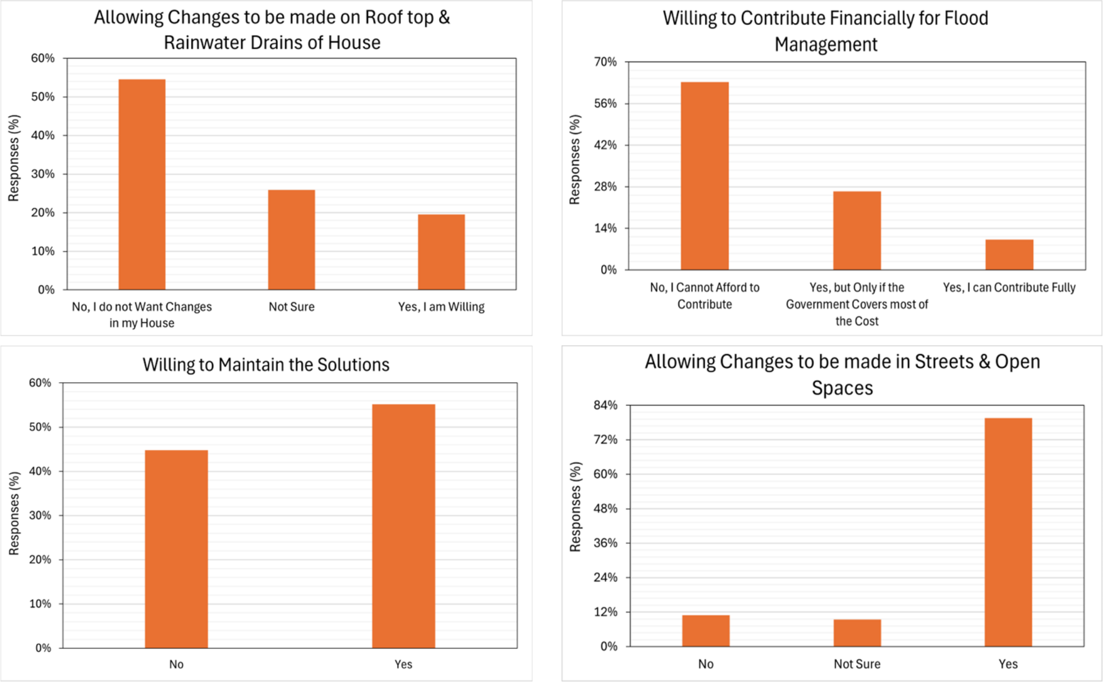
4.4.3. Community preference of green infrastructure

Due to concerns about cost, upkeep, and space, only 19.54% of respondents preferred house-level solutions like green roofs, rain barrels, whereas 79.62% supported street-level GI like rain gardens, permeable pavements and so on. DHA and Regi Model Town, two more recent developments, demonstrated greater receptivity to such policies.

One of the main obstacles to the adoption of GI is the cost. Of the 94 respondents who were amenable to house-level GIs, 55 chose not to make a monetary contribution. Of these, 44.81% expected the government to cover both installation and maintenance, while 55.19% were willing to maintain the GIs if the government paid for the installation.

Just 10.26% said they would be willing to pay in full for flood management, while a large proportion of the community (63.29%) reported financial difficulties. Subsidies from the government may promote the adoption and use of GI in cities.

Figure 8: Respondents' preference for house-level solutions

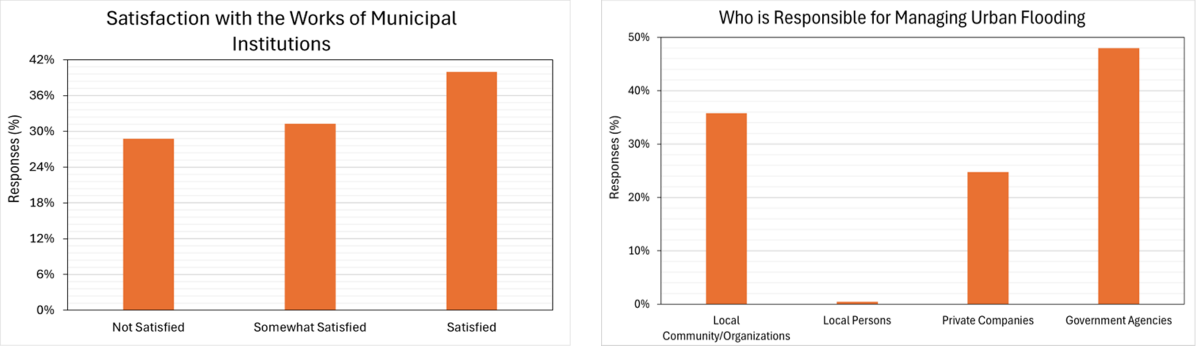


4.4.4. Level of satisfaction with municipal institutions

The survey's findings, which emphasise the need for stronger institutional efforts, reveal that 39.97% of respondents were satisfied with municipal performance, 31.27% were partially satisfied, and 28.76% were dissatisfied because of inadequate flood control.

There is potential for public-private partnerships to enhance urban resilience through green infrastructure and innovative drainage solutions, as nearly 48% of respondents believe government agencies should oversee urban flood management, and 25% favour private sector involvement.

Figure 9: Respondents' satisfaction level with municipal institutions



5. Discussion

5.1. Comparative analysis

The results of this study highlight the effectiveness of GI in mitigating urban flooding in Peshawar. While GI solutions such as PP and BR have been widely recognised for their ability to manage stormwater and reduce urban flood risks globally, this study reaffirms that their performance is highly influenced by local factors including climate conditions, urban density, and hydrological characteristics.

Figure 10: Flooding scenario under 5-year return period rainfall event

Based on the discussion above, the Permeable Pavement is one of the most effective GI options as a Standalone Option, based on affordability, reducing surface flow volumes, and social acceptance. The given outputs are also in line with previous research studies conducted in other urban areas prone to urban flooding, such as Beijing, China (Hu *et al.*, 2018).

For combined GI Options, the Bio Retention system with Permeable Pavement offers greater resilience and surface flow reduction in densely populated settlements, such as Peshawar. The 3D maps illustrate the extent of urban flooding without GI, as well as the effectiveness of GI as a standalone (PP) and in combination with BR (PP+BR), which is evident in the results.

5.2. Practical implications for urban planning and policy

The social dimension, as assessed by household-level surveys, emerged as a crucial component in determining the viability and long-term success of GI interventions, even though technical modelling and economic analysis also contributed to the integrated assessment. Incorporating community preferences into urban planning frameworks is crucial, as evidenced by survey responses that demonstrate a general willingness to support and maintain GI, as well as significant public concern over the severity of urban flooding. The social assessment reveals that the majority of people do not want to take the financial burden of proposing GI but are willing to maintain it.

GI options proposed at street level, i.e., Permeable Pavements, bioretention systems, and rain gardens, are socially considered to be the most viable options. According to these results, planning and policy initiatives should prioritise interventions that not only yield positive hydrological and economic outcomes but also align with local social dynamics and values.

Public awareness campaigns are crucial for conveying the benefits of GI in terms of environmental sustainability, aesthetics, and flood reduction, in order to encourage community adoption. Incorporating participatory decision-making procedures into planning can also enhance residents' sense of ownership, ensure relevance, and foster trust.

5.3. Broader implications

The study contributes to broader discussions on resilient and sustainable urban development beyond its local context. A replicable model for evidence-based planning is provided by the multi-criteria framework, which evaluates GI options from technical, financial, and social perspectives. By matching infrastructure choices with community needs and economic viability, this strategy improves the relevance and acceptability of GI interventions. The study supports the Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities), by promoting inclusive, nature-based, and community-informed solutions to manage urban flooding and enhance long-term resilience planning, despite not directly modelling future climate scenarios.

6. Conclusion

Rapid urbanisation, poor drainage systems, and heavier rainfall have all contributed to the growing risk of urban flooding in Peshawar, one of Pakistan's most flood-prone cities. The importance of the much-needed integration of Green Infrastructure (GI) into urban planning frameworks is highlighted by this study. The findings demonstrate the effectiveness of both standalone and combined GIs in reducing surface flows. Even the best suitable GI works when used in combination. The 3D GIS-based visualisation and hydrological modelling carried out in this study is one of its main innovations. This allows key stakeholders to make well-informed decisions by visualising the impact of GIs on urban flooding. Furthermore, this study also enables the selection of the best-performing GIs in congested urban settlements based on their technical suitability, economic affordability, and social acceptability.

6.1. Recommendations

There are also chances to improve GI performance and monitoring through the integration of cutting-edge technologies. For real-time flood detection and adaptive response, future studies should investigate smart stormwater management systems, such as those that use sensors based on the Internet of Things (IoT). These tools may be beneficial in crowded cities with limited traditional infrastructure, where prompt action is crucial for mitigating the effects of flooding.

Another promising approach is to support community-led GI projects. Green roof (GR) is an example of a small-scale GI element that can be greatly improved in sustainability, public acceptance, and maintenance costs by involving residents in their design, implementation, and maintenance. Involving the community at the grassroots level fosters environmental stewardship and community resilience, while also ensuring that interventions are contextually appropriate.

Ultimately, it is crucial to understand the hydrological benefits of GI beyond its capacity to mitigate surface runoff. Given the rapid population growth and over-extraction that have resulted in declining water tables, GI's role in groundwater recharge is particularly significant in water-stressed cities like Peshawar. To position GI as a multipurpose solution for both flood mitigation and long-term water sustainability, future research should evaluate the role that GI interventions play in integrated urban water resource management.

6.2. Limitations of the study

The study's emphasis on historical rainfall data, which helps understand system performance today, but excludes future variability brought on by climate change, is a drawback. Future research that incorporates projections may provide a more comprehensive understanding of GI effectiveness in situations with excessive rainfall. With rapid urbanisation, converting pervious surfaces into impervious ones and increasing surface runoff, it is essential to incorporate the impacts of land cover change over time on runoff generation, which is lacking in this study. Likewise, although a preliminary cost assessment (CAPEX) is part of the study, more comprehensive and longer-term cost-benefit analyses are also required. This should also consider GI co-benefits, which can strengthen the economic case for GI investment. These include improved air quality, enhanced urban aesthetics, reduced flood damage, and higher property values.

Declaration of conflict of interest

The author(s) declared no potential conflicts of interest(s) with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship and/or publication of this article.

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Publisher's Note

IDEA Publishers Group (AJSET IDEA-PG) stands neutral with regard to the jurisdictional claims in the published maps and the institutional affiliations.

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