Journal of
Water Resource Engineering and Management

ISSN: 2349-4336
Volume 13, Issue 1, 2026
January–April
DOI (Journal): 10.37591/JoWREM

https://journals.stmjournals.com/jowrem

Research JoWREM

Physiographic, Climatic, and Hydrogeological Determinants of Urban Flooding in Bhopal: A Spatial Assessment

Mahima Vishwakarma[1,*], K.K. Dhote[2], Neha Pranav Kolhe[3]

Abstract

Bhopal, capital city of Madhya Pradesh, is uniquely shaped by hilly terrain, lake systems, and complex hydrogeological characteristics, which historically supported efficient natural drainage. However, rapid urbanization, encroachment, and alterations in land use have increasingly disrupted these natural systems, amplifying city susceptibility to urban flooding. The city's physiography – defined by five major hills, undulating slopes, and a network of natural drainage channels – directs runoff toward low-lying zones that frequently experience waterlogging during intense rainfall events. Climatic variations, including rising precipitation anomalies and erratic monsoon patterns, further aggravate the situation. Geological factors, such as basaltic formations and limited infiltration capacity in certain regions, influence both runoff behavior and groundwater recharge. This study evaluates these interconnected physical determinants to understand spatial distribution and causes of urban flooding in Bhopal. It highlights strategic potential of institutional campuses – due to their permeable open spaces and micro-catchment positioning – in mitigating stormwater impacts. By analyzing representative campuses and their runoff behavior, study emphasizes importance of decentralized, nature-based interventions for enhancing resilience. Research underscores the need for integrated planning strategies that align topography, hydrology, and land use to reduce Bhopal's flood vulnerability.

Keywords: Bhopal, climatic anomalies, hydrogeology, institutional campuses, nature-based solutions, physiography, stormwater management, urban flooding

INTRODUCTION

Bhopal, popularly known as the "City of Lakes," is the state capital and second-largest city of Madhya Pradesh, India. This city is known for its old, scenic, and picturesque landscape that has evolved out of the stability and turmoil of its long but glorious historic past. The name Bhopal is popularly derived from Bhojpal or Bhoj's dam, including the upper lake and the lower lakes [1–3].

Apart from being the administrative capital of Madhya Pradesh, Bhopal is one of the major cities in Madhya Pradesh that still has a "blue-green" footprint, sustaining its physical form in sync and harmony with the natural elements of greenery and water. Situated in the Vindhya and Malwa plateau region, it exhibits a unique physiography with the Narmada valley in the central-east, Bhoj wetland toward the southeast, Berasia shrub forests in the west, upper and lower lake views, and various hill points [4].

***Author for Correspondence**
Mahima Vishwakarma
E-mail: mahima6799@gmail.com

[1]Research Scholar Department of Architecture and Planning, Maulana Azad National Institute of Technology, Bhopal, Madhya Pradesh, India
[2]Professor, Department of Architecture and Planning, Maulana Azad National Institute of Technology, Bhopal, Madhya Pradesh, India
[3]Assistant Professor, Department of Architecture and Planning, Maulana Azad National Institute of Technology, Bhopal, Madhya Pradesh, India

Received Date: December 19, 2025
Accepted Date: January 23, 2026
Published Date: January 28, 2026

Citation: Mahima Vishwakarma, K.K. Dhote, Neha Pranav Kolhe. Physiographic, Climatic, and Hydrogeological Determinants of Urban Flooding in Bhopal: A Spatial Assessment. Journal of Water Resource Engineering and Management. 2026; 13(1): 25–32p.

Table 1. City profile of Bhopal.

Parameter	Description
State	Madhya Pradesh
Geographical area	Covers approximately 837.24 sq. km
Languages spoken	Predominantly Hindi, with Urdu and English also used
Administrative status	Functions as the district and divisional headquarters of the Bhopal Division
Number of divisions	10 administrative divisions
Number of tehsils	438 tehsils across the state
Number of villages	Around 24,000 villages
Elevation	Situated at an altitude of about 427 meters above sea level
Latitude	Located at 23°16’ North
Longitude	Positioned at 77°36’ East
Average annual rainfall	Receives around 112 cm of rainfall annually
Winter temperature range	Varies between 16°C and 30°C
Summer temperature range	Ranges from 30°C to 45°C
Relative humidity	Approximately 58%
Wind Speed	Average wind velocity varies between 3 m/s and 8 m/s
Lakes & water bodies	Contains around 18 major and minor water bodies
Hills & mountain ranges	Spread over five hills: Arera, Shyamla, Idgah, Katara, Neori
Geology & geomorphology	Characterized by Deccan Trap Basalt along with Vindhyan shales and sandstones
Total population	2,368,145 residents
Male Population	1,239,378 males
Female population	1,128,767 females
Population density	About 855 persons per sq. km
Sex Ratio	918 females per 1,000 males
Literacy Rate	Approximately 83.47%
Municipal corporation	1 Nagar Nigam
Administrative zones	Divided into 19 zones
Urban Wards	Comprises 85 municipal wards

Through general observations and records of secondary data, it has been observed that large sections of migrant populations who are migrating from rural to urban settings are preferring to settle in Bhopal as compared to other tier 1 towns like Indore, Gwalior, and Jabalpur not only for their economic stability but with the primary aim of getting a good quality of life and a healthier environment which they find more in Bhopal as compared to the other cities with similar traits (LU-Bhopal2005, n.d.). This speeds up the pace of urbanization and puts stress on the limited infrastructural resources of the city Table 1 [5–7].

Objectives

This study analyzes how Bhopal’s physiography, geology, hydrogeology, soil characteristics, and climatic conditions collectively shape its vulnerability to urban flooding. It examines the city’s terrain-driven runoff patterns, the influence of hill systems on stormwater flow, and the role of natural drainage channels in water movement across its landscape. It explores how alterations due to urban expansion – such as encroachments, increased impervious surfaces, and disruption of natural hydrological pathways – have intensified flood risk. An additional objective is to evaluate institutional campuses as decentralized systems for stormwater mitigation, particularly through rainwater harvesting and infiltration-based solutions. This research intends to inform urban planning strategies that integrate environmental conditions with sustainable flood management responses [8–13].

Physiography, Geology, and Climatic Controls Influencing Urban Flooding in Bhopal

Physiography

Situated at a height of 427 m above sea level, the city of Bhopal is built on a hilly area with slopes inclined in the north and southeast directions. The expansion of the city is determined by the shape of the five hills, namely, Arera, Shyamla, Idgah, Katara, and Neori Hills, which cover the expansion of Bhopal up to its planning boundary. The Vindhyachal mountain range has a constant range. The area toward the southern and southeast direction of the city is the area of the normal slope. The eastern side is a hilly area near the bypass road, which is under a protected forest. The southwest area of the city extends into a broad hilly area; the northwest area is also flat, but the northeast region is located in a mountainous region, as shown in Figures 1 and 2 [14–17].

In this map, areas are shaded in varying tones of green to blue, with lighter shades representing relatively flat or gently sloping terrain and darker shades (especially blue) indicating steeper slopes, ridges, and elevated terrain features. The central and northeastern zones of Bhopal show lighter shades, suggesting low-lying, flatter terrains, which are typically more prone to surface water accumulation and urban flooding if the drainage systems are inadequate. Conversely, the outer fringes and southwestern zones, highlighted in deep blue, represent hillier and more elevated terrains, which often function as natural runoff source zones. The elevated portions of the terrain play a crucial role in influencing surface runoff patterns, as they naturally guide stormwater toward the lower-lying regions of the city [18–22].

Geological Description

Bhopal is situated within the Malwa Plateau and is characterized by a gently undulating terrain. The eastern part of the Phanda block, which includes a significant portion of Bhopal city, is occupied by the Vindhyan Hill Range. The maximum elevation in the district, approximately 622 m above mean sea level, is observed at Singar Choli, a Vindhyan hillock located near the Bhopal airport. In contrast, the minimum elevation of approximately 421 m above mean sea level is observed near Padariya Jat village in the Phanda block [23–25].

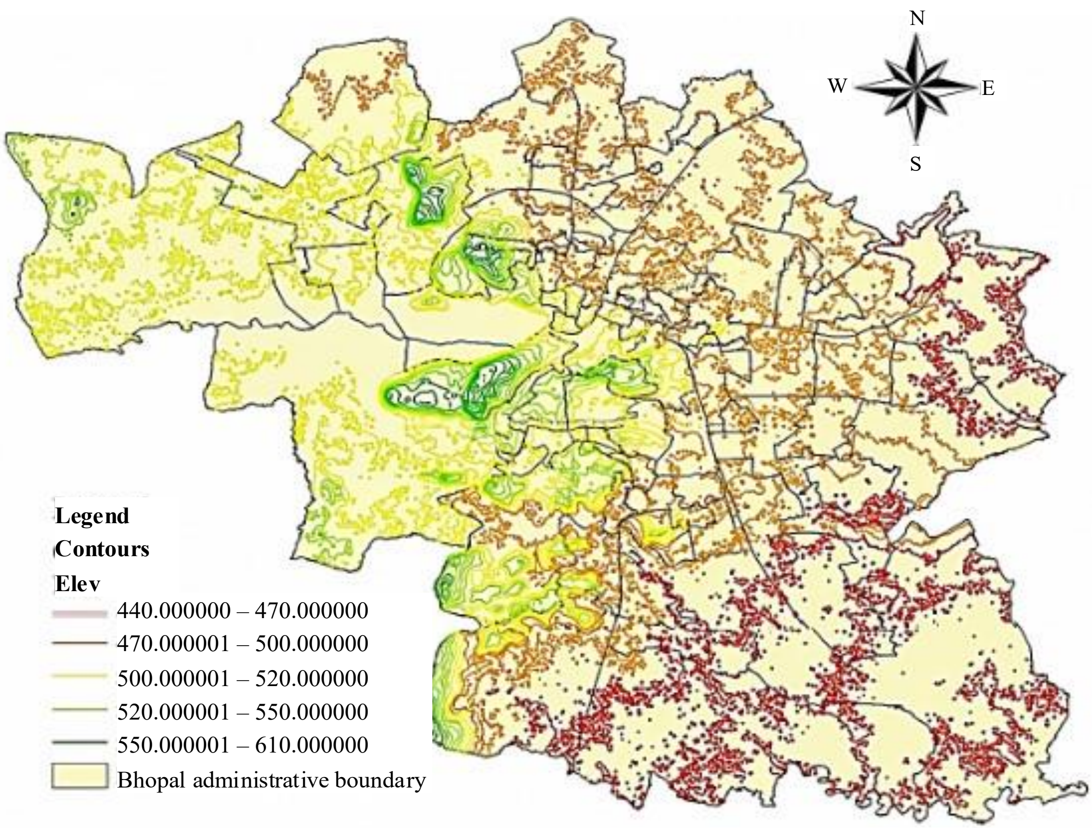

Figure 1. Contour map of Bhopal.

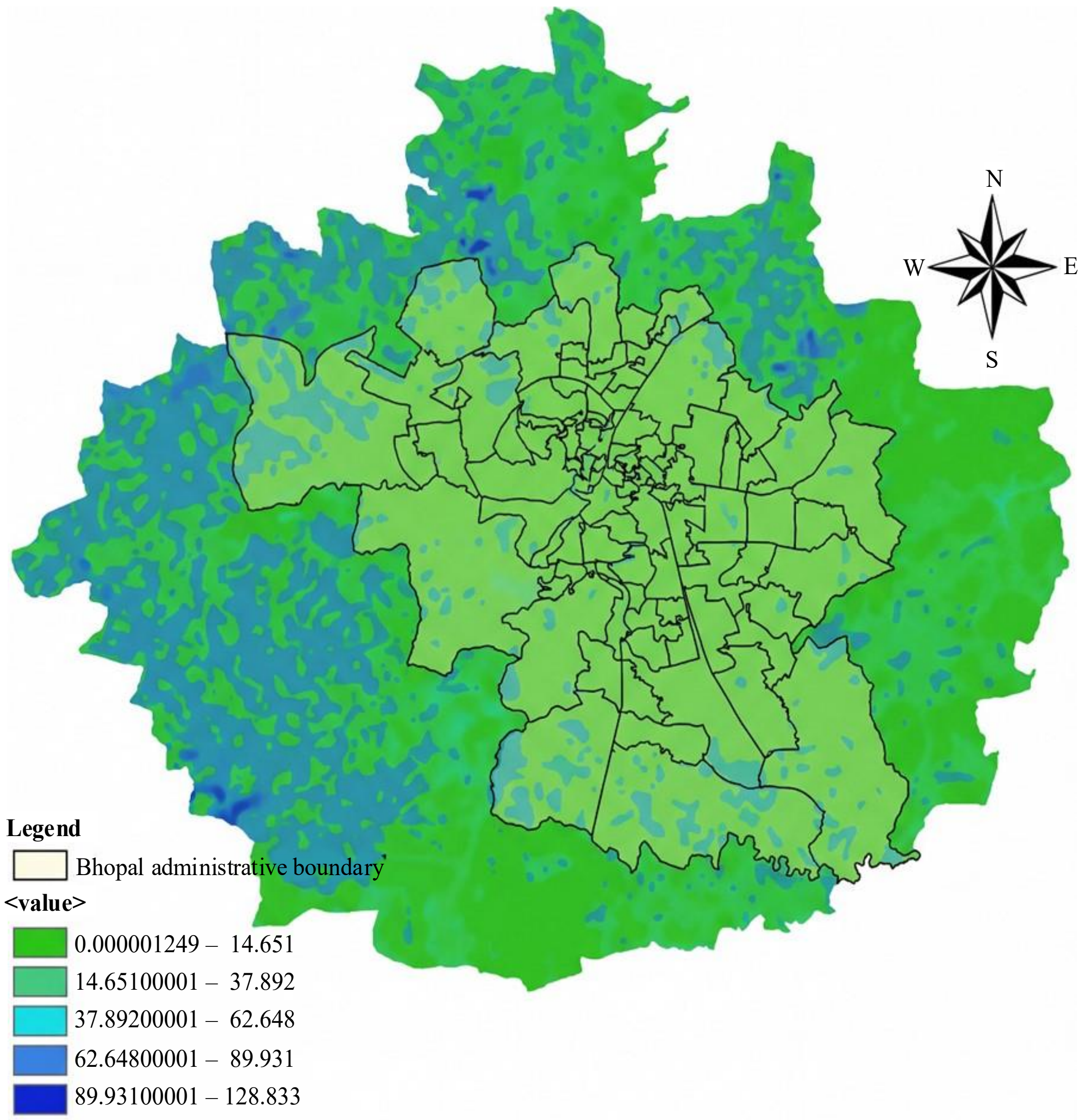

Figure 2. Hill shade map of Bhopal.

The district lies within two major river sub-basins. Nearly 82% of the area falls under the Betwa River sub-basin, whereas the remaining 18% is part of the Lower Chambal sub-basin. Drainage in the district is primarily governed by the Betwa River and its important tributaries, including the Kaliasot, Kerwa, Ajnal, Bah, Halali, and Kolans rivers. Additionally, the Parwati River defines the northwestern boundary of the district, with its tributaries, Mawal and Ulti, contributing to the regional drainage network. The details are shown through a hydrogeological map in Figure 3 [26–29].

Geomorphology and Soil Types

The region lies within the Vindhyan plateau and exhibits a varying topography with sandstone outcrops and fertile valleys. The geomorphology is shaped by both fluvial and structural processes, with the Upper Lake (Bhojtal) serving as a prominent geomorphic feature. In terms of soil types, Bhopal primarily consists of black cotton soil (regur), which is rich in clay and has high moisture retention capacity – ideal for crops such as soybeans and wheat. Red and yellow soils, derived from the weathering of ancient crystalline rocks, are also found in parts of the region, especially on higher terrain. These soils are generally well-drained and moderately fertile, supporting a range of agricultural activities.

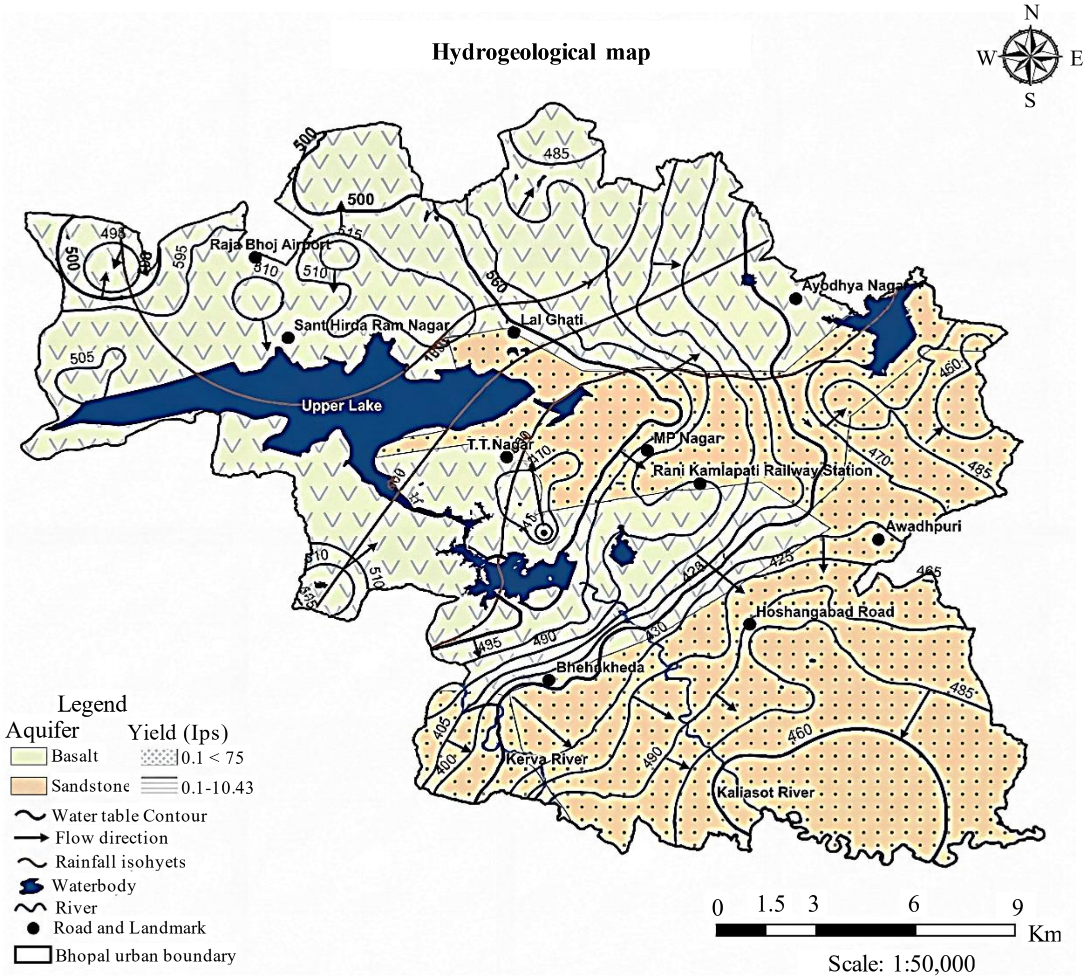

Figure 3. Hydrogeological map of Bhopal.

Climatic Conditions

The climate in the Bhopal district exhibits pronounced seasonal variations, with extremely warm conditions during summer and relatively cold winters, followed by rainfall that is largely governed by the southwest monsoon. The long-term average of the monthly maximum daily temperature reaches approximately 40.7°C, while the mean monthly minimum temperature is approximately 25.3°C. Lowest recorded daily minimum temperature, about 10.2°C, generally occurs in January. Summer represents the driest phase of the annual climatic cycle, during which atmospheric moisture levels are significantly reduced. Relative humidity attains its lowest values in April and shows considerable seasonal fluctuation, ranging from approximately 26% during dry periods to nearly 88% during humid conditions. Seasonal and interannual trends in temperature variations in Bhopal are illustrated in Figure 4. Rainfall monitoring in the district is supported by nine rain-gauge stations. Among these, one station is operated by the India Meteorological Department (IMD) at Bairagarh, one by the Revenue Department at Berasia, one by the Agriculture Department in Bhopal, and six additional stations are managed by the Irrigation Department. These stations provide reliable long-term precipitation records for climatic assessment. Analysis of rainfall data from the Bairagarh and Berasia stations indicates that the mean annual rainfall in the Bhopal district is approximately 1126.7 mm. However, data from the IMD-maintained Bairagarh station alone suggest a higher annual normal rainfall of approximately 1260.2 mm. Precipitation in the region is highly concentrated during the southwest monsoon season, which contributes nearly 92% of the total annual rainfall. July is the wettest month, accounting for approximately 39% of the yearly precipitation. In recent years, however, noticeable deviations from historical rainfall patterns have been observed, indicating emerging anomalies in precipitation trends, as depicted in Figures 4 and 5.

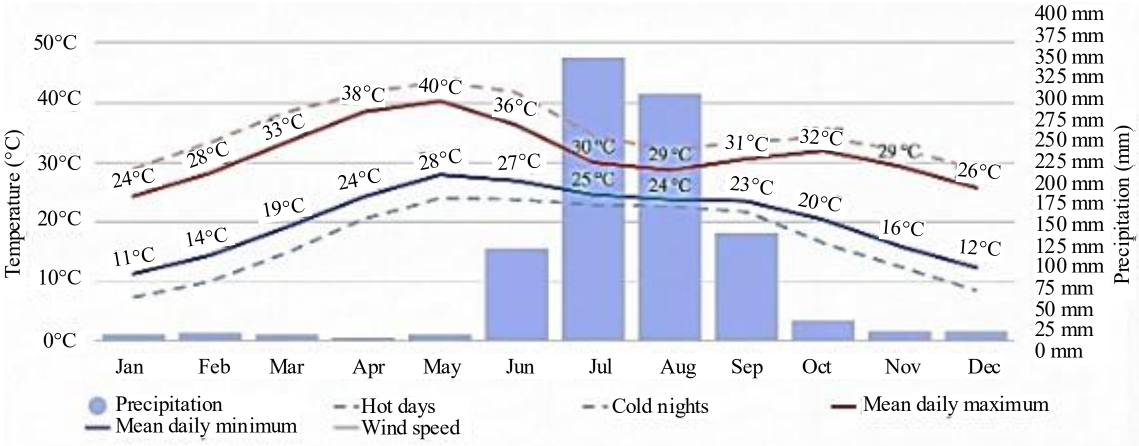

Figure 4. Temperature variation in Bhopal.

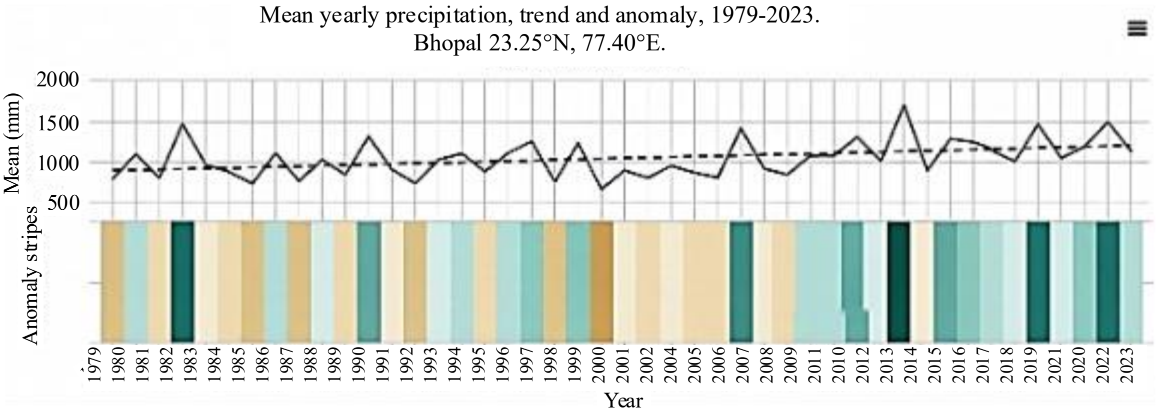

Figure 5. Precipitation anomaly in Bhopal.

Urban Flooding in Bhopal

The physical setting of Bhopal, characterized by undulating terrain and surrounding hill ranges, naturally directs surface runoff toward the lower parts of the city through a network of drainage channels. However, rapid and unplanned urban expansion has significantly altered these natural pathways. Encroachments, obstruction of natural drains, and inadequate stormwater infrastructure have restricted the free movement of runoff, resulting in frequent waterlogging across several urban stretches.

Bhopal has a documented history of urban flooding triggered by intense rainfall events. Major flood occurrences were recorded in 1973, 2006, 2016, and 2018 (Maps 4.1, 4.2, 4.3, and 4.4, respectively). These flood events primarily affected low-lying neighborhoods, where excessive rainfall combined with poor drainage led to severe inundation. Areas such as Gautam Nagar, Jamalpura, Indiranagar, Jagjivan Colony, Dharmapuri, Mahamai Bagh, Rahul Nagar, Panchsheel Nagar, Rajendra Nagar, the surroundings of Shahpura Lake, Munshi Hussain's pond, and Motia Talab were particularly vulnerable to flooding (LU-Bhopal, 2005). On July 22, 1973, an extreme rainfall event of approximately 275.7 mm was recorded, resulting in widespread inundation and loss of life, especially in the low-lying zones of South TT Nagar. Another significant flood episode occurred in August 2006, when nearly 29 cm of rainfall was received within a short duration of approximately five hours. This intense precipitation caused water depths of three to four feet in nearly 15 low-lying localities across the city. More recently, on July 9, 2016, Bhopal experienced a heavy rainfall event measuring approximately 277.6 mm. This led to extensive flooding in areas such as Ashoka Garden, Nehru Nagar, Shahpura, and Shabri Nagar. Major arterial roads, including Jail Road, New Market Road, and MP Nagar, experienced severe traffic disruptions due to waterlogging. Residents reported knee-deep water on roadways, highlighting deficiencies in the city's drainage system, while submerged roads and open drains created widespread disruption and safety concerns. On July 17, 2018, water entered many houses in low-lying slum areas within the city. People residing in Banganga, Panchsheel Nagar, and Rahul Nagar suffered considerably because of poor drainage and sewerage network systems.

CONCLUSIONS

The analysis of Bhopal's physiography, geology, hydrogeology, geomorphology, and climatic conditions clearly demonstrates that the city's natural landscape plays a decisive role in shaping flood vulnerability. The hilly terrain and undulating slopes, combined with confined valleys and low-lying basins, naturally channel stormwater from elevated areas toward densely populated urban pockets. Although these features once enabled efficient drainage, rapid and often unplanned urban growth has increasingly obstructed natural flow paths. Encroachments on hill slopes, lake catchments, and drainage channels, along with rising impervious surfaces, have diminished infiltration and caused stormwater to accumulate in critical zones. Additionally, climatic anomalies, including irregular rainfall patterns and heightened monsoon intensity, have intensified runoff volumes beyond the city's drainage capacity.

Bhopal's hydrogeological framework, characterized by basaltic formations, shallow water tables in certain areas, and multiple river sub-basins, further influences water movement and accumulation. These combined factors highlight the urgent need for decentralized, nature-based approaches to flood mitigation. Institutional campuses, with their extensive permeable land cover and semi-autonomous management structures, provide an underutilized opportunity to act as micro-catchments for stormwater retention and infiltration. Their strategic spatial distribution across the city enables them to function collectively as a distributed flood management system. Integrating rainwater harvesting, recharge wells, vegetated swales, and detention landscapes within these campuses offers a scalable and sustainable pathway to reduce peak runoff, restore hydrological balance, and enhance urban resilience.

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