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Hydrological Modelling–Based Flood Inundation and Risk Assessment of Kolhapur City, India

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Abstract: *Flooding is a recurrent and damaging hazard in riverine cities of India due to intense monsoonal rainfall, rapid urbanisation, and modification of natural drainage systems. Kolhapur City, located along the Panchganga River in Maharashtra, has experienced frequent flooding with significant impacts on infrastructure and socioeconomic activities. This study assesses flood inundation and flood risk in Kolhapur City using an integrated hydrological modelling and GIS-based multi-criteria framework.*

Rainfall–runoff processes were simulated using the Soil Conservation Service–Curve Number (SCS-CN) method, while flood hydrographs were generated using the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS). The model was calibrated and validated using observed rainfall and discharge data, and performance was evaluated using NSE, R^2, RMSE, PBIAS, and RSR. Simulated hydrographs were used to generate flood inundation extent and depth maps.

Results indicate that low-lying floodplain areas along the Panchganga River are highly susceptible to inundation during high-flow conditions. Flood hazard, vulnerability, and risk were assessed using the Analytical Hierarchy Process (AHP) integrated with GIS by combining physical, hydrological, socioeconomic, and infrastructure-related factors. The analysis reveals that several parts of Kolhapur City fall within high to very high flood risk zones due to the combined effects of elevated flood hazard and high socioeconomic vulnerability.

The study demonstrates that hydrological modelling coupled with GIS-based multi-criteria analysis provides a robust and transferable framework for urban flood risk assessment and supports effective flood mitigation and disaster management planning.

Keywords: Flood inundation; Hydrological modelling; HEC-HMS; SCS-CN; Flood risk assessment; GIS; AHP; Kolhapur City

1. INTRODUCTION

Flooding is one of the most frequent and destructive natural hazards worldwide, causing significant loss of life, damage to infrastructure, and disruption of socioeconomic activities, particularly in riverine and urban regions. In developing countries such as India, flood impacts are intensified by high monsoonal rainfall, complex watershed characteristics, and rapid urbanisation that alters natural hydrological processes [1]. Changes in land use–land cover, reduction in infiltration capacity, and encroachment of floodplains have substantially increased runoff generation and flood magnitude in urban river basins [2].

Kolhapur City, located along the banks of the Panchganga River in Maharashtra, is a prominent example of an urban area frequently affected by riverine flooding. The city lies in a monsoon-dominated climatic region and experiences intense rainfall during the southwest monsoon season, often leading to river overbank flooding. Historical flood events in Kolhapur have resulted in extensive inundation of residential zones, damage to transportation networks, disruption of public utilities, and economic losses, underscoring the need for comprehensive flood assessment and mitigation planning [3].

Conventional flood management strategies in Indian cities have largely relied on structural interventions such as embankments, channel modifications, and drainage improvements. While these measures provide some level of protection, they are often inadequate in addressing the growing complexity of flood risk driven by urban expansion and climate variability [4]. As a result, there has been increasing emphasis on non-structural and integrated approaches that combine hydrological modelling, flood inundation mapping, and spatial decision-support tools to better understand flood behaviour and risk [5].

Hydrological modelling plays a critical role in simulating rainfall–runoff processes and generating flood hydrographs for river basins. Among various modelling approaches, the Soil Conservation Service–Curve Number (SCS-CN) method has been widely used for estimating direct runoff due to its simplicity, minimal data requirements, and suitability for ungauged and data-scarce basins [6]. The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) is a commonly applied tool for rainfall–runoff simulation and flood hydrograph generation, allowing representation of watershed processes through loss, transform, and routing components [7].

Accurate calibration and validation of hydrological models are essential to ensure reliable simulation of flood flows. Statistical performance indicators such as Nash–Sutcliffe Efficiency (NSE), Coefficient of Determination (R^2), Root Mean Square Error (RMSE), Percent Bias (PBIAS), and RMSE–standard deviation ratio (RSR) are widely used to evaluate model accuracy and robustness [8]. These indicators provide quantitative measures of model performance and are recommended for hydrological model assessment prior to flood analysis applications [9].

Flood inundation mapping is a key element of flood risk assessment, as it enables the spatial delineation of flood extent and depth under different flow scenarios. Inundation maps are essential for identifying flood-prone zones, assessing potential impacts, and supporting emergency response and urban planning [10]. However, flood risk is not solely determined by hazard characteristics; it is also influenced by the vulnerability of exposed populations, infrastructure, and socioeconomic systems [11].

To address the multi-dimensional nature of flood risk, multi-criteria decision analysis (MCDA) techniques have been increasingly integrated with GIS-based flood studies. The Analytical Hierarchy Process (AHP) is one of the most widely used MCDA methods due to its ability to systematically assign relative weights to multiple criteria based on expert judgement [12]. AHP has been successfully applied in flood hazard, vulnerability, and risk assessment by integrating physical, hydrological, socioeconomic, and infrastructural factors within a GIS framework [13].

Although several studies have applied hydrological modelling and GIS-based flood mapping in different regions of India, comprehensive investigations integrating hydrological modelling, flood inundation analysis, and AHP-based flood risk assessment for Kolhapur City remain limited. Therefore, the present study aims to develop an integrated hydrological modelling–based framework to assess flood inundation and flood risk in Kolhapur City, India. The study combines SCS-CN-based runoff estimation, HEC-HMS hydrological modelling, flood inundation mapping, and AHP-based multi-criteria analysis within a GIS environment to support informed flood management and urban planning decisions.

2. Review of Literature

Flood risk assessment has evolved significantly over the past few decades, shifting from purely structural and deterministic approaches toward integrated frameworks that combine hydrological modelling, spatial analysis, and decision-support techniques. Early flood studies primarily focused on hydrological and hydraulic simulations to estimate flood discharge and water levels, often neglecting the spatial and socioeconomic dimensions of flood risk [16]. However, increasing flood losses in urban areas have highlighted the importance of understanding not only flood hazards but also exposure and vulnerability.

Rainfall–runoff modelling is a fundamental component of flood assessment studies. Several researchers have applied the Soil Conservation Service–Curve Number (SCS-CN) method to estimate direct runoff due to its simplicity and effectiveness in incorporating land use, soil type, and antecedent moisture conditions [17]. Studies have demonstrated that SCS-CN performs well in monsoon-dominated basins, particularly when integrated with GIS for spatially distributed runoff estimation [18]. The use of remote sensing-derived land use–land cover data has further improved runoff estimation accuracy in urbanising watersheds [19].

Hydrological models such as the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) have been extensively employed to simulate rainfall–runoff processes and generate flood hydrographs for river basins of varying scales [20]. Researchers have shown that HEC-HMS is well-suited for flood simulation in data-scarce regions due to its flexible structure and moderate data requirements [21]. Calibration and validation using observed discharge data are essential to ensure model reliability, and statistical indicators such as Nash–Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), and Percent Bias (PBIAS) are commonly adopted for performance evaluation [22].

Flood inundation mapping has gained prominence as a critical tool for visualising flood extent and depth, particularly in urban environments where spatial variability in topography and land use plays a significant role in flood propagation [23]. Two-dimensional inundation models integrated with GIS have been widely used to identify flood-prone zones and assess potential impacts on infrastructure and settlements [24]. Inundation maps generated from hydrological model outputs have proven valuable for emergency planning and flood mitigation strategies [25].

Beyond hazard assessment, flood risk is increasingly recognised as a function of hazard, exposure, and vulnerability. Several studies have emphasised the need to incorporate socioeconomic and infrastructural factors into flood risk assessment frameworks [26]. Vulnerability indicators such as population density, building characteristics, land use, and proximity to critical facilities have been widely used to assess the susceptibility of urban areas to flood impacts [27].

Multi-criteria decision analysis (MCDA) techniques have been increasingly integrated with GIS-based flood studies to address the multi-dimensional nature of flood risk. Among these techniques, the Analytical Hierarchy Process (AHP) has been widely adopted due to its systematic structure and ability to incorporate expert judgement in weighting multiple criteria [28]. Numerous studies have successfully applied AHP to generate flood hazard, vulnerability, and risk maps, demonstrating its effectiveness in urban flood risk assessment [29].

In the Indian context, several researchers have applied integrated hydrological and GIS-based approaches to assess flood risk in urban and semi-urban regions. These studies highlight the influence of rapid urbanisation, inadequate drainage infrastructure, and floodplain encroachment on increasing flood vulnerability [30]. However, despite the frequent flooding experienced in Kolhapur City, comprehensive studies integrating hydrological modelling, flood inundation mapping, and AHP-based flood risk assessment remain limited. This research aims to address this gap by developing a robust and transferable flood risk assessment framework for Kolhapur City using hydrological modelling and GIS-based multi-criteria analysis.

3. Study Area: Kolhapur City

Kolhapur City is located in the southwestern part of Maharashtra, India, and lies along the banks of the Panchganga River, a major tributary of the Krishna River system. The city occupies a strategically important position within a monsoon-dominated river basin and has historically been prone to riverine flooding due to its geographical setting, hydrological characteristics, and climatic conditions [1], [3]. Kolhapur serves as a major urban, cultural, and economic centre in the region, and recurrent flooding poses significant challenges to urban development and disaster management. Figure 1 shows the study area and Figure 2. Shows Kolhapur City along the Panchganga River.

The Panchganga River basin is formed by the confluence of five tributaries—Kasari, Kumbhi, Tulsi, Bhogawati, and Sarangi—upstream of Kolhapur city. The basin exhibits diverse topographic and geomorphological features, ranging from moderately elevated terrain in the upstream Western Ghats region to relatively flat floodplain areas within and downstream of the city. These low-lying floodplain zones play a critical role in flood propagation and inundation during high-flow conditions [2], [10].

Kolhapur experiences a tropical monsoon climate characterised by distinct wet and dry seasons. The southwest monsoon, occurring between June and September, accounts for the majority of the annual rainfall, often delivered through high-intensity storm events. Such rainfall patterns generate substantial surface runoff, particularly when combined with saturated soil conditions and reduced infiltration capacity during prolonged monsoon spells [6], [17]. These hydrometeorological conditions frequently result in rapid rises in river stage and subsequent overbank flooding.

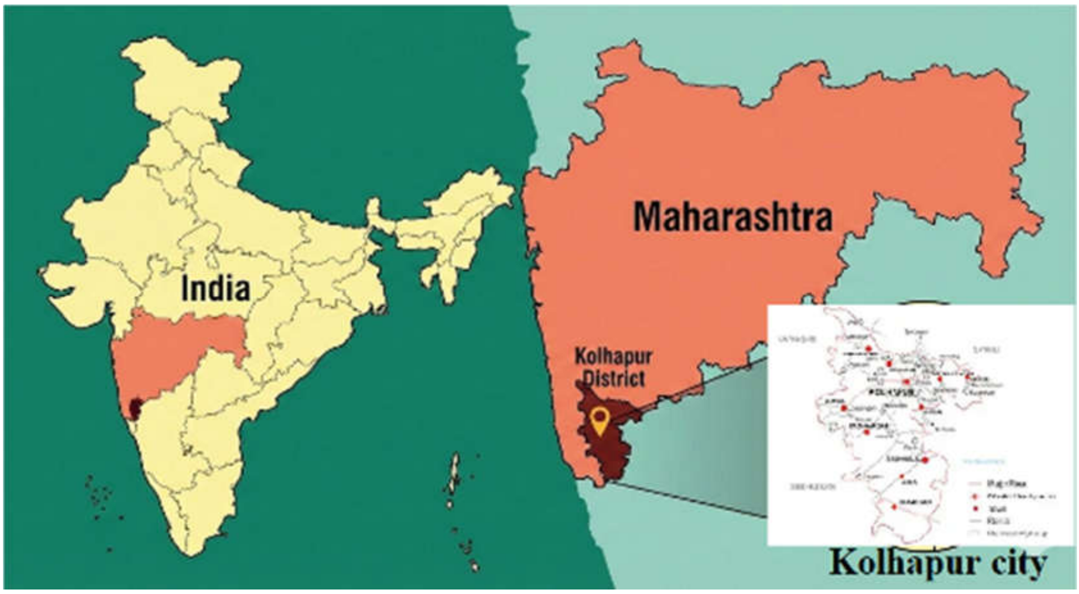

Figure 1. Study Area

Rapid urbanisation in Kolhapur City has significantly altered the natural hydrological response of the basin. Expansion of built-up areas, reduction in permeable surfaces, modification of natural drainage networks, and encroachment of floodplains have collectively increased surface runoff and reduced the basin's capacity to attenuate flood flows [2], [19]. These land use–land cover changes have amplified flood hazards and increased the exposure of residential areas, transportation networks, and critical infrastructure to flooding [26].

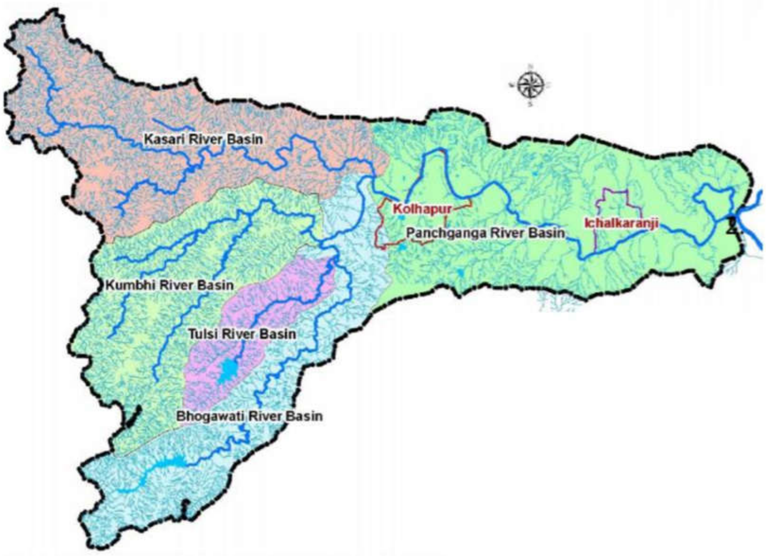

Figure 2. Kolhapur City along the Panchganga River

From a hydrological perspective, the Panchganga River basin exhibits a quick runoff response to intense rainfall events, making it particularly susceptible to flash flooding and prolonged inundation. The basin's drainage characteristics, coupled with relatively gentle slopes within the urban stretch, contribute to slower recession of floodwaters once overbank flow occurs [7], [20]. These factors underline the importance of accurate rainfall–runoff modelling and flood hydrograph simulation for effective flood assessment in the study area.

Socioeconomic vulnerability further exacerbates flood risk in Kolhapur City. High population density in flood-prone areas, concentration of commercial activities, and the presence of critical facilities such as roads, bridges, and public utilities increase the potential impacts of flooding [11], [27]. Previous studies have emphasised that flood risk in urban areas is a combined outcome of physical flood hazard and socioeconomic vulnerability, necessitating integrated assessment approaches [12], [28].

Given the recurrent flooding history, complex basin characteristics, and increasing urban pressures, Kolhapur City represents an appropriate and relevant study area for hydrological modelling–based flood inundation and risk assessment. The integrated approach adopted in this study aims to capture the interaction between hydrological processes, spatial flood dynamics, and vulnerability patterns to support informed flood management and urban planning decisions [5], [13], [30].

4. Methodology

The methodology adopted in this study integrates hydrological modelling, flood inundation analysis, and GIS-based multi-criteria decision analysis to assess flood hazard, vulnerability, and risk in Kolhapur City. The overall framework consists of five major components: (i) data preparation, (ii) rainfall–runoff estimation using the SCS-CN method, (iii) hydrological modelling using HEC-HMS, (iv) flood inundation mapping, and (v) flood risk assessment using the Analytical Hierarchy Process (AHP) integrated with GIS [6], [7], [12]. Figure 2 shows the detailed methodology.

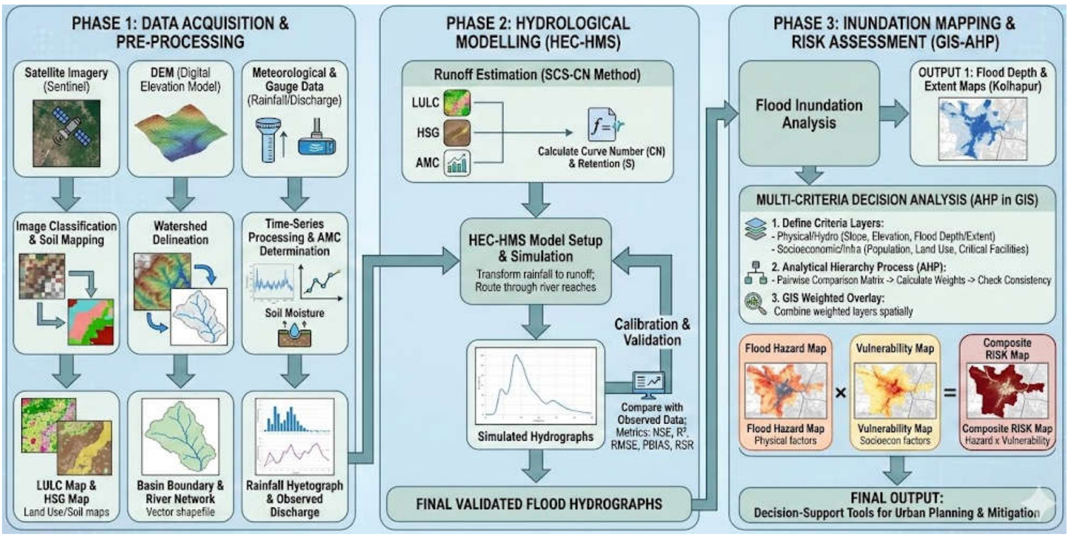

Figure 3. Detailed Methodology

4.1 Data Preparation and Processing

Spatial and non-spatial datasets required for the study include rainfall data, discharge records, digital elevation model (DEM), land use–land cover (LULC) data, soil maps, drainage networks, and administrative boundaries. DEM data were used for watershed delineation, stream network extraction, and slope analysis. LULC and soil data were processed in a GIS environment to generate hydrological soil groups and Curve Number (CN) maps required for runoff estimation [6], [19]. The spatial and non-spatial datasets used in the present study are summarised in Table 1.

This step involves the collection and pre-processing of spatial and non-spatial data. As shown in the image, various data layers like DEM, LULC, and soil maps are stacked and processed in a GIS environment to derive key inputs such as watershed boundaries, stream networks, and Curve Number (CN) maps. Figure 4 Shows the Data Preparation and Processing.

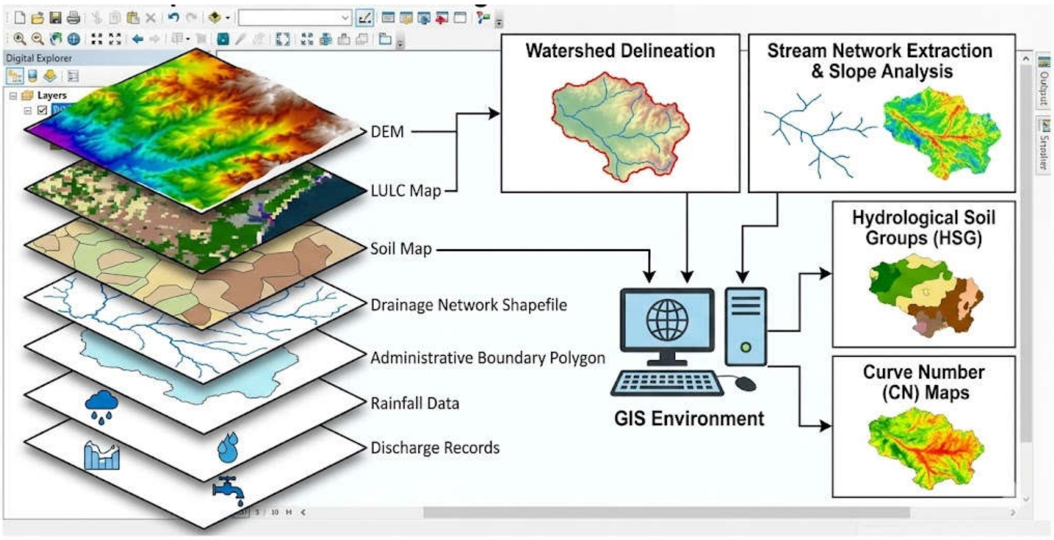

Figure 4. Detailed Methodology

Table 1. List of datasets used in the study

S.N.	Data Type	Description	Source	Purpose
1	Rainfall data	Daily rainfall records for monsoon seasons	IMD / Local rain gauge	Rainfall–runoff modelling
2	Discharge data	Observed streamflow at Panchganga River	WRD Maharashtra	Model calibration and validation
3	DEM	Digital Elevation Model (30 m resolution)	SRTM / USGS	Watershed delineation and slope analysis
4	LULC	Land use–land cover map	NRSC / Classified satellite data	Curve Number estimation
5	Soil map	Hydrological soil group data	NBSS & LUP	Runoff estimation
6	River network	Panchganga River and tributaries	Survey of India / WRD	Flood inundation analysis
7	Administrative boundary	Kolhapur City boundary	KMC / Census of India	Study area definition
8	Socioeconomic data	Population and infrastructure data	Census of India	Vulnerability assessment

4.2 Rainfall–Runoff Estimation Using SCS-CN Method

The Soil Conservation Service–Curve Number (SCS-CN) method was employed to estimate direct runoff from rainfall events. The method relates rainfall to runoff based on land use, soil type, and antecedent moisture condition [6], [17]. Curve Number values were assigned based on hydrological soil groups as shown in Table 2.

Table 2. Hydrological Soil Groups and Curve Number assignment

Hydrological Soil Group	Soil Characteristics	Infiltration Capacity	CN Range
Group A	Sandy, well-drained soils	High	30–55
Group B	Moderately permeable soils	Moderate	55–70
Group C	Fine-textured soils	Low	70–85
Hydrological Soil Group	Soil Characteristics	Infiltration Capacity	CN Range

Typical Curve Number values corresponding to different land use classes are presented in Table 3.

The potential maximum retention, *S* (mm), is calculated as:

$$S = \frac{25400}{CN} - 254 \quad (1)$$

where *CN* is the Curve Number.

The direct runoff depth, *Q* (mm), is computed as:

$$Q = \begin{cases} \frac{(P-0.2S)^2}{(P+0.8S)}, & \text{if } P > 0.2S \\ 0, & \text{if } P \leq 0.2S \end{cases} \quad (2)$$

Where, *P* is the total rainfall (mm).

Spatially distributed CN values were assigned in GIS by overlaying LULC and hydrological soil group maps, allowing estimation of runoff depth across the study area [18].

Table 3. Land use–land cover classes and associated Curve Numbers

LULC Class	Description	Typical CN Value
Built-up area	Residential, commercial, roads	85–95
Agricultural land	Cropland and plantations	65–80
Forest	Dense and open vegetation	40–60
Open land	Barren and fallow land	70–85
Water bodies	Rivers, lakes, ponds	100

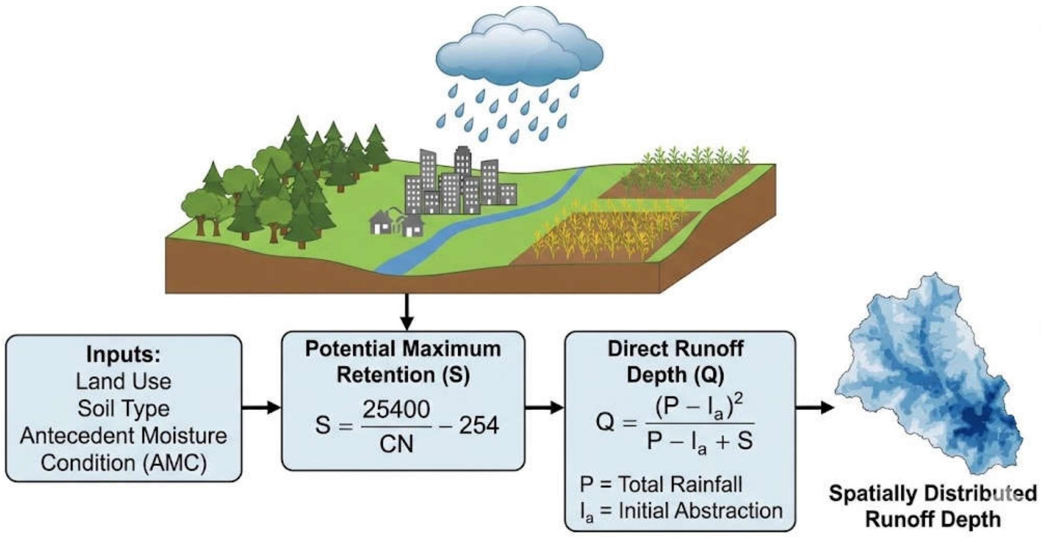

Figure 5. Rainfall–Runoff Estimation Using SCS-CN Method

Figure 5. Rainfall–Runoff Estimation Using SCS-CN Method. The SCS-CN method is used to estimate direct runoff from rainfall. The infographic illustrates how inputs like land use, soil type, and antecedent moisture condition (AMC) are used to determine the potential maximum retention (S), which is then used to calculate the direct runoff depth (Q), resulting in a spatially distributed runoff map.

4.3 Hydrological Modelling Using HEC-HMS

Hydrological modelling was carried out using the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) to transform estimated runoff into streamflow hydrographs [7], [20]. Watershed and sub-basins were delineated using DEM data. The model structure included loss, transform, and routing components. The hydrological model configuration adopted in HEC-HMS is summarised in Table 4.

Table 4. HEC-HMS model components used in the study

Model Component	Method Used	Description
Loss method	SCS Curve Number	Estimation of rainfall losses
Transform method	SCS Unit Hydrograph	Conversion of excess rainfall to runoff
Baseflow method	Constant monthly	Representation of baseflow
Routing method	Muskingum / Lag method	Channel flow routing
Time step	Model-defined	Hydrological simulation interval

The SCS-CN method was used as the loss model, while the SCS Unit Hydrograph was adopted for runoff transformation. Channel routing was performed using appropriate routing methods based on basin characteristics. Model calibration and validation were conducted using observed rainfall and discharge data to ensure realistic simulation of flood hydrographs [21]. Figure 6 shows Hydrological Modelling Using HEC-HMS.

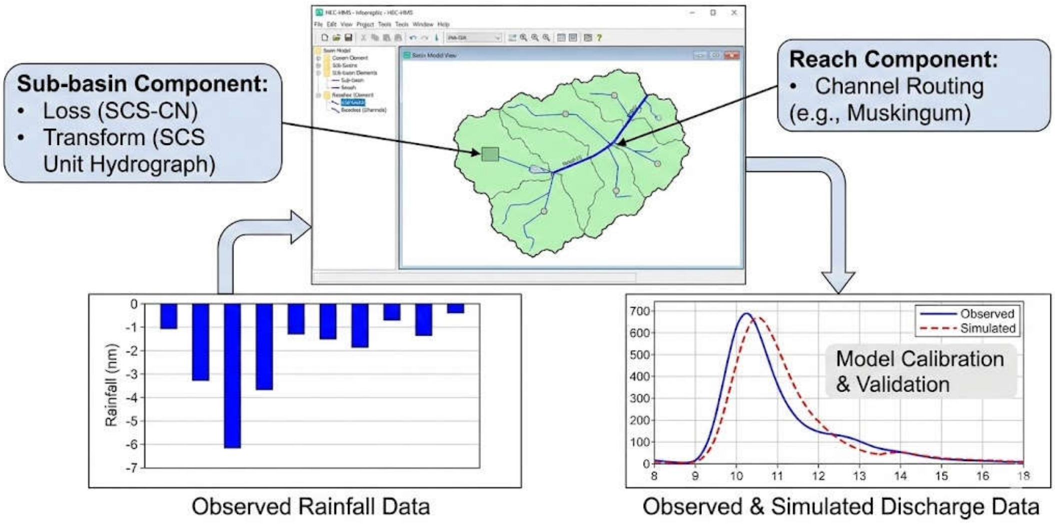

Figure 6. Hydrological Modelling Using HEC-HMS.

4.4 Model Performance Evaluation

The performance of the HEC-HMS model was evaluated using standard statistical indicators recommended for hydrological model assessment [8], [22]. Model performance was evaluated using standard statistical criteria listed in Table 5.

Table 5. Statistical performance criteria and acceptable ranges

Performance Indicator	Equation Reference	Acceptable Range	Interpretation
Nash–Sutcliffe Efficiency (NSE)	Eq. (3)	> 0.50	Good model performance
Coefficient of Determination (R^2)	Eq. (4)	> 0.60	Strong correlation
RMSE	Eq. (5)	Low value	Low simulation error
PBIAS (%)	Eq. (6)	±25%	Acceptable bias
RSR	Eq. (7)	< 0.70	Satisfactory performance

Nash–Sutcliffe Efficiency (NSE)

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \overline{Q}_{obs})^2} \quad (3)$$

Coefficient of Determination (R^2)

$$R^2 = \frac{\left[\sum(Q_{obs} - \overline{Q}_{obs})(Q_{sim} - \overline{Q}_{sim})\right]^2}{\sum(Q_{obs} - \overline{Q}_{obs})^2 \sum(Q_{sim} - \overline{Q}_{sim})^2} \quad (4)$$

Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Q_{sim,i} - Q_{obs,i})^2} \quad (5)$$

Percent Bias (PBIAS)

$$PBIAS = 100 \times \frac{\sum(Q_{sim} - Q_{obs})}{\sum Q_{obs}} \quad (6)$$

RMSE–Standard Deviation Ratio (RSR)

$$RSR = \frac{RMSE}{SD_{obs}} \quad (7)$$

where Qobs and Qsim are observed and simulated discharges, respectively.

Figure 7 shows Model Performance Evaluation.

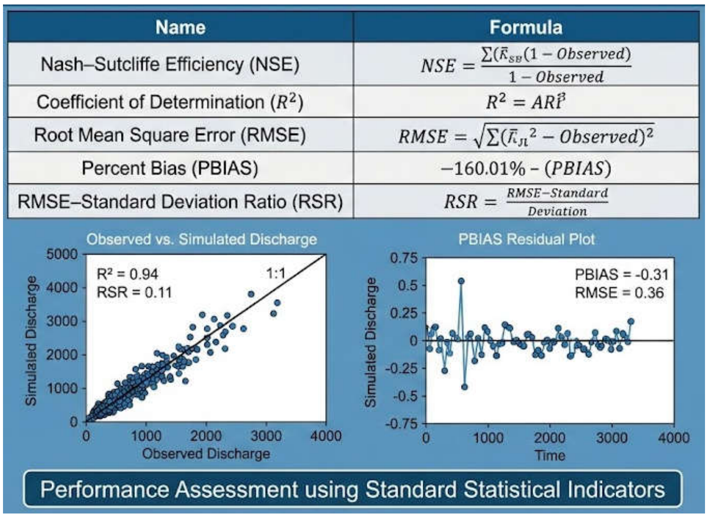

Figure 7. Model Performance Evaluation

4.5 Flood Inundation Mapping

The simulated flood hydrographs generated from HEC-HMS were used for flood inundation analysis to delineate flood extent and depth across Kolhapur City. Flood inundation maps were generated in GIS by integrating simulated discharge with terrain characteristics derived from DEM data [23], [25]. These maps provided spatial information on flood-prone areas and inundation depth distribution. Figure 8 shows Flood Inundation Mapping.

4.6 Flood Risk Assessment Using AHP and GIS

Flood risk assessment was performed by integrating flood hazard and vulnerability using the Analytical Hierarchy Process (AHP) within a GIS environment [12], [28]. The criteria considered for flood hazard assessment are listed in Table 6.

Table 6. Flood hazard criteria used in AHP analysis

Criterion	Description	Influence on Flooding
Elevation	Ground height above mean sea level	Lower elevation → higher hazard
Slope	Terrain slope	Gentle slope → higher inundation
Distance from river	Proximity to Panchganga River	Closer distance → higher hazard

Drainage density	Density of drainage network	Poor drainage → higher hazard
Flood depth	Simulated inundation depth	Higher depth → higher hazard
Land use	Surface characteristics	Built-up areas → higher hazard

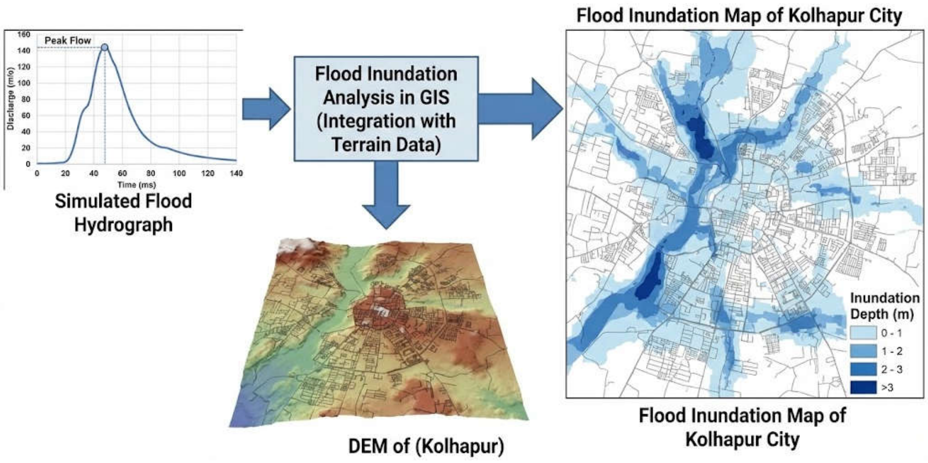

Figure 8. Flood Inundation Mapping

Socioeconomic and infrastructural indicators used for vulnerability assessment are shown in Table 7.

Table 7. Flood vulnerability indicators

Indicator	Description	Vulnerability Influence
Population density	People per unit area	Higher density → higher vulnerability
Built-up density	Degree of urbanisation	Higher density → higher vulnerability
Road network	Transport infrastructure	Damage potential
Critical facilities	Hospitals, schools, utilities	High importance areas
Economic activity	Commercial zones	Higher loss potential

AHP Pairwise Comparison Matrix

AHP uses a pairwise comparison matrix A:

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ 1/a_{12} & 1 & a_{23} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots & \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 & \end{bmatrix} \quad (8)$$

The normalized weight (w) of each criterion is obtained from the principal eigenvector of the matrix. The Saaty pairwise comparison scale adopted in the AHP analysis is presented in Table 8.

Table 8. AHP pairwise comparison scale

Scale Value	Importance Level
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values

Consistency Ratio (CR)

$$CR = \frac{CI}{RI} \quad \text{where} \quad CI = \frac{\lambda_{max} - n}{n - 1} \tag{9}$$

A consistency ratio (CR) less than 0.1 indicates acceptable consistency in judgement [12].

Figure 9 shows Flood Risk Assessment Using AHP and GIS

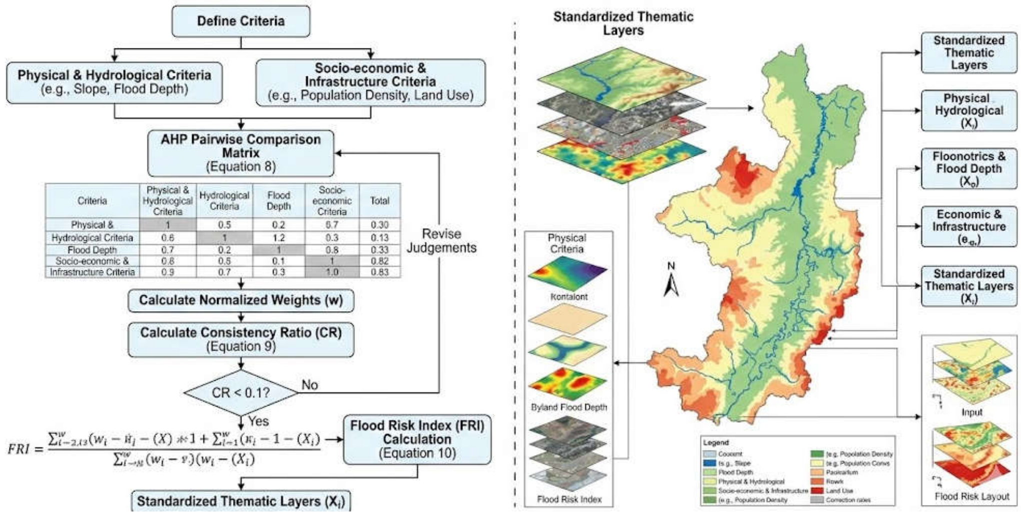

Figure 9. Flood Risk Assessment Using AHP and GIS

Flood Risk Index

The flood risk index (*FRI*) was computed as:

$$FRI = \sum_{i=1}^{n} w_i \times X_i \tag{10}$$

where w_i is the weight of criterion i and X_i is the standardized thematic layer.

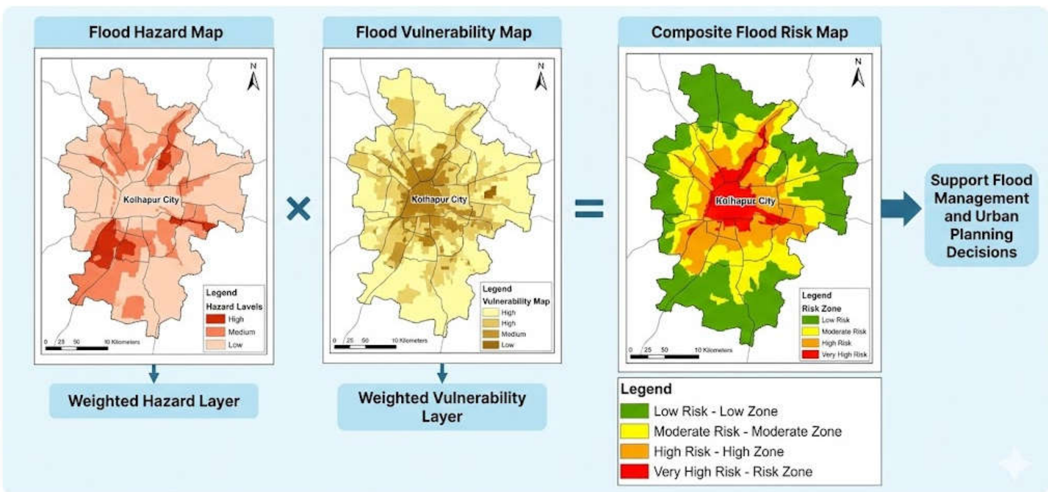

Figure 10. Integration and Mapping

4.7 Integration and Mapping

The weighted hazard and vulnerability layers were overlaid in GIS to generate composite flood risk maps. The final outputs include flood hazard, vulnerability, and risk zonation maps, which were classified into low, moderate, high, and very high risk zones to support flood management and urban planning decisions [13], [29], [30]. Figure 10 shows Integration and Mapping

5. Results and Discussion

5.1 Rainfall–Runoff Estimation

Rainfall–runoff estimation using the SCS-CN method provided spatially distributed runoff depths across Kolhapur City for selected rainfall events. Curve Number (CN) values derived from land use–land cover and hydrological soil group maps indicated higher CN values in densely built-up areas, reflecting reduced infiltration capacity and increased runoff generation. In contrast, vegetated and agricultural areas exhibited comparatively lower CN values, resulting in reduced runoff response.

The application of Eq. (1) and Eq. (2) demonstrated that runoff depth increased significantly during high-intensity monsoonal rainfall events, particularly under antecedent moisture conditions associated with prolonged rainfall spells. These findings are consistent with earlier studies that reported enhanced runoff generation in urbanised watersheds due to impervious surface expansion [6], [17], [19]. The spatial runoff patterns highlight the influence of urban growth on hydrological response and underline the importance of incorporating land use dynamics in flood assessment studies.

5.2 Hydrological Modelling Results

Hydrological modelling using HEC-HMS successfully simulated flood hydrographs for the Panchganga River basin upstream of Kolhapur City. The model captured the timing and magnitude of peak discharge reasonably well during calibration and validation periods. Simulated hydrographs showed rapid rising limbs during intense rainfall events, indicating a quick runoff response characteristic of monsoon-dominated urban river basins.

Model performance evaluation using statistical indicators showed satisfactory agreement between observed and simulated discharge. The Nash–Sutcliffe Efficiency (NSE) values computed using Eq. (3) indicated good model performance, while high Coefficient of Determination (R^2) values obtained from Eq. (4) confirmed a strong linear relationship between simulated and observed flows. Low RMSE values (Eq. (5)) and acceptable PBIAS values (Eq. (6)) suggested limited overall error and minimal systematic bias in model simulations. The RMSE–standard deviation ratio (RSR) calculated using Eq. (7) further confirmed the reliability of the hydrological model.

These results align with previous studies that have demonstrated the suitability of HEC-HMS for flood simulation in data-scarce and urbanising basins [20], [21], [22]. The validated hydrological model provided a reliable basis for subsequent flood inundation analysis.

5.3 Flood Inundation Mapping

Flood inundation analysis (Figure 11) based on simulated flood hydrographs reveals distinct spatial patterns of flood extent and depth across Kolhapur City. The results indicate that low-lying areas along the Panchganga River and its adjoining floodplains experience the highest inundation depths during peak discharge conditions. Prolonged inundation is observed in zones characterised by gentle slopes and limited drainage capacity, reflecting the strong influence of topography and river proximity on flood propagation [23], [25].

Flood inundation maps were generated for multiple rainfall return periods (25-, 50-, 75-, and 100-year events) to evaluate the progression of flood severity. The spatial comparison demonstrates a systematic increase in inundation extent with increasing return period. During the 25-year event, inundation is largely confined to the immediate riverbanks and low-lying floodplain areas. The 50-year flood shows lateral expansion into adjacent residential and agricultural zones, indicating increased overbank flow and reduced channel conveyance.

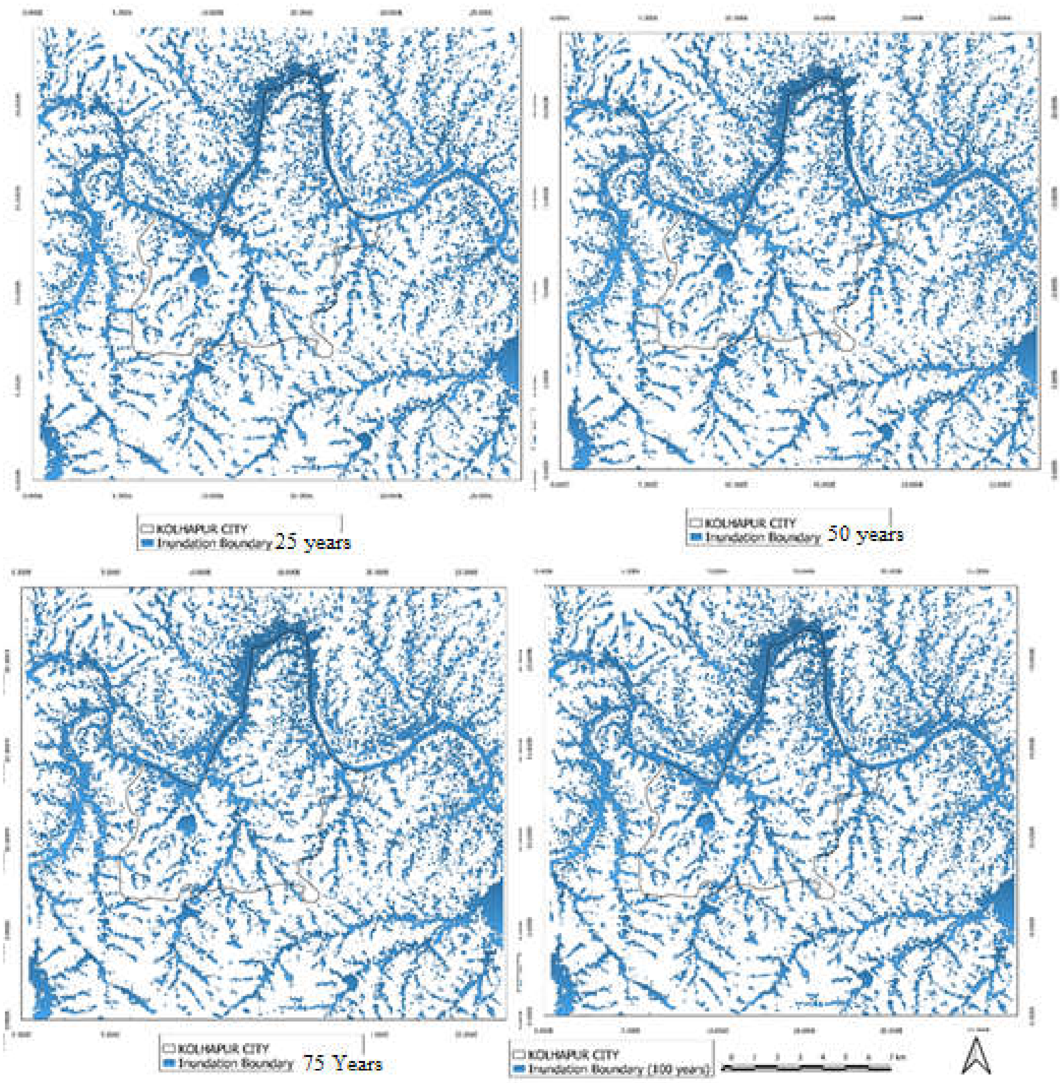

Figure 11. Flood inundation analysis

For the 75- and 100-year flood scenarios, inundation extends significantly into urbanised parts of Kolhapur City, affecting densely built-up areas and major transportation corridors. The 100-year event represents an extreme condition, with widespread inundation across low-elevation zones along the Panchganga River, highlighting the severe flood hazard associated with extreme rainfall events.

Overall, the results establish a clear relationship between flood magnitude and inundation extent. Areas consistently inundated across all return periods represent high-risk zones, while areas affected only during higher return periods correspond to moderate to extreme flood risk. These inundation maps provide essential spatial inputs for flood hazard assessment, land-use planning, and disaster risk management in Kolhapur City.

5.4 Flood Hazard Assessment

Flood hazard maps generated using GIS-based integration of hydrological and physical parameters revealed significant spatial variability in flood hazard levels across Kolhapur City. Areas in close proximity to the Panchganga River, characterised by low elevation and gentle slopes, were classified as high to very high flood hazard zones. Conversely, relatively elevated areas located farther from the river exhibited lower hazard levels.

The results demonstrate that flood hazard is strongly influenced by terrain characteristics, drainage density, land use, and flood depth. Similar patterns have been reported in previous studies where topography and hydrological factors were identified as dominant contributors to flood hazard in urban environments.

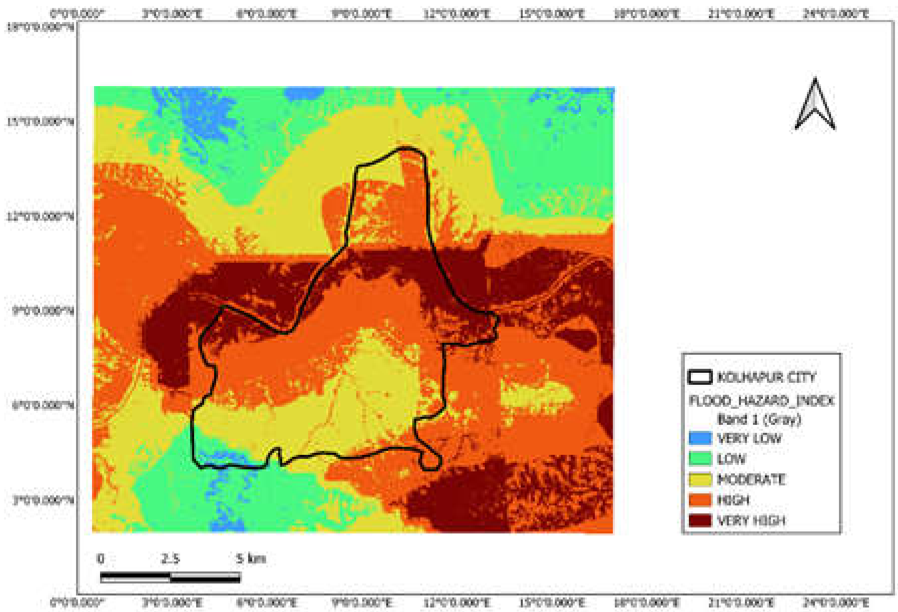

Figure 12. Flood hazard index map showing spatial variation of flood hazard levels.

The figure 12 presents the flood hazard index map of Kolhapur City, classified into five categories: very low, low, moderate, high, and very high hazard. The results indicate that high to very high flood hazard zones are predominantly concentrated along the Panchganga River and its adjoining low-lying floodplains, where elevation is low and proximity to the river is high. Moderate hazard zones occupy transitional areas extending away from the river channel, while low and very low hazard zones are mainly observed in relatively elevated regions located farther from the river. The spatial distribution highlights the strong influence of topography, river proximity, and drainage characteristics on flood hazard patterns within Kolhapur City.

5.5 Flood Vulnerability Assessment

Flood vulnerability assessment revealed that socioeconomic and infrastructural factors play a critical role in determining flood risk in Kolhapur City. Areas with high population density, dense built-up development, and concentration of critical infrastructure such as roads and public facilities exhibited higher vulnerability levels. Informal settlements and older residential zones located within floodplains were particularly vulnerable due to limited adaptive capacity and inadequate drainage infrastructure.

These results corroborate findings from earlier studies that emphasized the importance of incorporating social vulnerability indicators into flood risk assessment frameworks. The vulnerability maps highlight areas where flood impacts are likely to be most severe, even under moderate flood hazard conditions.

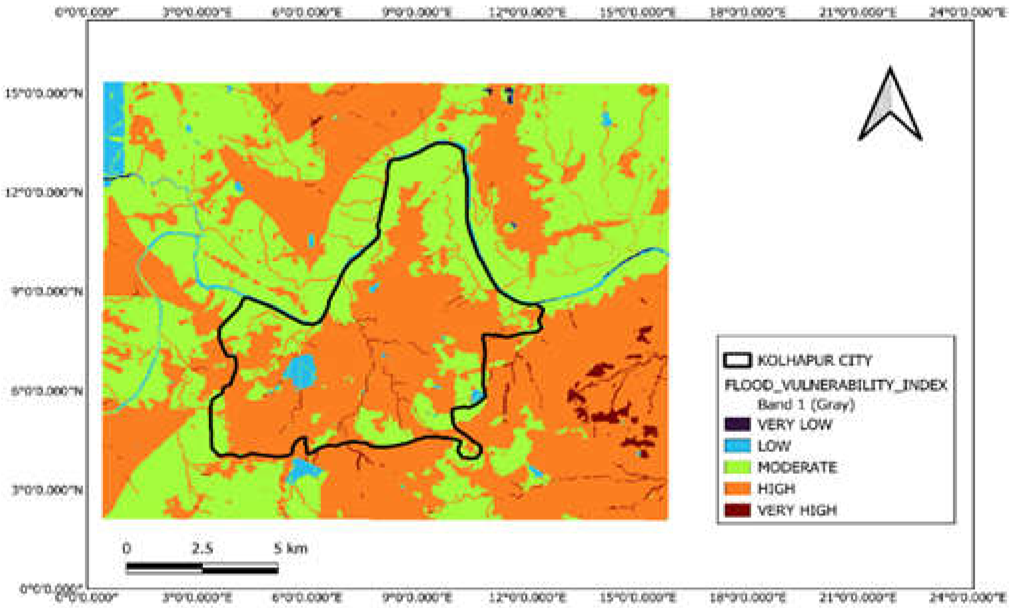

Figure 13. Flood vulnerability index map showing spatial distribution of vulnerability levels.

Figure 13 shows the flood vulnerability index map of Kolhapur City, classified into five categories: very low, low, moderate, high, and very high vulnerability. The results indicate that high and very high vulnerability zones are mainly concentrated in densely built-up and populated areas, reflecting increased exposure of people and infrastructure to flooding. Moderate vulnerability zones are distributed across transitional urban and peri-urban areas, while low to very low vulnerability zones occur in less developed or relatively open areas. The spatial pattern highlights the dominant influence of population density, land use, and infrastructure concentration on flood vulnerability in Kolhapur City.

5.6 Flood Risk Assessment

Flood risk maps generated by integrating hazard and vulnerability layers using the AHP-based approach (Eq. (10)) indicated that several parts of Kolhapur City fall within high to very high flood risk zones. These zones are primarily concentrated along the Panchganga River and in densely populated floodplain areas where high hazard coincides with high socioeconomic vulnerability. Flood risk zones were classified into five categories as shown in Table 9.

Table 9. Flood risk classification

Flood Risk Index Range	Risk Category
Very Low	Minimal risk
Low	Minor risk
Moderate	Moderate risk

High	High risk
Very High	Severe flood risk

The AHP pairwise comparison matrix satisfied the consistency requirement, with the consistency ratio (CR) calculated using Eq. (9) remaining within acceptable limits. This confirms the reliability of the weighting scheme used in the multi-criteria analysis. The results demonstrate that flood risk is not solely a function of flood magnitude but is significantly influenced by exposure and vulnerability characteristics.

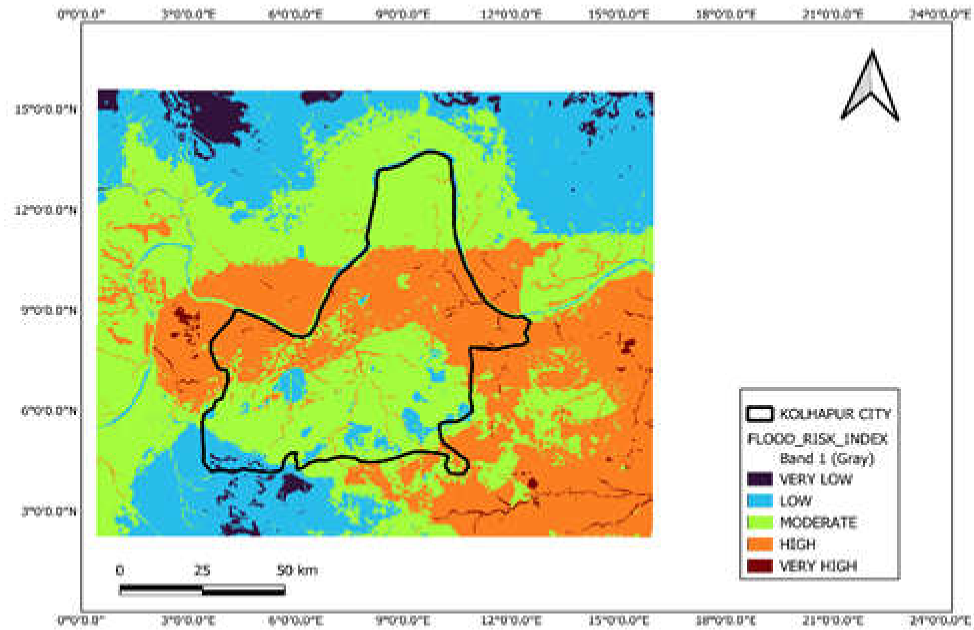

Figure 13. Flood risk index map showing spatial variation of flood risk levels.

Figure 14 presents the flood risk index map of Kolhapur City, integrating flood hazard and vulnerability components. The map classifies flood risk into five categories: very low, low, moderate, high, and very high. High to very high flood risk zones are predominantly concentrated along the Panchganga River and adjoining floodplain areas, where high flood hazard coincides with dense urban development and socioeconomic vulnerability. Moderate risk zones are observed in transitional areas away from the river, while low and very low risk zones occur in relatively elevated and less developed regions. The spatial pattern highlights the combined influence of hydrological conditions and urban vulnerability on overall flood risk in Kolhapur City.

5.7 Implications for Flood Management

The integrated flood assessment results have important implications for urban flood management and planning in Kolhapur City. High-risk zones identified in this study require priority attention in terms of flood mitigation measures, land-use regulation, and disaster preparedness planning. Structural measures such as channel improvement and floodplain restoration should be complemented by non-structural strategies, including early warning systems, zoning regulations, and community awareness programmes.

The findings reinforce the effectiveness of combining hydrological modelling, flood inundation mapping, and GIS-based multi-criteria analysis for comprehensive flood risk assessment. Similar integrated approaches have been recommended in previous studies for improving urban flood resilience and supporting evidence-based decision-making. A summary of the major outputs generated in this study is provided in Table 10.

Table 10. Summary of key outputs

Output	Description
Runoff maps	Spatial runoff depth distribution
Flood hydrographs	Peak discharge and timing
Inundation maps	Flood extent and depth
Hazard map	Physical flood hazard zones
Vulnerability map	Socioeconomic susceptibility
Risk map	Composite flood risk zones

6. Conclusion

This study developed an integrated hydrological modelling framework for flood inundation and flood risk assessment in Kolhapur City by coupling SCS-CN–based runoff estimation, HEC-HMS hydrological simulation, flood inundation mapping, and GIS-based multi-criteria analysis using AHP. The modelling results indicate that rainfall–runoff response in the city is strongly controlled by land use–land cover and soil characteristics, with urbanised areas producing significantly higher runoff during intense monsoonal events. Model calibration and validation using standard statistical indicators (NSE, R^2, RMSE, PBIAS, and RSR) demonstrated satisfactory performance, confirming the reliability of the adopted hydrological framework.

Flood inundation mapping identified low-lying floodplain areas along the Panchganga River as highly susceptible to deep and prolonged inundation under high-flow conditions. The integrated hazard–vulnerability analysis revealed pronounced spatial variability in flood risk, with high and very high risk zones primarily associated with river-proximate areas characterised by low elevation, dense population, and critical infrastructure concentration. Overall, the results highlight that urban flood risk is governed by the combined effects of hydrological processes and socioeconomic exposure.

The proposed integrated framework provides a robust and transferable approach for urban flood risk assessment and offers valuable decision-support information for flood mitigation planning, disaster preparedness, and sustainable urban development in flood-prone river basins.

7. Limitations and Future Scope

7.1 Limitations

Although this study provides a comprehensive assessment of flood inundation and flood risk in Kolhapur City, certain limitations exist. Hydrological modelling relied on available rainfall and discharge data, which may include uncertainties due to measurement errors, spatial rainfall variability, and limited gauge density, particularly affecting extreme event simulation. The SCS-CN method assumes uniform rainfall and homogeneous watershed conditions, which may not fully represent spatial heterogeneity in complex urban environments. Similarly, HEC-HMS employs conceptual representations that may simplify urban drainage processes.

Flood inundation mapping was dependent on DEM-derived terrain data, where resolution and accuracy can influence flood extent and depth estimation, especially in flat floodplain areas. Additionally, the absence of detailed urban hydraulic structures such as stormwater drains and culverts may lead to simplified flood dynamics representation. The flood vulnerability assessment was constrained by data availability and relied on selected socioeconomic indicators. Moreover, the AHP-based weighting process involves a degree of subjectivity despite consistency checks.

7.2 Future Scope

Future research can enhance flood risk assessment by integrating high-resolution rainfall data from radar or satellite sources and longer-term hydrometeorological records to improve extreme flood analysis. Coupling hydrological models with two-dimensional hydraulic models and using high-resolution LiDAR-based DEMs would improve inundation accuracy, particularly in dense urban areas.

Incorporating climate change scenarios can support long-term flood mitigation and climate-resilient urban planning. The integration of real-time modelling with early warning systems would further strengthen flood preparedness. Additionally, future studies may include dynamic socioeconomic indicators and advanced data-driven multi-criteria approaches to better capture vulnerability and reduce subjectivity in flood risk assessment stainable urban planning and disaster risk reduction in flood-prone cities such as Kolhapur.

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Conflict of interest

No potential conflict of interest.

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Data availability statement

The data will be made available upon reasonable request.

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Shrikant Kate: Conceptualization; methodology; data curation; formal analysis; investigation; software; visualization; writing – original draft; writing – review and editing; validation; project administration; resources.

Dr. Vidula Swami: Supervision; guidance; conceptual support; writing – review and editing; critical feedback; validation.

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