

## **ASSESSING FLOOD VULNERABILITY OF THE EASTERN REGION OF BANGLADESH USING ANALYTIC HIERARCHY PROCESS AND GIS-BASED SPATIAL ANALYSIS**

**Md. Aminul Haque Laskor<sup>1\*</sup>, M. Shahjahan Mondal<sup>2</sup>, Salah Uddin Ahmed Dipu<sup>3</sup>, Faysal Bhuiyan<sup>4</sup>**

<sup>1</sup>*Institute of Water and Flood Management (IWFm), Bangladesh University of Engineering and Technology (BUET), Dhaka-1000, Bangladesh, e-mail: [ahl.aminlaskor@gmail.com](mailto:ahl.aminlaskor@gmail.com)*

<sup>2</sup>*Institute of Water and Flood Management (IWFm), Bangladesh University of Engineering and Technology (BUET), Dhaka-1000, Bangladesh, e-mail: [mshahjahanmondal@iwfm.buet.ac.bd](mailto:mshahjahanmondal@iwfm.buet.ac.bd)*

<sup>3</sup>*Institute of Water and Flood Management (IWFm), Bangladesh University of Engineering and Technology (BUET), Dhaka-1000, Bangladesh, e-mail: [salahuddinahmeddipu42@gmail.com](mailto:salahuddinahmeddipu42@gmail.com)*

<sup>4</sup>*Institute of Water and Flood Management (IWFm), Bangladesh University of Engineering and Technology (BUET), Dhaka-1000, Bangladesh, e-mail: [faysalbhuiyan001@gmail.com](mailto:faysalbhuiyan001@gmail.com)*

**\*Corresponding Author**

### **ABSTRACT**

Flooding is the most devastating hydro-meteorological hazard, causing widespread economic losses, environmental degradation, and human casualties. Bangladesh is highly vulnerable to recurrent flooding due to its complex hydrological and geomorphological characteristics. This study employs the Analytic Hierarchy Process, combined with Geographic Information Systems, to assess flood vulnerability across eleven districts in the eastern region of Bangladesh. The study integrates exposure, sensitivity, and adaptive capacity components to compute a Flood Vulnerability Index. Exposure indicators include land use/land cover, elevation, slope, rain, and proximity to rivers and roads, and sensitivity indicators include population density, housing types, dependency ratio, disabled population, female population, and employment rates, and adaptive capacity indicators include literacy rate, access to safe sanitation, availability of flood shelters, access to road network, and remittance inflows. The results indicate that Feni, Noakhali, and Lakshmipur districts are the highest vulnerable due to a combination of high exposure and sensitivity with limited adaptive capacity, whereas Khagrachari is less vulnerable due to its elevated topography and high resilience. The findings provide critical insights for multi-dimensional risk assessment, which would be useful for evidence-based policy, climate-resilience planning, and focused mitigation.

**Keywords:** *vulnerability components, flood vulnerability mapping, analytic hierarchy process, spatial analysis*

## 1. INTRODUCTION

Flooding is among the most destructive natural disasters globally, affecting over 3.2 billion people from 1990 to 2022 and causing severe damage to lives, livelihoods, and infrastructure (Liu et al., 2024). Its frequency and intensity are projected to increase under climate change, potentially doubling impacts by 2050 (Chan et al., 2022). Drivers include climate change, deforestation, rapid urbanization, and population growth (Fox et al., 2024). From 2015 to 2024, India, Pakistan, and Bangladesh recorded 392 major floods, affecting 450 million people and causing nearly \$80 billion in damages (Mondol et al., 2025). Bangladesh, situated in the Ganges–Brahmaputra–Meghna delta with over 405 rivers, receives approximately 2300 mm of annual rainfall, with 20–25% of its land flooded annually and extreme events inundating up to 70% (Choudhury & Yabar, 2025; Hasan et al., 2025). Floods disrupt livelihoods, damage agriculture and infrastructure, and threaten millions of lives, with indicators such as excessive rainfall, Himalayan snowmelt, deforestation, and unplanned development intensifying vulnerability (Rifath et al., 2024). Nearly 60% of the population is exposed to flood hazards, and twelve major floods since 1955 have inundated up to 68% of the country's land (Rahman et al., 2025).

Comprehensive flood vulnerability assessments are essential for effective mitigation and management, particularly in climate-vulnerable countries like Bangladesh (Sarker et al., 2025). Vulnerability, defined by UNDRR, is a system's susceptibility to harm, influenced by social, physical, economic, and environmental indicators (UNDRR, 2017). According to the IPCC, vulnerability comprises exposure, sensitivity, and adaptive capacity (IPCC, 2022; Lee & Choi, 2019). Exposure reflects location-specific stressors, including LULC, elevation, slope, and distance from rivers (Hamidi et al., 2022). Sensitivity indicates the degree to which populations are affected, considering indicators such as population density, disability prevalence, and dependency ratios (Babanawo et al., 2022). Adaptive capacity measures a system's ability to cope, incorporating literacy, flood shelters, internet access, and sanitation (Hoque et al., 2019; Xu et al., 2024).

Floods cannot be entirely prevented, making accurate identification of vulnerable areas and potential damage assessment critical for management (Choudhury & Yabar, 2025). Vulnerability assessment complements hazard analysis and guides strategies to mitigate flood risk under rapid environmental change (Jerin et al., 2023). GIS-based Multi-Criteria Decision Analysis (MCDA), particularly the Analytic Hierarchy Process (AHP), effectively integrates spatial data with expert weighted criteria to evaluate flood vulnerability (Karymbalis et al., 2021; Sofi et al., 2024).

Despite extensive flood-related studies in Bangladesh, most existing research is limited to single districts or a limited number of districts, focuses primarily on flood hazard or susceptibility, or emphasizes exposure without explicitly integrating sensitivity and adaptive capacity within a unified vulnerability framework. Moreover, regional-scale comparative flood vulnerability assessments incorporating recent socio-economic and infrastructural datasets remain scarce, particularly in eastern Bangladesh, where flood dynamics vary across haor, coastal, and hilly environments. To address this gap, this study conducts a GIS-based flood vulnerability assessment for eleven districts of eastern Bangladesh by integrating exposure, sensitivity, and adaptive capacity components following the IPCC framework. Using the Analytic Hierarchy Process (AHP), the objectives of this study are to (i) assess flood vulnerability in the context of exposure, sensitivity, and adaptive capacity, and (ii) assess the overall Flood Vulnerability Index (FVI) for the study area. The findings provide region-specific insights to support evidence-based flood risk reduction, prioritization of vulnerable districts, and climate-resilient planning.

## 2. METHODOLOGY

### 2.1 Study Area

This study focuses on the districts of Moulvibazar, Habiganj, Sylhet, Feni, Comilla, Noakhali, Khagrachhari, Lakshmipur, Brahmanbaria, Chattogram, and Cox's Bazar, shown in Figure 1. These districts are characterized by diverse topographies, including floodplains and hilly terrains, making them susceptible to varying flood risk.

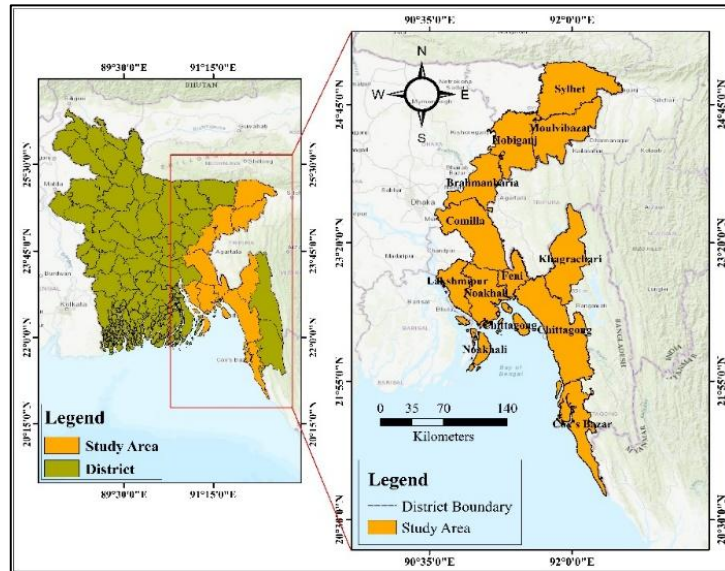


Figure 1: Location of the study area

### 2.2 Data Collection

This study utilized a range of physical and socio-economic data to assess flood vulnerability, focusing on three components: exposure, sensitivity, and adaptive capacity. These physical and socio-economic data, under three components, were selected based on the literature, data availability, and their relevance and influence on flood vulnerability. The characteristics of the datasets that are used in this study are shown in Table 1.

Table 1: Data type and sources used in this study

Indicator	Data Type	Source	Period	Mapping Output
Exposure	Landsat 8 OLI	United States Geological Survey (USGS) Earth Explorer	March 2, 2024	Land use and land cover
	SRTM-DEM (30m resolution)	USGS Earth Explorer	March 2, 2024	Elevation Slope
	Precipitation	Bangladesh Meteorological Department (BMD)	2014-2024	Precipitation
	River Channel	USGS Earth Explorer	March 2, 2024	Distance from river
	Road	Open Street Map (OSM)	March 2, 2024	Distance to road
Sensitivity	Population Density	Bangladesh Bureau of Statistics (BBS)	Population and Housing Census 2022	Population density
	Unemployed Population			Unemployed Population

	Katcha or Jhupri Houses		Katcha or Jhupri Houses
	Disabled Population		Disabled Population
	Female Population		Female Population
	Dependency Ratio		Dependency Ratio
	Male to Female Ratio		Male to Female Ratio
	Households Receiving Foreign Remittance		Households receiving foreign remittance
<b>Adaptive Capacity</b>	Access to Safe Sanitation Facilities	Bangladesh Bureau of Statistics (BBS)	Access to Safe Sanitation Facilities
	Access to Internet		Access to Internet
	Literacy Rate		Literacy Rate
	No. of Flood Shelters		No. of Flood Shelters
		Population and Housing Census 2022	
		BRAC Report, 2024	

Exposure represents the likelihood of people and settlements being affected by floods (Birkmann et al., 2013). It includes eight indicators: land use/land cover, elevation, slope, precipitation, distance from river, and distance to road (Hoque et al., 2019). These determine flood likelihood and severity, with terrain, rainfall, and land use influencing water flow and accumulation (Ghosh & Kar, 2018; Mohamed, 2019). Sensitivity captures socio-economic conditions that heighten flood impacts, including population density, sex and dependency ratios, employment, disability, and housing type (Yang et al., 2018). High population density, social imbalance, and non-durable housing increase vulnerability, while employment and durable structures enhance resilience (Deepak et al., 2020; Tascón-González et al., 2020). Adaptive capacity refers to the ability to cope and recover. Remittances and literacy were key indicators, reflecting financial security and awareness that improve disaster preparedness and recovery (Le De et al., 2013; Tascón-González et al., 2020). Collectively, these indicators provide a holistic understanding of flood vulnerability in the study area.

### 2.3 Data Processing

Flood vulnerability was assessed using geospatial analysis of selected indicators. Exposure indicators, such as elevation, slope, and distance from river, were derived from DEM data using hydrological tools in ArcGIS after sink correction while distance to road was calculated from OpenStreetMap (OSM) data using the Euclidean Distance tool. LULC was classified from Landsat 8 imagery (2021) through supervised classification (Roy et al., 2014). Precipitation intensity (2014–2024) was mapped using daily BMD data from 35 stations interpolated by IDW (Lu & Wong, 2008).

For sensitivity, population density, sex ratio, dependency ratio, employed population, disability rate, and pucca/semi-pucca households were taken from the Bangladesh Bureau of Statistics (BBS, 2022) and converted to raster form. Adaptive capacity indicators, including male-to-female ratio, literacy rate, remittance-receiving households, access to safe sanitation, and internet access, were derived from BBS Census 2022 data, and flood shelter information was obtained from BRAC (2024). These indicators were processed to generate spatial layers for analysis.

### 2.4 Ranking and Standardization

Each spatial criterion layer for the three vulnerability indicators was ranked from 1 (very low) to 5 (very high) following the Analytical Hierarchy Process (AHP) to reflect its relative contribution to flood vulnerability. All spatial datasets were converted to a 30 m raster format for weighted overlay analysis. The ranked layers were then standardized to a uniform scale (0–1) using a linear transformation equation

(1) (Mitrică et al., 2026), ensuring compatibility for multi-criteria decision-making in the AHP framework:

$$p = \begin{cases} \frac{X_i - X_{min}}{X_{max} - X_{min}}, & \text{positive relationship} \\ \frac{X_{max} - X_i}{X_{max} - X_{min}}, & \text{negative relationship} \end{cases} \quad (1)$$

Where  $p$  represents the standardized score,  $X_i$  is the original raster cell value, and  $X_{min}$  and  $X_{max}$  denote the minimum and maximum values of the respective dataset. This formulation ensures that higher standardized values consistently correspond to higher flood vulnerability across all criteria.

## 2.5 Weight Assigning with AHP

The Analytical Hierarchy Process (AHP) was used to assign weights to criteria under exposure, sensitivity, and adaptive capacity. Pairwise comparison matrices, in which each criterion was compared against others using Saaty (1987) scale of relative importance, were developed based on expert judgments collected through a 10-question survey. The survey included 10 experts: 3 faculty members from BUET, SUST, and JU; 5 government officers from BIWTA, BWDB, and DDM; and 2 NGO personnel from WSUP and O.Creeds. Experts were selected based on their academic qualifications and professional experience in flood risk management, disaster mitigation, water resources, and geospatial analysis. Individual expert judgments were combined using the geometric mean method to generate a consensus matrix. The resulting combined weights for exposure, sensitivity, and adaptive capacity sum to 1.

Table 2: Scale of relative importance (Saaty, 1987)

Relative Importance	Definition	Description
1	Equal importance	Two factors equally influence the objective
3	Moderate importance	Experience and judgment slightly favor one factor over another
5	Strong importance	Experience and judgment strongly favor one factor over another
7	Very strong importance	One decision factor is strongly favored over another, and its supremacy is established in practice
9	Extreme importance	The evidence favoring one decision factor over another is of the highest possible orders of validity
2, 4, 6, and 8	Intermediate values between adjacent judgments,	When compromise is required

To validate the pairwise matrices and assigned weights, the Consistency Ratio (CR) was calculated, which must be less than 0.1; otherwise, expert judgments are revised, and weights recalculated. The CR was computed using equation (2) (Malczewski, 2010).

$$CR = \frac{CI}{RI} \quad (2)$$

Where  $CR$  is the consistency ratio,  $RI$  is the random index, and  $CI$  is the consistency index.  $CI$  is defined as follows:

$$CI = \frac{\gamma_{max} - n}{n - 1} \quad (3)$$

Where  $\gamma_{max}$  represents the largest eigenvalue of the matrix and  $n$  refers to the order of the matrix (Mahapatra et al., 2015).

## 2.6 Flood Vulnerability Assessment

A weighted overlay analysis was conducted for the spatial criteria of exposure, sensitivity, and adaptive capacity. Individual indices for each indicator were generated by integrating their respective weights and classified into five categories: very low, low, moderate, high, and very high. To maintain consistency, all indices were standardized to a 0–1 range using a linear scale transformation. The final Flood Vulnerability Index Map was produced by combining the weighted indicators through raster calculation, following IPCC (2007).

$$FVI = E + S - AC \quad (4)$$

Where FVI is the flood vulnerability index, E, S, and AC stand for exposure, sensitivity, and adaptive capacity, representing the three main components of the FVI, respectively.

## 3. RESULTS & DISCUSSION

### 3.1 Weight Assigning and Consistency Analysis

The Analytical Hierarchy Process (AHP) was applied to assign relative weights to all indicators. The weighting results are presented in Table 2 (Exposure), Table 3 (Sensitivity), and Table 4 (Adaptive Capacity). The reliability of the pairwise comparisons was evaluated using the Consistency Ratio (CR), and all CR values were found to be below the acceptable threshold of 0.10, indicating satisfactory consistency and robustness of the assigned weights.

Table 2: Weighting of exposure component

Component	Criteria	Weight
Exposure	Elevation	0.25
	Slope	0.15
	LULC	0.06
	Distance from River	0.35
	Distance from Road	0.04
	Rainfall	0.15
	CR: 0.05	

Table 3: Weighting of sensitivity component

Component	Criteria	Weight
Sensitivity	Population Density	0.7
	Unemployed Population	0.09
	Katcha or Jhupri Houses	0.21
	Disabled Population	0.32
	Female Population	0.16
	Dependency Ratio	0.18
CR: 0.04		

Table 4: Weighting of adaptive capacity component

Component	Criteria	Weight
Adaptive Capacity	Male to Female Ratio	0.17
	Households receiving foreign remittance	0.15
	Access to Safe Sanitation Facilities	0.13
	Access to Internet	0.09
	Literacy Rate	0.21
	No. of Flood Shelters	0.25
	CR: 0.04	

### 3.2 Vulnerability in context to exposure

The exposure indicator maps shown in Figure 2 illustrate six key indicators influencing regional vulnerability. Built-up and agricultural areas show higher flood exposure, while densely vegetated zones offer natural protection. Lower elevations and flatter slopes are more flood-prone, whereas higher and steeper areas face lower risks. Proximity to rivers (<8.8 km) and roads increases exposure, though road access can improve disaster response. Rainfall intensity (203–233 mm) further elevates flood risk, while lower rainfall reduces vulnerability.

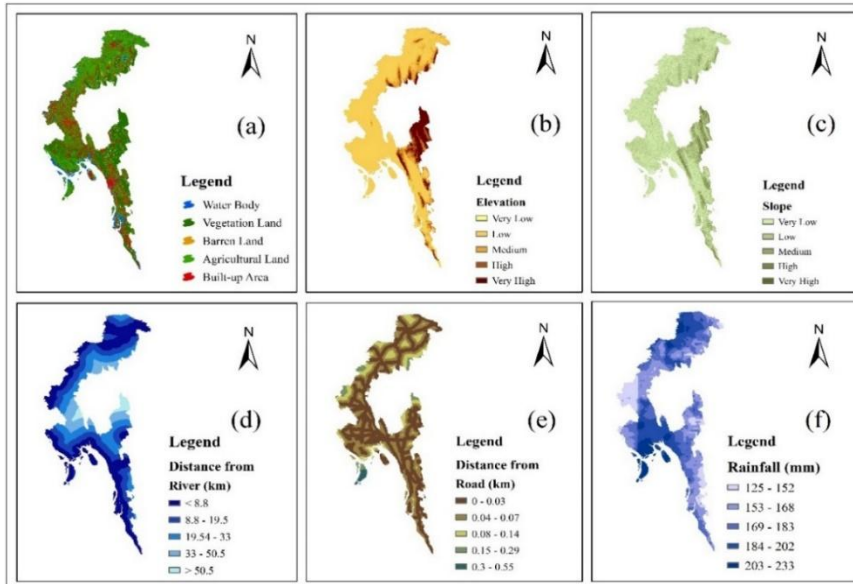


Figure 2: Exposure indicator maps: (a) LULC, (b) Elevation, (c) Slope, (d) Distance from River (km), (e) Distance from Road (km), and (f) Rainfall

### 3.3 Vulnerability in context to sensitivity

The sensitivity indicator maps shown in Figure 3 depict factors influencing population sensitivity to flooding. High population density strains resources, while higher unemployment limits recovery capacity. Katcha or Jhupri housing increases sensitivity because these structures are easily damaged. Higher proportions of disabled individuals and females increase vulnerability due to greater support needs and gender disparities. High dependency ratios raise sensitivity by putting pressure on fewer income earners for recovery.

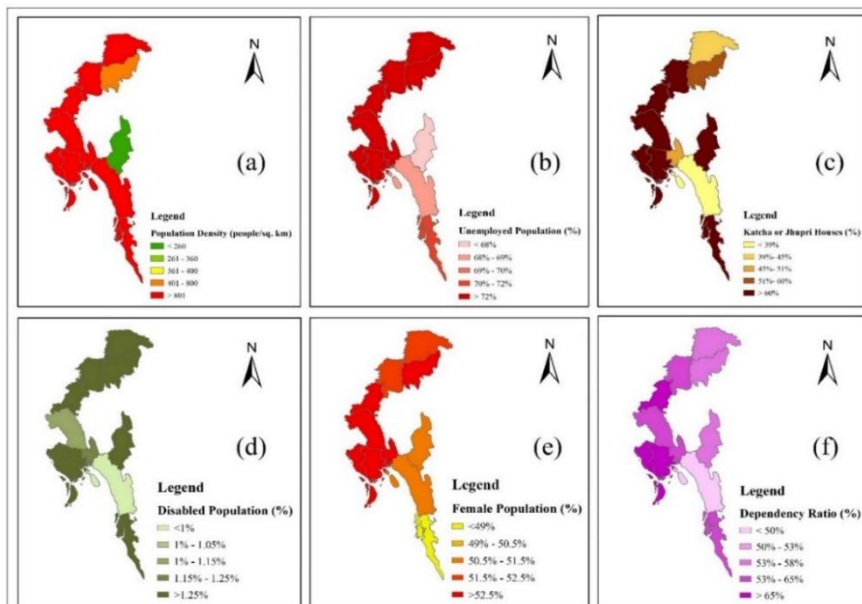


Figure 3: Sensitivity indicator maps: (a) Population Density, (b) Unemployed Population, (c) Katcha or Jhupri Houses, (d) Disabled Population, (e) Female Population, and (f) Dependency Ratio

### 3.4 Vulnerability in context to adaptive capacity

The adaptive capacity indicator maps shown in Figure 4 illustrate indicators that strengthen a district's ability to cope with floods. Higher literacy rates enhance awareness and preparedness, while lower rates limit adaptive potential. Greater availability of flood shelters improves protection and response capacity. Internet access facilitates communication, early warnings, and disaster information sharing. Access to safe sanitation reduces health risks during floods, boosting resilience. Foreign remittances enhance financial stability, supporting recovery and adaptation. A higher male-to-female ratio is also associated with greater adaptive capacity.

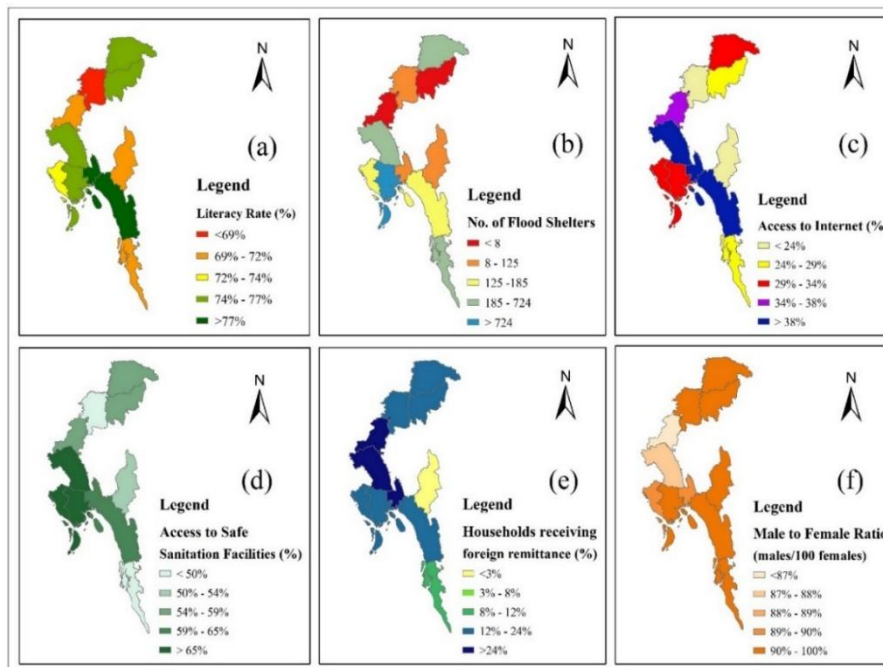


Figure 4: Adaptive capacity indicator maps: (a) Literacy Rate, (b) No. of Flood Shelters, (c) Access to Internet, (d) Access to Safe Sanitation Facilities, (e) Households Receiving Foreign Remittance, and (f) Male to Female Ratio

### 3.5 Flood vulnerability mapping

The exposure map shown in Figure 5(a) delineates spatial heterogeneity in flood exposure across districts. Sylhet, Moulvibazar, and Habiganj exhibit very high vulnerability, attributable to their low-lying topography, substantial precipitation, and proximity to river networks. Chattogram and Cox's Bazar manifest high to very high exposure, influenced by coastal positioning, low elevation, and intense rainfall regimes. Noakhali, Feni, and Lakshmipur predominantly occupy high-exposure zones where moderate elevation and hydrological connectivity exacerbate inundation potential. Brahmanbaria and Comilla are largely within moderate to high exposure categories, whereas Khagrachari remains minimally exposed owing to elevated terrain, extensive vegetation cover, and distance from major rivers.

The sensitivity map shown in Figure 5(b) elucidates population and infrastructure-related determinants of flood susceptibility. Noakhali, Lakshmipur, and Brahmanbaria are characterized by high sensitivity due to dense population, a predominance of temporary dwellings, elevated unemployment, and higher dependency ratios. Districts including Habiganj, Moulvibazar, Comilla, Feni, Khagrachari, and Cox's Bazar demonstrate moderate sensitivity, while Sylhet and Chattogram exhibit comparatively lower sensitivity, underpinned by reduced population density, limited temporary housing, and manageable dependency ratios.

The adaptive capacity map shown in Figure 5(c) significantly varies, as depicted in the corresponding map. Habiganj, Brahmanbaria, and Khagrachari possess high adaptive potential, supported by superior education, greater flood shelter availability, and enhanced resource accessibility. Moderate adaptive

capacity characterizes Moulvibazar, Lakshmipur, and Cox’s Bazar, whereas Sylhet, Comilla, Feni, Noakhali, and Chattogram exhibit limited capacity due to infrastructural and financial constraints.

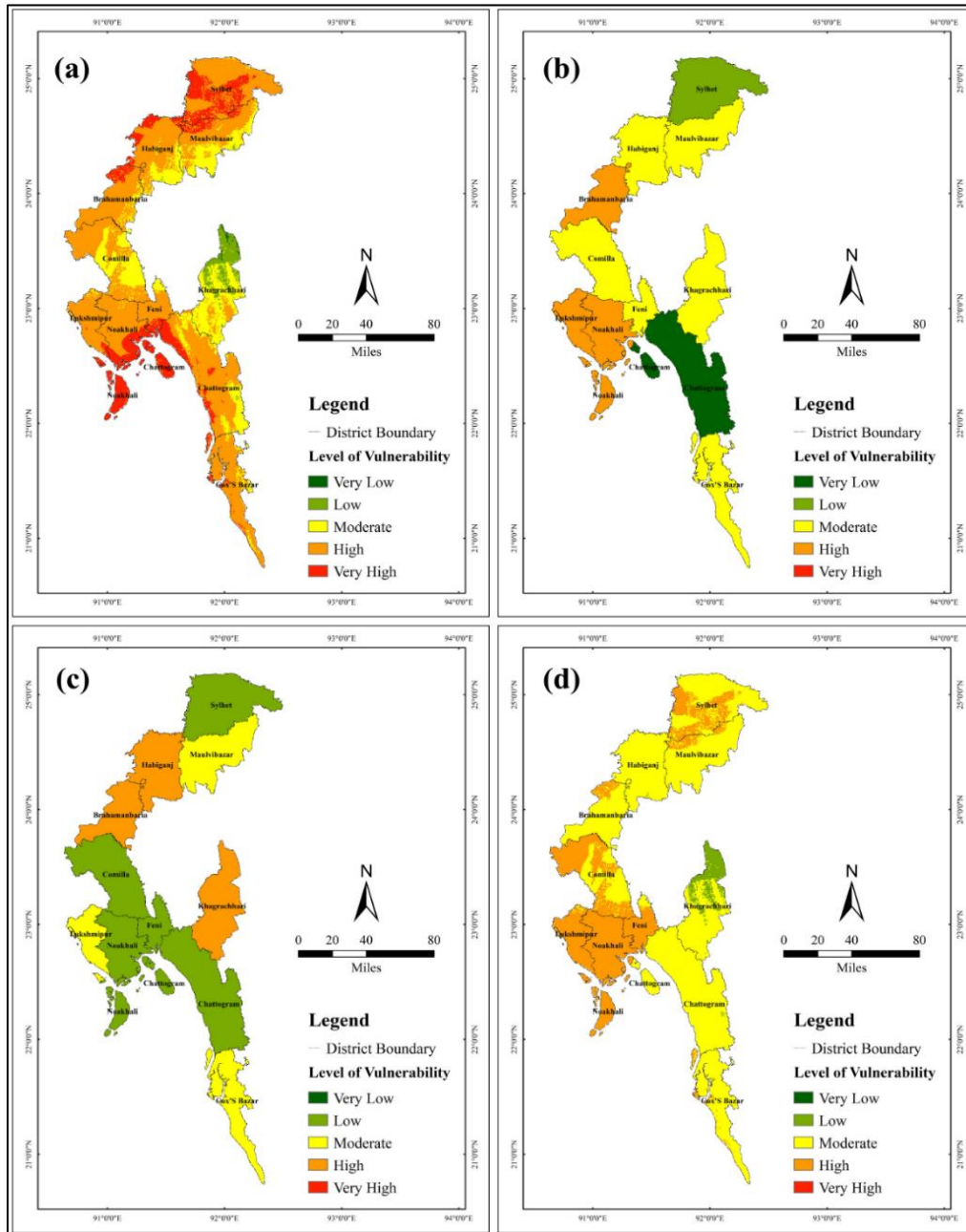


Figure 5: Maps of flood (a) exposure, (b) sensitivity, (c) adaptive capacity, and (d) vulnerability index

The Flood Vulnerability Index Map shown in Figure 5(d) provides a spatial overview of flood vulnerability levels across different districts. Feni, Noakhali, and Lakshmipur are highly vulnerable due to high exposure, high sensitivity, and limited adaptive capacity, while Comilla shows high vulnerability with low adaptive capacity. Sylhet, Moulvibazar, and Brahmanbaria face moderate flooding risks due to a combination of moderate exposure, sensitivity, and limited adaptive capacity. Habiganj, Chattogram, and Cox’s Bazar have moderate vulnerability. Low exposure and strong adaptive capacity make Khagrachari the least vulnerable district, though moderate sensitivity indicators exist.

The validity of the Flood Vulnerability Index (FVI) derived in this study is evaluated through comparison with flood susceptibility and impact assessments reported in previous research. The high

vulnerability of Feni identified in the present analysis is consistent with the flash flood vulnerability assessment of (Sarker et al., 2025) and the multi-sectoral flood impact assessment of the August 2024 flood by (Hasan et al., 2024), which documented severe flood impacts in the district. Similarly, the high vulnerability classification of Comilla aligns with its inclusion within the high-risk eastern region reported by (Hasan et al., 2024) and with the national-scale subdistrict assessment of cyclone-induced flood vulnerability by (Imam et al., 2024). The moderate vulnerability observed in Sylhet Division is in agreement with the findings of (Islam et al., 2025) and (Rob & Apu, 2024), who reported substantial flood susceptibility in the northern haor basins, while (Haque et al., 2021) highlighted scale-dependent variations in flash flood susceptibility within specific haor areas. The moderate vulnerability of Chattogram and Cox's Bazar is also supported at the regional scale by (Imam et al., 2024), who identified the southeastern coastal zone as highly exposed to flood hazards. In contrast, the moderate vulnerability classification of Brahmanbaria differs from the high flash flood susceptibility reported by (Haque et al., 2021), suggesting that flash flood risk may be more pronounced than general flood vulnerability in this district. The low vulnerability of Khagrachari, attributed to its elevated terrain and extensive vegetation cover, is consistent with topography-driven susceptibility patterns reported in haor-focused studies (Haque et al., 2021). Overall, the agreement between the present FVI patterns and earlier flood susceptibility assessments provides qualitative validation of the spatial heterogeneity in flood vulnerability identified in this study.

#### **4. CONCLUSIONS**

This study presents a GIS and AHP-based flood vulnerability assessment framework for eastern Bangladesh. The findings reveal significant spatial variations in flood vulnerability, with Feni, Noakhali, and Lakshmipur identified as highly vulnerable due to their high exposure and sensitivity coupled with low adaptive capacity. In contrast, Khagrachari demonstrates the lowest vulnerability owing to its high elevation and strong adaptive measures. The study underscores the importance of integrating multi-criteria decision analysis and geospatial techniques for more precise and actionable flood risk assessments. The Flood Vulnerability Index generated in this study provides crucial data to inform policymakers and disaster management authorities in formulating targeted interventions, infrastructure planning, and community resilience strategies. Future research should incorporate real-time flood monitoring and socio-economic dynamics to enhance the robustness of flood risk assessments.

#### **Declaration of Use of AI**

During the preparation of this work, the authors used paraphrasing tools to improve the readability and language of the manuscript. After using these tools, the authors reviewed and edited the content as needed and took full responsibility for the manuscript.

#### **REFERENCES**

- Babanawo, D., Mattah, P. A. D., Agblorti, S. K. M., Brempong, E. K., Mattah, M. M., & Aheto, D. W. (2022). Local Indicator-Based Flood Vulnerability Indices and Predictors of Relocation in the Ketu South Municipal Area of Ghana. *Sustainability*, 14(9). <https://doi.org/10.3390/su14095698>
- BBS. (2022). Statistical Yearbook Bangladesh 2022. [www.bbs.gov.bd](http://www.bbs.gov.bd)
- Birkmann, J., Cardona, O. D., Carreño, M. L., Barbat, A. H., Pelling, M., Schneiderbauer, S., Kienberger, S., Keiler, M., Alexander, D., Zeil, P., & Welle, T. (2013). Framing vulnerability, risk and societal responses: The MOVE framework. *Natural Hazards*, 67(2), 193–211. <https://doi.org/10.1007/s11069-013-0558-5>
- Chan, S. W., Abid, S. K., Sulaiman, N., Nazir, U., & Azam, K. (2022). A systematic review of the flood vulnerability using geographic information system. *Heliyon*, 8(3). Elsevier Ltd. <https://doi.org/10.1016/j.heliyon.2022.e09075>
- Choudhury, K. N., & Yabar, H. (2025). Flood Hazard Assessment and Monitoring in Bangladesh: An Integrated Approach for Disaster Risk Mitigation. *Earth*, 6(3). <https://doi.org/10.3390/earth6030090>

- Deepak, S., Rajan, G., & Jairaj, P. G. (2020). Geospatial approach for assessment of vulnerability to flood in local self governments. *Geoenvironmental Disasters*, 7(1). <https://doi.org/10.1186/s40677-020-00172-w>
- Fox, S., Agyemang, F., Hawker, L., & Neal, J. (2024). Integrating social vulnerability into high-resolution global flood risk mapping. *Nature Communications*, 15(1). <https://doi.org/10.1038/s41467-024-47394-2>
- Ghosh, A., & Kar, S. K. (2018). Application of analytical hierarchy process (AHP) for flood risk assessment: a case study in Malda district of West Bengal, India. *Natural Hazards*, 94(1), 349–368. <https://doi.org/10.1007/s11069-018-3392-y>
- Hamidi, A. R., Jing, L., Shahab, M., Azam, K., Tariq, M. A. U. R., & Ng, A. W. M. (2022). Flood Exposure and Social Vulnerability Analysis in Rural Areas of Developing Countries: An Empirical Study of Charsadda District, Pakistan. *Water*, 14(7). <https://doi.org/10.3390/w14071176>
- Hasan, I., Rakib, M. M. H., Roy, D. K., Ovi, M. H., Hasan, M. F., & Majumder, M. S. I. (2025). Geospatial flood susceptibility modelling using analytical hierarchy process: A case study in the south-central coastal region of Bangladesh. *Geosystems and Geoenvironment*, 5(1), 100457. <https://doi.org/10.1016/J.GEOGEO.2025.100457>
- Haque, M. N., Siddika, S., Sresto, M. A., Saroar, M., & Shabab, K. R. (2021). Geo-spatial analysis for flash flood susceptibility mapping in the north-east haor (wetland) region in Bangladesh. *Earth Systems and Environment*, 5, 365–384. <https://doi.org/10.1007/s41748-021-00221-w>
- Hasan, N., Nasir, N. N., Wardi, M., Alam, R., Sarker, C. K., Siam, R. S., Arabi, K. A. A., & Azim, A. (2024). Multi-sectoral impact assessment and flood risk zoning of eastern Bangladesh for the August 2024 flood (Preprint). ResearchGate. <https://www.researchgate.net/publication/399397813>
- Hoque, M. A. A., Tasfia, S., Ahmed, N., & Pradhan, B. (2019). Assessing spatial flood vulnerability at kalapara upazila in Bangladesh using an analytic hierarchy process. *Sensors*, 19(6). <https://doi.org/10.3390/s19061302>
- Imam, M. F., Ahsan, U., Hoque, F., Rahman, M. A., & Prodhon, F. A. (2024). Assessing and mapping the vulnerability index of Bangladesh to natural and climate-induced disasters: A spatial analysis at the subdistrict level. *Journal of Agrometeorology*, 26(4), 465–472. <https://doi.org/10.54386/jam.v26i4.2710>
- IPCC. (2022). The Concept of Risk in the IPCC Sixth Assessment Report the Concept of Risk in the IPCC Sixth Assessment Report.
- Islam, I., Rahman, M. A., Adham, M. I., & Haque, S. (2025). Assessment and zonation of flood susceptibility in Sylhet Division, Bangladesh using GIS and analytic hierarchy process (AHP). *Journal of Flood Risk Management*, 18(1), e70121. <https://doi.org/10.1111/jfr3.70121>
- Jerin, T., Azad, M. A. K., & Khan, M. N. (2023). Climate change-triggered vulnerability assessment of the flood-prone communities in Bangladesh: A gender perspective. *International Journal of Disaster Risk Reduction*, 95, 103851. <https://doi.org/10.1016/J.IJDRR.2023.103851>
- Karymbalis, E., Andreou, M., Batzakis, D.-V., Tsanakas, K., & Karalis, S. (2021). Integration of GIS-Based Multicriteria Decision Analysis and Analytic Hierarchy Process for Flood-Hazard Assessment in the Megalo Rema River Catchment (East Attica, Greece). <https://doi.org/10.3390/su>
- Le De, L., Gaillard, J. C., & Friesen, W. (2013). Remittances and disaster: a review. *International Journal of Disaster Risk Reduction*, 4, 34–43. <https://doi.org/10.1016/J.IJDRR.2013.03.007>
- Lee, J. S., & Choi, H. Il. (2019). Comparative analysis of flood vulnerability indicators by aggregation frameworks for the IPCC's assessment components to climate change. *Applied Sciences*, 9(11). <https://doi.org/10.3390/app9112321>
- Liu, Q., Du, M., Wang, Y., Deng, J., Yan, W., Qin, C., Liu, M., & Liu, J. (2024). Global, regional and national trends and impacts of natural flood1990–2022. *Bulletin of the World Health Organization*, 102(6), 410–420. <https://doi.org/10.2471/BLT.23.290243>
- Lu, G. Y., & Wong, D. W. (2008). An adaptive inverse-distance weighting spatial interpolation technique. *Computers & Geosciences*, 34(9), 1044–1055. <https://doi.org/10.1016/J.CAGEO.2007.07.010>

- Mahapatra, M., Ramakrishnan, R., & Rajawat, A. S. (2015). Coastal vulnerability assessment using analytical hierarchical process for South Gujarat coast, India. *Natural Hazards*, 76(1), 139–159. <https://doi.org/10.1007/s11069-014-1491-y>
- Malczewski, J. (2010). *Trends in Multiple Criteria Decision Analysis* (M. Ehrgott, J. R. Figueira, & S. Greco, Eds.; Vol. 142). Springer US. <https://doi.org/10.1007/978-1-4419-5904-1>
- Mitrică, B., Roznoviețchi, I., Micu, D., Serban, P. R., & Damian, N. The Vulnerability of the Romanian Danube Valley to Heat-Related Phenomena. *The Palgrave Handbook of Just Green Transitions in the Western Balkans and Beyond*, 437. [https://doi.org/10.1007/978-3-031-95075-9\\_24](https://doi.org/10.1007/978-3-031-95075-9_24)
- Mohamed, S. A. (2019). Application of satellite image processing and GIS-Spatial modeling for mapping urban areas prone to flash floods in Qena governorate, Egypt. *Journal of African Earth Sciences*, 158, 103507. <https://doi.org/10.1016/J.JAFREARSCI.2019.05.015>
- Mondol, M. F., Rifath, A. R., Muktadir, M. G., Sakib, N., Bagee, A., & Islam, M. A. (2025). Flood vulnerability assessment in Jamuna river floodplain: A Synthesis of multi-dimensional vulnerability indicators using geospatial and Fuzzy-AHP techniques. *Natural Hazards Research*. <https://doi.org/10.1016/J.NHRES.2025.07.002>
- Rahman, M. M., Tanni, K. N., Shobuj, I. A., Hossain, M. T., Alam, E., Al Hattaw, K. S., & Islam, M. K. (2025). Multidimensional Vulnerability Assessment for Floods: Evidence From Flood-Prone Areas of Bangladesh. *Journal of Flood Risk Management*, 18(3). <https://doi.org/10.1111/jfr3.70089>
- Rifath, A. R., Muktadir, M. G., Hasan, M., & Islam, M. A. (2024). Flash flood prediction modeling in the hilly regions of Southeastern Bangladesh: A machine learning attempt on present and future climate scenarios. *Environmental Challenges*, 17, 101029. <https://doi.org/10.1016/J.ENVC.2024.101029>
- Rob, M. A., & Apu, M. A. (2024). Flood risk and resilience in the Greater Sylhet Region: A disaster management perspective. *Journal of One Initiative Research and Development (JOIRD)*, 4(1). <https://joiresearch.com/issues-archive/vol-04-issue-no-1/EX6jR8GIMjV6/>
- Roy, D. P., Wulder, M. A., Loveland, T. R., C.E., W., Allen, R. G., Anderson, M. C., Helder, D., Irons, J. R., Johnson, D. M., Kennedy, R., Scambos, T. A., Schaaf, C. B., Schott, J. R., Sheng, Y., Vermote, E. F., Belward, A. S., Bindschadler, R., Cohen, W. B., Gao, F., ... Zhu, Z. (2014). Landsat-8: Science and product vision for terrestrial global change research. *Remote Sensing of Environment*, 145, 154–172. <https://doi.org/10.1016/j.rse.2014.02.001>
- Saaty, R. W. (1987). The analytic hierarchy process—what it is and how it is used. *Mathematical Modelling*, 9(3–5), 161–176. [https://doi.org/10.1016/0270-0255\(87\)90473-8](https://doi.org/10.1016/0270-0255(87)90473-8)
- Sarker, S., Jahan, I., Wang, X., & Azad, A. (2025). Geospatial Approach to Assess Flash Flood Vulnerability in a Coastal District of Bangladesh: Integrating the Multifaceted Dimension of Vulnerabilities. *ISPRS International Journal of Geo-Information*, 14(5). <https://doi.org/10.3390/ijgi14050194>
- Sofi, M. S., Rautela, K. S., Muslim, M., & Bhat, S. U. (2024). From data to decisions: evaluating flood vulnerability in the Sindh watershed through Analytical Hierarchy Process. *Frontiers of Urban and Rural Planning*, 2(1). <https://doi.org/10.1007/s44243-024-00036-z>
- Tascón-González, L., Ferrer-Julιά, M., Ruiz, M., & García-Meléndez, E. (2020). Social vulnerability assessment for flood risk analysis. *Water*, 12(2). <https://doi.org/10.3390/w12020558>
- UNDRR. (2017). United Nations Office for Disaster Risk Reduction (UNDRR). 2017. The Sendai Framework Terminology on Disaster Risk Reduction. <https://www.undrr.org/drr-glossary/terminology>
- Xu, J., Takahashi, M., & Li, W. (2024). Identifying vulnerable populations in urban society: a case study in a flood-prone district of Wuhan, China. *Natural Hazards and Earth System Sciences*, 24(1), 179–197. <https://doi.org/10.5194/nhess-24-179-2024>
- Yang, W., Xu, K., Lian, J., Bin, L., & Ma, C. (2018). Multiple flood vulnerability assessment approach based on fuzzy comprehensive evaluation method and coordinated development degree model. *Journal of Environmental Management*, 213, 440–450. <https://doi.org/10.1016/J.JENVMAN.2018.02.085>