FLOOD VULNERABILITY ASSESSMENT IN SOUTH EASTERN BANGLADESH DUE TO 2024 FLOOD USING ANALYTIC HIERARCHY PROCESS

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ABSTRACT

Flooding is one of the most frequent and devastating natural hazards in Bangladesh, causing significant threats to lives, property, and livelihoods. The south-eastern region, including Comilla, Lakshmipur, Noakhali, Feni, and Brahmanbaria, is particularly vulnerable due to its low elevation, dense population, proximity to major rivers, and heavy monsoon rainfall. The 2024 flood event highlights the increasing risk posed by climate change and extreme weather, prompting the immediate necessity for a comprehensive flood vulnerability assessment in this region. This study combines the Analytic Hierarchy Process (AHP) with Geographic Information Systems (GIS) to assess flood vulnerability based on twelve indicators grouped into three components: physical (elevation, slope, land use, rainfall intensity), social (population density, number of households, slum and disabled population), and coping capacity (literacy rate, hospital access, employment rate, and growth centers). Data were collected from USGS, CHIRPS, LGED, and BBS census sources. The indicators were standardized and weighted using AHP, then analyzed in GIS to produce thematic maps under two scenarios: with and without coping capacity. The initial vulnerability (excluding coping capacity) specified a range from low to extreme vulnerability, with 30% of the area classified as very highly vulnerable and 2% as extreme, particularly in Comilla and Noakhali. However, incorporating coping capacity significantly altered the vulnerability distribution. Extreme vulnerability was eliminated, and very high vulnerability decreased to 15%. Meanwhile, moderate and high vulnerability increased to 19% and 32%, respectively, indicating a shift of higher-vulnerable zones into lower-vulnerable categories due to improved socio-economic resilience. Notably, the district of Feni exhibits a slight increase in vulnerability from low to moderate despite the inclusion of coping capacity, indicating that its existing resilience mechanisms may be insufficient and warrant targeted interventions. Spatial agreement between the vulnerability model and the observed flood damages based on the evidence of the empirical data supports the accuracy of the developed AHP-GIS model. These findings underscore the importance of including socio-economic resilience in flood vulnerability assessments. By integrating physical, social, and coping factors, this AHP-GIS approach provides a comprehensive framework for identifying risk-prone areas and guiding targeted interventions. The resulting maps support evidence-based planning for disaster preparedness, land-use regulation, and sustainable flood risk management in south-eastern Bangladesh.

Keywords: *Flood vulnerability, AHP, GIS, Coping capacity, South-eastern Bangladesh*

INTRODUCTION

Flood is one of the most destructive and common natural disasters in Bangladesh, which causes threats to human life, property, and livelihoods (Rimba et al., 2017). The eastern part of Bangladesh is of low topography, close to the major river systems, and this causes Comilla, Lakhsmipur, Noakhali, Feni, and Brahmanbaria to be highly vulnerable to floods. Additionally, the hydrological behavior shaped by the monsoon pattern causes floods in these eastern districts.

In the past, this area has faced many flash floods, river overflows, and pluvial floods. Notable floods in 1988,1998, and 2004 destroyed agricultural lands, farms, and human habitats, hence highlighting the continued susceptibility of the area to extreme water events (Islam et al., 2024). Recently, the 2024 flood, due to extreme rainfall, pointed out that floods are becoming more severe because of climate change and unpredictable weather.

The flood vulnerability is a combination of physical, environmental, and socio-economic factors (Deepak et al., 2020). This study specifically focuses on the physical, social, and coping capacity aspects of vulnerability, which result from the interaction of natural factors such as topography, rainfall intensity, land use, and drainage conditions with social and economic characteristics, including population density, accommodation conditions, and coping resources (Dandapat & Panda, 2017).

This study used a decision-making method, the Analytical Hierarchy Process (AHP), which compares things in pairs and also combines several factors (Feloni et al., 2020). The Geographic Information System (GIS) is a powerful tool used for combining spatial data and visualizing the physical variables through a map that influences the flood behavior (Saaty, 2008). This GIS methodology effectively evaluates and helps to provide a decision based on flood risk management and its preparedness.

Since a number of floods have been caused by rainfall, the flood vulnerability in this region needs to be evaluated in a detailed manner. This study determines the flood-prone area with thematic maps, which gives information that will help in risk mitigation and sustainable development of infrastructure in Eastern Bangladesh. Flood vulnerability assessment is important for identifying areas with high risk to flood and also for guiding flood mitigation and adaptation strategies, making the community more capable of withstanding and recovering from flood (Roy & Blaschke, 2015).

METHODOLOGY

1.1 Study Area

The study area considered five administrative districts of eastern Bangladesh: Comilla, Lakshmipur, Noakhali, Feni, and Brahmanbaria (Figure 1). Geographically, they are located between the latitude 23°00′ to 24°15′ N and longitude 90°35′ to 91°45′ E. The terrain is a combination of low floodplains, coastal areas, and uplands, which makes it very vulnerable to flooding caused by heavy rainfall, riverine breaches, and poor drainage systems (Bernard et al., 2022).

The climate in Eastern Bangladesh is a monsoon sub-tropical climate, which is characterized by hot summer months, high rainy seasons (during the monsoon season, June to September), and comparatively mild winters. Precipitation is often above 2000mm/year, increasing the seasonal flood potential. Recent statistics show that extreme rainfall events have increased in intensity, and this has led to localized flash floods and riverine flooding, a process that has been recorded in the 2022 monsoon floods (Global Rapid Post-Disaster Damage Estimation (GRADE), 2024). Moreover, the region has great population densities, and urban centers like Comilla are growing at a high rate. The roads, schools, and hospitals, which are considered to be critical infrastructure, are very vulnerable to floods, and thus, there is an absolute need to have sound flood mitigation strategies.

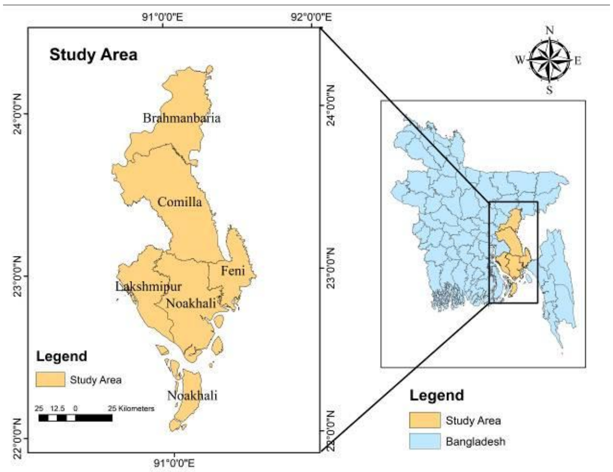

Figure 1: Study Area Map

1.2 Datasets and Sources

This study has used an Analytic Hierarchy Process (AHP)-based geospatial multi-criteria evaluation model to integrate natural, social, and anthropogenic factors in the analysis of flood vulnerability. Although there are several formulations that can be used to assess hazard vulnerability, the equation below was chosen to measure flood vulnerability related to the 2024 flood event:

$$\text{Vulnerability} = \text{Physical vulnerability} \times \text{Social vulnerability}/\text{Coping capacity} \tag{1}$$

This study integrates various datasets, including topographic data, morphological data, satellite imagery, and 2022 census data acquired from relevant institutions, to assess flood vulnerability using the Analytic Hierarchy Process (AHP). GIS techniques were extensively employed to process, analyze, and integrate spatial data for generating physical and social vulnerability maps, as well as coping capacity maps, in response to the 2024 flood in Eastern Bangladesh. The study follows the methodological flowchart shown in Figure 2. The source, time period and mapping output of the datasets used in this analysis are mentioned in Table 1.

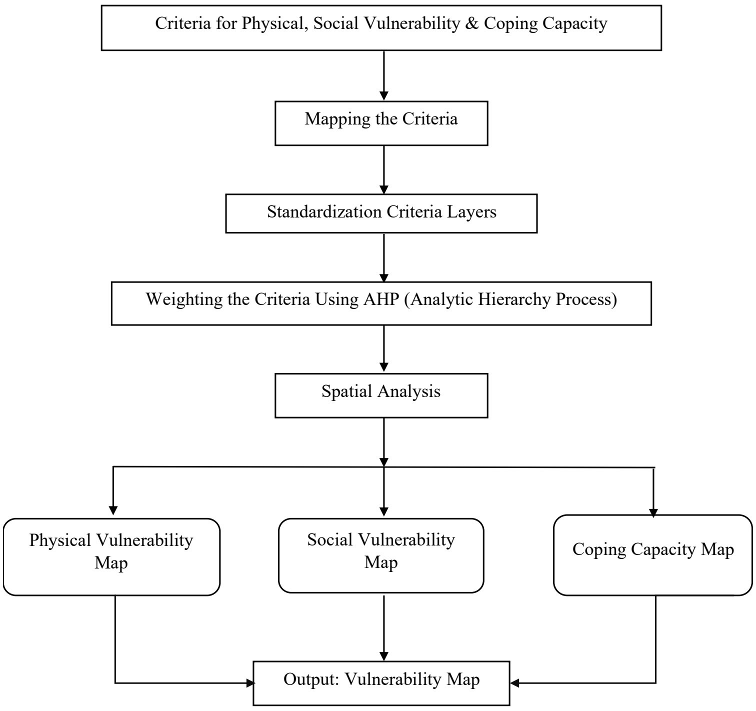

Figure 2: Flowchart illustrating the methodological framework adopted for the study

Table 1: Data type and sources used in this study

Data Type	Source	Period	Mapping Output
Landsat 8	United States Geological Survey (USGS) Earth Explorer	2024	Land use and cover
SRTM-DEM (30m resolution)	USGS Earth Explorer	2024	Elevation and slope
Precipitation	CHIRPS	2024	Precipitation
Population	Bangladesh Bureau of Statistics (BBS)	Population census of 2022	Population density, Disabled population, Employment rate, literacy rate
Household	Bangladesh Bureau of Statistics (BBS)	Population census of 2022	Household, Households in Slum & Floating
Growth Center	Local Government Engineering Department (LGED)	2024	Growth Center
Damage	Centre for Policy Dialogue (CPD)	2024	Validation

Although drainage density, distance from rivers, and flooded vegetation are recognized as important flood conditioning factors, they were not included in the present study due to data limitations and the regional scale of analysis. However, elevation, slope, land use, and precipitation indirectly represent drainage and flow accumulation characteristics derived from DEM data. Future studies may incorporate these parameters for higher-resolution local-scale analysis.

2.1 Vulnerability Evaluation Criteria

In this study, the criteria were selected based on literature review, data availability and their importance in impacting flood vulnerability. 12 spatial maps were generated from the environmental, social and coping capacity components using ArcGIS software.

2.1.1 Criteria for Physical Vulnerability Mapping

Physical factors have a vital role in determining flood vulnerability since they directly influence the extent and severity of flooding. Topography, elevation, slope and land use are key physical factors that affect flood behavior and its impacts. This study selected four physical vulnerability criteria such as slope, elevation, land use and land cover, and precipitation intensity for assessing flood vulnerability.

Flood damage and vulnerability are closely linked to specific types of land cover. In this study, Landsat 8 imagery was utilized to create a map of LULC (Figure 3). A hybrid classification approach was employed, combining both unsupervised and supervised techniques to accurately classify five distinct land use and land cover categories: water bodies, vegetation, settlements, agricultural lands, and bare lands.

Elevation and slope play a critical role in assessing flood vulnerability, as lower-lying, flat areas with gentle slopes are generally more prone to compared to higher elevations and steep slopes. The spatial criterion layers for elevation and slope were generated using six raster images of the modified Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) (Figure 3).

Precipitation intensity is another key factor influencing flood vulnerability, with areas experiencing higher precipitation being more vulnerable than those with lower precipitation levels. The rainfall intensity map was developed using average monthly rainfall data collected from the rainfall dataset of CHIRPS.

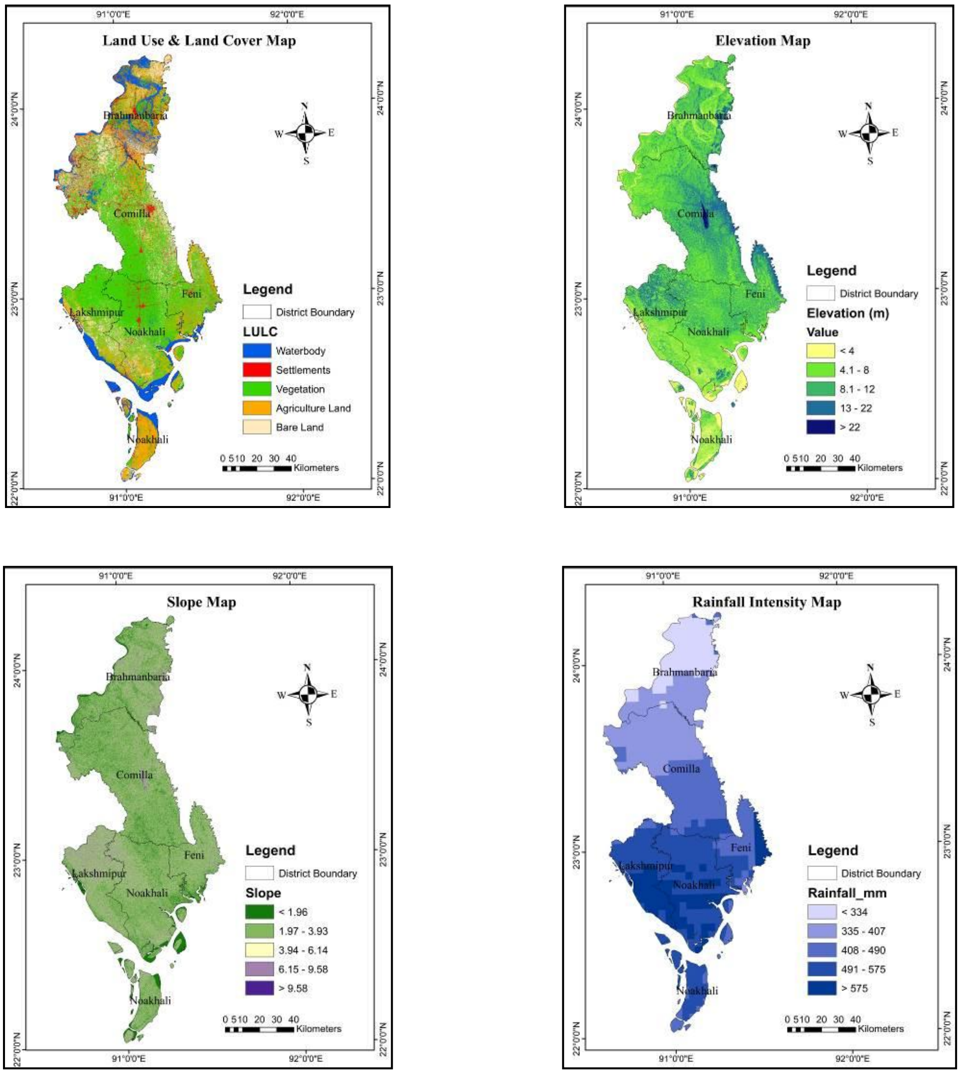

Figure 3: Physical vulnerability criterion layers of LULC, elevation, slope, and rainfall intensity

2.1.2 Criteria for Social Vulnerability Mapping

Social vulnerability is the incompetence of communities and organizations to successfully address the harmful effects of hazards, in terms of social and institutional components. The vulnerability to floods is influenced by several social criteria that alter the negative impact of the floods. The social vulnerability map of the study area was created by considering population density, disabled population, households, and slum and floating households components.

Higher density of people often face increased physical and psychological challenges during flood events, which makes population density a vital component for social vulnerability. Moreover, evacuating a densely populated area requires higher resources and manpower. The population density layer was developed in ArcGIS using census data from the BBS report of 2022 (Figure 4).

Individuals with disabilities often suffer highly physically and psychologically during floods in accessing flood shelters and evacuation routes. The data on the percentage of disabled people living in each district, collected from the BBS report, is used in this study.

A larger number of households in flood-prone regions increases exposure and burdens limited resources such as shelter, emergency response, and evacuation procedures.

The proportion of households in the slum and floating settlements is also a major contributor to flood vulnerability. Such houses are usually located within the low-lying flood-prone regions that have poor housing facilities, drainage systems, and access to basic services. Higher percentages of these households indicate a lack of permanent and secure housing. As a result, they become more susceptible to displacement, property damage, and loss of livelihoods during floods. The data for the number of households, households in slums and floating areas were taken from the 2022 population census of the BBS report.

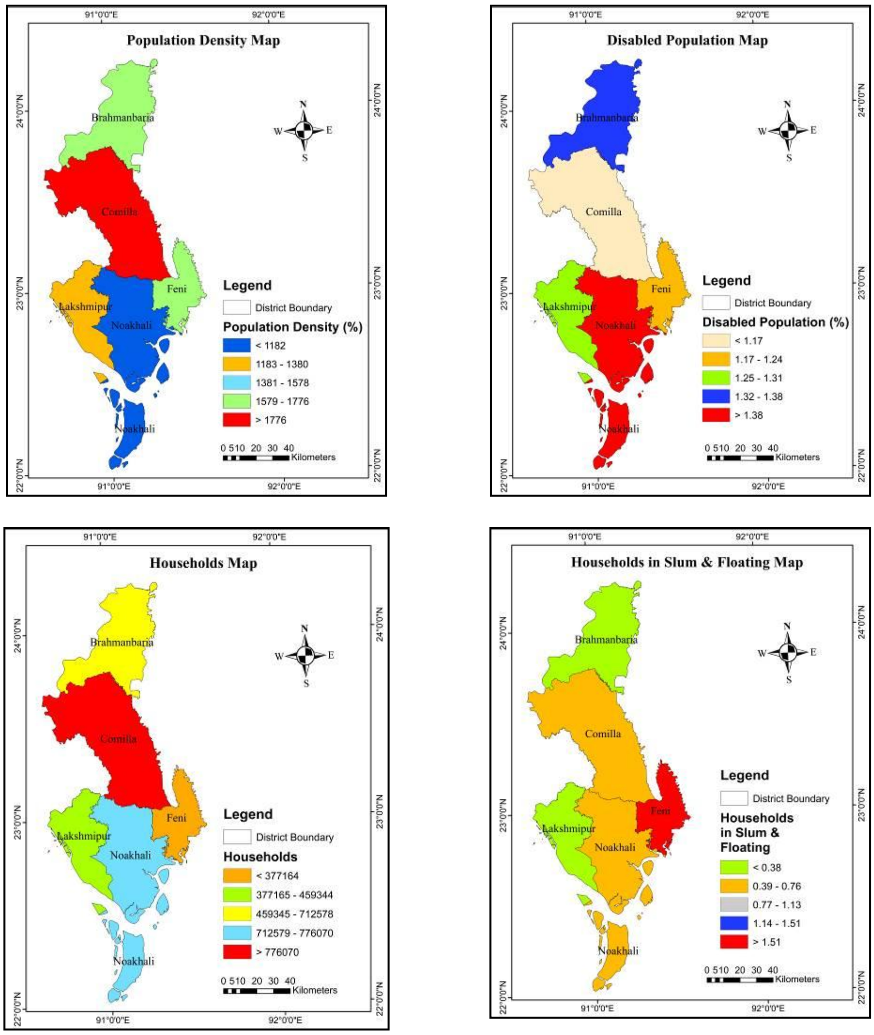

Figure 4: Social vulnerability criterion layers of population density, disabled population, households, and households in slums and floating

2.1.3 Criteria for Coping Capacity Mapping

The ability to manage and mitigate the impacts of calamities like floods by the proper use of available skills, knowledge, and resources is known as coping capacity. The adverse effects of disasters, particularly floods, can be reduced by increasing resilience and improving recovery efforts. In this study, four key coping capacity criteria, such as literacy rate, employment rate, number of hospitals, and number of growth centers, were selected to map the condition of coping capacity of this region (Figure 5).

Higher literacy rates help in raising better awareness and preparedness to make proper decisions in case of floods. The economically disadvantaged groups tend to lack access to resources, including flood-resistant infrastructure, insurance, and evacuation means, making the employment rate an important factor in coping capacity. Moreover, the number of hospitals and growth centers also reduces the consequences of floods. These factors determine areas with different levels of coping capacity and tailor interventions in reducing vulnerability to floods.

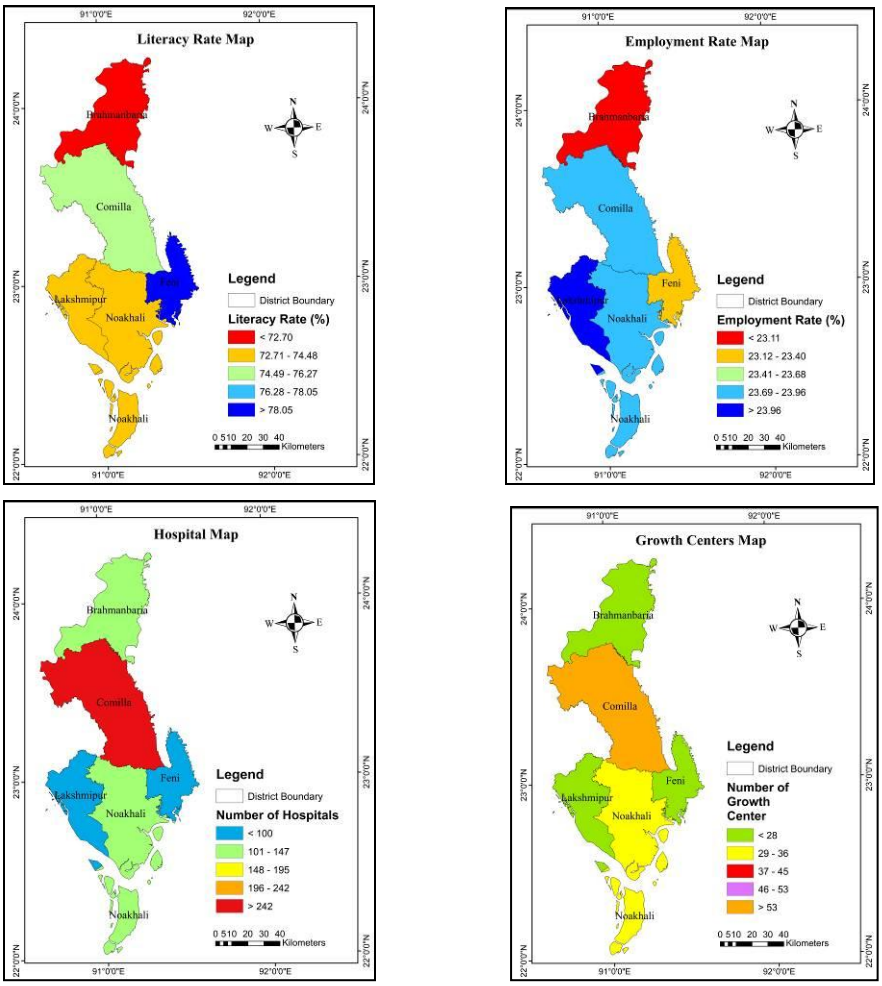

Figure 5: Coping Capacity criterion layers of literacy rate, growth centers, hospitals, and employment rate

2.2 Alternative Ranking and Standardization Criterion Layer

Each spatial criterion layer was reclassified using ArcGIS using the vulnerability levels (ranging from 1 to 5) (Table 2). Vulnerability ranks of 1 to 5 represent very low to very high vulnerability levels, respectively. The ranking of the alternatives was included in accordance with contribution to vulnerability, following AHP (Analytic Hierarchy Process) principles, and the weighted overlay procedure was implemented by ArcGIS. Subsequently, standardization was applied to convert ranked values of each spatial criterion layer into a common scale ranging from 0 to 1, to allow the combination of various criteria to assess the vulnerability through AHP. The standardization ensures consistency and comparability across various spatial layers to assess flood vulnerability.

2.3 Weighting of the Criteria

Pairwise comparison of the criteria was done following the scale of relative importance proposed by Saaty (Saaty, 2008). Expert judgment was utilized to construct the comparison matrix. The indicators were rated on a 1-9 scale, with 1 representing equal and 9 extreme preferences. Then the weight of each criterion was provided by the normalized principal eigenvector of the given matrix.

Table 2: Alternative ranking scheme based on the contribution to the risk of flood disaster

Component	Criteria	Ranking (Based on Vulnerability)				
		Very Low (1)	**Low (2)**	**Moderate (3)**	**High (4)**	**Very High (5)**
Physical Vulnerability	Elevation (m)	<4	4.1-8	8.1-12	13-22	>22
	Slope (%)	<1.96	1.97-3.93	3.94-6.14	6.15-9.58	>9.58
	Precipitation (mm)	<334	335-407	408-490	491-575	>575
	Land use and cover	Waterbody	Settlements	Vegetation	Agricultural Land	Bare Land
Social Vulnerability	Population Density	<1180	1183-1380	1381-1578	1579-1776	>1776
	Household	<377164	377165-459344	459345-712578	712579-776070	>776070
	Disabled Population (%)	<1.17	1.17-1.24	1.25-1.31	1.32-1.38	>1.38
	Households in Slum & Floating (%)	<0.38	0.39-0.76	0.77-1.13	1.14-1.51	>1.51
Coping Capacity	Literacy Rate (%)	<72.70	72.71 - 74.48	74.49 - 76.27	76.28 - 78.05	>78.06
	Hospital Access	<100	101-147	148-195	196-242	>242
	Employment Rate (%)	<23.11	23.12-23.40	23.41-23.68	23.69-23.96	>23.96
	Growth Center	<28	29-36	37-45	46-53	>53

2.4 Consistency Ratio (CR) Testing

In order to assess the consistency of the weighting of the factors, Consistency Ratio (CR) was determined as the ratio of the Consistency Index (CI) to the Random Index (RI). A CR value ≤ 0.10 was taken to be acceptable which implies reliable pair-wise comparison. Weights that exceeded this number were further recalculated until a level of consistency was achieved thereby rendering weight assignment strong.

The maximum eigenvalue (λmax) is calculated using the equation,

$$\lambda = E / K \qquad (2)$$

where E represents the weighted sum and K is the number of criteria.

The Consistency Index (CI) is then determined using the formula,

$$CI = (\lambda max - K) / (K - 1) \qquad (3)$$

The Consistency Ratio (CR) is computed as

$$CR = CI / RI \qquad (4)$$

where RI denotes the Random Index, which depends on the number of elements being compared.

2.5 Vulnerability Assessment

The weighted overlay tool in ArcGIS is used for mapping the physical vulnerability, social vulnerability, and coping capacity spatial layers, using the calculated weights by AHP (Table 3). The indices of these layers were computed and the indices were categorized into five classes: very low, low, moderate, high, and very high. These layers were reclassified to a scale of 1 to 5 following the alternative ranking values to use these layers for calculating the overall vulnerability maps. After that, the vulnerability without coping capacity index was calculated by multiplying the physical and social vulnerability indices. Then, the vulnerability integrating the coping capacity map was created by dividing the product of the physical and social vulnerability indices by the coping capacity index using the raster calculator tool of ArcGIS. The maps of vulnerability with and without coping capacity were also categorized into five classes: very low, low, moderate, high, and very high. The generated maps represent clear and meaningful vulnerability levels that identify the susceptible areas to floods.

Table 3: Weighting the criteria using AHP

Component	Criteria	Weight	Consistency Ratio (CR)
Physical vulnerability	Elevation	0.27	0.09
	Slope	0.18	
	Precipitation	0.49	
	Land use and cover	0.06	
Social Vulnerability	Population Density	0.19	0.04
	Household	0.07	
	Disabled Population	0.43	
	Households in Slum & Floating	0.31	
Coping Capacity	Literacy Rate	0.19	0.04
	Hospital Access	0.31	
	Employment Rate	0.43	
	Growth Centre	0.07	

3. RESULTS AND DISCUSSION

3.1 Physical Vulnerability Mapping

A physical vulnerability map of floods was generated and categorized into five classes (Figure 6). The map has shown that almost 85% of the area of study is in the moderate to very high vulnerability classes, and only 15% is in very low or low vulnerability. The south-western and southern areas are categorized as having a high vulnerability to flood impacts because of low elevation and low slopes. Southern Lakhsmipur and Noakhali, and eastern Feni among the five districts, are the most physically vulnerable to floods, with their topography contributing to it. Because of the steeper slopes and elevation, the Brahmanbaria district is less vulnerable. The Comilla district showed moderate physical vulnerability. These differences in physical vulnerability bring out the significance of topography in managing the risks of floods in different districts.

3.2 Social Vulnerability Mapping

The social vulnerability map discloses that communities situated in Feni, Noakhali, and Brahmanbaria districts are classified as high and very highly vulnerable areas (Figure 6). These areas cover 56% of the entire study area, primarily due to high population density and the large number of households, which increases exposure and low resilience during floods. Conversely, low and very low socially vulnerable zones occupy 13% of the study area situated in the Lakshmipur district. Such regions are described as having a better socio-economic status, lower population density, and fewer households, which leads to a decreased vulnerability level.

3.3 Coping Capacity Mapping

The coping capacity map was created by classifying the calculated index values into five levels. As shown in Figure 6, the moderate to very high levels of coping capacities encompass 41% of the study area, which includes the Brahmanbaria, Lakshmipur, and Feni districts. These areas are more affluent, have better employment, and education level. On the contrary, low to very low coping capacity areas occupy 59% of the observed area, mostly in the Comilla and Noakhali districts. Such regions are characterised by low educational attainment, deficiency of access to economic opportunities, and low income levels and therefore limit their capacity to use productive coping measures during floods.

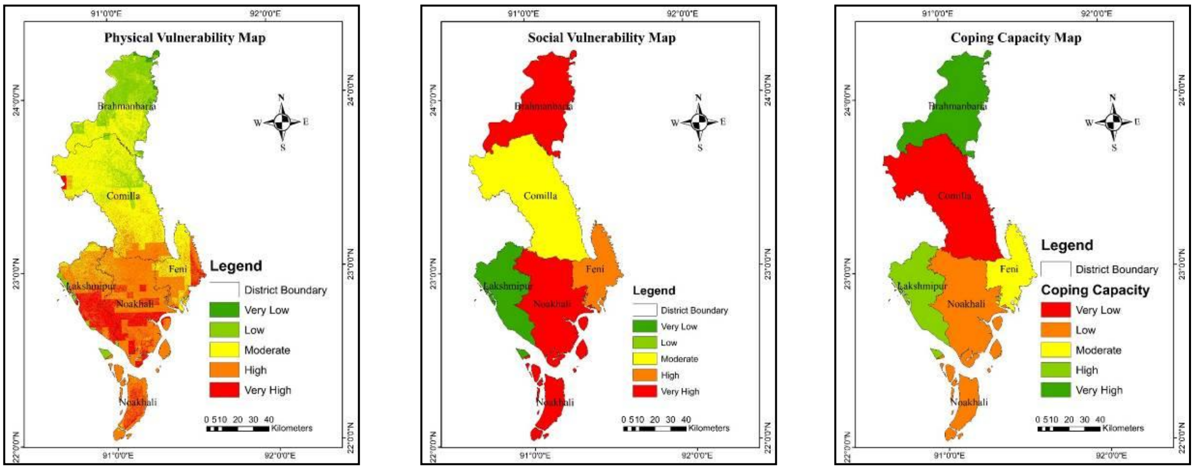

Figure 6**:** Physical vulnerability, Social vulnerability, and coping capacity map exhibiting spatial patterns and the degree of social vulnerability to floods

3.4 Vulnerability without Integrated Coping Capacity

Vulnerability to floods without integrated coping capacity was assessed by multiplying the physical and social vulnerability indices, which were then categorized into five classes (Figure 7). The map shows that the extremely vulnerable area occupies 2% of the study area, which lies in the south and south-western areas of Comilla and Noakhali districts (Table 4). These areas are characterized by low elevation, gentle slopes, dense populations, a high concentration of housing, and intense rainfall, which is making them more vulnerable to floods. The northern parts of Comilla and Noakhali were moderately to highly vulnerable, whereas the eastern part of the Feni district is found to be moderately vulnerable. Brahmanbaria, Lakshmipur, and the western part of the Feni districts are termed as low to very low vulnerable areas, which is almost 37% of the total area.

3.5 Vulnerability with Integrated Coping Capacity

A vulnerability index that was composed of a coping capacity was created by multiplying the physical and social vulnerability indices and then dividing the value by the coping capacity indices. This index of coping capacity integrated vulnerability was classified into five levels, and the map in Figure 7 was obtained. In the map where the coping capacity was not integrated, the southern parts of Comilla and Noakhali districts were extremely vulnerable (2% area). With the incorporation of the coping capacity, these areas are now moved from extremely high to very high vulnerability areas, reducing extreme vulnerability to 0%. In contrast, Feni was classified as a low-vulnerability area previously, but after adding coping capacity, it moved to the moderate class, which indicates the relatively lower coping capacity of this district.

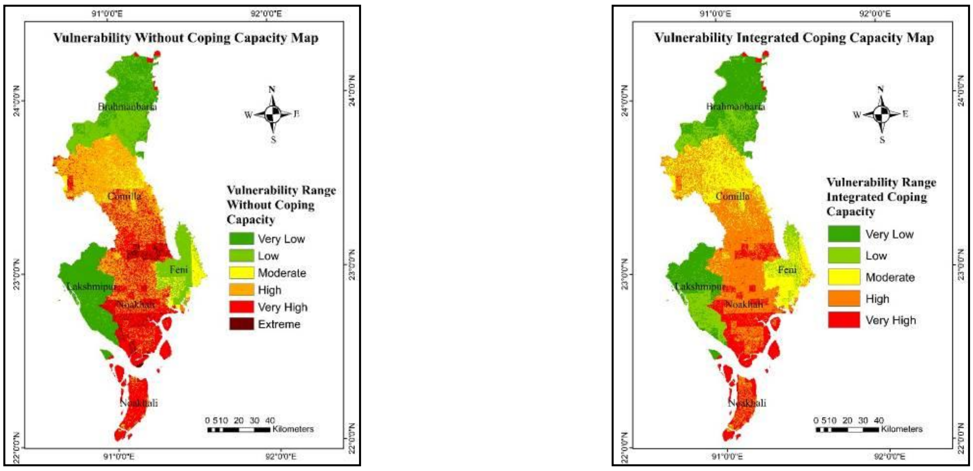

Figure 7: Vulnerability without and with integrating the coping capacity map

Table 4: Percentage of area across vulnerability catagories with and without coping capacity incorporating coping capacity

Vulnerability Class	Without Coping Capacity (%)	With Coping Capacity (%)
Very Low	20	21
Low	17	13
Moderate	5	19
High	26	32
Very High	30	15
Extreme	2	0

3.6 Validation

A spatial validation was performed using the observed economic damage map (Figure 8) from the 2024 flood event. The damage was calculated in BDT crore. The spatial pattern of damages shows a clear correspondence with the modeled vulnerability distribution, where high-damage districts such as Noakhali and Comilla align with the high and very high vulnerability zones in the integrated coping capacity map. Conversely, Brahmanbaria and Lakshmipur, which had minimal economic losses in the flood, correspond to low vulnerability areas. This strong spatial agreement indicates that the developed AHP-GIS based vulnerability model effectively represents the real flood impact conditions across the study area.

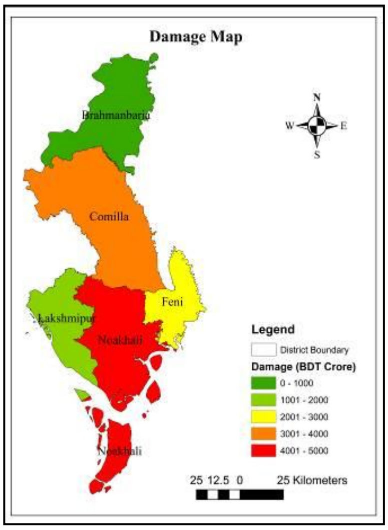

Figure 8: Damage map of flood 2024

4. CONCLUSION

In this study, the susceptibility of Eastern Bangladesh to the 2024 flood was assessed using an Analytic Hierarchy Process (AHP) based geospatial multi-criteria evaluation model, incorporating parameters related to physical, social, and coping capacities. The results showed that low elevation, low slope, and high precipitation intensity are the main factors behind physical vulnerability. Nearly 85% of the study area was rated as moderate to very high physical vulnerability, with the Noakhali and Lakshmipur districts being the most susceptible because of the topographic and hydrological features. Social vulnerability analysis revealed that Noakhali and Brahmanbaria were classified as high to very high vulnerability regions. The population density, existence of slum households, and socio-economic limitations increase the risk in these areas. Conversely, Lakshmipur had a better socio-economic status and showed lower social vulnerability. Coping capacity mapping highlighted the importance of resources like literacy, hospitals, growth centers, and employment in boosting resiliency. High coping capabilities were recorded in districts such as Brahmanbaria and Lakshmipur, which was translated into low overall vulnerability. Nonetheless, Comilla and Noakhali districts were still hampered by low coping capacities, which reduced their capacity to reduce the risk of floods. The coping capacity included within the vulnerability assessment provided a more subtle insight into the risk of floods in the area under study. High coping capacity significantly decreased the degree of vulnerability in the extremely vulnerable areas, especially in the southern parts of Noakhali and Comilla. This emphasized the need to incorporate the effects of resilience-building measures into the flood risk management plans to mitigate the effects of future floods. The outcomes can be used by policy makers and planners to prioritize interventions within the high-risk areas, to strengthen the socio-economic resilience, and to initiate sustainable flood mitigation measures. These maps assist in identifying priority zones for flood mitigation measures such as drainage improvement, flood shelter allocation, embankment strengthening, and regulation of development in high-risk areas. In addition, areas characterized by high vulnerability and low coping capacity can be prioritized for community-based preparedness programs, early warning dissemination, and resilience-building initiatives. Under future climate change scenarios, increased rainfall intensity and rapid urban expansion are expected to exacerbate flood vulnerability in south-eastern Bangladesh. The proposed AHP–GIS framework can be adapted by incorporating projected rainfall from climate models (e.g., CMIP6) and future land-use change scenarios to support long-term flood risk planning. Further studies ought to build on this by incorporating the aspect of climate change projections and long-term hydrology information to work out the adaptive measures that can be taken to help deal with the changing phenomenon of flood risks in Bangladesh.

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DECLARATION OF USE OF AI

The data analysis, methodology, results, interpretations, and conclusions are entirely the work of the authors. No AI tools were used to generate data, perform analysis, or influence scientific decisions.

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