

FLASH FLOOD HAZARD ASSESSMENT USING A GIS-INTEGRATED FUZZY AHP-MCDA TO INFORM NATURE-BASED SOLUTIONS IN FENI AND NOAKHALI, BANGLADESH

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ABSTRACT

Bangladesh is one of the world's most flood-prone countries, with escalating flash flood events in recent decades. In August 2024, more than 5.8 million people were affected by flash floods due to heavy monsoon rainfalls and upstream inflow in eastern Bangladesh. Noakhali and Feni were among the most badly affected districts, with more than 502,000 people displaced into 3,403 emergency shelters and approximately 296,852 hectares of cropland submerged, leading to major agricultural and fisheries losses. This study identifies flash flood susceptibility by integrating Fuzzy Analytical Hierarchy Process (FAHP) and GIS-based Multi-Criteria Decision Analysis (MCDA) to find out hazard-prone areas in Noakhali and Feni and suggest Nature-based Solutions (NbS) for mitigation. Physical and environmental factors such as elevation, slope, drainage density, distance to river, rainfall, geology, and soil were weighted through expert-based fuzzy pairwise comparisons to obtain a Flood Hazard Index (FHI) through weighted overlay in ArcGIS Pro software. The region was categorised into five risk zones from very high to very low. Results indicate that approximately 28% of Noakhali (Subarnachar, Companiganj) and 34% of Feni (Fulgazi, Parshuram) are at high risk, affecting about 1.2 million individuals. The following NbS are recommended: wetland restoration, afforestation, vegetated bunds, riparian buffers, and floating agriculture. Mangroves can reduce surge speed by 90%, wetlands reduce runoff and enhance recharge, and reforestation reduces runoff by 25% along with erosion by 40%. In downstream areas like Noakhali and Feni, these can provide climate-resilient alternatives to concrete infrastructure. In addition, the Feni River closure was demolished, which increased flooding, highlighting the urgent need to reinstate the structure alongside NbS. Once and for all, this study provides a replicable FAHP-GIS model for ecosystem-based flood management and resilience planning in alignment with SDG 13.

Keywords: *Flash Flood; Fuzzy Analytical Hierarchy Process (FAHP); Nature-Based Solutions (NbS); Multi-Criteria Decision Analysis (MCDA); Flood Hazard Index (FHI)*

1. INTRODUCTION

Flooding is one of the most recurrent and devastating natural hazards globally, posing severe challenges to human settlements, agriculture, and ecosystems, particularly in low-lying deltaic regions. Bangladesh is globally known as one of the most flood-prone countries due to the country's low-lying shape, vast river systems, and its densely populated deltaic environment (Gazi et al., 2019; Sarker et al., 2025). This perennial risk is increasing worldwide: extreme flood events with rising intensity, frequency, and continued duration are a critical outcome of anthropogenic climate change and intermittent transboundary water flows (Rana et al., 2024; Uddin et al., 2025). Among the most destructive of these events are flash floods, which every year represent a serious threat to food security, community displacement, and public health throughout the country (Uddin et al., 2025). How terrible this hazard was abundantly shown in August 2024, when severe flash floods, caused by excessive monsoon rains and massive upstream inflow, impacted roughly 5.8 million people in the eastern part of Bangladesh, calling for urgent and accurate risk mitigation strategies (ActionAid, 2024). The coastal districts of Noakhali and Feni, which are in the high-risk coastal and transboundary zones, were disproportionately affected by the event in August 2024, with approximately 296,852 hectares of cultivated lands submerged and more than 502,000 people being transferred to evacuation centres (ActionAid, 2024). The unique hydro ecological conditions add to this susceptibility: Noakhali's low-lying and coastal topography renders it vulnerable to multi-hazards such as storm surges, tidal and Riverine flooding (Sarker et al., 2025), while Feni is complicated due to its location on the Muhuri River basin, which makes it prone to transboundary water releases (Shome & Afroj, 2019). Effective disaster risk reduction (DRR) calls for a shift from reactive to predictive modelling, which makes the process of susceptibility mapping of these space areas quickly and accurately an urgent need (Uddin et al., 2025; Uddin & Matin, 2021).

An important gap exists in the existing literature about integrated high-resolution hazard assessment for these critical areas. While prior research has already given valuable knowledge of regional flood hazard through the use of Geographic Information Systems (GIS) with the standard Analytical Hierarchy Process (AHP) or Machine Learning (ML) models (Hasan et al., 2025; Sarker et al., 2025), these approaches often struggle to fully capture the inherent subjectivity and epistemic uncertainty in expert-based parameter weighting, a limitation the Fuzzy Analytical Hierarchy Process (FAHP) is designed to reconquer (Choudhury & Yabar, 2025). Furthermore, most susceptibility assessments, although important for the hazard zoning (Gazi et al., 2019; Uddin & Matin, 2021), do not offer a direct connection to implementable, site-specific climate adaptation strategies, such as Nature-Based Solutions (NbS). Therefore, this study fills the important research gap to implement a robust FAHP-MCDA integrated with GIS for holistic assessment of flash flood susceptibility, specifically targeting the most critically affected upazilas Hatiya, Noakhali Sadar, and Begumganj, in Noakhali and Chhagalnaiya, in Feni, and combining the results with a framework for NbS.

This study has been guided by three fundamental questions: What are the spatial patterns of flash flood hazard in Noakhali and Feni districts of Bangladesh? What are the most influential contributing physical and socio-environmental factors in the risk? And last, how can Nature-Based Solutions be best incorporated in a flood management framework for the identified high-hazard zones? Accordingly, the main aims of the current study are to evaluate flash flood hazard by FAHP-MCDA combined with GIS, to identify and categorise the region into different hazard zones considering a fuzzy expert-driven weighting scheme, and to specify some specific and resilient Nature-based Solutions for mitigation. This study used the FAHP to derive more reliable weights for seven flood conditioning factors that are then combined in the GIS-based Multi-Criteria Decision Analysis to create the Flood Hazard Index (FHI). The main results are a validated map of hazard classifying upazilas into different hazard zones, which will predict Hatiya as a Very High hazard area, Noakhali Sadar and Chhagalnaiya as High hazard area, and Begumganj as Moderate hazard area, which will lead to targeted recommendations for NbS, such as wetland restoration, afforestation, and floating agriculture.

2. LITERATURE REVIEW

Flooding is the world's leading hydro-meteorological natural disaster (HND) in terms of the economic and infrastructural losses it causes, a condition that is felt most severely by low-lying developing countries such as Bangladesh (Choudhury & Yabar, 2025). The country's deltaic setting, low elevation, and immense river systems make it highly vulnerable to recurrent and devastating flood events, which have made it necessary to conduct continuous mapping efforts on regional scales that can contribute to national disaster preparedness (Gazi et al., 2019; Rana et al., 2024). Compounding this inherent risk, climate change is adding to a worrisome trend of more frequent and more intense flooding caused by changing rainfall patterns and irregular transboundary river flows (Rana et al., 2024; Uddin et al., 2025). Historical evidence supports that the past events in the overall Chattogram Division had been devastating, where severe flash floods were observed frequently due to the heavy monsoon rains and the releases of waters from the upstream (Shome & Afroj, 2019). The worsening of these hazards demands sophisticated, data-driven assessment approaches that contribute to sound disaster risk reduction (DRR) strategies (Uddin et al., 2025).

The study areas - Noakhali and Feni districts - are representative of the complex and multiple-hazard environment of coastal and transboundary Bangladesh. As the location of the study area, Noakhali is exposed to multi-hazard threats due to coastal flooding hazard, storm surge and riverine inundation hazard (Sarker et al., 2025), which is validated by the regional context (Shome & Afroj, 2019). This coastal environment is also vulnerable to multi-hazard events triggered by tropical cyclones, namely extreme precipitation and salinity intrusion, which is the rationale for the need for robust FAHP methods to analyse these complex and uncertain risks (Sarker & Adnan, 2024). The topography, mainly low-lying land and geographical height from 18 to 32, is the main physical factor of vulnerability (Hasan et al., 2025; Sarker et al., 2025). Feni district is situated in the transboundary Muhuri River basin, but its flash flood vulnerability is further exacerbated by the upstream release of water (Shome & Afroj, 2019). Beyond physical dangers, population density and dependence on sensitive sectors such as agriculture increase the socio-economic vulnerability. This complexity justifies the integrated approach of risk mapping, which requires the integration of physical factors and social factors, such as the housing parameter used in this study, to obtain a detailed risk profile that can be targeted for intervention (Rana et al. 2024).

The Analytical Hierarchy Process (AHP) has been used as a standardization approach and systematic method in Multi-Criteria Decision Analysis (MCDA) to quantify the relative importance of the flood conditioning factors in Bangladesh (Hasan et al., 2025; Rana et al., 2024). AHP can organize the complex decision problems and translate qualitative expert judgments into quantitative weights as long as the Consistency Ratio (CR) is within the acceptable range of 0.10. However, the conventional AHP technique is based on crisp (non-fuzzy) numerical inputs, which is a great disadvantage when modelling the inherent vagueness and uncertainty associated with expert knowledge and the complexity of natural phenomena (Choudhury & Yabar, 2025). To make the model more reliable and robust, the Fuzzy Analytical Hierarchy Process (FAHP), which is a combination of fuzzy set theory and the AHP, has become a superior method that is better at dealing with the subjectivity in the comparisons of the parameters (Choudhury & Yabar, 2025). While this methodological approach is highly appropriate in the coastal zone, multi-hazard and climate change risks bring a high degree of ambiguity and uncertainty into the assessment process (Sarker & Adnan, 2024).

It is vitally important that in the successful application of GIS-based MCDA, the influential factors are chosen and weighted appropriately. Across the region studies for Bangladesh, the list of vulnerability factors was the same: Elevation and Rainfall are continually cited as the most influential factors because of the low-lying nature of Bangladesh and monsoonal precipitation (Choudhury & Yabar, 2025; Shome & Afroj, 2019). Other basic geographic and hydrological variables are always used in hazard modelling, such as Slope, Drainage Density, and Distance from River, which are an indication of topographic control and closeness to flood sources (Hasan et al., 2025; Shome & Afroj, 2019). Furthermore, studies have also been conducted using more advanced topographic proxies such as Topographic Wetness

Index (TWI) and Height Above Nearest Drainage (HAND) (Rana et al., 2024), showing the need for accurate topographic representation. The significance of Land Use/Land Cover (LULC) is also confirmed in consideration of its role in reflecting the surface runoff and infiltration capacity (Sarker et al., 2025). Finally, including social aspects, such as the "housing" parameter used here, helps move from strictly hazard-based to a comprehensive flood risk map for actionable planning (Rana et al., 2024).

To build climate resilience, long-held, highly disruptive, 'hard' engineering solutions need to be replaced by sustainable ecosystem-based solutions. Nature-Based Solutions (NbS) use ecological processes to deliver effective flood mitigation, in combination with environmental co-benefits. Particularly for the coastal and flash flood-prone areas of Bangladesh, specific NbS are identified to be suitable. For example, coastal afforestation, especially mangrove restoration, has been found to be very effective with the ability to reduce storm surge velocity by up to 90% (Mubeen et al., 2021). Similarly, wetland restoration for strategic use of reducing surface runoff and improving groundwater recharge, floating agriculture as a resilient livelihood solution, and more practical adaptation measures are examples of adaptation measures that were identified (Mubeen et al., 2021). The general purpose of overall hazard zonation is to allow a shift from a mere mapping of risk to the actual implementation of preparedness and mitigation-related actions, such as planning of resilient infrastructure or flood shelters, which save lives and protect assets (Uddin & Matin, 2021).

While the literature basis is sound (high flood vulnerability of coastal zone (Sarker et al., 2025), FAHP to deal with uncertainty (Choudhury & Yabar, 2025), consistency of key conditioning factors (Hasan et al., 2025) a key multi-faceted gap still exists. Still, no study has integrated the FAHP-MCDA integrated GIS approach to Noakhali and Feni districts to capture the complex multi-factorial risk from socio-environmental data, such as housing, while also relating the resulting susceptibility map to a specific, actionable NBS-based disaster risk reduction framework. This research directly addresses this deficiency by producing a methodologically advanced and highly granular assessment, which was validated against the severe August 2024 flood event in order to inform sustainable land use and climate adaptation planning in these two highly exposed districts.

3. METHODOLOGY

3.1 Study Area

This study was conducted on Noakhali and Feni Districts, which are two very flood-prone areas in the southeastern coastal and transboundary area of Bangladesh. Noakhali Coast, between the latitudes of 22°26'–22°56' N and the longitudes of 90°24'–91°52' E, is located in the northeastern part of the Bay of Bengal. The coastline spans about 75 km, consisting of muddy to sandy shores along mudflats of up to 4 km width at the intertidal level. The southwestern part is dominated by intense coastal erosion caused by high-energy discharges from the Ganges-Brahmaputra-Meghna system, while active land accretion is taking place in the southeastern part. The region has a tropical monsoon type climate where the temperature ranges from 25.5°C to 31.5°C in summer and 10.6°C to 25.8°C in winter. Peak rainfall is more than 3400 mm in July, and the monsoon season (April-October) has led to frequent flooding caused by tidal flows and riverine flooding (Shampa et al., 2025). Feni District is situated between 22°44'–23°17' N and 90°15'–91°35' E, which is an area of nearly 990 km². Around 68% of the district is rural in nature, with agriculture as the predominant livelihood. Major rivers Feni, Muhuri, and Kohua are navigable all year round and are important irrigation and transport routes.

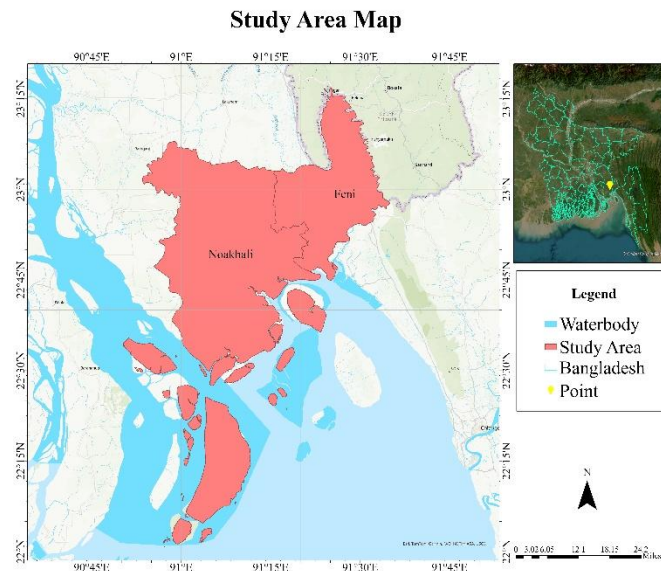


Figure 1: Study Area (Noakhali & Feni)

The district is in an area that receives 2600-2900 mm of rainfall per year, more than 80% being during the monsoon, which leads to flash flood conditions considering the low elevation, flat topographic features, and poor drainage infrastructure (Sarker et al., 2025). Historically, Feni has seen major flood events occurring, with the flash flood of August 2024 leading to massive internal displacement of more than 150,000 people and extended waterlogging and immobility in several upazilas.

3.2 Methodological Overview

This study used an integrated Fuzzy Analytical Hierarchy Process (FAHP) and Geographic Information System (GIS)-based Multi-Criteria Decision Analysis (MCDA) framework to analyse flash flood hazard in Noakhali and Feni Districts from the eastern part of Bangladesh. The approach is based on a combination of expert-based fuzzy weighting and spatial data processing to build up a comprehensive Flood Hazard Index (FHI) map. The model includes seven important flood-conditioning parameters, such as elevation, slope, drainage density, distance from river, distance from road, rainfall, and soil type, based on literature review, expert judgment, and regional geomorphological context.

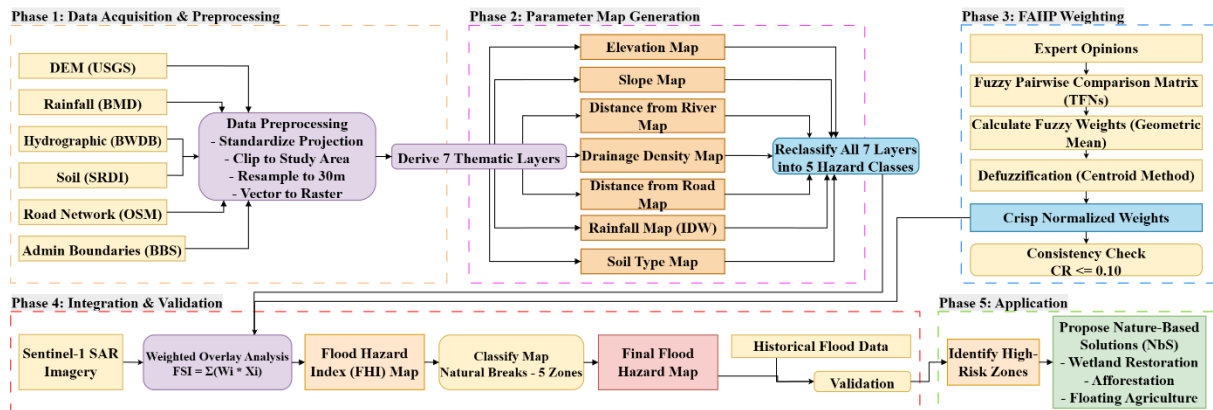


Figure 2: Graphical Methodology

3.2.1 Data Acquisition and Pre-processing

All datasets were standardized to a common projection (WGS 84, UTM Zone 46N), and clipped to the boundary of the study area. Pre-processing included mosaicking, resampling and conversion to raster of vector data to a 30-meter spatial resolution to ensure consistency across all layers.

3.2.2 Flood Hazard Parameters

3.2.2.1 Elevation

Elevation is a key basic topographic determinant of flood vulnerability as it separates low-lying floodplains from highland areas. The (Digital Elevation Model) DEM data were analysed in ArcGIS to produce the elevation map, which has values between 18 m and 32 m for Noakhali and Feni. Lower elevation areas surrounding river channels and coastal boundaries were found to be highly flood susceptible, while areas above 14 m had low flood susceptibility. Reclassify tool was used to classify elevation into five classes of Very Low (18-4 m), Low (5-9 m), Moderate (10-13 m), High (14-20 m), and Very High (21-32 m) based on the method of Lyu et al. (2018).

3.2.2.2 Slope

Slope controls the surface run-off velocity as well as the water accumulation potential. Steeper slopes promote quick runoff, and the flatter areas experience long inundation. Slope maps were created from the DEM using the spatial analyst - surface - slope tool in ArcGIS Pro. The slope values were reclassified into 5 hazard categories using the reclassify tool. (0.001° – 0.689°) very low, (0.690° – 1.47°) low, (1.48° – 2.94°) moderate, (2.95° – 6.0°) high, (6.1° – 9.767°) very high. Areas with low slopes ($<1^{\circ}$) were given higher hazard values because of slower runoff flow and higher water stagnation potential (Thanh Son et al., 2022).

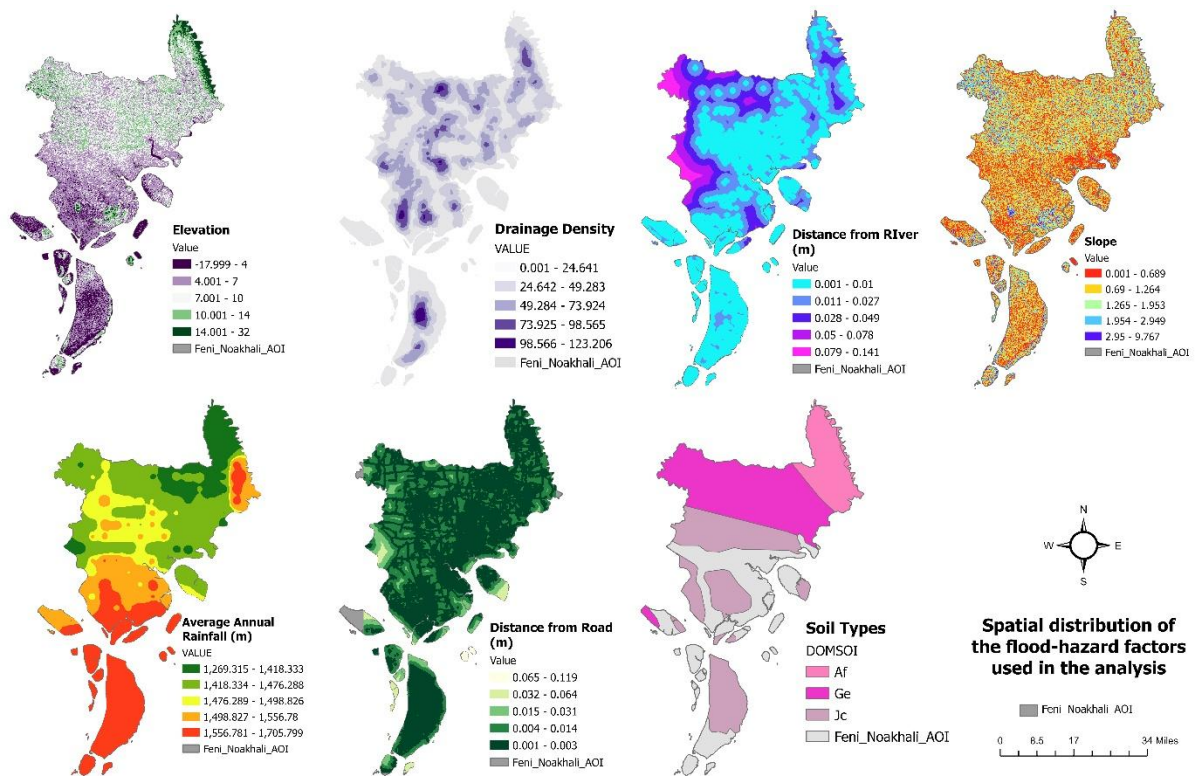


Figure 3: Spatial Distributions of the Flood Hazard Factors & Flood Hazard Map

3.2.2.3 Drainage Density

Drainage density is an expression of the total length of streams per unit of area and is an expression of surface runoff efficiency. Increased drainage density indicates increased flow accumulation and flood potential. The drainage density map was produced using a series of hydrological analysis tools on the DEM, including Fill, Flow Direction, Flow Accumulation, Stream Order, and Stream to Feature. The Line Density function was then used to determine drainage density (km/km²). The output was reclassified into five categories: Very Low (0.001 to 24.641 km/km²), Low (24.642 to 49.283 km/km²), Moderate (49.284 to 73.924 km/km²), High (73.925 to 98.565 km/km²), and Very High (98.566 to 123.206 km/km²).

3.2.2.4 Distance from River

Proximity to river channels has a great influence on flood exposure. The Distance from River map was calculated using the Euclidean Distance tool in ArcGIS using river shapefiles downloaded from the BWDB dataset. The raster output was reclassified as five hazard classes: Very Low (0.001-0.01 m), Low (0.011-0.027 m), Moderate (0.028-0.049 m), High (0.05-0.078 m), and Very High (0.079-0.141 m). Areas that lie nearer to rivers were given higher hazard scores because of the greater chances of overbank inundation during the monsoon events (Mojaddadi et al., 2017).

3.2.2.5 Distance from Road

Road networks change the permeability of the surface, sometimes decreasing the infiltration and increasing the accumulation of runoff. Using the OpenStreetMap road information, the Euclidean Distance tool was used to produce Distance from Road raster which was reclassified into five levels of hazard: Very High (0.001-0.003 m), High (0.004-0.014 m), Moderate (0.015-0.031 m), Low (0.032-0.064 m), and Very Low (0.065-0.119 m). Densely built-up areas and impervious surfaces near major roads were linked to a greater flood vulnerability because of poor drainage and sealing of the surface.

3.2.2.6 Rainfall

The event of flooding is directly caused by rainfall intensity by overwhelming natural and artificial drainage systems. Annual rainfall data (average 1269-1705 mm) were interpolated by using the Inverse Distance Weighted (IDW) method in ArcGIS to obtain a continuous spatial distribution map. Rainfall amount was divided into five hazard classes: Very Low (1269.315-1418.333 mm), Low (1418.334-1476.288 mm), Moderate (1476.289-1498.826 mm), High (1498.827-1556.780 mm), and Very High (1556.781-1705.799 mm). Higher rainfall zones, especially in upstream and coastal catchments, were considered as high-risk flood zones (Mojaddadi et al., 2017).

3.2.2.7 Soil Type

Soil type determines infiltration, water holding, and potential runoff. Soil data collected from SRDI were managed from vector to raster visualization and reclassified into five hydrological response classes according to texture and permeability (Feizizadeh et al., 2021). The dominant soil types of the study area were Ferric Acrisols (Af), Gleyic Fluvisols (Ge), and Calcaric Cambisols (Jc). Heavy clay-rich soils such as Ferric Acrisols have low infiltration rates, poor drainage, and high runoff; thus, they are easily susceptible to flood accumulation.

3.2.3 FAHP Weighting and Flood Hazard Index (FHI) Development

In order to incorporate the uncertainty in the expert judgment, the Fuzzy Analytical Hierarchy Process (FAHP) was used to identify the relative importance of each flood-conditioning parameter. Expert opinions obtained from hydrologists, geomorphologists, and GIS experts were used in the construction of a fuzzy pairwise comparison matrix according to Saaty's scale of nine points (Saaty, 1977). Triangular fuzzy numbers (TFNs) indicated the range of uncertainty of each judgment.

3.2.3.1 Pairwise Comparison Matrix Construction

Seven factors that were considered have been compared pairwise based on their contribution to flood occurrence.

Table 1: Pairwise comparison matrix for flood hazard contributing factors

Factors	Elevation	Slope	Drainage density	Distance from river	Rainfall	Distance from Road	Soil
Elevation	1	2	3	4	4	3	5
Slope	1/2	1	3	3	2	3	3
Drainage density	1/3	1/3	1	2	2	3	2
Distance to river	1/4	1/3	1/2	1	3	2	3
Rainfall	1/4	1/2	1/2	1/3	1	2	2
Geology	1/3	1/3	1/2	1/2	1/2	1	2
Soil	1/5	1/3	1/2	1/3	1/2	1/2	1
Sum	2.87	4.83	8.83	11.17	13	14.50	18.00

3.2.3.2 Fuzzy Weight Calculation

The geometric mean of each row was calculated and normalized to obtain fuzzy weights.

$$GM = \left[\prod_{i=1}^N a_{ij} \right]^{1/N} \quad (1)$$

3.2.3.3 Defuzzification

The fuzzy weights were converted into crisp values using the centroid method to obtain Final normalized weights. The normalized weight of each criterion was calculated by dividing each GM value by the sum of all the GMs.

$$W = \frac{GM}{\sum_{i=1}^N GM} \quad (2)$$

3.2.3.4 Consistency Verification

The Consistency Ratio (CR) was calculated, and the matrices with $CR \leq 0.10$ were accepted (Saaty, 1990).

$$CR = \frac{CI}{RI} \quad (3)$$

Where, CR = consistency ratio; RI = random index.

Consistency Index (CI) calculation: The Consistency Index (CI) was calculated using this formula:

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \quad (4)$$

Where CI = consistency index; λ_{max} = maximum eigenvalue of the matrix; n = dimension of the matrix. If $CR \leq 0.10$, the pairwise comparisons were considered consistent. When $CR > 0.10$, the comparison process is repeated until an acceptable level of consistency is achieved.

3.2.3.5 Weight Integration

The validated fuzzy weights were fed to the GIS based MCDA model for spatial overlay analysis.

3.2.4 Spatial Analysis & Flood Hazard Index

Each thematic layer was converted to raster format and standardized to a common resolution. The fuzzy weights as obtained from FAHP were used through the Weighted Overlay Analysis tool of ArcGIS software to calculate the Flood Hazard Index (FHI) as in Equation (1):

$$FHI = \sum_{i=0}^n (W_i \times X_i) \quad (5)$$

Where W_i denotes the normalized fuzzy weight of factor i , and X_i represents the standardized raster value of that factor.

3.2.5 Classification & Validation

The resultant FHI raster was classified into five flood hazard zones, i.e. Very Low, Low, Moderate, High, and Very High, by using the Natural Breaks (Jenks) method. Validation was performed using historical flood inundation information of the August 2024 flash flood event and Sentinel-1 SAR imagery.

4. RESULTS & DISCUSSIONS

The Flood Hazard Index (FHI) map (Figure 3) which is produced through the integration of FAHP weighted parameters in the GIS environment reveals a spatial differentiation in the flood susceptibility in the study area. The results show that Hatiya Island has a very high flood hazard potential followed by Noakhali Sadar and Chhagalnaiya which are located in high hazard zone, whereas Begumganj has a moderate flood hazard potential. These variations are determined by the topographic, hydrological, and climatic conditions, highlighting the high spatial differences in vulnerability in Noakhali District.

The most inundation prone island was Hatiya Island and its low-lying nature and exposure to multiple climate-related hazards makes this area the most vulnerable to climate change. These are riverbank erosion, cyclonic intensity, coastal flooding, saltwater intrusion, and unpredictable rainfall pattern (Rahman et al., 2025). The proximity of the island to the Bay of Bengal also increases its vulnerability to tidal surges and inundation by storms. Therefore, Hatiya is a high-risk area from the intersection between environmental fragility and human exposure.

Waterlogging has increased in the last few years in Noakhali District because of heavy rainfall and the rise of the water level of Muhuri River. According to a report by the District Weather Office, it had rained 71 mm in 24 hours, and this resulted in roads, agricultural fields, and fish ponds being inundated, and close to 2 million people were stranded due to this rainfall (Shafi, 2024). Furthermore, on September 1, 2024, according to the Noakhali Meteorological Office, 174mm of rain fell in 12 hours, worsening the mass flooding and waterlogging of low-lying areas (The Daily Star, 2025). Similarly, affected upazilas (Noakhali, Senbagh, Sonaimuri, Chatkhil, Begumganj, Kabirhat, Companiganj, Subarnachar) as a whole show the systemic weakness of the district in terms of disaster preparedness and water management (Shafi, 2025).

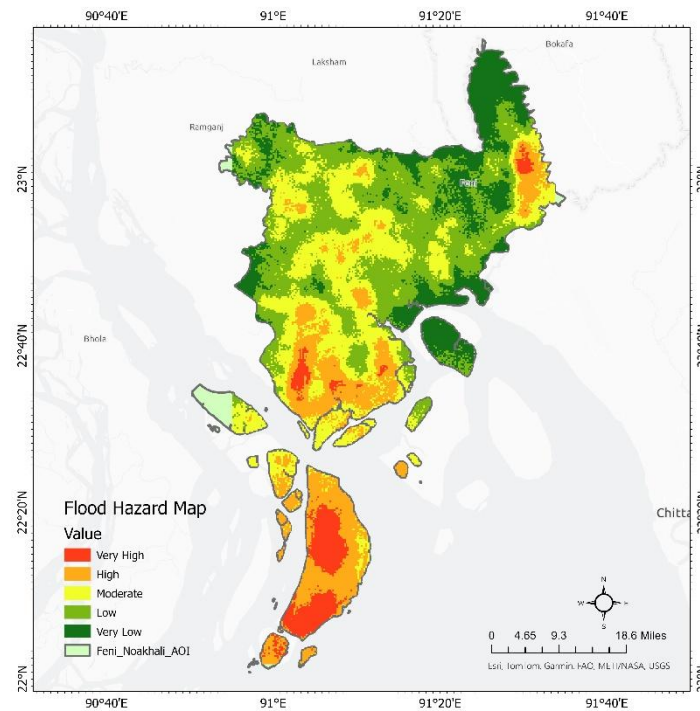


Figure 4: Flood Hazard Map (FHI) of Noakhali and Feni

Similarly, the Chhagalnaiya Upazila, with an area coverage of about 139.59 square km and a population of 187,156 has also witnessed recurrent flood events. In August 2024, massive amounts of rain and transboundary water flowing down from India caused local rivers to overflow, flooding villages and isolating communities. The agriculture-based economy of the area further increased its socioeconomic vulnerability in the time of flood events (Rahman et al., 2025). Combined, these results confirm that Noakhali District and specifically its coastal and low-lying areas are exposed to multi-dimensional flood risks - physical, economic, and social.

The resulting spatial distribution is a result of the strong interaction between topography, hydrology and climate variable. It was found that high rainfall intensity, low elevation, and dense drainage network caused flood risk in the study area, which was in agreement with other regional studies with the same data (Uddin and Matin, 2021). Coastal erosion, tides inundation, and decay of the river embankment of Feni and Meghna Rivers are increasing flood vulnerability in both districts. In addition, the landscape's attenuation capacity has been greatly diminished by anthropogenic factors including unfettered land conversion, conversion of wetlands to settlements, and loss of mangrove buffers. These findings underscore the need for an ecosystem-based approach to adaptation and a nature-based approach to mitigation to be integrated as part of regional flood management frameworks. As different from the spatially large-scale and recurrent flood hazards, this study aims to propose the incorporation of NbS as sustainable and adaptive mitigation measures. NbS take advantage of natural processes and ecosystem functions to increase flood resilience while delivering co-benefits for biodiversity conservation, livelihood security, and climate adaptation. Key interventions include mangrove afforestation on exposed coastal zones to buffer storm surges and fix sediments, wetland restoration in floodplain areas to enhance water retention and reduce runoff velocity, vegetated embankments and riparian buffer zones to stabilize riverbanks and filter surface runoff, and floating agriculture systems in areas prone to flood areas to maintain livelihoods during flood periods. These measures are consistent with the goals of Sustainable Development Goal (SDG) 13: Climate Action, with a focus on resilience building, through ecological restoration and community-centred adaptation. By combining NbS with the traditional structural approaches, flood management can shift away from reactive engineering solutions and towards a proactive, ecosystem-based resilience framework, which will guarantee long-term environmental sustainability and social well-being. Beyond rural and coastal settings, the Sponge

City concept has offered a transformative way of dealing with flood risk in urban and peri-urban areas. Initiated in China in 2014, this model envisions cities as living systems that absorb, store, purify and reuse water from rain, like a sponge. Instead of using only traditional "grey infrastructure" (concrete drainage, embankments or other forms of man-made engineering), the Sponge City approach incorporates "blue-green infrastructure" (wetlands, green roofs, rain gardens, bio-swales, permeable pavements, etc.) (Chan et al. 2018). For the flood-prone areas such as Hatiya, Noakhali and Chhagalnaiya, Sponge City principles can help to reduce a lot of runoffs, solve the problem of waterlogging in the cities and increase groundwater recharge. The model's efficacy in China, Singapore and other places in South East Asia clearly demonstrates its applicability in the deltaic cities of Bangladesh, where rapid urbanization and insufficient drainage aggravate the flood risk. Integrating such a model into regional development plans could therefore contribute to a more resilient, adaptive and sustainable urban landscape.

5. CONCLUSION

This research offers a thorough and methodologically sound evaluation of flash flood vulnerability in the Noakhali and Feni districts by employing the Fuzzy Analytical Hierarchy Process (FAHP) alongside GIS-based Multi-Criteria Decision Analysis (MCDA). The study integrated expert-derived fuzzy weights with spatially explicit hydro-geomorphological and socio-environmental parameters to delineate specific flood risk zones, identifying Hatiya Island and adjacent low-lying coastal areas as the most susceptible. The findings reveal the urgent necessity to exceed traditional structural flood control methods in favor of adaptive, ecosystem-focused resilience strategies. By Integrating Nature-Based Solutions (NbS) into flood risk management systems is a long-term solution to improve both the environment and community resilience. Restoring mangroves, rehabilitating wetlands, creating vegetated embankments, riparian buffers, and floating agriculture are all examples of interventions that can greatly improve the ability of the environment to absorb floods while also helping biodiversity and people's livelihoods. In addition, using Sponge City ideas in planning for cities and suburbs can help retain stormwater, lower surface runoff, and encourage groundwater recharge for long-term climate adaptation. Future research should focus on dynamic, data-driven modelling methodologies that incorporate time-series analysis, hydrological simulations, and participatory vulnerability assessments to predict accurately. Policymakers are strongly urged to institutionalize Nature-based Solutions (NbS) and hybrid green–grey infrastructure within national disaster risk reduction frameworks to promote climate-resilient, inclusive, and sustainable development in accordance with Sustainable Development Goal (SDG) 13: Climate Action. The FAHP–GIS framework proposed in this study offers a replicable, scalable, and policy-relevant model for data-informed flood management and adaptive land-use planning in flood-prone areas of Bangladesh and beyond.

DECLARATION OF USE OF AI

The authors used AI-powered tools solely for proofreading and grammatical refinement of the final manuscript. All conceptualization, methodology, and original drafting were conducted by the authors without the use of generative AI.

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