

SPATIAL ANALYSIS OF MULTI-HAZARD RISKS IN THE HALDA RIVER BASIN THROUGH AHP-BASED MODELING

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ABSTRACT

The Halda River Basin in southeastern Bangladesh is increasingly exposed to multiple natural hazards, particularly floods, cyclones, and landslides, which threaten ecosystems, agriculture, infrastructure, and local livelihoods. Given the basin's complex topography and climatic variability, understanding spatial patterns of hazard susceptibility is essential for effective disaster risk management and sustainable planning. This study integrates the Analytic Hierarchy Process (AHP) with Geographic Information System (GIS) techniques to map and assess multi-hazard susceptibility across the basin. Twelve environmental, hydrological, and topographic factors were standardized, weighted, and overlaid to generate individual hazard maps. The AHP-derived weights had consistency ratios below 0.05, indicating reliable expert-based evaluations. Key controlling factors include drainage density (weight = 0.38) for flood susceptibility, elevation (0.46) for cyclone susceptibility, and lithology (0.41) for landslide susceptibility. The individual hazard maps were integrated into a composite multi-hazard model using weights of 0.53, 0.33, and 0.14 for flood, cyclone, and landslide hazards, respectively. The resulting multi-hazard map classified the basin into five zones: very low (18.03%), low (19.95%), moderate (19.39%), high (24.10%), and very high (18.53%). Overall, approximately 61.63% of the basin falls within moderate to very high susceptibility areas, concentrated in floodplains and hilly terrain. These findings highlight the spatial interplay of hydrogeomorphic and land-use factors that amplify hazard risk. The AHP-GIS framework provides a scientifically robust and transferable approach for multi-hazard assessment, offering actionable insights for policymakers, planners, and environmental managers engaged in disaster risk reduction, climate resilience, and sustainable land-use management in the Halda River Basin and similar regions.

Keywords: MCDM; Multi-hazard Susceptibility; AHP; GIS; Halda River Basin.

1. INTRODUCTION

River basins are complex systems where hydrological, geological, and ecological processes interact, and their vulnerability is increasing under climate change (Padhiary, 2025). Bangladesh, located in the Ganges-Brahmaputra-Meghna delta, is highly exposed to multiple hydro-meteorological and geophysical hazards, including floods, cyclones, and landslides, due to its low-lying coastal plains and unstable hilly terrains (Alshayeb et al., 2024). The Halda River Basin (HRB) in southeastern Chittagong is ecologically significant as it supplies the world's only major source of fertilized Indian carp eggs (Akther et al., 2024). Its lower deltaic regions experience frequent flooding and cyclones, while upper hilly areas are prone to landslides, risks exacerbated by urbanization, deforestation, and land-use changes (Uddin et al., 2024). Understanding the interactions among these hazards is essential for effective basin management, disaster risk reduction, and climate adaptation planning.

Although considerable research exists on individual hazards, integrated multi-hazard studies remain limited. Flood susceptibility has been mapped using hydrological, statistical, and machine learning approaches (Hussain et al., 2025; Kim et al., 2025), cyclone risk often relies on coastal vulnerability indices (Mollah et al., 2025), and landslide susceptibility is commonly assessed with deterministic or multi-criteria decision-making methods, particularly the AHP (Chaabane et al., 2024; Islam et al., 2025). Integrating AHP with GIS provides a robust framework for multi-hazard assessment by combining expert-based factor weighting with spatial overlay techniques, generating composite susceptibility maps even with limited data (Daoud et al., 2025; Hussain et al., 2025). This approach is especially suitable for Bangladesh, where interacting hazards can compound overall risk.

Despite these advances, most studies focus on single hazards or broader administrative scales, leaving basin-specific multi-hazard assessments underexplored, particularly for the HRB (Hosen et al., 2025; Hossain et al., 2024). This study addresses this gap by applying an AHP-GIS framework to quantify the influence of environmental and climatic factors on floods, cyclones, and landslides, producing a composite, spatially explicit multi-hazard risk map. The objectives are: (i) to determine factor weights for floods, cyclones, and landslides using AHP; (ii) to integrate these hazards into a composite multi-hazard risk map; and (iii) to identify priority zones for land-use planning, disaster risk reduction, and climate adaptation. The resulting outputs provide actionable guidance for policymakers, planners, and local authorities to prioritize risk mitigation, design resilient infrastructure, and implement targeted disaster preparedness strategies within the Halda River Basin.

2. MATERIALS AND METHODS

2.1 Study area

The Halda River in southeastern Bangladesh (22°24'–22°54' N, 91°48'–91°53' E) originates from the Badnatali Hills, flowing through Fatikchhari, Hathazari, Raozan, and Chittagong before joining the Karnaphuli River ~35 km from the Bay of Bengal (Figure 1). The basin has loam-to-clay soils, predominantly tropical forests, and varied topography with hilly and flat regions. The climate is warm, humid, and monsoon-influenced, with annual rainfall of 2,442–3,412 mm and temperatures of 12–32°C. The area is highly vulnerable to floods, cyclones, coastal surges, and urban inundation, highlighting the need for integrated multi-hazard assessment (Hossain et al., 2024; Shoumik et al., 2025).

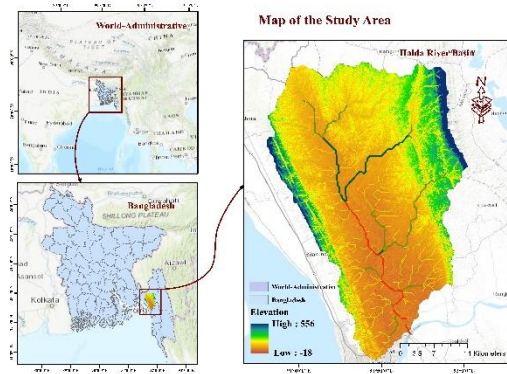


Figure 1: Study area of Halda Basin

2.2 Data Collection and Pre-processing

Twelve factors influencing flood, cyclone, and landslide susceptibility: elevation, slope, drainage density, LULC, precipitation, distance to rivers, soil texture, lithology, distance to roads, cyclone tracks, population density, and curvature, were selected based on their relevance to hazard occurrence. All datasets were standardized in GIS (ArcGIS 10.8), projected to WGS 1984 UTM Zone 46N, and resampled to a uniform 30 m resolution. Continuous variables were converted to categorical susceptibility classes using literature thresholds and expert judgment.

Table 1: Data sources

SN	Factors	Description (Sources)	Spatial Resolution (Year)	Format
1	DEM	US Geological Survey (USGS) (https://earthexplorer.usgs.gov)	30m × 30m (2014)	Raster
2	LULC	Sentinel-2 data (https://livingatlas.arcgis.com/landcoverexplore)	10m×10m m (2024)	Raster
3	Lithology	Global Lithological Map database v1.1 (https://www.geo.uni-hamburg.de/geologie/forschung/aquatische-geochemie/glim.html)	N/A	Vector
4	Soil type	Bangladesh Agricultural Research Council (BARC) (https://www.barc.gov.bd/)	N/A	Vector
5	Rainfall	Bangladesh Meteorological Department (BMD) (http://www.bmd.gov.bd/)	N/A (2021-2024)	.CSV
6	Distance to rivers, Distance to roads, Settlements	BBBike extracts OpenStreetMap (https://extract.bbbike.org/)	N/A	Vector
7	Cyclone track	International Best Track Archive for Climate Stewardship (IBTrACS) (https://www.ncei.noaa.gov/products/international-best-track-archive)	N/A (1980-2024)	Vector
8	Population density	Bangladesh Bureau of Statistics (BBS) (https://data.humdata.org/dataset/cod-ps-global)	N/A (2022)	.CSV

2.3 Methodology

A GIS-based multi-criteria decision-making (MCDM) approach using the Analytic Hierarchy Process (AHP) was applied to assess flood, cyclone, and landslide susceptibility in the Halda River Basin. All spatial datasets were preprocessed to ensure uniformity in coordinate system (WGS 1984 UTM Zone 46N), data type (raster), and resolution (30 × 30 m). Continuous and categorical layers were standardized, reclassified, and normalized into suitability indices to enable consistent integration of diverse environmental variables. Hazard-specific factors were selected based on literature and expert judgment, and their relative importance was determined

through AHP pairwise comparisons, with consistency ratios checked to ensure reliable weighting. In GIS, each factor layer was multiplied by its AHP-derived weight and combined using a weighted overlay to generate individual hazard susceptibility maps. These maps were classified into five categories, ranging from very low to very high risk. To identify areas exposed to multiple hazards, the flood, cyclone, and landslide maps were integrated to produce a composite multi-hazard susceptibility map, highlighting regions with compounded risk. The workflow (Figure 2) provides a systematic and reproducible framework encompassing data preprocessing, criteria selection, weighting, GIS-based spatial analysis, and multi-hazard integration. This approach offers a robust tool for risk-informed planning and management in the Halda River Basin.

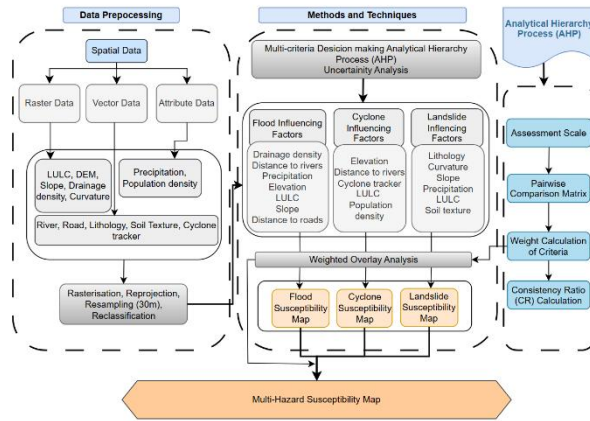


Figure 2: Methodological flowchart

2.3.1 Thematic Layer Preparation

2.3.1.1 Thematic Layers for Flood Susceptibility

Flood susceptibility in the study area was evaluated using seven key factors: elevation, slope, drainage density, LULC, precipitation, soil texture, and distance from rivers. These factors were selected based on their well-established hydrological relevance and their influence on flood generation, flow concentration, and water retention across the landscape. All thematic layers were reclassified into five susceptibility classes as very low, low, moderate, high, and very high, using literature-based thresholds and the statistical distribution of values within the study area (Figure 3 (a)).

2.3.1.2 Thematic Layers for Cyclone Susceptibility

Cyclone susceptibility was assessed using five thematic layers: elevation, distance to rivers, cyclone track density, LULC, and population density. These factors were selected to represent the spatial variability of cyclone exposure and vulnerability across the study area. All datasets were processed and standardized in ArcGIS 10.8 to ensure analytical consistency. Each layer was reclassified into five susceptibility classes, ranging from very low to very high, based on literature-derived thresholds and the statistical distribution of values. The standardized layers were subsequently integrated using a weighted overlay approach to produce the cyclone susceptibility map. Figure 3(b) presents the spatial distribution of the reclassified thematic layers.

2.3.1.3 Thematic Layers for Landslide Susceptibility

Landslide susceptibility was assessed using six thematic layers: lithology, curvature, slope, precipitation, LULC, and soil texture. These factors represent the geological, topographical, hydrological, and surface

conditions that influence landslide occurrence. All datasets were processed and standardized in the GIS environment to ensure spatial consistency. Following preprocessing, four layers were reclassified into five susceptibility classes, ranging from very low to very high, while two layers were reclassified into three classes (very low, moderate, and very high) based on literature-based thresholds and statistical distributions. Figure 3(c) illustrates the spatial distribution of the reclassified layers.

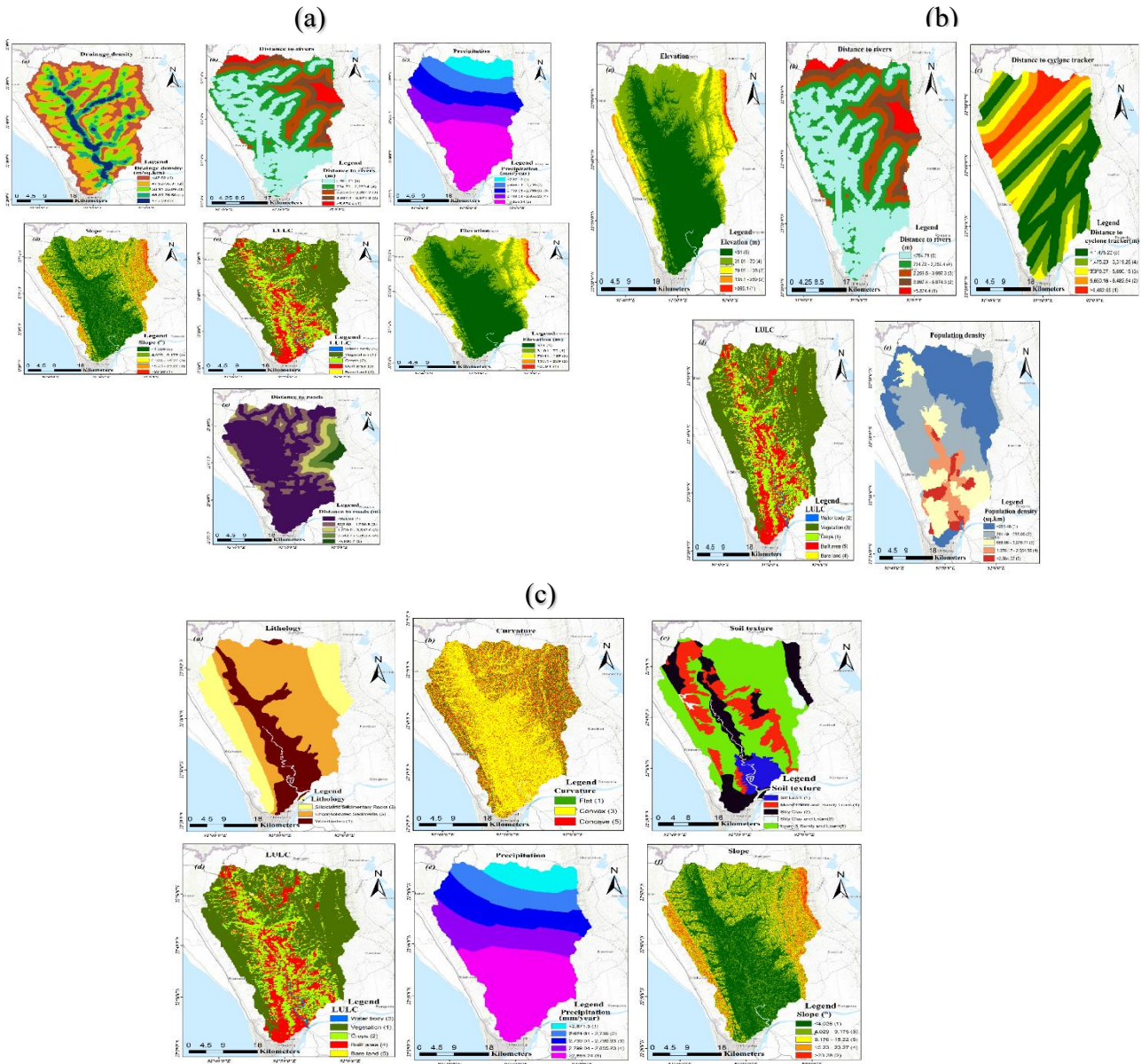


Figure 3: Thematic layers of the reclassified causal factors contributing to the (a) flood susceptible map, (b) cyclone susceptibility, (c) landslide susceptible map

2.3.2 Determination of Weights of the Criteria Using AHP

The weights of the selected criteria were determined using the AHP, a widely used multi-criteria decision-making technique suitable for semi-quantitative prioritization of factors in hazard assessment. AHP is appropriate for this study because it integrates diverse environmental, hydrological, and anthropogenic factors, allowing structured expert judgment while minimizing inconsistencies. The AHP procedure involves three main steps: (i) decomposing the decision problem into a hierarchical structure of the overall goal, criteria, and sub-criteria; (ii) arranging factors according to their expected influence on each hazard; and (iii)

performing pairwise comparisons of factors to assign relative importance. Numerical weights are calculated from the comparison matrices and normalized to ensure consistency. The Consistency Ratio (CR) is computed (Equations 1 and 2) to evaluate the reliability of the assigned weights, with CR values <0.1 considered acceptable (Lakshmi & Kumara, 2024).

$$CR = \frac{CI}{RI} \quad (1)$$

$$CI = \frac{\lambda_{\max} - 1}{n - 1} \quad (2)$$

This approach ensures that the criteria are weighted in a technically sound and reproducible manner, providing a robust basis for subsequent hazard susceptibility modeling.

2.3.3 Flood, Cyclone, and Landslide Hazard Susceptibility Assessment

This study employed a multi-criteria decision-making approach based on the AHP to evaluate individual hazard susceptibilities within the Halda River Basin. The assessment was conducted separately for flood, cyclone, and landslide hazards to capture their distinct geophysical and environmental dynamics.

2.3.3.1 Flood Susceptibility Assessment

Flood susceptibility was assessed using seven factors: elevation, slope, drainage density, LULC, precipitation, soil texture, and distance to rivers. Each factor was reclassified into five susceptibility classes and assigned scores ranging from 1 (very low) to 5 (very high) based on its contribution to flood potential. The CR of 0.041 indicates acceptable consistency in the AHP weighting process (Table 2). The Flood Hazard Index (FHI) was calculated using Equation (3):

$$HI = \sum_{i=1}^n RiWi \quad (3)$$

Table 2: Factor weights for flood susceptibility

	Drainage density	Distance to rivers	Precipitation	Elevation	LULC	Slope	Distance to roads	Weights
Drainage density	1	3	3	5	5	5	7	0.38
Distance to rivers	1/3	1	3	3	5	5	5	0.24
Precipitation	1/3	1/3	1	1	3	3	5	0.13
Elevation	1/5	1/3	1	1	1	2	3	0.09
LULC	1/5	1/5	1/3	1	1	1	3	0.07
Slope	1/5	1/5	1/3	1/2	1	1	1	0.05
Distance to roads	1/7	1/5	1/5	1/3	1/3	1	1	0.04

2.3.3.2 Cyclone Susceptibility Assessment

Cyclone susceptibility in the Halda River Basin was evaluated using five key factors: elevation, distance to rivers, distance to cyclone tracks, LULC, and population density. These factors represent the geographical, hydrological, climatic, and socio-economic dimensions influencing cyclone exposure. The CR of 0.047 indicates acceptable consistency of the AHP pairwise comparison matrix. The Cyclone Hazard Index (CHI) was calculated using the WLC method, following the same procedure as the flood hazard assessment, with detailed factor weights presented in Table 3.

Table 3: The weighting coefficient for cyclone susceptibility assessment.

	Elevation	Distance to rivers	Cyclone tracker	LULC	Population density	Weights
Elevation	1	3	3	5	5	0.46
Distance to rivers	1/3	1	3	3	5	0.27
Cyclone tracker	1/3	1/3	1	1	3	0.12
LULC	1/5	1/3	1	1	1	0.08
Population density	1/5	1/5	1/3	1	1	0.07

2.3.3.3 Landslide Susceptibility Assessment

Landslide susceptibility in the Halda River Basin was evaluated using six key parameters: lithology, curvature, LULC, precipitation, soil texture, and slope. These factors were reclassified into five susceptibility classes representing increasing landslide potential. Lithology received the highest weight (0.414) due to its strong control on slope stability and material strength, whereas soil texture had the lowest weight (0.053) (Table 4). The CR of 0.038 indicates acceptable reliability of the AHP weighting. The Landslide Hazard Index (LHI) was calculated using the WLC method (Equation 3), with factor weights summarized in Table 8.

Table 4: The weighting coefficient for land susceptibility assessment.

	Lithology	Curvature	Slope	Precipitation	LULC	Soil texture	Weights
Lithology	1	3	3	5	5	5	0.414
Curvature	1/3	1	3	3	5	5	0.258
Slope	1/3	1/3	1	1	3	3	0.125
Precipitation	1/5	1/3	1	1	1	2	0.089
LULC	1/5	1/5	1/3	1	1	1	0.061
Soil texture	1/5	1/5	1/3	1/2	1	1	0.053

2.3.4 Multi-Hazard Susceptibility Assessment

The integrated multi-hazard assessment identified areas in the Halda River Basin simultaneously exposed to floods, cyclones, and landslides. Using AHP-derived weights and weighted overlay in ArcGIS, individual hazard maps were combined to produce a composite susceptibility map (Figure 9) classified into five categories: very low, low, moderate, high, and very high. Very low and low zones cover 289.15 km² (18.03%) and 319.99 km² (19.95%) in elevated northern and northwestern uplands, where stable terrain and efficient drainage reduce cumulative risk. Moderate zones occupy transitional areas between uplands and floodplains, while high and very high zones dominate central and southern regions, where low elevation, dense drainage, and unstable slopes overlap. Overall, over 60% of the basin falls within moderate to very high susceptibility zones, highlighting concentrated multi-hazard exposure in densely populated floodplains and hilly areas. This integrated mapping provides a spatially explicit framework to guide risk mitigation, land-use planning, and resilience-building efforts across the basin.:

$$MHI = \sum_{i=1}^n H_i W_i \quad (4)$$

Table 5: The weighting coefficient multi-hazard susceptible assessment.

Factors	Flood	Cyclone	Landslide	Weights
Flood	1	2	3	0.53
Cyclone	1/3	1	3	0.33
Landslide	1/3	1/3	1	0.14

2.3.4.1 Validation

The predictive performance of the AHP-based flood, cyclone, and landslide susceptibility models was evaluated using ROC curves and AUC statistics (Shivhare et al., 2024; Singha et al., 2025). The ROC–AUC method is robust for binary classification and insensitive to class imbalance, making it suitable for hazard prediction. Validation was performed in ArcGIS using the ArcSDM extension, plotting the True Positive Rate against the False Positive Rate across susceptibility thresholds. AUC values indicate model accuracy: < 0.6 = weak, 0.6–0.7 = moderate, 0.7–0.8 = good, and > 0.9 = very good (Tsumita et al., 2025).

Historical events were used as reference data, including flood-inundated locations from disaster archives, cyclone impact points from IBTrACS, and 54 documented landslides from literature and local reports. Susceptibility values at these event locations were extracted and compared with randomly generated non-event points. ROC–AUC analysis quantified the model’s ability to distinguish hazardous from non-hazardous areas.

3. RESULTS AND DISCUSSION

3.1 Individual Hazard Susceptibility Assessment

3.1.1.1 Flood Hazard Susceptibility Assessment

Flood susceptibility was mapped using seven AHP-weighted factors: elevation, slope, drainage density, LULC, precipitation, soil texture, and distance to rivers, classified into five categories (Figure 4). Very low and low zones cover 231.25 km² (14.16%) and 281.43 km² (17.23%) in northern and northeastern uplands. Moderate zones (303.77 km²; 18.60%) occur in transitional terrain, while high and very high zones (444.16 km²; 27.19% and 373.16 km²; 22.84%) are concentrated along central and southern floodplains. These areas, with low elevation, gentle slopes, dense drainage, and fine soils, experience greater runoff and prolonged flooding. Overall, 50% of the basin is highly susceptible, aligning with historical flood patterns.

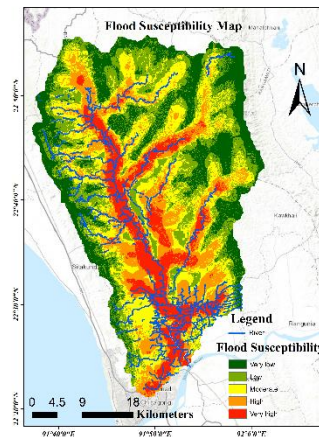


Figure 4: Flood susceptibility map of the study area

3.1.1.2 Cyclone Hazard Susceptible Assessment

Cyclone susceptibility in the Halda River Basin was assessed using multiple environmental and physical factors via AHP-weighted overlay, producing five classes: very low, low, moderate, high, and very high (Figure 5). Very low and low zones cover 153.68 km² (9.20%) and 331.73 km² (19.85%) in inland northern and northwestern areas, where higher elevation and greater distance from the coast reduce cyclone impact. Moderate zones (275.89 km²; 16.51%) occur in transitional areas with occasional wind and rainfall effects. High and very high zones (445.13 km²; 26.64% and 464.50 km²; 27.80%) dominate central and southern floodplains, where low elevation, open terrain, and sparse vegetation amplify wind and surge impacts. Overall, 54% of the basin falls under high to very high cyclone susceptibility, consistent with historical cyclone tracks and damage records, emphasizing the need for resilient infrastructure and targeted mitigation in vulnerable areas.

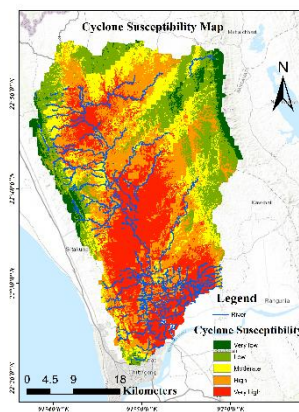


Figure 5: Cyclone susceptibility map of the study area

3.1.1.3 Landslide Hazard Susceptibility Assessment

Landslide susceptibility in the Halda River Basin was assessed using AHP-weighted GIS overlay of key conditioning factors. The resulting map (Figure 6) was classified into five categories: very low, low, moderate, high, and very high. Very low and low zones cover 322.76 km² (19.16%) and 341.05 km² (20.25%) across stable, vegetated plains in the north and west, where gentle slopes and consolidated lithology reduce failure risk. Moderate zones (425.34 km²; 25.25%) occur in transitional terrain with moderate slopes and partial vegetation, showing occasional instability during heavy rainfall. High and very high zones (424.95

km²; 25.23% and 170.48 km²; 10.12%) dominate southeastern hill slopes and dissected valleys, where steep gradients, loose soils, deforestation, and road cuts amplify landslide potential. Overall, 35% of the basin is highly susceptible, emphasizing the geomorphological vulnerability of southeastern hilly regions.

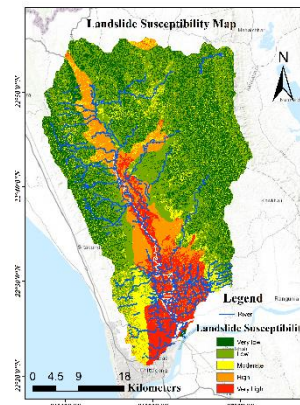


Figure 6: Landslide susceptibility map of the study area

3.1.2 Multi-Hazard Susceptible Assessment

The integrated multi-hazard assessment identified areas in the Halda River Basin simultaneously exposed to floods, cyclones, and landslides. Using AHP-derived weights and weighted overlay in ArcGIS, individual hazard maps were combined to produce a composite susceptibility map (Figure 7) classified into five categories: very low, low, moderate, high, and very high. Very low and low zones cover 289.15 km² (18.03%) and 319.99 km² (19.95%) in elevated northern and northwestern uplands, where stable terrain and efficient drainage reduce cumulative risk. Moderate zones occupy transitional areas between uplands and floodplains, while high and very high zones dominate central and southern regions, where low elevation, dense drainage, and unstable slopes overlap. Overall, over 60% of the basin falls within moderate to very high susceptibility zones, highlighting concentrated multi-hazard exposure in densely populated floodplains and hilly areas. This integrated mapping provides a spatially explicit framework to guide risk mitigation, land-use planning, and resilience-building efforts across the basin.

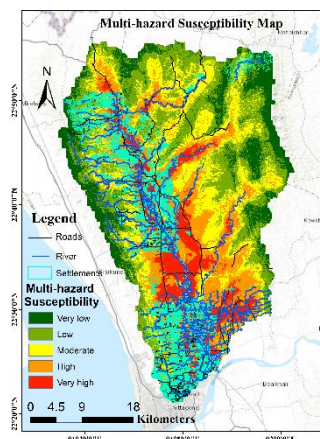


Figure 7: Multi-hazard susceptibility map of the study area

3.2 Validation

The AHP-based flood, cyclone, and landslide models were validated using ROC–AUC analysis, showing effective discrimination between hazardous and non-hazardous areas (Figure 8 a–c). The flood model

achieved an AUC of 0.795, indicating good predictive accuracy. High True Positive Rates at moderate False Positive Rates suggest that factors such as drainage density, elevation, slope, and distance to rivers effectively capture flood-prone areas, consistent with study in the Bengal delta (Kader et al., 2024). The cyclone model produced an AUC of 0.757, reflecting acceptable-to-good performance, aligning with the spatial variability of cyclone impacts reported in coastal Bangladesh (Mamun et al., 2024). The landslide model performed best, with an AUC of 0.832, highlighting the strong influence of lithology, slope, curvature, precipitation, and land use, in agreement with previous AHP-based study in hilly terrains (Muqit et al., 2025). Overall, AUC values >0.75 confirm that the AHP–GIS framework provides reliable susceptibility maps for multi-hazard integration and risk-informed planning in the Halda River Basin.

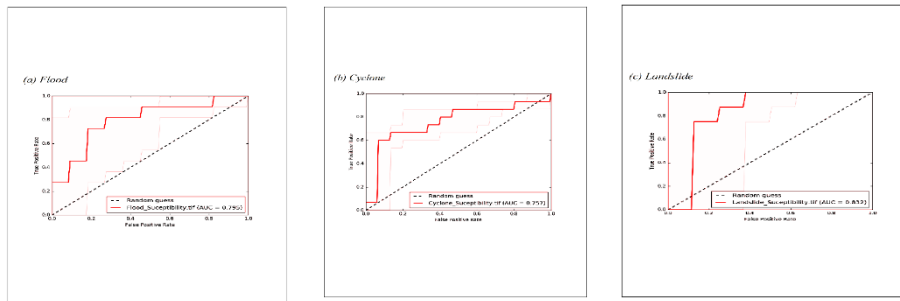


Figure 8. ROC–AUC validation curves for the susceptibility models: (a) Flood, (b) Cyclone, and (c) Landslide.

4. CONCLUSIONS

This study presents a comprehensive multi-hazard susceptibility assessment of the Halda River Basin using an AHP–GIS framework integrating twelve key environmental and climatic factors. The analysis identifies central floodplains, northern hills, and southern coastal margins as areas of moderate to very high susceptibility, while western uplands and stable floodplains exhibit low susceptibility. These findings provide a spatially explicit basis for targeted risk management and hazard-informed planning. The susceptibility maps reflect relative likelihoods derived from static spatial indicators and expert-assigned weights rather than actual hazard events. Nevertheless, their consistency with geomorphological characteristics and historical hazard records supports the reliability of the results. The composite multi-hazard map, in particular, offers practical value for guiding land-use planning, environmental monitoring, and localized disaster preparedness.

Future research should incorporate higher-resolution and multi-temporal datasets, dynamic modeling of hazard interactions, socioeconomic vulnerability indicators, and machine-learning approaches for validation and refined weighting. Such advancements will enhance predictive accuracy, improve methodological robustness, and strengthen the application of this framework for sustainable development, resilience planning, and disaster risk reduction in the Halda River Basin and other hazard-prone regions.

AI Declaration

The authors used AI-assisted tools for language editing and manuscript condensation, as the initial version exceeded the 12-page limit; the scientific content was not altered.

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