

Assessing and Mapping the Flood Susceptibility of the Krueng Aceh River Basin in Indrapuri District, Aceh Besar Regency, Aceh Province, Indonesia Using GIS-Based Hierarchical Criteria Analysis

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Abstract

Extreme weather, such as the Senyar cyclone in November 2025, generated river flooding in the Krueng Aceh River Basin. River flooding is a major natural hazard in river basin areas, particularly where low-lying topography, fluvial geomorphology, and intensive land use increase flood susceptibility. Indrapuri District, Aceh Besar Regency, is susceptible to flooding from the Krueng Aceh River due to its location within the downstream transition zone of the Krueng Aceh River Basin, which is predominantly characterized by fluvial landforms. This study aims to evaluate and spatially delineate flood susceptibility in the Krueng Aceh River Basin through an integrated Analytical Hierarchy Process (AHP) and Geographic Information System (GIS) approach. Nine physical-environmental parameters were incorporated into the analysis, comprising rainfall, elevation, slope, curvature, Topographic Wetness Index (TWI), distance from river channels, drainage density, land use, and landform. The AHP-based weighting revealed that proximity to river channels exerted the greatest influence on flood susceptibility, followed by landform and elevation. The resulting susceptibility index indicates that part of the area is classified as highly susceptible (303.38 ha), moderately susceptible (412.03 ha), and low susceptibility (1,282.87 ha) to flooding. The highly susceptible areas are concentrated primarily in low-elevation zones adjacent to river channels, where elevated TWI values and the floodplain create favorable conditions for water accumulation and prolonged inundation. Conversely, areas with low susceptibility are generally situated at higher elevations and exhibit comparatively favorable drainage conditions, reducing the likelihood of surface-water accumulation. Overall, the findings demonstrate that the integrated AHP-GIS framework can effectively capture the spatial variability of flood susceptibility within the Krueng Aceh River Basin. The resulting map provides a spatially explicit basis for flood mitigation planning, risk-informed land-use management, and the prioritization of vulnerable areas by local authorities. Furthermore, the assessment can support community-based disaster preparedness and contribute to sustainable regional development by promoting land-use decisions that are better adapted to existing geomorphological and hydrological conditions.

Keywords: Disaster Mitigation, Krueng Aceh River, Flood Susceptibility, Analytical Hierarchy Process (AHP), Geographic Information System (GIS)

INTRODUCTION

Flooding is one of the major hazards associated with extreme weather, particularly when intense or prolonged rainfall exceeds the capacity of rivers, drainage systems, and soils to absorb or convey water. The IPCC reports that the frequency and intensity of heavy precipitation events have increased in many land regions, including Asia, and that human-induced climate change has contributed to this intensification (IPCC, 2021). Recent observations also demonstrate the serious impacts of extreme rainfall and flooding in Asia. The World Meteorological Organization reported that exceptional monsoon and tropical-cyclone-related rainfall contributed to devastating floods across several Asian countries, emphasizing the importance of early-warning systems and coordinated disaster preparedness (WMO, 2026). Extreme rainfall can increase the likelihood and severity of flooding, particularly in areas with high exposure, inadequate drainage, and degraded natural ecosystems (IPCC, 2021; UNDRR, 2025). Recent events in Asia demonstrate that intense rainfall associated with monsoon systems and tropical cyclones can produce widespread flooding and significant socioeconomic impacts (WMO, 2026). The Tropical Cyclone Senyar event in late November 2025 is a strong recent case study to include in a discussion of flooding after extreme weather, particularly for Aceh and northern Sumatra. Recent research describes extreme rainfall associated with Senyar as a major driver of widespread flooding in Aceh; rainfall locally exceeded 400 mm in a day during 25–26 November 2025. Syahreza et al. (2026) and TDMRC (2025) data claim that the Senyar event demonstrates how extreme rainfall can rapidly exceed the capacity of river systems,

drainage infrastructure, and soils to absorb water. In Aceh, flooding also damaged roads and bridges, disrupted electricity supplies, affected settlements, and isolated communities. NASA satellite observations documented extensive floodwater across parts of northern Sumatra following the cyclone, providing additional evidence of the large spatial extent of the event (NASA Earth Observatory, 2025).

Kecamatan Indrapuri, Aceh Besar Regency, Aceh Province, has a gently undulating physiographic landscape extending from northwest to southeast, with elevations increasing toward the south. The area is traversed by the Krueng Aceh River. This physiographic condition is influenced by the dynamics of the Krueng Aceh River, which has formed floodplains, deposited sediments, and contributed to the development of the surrounding alluvial plain morphology (Iwaco, 1993, as cited in Moechtar et al., 2009). According to Kodoatie and Sugiyanto (2002), as cited in Sudarmadi (2017), there are two main factors contributing to flooding in Aceh Besar: natural factors and human factors. Natural factors include rainfall, physiography, geological features, erosion and sedimentation, river capacity, drainage capacity, and tidal influences. The geological units underlying the study area consist of Indrapuri Formation (Qpin) and Alluvial Deposits (Qh). The Indrapuri Formation consists of older terrace deposits containing gravel and volcanic sand, with sedimentary structures indicating a fluvial depositional environment, dated to the Pliocene–Pleistocene. The Alluvial Deposit (Qh) consists of gravel, sand, and mud (Holocene) are formed by Krueng River dynamics. (Bennett et al., 1981). Meanwhile, human activities affect environmental conditions through extensive changes within watersheds, the development of settlements along riverbanks, inadequate or delayed land drainage, and land-use conversion into non-vegetated areas. These changes can cause flood-control systems and flood management measures to become ineffective. The combination of these factors increases the vulnerability of the region to flooding, making flood hazards increasingly difficult to control. The Krueng Aceh Watershed (DAS Krueng Aceh) covers an area of 176,552.45 hectares, equivalent to approximately 3.06% of the total area of Aceh Province (5,765,798.45 hectares). The primary function of a watershed is to absorb rainfall and convey water downstream through surface runoff and subsurface flow. However, increasing population pressure on land within the watershed has contributed to its growing environmental degradation, particularly through land-use changes and conversion. These changes can reduce the watershed's capacity to retain and infiltrate rainfall, increase surface runoff, and consequently contribute to a higher risk of flooding.

METHODS

Study Area



Figure 1. Area of Interest, Indrapuri District, Aceh Besar Regency, Aceh Province, Indonesia

The study was conducted in Indrapuri District and its surrounding areas, Aceh Besar Regency, Aceh Province. Geographically, the study area is located between 95°23'30" E–95°20'00" E longitude and 5°27'30" N–5°25'00" N latitude, as shown on the map. The topography of the study area is predominantly characterized by low-lying plains extending along the Krueng Aceh River channel, while the southern and western parts of the study area exhibit increasingly hilly terrain (Figure 1).

Research Steps

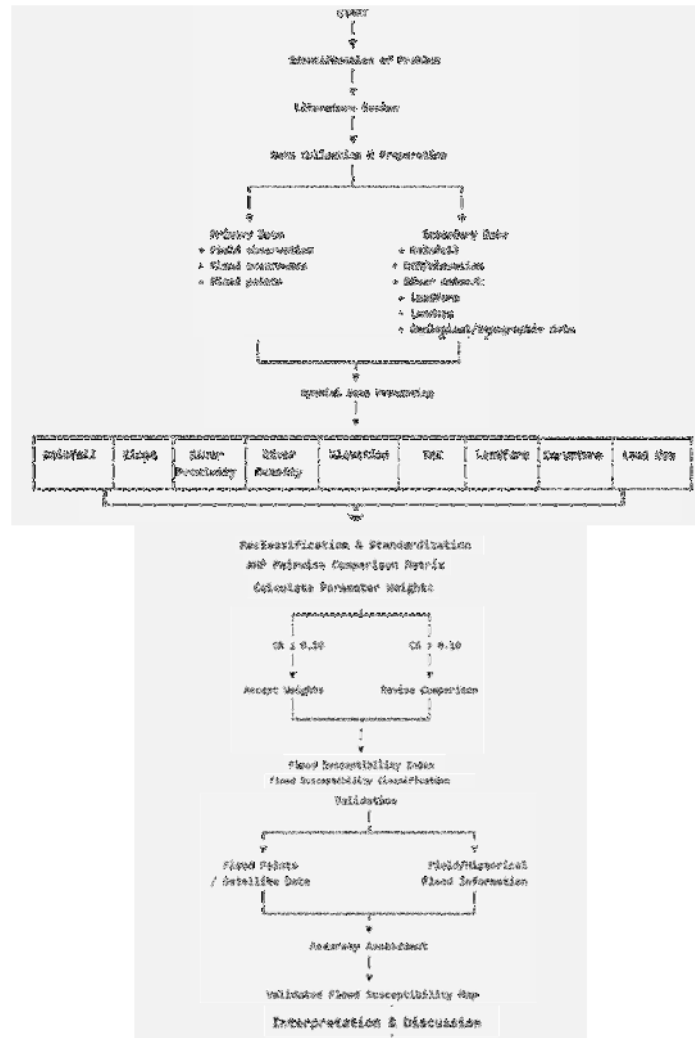


Figure 2. Research Steps for Flood Susceptibility Mapping

AHP (Analytical Hierarchy Process) Process and Validation for Flood Susceptibility

Using AHP (Analytical Hierarchy Process) for flood-susceptibility mapping, data validation should demonstrate that the criteria, pairwise comparisons, weights, and resulting flood-susceptibility classes are reliable. Validation of the AHP-based flood susceptibility model was conducted in two stages. First, the consistency of the pairwise comparison matrix was evaluated using the Consistency Ratio (CR). The comparison matrix was considered acceptable when $CR \leq 0.10$, indicating that the judgments used to determine the relative importance of the flood-susceptibility criteria were sufficiently consistent. Second, the resulting flood-

susceptibility map was validated against observed flood occurrences obtained from field observations, historical flood records, and/or satellite imagery. The predicted susceptibility classes were compared with the observed flood locations to evaluate the accuracy and reliability of the model. This validation process was performed to ensure that the AHP weighting procedure and the resulting flood-susceptibility map adequately represented actual flood conditions in the study area.

Indrapuri District, Aceh Besar, has an average annual rainfall of approximately 1,969 mm/year, based on climatological data for the Indrapuri area. The monthly rainfall pattern shows considerable seasonal variation, with the highest average rainfall occurring in November (242 mm) and December (245 mm), while the lowest occurs in July (81 mm) and June (86 mm). BMKG data compiled for 2015–2024 indicate an average annual maximum daily rainfall of approximately 159.29 mm/day, with a maximum recorded value of 200 mm/day in the dataset. The rainfall parameter in the research area has assumed there is no significant variation in depth. So, calculating AHP can be proceeded with 8 parameters: River proximity, landform, elevation, slope, river density, TWI, curvature, and land use (Figure 2)

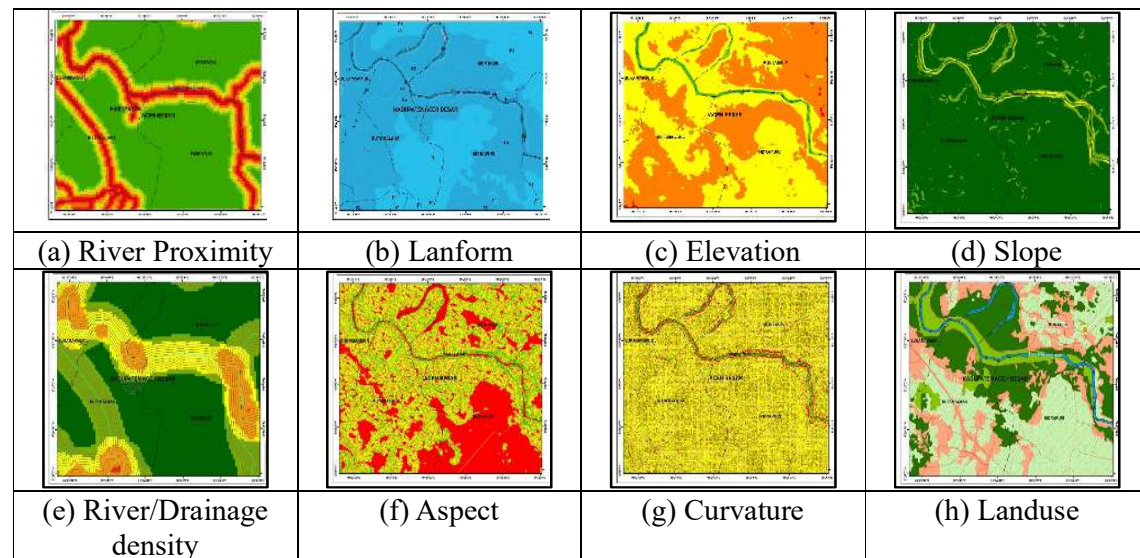


Figure 3. Points a to g are a layout map of parameters that are used for flood susceptibility mapping in Indrapuri

Table 1. Pairwise comparison matrix: Elevation (E), Slope (S), Curvature (Cv), River Proximity (RA), River Density (Rd), Land Use (LU), and Landform (Lf).

	E	S	Cv	TWI	RA	RD	LU	Lf
E	1.00	2.00	3.00	3.00	0.20	3.00	3.00	0.33
S	0.50	1.00	2.00	3.00	0.33	3.00	2.00	0.50
Cv	0.33	0.50	1.00	0.20	0.33	0.33	4.00	0.33
TWI	0.33	0.33	5.00	1.00	0.25	0.33	2.00	0.33
RA	5.00	3.00	3.00	4.00	1.00	4.00	3.00	3.00
RD	0.33	0.33	3.00	3.00	0.25	1.00	0.50	2.00
LU	0.33	0.50	0.25	0.50	0.33	2.00	1.00	0.20
Lf	3.00	2.00	3.00	3.00	0.33	0.50	5.00	1.00
Total	10.83	9.67	20.25	17.70	3.03	14.17	20.50	7.70

The final flood-susceptibility index can then be calculated using:

$$FSI = \sum_{i=1}^n W_i X_i$$

where:

- * FSI = Flood Susceptibility Index
- * W_i = AHP weight of parameter i
- * X_i = standardized score of parameter i

Parameters	$W_{\text{parameter } s}$	Value	Class	Score
Elevation	0.14	<5m	5	0,6105
		6 - 10m	4	0,4884
		11 - 15m	3	0,3663
		15 - 30m	2	0,2442
		>30m	1	0,1221
Slope	0.11	<5°	5	0,5079
		5° - 15°	4	0,4063
		15° - 25°	3	0,3047
		25° - 35°	2	0,2032
		>35°	1	0,1016
Curvature	0.06	Convex	3	0,1740
		Linier	2	0,1160
		Concave	1	0,0580
TWI	0.08	>10	5	0,3465
		8 - 10	4	0,2772
		6 - 8	3	0,2079
		5 - 6	2	0,1386
		1 - 5	1	0,0693
River proximity	0.29	50m	5	1,2917
		100m	4	1,0333
		150m	3	0,7750
		200m	2	0,5167

		250m	1	0,2583
		>25	5	0,4617
		20-25	4	0,3694
		15-20	3	0,2770
		10-15	2	0,1847
		0-10	1	0,0923
		Settlement, Bare land, Wetland/Marsh, Water Body	5	0,25 28
		Rice Field, grassland	4	0,2022
		Shrubland, Cropland / Dryland Agriculture	3	0,1517
		Mixed Garden	2	0,1011
		Plantation, Forest	1	0,0506
		Backswamp, Bar, Oxbow lake, Water Body	5	0,7435
		Abandon valley, Floodplain,	4	0,5948
		River Terrace	3	0,4461
		Alluvial Plain	2	0,2974
		Others	1	0,1487
			111	12,99

RESULTS AND DISCUSSION

Table 2. The Relationship between Flood Susceptibility Parameters and Their Risk.

No.	Parameter	Relationship with Flood Susceptibility	Expected Flood Risk
1	Rainfall	Higher rainfall increases runoff and river discharge	Higher rainfall → higher risk
2	Slope	Gentle slopes allow water to accumulate and move more slowly	Lower slope → higher risk
3	River proximity	Areas close to rivers are more exposed to overflow	Closer to river → higher risk
4	River density	High drainage density can indicate greater concentration of surface runoff	Higher density → potentially higher risk
5	Elevation	Low-lying areas are more susceptible to water accumulation	Lower elevation → higher risk
6	TWI	Indicates potential water accumulation and soil wetness	Higher TWI → higher risk
7	Landform	Floodplains and alluvial plains are more susceptible to inundation	Floodplain → higher risk
8	Curvature	Concave terrain tends to concentrate water	Concave → higher risk
9	Land use	Built-up and poorly infiltrating areas can increase surface runoff	Higher runoff → higher risk

Validation of the flood susceptibility mapping was conducted through field observations and geomorphological cross-sectional profile analysis. The validation results demonstrated a high level of agreement between the mapped flood-susceptibility zones and actual field

conditions. Documentation of the flood event provided by the Regional Disaster Management Agency (BPBD) of Aceh Besar Regency on November 25, 2024, indicates that inundation primarily occurred in low-lying areas located near river channels (Figure 4). Then, one year later, flooding occurred when Cyclone Senyar caused the river to overflow on November 2025. This finding is consistent with the high-susceptibility zones shown on the map, which are concentrated along the Krueng Aceh River and its tributaries. The geomorphological cross-sectional profiles further confirm a clear contrast in the floodplain surrounding the river, which serves as an area of water accumulation, and the higher hills in the eastern part of the study area, which are relatively less susceptible to flooding.



Figure 4. Flood conditions in Indrapuri, Aceh Besar, on Monday, November 25, 2024 (Source: BPBD Aceh Besar Documentation) and floodplain.

Badan Pusat Statistik (BPS) of Aceh Besar Regency (2025) recorded that flooding occurred once in Indrapuri District in 2023. Although the frequency of flooding was lower than in other districts, the finding is consistent with the flood-susceptibility mapping results. This suggests that the spatial exposure of the area to flooding is influenced more strongly by proximity to river channels and local geomorphological conditions.

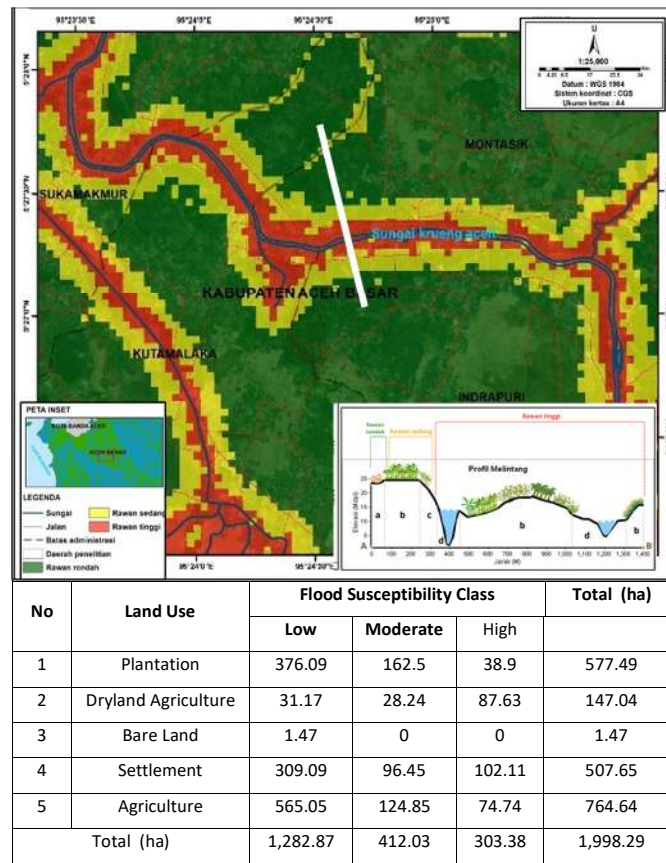


Figure 5. The Flood Susceptibility Map and Area calculation in Indrapuri District, Aceh Besar Regency, Indonesia

	Krueng Aceh River Basin Geomorphological Section			
	a	b	C	D
Landform Unit	Dataran alluvial	Floodplain	Natural Levee and point bar	Water Body
Morphology	Undulating plain	Undulating plain	Rolling plain – slope	-
Morphogenesis	Fluvial	Fluvial	Fluvial	-
Lithology	Qh: Gravel, Sand, Mud, etc.			
Elevation	21 – 30 m	11 – 20 m	6 – 10 m	<5 m
Slope Class	Gentle	Gentle	Moderately Sloping – Slightly Steep	-
TWI	Moist	Moist	Moist	Basah
Curvature	Straight	Straight	Convex	Concave
River Proximity	Distant	Very Close	Very Close	Very Close
Drainage density	Moderate	High – Very High	High	High – Very High
Land use	Settlement	Plantation	Dryland Agriculture	Watershed & Canal

	Krueng Aceh River Basin Geomorphological Section			
	a	b	C	D
Susceptibility Class	Low	Moderate	High	High

The spatial distribution of flood-susceptibility classes indicates that 15% (303.38 ha) of the study area is categorized as having high susceptibility, 21% (412.03 ha) as moderate susceptibility, and the remaining 64% (1,282.87 ha) as low susceptibility. The high-susceptibility areas exhibit a predominantly linear spatial pattern along the natural floodplain, particularly within a 0–100 m buffer from the river channels. Areas with moderate susceptibility generally form a transitional zone across relatively low-lying terrain at elevations of approximately 6–20 m. In contrast, areas classified as having low flood susceptibility are predominantly distributed across hilly and gently undulating terrain with elevations exceeding 20 m. This spatial pattern indicates that elevation, proximity to river channels, and geomorphological characteristics play an important role in controlling the spatial distribution of flood susceptibility within the study area.

CONCLUSION

The flood-susceptibility analysis shows that the high-susceptibility zone covers 303.38 ha (15.18%), primarily concentrated along river channels, low-elevation floodplains, and areas with high TWI values. These areas are predominantly used for settlements and intensive agriculture, increasing the potential for infrastructure damage, socioeconomic disruption, and crop losses.

The moderate-susceptibility zone covers 412.03 ha (21%) and is mainly distributed across transitional areas between floodplains and hills, with elevations of approximately 6–20 m and landforms dominated by alluvial plains and river terraces. Meanwhile, the low-susceptibility zone covers 1,282.87 ha (64%), predominantly occurring in higher-elevation areas with relatively better drainage conditions.

Mitigation should prioritize high-susceptibility settlement areas through structural measures such as flood embankments and improved drainage, complemented by early-warning systems, disaster education, and community preparedness. Moderate- to low-susceptibility areas should focus on land conservation, sustainable land-use management, and community preparedness. Strengthening hydrological and climatological databases and integrating rainfall and river-discharge data into future flood-prediction models are also recommended to improve long-term flood-risk management.

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