GIS AND AHP-BASED FLOOD ZONING AND CONSERVATION STRATEGIES IN THE TARUSAN WATERSHED, INDONESIA

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ABSTRACT

This study aims to identify flood hazard zones and formulate flood disaster mitigation strategies through an integrated watershed conservation framework in the Tarusan Watershed, Pesisir Selatan Regency, West Sumatra, Indonesia. This study applied a Geographic Information System (GIS)-based spatial analysis combined with the Analytical Hierarchy Process (AHP) method to map flood hazard zones and prioritize flood mitigation strategies. Flood hazard assessment was carried out using six indicators (rainfall, slope, landform, land use, soil type, and geological formation). Flood hazard zones were classified into three categories (low, medium, and high) based on a composite scoring system ranging from 65 to 325. The results indicated that the high flood hazard zone (22%) was concentrated in the downstream areas, influenced by flat slopes, high rainfall, alluvium deposits, and intensive human activities. Medium hazard zones (58%) were found in the midstream areas, while low hazard zones (20%) were located in upstream regions with steep slopes and dense forest cover. The AHP analysis involved 25 experts from diverse institutions, identifying seven strategic alternatives categorized into three main priorities: regulation, education, and institutional strengthening. The most dominant strategy was increasing community knowledge about forest functions (weight 0.301), followed by strengthening local institutions (0.149), and improving collaboration with government agencies (0.149). Integration between flood hazard zoning and AHP-based strategies shows that upstream areas require forest conservation and environmental education, midstream areas need sustainable livelihood development, while downstream areas demand regulation enforcement and improved land-use control.

Key-words: *Flood Hazard; Watershed Conservation; Analytical Hierarchy Process (AHP); GIS-Based Analysis; Tarusan Watershed.*

1. INTRODUCTION

Flooding is a recurring hydrometeorological event that occurs when precipitation intensity exceeds the capacity of a watershed to manage surface runoff, resulting in the inundation of both urban and rural areas (Cea & Costabile, 2022). As Tang et al. (2021); Merz et al (2021) identified, the key drivers of flood disasters can be grouped into meteorological factors, anthropogenic activities, and geomorphological conditions of the watershed.

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Additionally, Umar et al. (2019); Dewata & Umar (2019); Barlian et al (2024) classified flood causative factors into natural causes such as high rainfall, flat topography, sedimentation, and human activities, including extensive deforestation, settlement encroachment on riverbanks, and poor waste management practices.

The accuracy of flood hazard prediction can be significantly improved by utilizing a high-resolution Digital Elevation Model (DEM). Schumann & Andreadis (2016) assert that the application of refined DEM data enhances flood-inundation models by up to 30%, minimizing the extent of population exposure and reducing potential economic losses. They emphasized that "Higher resolution measurements would improve large-scale flood inundation prediction capabilities and significantly reduce the number of people affected as well as the economic losses associated with high magnitude flooding". In the present study, both the Shuttle Radar Topography Mission (SRTM) 1 Arc Second data with approximately 30-meter resolution and the National DEM (DEM-NAS) with an 8-meter spatial resolution were utilized to improve the accuracy of topographic and hydrological modeling. In the present study, both the SRTM 1 Arc Second data with approximately 30-meter resolution and the DEM-NAS with an 8-meter spatial resolution were utilized to improve the accuracy of topographic and hydrological modeling. The integration of these datasets enabled a more precise delineation of watershed boundaries, slope characteristics, and flood-prone zones within the Tarusan Watershed. This multi-scale DEM-NAS approach significantly enhanced the quality of slope classification and runoff direction modeling, thus improving the overall reliability of flood hazard mapping (Abo-Salim, 2023; Javas et al., 2024).

In Indonesia, flood disasters have consistently been the most frequent hazard. According to Data from the Indonesian National Disaster Management Agency (BNPB) from 2009, 2017, and 2018, floods represent 34.7% of all recorded natural disasters from 1815 to 2022, with nearly 45% linked directly to human-induced factors, particularly changes in land use and reduced infiltration. The inclusion of the year 1815 marks the earliest systematically documented flood event in the BNPB historical database, which compiles archival, colonial-era, and geological records as part of Indonesia disaster chronology. This historical baseline is significant because it reflects the beginning of organized documentation during the Dutch East Indies period, making it a useful point of reference for long-term flood trend analysis (Faral et al., 2024). One of the critical flood-prone areas in Indonesia is the Tarusan Watershed, located in Pesisir Selatan Regency, West Sumatra. This watershed experiences frequent flooding, which disrupts vital transportation routes between Padang City, Painan, and Bengkulu Province, with delays in mobility that can extend up to nine hours during severe flood events (Triyatno et al., 2019; Triyatno et al., 2020; Triyatno et al., 2023).

Watershed conservation is recognized as a fundamental component in reducing flood risks and promoting sustainable land and water management. Healthy watersheds regulate hydrological processes, including reducing surface runoff, enhancing infiltration, and maintaining groundwater recharge. Darghouth et al (2008) emphasized that watershed conservation activities are instrumental in maintaining groundwater recharge, reducing erosion, and preventing the degradation of downstream ecosystems, including beaches and coral reefs. In the Indonesian context, watershed conservation and flood risk reduction are strongly supported by a legal framework that includes Law No. 26/2007 on Spatial Planning, Law No. 32/2009 on Environmental Protection and Management, and Government Regulation No. 37/2012 on River Management (Pambudi, 2015; Pambudi & Kusumanto, 2023). These regulations emphasize the importance of protecting watershed areas, ensuring environmental sustainability, and integrating disaster mitigation into spatial development planning. This study aligns with these national policies by combining spatial-based flood hazard analysis with watershed conservation strategies, by Indonesia's regulatory emphasis on integrated, participatory, and ecosystem-based management approaches. In Taiwan, watershed conservation programs have demonstrated significant environmental and economic benefits. Lin et al. (2021) highlighted that government-led investments in watershed restoration resulted in 49% improvement in water quality, 20% increase in water supply stability. This analysis showed that watershed conservation and restoration efforts yield long-term environmental benefits, including sediment reduction, and resilience to natural disasters. In addition, Cheng et al. (2002) described Taiwan

watershed management efforts as a successful integration of soil and water conservation practices aimed at disaster mitigation and sustainable resource development.

Community involvement has been identified as a critical factor for the success of watershed conservation initiatives. Thapa et al. (2022) reported that community participation in soil and water conservation is key to effective disaster mitigation, particularly in upstream watershed areas prone to degradation. Their study underlines the importance of engaging local stakeholders to foster stewardship and ensure the sustainability of conservation programs. In Indonesia, the National Water Rescue Partnership Movement (WRPM), coordinated by the Ministry of Environment and Forestry, exemplifies a national effort integrating community-based watershed conservation through tree planting, soil conservation, and local awareness campaigns (Suwarto et al., 2022).

Another successful initiative is the Desa Tangguh Bencana (Disaster Resilient Village) program, which encourages local communities to participate actively in risk reduction planning and watershed protection at the village level (Sunarto et al., 2025). These programs have demonstrated that empowering local communities leads to more adaptive and sustainable watershed governance. Internationally, the Watershed Management Program in Ethiopia, supported by local institutions and international partners, has mobilized rural communities to construct soil bunds and reforest degraded hillsides, resulting in increased water retention and reduced erosion (Nafli et al., 2024). Similarly, the Payment for Ecosystem Services (PEs) scheme in Costa Rica incentivizes farmers to protect forests and water sources, with community engagement playing a central role in the program transparency and long-term success (Viguera et al., 2024). Furthermore, Debele et al. (2023); Griffiths et al. (2024) argued that Nature-Based Solutions (NBS), including reforestation, wetland restoration, and the protection of riparian buffers, offer cost-effective and sustainable alternatives to conventional engineering approaches for managing hydro-meteorological risks. NBS not only reduces flood risks but also provides multiple co-benefits, such as biodiversity conservation, carbon sequestration, and the enhancement of ecosystem services.

This study aims to identify flood hazard zones and develop flood disaster mitigation strategies as part of an integrated watershed conservation framework in the Tarusan Watershed in Pesisir Selatan Regency, West Sumatra, Indonesia. The novelty of this study lies in integrating flood hazard zoning with the Analytical Hierarchy Process (AHP) based strategy prioritization to develop targeted mitigation actions for each flood risk zone in the Tarusan Watershed. This approach offers a framework by linking spatial flood risk levels with prioritized watershed management strategies.

2. STUDY AREA

This study was conducted in the Tarusan Watershed, situated in Pesisir Selatan Regency, West Sumatra Province, Indonesia. Geographically, the watershed lies between 1°24'00" to 1°47'00" South Latitude and 100°28'00" to 100°42'00" East Longitude. As shown in **Figure 1**, the Tarusan Watershed covers an area of 300.27 km², making it one of the ten largest river basins in the West Sumatra province (Umar & Triyatno, 2024; Umar., 2024).

The Tarusan watershed flows into the Indian Ocean and features diverse topography. Based on SRTM 1 Arc Second data and DEM-NAS analysis, approximately 30% of the area comprises flat terrain, while the remaining regions consist of moderately steep to very steep slopes, particularly in the upstream and midstream areas. The region receives high annual rainfall ± 3,000 mm each year, which significantly impacts the hydrological processes (Hamada et al., 2008); Kaiser et al., 1999).

3. DATA AND METHODS

3.1. Data Sources

This study was conducted over five months, from January to May 2022. Six primary indicators were analyzed to identify flood hazard zones and support conservation planning in the Tarusan Watershed. The data for these indicators, namely rainfall, slope, landform, land use, soil type, and geological formation, were collected from various sources and are detailed in **Table 1**.

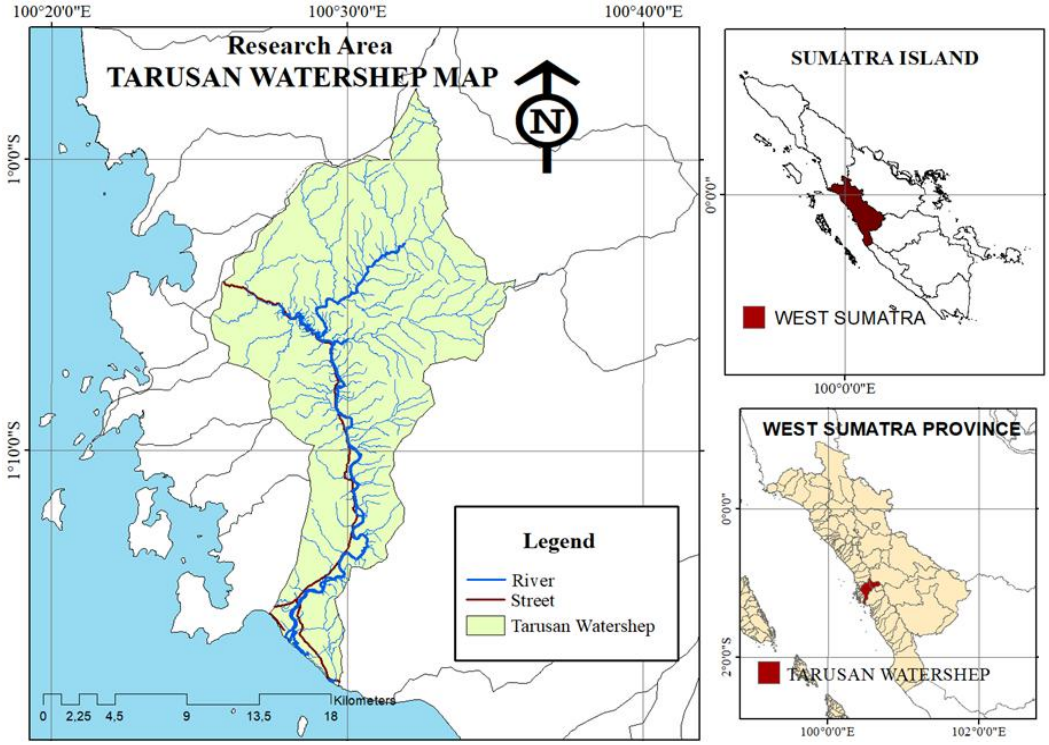

Fig. 1. Location map of Tarusan Watershed in Pesisir Selatan Regency, West Sumatra Province.

Table 1.

Study data and sources.

No	Data	Specification	Source
1	Rainfall	1975–2022	Climatological and Geophysics (BMKG)
2	Land Use	Landsat OLI 8 (2020)	United States Geological Survey (USGS)
4	Slope and slope (High-res)	SRTM 1 Arc Second and DEMNAS (8 m resolution)	USGS and Geospatial Information Agency (BIG)
5	Landform	Geological and DEM Analysis	In-house Interpretation
6	Soil Type	1:250,000 Map (1990)	Research Center of Bogor Soil
7	Geological	1:250,000 Map (2007)	Geological Agency of Bandung

The land use data for the Tarusan Watershed were extracted and analyzed using Landsat Operational Land Imager (OLI) 8 acquired in 2022 from the USGS Earth Explorer. The imagery has a spatial resolution of 30 meters for multispectral bands, which is suitable for medium-scale land cover classification and watershed analysis in large and heterogeneous areas such as the Tarusan Watershed. Several pre-processing steps were undertaken, consisting of:

1) Radiometric correction conducted to correct sensor noise and convert raw Digital Numbers (DN) into surface reflectance values;

2) Geometric correction applied to align the imagery with spatial reference systems, using Universal Transverse Mercator (UTM) Zone 47S, WGS 84, to ensure the spatial accuracy of land use mapping; and

3) Atmospheric correction performed using the Dark Object Subtraction (DOS) method, minimizing the effects of atmospheric scattering and enhancing the clarity of surface features (Bernardo et al., 2017).

A supervised classification technique was implemented using the Maximum Likelihood Classifier (MLC) algorithm. The classification process produced a detailed map of land use categories, consisting of bare land, settlement, farming area, mixed garden, shrub, plantation, and forest (Putra et al., 2023). Although Landsat 8 OLI has a 30-meter spatial resolution, which may not capture very small land patches or narrow land use boundaries, it provides a balanced trade-off between spatial detail and regional coverage. This level of resolution is sufficient for analyzing land use patterns that influence surface runoff, infiltration rates, and flood susceptibility at the watershed scale.

3.2. Data analysis techniques

3.2.1. Flood Hazard Mapping and Scoring Analysis

Each of the six indicators presented in **Table 1** was further classified into sub-indicators based on their characteristics and influence on flood susceptibility. The weighting system was adapted from Umar et al. (2017). The resulting composite scores ranged from 65 (lowest) to 325 (highest). To categorize these scores into distinct hazard classes, Equation 1 was used to calculate the class intervals. The flood hazard zones were subsequently divided into three classes (high, medium, and low). The detailed criteria for each indicator, along with their assigned weights, sub-indicators, values, and corresponding scores, are presented in **Table 2** below.

Table 2.

Indicators for flood hazard assessment.

Indicator (Weight)	Sub-Indicator	Value	Score
Rainfall (mm/year) (15)	> 4500	5	75
	4000 – 4500	4	60
	3500 – 4000	3	45
	3000 – 3500	2	30
	< 3000	1	15
Slope (%) (15)	Flat (0 – 8%)	5	75
	Tilted (9 – 16%)	4	60
	Slightly Steep (17 – 26%)	3	45
	Steep (27 – 40%)	2	30
	Very Steep (> 40%)	1	15
Landform (10)	Marine	5	50
	Fluvial	4	40
	Denudational	1	10
	Structural	1	10
	Volcanic	1	10
Land Use (10)	Bare Land	5	50
	Settlement	4	40
	Farming Area	4	40
	Mixed Garden	3	30
	Shrub	3	30
	Plantation	2	20
	Forest	1	10
Soil Type (10)	Ultisols	5	50
	Entisols	4	40
	Histosols	3	30
	Oxisols	2	20
	Inceptisols	1	10
Geological Formation (5)	Alluvium (Qal)	5	25
	Latih (Tml)	3	15
	Jura Sediment (Jr)	3	15
	Granite (Tgr)	1	5
	Quaternary Volcanic Rocks (Qv)	1	5

The determination of flood-prone zones in the Tarusan Watershed was conducted through a weighted scoring method, utilizing overlay analysis techniques within a GIS. This method integrates multiple spatial data layers corresponding to the six indicators, each of which is subdivided into sub-indicators with specific values and weights. To classify the total scores into distinct flood hazard classes, Equation 1 was applied to determine the class interval as follows.

$$I = \frac{c-d}{k} \quad (1)$$

where: I = Interval; c = Highest total (325); b = Lowest total (65); and k = Number of 3 classes.

By applying Equation 1, the class interval was calculated as follows:

$$I = \frac{325-65}{3} = 86.67 \approx \mathbf{86} \quad (2)$$

Based on the calculated class intervals, the flood hazard zones were classified into three categories, as can be seen in **Table 3** below.

Table 3.

Flood hazard class intervals in the tarusan watershed.

Flood Hazard Class	Score Interval	Category
Low Hazard	65 – 115	Low Risk
Medium Hazard	116 – 237	Medium Risk
High Hazard	238 – 325	High Risk

The resulting flood hazard zones serve as a foundation for watershed conservation strategies and flood disaster mitigation planning. Priority interventions, such as reforestation in high-risk areas and implementation of erosion control measures, are recommended to enhance the resilience of the Tarusan Watershed against flood events (Debele et al., 2023).

3.2.2. Flood Disaster Mitigation Assessment through the AHP Method

The AHP approach was utilized (Saaty, 1983; Marimin & Maghfiroh, 2010). A panel of 25 experts was engaged in this study, representing diverse stakeholders, including the Public Works Department, Regional Disaster Management Agency, local universities, community leaders, Non-Governmental Organizations (NGOs), religious leaders, and the Regional Planning and Development Agency. These experts were selected for their expertise in disaster risk reduction, environmental management, and community development. The experts conducted pairwise comparisons of the identified criteria and sub-criteria for flood mitigation, using a 9-point scale as proposed by Saaty (1983) and refined by Marimin & Maghfiroh (2010). The scale used is presented in **Table 4**, providing a consistent framework for evaluating the relative importance of each criterion, and the hierarchy, shown in **Figure 2**, demonstrates the interconnection between policy, community education, and institutional strengthening.

Table 4.

AHP Assessment Criteria (Saaty's Scale).

Value	Description
1	A is equally important as B
3	A is slightly more important than B
5	A is significantly more important than B
7	A is very strongly more important than B
9	A is absolutely more important than B
2, 4, 6, 8	Intermediate values when compromise is needed between adjacent scales

Sources: Saaty (1983); Marimin & Maghfiroh (2010).

The AHP analysis was conducted using Expert Choice software to process the comparison matrices and calculate the priority weights of each strategy. A critical aspect of AHP is the Consistency Ratio (CR), which measures the consistency of expert judgments. In **Figure 2** shows three core strategic pillars aimed at reducing flood risk and promoting watershed conservation, namely Regulation, Education, and Institutional Strengthening. Each pillar encompasses targeted action programs derived from expert consensus, designed to address the physical and social dimensions of flood disaster mitigation and watershed management. The actions include:

A1: Consistent enforcement of environmental regulations
A2: Establishment of clear and transparent rules for sustainable resource use
A3: Increasing community awareness of the critical role forests play in mitigating floods
A4: Promoting alternative livelihoods for communities dependent on forest resources
A5: Enhancing community skills in the sustainable utilization and value addition of forest products
A6: Strengthening local institutions and customary community groups
A7: Fostering collaborative partnerships between communities and government agencies

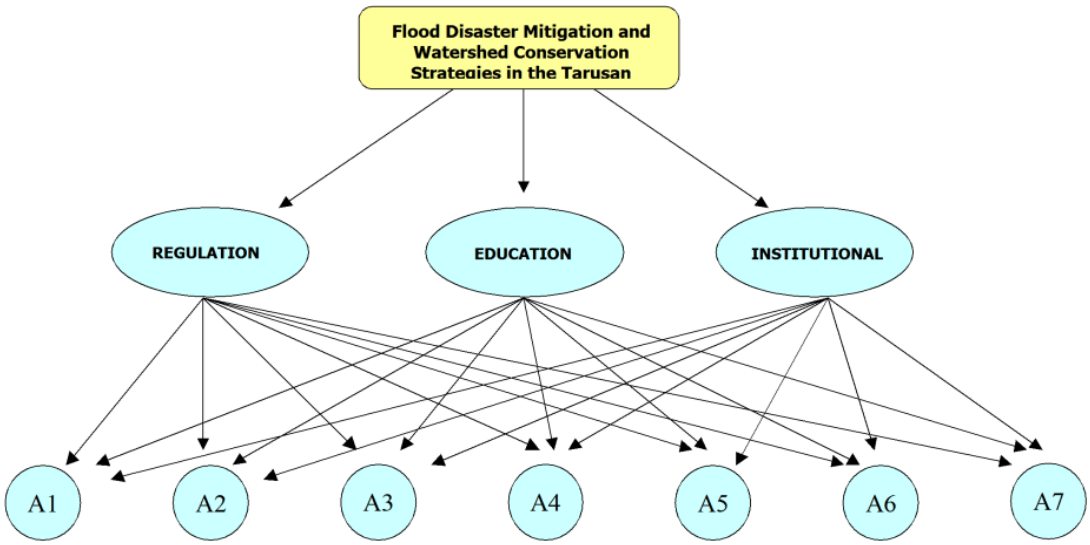

Fig. 2. Hierarchy of flood disaster mitigation and watershed conservation strategies in the Tarusan Watershed.

This strategic framework aligns with the principles of Ecosystem-based Disaster Risk Reduction (Eco-DRR), as recommended by the United Nations Environment Programme (UNEP, 2014), and is supported by findings from Debele et al. (2019). By integrating Nature-Based Solutions (NBS) within a watershed conservation context, the framework not only reduces flood risk but also enhances biodiversity, improves water quality, and sustains local livelihoods.

Furthermore, the AHP-based prioritization process involved 25 experts from various institutions including government agencies, NGOs, academics, and community leaders ensuring that the resulting strategies are context-specific, socially inclusive, and institutionally grounded. The seven action strategies derived from the AHP analysis address key domains such as forest conservation (A3), alternative livelihoods (A4), regulation enforcement (A1), and institutional collaboration (A6, A7), which are all consistent with Eco-DRR principles that emphasize local participation, ecosystem health, and multi-stakeholder governance. Hence, this integrative approach offers not only a technical assessment of flood risk but also a policy-relevant and community-responsive pathway for implementing sustainable watershed management.

4. RESULTS

4.1. Slope and Rainfall

Slope and rainfall characteristics are the main factors that influence the hydrological and flood potential of a watershed area. This study utilized SRTM 1 Arc Second data and long-term rainfall data (1975–2022) to classify the physical characteristics of the Tarusan Watershed. In addition, high-resolution DEMNAS (8-meter) data were incorporated to improve the accuracy of slope gradient analysis, especially in the upstream and midstream regions where topographic complexity is high. The slope classification was used to identify areas with varying degrees of land steepness, while rainfall data provided an overview of the distribution of precipitation intensity throughout the watershed. The results of this spatial analysis are shown in **Figure 3**, which presents the slope classes (**Figure 3a**) and annual rainfall intensity (**Figure 3b**) in the Tarusan Watershed.

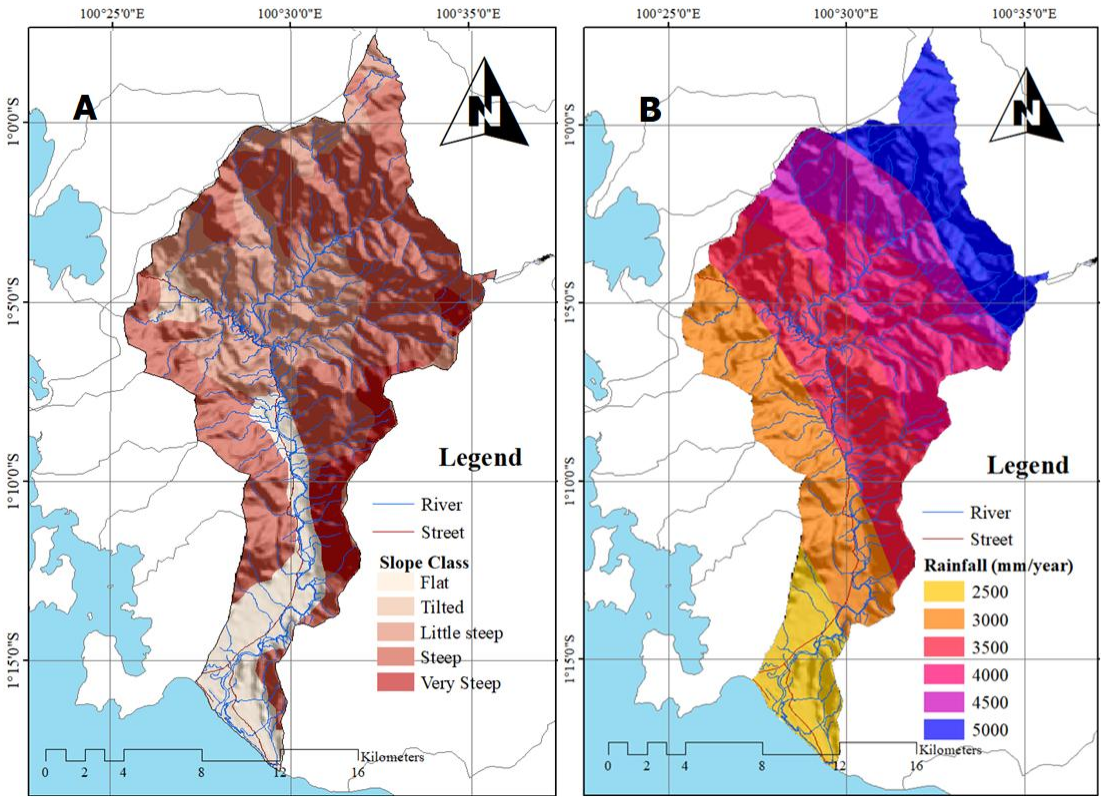

Fig. 3. Map of slope (a) and rainfall (b) in the Tarusan watershed.

The analysis results in **Figure 3** above show that the slope and rainfall characteristics of the Tarusan Watershed are critical factors influencing its hydrological behavior and susceptibility to flooding. The spatial analysis of slope classification (**Figure 3a**) indicates that the Tarusan Watershed is dominated by steep to very steep slopes, particularly in the upstream and midstream regions. Approximately 63% of the total watershed area consists of slopes ranging from 27% to more than 40%, which significantly increases the potential for surface runoff, accelerates soil erosion, and reduces water infiltration capacity, especially in areas undergoing deforestation and land-use changes (Hoch et al., 2019). Meanwhile, the downstream and southern coastal regions of the watershed are characterized by flatter terrain, with slope classes ranging from 0% to 16%. For more details, please see **Table 5** below.

Table 5.

Slope classification and flood hazard score in the Tarusan Watershed.

Slope Class	Area (%)	Score
Flat (0-8%)	5	75
Tilted (9-16%)	10	60
Slightly Steep (17-26%)	22	45
Steep (27-40%)	35	30
Very Steep (>40%)	28	15

Source: Results of data analysis 2023.

In addition to the slope factor, rainfall distribution also plays a significant role in influencing flood risk within the watershed. **Figure 3b** shows that the upstream and central parts of the Tarusan Watershed receive very high annual rainfall, ranging from 4,000 mm to over 5,000 mm. These conditions are primarily caused by orographic precipitation from the Barisan Mountain range. High rainfall intensity increases surface runoff, triggers landslides, and accelerates the flow of water downstream, especially during the peak rainy season. In contrast, the downstream and coastal areas receive lower rainfall intensities, ranging from 2,500 mm to 3,000 mm annually. However, these lower rainfall regions remain vulnerable to flooding due to water accumulation from upstream discharge and limited drainage capacity. For more details, please see **Table 6** below.

Table 6.

Rainfall intensity classification and flood hazard score in the Tarusan Watershed.

Rainfall (mm/year)	Area (%)	Score
<3000	15	15
3000-3500	20	30
3500-4000	25	45
4000-4500	25	60
>4500	15	75

Source: Results of data analysis 2023.

Based on the flood hazard scoring criteria applied in this study, the combination of steep to very steep slopes in the upstream and midstream regions, along with high rainfall intensity exceeding 4,000 mm annually, places these areas within the highest flood hazard category. Conversely, although the downstream and coastal regions experience lower rainfall intensity and gentler slopes, they remain vulnerable to flooding due to sediment deposition and reduced river channel capacity from upstream erosion. Therefore, effective mitigation strategies should prioritize upstream watershed conservation, erosion control, and sustainable land-use practices to reduce surface runoff, enhance infiltration, and minimize sediment transport to downstream areas.

4.2. Soil and Landform

Soil and landform characteristics are essential physical factors that strongly influence the hydrological response and flood vulnerability of a watershed area. The distribution of soil types and landforms in the Tarusan Watershed plays a crucial role in determining surface runoff patterns, erosion potential, sediment transport, and flood risk levels. The results of this spatial analysis are shown in **Figure 4**, which presents the distribution of soil (**Figure 4a**) and landform (**Figure 4b**) in the Tarusan Watershed.

The analysis results in **Figure 4** above indicate that the Tarusan Watershed is dominated by Oxisols and Ultisols soil types (**Figure 4a**). Oxisols cover approximately 45% of the watershed area, while Ultisols cover around 30%. These soil types are highly susceptible to erosion and have low infiltration capacity, which increases surface runoff and sediment transport (Namdar & Pelko, 2009). In contrast, Entisols (15%), Histosols (5%), and Inceptisols (5%) are distributed in specific areas, mainly in the midstream and downstream regions. Among these soil types, Ultisols have the highest flood hazard score (50), followed by Entisols (40), reflecting their critical role in generating sediment and exacerbating flood risks downstream. For more details, please see **Table 7.**

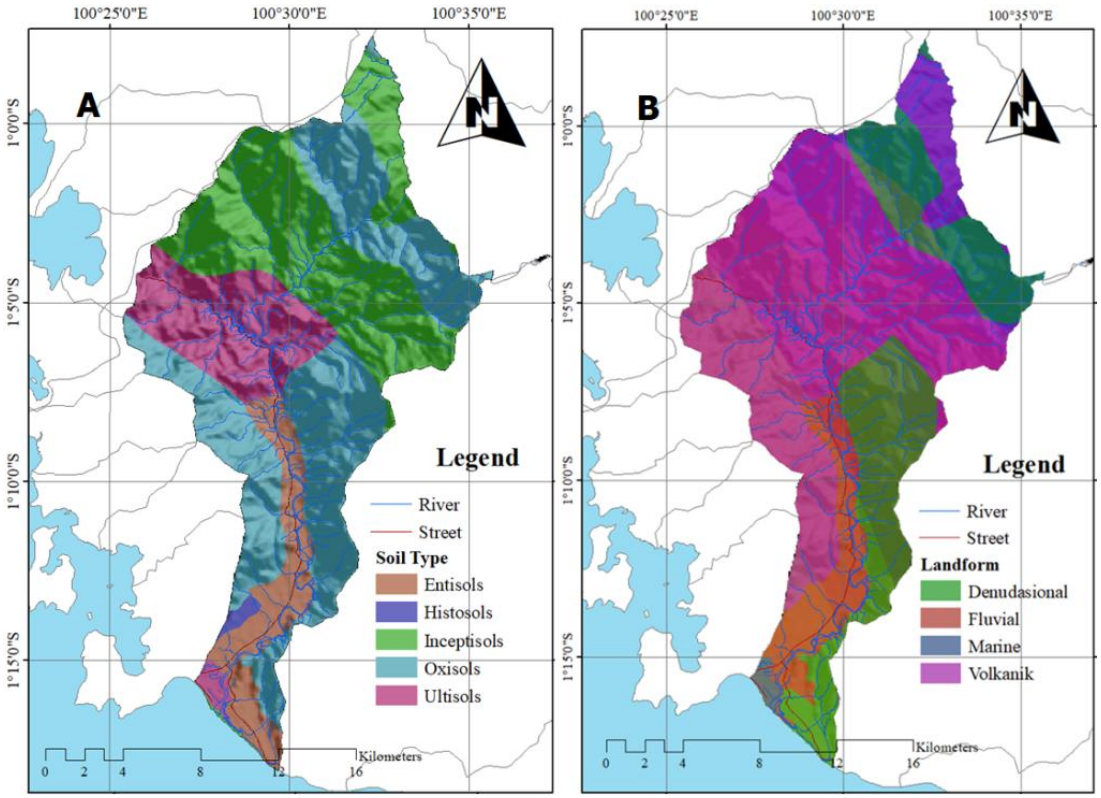

Fig. 4. Map of Soil Types (a) and Landforms (b) in the Tarusan Watershed.

Table 7.

Soil classification and flood hazard score in the Tarusan Watershed.

Soil Type	Area (%)	Score
Ultisols	30	50
Entisols	15	40
Histosols	5	30
Oxisols	45	20
Inceptisols	5	10

Source: Results of data analysis 2023.

Meanwhile, the landform classification (**Figure 4b**) shows that the Tarusan Watershed consists of five primary landform types: Denudational (35%), Structural (25%), Fluvial (20%), Marine (10%), and Volcanic (10%). Fluvial and Marine landforms, primarily located along river systems and the southern coastal area, are particularly vulnerable to flooding due to their low elevation and function as sediment deposition zones (Hoch et al., 2019).

Marine landforms have the highest flood hazard score (50) due to their proximity to estuarine systems and high groundwater influence, while Fluvial landforms have a score of 40. In contrast, Denudational, Structural, and Volcanic landforms in the upstream areas have lower scores but contribute significantly to sediment production and downstream siltation. For more details, please see **Table 8** below.

Table 8.

Landform classification and flood hazard score in the Tarusan Watershed.

Landform Type	Area (%)	Score
Marine	10	50
Fluvial	20	40
Denudational	35	10
Structural	25	10
Volcanic	10	10

Source: Results of data analysis 2023.

The combination of highly erodible soil types (Ultisols and Entisols) and flood-prone landforms (Marine and Fluvial) in the Tarusan Watershed creates critical zones that require priority attention in flood hazard mitigation planning. These fragile physical conditions, when combined with unsustainable land conversion and agricultural expansion, further increase the risk of land degradation, soil erosion, and sediment transport to downstream areas. Conservation strategies should focus on 1) Reforestation of erosion-prone upstream areas; 2) Restoration of riparian buffer zones; 3) Implementation of soil conservation techniques; and 4) Sustainable land-use management practices. Community-based participation and institutional collaboration are also important to support the successful implementation of conservation programs, especially in promoting local awareness and adaptive capacity. These measures are essential to reduce surface runoff, control sedimentation, and enhance the resilience of the Tarusan Watershed to flood disasters, in line with Eco-DRR and NBS approaches (Debele et al., 2019).

4.3. Land Use and Geological Formations

Land use and geological formation represent essential biophysical factors that directly influence flood hazard conditions within the Tarusan Watershed. The integration of these parameters in a GIS-based analysis provides critical insights into the relationship between land cover dynamics, watershed degradation, and flood vulnerability. Land use patterns reflect the intensity of human activities within the watershed, while geological formations determine the physical properties of the landscape, including infiltration capacity, erosion potential, and sediment production.

The overlay analysis of these indicators allows for a more comprehensive assessment of flood-prone areas and the identification of priority zones for conservation and mitigation interventions. In this study, land use data were generated through a supervised classification approach using Landsat 8 OLI (2022) obtained from the USGS Earth Explorer. Pre-processing steps, including radiometric, geometric, and atmospheric corrections, were conducted to improve the accuracy of the satellite imagery. This classification identified seven land use categories (bare land, settlement, farming area, mixed garden, shrub, plantation, and forest). In addition, geological mapping at a 1:250,000 scale was used to determine the distribution of rock formations, lithology, and soil characteristics. Based on the interpretation of Landsat 8 OLI (2022) and geological mapping at a 1:250,000 scale, the spatial distribution of land use types (**Figure 5a**) and geological formations (**Figure 5b**) in the Tarusan Watershed is presented in **Figure 5** below.

An analysis of land use conditions in 2022 shows a heterogeneous landscape within the Tarusan Watershed. The upstream area is still dominated by forest cover, while the midstream and downstream regions have undergone intensive land conversion into agriculture, mixed gardens, settlements, and plantations. In terms of area coverage, forested land has decreased significantly compared to 2019 conditions. Forest areas currently cover only 21.6% of the watershed, while mixed gardens dominate with 32.7%, followed by agricultural land with 25.9%. Settlements and bare land are particularly concentrated in the midstream and downstream regions, contributing significantly to flood vulnerability. This land use change is related to population growth and the expansion of economic activities, especially agricultural development.

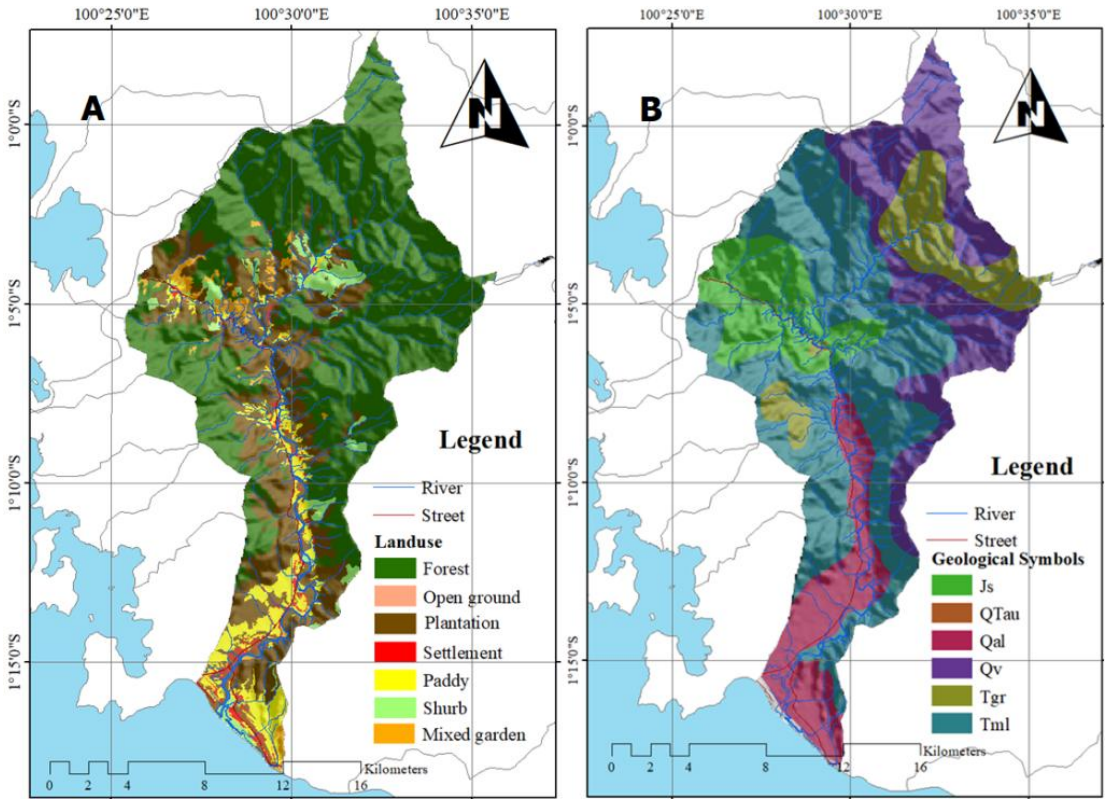

Fig. 5. Map of land use (a) and geological (b) in the Tarusan watershed.

The reduction of forest areas and increase of impermeable surfaces in settlements have reduced the watershed's ability to retain water, triggering more runoff, erosion, and sedimentation. These conditions directly exacerbate flooding in downstream areas. For more details, please see **Table 9** below.

Table 9.

Land use types and flood hazard scores in the Tarusan Watershed.

Land Use Type	Area (%)	Flood Hazard Score
Forest	21.6	10
Mixed Garden	32.7	30
Agriculture/Farming	25.9	40
Settlement	9.8	40
Shrub	6.7	30
Bare Land	2	50
Plantation	1.3	20

Source: Results of data analysis 2023.

The highest flood hazard score is found in bare land (50 points), followed by settlement and agricultural areas (40 points). These land uses contribute to increased surface runoff, decreased infiltration, and accelerated flooding, especially in riverine and downstream areas. On the other hand, forest cover serves as a critical component in flood mitigation due to its ability to absorb water, stabilize slopes, and reduce erosion (Akhter & Hewa, 2016; Chen & Tfwala, 2018; Febriandi et al., 2025).

In particular, the loss of forest and vegetation cover in upstream areas has intensified watershed degradation and heightened flood risk in lower zones. Human activities, such as land clearing, agricultural expansion, and infrastructure development, have significantly altered the natural hydrological cycle, increasing vulnerability to flood hazards. From the geological perspective, **Figure 5b** shows that the Tarusan Watershed consists of six primary geological formations. Alluvium (Qal) deposits are dominantly found in the downstream floodplain areas and are highly vulnerable to flooding due to their loose sedimentary characteristics. Conversely, granite (Tgr) and quaternary volcanic (Qv) formations found in upstream regions exhibit lower flood susceptibility. For more details, please see **Table 10** below.

Table 10.

Geological Formations and Flood Hazard Scores in the Tarusan Watershed.

Geological Formation	Spatial Distribution	Flood Hazard Score
Alluvium (Qal)	Downstream	25
Latih (Tml)	Western & Eastern Margins	15
Jurassic Sediment (Js)	Upstream & Midstream	15
Tau Formation (QTau)	Upstream & Midstream	15
Granite (Tgr)	Upstream	5
Quaternary Volcanic (Qv)	Upstream	5

Source: Results of data analysis 2023.

The integration of land use and geological formations highlights the spatial variability of flood hazard conditions in the Tarusan Watershed. The highest flood vulnerability is concentrated in the downstream regions, where intensive land use changes and the presence of alluvium deposits exacerbate flood risks. To minimize flood impacts, watershed management strategies must focus on 1) Strengthening Forest protection in upstream areaS; 2) Implementing erosion control and soil conservation in midstream zones; 3) Restoring riparian buffer zones; 3) Regulating land use changes, especially in floodplain areas; and 4) Integrating land use planning with geological risk mapping. These efforts are essential to support sustainable watershed management while ensuring the balance between environmental conservation and socio-economic development.

4.4. Flood Hazard Zoning

The delineation of flood-prone zones in the Tarusan Watershed was conducted using a weighted scoring method integrated with GIS-based spatial analysis. This method combines six primary biophysical indicators (rainfall, slope, landform, land use, soil type, and geological formation). Each indicator was classified into sub-indicators, weighted according to their relative importance, and assigned specific scores. The total composite score for each spatial unit (grid) was calculated by multiplying the indicator weight with its corresponding sub-indicator score. This approach allows for a comprehensive and objective assessment of flood risk based on the spatial variability of natural and anthropogenic factors across the watershed. It also helps to prioritize areas for intervention based on their hazard levels. The final score ranges from 65 (lowest hazard) to 325 (highest hazard). To classify flood hazard zones, Eq. 1 was applied to generate class intervals of 86, resulting in three hazard classes (low, medium, and high). The spatial distribution of these flood hazard zones is presented in **Figure 6** below. **Figure 6** shows that flood-prone areas in the Tarusan Watershed are closely correlated with the spatial interaction of biophysical characteristics and land use patterns. The classification results indicate:

1) High Hazard Zone (22% of the watershed, 65.95 km²) concentrated in downstream and lowland areas along the main river corridors. Influenced by flat slopes, high rainfall, alluvium deposits (Qal), and intensive human activities (agriculture and settlements). Similar findings were reported by Barrocu & Eslamian (2022), who found that downstream zones with loose sediment and human pressures are highly vulnerable to flooding;

2) Medium Hazard Zone (58% of the watershed, 174.16 km²) dominant in the midstream region. Characterized by moderate slopes, mixed land uses (gardens and farming), and geological diversity.

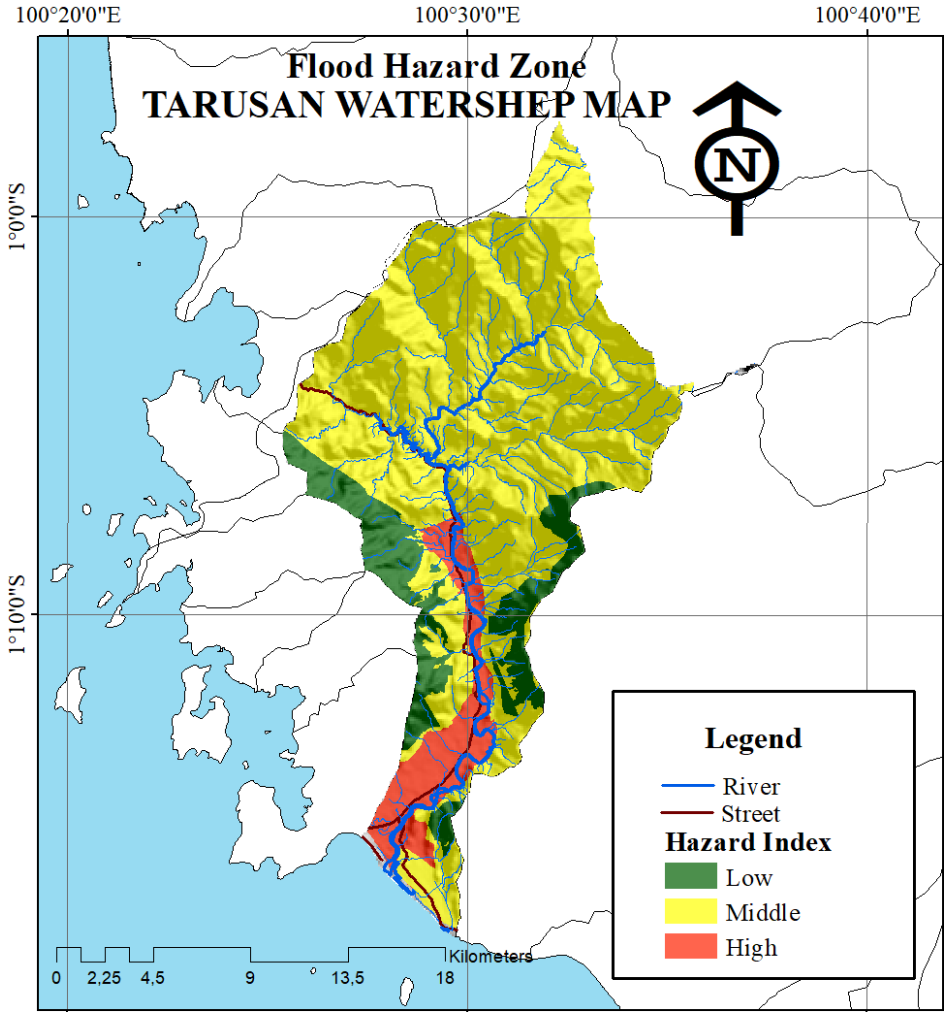

Fig. 6. Map of The Flood Hazard Zone Map in the Tarusan Watershed.

Aligned with findings of Robertella (2010), who emphasized that transitional slopes combined with land conversion activities lead to increased runoff; and 3) Low Hazard Zone (20% of the watershed, 60.16 km²) located in the upstream region with steep slopes, dense forest cover, and resistant geological formations (Granite-Tgr and Volcanic-Qv). This confirms the protective role of forests in reducing runoff and controlling peak discharge, as supported by Sakals et al. (2006). For more details, please see **Table 11.**

The distribution of flood hazard zones in the Tarusan Watershed reflects the interaction of environmental conditions, land cover changes, and geological formations. The results align with previous studies that emphasize the importance of combining structural factors (topography and geology) with non-structural factors (land use and rainfall) for accurate flood hazard assessment. Studies such as Tehrany et al. (2014) in Malaysia; Mohammadifar et al. (2023) in Ghana confirm the effectiveness of integrated geospatial modeling approaches, such as the use of GIS-based multi-criteria evaluation and machine learning, in accurately delineating flood susceptibility zones by combining both structural variables (e.g., slope, elevation, and drainage density) and non-structural factors (e.g., land use, rainfall intensity, and human activity).

Table 11.

Flood Hazard Zone Classification in the Tarusan Watershed.

Flood Hazard Class	Score Interval	Area (km²)	Area (%)	Recommended
Low Hazard	65 – 115	60.16	20	Forest protection, reforestation with native species, check dams, micro-catchments
Medium Hazard	116 – 237	174.16	58	Agroforestry, vegetative buffer strips, contour trenching, sustainable farming practices
High Hazard	238 – 325	65.95	22	Riparian buffer zones, infiltration trenches, retention ponds, settlement zoning regulation

Source: Results of data analysis 2023.

These methods have proven particularly valuable in tropical and developing regions, where rapid land cover change intensifies flood risks. Similarly, Samela et al. (2025) in Italy and Crăciun et al. (2022) in Romania demonstrated that terrain morphology, vegetation cover, and hydrological dynamics significantly influence flood-prone areas. Their findings emphasize the necessity of integrating physical watershed characteristics with anthropogenic drivers to produce realistic and actionable flood hazard maps. Such international evidence reinforces the relevance and applicability of a hybrid structural–non-structural mitigation strategy as proposed for the Tarusan Watershed. Flood hazard mitigation strategies in this watershed should focus on:

1) Reforestation and forest conservation in upstream regions;
2) Slope stabilization and erosion control in midstream areas;
3) Regulation of land use change, especially in downstream floodplain zones; and
4) Integrated watershed management combining structural and non-structural approaches.

Each of these strategies should be supported by specific conservation techniques tailored to the hazard level of the area, such as forest protection and check dams in low-risk zones, agroforestry and contour trenches in moderate-risk areas, and riparian buffers and retention ponds in high-risk floodplains. The approach follows the Indonesian Government's policy on disaster risk reduction (Law No. 24/2007), BNPB's implementation of NBS, and sustainable watershed management practices (Hadi, 2020).

4.5. Integration of AHP-Based Strategies with Flood Hazard Zoning Results in the Tarusan Watershed

The integration between the flood hazard zoning results (**Figure 6**) and the priority strategies produced from the AHP method (**Figure 7** based on **Table 12**) provides a comprehensive framework for designing effective flood disaster mitigation and watershed conservation strategies in the Tarusan Watershed. The flood hazard mapping analysis classified the watershed into three hazard zones (low, medium, and high) based on the weighted scoring of six main indicators (rainfall, slope, landform, land use, soil type, and geological formation).

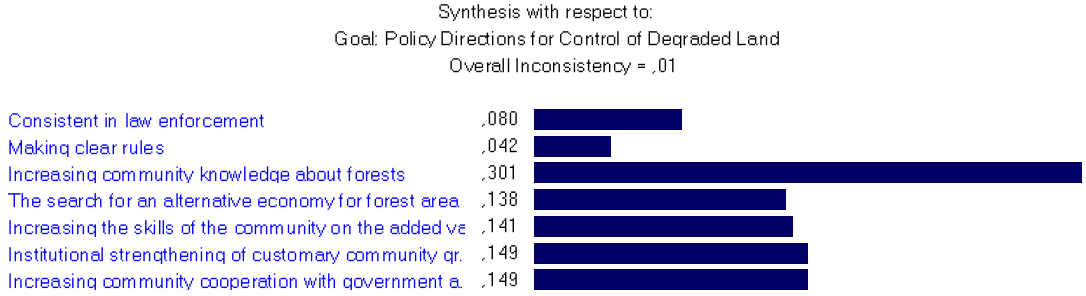

Fig. 7. Priority Weight of Flood Disaster Mitigation Strategies using the AHP in the Tarusan Watershed.

Each zone exhibits different environmental characteristics, requiring different strategic interventions. Meanwhile, the AHP analysis involved 25 experts from various relevant institutions in the Pesisir Selatan Regency. The evaluation identified seven strategic alternatives (A1–A7) under three main strategic pillars (Regulation, Education, and Institutional Strengthening). The highest priority strategy was increasing community knowledge about forests (A3), followed by strengthening customary community institutions (A6), and enhancing community-government collaboration (A7).

Table 12.

Priority Ranking of Flood Disaster Mitigation Strategies in the Tarusan Watershed.

Strategic Action	Code	Priority Weight	Rank
Increasing community knowledge about forests	A3	0.301	1
Strengthening customary community institutions	A6	0.149	2
Increasing community cooperation with government agencies	A7	0.149	2
Enhancing community skills in forest product utilization	A5	0.141	4
Promoting alternative forest-based economies	A4	0.138	5
Consistent enforcement of environmental regulations	A1	0.080	6
Establishment of clear and transparent rules	A2	0.042	7

The integrated analysis shows a strong correlation between the AHP-based strategies and the specific conditions of each flood hazard zone within the Tarusan Watershed. The recommended strategies are summarized in **Table 13** below.

Table 13.

Strategic Relationship between AHP Priority Strategies and Flood Hazard Zones in the Tarusan Watershed.

Flood Hazard Zone	AHP Priority Strategy	Explanation
Upstream (Low Hazard)	A3, A6	Reinforce environmental literacy and participatory forest governance to maintain protective forest functions. Forest conservation is crucial to reduce runoff and prevent land degradation.
Midstream (Medium Hazard)	A4, A5, A7	Promote alternative livelihoods and improve community skills in sustainable forest product utilization. Encourage collaboration between local communities and government to stabilize land use and control erosion.
Downstream (High Hazard)	A1, A2, A7	Strengthen regulation enforcement, formulate clear and transparent land use rules, and foster community-government synergy to manage flood risks effectively in high-risk areas dominated by settlements and agricultural activities

This strategic integration confirms that flood disaster mitigation in the Tarusan Watershed cannot rely solely on structural engineering approaches (such as embankments or dams) but must be strengthened by non-structural measures through community-based efforts, education, and institutional empowerment. In the upstream regions, classified as low hazard zones, the main concern is maintaining forest cover and preventing further degradation through environmental education (A3) and strengthening local institutions (A6). In the midstream areas, categorized as medium-hazard zones, the focus should be on reducing forest exploitation by improving local skills (A5), promoting alternative economies (A4), and enhancing collaboration with the government (A7). Meanwhile, in downstream regions categorized as high hazard zones, regulation and law enforcement (A1 and A2) are essential to control settlement expansion and prevent land use conversion. Community involvement (A7) is also critical in improving adaptive capacity and disaster preparedness.

This finding supports previous study and Indonesian government policies, particularly Law No. 24/2007 concerning "Disaster Management" and Presidential Regulation No. 87/2017 concerning "Social Forestry", which emphasize the importance of Community-based Disaster Risk Reduction (CBDRR) and sustainable watershed management.

5. CONCLUSIONS

This study concludes that the physical and environmental characteristics of the Tarusan Watershed play a crucial role in shaping its hydrological response and vulnerability to flood disasters. A spatial analysis of slope gradients and rainfall intensity shows that the upstream and midstream regions are predominantly characterized by steep to very steep slopes, covering approximately 63% of the total watershed area. These steep slopes significantly increase surface runoff, accelerate erosion, and reduce infiltration capacity, particularly in areas affected by deforestation and land-use change. Moreover, the northern and central zones receive high annual rainfall, ranging from 4,000 mm to over 5,000 mm, which intensifies peak runoff during extreme weather events. Soil and landform analysis further supports the identification of high-risk flood zones. Oxisols and Ultisols dominate the watershed's soil types, accounting for 45% and 30%, respectively. These soils have low infiltration capacity and high erodibility, contributing to rapid water movement and downstream sedimentation.

The presence of fluvial and marine landforms in low-lying areas, especially in the southern coastal region, increases flood susceptibility due to their function as sediment deposition zones and their proximity to estuarine systems. Land use classification reveals significant landscape transformation. Forested areas now cover only 21.6% of the watershed, while mixed gardens (32.7%) and agricultural land (25.9%) have expanded, particularly in the midstream and downstream regions. Settlements and bare land often located near riverbanks contribute heavily to increased flood risk due to impervious surfaces and land degradation.

Flood hazard zoning, derived from a weighted scoring model using six indicators (slope, rainfall, soil, landform, geology, and land use), classifies the watershed into three zones: low (20%), medium (58%), and high (22%) hazard. High-risk zones are concentrated downstream, while low-risk zones lie upstream with steep terrain and dense forest cover.

Integrating these findings with AHP-based strategic priorities shows that different zones require tailored interventions. In upstream areas, priority strategies include increasing environmental knowledge (A3) and strengthening local institutions (A6). Midstream areas benefit from promoting alternative livelihoods (A4), enhancing community skills (A5), and fostering cooperation (A7). Downstream areas require strong regulation (A1), clear land-use rules (A2), and community-government synergy (A7). Where the recommendations from the results of this research are 1) To enhance flood resilience and ensure sustainable watershed management, we recommend; 2) Community-based environmental education and awareness programs in upstream zones; 3) Development of forest-based economies and skill-building programs in midstream areas; 4) Strengthened enforcement of land use regulations and collaborative governance in downstream regions; and 5) Integration of NBS and Eco-DRR into local policy frameworks.

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