Landslide Hazard Index Assessment Using GIS and AHP in Tapalang, Mamuju, West Sulawesi Province, Indonesia

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ABSTRACT

Landslides pose a significant threat to the Tapalang District in Mamuju, because of its geographical conditions, steep slopes, high rainfall intensity, and frequent seismic activity. This study aims to analyze the Landslide Hazard Index (LHI) in the region using Geographic Information Systems (GIS) and the Analytical Hierarchy Process (AHP) to determine the spatial distribution of the landslide risks and identify high-risk zones. The methodology incorporates topographical, geological, land use, soil type, and rainfall data, assessed through an AHP-based multi-criteria analysis, and mapped using GIS tools to create a comprehensive landslide susceptibility map. The results indicate that Tapalang District shows different levels of landslide susceptibility, with high-risk areas primarily found in regions featuring steep slopes, loose soil composition, and notable land-use changes. Moderate-risk zones encompass a significant portion of the district and necessitate ongoing monitoring, whereas low-risk areas are largely situated in flatter, more stable regions. The novelty of this study lies in the integrated use of GIS and AHP to improve the accuracy of landslide risk assessment by offering a quantitative and spatially detailed risk classification. This innovation provides a replicable and scalable decision-support model for local governments and disaster management agencies to develop proactive mitigation strategies, including early warning systems, land-use regulation enforcement, and slope stabilization measures. This research contributes to disaster management planning by providing a robust framework for assessing and mitigating landslide hazards in Tapalang and other similarly vulnerable regions.

Keywords-landslide hazard index; GIS; AHP; disaster risk assessment; Tapalang; Mamuju

I. INTRODUCTION

Landslides represent a common natural hazard, leading to substantial infrastructure damage, loss of life, and economic setbacks. The increasing frequency and intensity of these events have been linked to various factors, including climate change, deforestation, and urban expansion into vulnerable areas. Understanding and assessing landslide hazards is imperative for an effective disaster risk reduction and sustainable land-use planning [1-3]. The integration of advanced technologies has improved the accuracy of landslide hazard assessments. GIS allow for the analysis and visualization of spatial data related to landslide-prone areas. The former enable the integration of various thematic layers, including topography, geology, and land use, to identify areas prone to landslides. Analyzing spatial data is essential for developing precise hazard maps and guiding mitigation strategies [4]. In conjunction with GIS, AHP provides a structured decision-making framework that helps evaluate and prioritize factors contributing to landslide susceptibility. AHP involves breaking down the problem into a hierarchy of sub-problems, enabling pairwise comparisons and the assignment of weights to each criterion based on their relative importance. This method improves the objectivity and reliability of hazard assessments by systematically quantifying expert judgments [5]. The effectiveness of combining GIS and AHP in landslide hazard assessments has been demonstrated. For instance, research conducted in the Great Xi'an Region, China, utilized this integrated approach to delineate landslide susceptibility zones effectively. It was shown that the GIS-AHP model could accurately identify high-risk regions, thus supporting disaster preparedness and land-use planning [5]. Similarly, an assessment in the Reggio Calabria metropolitan area of Italy employed GIS and AHP to evaluate landslide risks. Factors, such as slope, rainfall, and proximity to roads, were incorporated into the performed analysis, resulting in a detailed susceptibility map. This map serves as a critical resource for local authorities in implementing targeted mitigation measures and optimizing resource allocation [6].

Landslides frequently occur in Indonesia, especially in areas with rugged terrain and heavy rainfall. The Tapalang District in Mamuju, West Sulawesi, is an indicative example of this. It has steep slopes and a history of landslides. Despite the evident risks, studies focusing on landslide hazard assessment in this district are still limited. Addressing this gap is crucial for developing effective mitigation strategies and safeguarding local communities. This research aims to provide a thorough landslide hazard assessment of Tapalang District by combining GIS and AHP. The resulting susceptibility map reflects the area's unique geological and environmental conditions. This map will be a valuable resource for policymakers, urban planners, and disaster management agencies, helping them develop evidence-based interventions. Furthermore, this study fills a gap in the existing literature by applying the GIS-AHP model in regions with limited data, such as Tapalang, hence demonstrating that reliable hazard assessments can be achieved even with limited resources. Analyzing the LHI in Tapalang will be achieved by identifying and assessing key vulnerability factors, creating a hazard map, and providing recommendations. Through this analysis, the study aims to strengthen the community's resilience against landslides and promote sustainable development practices in the region.

II. MATERIAL AND METHODS

A. Research Location

The research focuses on Tapalang, a sub-district in Mamuju Regency, West Sulawesi. This region is especially prone to landslides because of its steep landscape, unstable soil composition, significant rainfall, and frequent seismic events (Figure 1).

B. Strategic Issues of Landslide Disaster in Tapalang District

The 2021 earthquake worsened land instability, raising the risk of mass movements. Deforestation, uncontrolled land use, and infrastructure development without appropriate geological assessments have further accelerated environmental degradation [15]. These factors highlight the necessity for effective disaster risk management strategies that integrate scientific analysis with policy actions. Tapalang faces serious challenges due to the limited disaster preparedness and mitigation efforts. The lack of early warning systems, inadequate geotechnical monitoring, and low public awareness elevate the area's vulnerability to landslides. The insufficient emergency response infrastructure further hinders recovery. A coordinated effort involving government, communities, and researchers is essential to improve resilience. Utilizing GIS-based risk mapping and AHP decision-making can enhance prediction, planning, and response. Table I presents reported landslide incidents from 2021 to 2024.

C. GIS in Landslide Disaster Analysis

GIS is crucial for analyzing landslide risks by integrating data, such as topography, soil type, land use, rainfall, and past events to create hazard maps. Authors in [7, 8] showed that GIS improves risk assessments by identifying high-risk areas and supporting land-use planning and disaster management. Combining GIS with methods, like AHP and machine learning, further enhances accuracy, as highlighted in [9]. GIS-based mapping improves early warning systems and refines predictions in complex terrains, demonstrating its substantial role in landslide hazard assessment and proactive disaster management [10, 11].

D. AHP in Determining Landslide Hazard Index

The AHP is a decision-making method used to evaluate landslide hazards by assigning weight values to factors, such as slope, soil type, land cover, rainfall, and fault proximity. Introduced in [12], AHP helps organize complex problems into a clear hierarchy for consistent evaluations. Authors in [5, 8] demonstrated that AHP enhances landslide susceptibility mapping by combining expert judgment with geospatial data. When paired with GIS, AHP enhances hazard zoning accuracy and minimizes bias [5, 13]. Research in countries, like Bangladesh [9], confirms AHP’s reliability in landslide risk assessment and its role in effective mitigation planning.

E. Research Approach

This study evaluates the LHI in Tapalang District, Mamuju. GIS and AHP were integrated to develop a susceptibility map that categorizes the region into risk zones. This approach combines data-driven analysis with expert judgment, yielding reliable results to guide disaster risk reduction and land-use planning.

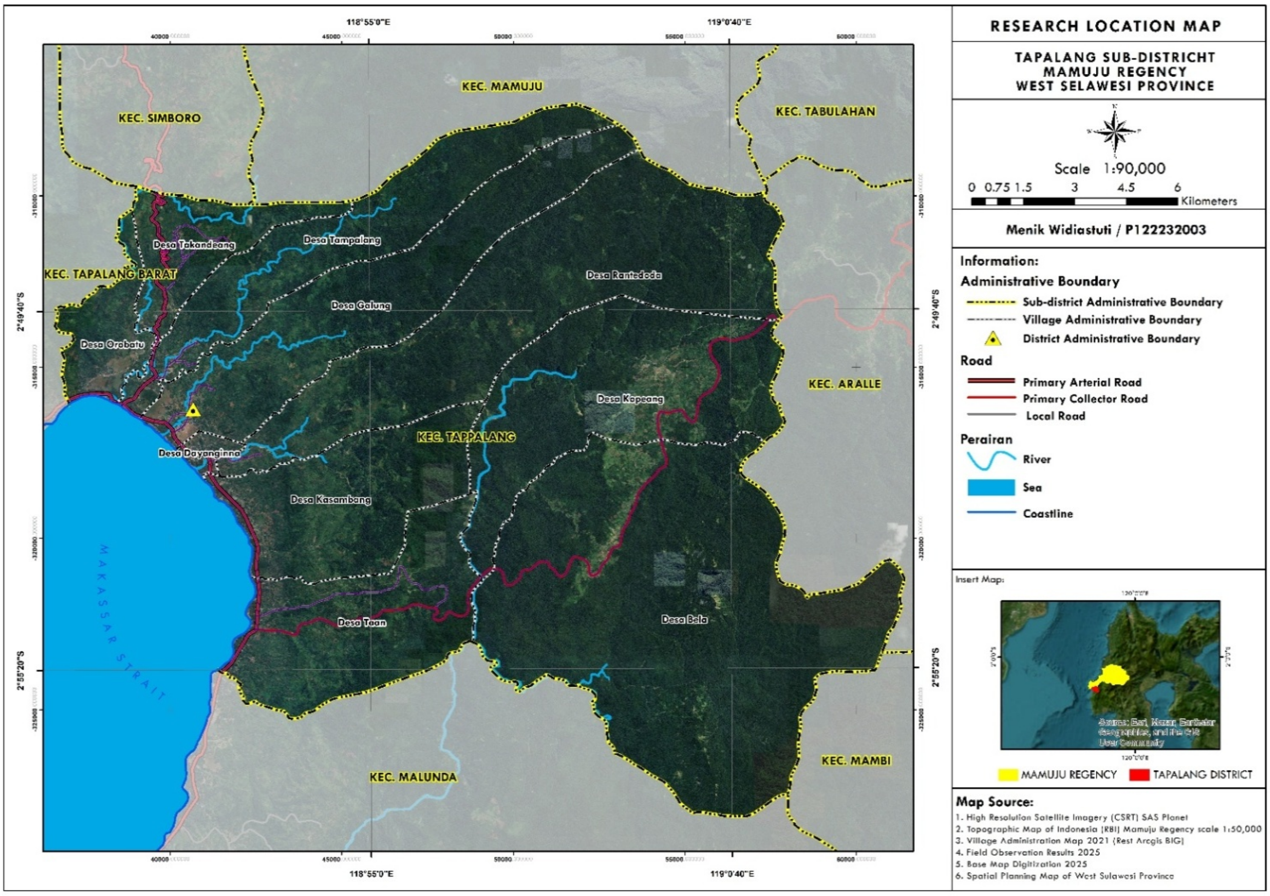

Fig. 1. Research location.

F. Research Methodology

The data collection includes geological maps, soil characteristics, Digital Elevation Models (DEM), slope measurements, meteorological data, satellite imagery, as well as field surveys (GPS points) of previous landslides. These datasets assist in identifying key landslide factors, including the slope gradient, soil type, rainfall, land use, and proximity to rivers, roads, and fault lines. The data are processed in GIS by being converted into thematic layers, which are subsequently analyzed through spatial overlays to identify vulnerable areas. AHP is used to assign weights to each factor based on expert judgment, with a consistency check to ensure reliable results. The weighted layers are integrated into GIS to generate the LHI map, categorizing the area into five risk levels, which is validated against historical landslide data for accuracy. The findings are utilized to identify high-risk areas and provide recommendations for land-use planning, infrastructure, and disaster mitigation, offering a comprehensive approach to managing landslide risks in the region.

III. RESULTS AND DISCUSSION

The first step in assessing landslide susceptibility is gathering data on key factors that contribute to landslide activity. In Tapalang District, Mamuju Regency, seven factors: slope, lithology, elevation, rainfall, land use, and proximity to roads and rivers, were chosen for their impact on landslides. This study enhances previous research by analyzing additional factor classes and refining the weightings for each, ensuring a more accurate and varied distribution of weights, in contrast to the uniform classifications.

A. Slope Factor

Slope is an important factor in landslide risk, as steeper slopes increase the shear stress on soil, which raises the likelihood of failure. The slope also influences stability by affecting exposure to rainfall, sunlight, and wind erosion. In this study, slope in degrees was derived from a DEM and ArcGIS, using topographic maps with 5-meter interval contours. Six slope categories were established to improve landslide susceptibility mapping, offering a more detailed risk assessment across various terrains. Table II presents these categories and their results, clarifying the role of slope in landslide hazard analysis.

Furthermore, Table II illustrates the weighted values of the main factors affecting landslides in Tapalang District, including slope, land use, elevation, rainfall, lithology, and proximity to rivers and roads. High-risk areas are associated with steep slopes, bare land, high rainfall, soft soils, and closeness to rivers or roads. These findings align with those of previous studies and emphasize both natural conditions and human activities as significant contributors to landslide risk. This study employs a more detailed classification method, offering better spatial insight for disaster mitigation and urban planning in Mamuju.

TABLE I. LANDSLIDE INCIDENT IN TAPALANG DISTRICT DATA SOURCE ONLINE MEDIA

No.	Description	Time of event	Source	Documentation
1	Landslide in Takandeang Village, Tapalang District due to earthquake	January 15, 2021	Tribunnews. Com, Mamuju	
2	Landslide in Takandeang Village, Tapalang District causes congestion on the Trans Sulawesi route	November 12, 2021	Antara	
3	Landslide Disaster in Kelapa Tujuh Village, Binanga Subdistrict, Mamuju District - Jl. Poros Takandeang Village, Tapalang Subdistrict - Kondobulo Village, Kalumpang Subdistrict	May 9, 2022	West Sulawesi Regional Disaster Management Agency	
4	Landslide Disaster - Binanga Sub-district - Takandeang Village - Kondobulo Village	May 10, 2022	West Sulawesi Regional Disaster Management Agency	
5	Landslide at 3 points in Takandeang Village, Tapalang District	October 24, 2024	Republika.Co .Id, Mamuju	

B. Lithology Factor

The lithology factor is significant to landslide risk in Tapalang District, with mixed sediments and soft soils having the highest weights (0.30 and 0.25), indicating a strong influence on slope instability. Weathered rocks and volcanic deposits also add to the risk, particularly under heavy rainfall conditions. These findings align with past research indicating that soft, unconsolidated soils increase landslide susceptibility. The results highlight the need for detailed geological studies and slope stabilization efforts in high-risk areas [13].

TABLE II. WEIGHT OF THE INDIVIDUAL CLASSES OF LANDSLIDE HAZARD FACTORS

Landslide hazard factor	Factor class	Wi,L
Slope degree	0° – 5° (Flat)	0.05
	5° – 15° (Gentle)	0.15
	15° – 25° (Moderate)	0.30
	25° – 35° (Steep)	0.25
	35° – 45° (Very Steep)	0.15
	> 45° (Extremely Steep)	0.10
Land use	Dense Vegetation	0.10
	Agricultural Land	0.20
	Settlement Area	0.25
	Bare Land	0.30
	Water Bodies	0.15
Elevation (m)	0 – 100	0.10
	100 – 300	0.20
	300 – 500	0.30
	500 – 1000	0.25
	> 1000	0.15
Rainfall (mm/year)	< 1500	0.10
	1500 – 2000	0.20
	2000 – 2500	0.30
	2500 – 3000	0.25
	> 3000	0.15
Lithology	Hard Rock	0.10
	Weathered Rock	0.20
	Mixed Sediments	0.30
	Soft Soil	0.25
	Volcanic Deposits	0.15
River distance (m)	< 100	0.30
	100 – 300	0.25
	300 – 500	0.20
	500 – 1000	0.15
	> 1000	0.10
Road distance (m)	< 100	0.30
	100 – 300	0.25
	300 – 500	0.20
	500 – 1000	0.15
	> 1000	0.10

C. Elevation Factor

Elevation significantly affects the landslide risk in Tapalang District, with areas between 300–500 m having the highest weight (0.30), followed by those between 500–1000 m (0.25). These mid-to-high elevations are more susceptible to landslides due to steeper slopes, increased runoff, and erosion. This complies with studies indicating that hilly regions face greater landslide threats. Conversely, lowland areas below 100 m are more stable. These findings emphasize the need for targeted mitigation in elevated zones where communities and infrastructure are at higher risk [8].

D. Rainfall Factor

Rainfall is a significant trigger for landslides in Tapalang District, with areas receiving 2000–3000 mm/year facing the highest risk (weight 0.30). The intense rainfall heightens soil saturation, weakens slopes, and increases pore water pressure, resulting in landslides. This corresponds with studies indicating that frequent, heavy rain leads to slope failures, particularly in steep and soft soil regions, like Mamuju. The combination of substantial rainfall and weak soil underscores the necessity for early warning systems and effective drainage to mitigate the aforementioned risk.

E. Land Use Factor

Land use significantly impacts landslide risk in Tapalang District, with bare land (0.30) and settlements (0.25) exhibiting the highest susceptibility. These areas are more vulnerable to landslides due to erosion, runoff, and weakened slopes resulting from human activity. It has been confirmed that deforestation and urban development elevate this risk. In contrast, dense vegetation (0.10) contributes to slope stability. This emphasizes the importance of sustainable land use, reforestation, and slope protection in mitigating landslide hazards.

F. Distance of Road and River Factor

Proximity to roads and rivers strongly affects the landslide risk in Tapalang District, particularly within 100 meters, which has the highest weight (0.30). The slopes near roads and rivers are more susceptible to landslides due to excavation, traffic vibrations, and erosion caused by water flow. Authors in [5] confirm that construction and riverbank undercutting increase slope instability. In Mamuju, poor road design and heavy rainfall exacerbate erosion in steep, unstable terrains. These findings emphasize the need for improved road planning, slope protection, and riverbank stabilization to mitigate landslide hazards [14].

G. Assign Weights

In this study, the weight of each landslide conditioning factor class was calculated using a Predictive Accuracy Index (PAI)-based weighting approach, which utilizes historical landslide data to quantify the contribution of each factor class to landslide susceptibility, as depicted in Table III.

This approach utilizes historical data to evaluate the strength of each factor's contribution to slope instability. Analyzing past incidents, delivers a more precise and data-driven assessment of landslide susceptibility. The method enhances the reliability of hazard mapping by quantifying the impact of each factor. As a result, it promotes more informed decision-making for land use planning and disaster mitigation. Table III enhances the previous classification by using Wi, PAI, which reflects the weight of each factor based on historical landslide events identified through the PAI method. The difference between Wi, L and Wi, PAI demonstrates how actual landslide data improve the accuracy of susceptibility mapping.

The AHP method [12] is a decision-making tool that compares multiple factors affecting landslide susceptibility. It utilizes a pairwise comparison matrix to assign weights based on expert judgment and past landslide events. In this study, a 7×7 matrix with a rating scale from 1 to 9 was employed, where higher values indicate greater importance. For instance, slope was deemed significantly more important than elevation, resulting in a weight of 8. This method aids in evaluating the relative impact of factors, such as slope, lithology, rainfall, and land use. Merging AHP with historical landslide data from the PAI method enhances the model's accuracy, corroborating theoretical assumptions with real-world data. Comparable studies indicate that the application of AHP improves the predictive accuracy compared to single-variable methods, rendering this combined approach more dependable for landslide risk management in Tapalang District.

TABLE III. WEIGHT OF FACTOR CLASSES IN THE LANDSLIDE AREAS IDENTIFIED BY PAI.

Landslide hazard factor	Factor class	Wi,L	Wi, PAI
Slope degree	0° – 5° (Flat)	0.05	0.04
	5° – 15° (Gentle)	0.15	0.08
	15° – 25° (Moderate)	0.30	0.14
	25° – 35° (Steep)	0.25	0.28
	35° – 45° (Very Steep)	0.15	0.22
	> 45° (Extremely Steep)	0.10	0.12
Land use	Dense vegetation	0.10	0.08
	Agricultural land	0.20	0.18
	Settlement area	0.25	0.27
	Bare Land	0.30	0.32
	Water bodies	0.15	0.15
Elevation (m)	0 – 100	0.10	0.09
	100 – 300	0.20	0.22
	300 – 500	0.30	0.31
	500 – 1000	0.25	0.26
	> 1000	0.15	0.12
Rainfall (mm/year)	< 1500	0.10	0.14
	1500 – 2000	0.20	0.22
	2000 – 2500	0.30	0.33
	2500 – 3000	0.25	0.24
	> 3000	0.15	0.07
Lithology	Hard rock	0.10	0.17
	Weathered rock	0.20	0.22
	Mixed sediments	0.30	0.33
	Soft soil	0.25	0.28
	Volcanic deposits	0.15	0.11
River distance (m)	< 100	0.30	0.34
	100 – 300	0.25	0.26
	300 – 500	0.20	0.18
	500 – 1000	0.15	0.12
	> 1000	0.10	0.08
Road distance (m)	< 100	0.30	0.32
	100 – 300	0.25	0.27
	300 – 500	0.20	0.18
	500 – 1000	0.15	0.13
	> 1000	0.10	0.08

TABLE IV. PAIRWISE COMPARISON MATRIX

Factor	Slope	Lith.	Elev.	Rainfall	Land use	Road distance	River distance
Slope	1.00	6.00	8.00	5.00	7.00	4.00	3.00
Lith..	0.17	1.00	3.00	2.00	4.00	2.00	2.00
Elev.	0.13	0.33	1.00	3.00	2.00	2.00	1.50
Rainfall	0.20	0.50	0.33	1.00	2.00	2.00	2.50
Land use	0.14	0.25	0.50	0.50	1.00	3.00	3.00
Road distance	0.25	0.50	0.50	0.50	0.33	1.00	3.00
River distance	0.33	0.50	0.67	0.40	0.33	0.33	1.00

The AHP pairwise comparison matrix, displayed in Table IV, evaluates the significance of landslide factors based on expert judgment and historical events. Slope is the most influential factor with the highest weight (8.00), followed by lithology (6.00) and rainfall (5.00), as steeper slopes contribute to an increased instability. Lithology influences soil strength and permeability, while elevation affects water drainage. Rainfall, a primary trigger, is weighted higher than the land use, road distance, and river distance, underscoring its role in landslide initiation. Urbanization and deforestation heighten susceptibility, while proximity to roads and rivers can exacerbate erosion. This comparison provides an objective ranking of factors, enhancing hazard mapping in Tapalang District. After assessing the eigenvector matrix, the weights for each factor were established and are presented in Table V.

TABLE V. WEIGHT OF NORMALIZED LANDSLIDE HAZARD FACTORS THROUGH AHP METHOD

Factor	Normalized weight (AHP)
Slope	0.30
Lithology	0.18
Elevation	0.12
Rainfall	0.15
Land use	0.10
Road distance	0.08
River distance	0.07

The AHP method demonstrates the influence of various factors on landslide susceptibility in Tapalang, Mamuju Regency. Slope has the highest weight (0.30), highlighting its major role in landslides due to increased gravitational force. Lithology (0.18) follows, impacting slope stability, while rainfall (0.15) initiates soil saturation and landslide events. Elevation (0.12) and land use (0.10) also affect water drainage and surface conditions. Road distance (0.08) and river distance (0.07) influence erosion and slope weakening. These weights offer a data-driven approach for effective hazard mapping and mitigation planning. The Landslide Index (LI) for each pixel was computed using a weighted sum, integrating three components (1): the weight from the land proportion of each factor (Wi, L), the weight from landslide-prone areas identified by PAI (Wi, PAI), and the weight from the AHP method (Wi, AHP):

$$LI = \sum_{i=1}^{n} W_{i,L} + W_{i,PAI} + W_{i,AHP} \quad (1)$$

Landslide susceptibility in Tapalang, Mamuju Regency, was classified into five risk levels: low risk (values below 0.17), moderate risk (0.1701–0.25), high risk (0.2501–0.3), and very high risk (above 0.301). The analysis revealed that 61% of the area has high to very high susceptibility. Specifically, 7% is low risk, 32% is moderate risk, 36% is high risk, and 25% is very high risk. The classification applied consistent thresholds to ensure a balanced and uniform distribution of the risk levels, which aids in accurate hazard assessment for disaster mitigation.

The analysis indicates that 35% of Tapalang District in Mamuju Regency is at moderate landslide risk, while 25% faces high risk. The model closely aligns with the PAI analysis, providing improved accuracy over previous studies, with only an 8% overestimation in moderate to high-risk areas. It also identifies landslide-prone zones overlooked by PAI, which are significant due to their proximity to infrastructure and transportation networks. This underscores the need to incorporate these findings into disaster mitigation and land-use planning.

This approach can be applied to other areas in Mamuju Regency to create a comprehensive landslide susceptibility map, aiding in planning slope stabilization and identifying critical roads for risk mitigation. The findings guide decision-makers in prioritizing resources and budgets for the most vulnerable areas. This study also establishes a foundation for field inspections and engineering evaluations to assess infrastructure risk. Future research will focus on refining these assessments and identifying effective strategies to reduce risks and enhance regional resilience.

IV. CONCLUSION

This study assessed landslide hazards in Tapalang, Mamuju Regency, using Geographic Information Systems (GIS) and the Analytical Hierarchy Process (AHP) to integrate seven key factors: slope, lithology, elevation, rainfall, land use, road distance, and river distance. A landslide susceptibility map was created, revealing that a large portion of the area is at high or very high risk. Slope and lithology were found to be the most influential factors, which aligns with previous research. The method's effectiveness was confirmed through pairwise comparisons, consistency checks, and validation against historical data, ensuring the model's accuracy and reliability.

The findings are essential for disaster risk reduction and spatial planning in Mamuju Regency. The landslide susceptibility map can assist local authorities in prioritizing land-use planning, infrastructure development, and mitigation measures. Future studies should aim to incorporate real-time data, climate change projections, and machine learning to further enhance prediction accuracy. The combination of GIS and AHP offers a robust tool for assessing landslide hazards and can be applied to other regions with similar conditions to develop more effective disaster resilience strategies.

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