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Analytical Hierarchy Process (AHP) for Landslide Vulnerability Zoning in the Gumelar Area

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Abstract

Landslides are geological disasters that frequently occur in regions with steep topography and limited vegetation cover, including Gumelar Subdistrict in Banyumas Regency. This study aims to map landslide vulnerability zones using a multi-criteria decision-making approach through the Analytical Hierarchy Process (AHP), integrated with a Geographic Information System (GIS). Four key parameters—slope gradient, rainfall, lithology, and land cover—were analyzed and weighted based on expert evaluations using a pairwise comparison matrix. The analysis reveals that slope gradient (49.2%) and rainfall (30.9%) are the most influential factors in determining vulnerability levels. The resulting vulnerability map, classified into low-, moderate-, and high-risk zones, was validated using field-observed landslide data. This study provides a reliable spatial foundation to support effective landslide disaster mitigation and risk reduction strategies in the study area.

Keyword: Landslides; Analytical Hierarchy Process; vulnerability mapping; GIS; Gumelar

Abstrak

Longsor merupakan bencana geologi yang sering terjadi di wilayah bertopografi curam dan minim vegetasi, seperti di Kecamatan Gumelar, Kabupaten Banyumas. Studi ini memetakan zona kerentanan longsor menggunakan metode AHP yang terintegrasi dengan SIG. Empat parameter utama—kemiringan lereng, curah hujan, litologi, dan tutupan lahan—diberi bobot berdasarkan evaluasi ahli. Hasil menunjukkan kemiringan lereng (49,2%) dan curah hujan (30,9%) sebagai faktor dominan. Peta kerentanan yang diklasifikasikan ke dalam zona rendah, sedang, dan tinggi ini divalidasi dengan data kejadian longsor lapangan, memberikan dasar spasial yang kuat untuk mitigasi risiko bencana.

Kata-kata kunci*: Tanah longsor; Analytical Hierarchy Process; pemetaan kerentanan; SIG; Gumelar*

1. Introduction

Landslides have long been considered a geological threat in tropical regions, particularly in areas with complex topography [1]. In Southeast Asia, approximately 85% of landslide incidents are triggered by a combination of natural factors and human activities [2]. In Indonesia, Central Java Province accounts for approximately 22% of all national landslide incidents, with Banyumas Regency among the areas with a high risk level, with potential annual economic losses reaching Rp1.2 trillion [3]. One of the most affected areas in Central Java is Banyumas Regency. Based on Podes 2024 data, Banyumas Regency recorded 76 villages across 18 sub-districts affected by landslides in the past year, with the highest distribution in Gumelar Sub-district, totaling 9 villages [4] [5].

This study focuses on Gumelar Sub-district, Banyumas Regency, specifically on two villages with high landslide vulnerability: Cihonje Village and Cilangkap Village. These villages were selected based on data from the Banyumas Regional Disaster Management Agency in 2024, which reported at least eight significant landslide events during the 2021 to 2024 period. These incidents not only caused damage to road infrastructure and settlements but also temporarily isolated inter-village access [6].

The Analytical Hierarchy Process (AHP) method has become a primary approach in decision support systems (DSS) for landslide risk management. This approach is used to assess the relative importance of various parameters such as slope gradient, rainfall, lithology, and land cover [7]. The advantage of AHP lies in its ability to minimize subjectivity through the use of pairwise comparison matrices. In the context of landslide vulnerability mapping, AHP has been widely applied in various studies due to its capability to systematically and quantitatively assign weights based on expert judgment [8]. Furthermore, this method enables the integration of spatial and non-spatial data into Geographic Information Systems (GIS), thus allowing for the production of more precise vulnerability zoning maps [9].

Several previous studies have shown that the application of the Analytic Hierarchy Process (AHP) is effective in determining the vulnerability level of an area to landslides. However, the accuracy level of AHP in vulnerability mapping highly depends on the consistency of expert evaluations and the quality of the spatial data used. For example, in the Cameron Highlands, this method achieved an accuracy of 78% with a consistency ratio (CR) of 0.08, indicating that the pairwise comparisons used were quite reliable. Meanwhile, in Magelang, a higher accuracy of 80.95% was obtained through field validation processes [10][11].

Based on previous findings, this study adopts the Analytic Hierarchy Process (AHP) as a systematic multicriteria decision-making framework for mapping landslide vulnerability levels. The main objective of this research is to provide an accurate and reliable vulnerability map to support more targeted disaster planning and risk mitigation efforts.

2. Method

This study uses a quantitative descriptive approach with the Analytical Hierarchy Process (AHP) method integrated into a Geographic Information System (GIS). This approach was chosen because it can systematically combine spatial and non-spatial data to determine the level of landslide vulnerability based on various parameters.

2.1. Research Flow

The overall research methodology flow can be seen in Figure 1, which includes the stages from problem identification to GIS integration.

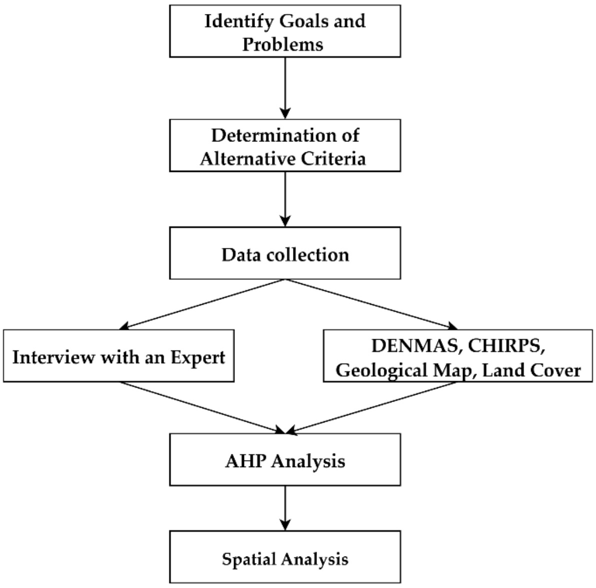

Figure 1. Research Flow

2.2. Identify Goals and Problems

The main objective of this study is to produce a landslide hazard zoning map. The hierarchical structure consists of three levels:

1. Level 1 (Goal): Determination of landslide risk level.
2. Level 2 (Criteria): Slope gradient, rainfall, lithology, and land cover.

3. Level 3 (Alternatives): Spatial units of the study area whose vulnerability will be mapped.

An illustration of the hierarchical structure is shown in **Figure 2**.

2.3. Determination of Alternative Criteria

The four main criteria used in the AHP analysis were determined based on a literature review and input from experts in geography and disaster mitigation. These criteria are: slope gradient derived from DEMNAS data with a resolution of 8.7 meters; rainfall based on CHIRPS data with a resolution of 0.05°; lithology sourced from a geological map at a 1:100,000 scale; and land cover obtained through interpretation of Landsat 8 OLI imagery. Each of these parameters was then classified into scoring classes with values ranging from 1 to 5, adjusted according to their level of vulnerability to landslide potential **[12] [13]**.

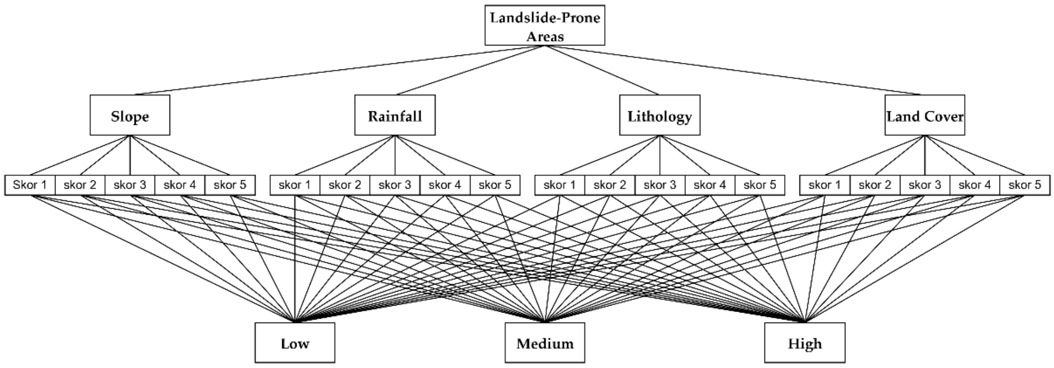

Figure 2. Hierarchical model of landslide cause parameters and vulnerability levels.

2.4. Data collection

This study used 100 random sample points taken from the study area using a raster-based random sampling method in QGIS. Each point was collected with parameter information including: slope gradient value (from DEMNAS), rainfall value (from CHIRPS data), lithology type (from the geological map), and land cover classification (from Landsat 8 OLI) [14][15][16][17]. The study area can be seen in **Figure 3**.

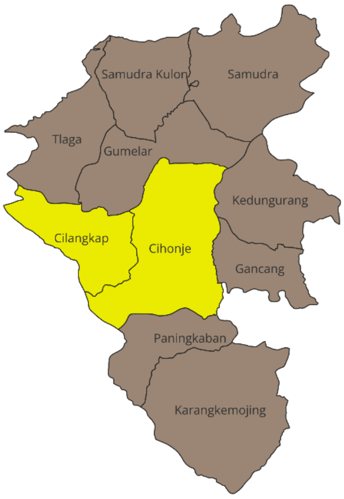

Figure 3. Research Location Map

To assess the vulnerability level at each sample point, a classification scheme based on the parameters in Table 2 was used. The slope gradient, rainfall, lithology type, and land cover of each point were converted into scores ranging from 1 to 5 according to their susceptibility to landslides. For example, a slope gradient of <5% is categorized as very low vulnerability and assigned a score of 1, whereas a slope of >35% is categorized as highly vulnerable and given a score of 5. These scores were determined based on their contribution to slope instability as explained by Suwarno et al. (2025).

The scoring process was carried out for all 100 random points using a raster-based random sampling method in QGIS. Each point was scored based on the parameter classifications, and the results were averaged per village to obtain representative values to be used in the AHP weighting and subsequent spatial analysis. The sampling process was conducted through the following steps:

1. The boundaries of the study area were determined based on the administrative maps of Cihonje Village and Cilangkap Village.
2. Using the "Random Points in Extent" tool in QGIS, sample points were generated randomly across the entire study area.
3. Each sample point was then extracted for information including: slope gradient value, rainfall, lithology type, and land cover.

The process of calculating the average vulnerability score for each parameter across all sample points can be mathematically explained through Equation (1) [18].

$$\boldsymbol{S_j = \frac{1}{n}\sum_{i=1}^{n} S_{i,j}} \quad (1)$$

Explanation:

S_j: the average score of the j-th parameter (for example, slope gradient) for one village.

$S_{i,j}$: the score of the i-th point for the j-th parameter.

N: the number of sample points.

2.5. AHP Analysis

In this study, the Analytic Hierarchy Process (AHP) was implemented by developing a web-based application using the Streamlit framework. The application was designed to facilitate users in performing the AHP calculation process in a structured and efficient manner. The following is a description of the AHP implementation through the features available in the application:

1. Pairwise Comparison among Criteria

After the criterion weights are determined, the next step is to compare alternatives for each landslide vulnerability criterion, such as slope gradient, rainfall, lithology, and land cover. At this stage, the application guides experts to assess spatial units (e.g., specific locations within the study area) by comparing the extent to which each unit exhibits landslide vulnerability across parameters. For example, the pairwise comparisons among alternatives based on the slope-gradient criterion are shown in **Table 1.**

Table 1. Pairwise Comparison by Criteria

Criteria	P1	P2	P3	P4
P1	1	2	3	4
P2	0,5	1	2	3
P3	0,33	0,5	1	2
P4	0,25	0,33	0,5	1
Amount	1,68	4,53	9,33	16

Source : Purbandini., 2019

Explanation:

P1: Slope Gradient

P2: Rainfall

P3: Lithology

P4: Land Cover

Example value:

Slope gradient compared to rainfall is assigned a value of 2 because rainfall is considered more influential than slope gradient.

1. Calculating the Eigenvector and Consistency Check

At this stage, the AHP method is used to calculate the final weights of each landslide vulnerability criterion and to check the consistency level of the pairwise comparison judgments provided by geography and disaster management experts. This process is carried out through the following steps:

a. Calculating the Eigenvector

The first step is to calculate the eigenvector values to determine the relative weights of each criterion. The calculation is based on Equation (2) [20]:

$$\boldsymbol{A \cdot w = \lambda\, maks \cdot w} \qquad (2)$$

Explanation :

λmaks : the maximum eigenvalue obtained from the multiplication.

w : the weight vector for each vulnerability criterion..

b. Weight normalization

After the initial weights are obtained, the next step is normalization so that the weights can be compared proportionally. Normalization is performed by dividing each criterion's weight by the total sum of all weights, as shown in Equation (3) [20]:

$$\boldsymbol{w_i^1 = \frac{w_i}{\sum_{j-1}^{n} w_j}} \qquad (3)$$

Explanation :

wi': normalized weight of the i-th criterion

wi: initial weight of the i-th criterion

n : total number of criteria

2. Calculating Consistency

To ensure that the judgments provided are logically consistent, the Consistency Index (CI) and Consistency Ratio (CR) are calculated. These values are computed using Equation (4) and Equation (5) [21].

$$\boldsymbol{CI = \frac{(\lambda\, maks - n)}{n-1}} \qquad (4)$$

$$\boldsymbol{CR = \frac{CI}{RI}} \qquad (5)$$

Explanation :

CI : *Consistency Index*

Λ Maks : Maximum eigenvalue

n : Number of parameters (4)

RI : Ratio Index (0.9 for 4 parameters)

CR : *Consistency Ratio*

2.6. Spatial Analysis

Spatial data covering lithology, rainfall, land cover, and slope gradient were processed through overlay analysis using a weighted sum approach, where the value of each parameter was multiplied by its AHP weight and then integrated to produce a landslide vulnerability map.

The spatial parameters, including slope gradient, soil type, land cover, and rainfall, were calculated using a weighted scoring method based on the landslide hazard parameter matrix developed by Suwarno et al. (2025) [22]. This weighting accounts for the relative contribution of each parameter to slope stability, with score values adjusted based on local geological criteria and empirical findings from previous studies in the Banyumas area. The scoring table is shown in **Table 2.**

Table 2. Landslide Hazard Parameter Matrix

Parameter	Class	Value
Slope Gradient	> 35	5
	20 – 35	4
	10 – 20	3
	5 – 10	2
	< 5	1
Lithology	Fragile sandstone, clay and silt, evaporite deposits, sandy clay, argillaceous limestone	5
	Marble, sandstone, shale, alternating conglomerate	4
	Sandstone, sandy limestone with shale intercalations, marl	3
	Sandstone, marl, clay with sandy intercalations, gravel, and sand	2
	Metamorphic and igneous rocks, limestone, and dolomite	1
Land Cover	Grassland, shrubs, rice fields, and herbaceous vegetation	5
	Fertile soil	4
	Gardens, heterogeneous agricultural areas	3
	Forest	2
	Urban areas and built-up areas	1
Rainfall	> 3019	5
	2667 – 3019	4
	2315 – 2667	3
	1963 – 2315	2
	< 1963	1

Source : Suwarno et al., 2025

3. Results and Discussion

3.1. Slope Gradient

Based on the analysis of 100 random sample points taken from the study area using DEMNAS data converted into a slope map, it was found that Cilangkap Village has an average slope value of 3.32, while Cihonje Village has an average of 3.77, which was rounded to the nearest whole number to match the discrete scoring system used in the AHP parameters. These values indicate that the topography of both villages is dominated by moderate to moderately steep slopes, with Cihonje Village tending to be steeper. The slope map can be seen in **Figure 4 [14]**.

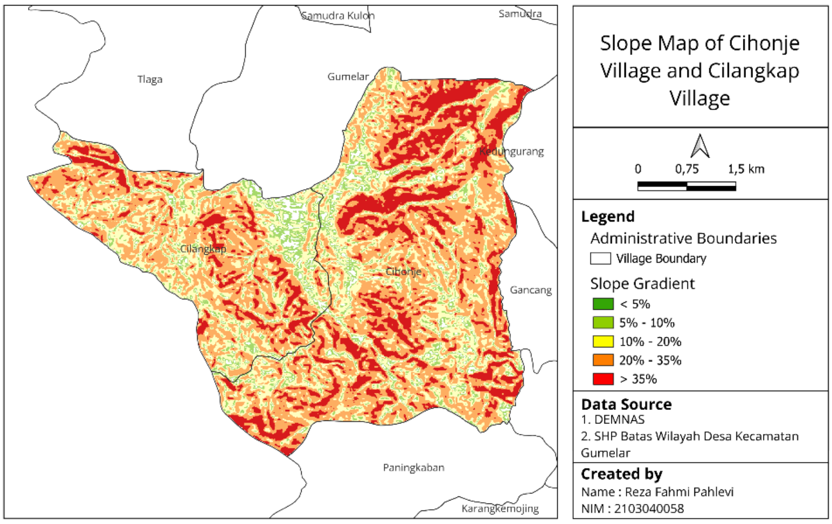

Figure 4. Slope Gradient Map

Source : DEMNAS, 2025

3.2. Lithology

The lithological distribution in the study area was obtained from a geological map based on spatial data analysis. According to the lithology classification, the area is predominantly composed of moderate sandy clay, which is spread across almost the entire region. In addition, sandstone, claystone, and siltstone are present in more limited quantities. The distribution of lithological units in the study area is shown in **Figure 5 [15]**.

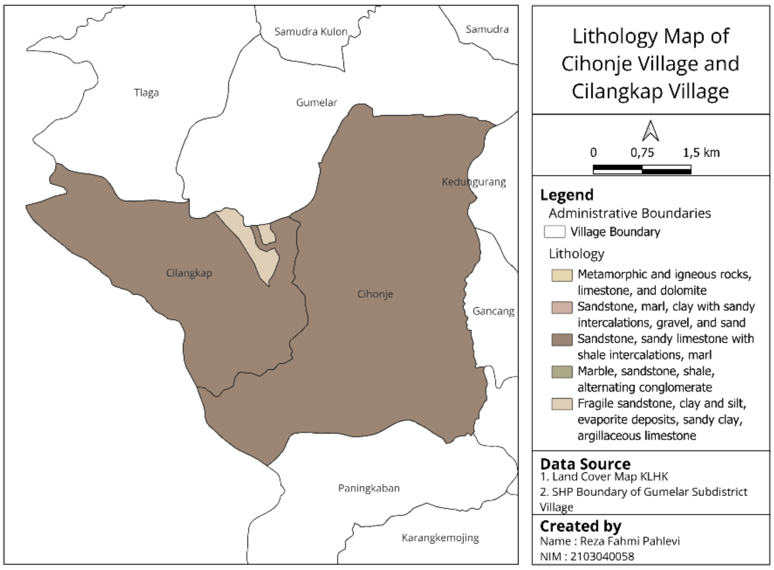

Figure 5. Lithology Map

Source : Kementerian ESDM., 2023

3.3. Land Cover

Based on the spatial data analysis in Figure 6, the average land-cover values from the random sampling points are 2.79 for Cilangkap Village and 3.13 for Cihonje Village. These values indicate that land cover in both villages generally consists of agricultural land and non-permanent vegetation, with Cihonje generally having more varied and intensive cover than Cilangkap. This aligns with the area's characteristics, which are dominated by heterogeneous agricultural activities, especially in gently sloping areas, potentially reducing slope stability due to the lack of permanent ground-covering vegetation **[17].**

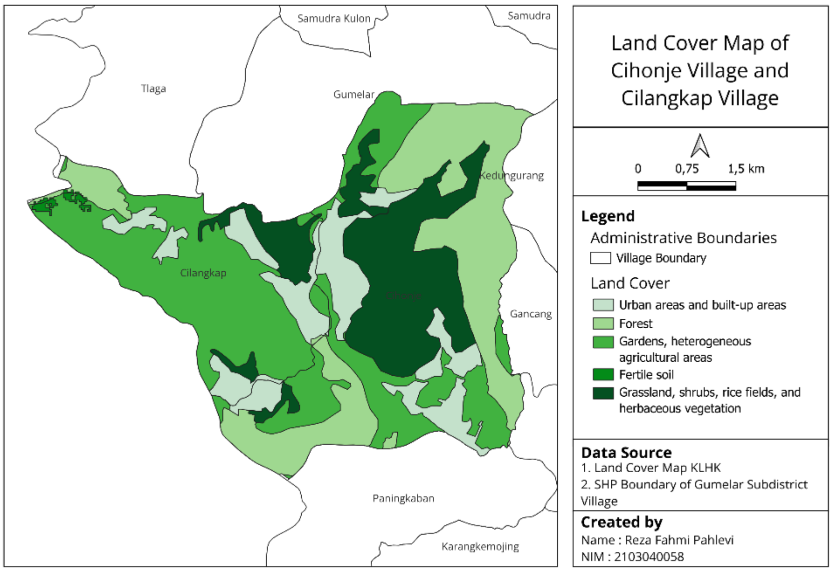

Figure 6. Land Cover Map

Source : KLHK, 2022

3.4. Rainfall

The annual rainfall data for Cilangkap Village and Cihonje Village were obtained from CHIRPS data [16]. Figure 7 reveals the spatial distribution pattern of annual rainfall in the study area, with a clear gradient visible from north to south. Areas with extreme rainfall (>3019 mm/year) are concentrated in parts of both Cilangkap and Cihonje Villages.

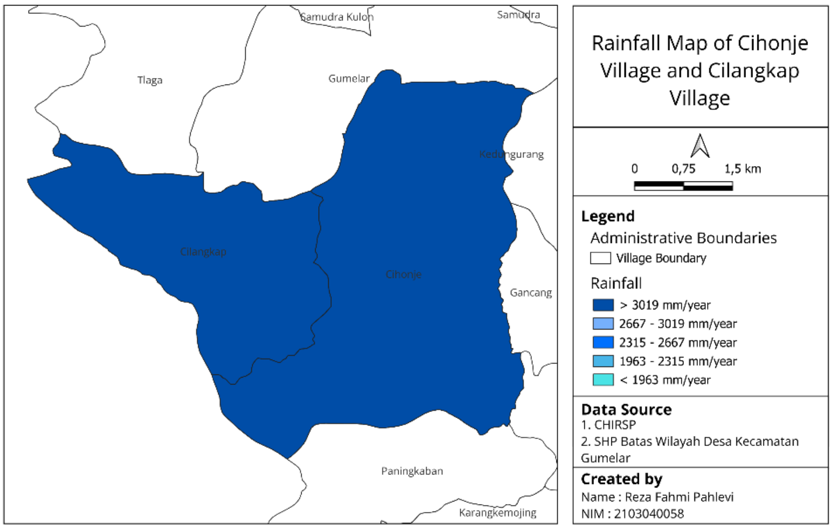

Figure 7. Rainfall Map

Source : CHRS, 2024

3.5. AHP Method Weighting

The AHP weighting process follows the consistency threshold established by Saaty (1994), where the Consistency Ratio (CR) must be less than 0.1 to ensure the validity of the results. The pairwise comparison matrix that meets this consistency criterion is then used as the basis for spatial overlay in mapping landslide vulnerability zones in Cilangkap and Cihonje Villages, Gumelar Sub-district. [21].

Based on the hierarchical criteria above, the first step is to create a pairwise comparison matrix for the selected criteria. The established parameters are prioritized by arranging pairwise comparisons in **Table 3**, in which each comparison evaluates the relative importance of one criterion over another for each alternative in the hierarchical system, represented in matrix form for numerical analysis.

Table 3. Pairwise Comparison Matrix for Landslide Vulnerability Assessment

Criteria	P1	P2	P3	P4
P1	1	2	4	6
P2	0,33	1	3	5
P3	0,20	0,33	1	3
P4	0,14	0,20	0,33	1
Amount	1,68	4,53	9,33	16

The normalization process of the pairwise comparison matrix is carried out to obtain consistent criterion weights. As shown in Table 4, the value of each matrix element is calculated by normalizing each column using the following equation:

Table 4. Normalized Pairwise Comparison Matrix

Criteria	P1	P2	P3	P4	Amount	Weight
P1	0,522	0,566	0,480	0,400	1,968	0,492
P2	0,33	0,261	0,283	0,333	1,237	0,309
P3	0,130	0,094	0,120	0,200	0,545	0,136
P4	0,087	0,057	0,040	0,067	0,250	0,063
Amount	1,68	4,53	9,33	16	4	1

The maximum λ value is obtained by multiplying the pairwise comparison matrix in Table 2 with the weight of each parameter listed in Table 3. Based on these calculations, the Consistency Index (CI) was found to be 0.0589 and the Consistency Ratio (CR) was 0.0654. A CR value below the threshold of 0.1 indicates that the weights derived from the pairwise comparisons have a good level of consistency and are suitable for further analysis.

The priority weights obtained from the AHP are then applied to calculate the landslide vulnerability scores. The scoring results can be seen in **Table 5.**

Table 5. Vulnerability Score Calculation Table

Parameter	AHP Weight	Cilangkap Value	Cihonje Value	Cilangkap Score	Cihonje Score
Slope Gradient	0,492	3	4	1,476	1,968
Rainfall	0,309	5	5	1,545	1,545
Lithology	0,136	3	3	0,408	0,408
Land Cover	0,063	4	4	0,252	0,252
Amount	1			3,681	4,173

3.6. Landslide Potential

The landslide potential in Cilangkap and Cihonje Villages was determined through an AHP-based overlay of weighted parameter maps, with the final result presented as a vulnerability map in **Figure 9.**

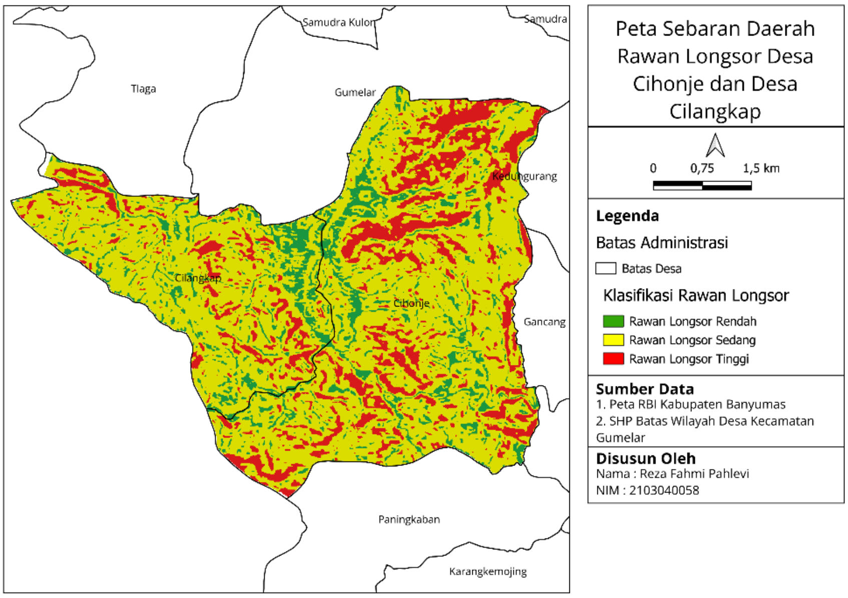

Figure 9. Landslide-Prone Area Distribution Map

The following is an explanation of each landslide vulnerability class and its distribution in Cilangkap and Cihonje Villages:

a. **Low Landslide Vulnerability Area**

This area features slopes of less than 5°, predominantly consisting of residential zones on flat terrain and underlain by geologically stable lithology. Due to its relatively safe morphological and geological characteristics against mass movement, this zone exhibits a very low landslide potential.

b. **Moderate Landslide Vulnerability Area**

This zone includes agricultural areas with slopes ranging from 10% to 20%, and is dominated by sandstone lithology. Due to the combination of land use activity and rock types with moderate to low cohesion, this geomorphological setting indicates a moderate landslide potential, especially during periods of heavy rainfall.

c. **High Landslide Vulnerability Area**

This area lies on steep slopes with gradients greater than 25%. The lithology consists of claystone, which has unstable physical properties and is easily degraded by water. Additionally, annual rainfall in this area exceeds 3000 mm, increasing the likelihood of mass soil movement. This zone has a high landslide potential and requires special attention for disaster risk reduction and management due to its steep terrain, highly weathered and softened rock types, and high rainfall levels.

3.7. Landslide Hazard Map Validation

Based on field observations, a landslide occurred in Cihonje Village, resulting in the disruption of the main road connecting Gumelar Sub-district with Ajibarang. This event was triggered by two consecutive days of heavy rainfall, exacerbated by the steep slope conditions. Visual documentation of the incident is presented in **Figure 10.**

Figure 10. Documentation of the Cihonje Village Landslide Incident

4. Conclusion

This study successfully mapped landslide vulnerability zones in Cilangkap and Cihonje Villages, Gumelar Sub-district, by integrating the Analytical Hierarchy Process (AHP) method with Geographic Information Systems (GIS). The analysis indicated that slope gradient (49.2%) and rainfall (30.9%) were the most influential factors, followed by lithology (13.6%) and land cover (6.3%), with a Consistency Ratio (CR) value of 0.065, confirming the reliability of the parameter weighting. Future research may incorporate dynamic environmental variables such as real-time vegetation indices, seismic activity data, and machine learning-based predictive models to improve prediction accuracy and support adaptive mitigation strategies.

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