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Landslide Susceptibility Zonation Using Analytic Hierarchy Process Method in the Karangbolong Hills Area, Indonesia

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Abstract
The highest frequency of landslides in Kebumen Regency is observed in the Ayah Subdistrict and Buayan Subdistrict, which are in the southern part of the Karangbolong Hills. This area are the targets for the construction of the 14.03 km Ayah-Jladri Southern Cross Road (JJLS). Consequently, the objective of this study is to create a landslide susceptibility map utilizing the Analytic Hierarchy Process (AHP) methodology. Some causative factors are used to develop landslide susceptibility maps i.e. elevation, slope gradient, aspect and curvature, lithology and lineament density, distance from streams, land use and distance from roads. A total number of 128 landslide events are considered in the study. This method identified five susceptibility zones based on LSI value: very low (141.79-241.74), low (241.75-293.73), moderate (293.74-334.52), high (334.53-374.89), and very high (374.90-460.50). The landslide susceptibility map was validated, with an AUC value of 0.749, suggesting that the map provides good results.

1. Introduction

Landslide is a broad term referring to the downward movement of soil, rocks, and organic materials along a slope, driven by the force of gravity, as well as the landforms resulting from such movement [1]. Landslides can be controlled by various factors, such as geomorphological conditions, geological conditions including lithology and geological structures, hydrogeology and land use. Landslides can be triggered by high rainfall intensity, vibrations (earthquakes), and human activities [2].

Locations with a high frequency of landslides in Kebumen Regency are Ayah Subdistrict and Buayan Subdistrict[3]. Both are the southern part of the Karangbolong Hills which are the targets for the construction of the 14.03 km Ayah-Jladri Southern Cross Road (JJLS) [4]. The southern part of the Karangbolong Hills has a medium-very high relief and a coarse-very coarse texture indicating that the research area is influenced by complex lithology and geological structures [5]. Most of this area has land use in the form of forests and settlements with a population density of 890 people/km^2 in Ayah Subdistrict [6] and 796 people/km^2 in Buayan Subdistrict [7], so that there is a possibility of loss of life if a landslide occurs.

Therefore, further research is needed regarding the influence of landslide causative factors including geomorphology, geology (lithology, structure geology) and land use on landslide susceptibility in the study area. The approach employed involves ranking and assigning weights to the factors controlling landslides through the semi-qualitative statistical method, the Analytical Hierarchy Process (AHP). The results of this study can provide recommendations for areas that are relatively safe from landslides.

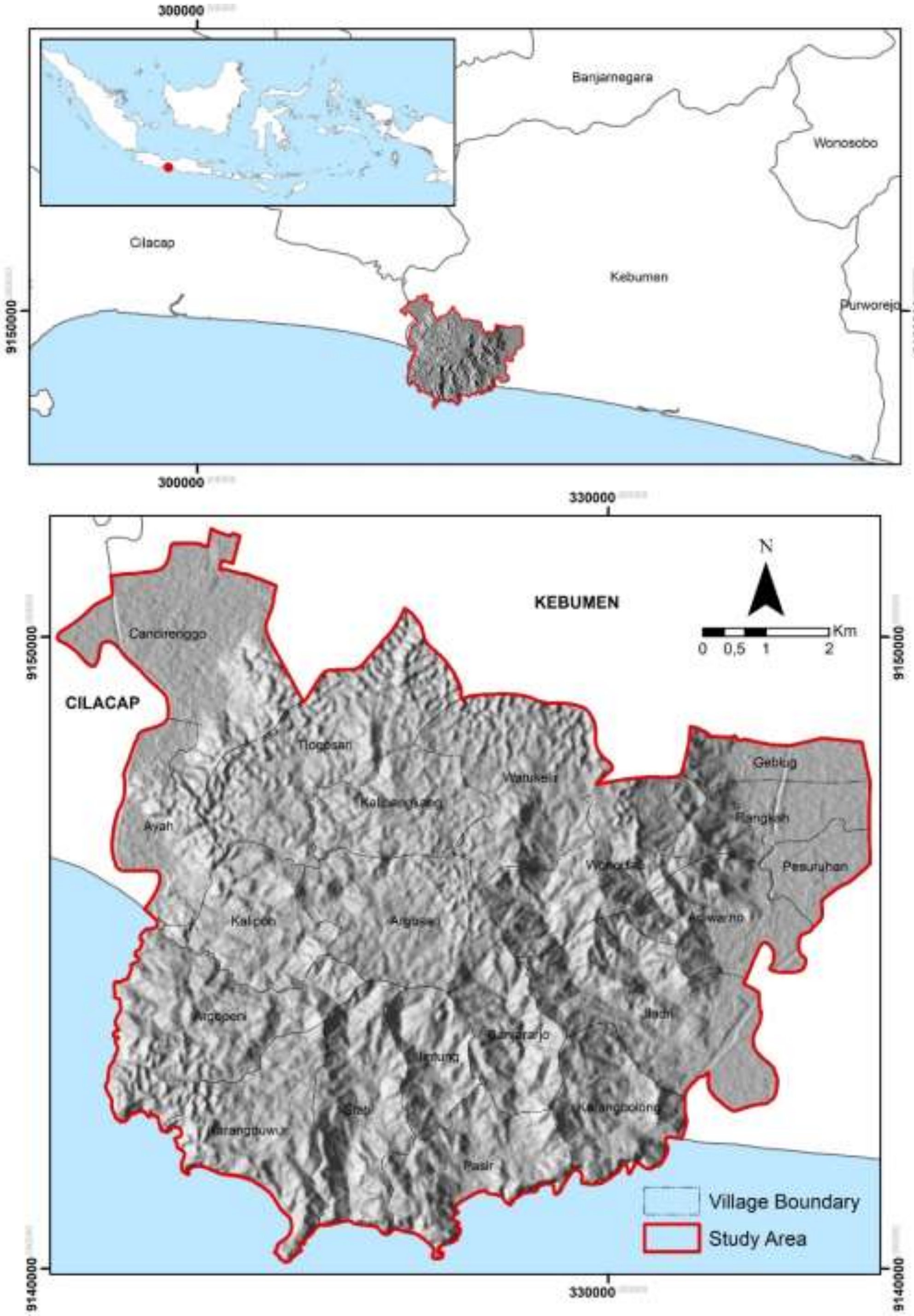

Figure 1. Location map of the study area

2. Study Area

The study area is part of the Karangbolong Hills, which were formed geologically as remains of the ancient Karangbolong volcano [5]. This region spans two subdistricts: Ayah and Buayan (see Figure 1). Geographically, the area is located between 109°22′47.83"E to 109°29′46.09"E and 7°40′17.31"S to 7°46′33.79"S, covering approximately 86.21 km².

The area has elevations ranging from 0 to 475 meters above sea level (masl). The water flow pattern is radial centrifugal which develops into sub dendritic indicating the influence of geological structure on ancient volcanoes. The flow directions of streams vary across the region: NE–SW on the western slope, SE–NW on the eastern slope, and N–S on the southern slope. Geologically, the region is primarily composed of Tertiary volcanic and intrusive rocks and Tertiary carbonate Kalipucang Formation.

Table 1. Dataset utilized for the research

Data	Data Source	Usage
Digital elevation model (DEM)	DEMNAS with a grid resolution of 8.23 m × 8.23 m [15]	Slope, elevation, distance from roads, distance from stream, curvature, lineament, aspect
Geological map	Geological map scale of 1:25.000 [5], [16]	Lithology and lineament
Road distribution	Road map scale of 1:25,000 [17]	Distance from roads
Stream distribution	Stream map scale of 1:25,000 [17]	Distance from stream
Land use map	Land use map scale of 1:25,000 [17]	Land use
Landslide inventory	Landslide event data [10], Field investigation	Landslide events

3. Methodology

3.1. Data Collection

In this study, data collection entails gathering the distribution of landslide occurrences from secondary sources and processing the causative factors through the use of Geographic Information System (GIS). The data employed to generate the landslide susceptibility maps are presented in Table 1. Seven causative factors extracted from the Digital Elevation Model (DEM) include slope, elevation, distance from roads, distance from streams, curvature, lineament, and aspect. Additional data, such as geology and landslide events, were gathered from secondary sources and field surveys.

3.2. Landslide Inventory

The landslide inventory illustrates the distribution of landslide data obtained from secondary sources and field investigations. The landslide inventory includes details regarding the locations of the landslides, dimension of landslides, direction of landslides [8], type of landslides, controlling factors around area and triggering factors. Generally, three types of landslides have been identified in the study area: rockfalls, rock sliding (including both rotational and translational slides), and creeping [9]. Several images of landslide events captured during the field surveys are displayed in Figure 2.

The study considers a total of 128 landslide events, where 70 landslide events from secondary data [10] and 58 landslide events from field surveys. All landslide events are employed to assess the accuracy of the landslide susceptibility map [11]. The size of the landslides found in the study area ranged between 20 m² -250 m², classified as small landslide [12]. Although the landslide may be small in size, in several areas, it still impacts human life and causes property loss, including damage to public infrastructure and people's homes.

Figure 2. Landslide occurred in the study area (a) Rockfall; (b) Rock sliding

Table 2. The fundamental scale of Analytic Hierarchy Process (AHP) [18], [20]

Intensity of importance on an absolute scale	Definition	Explanation
1	Equally Important	Both criteria are equally important, or both the factors have same effect on occurrence of landslides
3	Moderately Important	One factor is more effective compared to the other factor
5	Highly Important	One factor affects highly as compared to the other factor
7	Very Highly Important	A factor is highly dominated over other
9	Extremely Important	A factor has the highest possibility of affecting the occurrence of landslide over another factor
2, 4, 6, 8	Intermediate Values	If a compromise between two factors is required, intermediate values can be used

Table 3. Random consistency index [20]

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Landslide by itself does not automatically cause a disaster; instead, it is the decisions made by individuals that determine vulnerability, exposure, and the probability of a slide occurring and affecting individuals [13], [14]. The intensity and density of human populations are key factors that contribute to landslide risks, with the rapid pace of urbanization, these risks are growing. In the study area, 67 landslide points (52.34% of the total landslide points) were located around settlements area with a population density of around 796-960 people/km^2. This indicates that there is a fairly high risk of landslides which can cause property losses and even threaten human lives.

3.3. Analytic hierarchy process (AHP)

The Analytic Hierarchy Process (AHP) is a decision-making method used to simplify complex problems by breaking them down into simple criteria. It uses pairwise comparisons and expert judgment to establish priority scales [18], [19]. These criteria are compared to each other from actual measurements or from fundamental scale reflect the relative strength of preferences and feelings [20]. This process of comparing relative values is referred to as pairwise comparison proposed by [21] as in Table 2. The consistency of the weights assigned for relative importance during the pairwise comparison can be checked using Eq. (1) as shown below.

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

CI represents the consistency indicator, while CR represents the random consistency ratio, with a value below 0.1 being regarded as acceptable. max refers to the largest eigenvalue of the judgment matrix, n represents the order of the judgment matrix, and RI stands for the random index, which is provided in Table 3. CI is calculated using the Eq. (2) as follows:

$$Consistency\ Index\ (CI) = \frac{\lambda max - n}{n-1} \quad (2)'$$

By using the AHP method, the relative weights of all causative factors can be determined, leading to the calculation of the landslide susceptibility index (LSI) using the Eq. (3) as follows:

$$\begin{aligned} LSI_{\ AHP} = {} & \omega_1\ x\ AHP_{elevation} + \omega_2\ x\ AHP_{slope} + \omega_3\ x\ AHP_{aspect} + \omega_4\ x\ AHP_{curva} \\ & + \omega_5\ x\ AHP_{lithology} + \omega_6\ x\ AHP_{lineament} + \omega_7\ x\ AHP_{stream} \\ & + \omega_8\ x\ AHP_{landuse} + \omega_9\ x\ AHP_{roads} \end{aligned} \quad (3)'$$

where AHP is rating of influencing factors, and ωi is weight of influencing factor i in percent [22].

Table 4. Data quality classes based on AUC values [21]

AUC Value	Quality Classes
> 0,9	Excellent
0,8 - 0,9	Very Good
0,7 - 0,8	Good
0,6 – 0,7	Satisfactory
< 0,6	Unsatisfactory

3.4. Validation
Validation of landslide susceptibility maps was conducted using the Area Under the Curve (AUC) method through the creation of a Receiver Operating Characteristic (ROC) curve. The ROC curve is employed as a tool for assessing the effectiveness of landslide susceptibility maps generated using the AHP method [23], which curve compares the true positive rate with the false positive rate across various threshold levels. The true positive refers to a location correctly identified as having a high landslide risk, while a false positive is a location wrongly predicted to have high landslide risk when it does not [24]. The AUC value represents the overall accuracy of the model, with a higher AUC indicating better discrimination between landslide-prone and non-prone areas. The perfect model would have an AUC of 1.0, meaning it correctly identifies all true positives and no false positives. Validation using the AUC value can be divided into five classes [21] as in Table 4.

4. Results and discussions
4.1. Causative Factors of Landslides
The occurrence of landslides can be influenced by a variety of factors that are scientifically chosen [25]. In this study, there are nine factors categorized into four: geomorphological aspect (elevation, slope gradient, aspect and curvature), geological aspect (lithology and lineament density), hydrological aspect (distance from streams) and environmental aspect (land use and distance from roads). Figure 3 illustrates the details of the causative factors in the study area.

4.1.1. Elevation
Elevation influences the degree of weathering, variations in humidity, and erosion [26]. Higher elevations result in an increased degree of weathering, greater humidity variations, and more erosion, which contribute to the occurrence of landslides. The elevation map (see Figure. 3a) was created through DEM analysis and categorized into four classes: 0–50 masl, 51–100 masl, 101–200 masl and above 200 masl.

4.1.2. Slope Gradient
Slope affects shallow landslides by influencing the sliding force and the distribution of stress within the rock and soil [25]. The likelihood of landslides increases with the greater driving force present in steep slope conditions [11]. The slope data are derived from digital elevation model (DEM) analysis with an 8.23 × 8.23 m grid resolution. The slope map generated from the DEM analysis is categorized into five slope classes: 0°–3°,3°–9°,9°–17°, 17°–36° and above 36° [8], as shown in Figure 3b.

4.1.3. Aspect
Aspect determines the slope exposure wind direction, degree of saturation, discontinuity conditions and solar radiation, all of which can affect soil moisture and slope stability [27], [28]. The aspect map (see Figure 3c) generated from DEM analysis and categorized into ten classes: flat (-1), north (0–22.5), northeast (22.5–67.5), east (67.5–112.5), southeast (112.5-157.5), south (157.5–202.5), southwest (202.5-246.5), west (247.5–292.5), and north (337.5–360).

4.1.4. Curvature
The curvature map generated from DEM is then categorized into three main classes. A negative curvature value indicates the slope's concavity, while a positive curvature value indicates the slope's convexity. 0 value of curvature indicates the flat surface (see Figure 3d). The concentration of drainage across space is caused by high convexity and concavity, leading to slope saturation and failure [29].

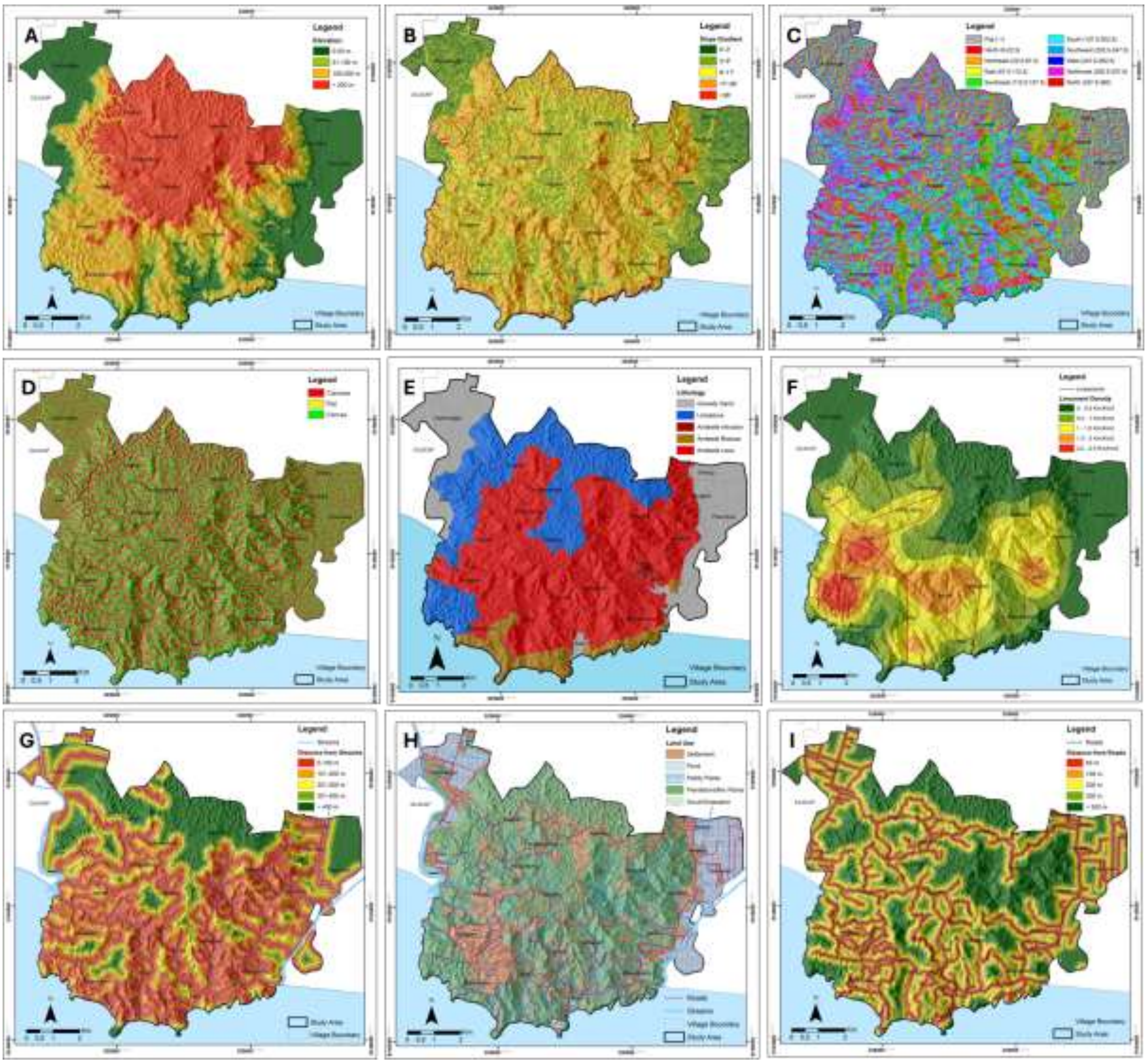

Figure 3. Landslide causative factor maps: (a) elevation; (b) slope; (c) aspect; (d) curvature; (e) lithology; (f) lineament density; (g) distance from streams; (h) land use; and (i) distance from roads.

4.1.5. Lithology

The lithologic map is categorized into five units: Gravelly Sand Unit, Limestone Unit, Andesite Intrusion Unit, Andesite Breccia Unit, and Andesite Breccia Unit, as shown in Figure 3e. The field survey indicates that the Andesite Intrusion Unit, Andesite Breccia Unit, and Andesite Breccia Unit are moderately to highly weathered, whereas the limestone is slightly to moderately weathered and undergoes dissolution. The more rocks are weathered, the greater the possibility of landslides.

4.1.6. Lineament Density

A lineament refers to a linear feature found on the Earth's surface, typically linked to geological structure i.e. faults, linear fault zones, bending deformation, and areas with enhanced permeability in the Earth's crust [30]. The dense geological structures that accelerate the weathering process can increase the possibility of landslides. The lineament density map is classified into five categories, i.e., 0–0.5 km/km^2, 0.51–1 km/km^2, 1.01–1.50 km/km^2, 1.51–2.0 km/km2 and 2.01–2.50 km/km^2 (see Figure 3f).

Table 5. Partwise comparation matrix of causative factors

Causative Factor	Slope Gradient	Elevation	Lithology	Distance from Roads	Distance from Streams	Curvature	Lineament Density	Land Use	Aspect	ωi
Slope Gradient	1									0.307
Elevation	1/2	1								0.218
Lithology	1/3	1/2	1							0.154
Distance from Roads	1/4	1/3	1/2	1						0.109
Distance from Streams	1/5	1/4	1/3	1/2	1					0.076
Curvature	1/6	1/5	1/4	1/3	1/2	1				0.053
Lineament Density	1/7	1/6	1/5	1/4	1/3	1/2	1			0.037
Land Use	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1		0.026
Aspect	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	0.019

$\lambda max = 9.604$, CI = 0.076, CR = 0.052

4.1.7. Distance from Streams
The distance from streams is an important factor that can reveal landslides and related erosion processes, which help to characterize changes in slope [11]. The distance from streams is determined through the buffering function in GIS analysis, where the river data [30]. The closer the distance to the streams, the greater the possibility of being affected by landslides. The distance from streams map (see Figure 3g) is categorized into five: 0-100 meters, 101-200 meters, 201-300 meters, 301-400 meters and above 400 meters.

4.1.8. Land Use
Land use types reflect the intensity of human activities that have influenced the mountain environment. The degree of human activity, especially on construction sites, undermines rock stability, which in turn raises the risk of landslide hazards [25]. The land use map (see Figure 3h) categorized into five land use types: settlements, pond, paddy fields, plantations, and scrub/grassland. Land use types are extracted from the 1:25,000 scale topographic map through digitization.

4.1.9. Distance from Roads
Road construction is closely associated to the removal of vegetation and excavation, which can create steep slopes. In study area, it involves the excavation of hills, which weakens the strength of the rock and soil. As a result, many slopes become exposed, making them more susceptible to landslide disasters, particularly during periods of heavy rainfall [25]. The distance from roads is determined through the buffering function in GIS analysis, where the river data [30]. The shorter the distance to the roads, the greater the possibility of being affected by landslides. The distance from roads map (Fig. 3i) is categorized into five: 0-50 meters, 51-100 meters, 101-200 meters, 201-300 meters and above 300 meters.

4.2. Landslide Susceptibility Map
The causative factors mentioned above are weighted to assess their influence on the landslide susceptibility map using the AHP (Analytic Hierarchy Process) method. The normalized weights for these factors are derived using AHP, as shown in Table 5. The table indicates that all Consistency Ratio (CR) values are below 0.10, confirming that the comparison matrices are consistent [20]. Slope gradient had the greatest influence on landslide occurrence [29], with a weight of 0.307 in the AHP matrix. Elevation was the second most influential factor, with a weight of 0.218. Lithology received a weight of 0.154, while the aspect was considered the least significant causative factor, with an AHP weight of 0.019.

Table 6. Rating each class of causative factors

Causative Factor	Class	AHP Rating	ωi	ωi (%)	Score
Slope Gradient	0-3	1	0.307	30.7	30.7
	3-9	2			61.4
	9-17	3			92.1
	17-36	4			122.8
	> 36	5			153.5
Elevation	0-50 m	2	0.218	21.8	43.6
	51-100 m	3			65.4
	101-200 m	4			87.2
	>200 m	5			109
Lithology	Gravelly Sand	1	0.154	15.4	15.4
	Andesite Intrusion	2			30.8
	Andesite Breccia	3			46.2
	Limestone	4			61.6
	Andesite Lava	5			77
Distance from Roads	0-50 m	5	0.109	10.9	54.5
	51-100 m	4			43.6
	101-200 m	3			32.7
	201-300 m	2			21.8
	>300	1			10.9
Distance from Streams	0-100 m	5	0.076	7.6	38
	101-200 m	4			30.4
	201-300 m	3			22.8
	301-400 m	2			15.2
	>400 m	1			7.6
Curvature	Flat	1	0.053	5.3	5.3
	Convex	3			15.9
	Concave	5			26.5
Lineament Density	0-0,5 km/km^2	1	0.037	3.7	3.7
	0,5-1 km/km^2	2			7.4
	1-1,5 km/km^2	3			11.1
	1-2 km/km^2	4			14.8
	2-2,5 km/km^2	5			18.5
Land Use	Settlement	5	0.026	2.6	13
	Ponds	4			10.4
	Paddy Fields	3			7.8
	Plantation/Mix Plants	2			5.2
	Scrub/Grassland	1			2.6
Aspect	North (337.5-360)	5	0.019	1.9	9.5
	Northwest (292.5-337.5)	5			9.5
	Southwest (247.5-292.5)	4			7.6
	West (202.5-247.5)	4			7.6
	South (157.5-202.5)	3			5.7
	Southeast (112.5-157.5)	3			5.7
	East (67.5-112.5)	2			3.8
	Northeast (22.5-67.5)	2			3.8
	North (0-22.5)	1			1.9
	Flat (-1)	1			1.9

The weight of each causative factor is multiplied by the rating of each factor class (expressed as a percentage) to calculate a score for each factor, as shown in Table 6. The scores for all causative factors are then summed to calculate the Landslide Susceptibility Index (LSI) value. The LSI value ranges from 141.79 to 460.50.

Based on landslide susceptibility index (LSI) value, the landslide susceptibility map for the study area is shown on Figure 4. The LSI values are classified into five categories using natural breaks [18]: very high (LSI 374.90-460.50), high (LSI 334.53-374.89), moderate (LSI 293.74-334.52), low (LSI 241.75-293.73), and very low (LSI 141.79-241.74).

a) The area with very high landslide susceptibility (LSI 374.90-460.50) covers approximately 21,43 km² (24.83% of the total area) located in the central part of study area. This zone dominated in six villages, namely Kalibangkang, Wonodadi, Banjararjo, Argosari, Argopeni and Kalipoh.
b) The area with high landslide susceptibility (LSI 334.53-374.89) covers approximately 31,22 km² (36.17% of the total area). This zone is the largest area spread throughout the study area.
c) The area with moderate landslide susceptibility (LSI 293.74-334.52) covers approximately 16,20 km² (18.77% of the total area). This zone is spread throughout the research area which consists of 20 villages.
d) The area with low landslide susceptibility (LSI 241.75-293.73) covers approximately 6,68 km² (7.74% of the total area). This is the narrowest area and located in the lowlands in seven villages, namely Candirejo, Ayah, Geblug, Rangkah, Pasuruhan, Adiwarno and Jladri.
e) The area with very low landslide susceptibility (LSI 141.79-241.74) covers approximately 10,79 km² (12.50% of the total area). This zone is flat areas in the western and eastern parts of the study area, namely Candirejo, Ayah, Geblug, Rangkah, Pasuruhan, Adiwarno and Jladri.

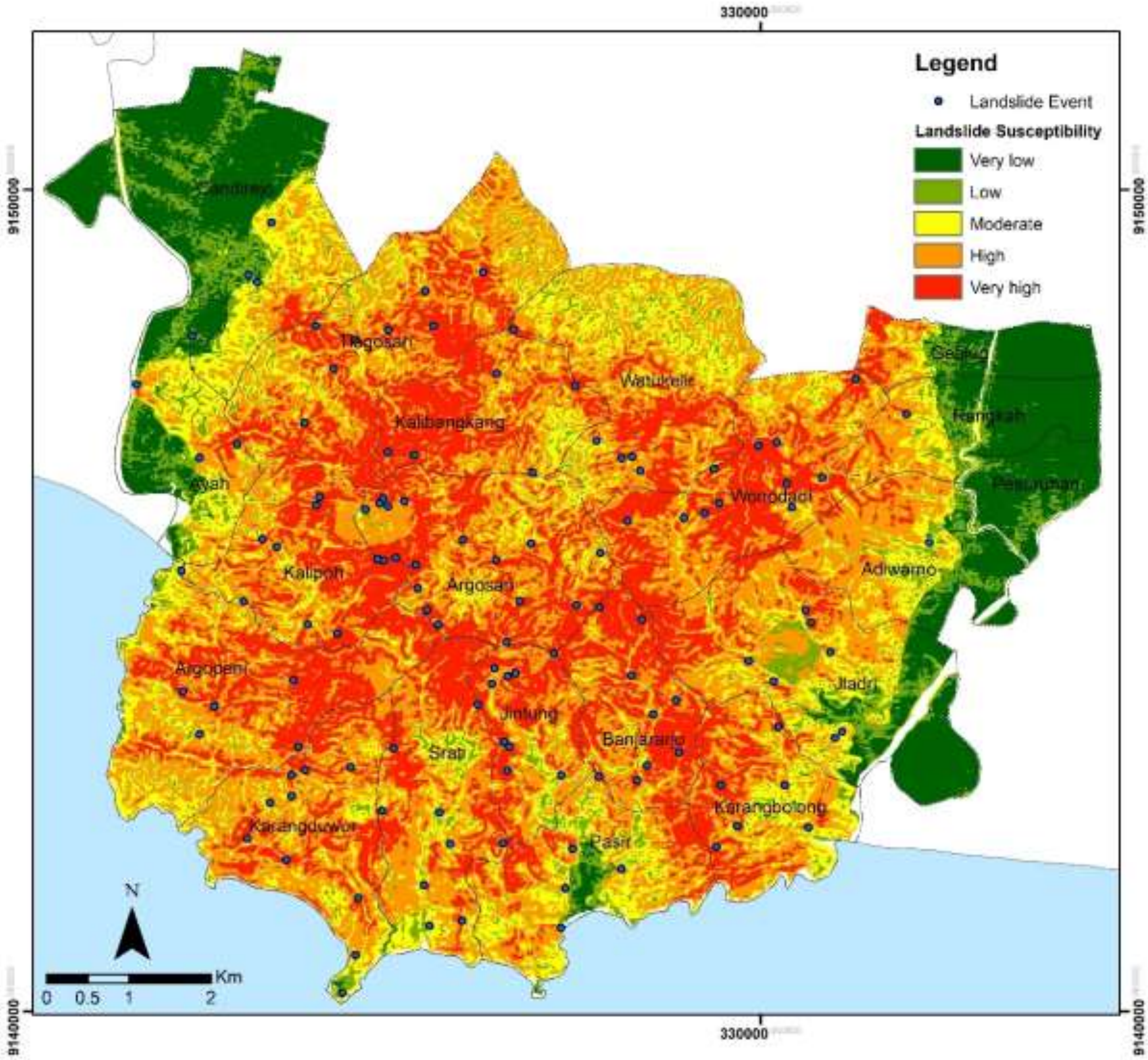

Figure 4. The landslide susceptibility map.

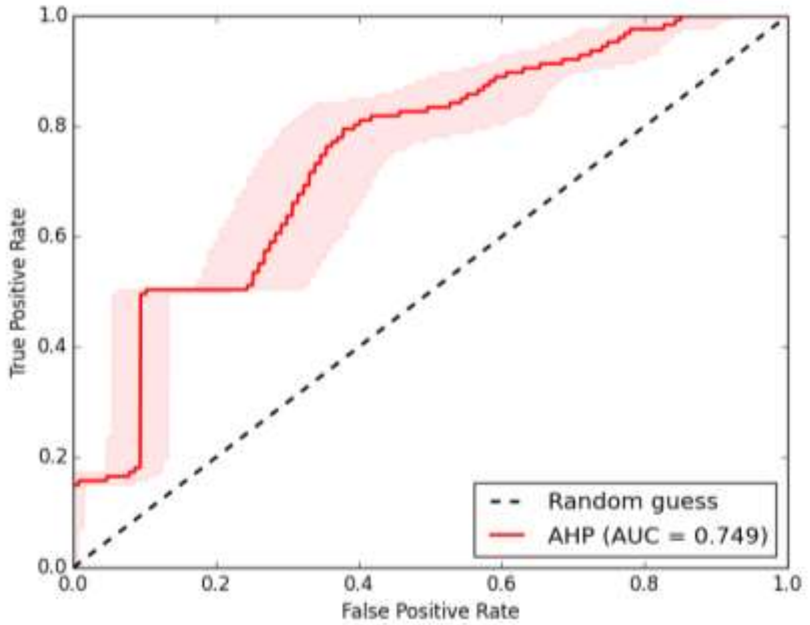

Figure 5. ROC curves for landslide susceptibility maps generated using the AHP method

In this study, landslide susceptibility maps are validated using the Receiver Operating Characteristic (ROC) curve. The ROC curve is plotted by comparing the area of landslide susceptibility classes with actual landslide events [18]. The Area Under the Curve (AUC) value is approximately 0.749 (see Figure 5.) indicating that the quality of the landslide susceptibility map is good [21]. An AUC value closer to 1 signifies better performance of the prediction models.

5. Recommendation

Based on the findings of this study, we offer a set of recommendations for local government authorities, urban planners, and community leaders to reduce landslide risks:

- Restrict Development in High-Risk Areas: Recommend that urban planners and local governments enforce zoning laws that prohibit construction in areas identified as having very high to high landslide susceptibility, as indicated by the susceptibility map.
- Implement Early Warning Systems: Encourage the installation of landslide detection systems in high-risk areas, such as rain gauges, soil moisture meters, and ground sensors.
- Infrastructure Improvements for Slope Stabilization: Recommend investing in infrastructure upgrades to reduce the likelihood of landslides. This includes measures such as constructing retaining walls, terracing slopes, and improving drainage systems to redirect water away from vulnerable areas.

The finding of this study can serve as a reference for future research, dealing with similar landslide causative factors. Currently, research is conducted using the AHP method with a single matrix comparison. For advanced research, it can be conducted with a double matrix comparison to produce a more accurate landslide susceptibility map. Future research needs to be developed and focused on comparing various methods for generating landslide susceptibility maps to improve prediction accuracy, such as the Weight of Evidence Ratio and Frequency.

6. Conclusion

Landslide susceptibility mapping using the AHP method in the Karangbolong Hills area, Indonesia, identified five susceptibility zones: very low, low, moderate, high, and very high. The central part of Karangbolong Hill shows a high to very high susceptibility, covering more than half of the study area, while the flat regions in the western and eastern parts exhibit low to very low susceptibility. The landslide susceptibility map was validated, with an AUC value of 0.749, suggesting that the map provides good results. This map can serve as a valuable tool for land use planning and mitigation strategies implemented by local government authorities.

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References
[1] Lynn M. Highland and Peter Bobrowsky, *The Landslide Handbook-A Guide to Understanding Landslides*. Reston, Virginia, U.S. Geological Survey Circular 1325, 2008.
[2] D. Karnawati, S. Pengajar Pascasarjana Jurusan Teknik Sipil dan Jurusan Teknik Geologi, and F. Teknik, "The Mechanism of Rock Mass Movements as The Impact of Earthquacke; Geology Engineering Review and Analysis," 2007.
[3] Badan Pusat Statistik Kebumen, "Jumlah Kejadian Bencana Alam Menurut Kecamatan di Kabupaten Kebumen, 2022-2023," Badan Pusat Statistik Kebumen. Accessed: Feb. 12, 2025. [Online]. Available: https://kebumenkab.bps.go.id/id/statistics-table/2/NDQyIzI=/jumlah-kejadian-bencana-alam-menurut-kecamatan-di-kabupaten-kebumen.html
[4] Ian, "Pansela Jateng DIY Tertangani 247,17 Km," Direktorat Jenderal Bina Marga. Accessed: Feb. 12, 2025. [Online]. Available: https://binamarga.pu.go.id/index.php/berita/pansela-jateng-diy-tertangani-24717-km
[5] A. Hendratno and S. Dwi Kurniawan, "Studi Fasies Gunung Api Purba Karangbolong," in *Seminar Nasional Kebumian ke-11*, Yogyakarta, Sep. 2018, pp. 982–995.
[6] Badan Pusat Statistik Kebumen, "Sekilas Angka Kependudukan Kecamatan Ayah," Badan Pusat Statistik Kebumen. Accessed: Feb. 12, 2025. [Online]. Available: https://kebumenkab.bps.go.id/id/news/2024/10/27/201/sekilas-angka-kependudukan-kecamatan-ayah.html
[7] Badan Pusat Statistik Kebumen, "Kecamatan Buayan Dalam Angka 2018," Kebumen, 2018.
[8] Badan Standarisasi Nasional, *SNI 8291:2024 Penyusunan Peta Zona Kerentanan Gerakan Tanah*. Indonesia, 2024, pp. 1–20.
[9] O. Hungr, S. Leroueil, and L. Picarelli, "The Varnes classification of landslide types, an update," 2014, *Springer Verlag*. doi: 10.1007/s10346-013-0436-y.
[10] Satria Danuningrat, "Evaluasi Geologi Teknik dan Analisis Kerentanan Gerakan Tanah Daerah Pembangunan Jalan Ayah-Jladri, Kabupaten Kebumen, Provinsi Jawa Tengah," Universitas Gadjah Mada, Yogyakarta, 2022.
[11] E. Erzagian, W. Wilopo, and T. F. Fathani, "Landslide Susceptibility Zonation Using GIS-Based Frequency Ratio Approach in the Kulon Progo Mountains Area, Indonesia," 2023, pp. 115–126. doi: 10.1007/978-3-031-44296-4_3.
[12] S. T. McColl and S. J. Cook, "A universal size classification system for landslides," *Landslides*, vol. 21, no. 1, pp. 111–120, Jan. 2024, doi: 10.1007/s10346-023-02131-6.
[13] B. Ahmed, "The root causes of landslide vulnerability in Bangladesh," *Landslides*, vol. 18, no. 5, pp. 1707–1720, May 2021, doi: 10.1007/s10346-020-01606-0.
[14] E. MacAfee, E. de Jong, and A. J. Lohr, "Leveraging local knowledge for landslide disaster risk reduction in an urban informal settlement in Manado, Indonesia," *International Journal of Disaster Risk Reduction*, vol. 111, Sep. 2024, doi: 10.1016/j.ijdrr.2024.104710.
[15] Badan Informasi Geospasial, "Geospasial untuk Negeri - Unduh Data Demnas," Badan Informasi Geospasial. Accessed: Feb. 12, 2025. [Online]. Available: https://tanahair.indonesia.go.id/portal-web/unduh/demnas
[16] Susilowati, I. Gde Budi Indrawan, and I. Wayan Warmada, "Geological and Geotechnical Assessment of Slope Stability Along Proposed Road of Ayah-Jladri Section, Kebumen, Central Java," in *AIP Conference Proceedings vol. 2891*, AIP Publishing, May 2024. doi: 10.1063/5.0201253.
[17] Badan Informasi Geospasial, "Geospasial untuk Negeri - Unduh Data RBI per Wilayah," Badan Informasi Geospasial. Accessed: Feb. 12, 2025. [Online]. Available: Badan Informasi Geospasial

[18] S. Panchal and A. K. Shrivastava, “Landslide hazard assessment using analytic hierarchy process (AHP): A case study of National Highway 5 in India,” *Ain Shams Engineering Journal*, vol. 13, no. 3, May 2022, doi: 10.1016/j.asej.2021.10.021.
[19] F. El Bchari, B. Theilen-Willige, and H. Ait Malek, “Landslide hazard zonation assessment using GIS analysis at the coastal area of Safi (Morocco),” *Proceedings of the ICA*, vol. 2, pp. 1–7, Jul. 2019, doi: 10.5194/ica-proc-2-24-2019.
[20] R. W. Saaty, “The Analytic Hierarchy Process-What It Is and How It Used,” 1987.
[21] A. R. Rasyid, N. P. Bhandary, and R. Yatabe, “Performance of frequency ratio and logistic regression model in creating GIS based landslides susceptibility map at Lompobattang Mountain, Indonesia,” *Geoenvironmental Disasters*, vol. 3, no. 1, Dec. 2016, doi: 10.1186/s40677-016-0053-x.
[22] C. Yu and J. Chen, “Application of a gis-based slope unit method for landslide susceptibility mapping in helong city: Comparative assessment of icm, ahp, and rf model,” *Symmetry (Basel)*, vol. 12, no. 11, pp. 1–21, Nov. 2020, doi: 10.3390/sym12111848.
[23] I. Sonker, J. N. Tripathi, and A. K. Singh, “Landslide susceptibility zonation using geospatial technique and analytical hierarchy process in Sikkim Himalaya,” *Quaternary Science Advances*, vol. 4, Oct. 2021, doi: 10.1016/j.qsa.2021.100039.
[24] R. Das, P. Van Tien, K. W. Wegmann, and M. Chakraborty, “Machine learning-based assessment of regional-scale variation of landslide susceptibility in central Vietnam,” *PLoS One*, vol. 19, no. 10, p. e0308494, Oct. 2024, doi: 10.1371/journal.pone.0308494.
[25] W. Wu, S. Guo, and Z. Shao, “Landslide risk evaluation and its causative factors in typical mountain environment of China: a case study of Yunfu City,” *Ecol Indic*, vol. 154, Oct. 2023, doi: 10.1016/j.ecolind.2023.110821.
[26] D. Asmare and T. Hailemariam, “Assessment of rock slope stability using slope stability probability classification (SSPC) system, around AlemKetema, North Shoa, Ethiopia,” *Sci Afr*, vol. 12, Jul. 2021, doi: 10.1016/j.sciaf.2021.e00730.
[27] N. Nepal, J. Chen, H. Chen, X. Wang, and T. P. Pangali Sharma, “Assessment of landslide susceptibility along the Araniko Highway in Poiqu/Bhote Koshi/Sun Koshi Watershed, Nepal Himalaya,” *Progress in Disaster Science*, vol. 3, Oct. 2019, doi: 10.1016/j.pdisas.2019.100037.
[28] T. Mersha and M. Meten, “GIS-based landslide susceptibility mapping and assessment using bivariate statistical methods in Simada area, northwestern Ethiopia,” *Geoenvironmental Disasters*, vol. 7, no. 1, Dec. 2020, doi: 10.1186/s40677-020-00155-x.
[29] D. Asmare, “Application and validation of AHP and FR methods for landslide susceptibility mapping around choke mountain, northwestern ethiopia,” *Sci Afr*, vol. 19, Mar. 2023, doi: 10.1016/j.sciaf.2022.e01470.
[30] I. N. Manyoe and R. Hutagalung, “The extraction and analysis of lineament density from digital elevation model (dem) in libungo geothermal area, gorontalo,” in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics, 2022. doi: 10.1088/1755-1315/1089/1/012012.