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LANDSLIDE VULNERABILITY MAPPING USING FUZZY LOGIC METHOD FOR DISASTER MITIGATION: Case Study of Bungaya District, Gowa Regency

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Abstract. Landslides are a significant threat to the Bungaya District in Gowa Regency, Indonesia, with five incidents recorded in 2019. This study aimed to map landslide vulnerability using the Fuzzy Logic method implemented in ArcGIS software and propose appropriate mitigation strategies. The analysis incorporated six parameters: rainfall intensity, soil type, elevation, slope, land cover type, and geology. The results revealed four categories of vulnerability: not vulnerable (592.91 ha), low (3,093.32 ha), medium (9,139.72 ha), and high (7,557.29 ha). Areas with high vulnerability were characterized by steep topography, easily eroded soil and rock types, and inappropriate land-use practices. Rannaloe, Sapaya, Bissoloro, and Buakkang villages were classified as highly susceptible to landslides. Mitigation strategies were proposed based on the vulnerability level, with a combination of technical and vegetative methods recommended for high- and moderate-vulnerability areas, whereas vegetative methods alone were deemed sufficient for low-vulnerability regions. This study contributes to advancing spatially informed disaster risk management by integrating susceptibility mapping with actionable mitigation recommendations tailored to the vulnerability levels identified in the Bungaya District.

Keywords: Landslide vulnerability, fuzzy logic, disaster mitigation
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INTRODUCTION

The Bungaya District in Gowa Regency is highly vulnerable to landslides. According to data from the Regional Disaster Management Agency (BPBD) of Gowa, five landslide incidents were recorded in the district in 2019. The primary factors contributing to the heightened risk of landslides are soil composition, steep slope gradients, high rainfall intensity, and other environmental variables. Characterized by high wet-season intensity, the district records a mean annual rainfall of about 1,500 to 3,500 mm, where extreme precipitation events peak predominantly from December through March. These

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hydrological conditions lead to significant infiltration and accumulation of subsurface water, thereby increasing the hydrostatic pressure and consequently exacerbating the susceptibility to landslides [1].

Effective mitigation of landslide hazards requires comprehensive mapping of susceptibility zones. The primary aim of such spatial analyses is to identify areas with increased landslide potential, thereby enabling the development of targeted and effective mitigation strategies for landslide risk reduction. Landslide susceptibility assessments have traditionally utilized parameter weighting methods that incorporate rainfall intensity, slope inclination, and soil characteristics [2], [3]. However, this approach is inherently limited by subjectivity and potential inaccuracies in assigning parameter weights, which may undermine the validity of susceptibility models [4], [5].

In this context, the implementation of Fuzzy Logic offers a viable and advantageous alternative[6],[4]. Fuzzy logic, a methodology for intelligent systems, effectively addresses the uncertainties and ambiguities inherent in spatial datasets by employing linguistic variables and membership functions, thereby eliminating the need for explicit mathematical formulations in models. This approach facilitates the simultaneous analysis of multiple parameters, including precipitation, soil type, slope gradient, land cover, and geological conditions, to produce a nuanced and precise classification of landslide susceptibility in the study area.

This study focuses on Bungaya District, Gowa Regency, with the dual objective of delineating landslide susceptibility zones by applying Fuzzy Logic and proposing spatially informed mitigation strategies tailored to the identified susceptibility classifications. In contrast to the existing literature, this study integrates susceptibility mapping with actionable mitigation recommendations, thereby advancing the theoretical understanding and practical applications of landslide risk management.

RESEARCH METHOD

This study employed a spatial descriptive quantitative approach to map landslide susceptibility in the Bungaya District. This study used several systematic processes, including data collection, pre-processing, processing, and evaluation. The primary spatial data utilized in this study were acquired from the Gowa Regency Spatial Planning Agency, encompassing five distinct parameters: rainfall intensity, soil type, slope gradient, land use, and geological conditions. All spatial data initially obtained in vector format were converted to raster format to facilitate further analysis. All these parameters were calculated in the area to determine the landslide potential.

The primary process began by fuzzifying each parameter using the Fuzzy Membership function[6], which converted the input data into a scale between 0 and 1, representing the degree of susceptibility in linguistic terms. The membership function quantifies the degree of membership, with commonly employed functions including triangular and trapezoidal functions. For example, the triangular membership function is mathematically defined as follows (1):

$$\mu_A(x)=\begin{cases}0, & x\le a\\ \dfrac{x-a}{b-a}, & a<x\le b\\ \dfrac{c-x}{c-b}, & b<x<c\\ 0, & x\ge c\end{cases} \tag{1}$$

where $\mu_A(x)$ denotes the membership degree of the input *x* (Landslide parameters in Tables 1 to 6) to the fuzzy set *A*, and *a, b* and *c* represent the parameters that define the shape and range of the function.

Table 1. Rainfall parameters in the Bungaya District.

Parameter	Class	Rainfall intensity	Linguistic value
Rainfall	Low	1500-2000	1500 < x ≤ 2000
	Moderate	2000-2500	2000 < x ≤ 2500
	Hight	2500-3000	2500 < x ≤ 3000
	Very high	3000-3500	3000 < x ≤ 3500

Table 2. Parameters of soil type in Bungaya District.

Sensitivity to Erosion	Soil type	Linguistic Value
Less Sensitive	Brown Forest Soil, Yellow Red Mediterranean	45 < x ≤ 60
Highly Sensitive	Latosol, litosol/regosol	x > 75

Table 3. Elevation parameters in Bungaya District.

Class	Elevation (m)	Linguistic Value
Low	< 300	x < 300
Moderate	300-500	300 < x ≤ 500
Hight	500-1000	500 < x ≤ 1000
Very Hight	1000-1500	1000 < x ≤ 1500

Table 4. Slope parameters in the Bungaya District.

Class	Slope (%)	Linguistic Value
Flat	0-8	x ≤ 8
Ramps	8-15	8 < x ≤ 15
Moderate steep	15-25	15 < x ≤ 25
Steep	25-45	25 < x ≤ 45
Highly steep	45>	x > 45

Table 5. Land cover parameters in Bungaya District.

Sensitivity to erosion	Land cover	Linguistic value

Slightly sensitive	Jungle, Sand	x< 10
Moderate sensitive	Plantation, Brushwood	10 < x ≤ 30
Sensitive	Rice fields, Rain-fed rice fields, Settlements, and residences.	30 < x ≤ 50
Highly sensitive	Fields, vacant land, and rivers.	x > 50

All landslide parameters in the above table are important in landslide susceptibility assessment as they affect the stability of the soil on the slope. For example, areas containing rocks with high sensitivity to erosion are more prone to landslides, especially if affected by extreme rainfall or landuse changes [7]. Therefore, geological maps that depict the distribution of these rocks are highly relevant for landslide potential analysis.

Table 6. Geologic parameter.

Sensitivity to erosion	Rock type	Linguistic value
Slightly sensitive	Lava stone, breccia, tuff, conglomerate	x < 7
Highly sensitive	Marine sedimentary rocks interbedded with volcanic rocks	X > 8

Following the fuzzification of these parameters, the fuzzy overlay technique was applied to integrate all fuzzy membership layers into a composite landslide susceptibility map. The overlay operator used in this study was fuzzy or suitable for assessing the union of the susceptibility factors.

RESULTS AND DISCUSSIONS

Table 7 presents the spatial distribution of rainfall intensity across Bungaya District, categorized into four classes: low, moderate, high, and very high rainfall intensities. The low rainfall class, ranging from 1500 to 2000 mm annually, covered 1,424.10 ha in the study area. The moderate rainfall class (2000–2500 mm/year) encompassed a much larger area of 8,657.79 ha than the other classes. The high rainfall category, defined as 2500–3000 mm annually, occupies the most significant portion of the district at 9,340.57 ha. These figures indicate that most of Bungaya experiences moderate to high rainfall, which is a critical factor contributing to landslide susceptibility in this area [8].

Table 7. Intensity of rainfall.

Class	Intensity of rainfall	Area (Ha)
Slight	1500-2000 mm/year	1424.10
Moderate	2000-2500 mm/year	8657.79
Hight	2500-3000 mm/year	9340.57
Very Hight	3000-3500 mm/year	960.77
	Overall	**20383.24**

The very high rainfall category (3000–3500 mm/year) represented the smallest area at 960.77 ha. Despite its limited spatial extent, this zone is of particular concern because of its increased potential for soil saturation and slope instability [9], [10]. Overall, the total area analyzed was 20,383.24 ha, providing a comprehensive view of the rainfall variability in the study area. This distribution highlights the importance of integrating rainfall intensity into landslide risk assessments and formulating mitigation strategies tailored to the spatial rainfall patterns.

Soil type

Table 8 shows the spatial distribution of soil types within Bungaya District and their corresponding sensitivity to erosion. The district is predominantly covered by two main soil classes: Brown Forest Soil, Mediterranean Red Yellow, and Latosol/Litosol/Regosol. Brown forest soil and Mediterranean red-yellow soils were classified as having low susceptibility to erosion, occupying a relatively small area of 375.08 ha. These soil types typically possess characteristics that confer greater resistance to erosive processes, thereby contributing to relatively stable land conditions in the limited areas where they are found.

Table 8. Sensitivity to erosion.

Soil type	Sensitivity to erosion	Area (Ha)
Brown Forest Soil, Red yellow Mediteran	Slight sensitive	375.08
Latosol, litosol/Regosol	Hight sensitive	20008.16
Overall		**20383.24**

In contrast, most of the district's land area, totalling 20,008.16 ha, is covered by Latosol, Litosol, and Regosol soils, which are highly susceptible to erosion. These soil types are characterized by lower cohesion and higher erodibility, making them vulnerable to surface runoff and mass waste, particularly under high rainfall conditions[8]. The extensive presence of erosion-prone soils significantly increases the overall landslide risk within the district, emphasizing the need for targeted soil conservation and erosion control measures in the region's risk mitigation strategies [11].

Table 9 presents the area distribution in Bungaya District according to the slope classification. The slope classification was segmented into five categories: flat, gentle, moderate, steep, and very steep. Each category delineates the degree of slope in percentage terms and the corresponding area within each category, as follows: This distribution highlights the potential susceptibility to landslides.

Table 9. Slope gradient.

Class	Slope	Area (Ha)
Flat	0-8%	1074.97
Gentle	8-15%	2133.32
Moderate	15-25%	5232.31
Steep	25-45%	6367.17
Very steep	45>	5575.47

Overall	**20383.24**

The Flat class, with an area of 1,074.97 hectares, was the lowest-slope class and had minimal landslide potential. The Steep class, with an area of 6,367.17 ha, has a higher potential for landslides, particularly if extreme rainfall occurs in this area. Finally, the steep class, with a slope of more than 45% and an area of 5,575.47 ha, had the highest potential for landslides. Analysis of the calculation results revealed that nearly half of the area of Bungaya District, encompassing 11,942.57 ha, was classified as having steep and very steep terrain. Gbadebo et al. (2018)[12] noted that slopes exceeding 20° (approximately 40%) are susceptible to land movement or landslides. Consequently, regions with slopes greater than 40%, categorized as very steep, warrant particular attention in landslide mitigation strategies. Conversely, areas characterized by low or gentle slopes, such as the Sapaya and Je 'nebatu Villages, exhibited a reduced likelihood of landslides but still required careful monitoring.

Using fuzzy logic, a map delineating the landslide vulnerability category was generated by integrating six parameters contributing to landslides. The analysis yielded four distinct classes of landslide vulnerability: not prone, low prone, medium prone, and high prone vulnerability. The spatial extent of each vulnerability class was determined, as shown in Table 10.

Table 10. Extent of landslide vulnerability parameters.

Class	Area (ha)
Light	592.91
Minor	3093.32
Moderate	9139.72
Hight	7557.29
Overall	**20383.24**

The results of the calculation of the area of each landslide-prone level in each village in the case study are presented in Table 11.

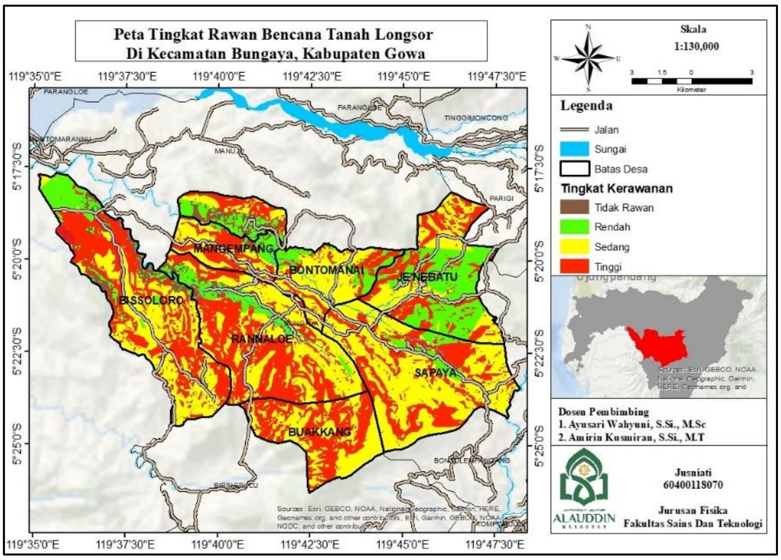

Figure 1. Map of landslide vulnerability levels in Bungaya District.

Table 11. Landslide vulnerability levels and areas.

Village	Area (ha)			
	Hight	**Moderate**	**Slight**	**Invulnerability**
Sapaya	1211.13	2548.73	238.95	0
Bontomanai	552.90	1056.33	551.57	158.06
Buakkang	1030.92	931.14	0.00	0
Bissoloro	1712.80	1682.68	479.32	229.08
Jenebatu	824.17	806.39	1233.01	0
Rannaloe	1815.84	1667.52	407.47	85.84
Mangempang	404.37	432.05	169.44	37.76

According to the landslide susceptibility map (Figure 1), four villages, namely Buakkang, Rannaloe, Sapaya, and Bissoloro, occupy the largest areas classified as being highly susceptible to landslides.

As shown in Figure 1, the landslide was caused by six factors: the slope of the area was notably steep, exceeding 45%, with altitudes ranging from 500 to 1000 m above sea level. The soil type at the research site is highly susceptible to erosion, as is the rock type, which is also prone to erosion, facilitating landslides [10], [13]. This susceptibility is attributed to the unconsolidated nature of the rock and soil, which is characterized by erodibility, porosity, and high permeability. Additionally, the high intensity of rainfall, measuring between 2000 and 2500 mm/year, coupled with inappropriate land use in the study area, constitutes a significant factor that can rapidly and intensively trigger landslides.

Based on the landslide vulnerability map, the following landslide mitigation strategies can be implemented in the Bungaya Sub-district, prioritized from the highest to lowest level of vulnerability:

a. High level of vulnerability

All villages within the Bungaya Sub-district exhibit significant vulnerability due to land use, predominantly characterized by jungle and shrubland, encompassing an area of 7066.56 hectares. Mitigation strategies have been implemented using technical and vegetative methods to address these issues[14]. Technical approaches involve the installation of wire gabions at the base of slopes to stabilize weathered rocks, the development of surface and subsurface drainage systems on slopes, and the construction of retaining walls along roadsides. Conversely, vegetative methods involve planting deep-rooted or robust vegetation to enhance water absorption, bind soil aggregates, and improve drainage systems in the middle and upper-slope sections. The objective is to decrease the water saturation level in the soil above the impermeable layer (sliding plane) and reduce the load of the seepage water.

b. Moderate level of vulnerability

Regions with medium vulnerability to landslides exhibit reduced susceptibility. Nevertheless, it remains imperative to implement mitigation strategies to further reduce the risk of landslides. Both technical and vegetative approaches can be employed for this purpose. Technical methods include the construction of retaining walls, installation of anchors at the base of slopes or along roadways, establishment of traps in plantation areas, and development of drainage systems. Conversely, vegetative methods involve the strategic planting of vegetation based on the density levels. When construction is planned in areas with moderate vulnerability, it is advisable to ensure that the buildings are equipped with robust foundations.

c. Light level of vulnerability

Areas characterized by low vulnerability lack the potential for landslide occurrence. At this level, the implementation of vegetative methods is considered an appropriate mitigation strategy.

Conclusion

Based on the findings of this study, it can be concluded that landslide susceptibility in the Bungaya Sub-district is classified into four categories: not prone, covering an area of 592.91 ha; low, encompassing 3,093.32 ha; medium, spanning 9,139.72 ha; and high, extending over 7,557.29 ha. Notably, the villages of Rannaloe, Sapaya, Bissoloro, and Buakkang predominantly fall within the high landslide susceptibility category. These results suggest that the Bungaya Sub-district is vulnerable to landslides.

In Bungaya Sub-district, disaster mitigation strategies should be tailored according to the level of vulnerability. It is advisable to implement technical and vegetative methods in areas of high vulnerability. A combination of technical and vegetative methods is recommended for regions with moderate vulnerabilities. Conversely, mitigation efforts can rely solely on vegetative methods in low-vulnerability areas.

References

[1] G. Pepe *et al.*, "A Study on the Factors Controlling the Kinematics of a Reactivated and Slow-Moving Landslide in the Eastern Liguria Region (NW Italy) Through the Integration of Automatic Geotechnical Sensors," *Applied Sciences*, vol. 14, no. 16, p. 6880, 2024, doi: 10.3390/app14166880.

[2] A. Ahmad, M. Farida, N. Juita, and M. Eng. Ir. R. Jayadi, "Soil Micromorphology for Modeling Spatial on Landslide Susceptibility Mapping: A Case Study in Kelara Subwatershed, Jeneponto Regency of South Sulawesi, Indonesia," 2023. doi: 10.1007/s11069-023-06063-1.

[3] M. S. Lanto, D. N. Syam, A. Wahyuni, and A. Kusmiran, "Pemetaan Risiko Bencana Tanah Longsor di Kabupaten Barru menggunakan Metode Pembobotan Parameter dan Inarisk BNPB," *Jurnal Geosaintek*, vol. 8, no. 3, 2022, doi: 10.12962/j25023659.v8i3.14758.

[4] A. Y. Günal and R. Mehdi, "Forecasting the Flow Coefficient of the River Basin Using Adaptive Fuzzy Inference System and Fuzzy SMRGT Method," 2023. doi: 10.12911/22998993/163367.

[5] A. Dikshit, R. Sarkar, B. Pradhan, S. Segoni, and A. Alamri, "Rainfall Induced Landslide Studies in Indian Himalayan Region: A Critical Review," 2020. doi: 10.3390/app10072466.

[6] L. P. Sharma, N. Patel, M. K. Ghose, and P. Debnath, "Synergistic Application of Fuzzy Logic and Geo-Informatics for Landslide Vulnerability Zonation—a Case Study in Sikkim Himalayas, India," 2013. doi: 10.1007/s12518-013-0115-7.

[7] R. A. Lubis, M. Rusdi, and H. Basri, "Pemetaan Tingkat Kerawanan Longsor Berdasarkan Curah Hujan dan Geologi Menggunakan Metode Fuzzy Logic Di

Kecamatan Leupung Kabupaten Aceh Besar," *Jurnal Ilmiah Mahasiswa Pertanian*, vol. 3, no. 2, 2018, doi: 10.17969/jimfp.v3i2.7506.

[8] Y. Liu, Z. Deng, and X. Wang, "The Effects of Rainfall, Soil Type and Slope on the Processes and Mechanisms of Rainfall-Induced Shallow Landslides," 2021. doi: 10.3390/app112411652.

[9] J. Li, W. Wang, Y. Li, Z. Han, and G. Chen, "Spatiotemporal Landslide Susceptibility Mapping Incorporating the Effects of Heavy Rainfall: A Case Study of the Heavy Rainfall in August 2021 in Kitakyushu, Fukuoka, Japan," 2021. doi: 10.3390/w13223312.

[10] G. Vessia *et al.*, "Automated Reconstruction of Rainfall Events Responsible for Shallow Landslides," 2014. doi: 10.5194/nhess-14-2399-2014.

[11] H. Wang *et al.*, "Water Erosion Response to Rainfall Type on Typical Land Use Slopes in the Red Soil Region of Southern China," 2024. doi: 10.3390/w16081076.

[12] A. M. Gbadebo, O. H. Adedeji, and A. S. Edogbo, "GIS-based Landslide Susceptibility Assessment in Eyinoke Hilly Area of Okeigbo, SW, Nigeria," 2018. doi: 10.4314/jasem.v22i6.13.

[13] J. R. Evans, F. Imaizumi, O. Ohsaka, and S. Ogawa, "Relationship Between Tree Height and Landslide Characteristics Obtained by GIS Assessment," 2020. doi: 10.1002/esp.4964.

[14] Z. Zakaria, "Model Starlet, suatu Usulan untuk Mitigasi Bencana Longsor dengan Pendekatan Genetika Wilayah (Studi Kasus: Longsoran Citatah, Padalarang, Jawa)," *Indonesian Journal on Geoscience*, vol. 5, no. 2, 2010, doi: 10.17014/ijog.v5i2.95.