



Landslide hazard spatial distribution for disaster mitigation in tutur sub-district

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Abstract

Landslides pose a significant threat to safety and infrastructure in the Tujur District, particularly following recent incidents that blocked major roads and inundated residential areas. This study was conducted to map the area's most at risk and understand the factors driving this instability. Using a geographic computer model, the research analyzed five key environmental factors: slope, precipitation, rock types, soil types, and how the land is currently used. The findings reveal that over half of the Tujur District (55.3%) falls into a high-risk category, with specific zones in villages like Ngadirejo and Tlogosari identified as being at very high risk. These dangerous zones are primarily caused by a combination of extremely steep slopes and intensive farming activities on loose volcanic soil. Comparisons of actual landslide events confirmed the high accuracy of the map. Notably, the study found that several government offices used for emergency gathering and primary transport routes are in these high-risk zones. These results provide a vital tool for local authorities to prioritize safety reinforcements, install warning systems, and manage land use to prevent future disasters.

Keywords

Landslide susceptibility, GIS, Weighted overlay, Disaster mitigation

Introduction

Landslides are mass movements of rock, earth, or debris down a slope, driven by gravity and triggered by a combination of natural and anthropogenic factors. They represent a significant natural hazard globally, causing thousands of fatalities and billions in economic losses annually, particularly in mountainous and tectonically active regions. The increasing frequency and severity of landslides, exacerbated by climate change, deforestation, and urban expansion, underscore their relevance to sustainable development and disaster risk reduction efforts worldwide. This report synthesizes current understanding of landslide mechanisms, impacts, assessment methods, and mitigation strategies, highlighting both theoretical foundations and practical insights

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from recent research [1] These events are often triggered by a combination of natural factors, such as high rainfall, steep topography, and geological instability and anthropogenic factors like improper land use [1], [2].

Landslides are a significant natural hazard with far-reaching impacts on human life, infrastructure, and the environment. Their effects can be categorized into several key areas, like human and socio-economic impact. Landslides are a significant natural hazard with extensive consequences for human life, infrastructure, and the environment, responsible for at least 17% of natural hazard fatalities globally [3] and frequently causing casualties and injuries [4]. Beyond the loss of life, they inflict severe property damage to homes and infrastructure [4], disrupting human activities [5] and imposing substantial economic burdens through both direct costs and indirect losses, such as restricted access to markets [6] notably, even frequent small landslides cumulatively result in significant financial costs [7]. Environmentally, landslides drive soil erosion and land degradation that threaten agricultural productivity [8], alter landscapes through debris accumulation [9], and degrade water quality and ecosystems by introducing sediment and destroying forest cover [10]. The impact extends to the psychological and social realms, causing trauma and long-term anxiety for individuals [11], [12] while severing remote communities from employment and education [6]. Addressing these risks requires a combination of preventive measures like slope stabilization and sustainable land-use practices [8], [13] community resilience strategies [13], and the application of technological tools such as GIS to identify landslide-prone areas [14], [15].

Tutur District, located in Pasuruan Regency on the slopes of Mount Bromo at an elevation exceeding 1,000 meters above sea level, covers an area of 86.3 km². The region is characterized by volcanic slopes with fertile soil rich in humus, a topographical condition that renders the area highly susceptible to landslides. Landslides are defined as the movement of soil or rock masses down a slope caused by the disruption of material stability. This instability is driven by causal factors such as slope steepness, lithology, and anthropogenic land use, as well as triggering factors like high-intensity rainfall and tectonic activity. Slope steepness is particularly critical; as the slope increases, so does the shear force influenced by gravity, disturbing stability. Furthermore, soil with loose texture and high permeability is prone to cracking in heat and saturation during rain, significantly increasing movement risks. Recent events have highlighted the vulnerability of Tutur District. On December 5, 2023, a landslide obstructed the main road in Kalipucang Village, followed by another event on January 4, 2024, which inundated residential yards with soil material. Although these incidents resulted in no fatalities, they pose a significant, ongoing threat to the safety of the local population and confirm that Tutur District is a landslide-prone area. Despite these evident risks, there is currently a lack of specific research regarding landslide hazards in the district [16].

Previous research on landslide hazards in Tutur District was conducted in 2022 by Fortunata et al., utilizing the Simple Multi-Attribute Rating Technique Exploiting Ranks

(SMARTER) method. This study identified high-risk areas in villages such as Kali Pucang and Kayu Kebek. However, the study relied on rainfall data only up to 2021. Rainfall patterns from 2022 to the present have shown a tendency toward higher intensity compared to previous years. Consequently, to reflect current conditions accurately, it is necessary to conduct updated research utilizing rainfall data up to 2024 [17]. To address this gap, this study proposes an “Analysis of Landslide Hazard Levels in Tukur District Using Geographic Information Systems (GIS)”. The research employs the weighted method derived from [18] scoring five key parameters: Slope (KL), Rainfall (CH), Lithology/Rock (B), Soil (T), and Land Use (PL). The primary objectives of this research are to create a Landslide Hazard Level Map and to determine the spatial distribution of landslide hazards in Tukur District. The resulting spatial information is indispensable for disaster mitigation efforts, including land-use modification, evacuation planning, and the remote identification of vulnerable areas through precise global coordinates.

Method

The research was conducted in Tukur District (57.49 km²), which comprises 12 villages (see Figure 1). The study utilized a quantitative spatial approach using GIS Software. The primary data sources included Digital Elevation Model with 0.27 arcsec resolution and supporting thematic maps including the geology, soil types, and land use maps obtained from Geospatial Information Agency of Indonesia.

We also obtained annual rainfall data from 2015 to 2024 from satellite data CHIRPS stations surrounding the study area (Tukur, Tumpang, Pasrepan, Puspo, Tosari, Karangploso, Jabung). The Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) is a robust and versatile satellite-based precipitation dataset that provides high-resolution (with spatial resolution of ± 5 km), long-term precipitation data. CHIRPS combines satellite imagery, in situ station data, and model rainfall fields to create gridded rainfall time series. Its integration of multiple data sources and bias correction techniques makes it a valuable tool for various hydrological and climatological applications, particularly in regions with limited ground-based observations [19], [20], [21].

In this study, we utilized 5 variables which are slope, precipitation, geological factors including rock types, and soil types, and land use. Based on previous studies, steeper slopes are more prone to landslide due to the gravitational force acting on the slope materials. The shape and angle of the slope influence water runoff and soil stability. Slopes with angles greater than 20° are particularly vulnerable [22], [23], [24], [25]. High-intensity rainfall over short periods or prolonged low-intensity rainfall can trigger landslides by increasing soil saturation and reducing shear strength. Previous rainfall events can saturate the soil, making it more susceptible to landslides during subsequent rainfalls. Specific rainfall thresholds (e.g., daily rainfall exceeding 50mm or cumulative rainfall over 100mm in 10 days) are critical in predicting landslide occurrences [26], [27], [28].

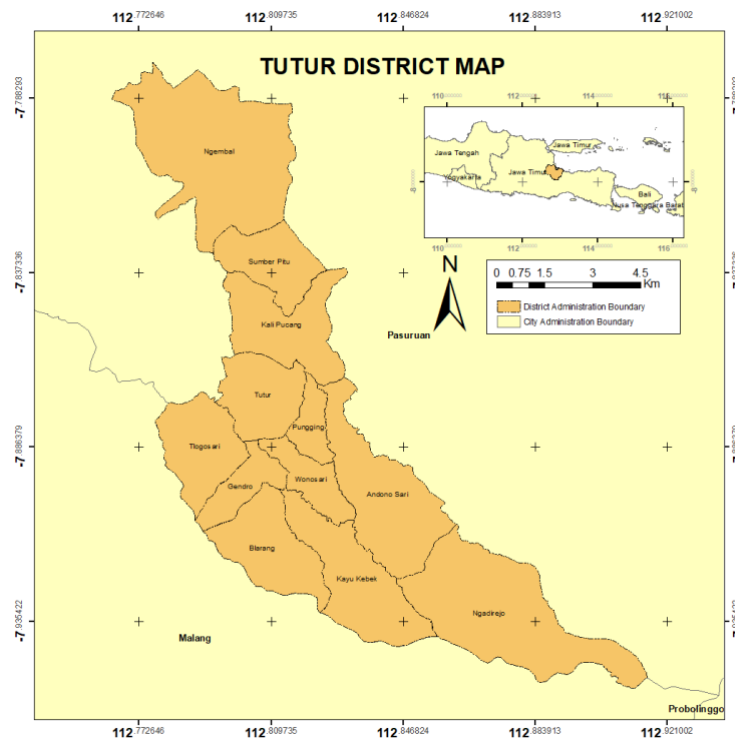


Figure 1. Tutur district map

Different rock types have varying susceptibilities to weathering and erosion. For example, sedimentary rocks are more prone to landslides compared to igneous rocks due to their lower permeability and higher weathering rates [29], [30], [31]. Faults, folds, and other geological structures can create weak zones that facilitate landslides [30], [32]. On the other hand, soils with high clay content, such as clayston, are more prone to landslide due to their low permeability and high swelling potential [31], [33], [34]. We also consider land use effect on the landslide vulnerability. Areas with dense vegetation, such as forests, are generally more stable due to root reinforcement, which increases soil cohesion and reduces erosion [35], [36]. Urbanization, deforestation, and agricultural practices can destabilize slopes by altering natural drainage patterns and removing vegetation cover. Different land use like mining, road construction, and agriculture, can increase landslide risk by disturbing the soil and rock structure [36], [37], [38].

We obtained weighted value of each variables from [puslitanak 2004]. Table 1 shows the class score on each variables. Each variable is classified into categories and assigned a score from 1 to 5, where 5 indicates the highest susceptibility (highest risk of landslide) and 1 indicates the lowest susceptibility.

The analysis of rainfall data involved calculating the average annual precipitation over a ten-year period (2015–2024) utilizing data from seven reference stations: Tutur, Tumpang, Pasrepan, Puspo, Tosari, Karangploso, Jabung, and Poncokusumo (see Table 5). The spatial distribution of rainfall was mapped using GIS, with the coordinate system projected to the Universal Transverse Mercator (UTM) Zone 49S using the WGS 84 datum. A spatial database containing station coordinates and cumulative rainfall values

was compiled and processed using the Inverse Distance Weighted (IDW) interpolation method. Inverse Distance Weighted (IDW) interpolation is a widely used spatial interpolation method that estimates unknown values based on the values of known points, with closer points having more influence on the estimated value than farther points. IDW assigns weights to known points inversely proportional to their distance from the point being estimated. The closer a known point is to the unknown point, the higher its weight in the interpolation calculation. This method is particularly popular due to its simplicity and ease of implementation [39], [40], [41]. Subsequently, the resulting rainfall map was scored according to the classification standards, and isohyet lines were generated using contour to determine the average areal rainfall distribution.

Table 1. Landslide hazard variables score [18]

Variables	Value	Score	Category
Annual Precipitation (mm)	> 3000	5	Very High
	2500 – 3000	4	High
	2000 – 2500	3	Moderate
	1500 – 2000	2	Low
	< 1500	1	Very Low
Slope (%)	> 45%	5	Very Steep
	30% – 45%	4	Steep
	15% – 30%	3	Moderately Steep
	8% – 15%	2	Sloping
	0% – 8%	1	Flat
Land Use Type		5	Agriculture
		4	Shrubs
		3	Forest Vegetation
		2	Built-up Area
		1	Water Body
Rock Type		5	Alluvial Deposits
		4	Sedimentary Rock 1
		3	Volcanic Rock 1
		2	Sedimentary Rock 2
		1	Volcanic Rock 2
Soil Type		5	Regosol, Litosol, Organosol
		4	Andosol, Laterit, Grumosol
		3	Brown Forest Soil, Mediteran
		2	Latosol
		1	Aluvial, Planosol, Hidromorf

The analysis employed the weighted overlay method based on the [18] standard. Five key parameters were analyzed, scored, and weighted according to their influence on landslide occurrences:

$$\text{Hazard Score} = 0.3(\text{KL}) + 0.2(\text{CH}) + 0.2(\text{G}) + 0.1(\text{JT}) + 0.2(\text{PL})$$

Where: KL (Slope): Weighted 30%; CH (Precipitation): Weighted 20%; G (Geology): Weighted 20%; JT (Soil Type): Weighted 10%; and PL (Land Use): Weighted 20%.

The resulting cumulative scores were classified into hazard levels: Low (1 < 2), Moderate (2 < 3), High (3 < 4), and Very High (4 - 5). The Table 2 illustrates the level of landslide hazard.

Table 2. Landslide hazard levels

Landslide Value	Landslide Hazard Level
1 < 2	Low
2 < 3	Moderate
3 < 4	High
4 - 5	Very High

Results and discussion

The spatial distribution of parameters reveals distinct patterns that contribute to the region’s overall hazard profile. Slope scores show in Table 3.

Table 3. Slope score

Slope Class	Score	Area (Ha)	Area (%)
Flat	1	3510.74	36.54
Sloping	2	2952.4	30.73
Moderately Steep	3	1739.74	18.11
Steep	4	1029.38	10.71
Very Steep	5	376.71	3.92
Total		9608.97	100

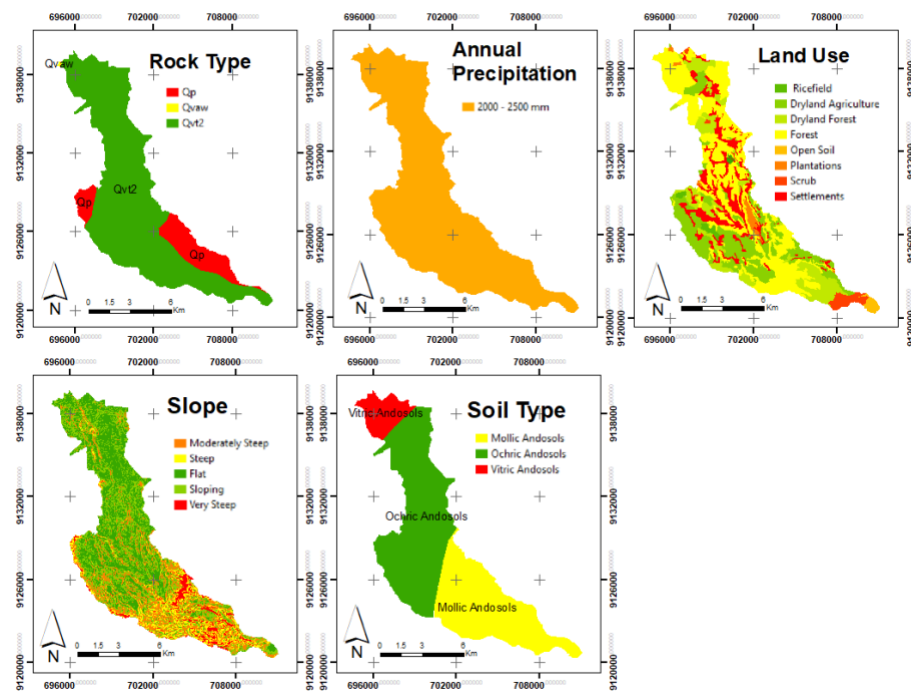


Figure 2. Landslide hazard variables spatial distribution

The slope analysis reveals a significant topographical variation across the district (see Figure 2 (d)). The northern region, particularly around Ngembal village, is characterized by “Flat” to “Sloping” terrain (0-15%), which corresponds to lower hazard scores. In contrast, the southern and central regions. These encompassing villages such as Ngadirejo, Kayu Kebek, and parts of Tlogosari, exhibit “Steep” to “Very Steep” slopes (>45%). According to the classification guidelines, these southern areas are assigned the maximum hazard score of 5, indicating that topography is a critical driving factor for landslide instability in the southern part of the district. The Land Use map highlights that Tukur District is heavily dominated by agricultural activities show in Table 4.

Table 4. Land use score

Land Use Class	Score	Area (Ha)	Area (%)
Shrubs	2	292.56	3.67
Secondary Dryland Forest	3	6.23	0.08
Plantation Forest	3	1764.88	22.12
Built-up Area	5	359.18	4.50
Plantation	2	89.38	1.12
Dryland Farming	3	5283.14	66.21
Field	4	18.5	0.23
Open Land	5	165.37	2.07
Total		7979.24	100

The spatial analysis shows a widespread distribution of Dryland Agriculture, represented in light green, which covers the majority of the district's slopes. This land use type is assigned a maximum score of 5 due to the loose nature of the soil and lack of deep root systems compared to forest vegetation. Settlements are linearly distributed along the main infrastructure spine running from north to south. The extensive presence of dryland agriculture, particularly in areas coinciding with steep slopes in the south, significantly amplifies the landslide susceptibility.

On the other hand, the rainfall distribution within Tukur District appears spatially homogenous. The interpolation of data from surrounding rainfall stations indicates that the entire study area falls within the range of 2000 – 2500 mm/year (see Figure 2 (b)). Based on the scoring standard, this places the entire district in the “Moderate” risk category with a score of 3. While this uniformity suggests that rainfall is a consistent triggering factor across all villages, it does not act as a spatial differentiator for hazard zoning within the district boundaries. Rainfall stations show in Table 5.

Table 5. Rainfall stations

Station	Latitude	Longitude	Annual Precipitation (mm)
Lawang	-7.8328	112.6976	2455
Singosari	-7.875	112.625	2486.8
Tumpang	-7.9996	112.7606	1921.3
Tukur	-7.8853	112.8125	2288.61
Pasrepan (Kejayan)	-7.7608	112.8722	2165.6
Puspo	-7.83	112.8681	2303.74
Tosari	-7.8811	112.9008	2338.9

To ensure an accurate representation of the climatic conditions influencing landslide susceptibility, this study utilized data from seven rainfall observation stations distributed within and surrounding the Tukur District (see Figure 3). As illustrated in the Rainfall Station map, the station network consists of one internal station (Tukur) and six external stations (Lawang, Singosari, Tumpang, Pasrepan, Puspo, and Tosari) that effectively encircle the study area. Soil type class score show in Table 6.

The Soil Type in Figure 2 (e) map reveals a zonal distribution. Vitric Andosols in the north, “Ochric Andosols in the central belt, and Mollic Andosols in the south. All three variants belong to the Andosol order, which typically receives a high susceptibility score (Score 4) due to its high porosity and potential for saturation. Vitric Andosols have a high

systems, fumaroles, and hot springs. [47], [48], [49], [50]. The Tengger volcanic complex, part of the larger Arjuna-Welirang system, includes a variety of volcanic formations such as lava flows and pyroclastic deposits. The area is characterized by steep slopes and significant geothermal activity [51], [52]. The combination of these porous volcanic soils with the steep topography in the southern villages creates a “High” to “Very High” composite hazard profile. Landslide susceptibility levels show in Table 8.

Table 8. Landslide susceptibility levels

Landslide Hazard Levels	Area (Ha)	Area (%)
Moderate	4235,983	43,81
High	5436,563	55,31
Very High	84,111	0,87
Total	9666,657	100

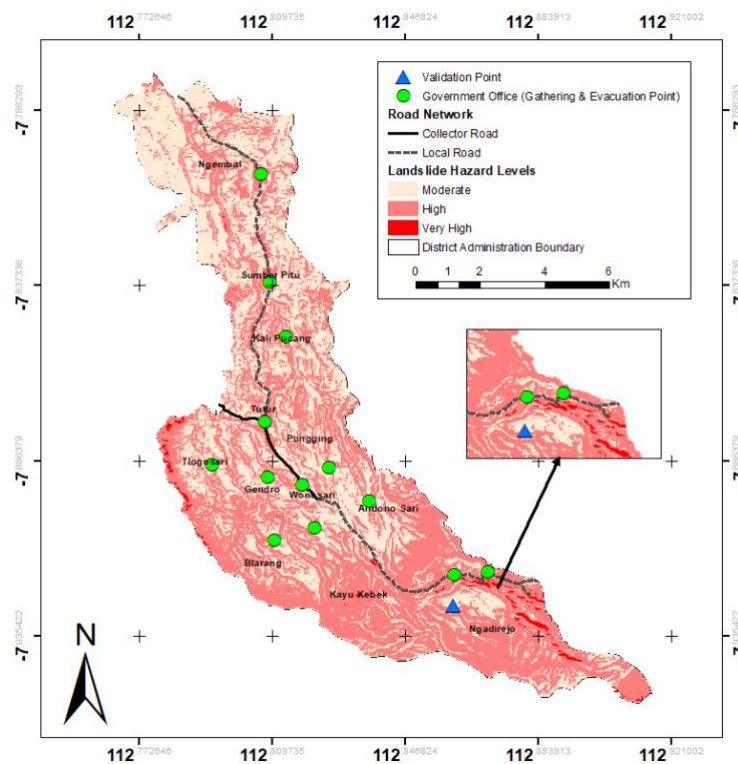


Figure 4. Landslide susceptibility map in tutur district

From the weighted variables above, we obtained the landslide hazard level by overlaying all weighted variables based on their score. The final Landslide Hazard Map, generated through the weighted overlay of five environmental parameters, classifies Tutar District into three distinct susceptibility levels: Moderate, High, and Very High. The spatial distribution of these levels is illustrated in Figure 4. The map reveals a dominant prevalence of “High” landslide susceptibility (indicated in pink) across the majority of the district’s territory. The southern region villages, specifically Ngadirejo, Kayu Kebek, Blarang, and Tlogosari exhibit the highest concentration of “Very High” hazard zones (indicated in red). These red zones correspond directly with the “Very Steep” (>45%) slopes identified in the topographical analysis. This area represents the most critical

zone requiring immediate mitigation prioritization. Villages such as Ngembal and Sumber Pitu are characterized by a mix of “Moderate” and “High” hazard levels. While less critical than the south, the “High” hazard designation still suggests a significant potential for ground movement, particularly during peak rainfall periods.

To assess the accuracy of the GIS model, a validation point (represented by the blue triangle) was plotted based on a known landslide event at Pura Satya Dharma Tirta in Ngadirejo Village [53]. The inset map highlights that this validation point falls precisely within the transition zone between “High” and “Very High” hazard areas. This spatial coincidence confirms that the model accurately reflects real-world instability conditions.

The map also evaluates the safety of critical infrastructure in relation to hazard zones:

1. **Evacuation Points:** The Government Offices (green circles), which often serve as ad-hoc gathering or evacuation points, are mostly located within “High” hazard zones. This finding is crucial for disaster planning, suggesting that some designated assembly points may themselves be vulnerable to landslides and require geotechnical reinforcement.
2. **Road Network:** The primary collector roads and local road networks frequently traverse “High” and “Very High” hazard areas, particularly in the south. This indicates a high risk of transportation disruption and isolation for southern villages during landslide events.

The widespread high-risk classification is attributed to the region’s overall geomorphological characteristics, specifically the combination of volcanic soil (Andosols) and heavy agricultural land use. Vitric Andosols have high volcanic glass content and low bulk density can contribute to instability, making these soils more susceptible to landslides, especially when saturated with water. Molic Andosols have high organic matter content can enhance soil structure and stability, potentially reducing landslide risk. However, if the soil becomes overly saturated, the increased weight and reduced cohesion can still pose a landslide risk. The soil characteristic around the area has high porosity and low bulk density, which can lead to increased water retention and reduced soil strength when saturated [43], [44]. This support the condition of Tukur District which are close to the Bromo Tengger Semeru volcanic mountain.

Table 9. Villages with highest level of landslide susceptibility

Village	Level	Area (Ha)
Ngadirejo	5 (Very High)	53.90
Tlogosari	5 (Very High)	20.49
Gendro	5 (Very High)	2.96
Kayukebek	5 (Very High)	1.80

The following villages are identified as containing the most critical landslide hazard zones in the district show in Table 9. Ngadirejo has the most significant exposure to the highest landslide hazard level, with 53.90 hectares classified as “Very High” risk. As shown on the hazard map, Ngadirejo is located in the southernmost part of the district

where the terrain is predominantly “Very Steep”. Tlogosari ranked second in risk exposure, Tlogosari contains 20.49 hectares of Level 5 hazard area. Gendro contains 2.96 hectares of very high-risk area. Among the critical villages, Kayukebek has the smallest Level 5 area, totaling 1.80 hectares.

Based on the Landslide Hazard Map and Table 9, these critical zones in Ngadirejo and Tlogosari are intersected by local road networks and are near Government Offices designated as gathering and evacuation points. The validation point located in Ngadirejo further confirms that the model accurately identifies real-world landslide susceptibility in these high-scored villages. “Very High” risk in villages like Ngadirejo (53.90 Ha) is not merely a topographical coincidence but a direct result of the interaction between slopes >45% and intensive agriculture. This land-use practice on steep slopes significantly reduces soil stability compared to forested areas (see Figure 5).

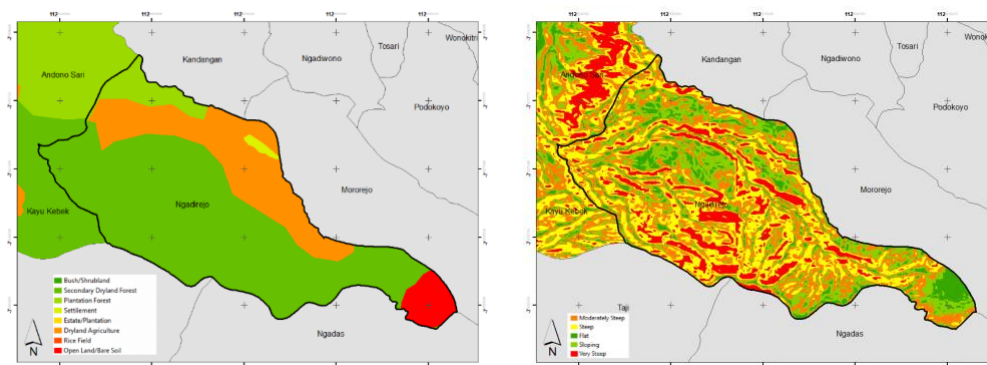


Figure 5. Ngadirejo land use (left) and slope (right)

Additionally, The spatial overlay analysis identified a total of 84.11 hectares within Tutur District as belonging to the “Very High” (see Table 8) landslide hazard category. While this represents only 0.87% of the total district area, these zones are concentrated in specific administrative areas that require urgent mitigation prioritization. The classification of these villages as “Very High” risk is a result of cumulative scoring across multiple physical and anthropogenic variables, including topographical condition with “Very Steep” level of slope and agricultural land use. Within these critical zones, 69.90 hectares are currently utilized for Dryland Agriculture. Alarmingly, 1.94 hectares of residential settlements are located within these “Very High” hazard zones, specifically occupying slopes that are steep to very steep. The Pura Satya Dharma Tirta incident in Ngadirejo, the temple’s location aligns with the modeled “High” to “Very High” transition zone, where a destructive landslide occurred in January 2024. This confirms that the villages of Ngadirejo and Tlogosari must be the primary focus for the installation of early warning systems and the implementation of slope stabilization programs.

The spatial distribution of landslide hazard levels in Tutur District presents a significant challenge for existing disaster mitigation frameworks. A critical finding in this study is the spatial vulnerability of designated safety points. As illustrated in Figure 4, several Government Offices, which currently function as primary gathering and evacuation points, are situated within or immediately adjacent to “High” and “Very High” hazard

zones. This condition represents a vulnerability shadow, where the infrastructure intended to protect the community is itself at risk of geotechnical failure during extreme weather events.

Furthermore, the functionality of the Road Network is identified as a critical bottleneck for post-disaster response. The primary Collector Roads and local access routes, the district's lifelines frequently traverse "Very High" hazard areas, particularly in the southern villages of Ngadirejo and Tlogosari. This finding aligns with the research [54] which prioritized infrastructure improvement in high-risk zones, but our results clarify the exact coordinates where road blockages are most likely to occur.

Based on these findings, the following mitigation strategies are proposed:

1. **Relocation or Reinforcement:** Evacuation points currently located in "High" hazard zones must undergo site-specific geotechnical stabilization or be relocated to "Moderate" zones.
2. **Early Warning Systems (EWS):** Priority installation of EWS is required in Ngadirejo and Tlogosari due to the concentration of Level 5 (Very High) hazard areas intersecting with residential settlements.
3. **Land-Use Modification:** Mitigation must go beyond structural engineering to include land-use policy; specifically, restricting Dryland Agriculture on slopes exceeding 45% to reduce the anthropogenic triggers of slope failure.

Conclusion

The spatial analysis of landslide susceptibility in Tukur District, conducted using the GIS weighted overlay method based on the [18] framework, indicates that the region is structurally highly vulnerable to ground movement. The results reveal that the district is primarily dominated by the High hazard class, covering 5,436.56 hectares (55.31%), followed by the Moderate hazard class at 4,235.98 hectares (43.81%). Although the Very High hazard category occupies a relatively small area of 84.11 hectares (0.87%), these zones represent critical hotspots for disaster management. Spatially, these critical zones are concentrated in four specific villages: Ngadirejo (53.90 Ha), Tlogosari (20.49 Ha), Gendro (2.96 Ha), and Kayukebek (1.80 Ha).

The primary determinants of driving the "Very High" hazard classification are the synergistic effects of extreme topography and anthropogenic land use. Specifically, these zones coincide with very steep slopes exceeding 45% and steep slopes between 25–45%. The risk is further intensified by the prevalence of dryland agriculture occupying 69.90 hectares and residential settlements spanning 1.94 hectares within these precarious slope boundaries. The reliability of the generated spatial model is validated by the real-world incident at Pura Satya Dharma Tirta in January 2024 [53], where the destructive landslide occurred exactly within the predicted high-hazard transition zone.

To optimize disaster mitigation strategies in Tukur District, this study proposes several urgent recommendations for local authorities and stakeholders. First, spatial mitigation

efforts should be prioritized in Ngadirejo and Tlogosari through the installation of Early Warning Systems (EWS) and the construction of slope stabilization structures in identified residential clusters. Second, an immediate technical audit is required for existing government offices designated as evacuation points; those situated in high-hazard zones must undergo geotechnical reinforcement or be relocated to areas classified as “Moderate” to ensure the safety of displaced populations during emergencies.

Furthermore, proactive land-use policies must be enforced to restrict dryland farming on slopes exceeding 45%, encouraging a transition toward agroforestry with deep-rooted perennial plants to enhance natural slope stability. Finally, future studies could incorporate SMAP (Soil Moisture Active Passive) satellite data to analyze how real-time soil saturation levels correlate with the identified hazard zones, providing a dynamic risk model instead of a static one. Additionally, transition from the weighted overlay method (Puslittanak) to machine learning algorithms such as Random Forest (RF), Support Vector Machines (SVM), or Logistic Regression to see if these models yield higher accuracy when compared with the landslide inventory. Using the ArcGIS Network Analyst extension, a study could model the most efficient and safest evacuation routes for the residents of Ngadirejo and Tlogosari, specifically calculating “Service Areas” for the designated gathering points to identify communities that might be cut off by road closures. Then, developing a Web-GIS platform or mobile application where local residents in study area can report ground cracks or small slides in real-time would create a crowdsourced database to validate and update the hazard map continuously.

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