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GIS-Based Landslide Susceptibility Mapping Using Weighted Overlay Method In East Suwawa Timur District, Bone Bolango Regency

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Abstract

Landslides are among the most frequent hydrometeorological disasters in Indonesia, particularly in hilly regions characterized by high rainfall intensity and unstable land conditions. East Suwawa District, Bone Bolango Regency, is characterized by mountainous terrain, intensive land-use activities, and recurring landslide events, making landslide susceptibility assessment essential for disaster mitigation and spatial planning. Previous studies have predominantly focused on landslide susceptibility mapping at broader regional scales, while detailed spatial analysis at the district level remains limited. Therefore, this study aims to map landslide susceptibility in East Suwawa District using a Geographic Information System (GIS)-based Weighted Overlay Method. The analysis incorporated five parameters, namely rainfall, slope, land use, soil type, and geological conditions. Spatial data were weighted according to their influence on landslide occurrence and subsequently integrated through overlay analysis to generate a landslide susceptibility map. The results reveal four susceptibility classes: low (0.13%), moderate (43.53%), high (55.75%), and very high (0.58%). High susceptibility areas dominate the district, particularly in the hilly regions of Tulabolo, Tulabolo Barat, and Tulabolo Timur villages. These findings provide important spatial information for disaster risk reduction, land-use planning, and sustainable regional development in landslide-prone areas.

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Keywords: GIS; Landslide Susceptibility; Weighted Overlay; Spatial Analysis; Disaster Mitigation

INTRODUCTION

Among the various natural hazards occurring in Indonesia, landslides represent one of the most frequent and destructive disasters, particularly in mountainous and hilly regions experiencing high annual rainfall. Indonesia's geological position at the convergence of the Eurasian, Indo-Australian, and Pacific tectonic plates makes the country highly susceptible to both geological and hydrometeorological hazards (Achmad, 2023). Landslide events frequently result in casualties, environmental degradation, infrastructure damage, and considerable socio-economic losses (Bolango, 2023). The occurrence of landslides is governed by the interaction of several environmental conditioning factors, including rainfall, slope gradient, geological conditions, soil characteristics, and land-use patterns (Arsyad et al., 2019). The combined influence of these factors determines slope stability and ultimately controls the spatial distribution of landslide susceptibility, especially in mountainous landscapes subjected to intensive human activities (Noho et al., 2025).

Recent advances in Geographic Information System (GIS) technology have significantly enhanced the capacity to evaluate and visualize landslide susceptibility through integrated spatial analysis. By combining multiple environmental variables within a unified analytical framework, GIS facilitates the identification of areas that are potentially vulnerable to landslide occurrence. Previous studies have demonstrated that the integration of GIS with scoring and weighted overlay techniques provides an effective approach for classifying susceptibility into different hazard levels (Putri et al., 2023). Furthermore, the weighted overlay method enables each environmental parameter to be represented according to its relative contribution to slope instability, thereby producing a transparent and reproducible susceptibility assessment. Consequently, GIS-based susceptibility mapping has become an essential component of disaster risk reduction, regional spatial planning, and environmental resource management.

In Gorontalo Province, landslide hazards have become an increasingly important environmental issue because of the region's mountainous topography, high rainfall intensity, and expanding human activities on steep terrain (BNPB, 2024). East Suwawa District, located within Bone Bolango Regency, represents one of the areas most vulnerable to landslide occurrence. The district is characterized by rugged topography, extensive agricultural activities, and artisanal mining operations that may accelerate slope degradation. Several landslide events have been

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documented in recent years, including the major disaster in the Tulabolo Timur mining area in 2024, which caused fatalities, environmental damage, and disruption to local socio-economic activities. These recurring events highlight the urgent need for detailed spatial assessments capable of identifying variations in landslide susceptibility across the district.

Existing studies on landslide susceptibility have predominantly been conducted at regional or provincial scales, whereas detailed investigations at the district level remain relatively limited. Although previous research has successfully applied GIS-based scoring and weighting techniques to generate susceptibility maps, comprehensive spatial information specifically describing landslide susceptibility in East Suwawa District is still lacking (Putri et al., 2023). This limitation represents an important research gap because local governments and surrounding communities require site-specific susceptibility information to support evidence-based disaster mitigation and sustainable land-use management.

Although considerable progress has been achieved in GIS-based landslide susceptibility assessment, the availability of detailed sub-district-scale analyses remains limited, particularly in disaster-prone regions such as East Suwawa District. Many previous investigations have emphasized broader administrative units or incorporated only a limited number of environmental conditioning factors, thereby reducing their usefulness for local disaster mitigation and spatial planning. To address this gap, the present study integrates CHIRPS rainfall data, Sentinel-2-derived land-use information, SRTM-based slope data, soil characteristics, and supporting geological information within a GIS-based weighted overlay framework. Field validation was additionally conducted to improve the reliability of the resulting susceptibility map and to provide updated spatial information for evidence-based disaster risk reduction and sustainable land-use planning.

Accordingly, this study aims to map landslide susceptibility in East Suwawa District, Bone Bolango Regency, using a GIS-based weighted overlay approach. The analysis incorporates five principal environmental parameters, namely rainfall, slope gradient, land use, soil type, and geological characteristics, to generate a district-scale landslide susceptibility map. The primary contribution of this research lies in providing detailed spatial information for an area that has experienced recurrent landslide events but has received limited attention in previous susceptibility assessments. The findings are expected to contribute to the advancement of GIS applications in landslide susceptibility assessment while providing practical references for disaster mitigation planning, sustainable land-use management, and regional development.

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LITERATURE REVIEW

Landslide Susceptibility Mapping And Geographic Information Systems

Landslides constitute one of the most significant natural hazards affecting tropical regions, particularly areas characterized by steep topography, intense rainfall, unstable geological formations, and extensive land-use modification. Their occurrence results from the interaction between natural environmental conditions and human activities, including rainfall variability, slope gradient, soil characteristics, lithological composition, and land-cover dynamics. Consequently, landslide susceptibility assessment has become an essential component of disaster risk reduction by providing spatial information that identifies areas potentially exposed to slope failure. Such information supports evidence-based land-use planning, infrastructure development, and disaster mitigation initiatives (Zulfa et al., 2022; Goma et al., 2022). Moreover, continuous advances in geospatial technologies have substantially improved the capability to analyze and map landslide susceptibility through the integration of multiple environmental variables within a spatial decision-support framework.

Geographic Information Systems (GIS) are widely recognized as an effective spatial analysis platform for investigating landslide susceptibility because they enable the acquisition, management, analysis, and visualization of geographically referenced information. Through the integration of multiple environmental conditioning factors, GIS facilitates the development of susceptibility maps that illustrate spatial variations in landslide potential. (Putranto & Jani, 2024) reported that GIS effectively combines spatial and attribute information to support environmental assessment and disaster-related decision-making. Likewise, (Paddiyatu et al., 2025) highlighted that GIS-based spatial analysis improves the accuracy and efficiency of hazard mapping by integrating thematic datasets, overlay analysis, and spatial visualization techniques. As a result, GIS has become an indispensable analytical framework for landslide susceptibility assessment across diverse geographical settings.

Weighted Overlay Method In Landslide Susceptibility Assessment

Among the available GIS-based spatial analysis techniques, the Weighted Overlay Method remains one of the most practical approaches for evaluating landslide susceptibility because it systematically integrates multiple environmental conditioning factors into a single analytical model. The method assigns relative weights and scores to each parameter according to its contribution to landslide occurrence before combining them through spatial overlay operations to generate susceptibility classes. The weighting framework developed by (Puslittanak, 2004), has

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been extensively adopted in Indonesia, emphasizing slope gradient, rainfall, land use, soil characteristics, and geological conditions as the principal determinants of landslide susceptibility. Within this framework, slope gradient generally receives the highest weighting because it directly controls gravitational forces acting on slope materials, followed by rainfall, land use, soil properties, and geological characteristics (Paimin et al., 2012; Puslittanak, 2004).

Recent studies have demonstrated the effectiveness of weighted overlay analysis in identifying spatial patterns of landslide susceptibility. For example, Madani et al. (2023) applied a GIS-based weighted overlay approach and successfully classified landslide-prone areas into several susceptibility levels ranging from low to very high. Similarly, (Rif'ah et al., 2024) reported that the integration of rainfall, slope, geology, soil type, and land-use parameters through weighted overlay analysis produced reliable susceptibility maps that can support regional disaster mitigation planning. Although more advanced methods such as machine learning and statistical modeling have gained popularity, the weighted overlay method remains relevant, particularly in developing regions where data availability and technical resources may be limited.

Factors Influencing Landslide Susceptibility

Previous studies consistently indicate that slope gradient, rainfall, land use, geology, and soil characteristics are among the most influential factors affecting landslide occurrence. High rainfall intensity increases soil moisture content and pore-water pressure, thereby reducing slope stability and increasing the likelihood of mass movement (Koven & Hamdany, 2024). Likewise, steep slopes accelerate gravitational forces acting on soil and rock materials, making them more susceptible to (Paimin et al., 2012). Geological conditions also play a significant role because weathered volcanic rocks and fractured lithological formations tend to exhibit lower resistance to erosion and slope instability (Yu et al., 2021).

Human-induced land-use modification has become an increasingly important driver of landslide susceptibility due to the rapid transformation of natural landscapes. Activities such as deforestation, agricultural expansion, mining operations, and infrastructure construction frequently reduce vegetation cover and disturb slope equilibrium, thereby increasing the likelihood of slope failure (Vidaletti, 2021). These conditions are particularly evident in mountainous regions of Indonesia, where land conversion often occurs on steep terrain. Therefore, integrating both environmental and anthropogenic variables is essential for producing comprehensive and reliable landslide susceptibility assessments.

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Research Gap And Study Position

Although numerous studies have successfully applied GIS-based spatial analysis to identify landslide-prone areas in Indonesia, most investigations have been conducted at provincial, watershed, or district scales. Consequently, detailed susceptibility assessments at the sub-district level remain relatively scarce, particularly in East Suwawa District despite its mountainous terrain, high rainfall intensity, and history of recurrent landslide events, including the major Tulabolo mining disaster in 2024 (Dzatir et al., 2024; Putri et al., 2023). However, studies specifically examining landslide susceptibility in East Suwawa District remain limited despite the area's mountainous topography, high rainfall intensity, and recurrent landslide events, including the major landslide disaster that occurred in the Tulabolo mining area in 2024.

Therefore, this study aims to fill this research gap by applying a GIS-based weighted overlay approach to assess landslide susceptibility in East Suwawa District, Bone Bolango Regency, Indonesia. Unlike previous studies that focused on broader administrative units, this research provides a more detailed spatial assessment at the sub-district level using five key parameters: rainfall, slope gradient, land use, soil type, and geological conditions. The resulting susceptibility map is expected to support disaster risk reduction efforts, land-use planning, and local government decision-making in mitigating future landslide hazards.

RESEARCH METHODOLOGY

Study Area

This study was conducted in East Suwawa District, Bone Bolango Regency, Gorontalo Province, Indonesia. East Suwawa District is located in a hilly area with fairly steep slopes and relatively high rainfall, making it highly prone to landslides. Geographically, the study area is located at coordinates approximately 0.550365 N and 123.281256 E, with a total area of approximately 266.12 km² or 26,611.59 hectares. The physiography of the study area is characterized by hilly terrain, agricultural land, forested areas, and small-scale mining activities, all of which may influence slope stability and increase landslide susceptibility. The study site was selected because several landslides have occurred in recent years, impacting community activities and local infrastructure. The geographical location of the study area is presented in Figure 1.

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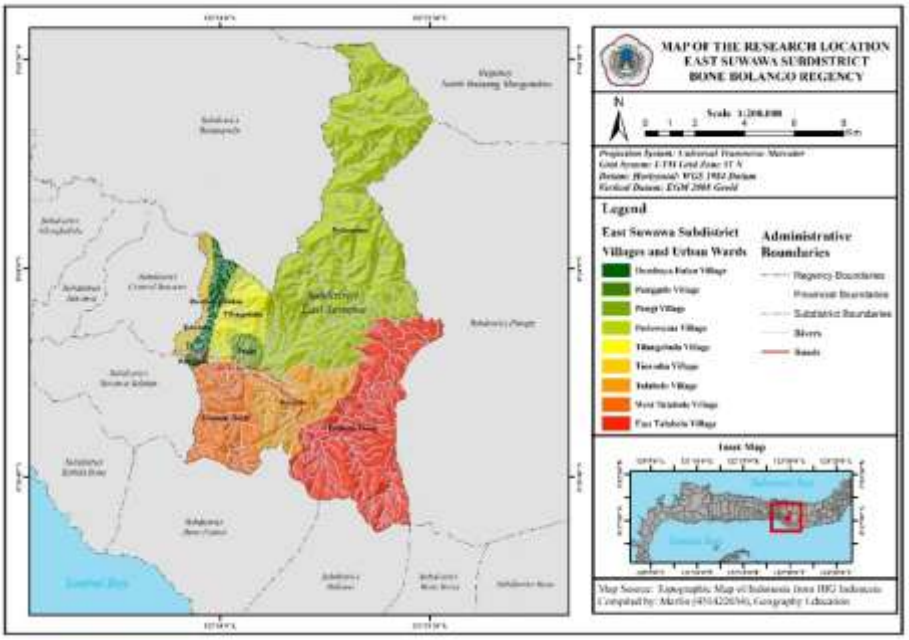


Figure 1. Location of the Study Area in East Suwawa District, Bone Bolango Regency

Data Collection And Research Variables

A quantitative research approach based on Geographic Information System (GIS) spatial analysis was employed to evaluate landslide susceptibility in East Suwawa District. The study utilized both primary and secondary datasets. Primary data were collected through field observations, documentation, and verification of landslide locations to validate the spatial analysis results. Secondary datasets comprised rainfall records, Digital Elevation Model (DEM) data, land-use maps, soil type information, and geological data obtained from relevant institutions. The susceptibility assessment incorporated five environmental conditioning factors, namely rainfall, slope gradient, land use, soil type, and geological conditions. These variables were selected because previous studies have consistently identified them as the principal factors controlling landslide occurrence in tropical mountainous environments. Details of the datasets and their respective sources are presented in Table 1.

Table 1. Research Data and Sources

No	Data	Source
1	Rainfall	Chirps

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2	DEM	USGS
3	Land Use	Sentinel-2 Land Cover Explorer
4	Soil Type	FAO
5	Geological Data	BIG
6	Landslide Observation Points	Field Survey

Gis-Based Weighted Overlay Analysis

The method used in this study is a GIS-based Weighted Overlay technique to determine landslide susceptibility levels. The research stages included data collection, data preprocessing, parameter classification, scoring and weighting, overlay analysis, and field validation. Each thematic layer was reclassified according to its relative contribution to landslide occurrence. Scores were then assigned to each class based on susceptibility levels, while weights were determined according to the relative importance of each parameter derived from previous studies. The analysis was performed using ArcGIS 10.8 through the Weighted Overlay tool to generate the landslide susceptibility map. Geological data were incorporated as a supporting parameter to improve the interpretation of landslide susceptibility patterns, although the weighted overlay calculation was primarily based on the four principal conditioning factors presented in Equation (1).

Landslide susceptibility is calculated using Equation (1):

$$LS = (0.3 \times RH) + (0.4 \times SL) + (0.2 \times LU) + (0.1 \times ST) \quad (1)$$

where:

LS = Landslide susceptibility index

RH = Rainfall

SL = Slope

LU = Land Use

ST = Soil Type

The resulting index values are then classified into four susceptibility classes: low, moderate, high, and very high susceptibility. The research framework is shown in Figure 2.

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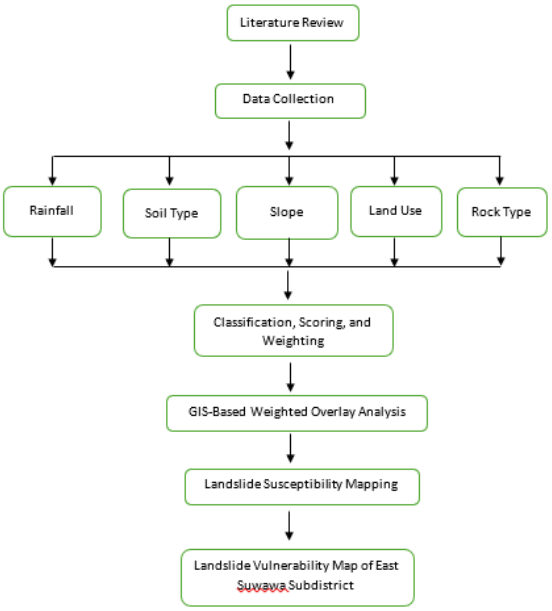


Figure 2. Research Framework

Field Validation And Data Credibility

Field validation was conducted at several landslide sites scattered throughout the Suwawa Timur subdistrict to evaluate the consistency between the mapping results and actual field conditions. The validation process involved direct observation, field documentation, recording of landslide location coordinates, and comparison with the landslide hazard classification results generated by the weighted overlay method. The credibility of the data in this study was ensured through the integration of various verified spatial data sources, the use of parameters commonly employed in landslide hazard mapping, and the validation of analysis results against actual field conditions. The integration of multiple verified spatial datasets and field validation enhanced the robustness, reliability, and reproducibility of the landslide susceptibility assessment.

RESULTS AND DISCUSSION

RESULTS

Rainfall Distribution

Rainfall is one of the principal conditioning factors influencing landslide occurrence because prolonged precipitation increases soil moisture, pore-water pressure, and slope loading, thereby reducing slope stability. Consequently, rainfall was incorporated as one of the principal

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parameters in the GIS-based landslide susceptibility analysis conducted in East Suwawa District. Based on CHIRPS rainfall data from 2020–2024, annual rainfall in East Suwawa District ranged from 1.441,82 mm to 2.073,16 mm, with an average of 1.676,85 mm/year. Spatial analysis classified rainfall into three categories: <1500 mm/year, 1501–2000 mm/year, and 2001–2500 mm/year. Rainfall Distribution data as presented in Table 2.

Table 2. Rainfall Distribution

Rainfall	Score	Area (ha)	Class Interval
< 1500 mm/year	1	1.188,29	4.47%
1501 - 2000 mm/year	2	25.337,30	95.22%
2002 - 2500 mm/year	3	82.15	0.31%

The dominant rainfall class (1501–2000 mm/year) covered 25.337,30 ha (95.22%) of the study area, indicating that most of East Suwawa District experiences moderate to high annual precipitation. Rainfall exceeding 2000 mm/year occupied only 82.15 ha (0.31%), primarily in localized upland areas. Higher rainfall classes received greater susceptibility scores because increased precipitation enhances infiltration, elevates pore-water pressure, and weakens slope stability. Accordingly, rainfall contributed 30% of the weighted overlay model, reflecting its substantial influence on landslide susceptibility. The rainfall map can be seen in Figure 3.

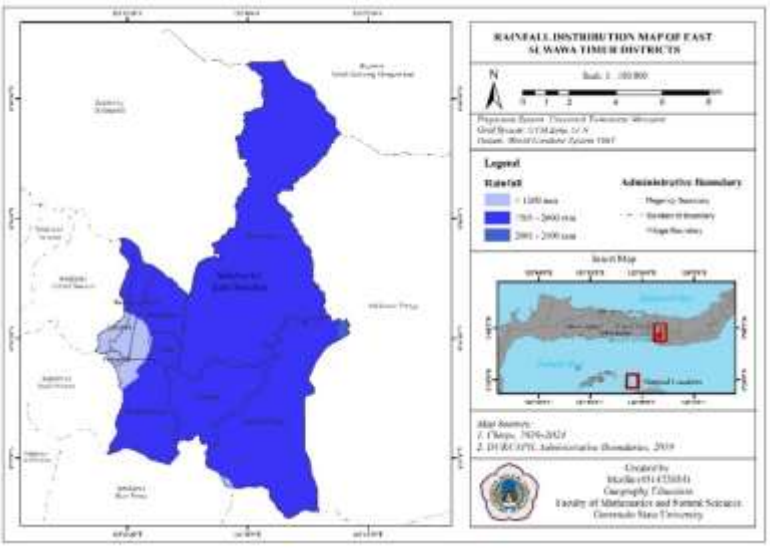


Figure 3. Rainfall Distribution Map of East Suwawa District

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Figure 3 shows that the 1501–2000 mm/year rainfall class is distributed throughout most villages, including Tulabolo, Tulabolo Timur, Tulabolo Barat, Poduwoma, Pangi, and Tilangobula. The concentration of the dominant rainfall class across the study area indicates that rainfall alone does not determine landslide occurrence. Instead, its influence becomes more significant when interacting with steep slopes, susceptible soil types, and land-use conditions. This finding highlights that rainfall functions as a triggering factor whose impact depends on the spatial interaction of multiple environmental variables. These findings are consistent with those reported by (Koven & Hamdany, 2024), who demonstrated that prolonged rainfall substantially increases slope instability in tropical mountainous regions, particularly when combined with unfavorable topographic and geological conditions.

Slope Characteristics

Slope gradient is widely recognized as the most influential conditioning factor controlling landslide susceptibility because it directly affects gravitational force, surface runoff, and slope stability. Consequently, this parameter received the highest weight (40%) in the weighted overlay analysis conducted in this study. Based on the analysis results, most areas with low to high slope gradients are distributed across several parts of East Suwawa Timur District. Areas classified as 0–8% (flat) and 8–15% (gentle) exhibit a relatively low potential for landslides due to their more stable topographic conditions. Meanwhile, areas classified as 15–25% (moderately steep), 25–45% (steep), and >45% (very steep) have higher susceptibility levels due to the increasing slope of the land surface. Steep slope conditions increase the likelihood of soil movement, particularly in areas affected by high rainfall, specific geological conditions, or changes in land use. Slope data are presented in Table 3.

Table 3. Slope Gradient

Slope Gradient (%)	Score	Area (ha)	Percentage (%)
Flat (0-8%)	1	4.692,45	17.82%
Gentle (8-15%)	2	6.891,86	26.17%
Moderately Steep(15-25%)	3	8.980,30	34.11%
Steep (25-45%)	4	5.616,12	21.33%
Very Steep(> 45%)	5	150.09	0.57%

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The dominant class was moderately steep slopes (15–25%), covering 8.980,30 ha (34.11%), followed by gentle slopes (26.17%) and steep slopes (21.33%). Very steep slopes occupied only 150.09 ha (0.57%) of the district. The predominance of moderate to steep terrain reflects the mountainous morphology of East Suwawa District. The Slope Gradient Map is shown in Figure 4.

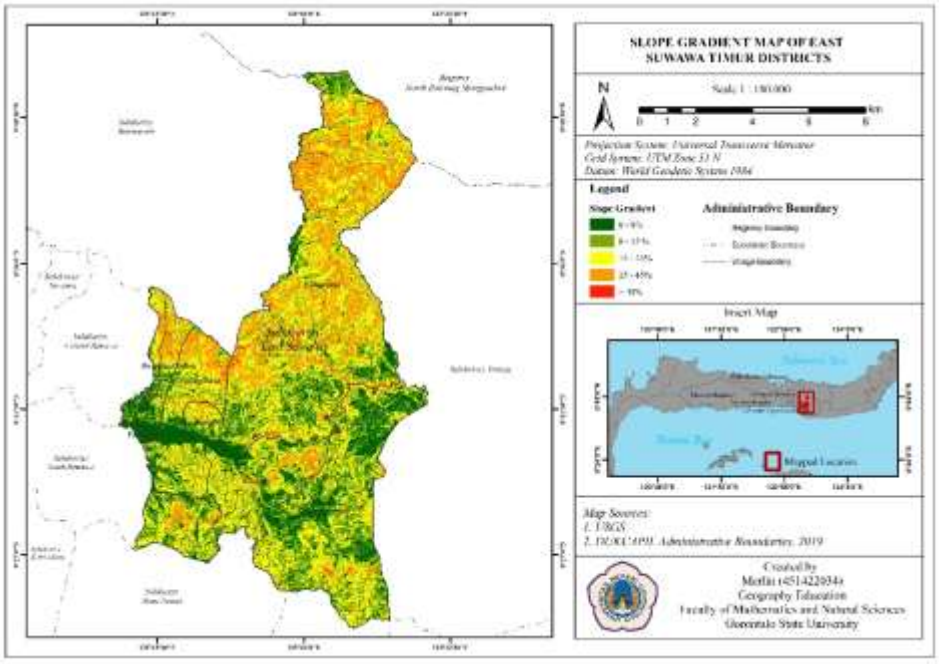


Figure 4. Slope Gradient Map of East Suwawa District

Figure 4 illustrates that steep and very steep slopes are concentrated in Tulabolo Timur, Tulabolo Barat, Poduwoma, and Dumbaya Bulan. Areas with higher slope gradients are more vulnerable to gravitational mass movement because the driving force acting on soil and rock materials increases with slope inclination. This finding is consistent with (Paimin et al., 2012), who identified slope gradient as the dominant parameter controlling landslide susceptibility in Indonesia.

Land Use Characteristics

Land use in East Suwawa District consists of forest areas, agricultural land, open land, and small-scale mining areas. Areas with open land use and mining activities have a higher risk of landslides compared to areas that still have good vegetation cover. Plantation and forest land dominate the East Suwawa District, while residential areas, rice paddies/dry fields, open land, and

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water bodies are scattered across specific parts of the region. This distribution pattern indicates variations in land use that contribute to landslide risk levels in the study area. East Suwawa District is dominated by land use consisting of plantations and forests, covering an area of 25.827,17 ha, or approximately 97.06% of the total study area. This category has a score of 3, indicating a moderate level of landslide susceptibility, as the vegetation in forest and plantation areas is still capable of helping to maintain slope stability. In addition, there are residential/urban areas covering 306.72 ha (1.15%), open land covering 295.73 ha (1.11%), and water bodies, fish ponds, and reservoirs covering 169.16 ha (0.64%). Rice paddies and dry-field crops cover the smallest area, at approximately 12.03 ha or 0.05%. Land-use data for the study area can be found in Table 4.

Table 4. Land Use

Land Use	Score	Area (ha)	Percentage (%)
Water Bodies, Fish Ponds, Reservoirs	1	169.16	0.64%
Residential Areas/Cities	2	306.72	1.15%
Plantations and Forests	3	25.827,17	97.06%
Open Land	4	295.73	1.11%
Rice Fields and Dry Fields	5	12.03	0.05%

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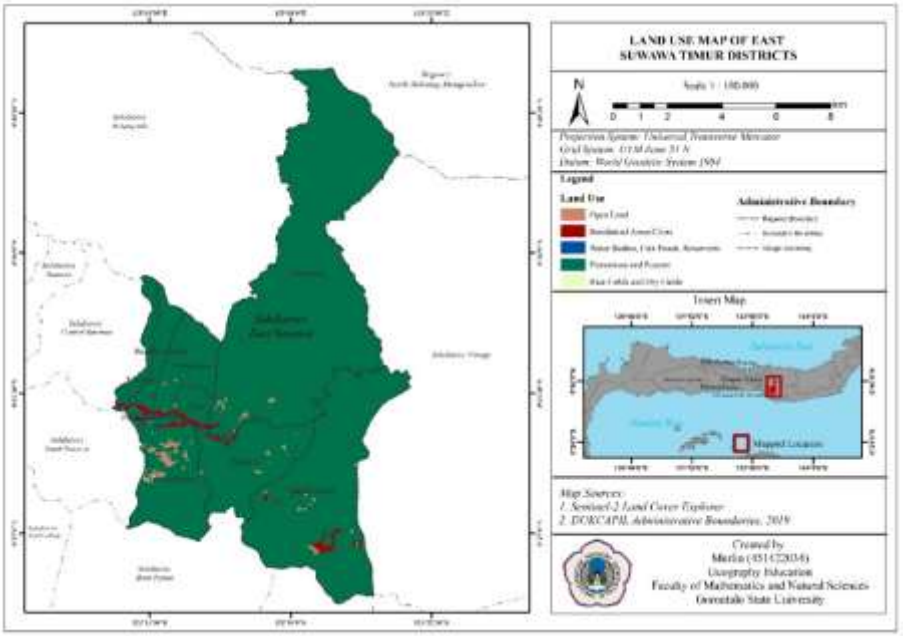


Figure 5. Land Use Map of East Suwawa District

Figure 5 indicates that forest and plantation land cover dominates the district, suggesting relatively good environmental conditions. However, localized land clearing on steep slopes may significantly increase landslide susceptibility. Similar observations were reported by (Vidaletti, 2021), who highlighted the relationship between land-cover change and increasing landslide risk in mountainous regions.

Soil Type Characteristics

Soil type is an important factor influencing landslide susceptibility because it affects soil strength, permeability, water retention capacity, and resistance to erosion. The soil map analysis revealed that the entire East Suwawa District is dominated by Acrisols/Podzolic soils, covering approximately 26.611,59 ha or 100% of the study area. According to the adopted susceptibility classification, this soil type was assigned a score of 4 and a weight of 10% due to its relatively high sensitivity to erosion and slope failure. Soil type data can be found in Table 5.

Table 5. Soil Types

Soil Type	Score	Area (ha)	Percentage (%)
Acrisols/Podzols (Sensitive)	4	26.611,59	100%

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Acrisols/Podzolic soils are generally characterized by high weathering intensity, acidic properties, and relatively low aggregate stability. Under conditions of prolonged rainfall, these soils tend to experience a reduction in shear strength and increased susceptibility to surface erosion and mass movement. Consequently, the widespread distribution of this soil type contributes significantly to landslide susceptibility across the district. The spatial distribution of soil types is presented in Figure 6.

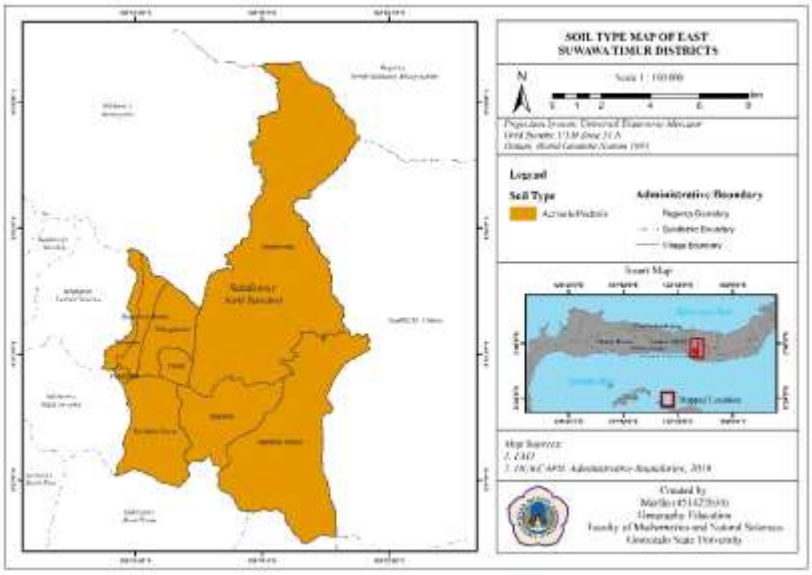


Figure 6 shows that Acrisols/Podzolic soils are uniformly distributed throughout all villages in East Suwawa District, including Poduwoma, Tulabolo, Tulabolo Timur, Tulabolo Barat, Pangi, Tilangobula, and Dumbaya Bulan. The homogeneous distribution indicates that soil conditions across the study area exhibit similar susceptibility characteristics. Therefore, variations in landslide susceptibility are primarily influenced by the interaction of soil conditions with other controlling factors such as rainfall intensity, slope gradient, land use, and geological formations. The dominance of Acrisols/Podzolic soils suggests that East Suwawa District possesses inherent environmental conditions that favor slope instability. Similar findings have been reported by (Yu et al., 2021), who found that highly weathered soils in tropical mountainous regions exhibit greater susceptibility to erosion and landslide occurrence, particularly when combined with steep terrain and intense precipitation.

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Geological Characteristics

The geological characteristics of the study area are primarily represented by volcanic and sedimentary rock formations, both of which influence landslide susceptibility through their contrasting lithological properties. Reef limestone and Ratatotok limestone were classified as sedimentary rocks with a susceptibility score of 2, whereas volcanic rocks and Bone Diorite were classified as volcanic rocks with a susceptibility score of 3. The distribution of Geological Characteristics in the study area is presented in Table 6.

Table 6. Geological Characteristics

Rock Types	Score	Area (ha)	Percentage (%)
Reef Limestone & Ratatok Limestone	2	9.715,09	36.51 %
Volcanic Rocks & Bone Diorite	3	16.896.50	63.49 %

As shown in Table 6, volcanic rocks and Bone Diorite dominate the study area, covering approximately 16.896,50 ha (63.49%), while reef limestone and Ratatotok limestone occupy approximately 9.715,09 ha (36.51%). The predominance of volcanic rocks indicates that a large proportion of East Suwawa District is underlain by weathered volcanic materials, which are generally more susceptible to slope failure than sedimentary formations under similar environmental conditions.

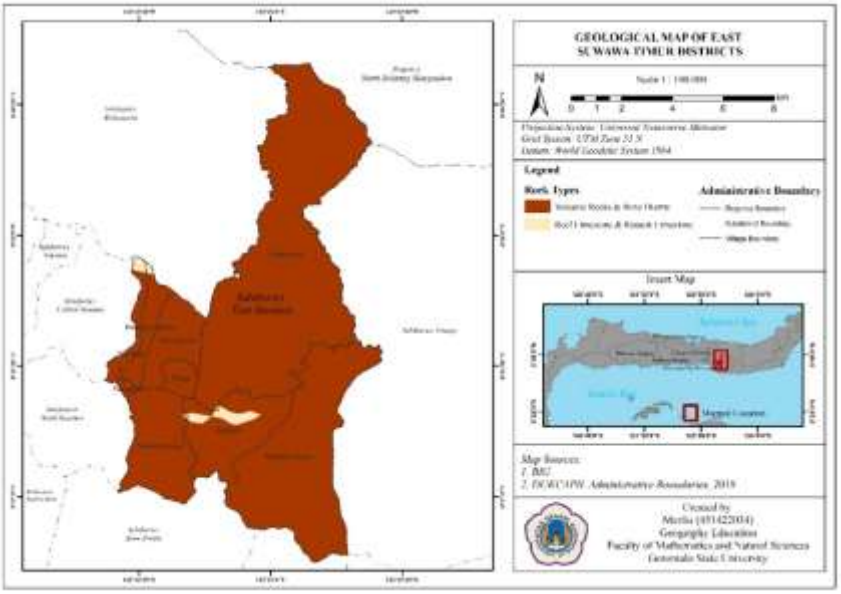


Figure 7. Geological Map of East Suwawa District

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Figure 7 illustrates that volcanic rocks are widely distributed throughout Poduwoma, Tulabolo, Tulabolo Timur, Tulabolo Barat, Pangi, Tilangobula, and Dumbaya Bulan. Meanwhile, sedimentary formations are concentrated in several localized areas, particularly in the western part of the district. The spatial dominance of volcanic materials reflects the geological history of the region and contributes to the formation of deeply weathered surface materials that are susceptible to slope failure. The influence of geological conditions on landslide susceptibility becomes more significant when volcanic rocks undergo intensive weathering and are exposed to high rainfall and steep slopes. Weathered volcanic materials tend to develop fractures and weakened structures that facilitate mass movement processes. These findings support previous studies indicating that volcanic terrains in tropical environments frequently exhibit elevated landslide susceptibility due to rapid weathering and high precipitation intensity (Madani et al., 2023; Rif'ah et al., 2024).

Landslide Susceptibility Mapping

The landslide susceptibility map of East Suwawa District was generated through a GIS-Based Weighted Overlay analysis integrating five conditioning factors: rainfall, slope gradient, land use, soil type, and geology. Each parameter was assigned a score and weight according to its contribution to landslide occurrence before being combined using raster overlay analysis. The resulting susceptibility index was classified into four categories: low, moderate, high, and very high susceptibility. The distribution of landslide susceptibility classes is presented in Table 7.

Table 7. Landslide Susceptibility Classes in East Suwawa District

Class	Susceptibility Level	Index Interval	Area (ha)	Percentage (%)
I	Low	1,6–2,1	35.10	0.13 %
II	Moderate	2,1–2,6	11.454,75	43.53 %
III	High	2,6–3,1	14.666,47	55.75%
IV	Very High	3,1–3,6	153.18	0.58 %

Based on Table 7, the high susceptibility class dominates East Suwawa District, covering 14.666,47 ha or 55.75% of the total study area. The moderate susceptibility class occupies 11.454,75 ha (43.53%), while the very high susceptibility class covers only 153.18 ha (0.58%). The low susceptibility class represents the smallest proportion, accounting for 35.10 ha (0.13%) of the

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district area. These results indicate that most parts of East Suwawa District are characterized by environmental conditions favorable to landslide occurrence. Landslide Susceptibility Map of East Suwawa District can be seen in Figure 8.

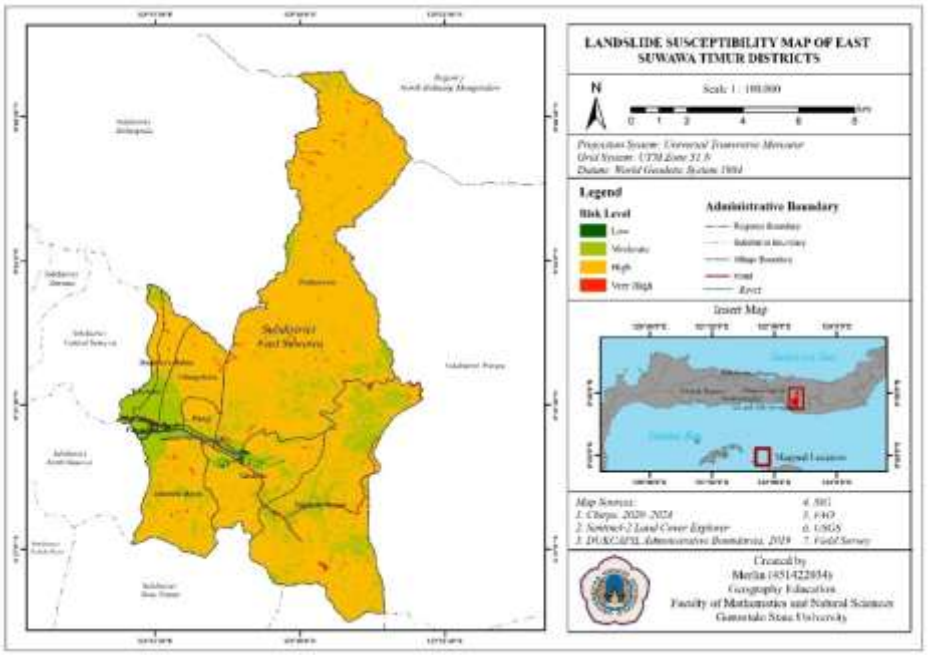


Figure 8. Landslide Susceptibility Map of East Suwawa District

The spatial distribution of landslide susceptibility shows that high susceptibility areas are widely distributed across Poduwoma, Tulabolo, Tulabolo Timur, Tulabolo Barat, Tilongobula, and Dumbaya Bulan Villages. Moderate susceptibility areas are generally located in western and central parts of the district, particularly around Pangi Village and relatively gentle river corridors. Very high susceptibility zones occur in limited areas characterized by steep slopes, especially in Tulabolo Timur and several hilly sectors of Poduwoma Village. Low susceptibility areas are concentrated in flat terrain and river-adjacent lowlands.

Field Validation

Field validation was conducted at several observation points in the villages of Tinemba, Dumbaya Bulan, Pangi, Poduwoma, Tilangobula, Tulabolo, and West Tulabolo. The observation results showed that areas classified as having high to very high landslide risk were dominated by steep slopes, unstable soil, limited vegetation, and small-scale mining activities. Most landslide

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sites are located in areas with high and very high susceptibility classes. This indicates that the weighted overlay results used in this study are able to adequately depict landslide susceptibility conditions in the field. The results of these observations and field validation were then visualized in the form of a map showing the distribution of landslide sites in East Suwawa District, as presented in Figure 9.

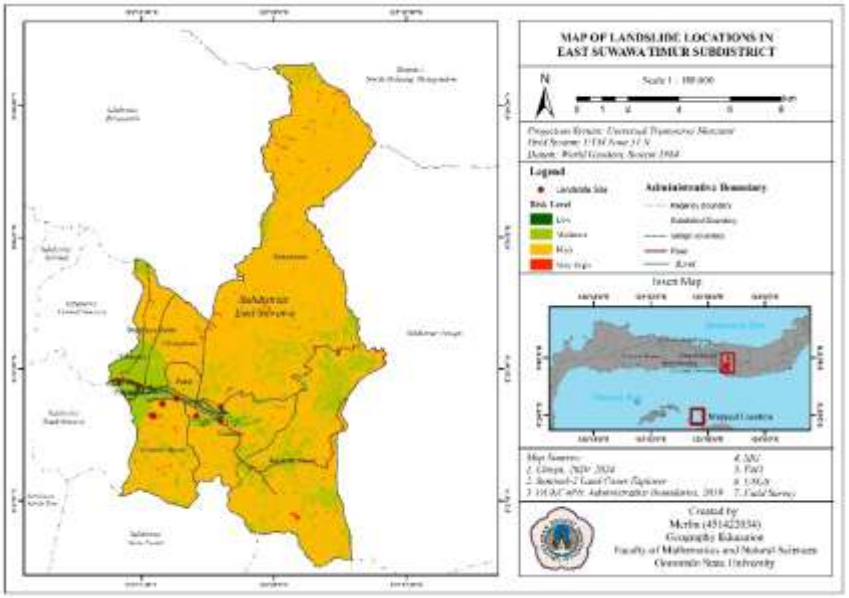


Figure 9. Map of Landslide Locations in East Suwawa District

A total of 18 landslide locations were identified during field observations; however, seven representative points were selected for validation purposes. The selected sites represent all susceptibility classes and different environmental conditions within the study area. Validation results indicate a strong correspondence between susceptibility classes and actual field characteristics. Areas classified as high and very high susceptibility generally exhibit steep slopes, unstable soils, visible landslide scars, and intensive human activities such as mining. Conversely, low susceptibility areas are characterized by gentle terrain and relatively dense vegetation cover. The spatial distribution of observed landslide points is concentrated in the central and southern portions of the district, particularly in Tulabolo and Tulabolo Barat Villages. Several landslide locations are also found in Poduwoma and Tilongobula Villages, where steep topography and erosion-prone soils are dominant. The observed pattern suggests that landslide occurrences are closely associated with steep slopes, transportation corridors, and areas with reduced vegetation cover.

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DISCUSSION

The spatial analysis conducted using the GIS-based weighted overlay method demonstrated that landslide susceptibility in East Suwawa District is controlled by the combined influence of multiple environmental factors rather than by a single conditioning variable. The integration of rainfall, slope gradient, land use, soil type, and supporting geological information successfully identified four levels of landslide susceptibility, namely low, moderate, high, and very high (Reichenbach et al., 2018). Among these factors, slope gradient emerged as the most influential parameter due to its highest weighting value, while rainfall acted as the principal triggering factor that intensified slope instability. The resulting susceptibility map reveals that areas characterized by steep terrain, weathered volcanic formations, and intensive land utilization exhibit a greater potential for landslide occurrence. These findings demonstrate the importance of integrating multiple spatial parameters to improve the accuracy and reliability of landslide susceptibility assessment in tropical mountainous environments (Mohamed & Reza, 2021).

The findings indicate that landslide susceptibility in East Suwawa District cannot be attributed to a single environmental factor but rather to the interaction of multiple conditioning variables. Although slope gradient received the highest weighting in the weighted overlay model, steep terrain alone is insufficient to trigger landslides without the influence of other supporting factors. Prolonged rainfall increases soil moisture and pore-water pressure, thereby reducing shear strength and destabilizing slopes. At the same time, land-use practices that reduce vegetation cover may decrease root reinforcement and increase surface runoff, while weathered volcanic materials further reduce slope stability. These interactions explain the spatial variability of landslide susceptibility across East Suwawa District, where the cumulative effects of terrain characteristics, climatic conditions, and environmental settings increase slope instability (Froude & Petley, 2018).

These findings reinforce the growing body of evidence indicating that GIS-based susceptibility assessment provides a reliable framework for identifying landslide-prone areas in tropical environments (Ajim et al., 2021). Compared with previous studies, the present research demonstrates that incorporating geological information as a supporting layer improves the interpretation of susceptibility patterns without altering the transparency of the weighted overlay procedure. This strengthens the applicability of the proposed framework for regional-scale landslide assessment, particularly in data-limited environments (Reichenbach et al., 2018).

Beyond confirming previous findings, this study contributes to the existing body of knowledge by integrating multiple environmental conditioning factors within a GIS-based

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weighted overlay framework to produce a spatially explicit assessment of landslide susceptibility in East Suwawa District. Unlike conventional susceptibility assessments that primarily emphasize hazard classification, this study incorporates geological information as a supporting spatial layer to strengthen the interpretation of susceptibility patterns while maintaining a transparent and reproducible weighting scheme (Fang et al., 2024). This approach provides a more comprehensive understanding of the spatial interaction among environmental factors and generates information that can support evidence-based disaster risk reduction and regional planning. Consequently, the resulting susceptibility map represents not only a technical mapping product but also a practical decision-support tool for local authorities in prioritizing landslide mitigation and sustainable land-use management.

From a practical perspective, the landslide susceptibility map developed in this study provides important implications for disaster risk reduction and sustainable regional development in East Suwawa District. The landslide susceptibility map can serve as a scientific basis for local governments in identifying priority areas for mitigation, improving spatial planning, and minimizing potential losses caused by landslide hazards. Furthermore, the generated spatial information may support the implementation of land-use management strategies, infrastructure development, and community-based disaster preparedness programs in vulnerable areas. In addition, the susceptibility map may serve as educational material for disaster awareness programs, enabling local communities to better understand landslide-prone areas and strengthen community-based disaster risk reduction initiatives. By integrating GIS-based spatial analysis into local planning processes, decision-makers can develop more effective and evidence-based policies to enhance community resilience against future landslide events (United Nations Office for Disaster Risk Reduction (UNDRR), 2015).

Despite the satisfactory performance of the GIS-based weighted overlay approach in identifying landslide susceptibility patterns, several limitations should be acknowledged. The weighting scheme applied in this study was derived from established literature and therefore may not fully represent the relative influence of environmental factors under local conditions. In addition, the analysis relied primarily on static environmental variables and did not incorporate dynamic triggering factors such as short-term rainfall intensity, seismic activity, or temporal land-use changes. Future studies are therefore encouraged to integrate higher-resolution spatial datasets, multi-temporal environmental information, and advanced spatial modeling techniques, including machine learning approaches, to further improve the accuracy and predictive capability of landslide susceptibility assessments.

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CONCLUSION

This research demonstrates the applicability of a Geographic Information System (GIS)-based weighted overlay approach for assessing landslide susceptibility in East Suwawa District, Bone Bolango Regency. By integrating rainfall, slope gradient, land use, soil type, and supporting geological information, the analysis successfully classified the study area into four susceptibility levels: low, moderate, high, and very high. The results further indicate that slope gradient represents the dominant conditioning factor, while rainfall functions as the primary triggering factor influencing slope instability. These findings contribute to the advancement of GIS-based landslide susceptibility assessment by providing a detailed district-scale spatial representation that can support disaster risk reduction in tropical mountainous environments.

From an applied perspective, the generated landslide susceptibility map provides valuable spatial information to support land-use planning, disaster mitigation, infrastructure development, and community-based disaster risk reduction initiatives in East Suwawa District. Nevertheless, the present study relied on literature-based parameter weighting and predominantly static environmental variables, which may not fully capture temporal changes affecting landslide occurrence. Future research is therefore recommended to integrate higher-resolution spatial datasets, dynamic environmental variables, and advanced spatial modeling techniques in order to improve the accuracy, robustness, and predictive performance of landslide susceptibility assessments.

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