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Natural-Factor-Based Landslide Vulnerability Assessment Using GIS in Padang Lawas Regency of Indonesia

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ABSTRACT

Landslides constitute a major environmental vulnerability in Padang Lawas Regency, where the interaction between steep terrain, heterogeneous geological formations, and intense tropical rainfall frequently drives slope instability. A clear understanding of how these physical factors operate spatially is essential for effective land-use regulation and disaster mitigation. This study develops a natural-factor-based landslide vulnerability assessment using seven key parameters slope gradient, soil type, lithology, rainfall intensity, slope water conditions, seismicity, and vegetation cover. Each parameter was systematically scored and weighted based on its relative influence on slope stability, and a weighted overlay analysis was performed in QGIS to generate a Landslide Vulnerability Index (LVI). Results indicate that moderate hazard dominates approximately 2,028.6 km² of the regency, while high-hazard zones cover 1,128.47 km², mainly concentrated in Sosopan, Ulu Barumun, and Batang Lubuk Sutam Districts. These spatial patterns highlight the combined effects of steep topography, weak lithological units, and high rainfall intensity in governing landslide vulnerability. The outputs provide an empirically grounded basis for strengthening spatial planning policies, guiding infrastructure placement, and enhancing local disaster risk reduction strategies.

Keywords: *GIS, landslide, natural disaster, vulnerability, Disaster risk reduction.*

1. Introduction

Indonesia is located at the intersection of three major tectonic plates the Eurasian, Indo-Australian, and Pacific Plates resulting in one of the highest levels of geological vulnerability worldwide. This condition places Indonesia at significant risk of various hazards, including earthquakes, volcanic eruptions, tsunamis, and landslides. Landslides are particularly common in hilly and mountainous regions.

Padang Lawas is one of the regencies in North Sumatra dominated by inland topography without coastal plains, with moderate river flows and year-round drainage activity. Rainfall data in 2021 indicate that rain occurred between 9 and 22 days per month, with maximum rainfall reaching 306.20 mm and minimum 34.60 mm. High rainfall frequency increases the likelihood of landslides.

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According to the 2021 Indonesian Disaster Risk Index (IRBI), Padang Lawas is categorized as a high-risk area for landslides [1]. Records from January 2020 show several landslide events in North Padang Lawas (Paluta) and surrounding regions.

Although several studies have applied GIS-based multi-parameter approaches to landslide assessment in Indonesia, most have focused on volcanic terrains or regions with rich historical inventories. Padang Lawas, however, represents a unique case where sedimentary lithology, uneven rainfall distribution, and limited landslide documentation coincide. This study therefore fills an important research gap by developing a natural-factor-based vulnerability assessment tailored specifically for Padang Lawas.

2. Theory and Methods

2.1 Landslide Concept

Landslides are mass movements of soil or rock that occur when the driving forces acting on a slope exceed the available resisting forces. Gravity plays a central role in this process, and instability typically arises when soil strength decreases or when external forces such as rainfall or seismic activity increase the shear stress on the slope surface. In Indonesia, landslides are most frequently recorded on slopes with gradients of 15°–45°, particularly in areas dominated by volcanic deposits that weather easily under tropical climatic conditions. High-intensity rainfall further accelerates this weathering process and increases pore-water pressure, making slopes more susceptible to failure.

2.2 Natural Factors Influencing Landslides

Seven natural parameters were selected due to their strong influence on slope stability: slope gradient, soil type, lithology, rainfall, slope water system, seismicity, and vegetation. Slope gradient and rainfall were given the highest weights, reflecting their dominant roles in tropical landslide processes. Steeper slopes produce higher shear stresses, while rainfall increases pore-water pressure and reduces soil cohesion traits widely confirmed in global literature. These parameters align with factors commonly used in Indonesian landslide-mitigation studies and provide a comprehensive foundation for vulnerability assessment.

3. Research Methods

3.1 Study Area

Padang Lawas Regency covers approximately 3,892.73 km² and is situated between 1°26'–2°11' N and 91°01'–95°53' E. The region is characterized by a mixture of lowlands and mountainous terrain, with 82.13% of the area classified as hilly or steep. Lithological formations range from igneous to metamorphic and sedimentary rocks, reflecting a complex geological setting that influences the distribution of landslide hazards.

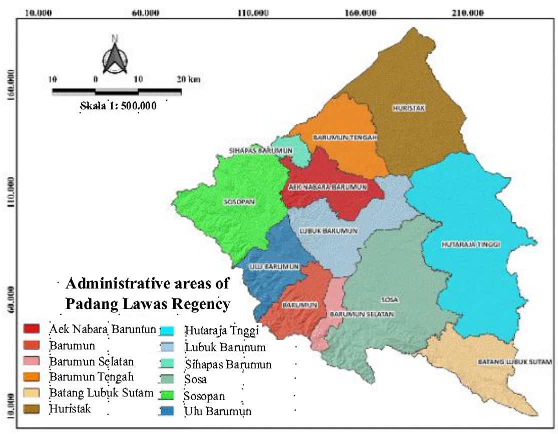

Figure 1. Administrative Map of Padang Lawas Regency

3.2 Data Sources and scoring

This research adopts a GIS-based multi-parameter approach by integrating seven natural factors that are widely recognized to influence slope stability, namely slope gradient, soil type, lithology, rainfall, slope water

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conditions, seismicity, and vegetation cover. The analysis is based entirely on secondary spatial data obtained from official government institutions and scientific sources to ensure data reliability and consistency.

Each thematic dataset was reclassified into vulnerability categories, and parameter scores were assigned based on their relative influence on landslide occurrence. Scores range from 1 to 5, where a value of 1 represents very low vulnerability and a value of 5 represents very high vulnerability. The scoring scheme for each parameter is summarized in Table 1.

Parameter weights were determined based on insights from previous landslide studies conducted in tropical regions, particularly those by Siregar (2020) [2] . In accordance with these studies, slope gradient and rainfall were assigned the highest weights due to their dominant role as primary controlling factors of landslide occurrence in tropical environments. Other parameters were weighted proportionally based on their relative contribution to slope instability processes.

Table 1. Natural Factor Parameter Sconing

Parameter	Classification	Weight	Score
Slope Gradient	0,2%	25%	1
	3 – 5%		2
	6 – 15%		3
	16 – 40%		4
	>40%		5
Soil Type	Spodsol, Andisol	10%	1
	Entisol, Histosol		2
	Inceptisol		3
	Alfisol, Ultisol, Mollisol		4
	Vertisol, Oxisol		5
Rock Type	Alluvial deposits	20%	1
	Sedimentary rocks 1		2
	Volcanic rocks 1		3
	Sedimentary roscks 2		4
	Volcanic rocks 2		5
Rainfall	<500	25%	1
	500 – 990		2
	1000 – 1990		3
	2000 – 3000		4
	>3000		5
Drainage Density	Adequate on all slopes	7%	1
	Adequate on some slopes		2
	Adequate		3
	Inadequate slope drainage		4
	No slope drainage		5
Seismicity (PGA)	<0,05	3%	1
	0,05 – 0,14		2
	0,15 – 0,34		3
	0,35 – 0,50		4
	>0,50		5
Vegetation	Forest	10%	1
	Settlements		2
	Plantation		3
	Shrubs		4
	Rice fields, Dry fields		5

Figure 2 illustrates the overall methodological workflow applied in this study to generate the landslide vulnerability map of Padang Lawas Regency. The workflow begins with data acquisition, followed by data preprocessing, including spatial standardization, reprojection, and conversion of all thematic layers into raster format at a uniform spatial resolution of 30 m. Subsequently, the reclassified and weighted raster layers were integrated using a weighted overlay technique in QGIS to calculate the Landslide Vulnerability Index (LVI), expressed as: $\text{LVI} = \sum(W_i \times X_i)$ where W_i denotes the weight assigned to each parameter and X_i represents the corresponding class score.

The resulting LVI values were classified using the natural breaks (Jenks) method into five landslide vulnerability levels, namely very low, low, moderate, high, and very high. This classification approach ensures that the vulnerability classes reflect the natural distribution of the data and preserve meaningful spatial variations in landslide susceptibility.

All datasets used in this study cover the period 2019–2023. Rainfall data were obtained from the Central Bureau of Statistics (BPS, 2021) [3], soil and lithology maps from the Geospatial Information Agency (BIG, 2020), vegetation maps from 2021, slope data from 2020, seismicity data from the Meteorology, Climatology, and Geophysics Agency (BMKG, 2020–2023), and river network data from the Ministry of Public Works (2021).

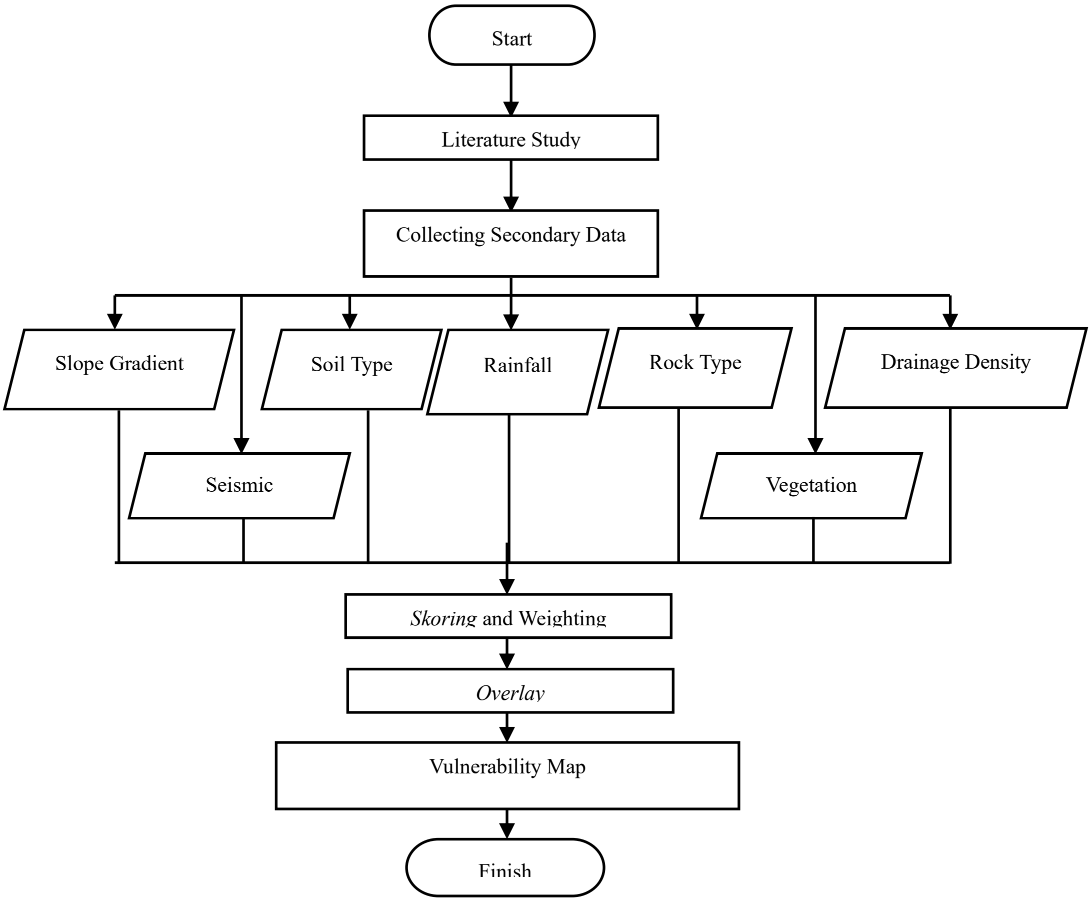

Figure 2. Flow Chart

4. Results and Discussion

Based on 7 parameters used in this research (slope gradient, soil characteristics, rock types, rainfall, slope water system, seismicity, and vegetation), the levels of landslide vulnerability in Padang Lawas Regency were dominated by medium and high vulnerability levels. By using the Geographic Information System (GIS), a landslide vulnerability mapping for each parameter was obtained.

4.1. Slope Gradient

Slope gradient is a fundamental determinant of landslide vulnerability because it directly governs the balance between driving and resisting forces acting on a slope. In Padang Lawas Regency, the landscape is dominated by slopes of 6–15% (37.32%), followed by steep slopes of 16–40% (25.41%) and very steep slopes exceeding 40%, which occupy 12.23% of the area. These steeper terrain classes constitute the primary high-risk zones, particularly where they coincide with weak or highly weathered lithological units. In contrast, gentle slopes ranging from 0–5%, which account for approximately 25% of the region, generally indicate low levels of landslide susceptibility.

The spatial distribution illustrated in Figure 3 shows that steep and very steep slopes are concentrated in the central and eastern sectors of the regency, corresponding to hilly areas with complex structural and geomorphological characteristics. GIS-based slope mapping confirms that the 6–15% slope class is the most

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widespread across the study area, forming extensive transitional zones between lowland and mountainous regions. This spatial pattern reinforces the understanding that slope morphology plays a dominant role in shaping landslide susceptibility across Padang Lawas.

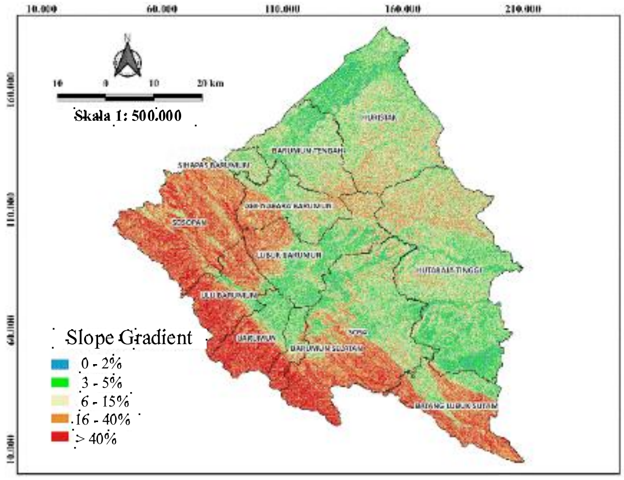

Figure 3. Slope Gradient Map

4.2. Soil Characteristics

Padang Lawas is characterized by four major soil types, with Mollisols comprising more than half of the total area (53.17%). Inceptisols, which account for 35.15%, represent the second most extensive soil group in the regency. Both Mollisols and Inceptisols typically contain significant proportions of clay and silt, materials that are highly sensitive to fluctuations in moisture content. Such sensitivity can lead to reductions in shear strength, making these soils particularly susceptible to shallow landslides during periods of intense rainfall or prolonged saturation.

Oxisols and Entisols occupy comparatively smaller portions of the landscape, yet they also contribute to slope instability, especially in areas where steep gradients intersect with weathered or loosely consolidated materials. The spatial distribution of soil types, presented in Figure 4, highlights the predominance of Mollisols and Inceptisols across the study area. The GIS-based soil map further illustrates the clustering of these moisture-sensitive soils, reinforcing their role as significant contributors to landslide susceptibility in Padang Lawas.

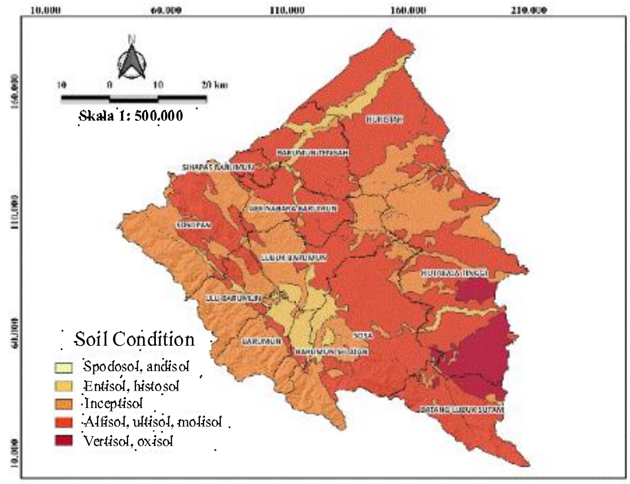

Figure 4. Soil Characteristics Map

4.3. Rocks Types

Sedimentary rocks constitute the dominant lithological unit in Padang Lawas, covering more than 64% of the regency. Much of this sedimentary assemblage consists of weakly cemented formations that are highly susceptible to weathering, disintegration, and erosion. These characteristics substantially reduce the mechanical strength of slopes, making sedimentary terrains particularly prone to instability when subjected to intense rainfall or increased pore-water pressure.

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In contrast, volcanic rocks occupy only 16.27% of the region and are generally concentrated in higher-elevation areas. Although these volcanic units tend to be harder and more resistant to weathering, their limited spatial extent reduces their overall influence on regional landslide susceptibility. The predominance of easily weathered sedimentary rocks therefore plays a major role in the emergence of medium- to high-vulnerability zones across Padang Lawas.

The spatial distribution of lithological units is illustrated in Figure 5, with the GIS-based mapping highlighting the extensive coverage of sedimentary rocks throughout the regency. This lithological pattern reinforces the conclusion that rock type is a critical factor influencing slope instability in the study area.

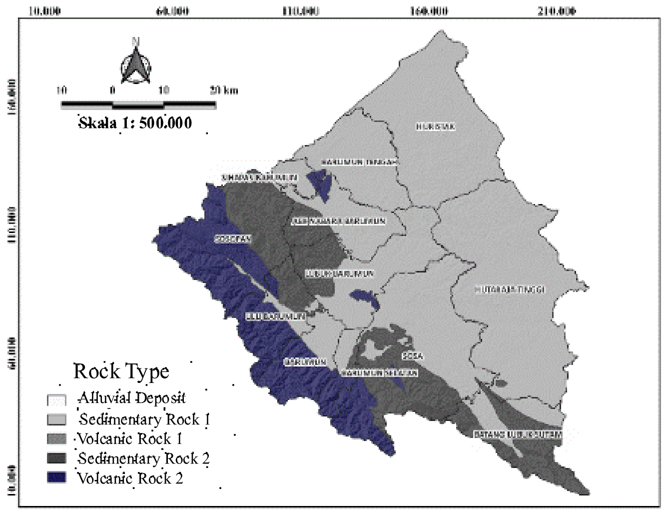

Figure 5. Rock Type Map

4.4. Rainfall

Rainfall represents one of the primary triggering factors for landslides in Padang Lawas, as intense and prolonged precipitation plays a critical role in increasing pore-water pressure and reducing soil cohesion. The majority of the regency (89.33%) receives annual rainfall ranging from 2001 to 2500 mm, while smaller pockets experience rainfall exceeding 3000 mm. These elevated rainfall levels contribute significantly to slope instability, particularly in areas where susceptible soils and weak lithology coincide with steep terrain.

The predominance of high rainfall across the region provides a clear justification for assigning rainfall one of the highest weights in the vulnerability model, given its strong influence on both hydrological loading and the mechanical behavior of slope materials. The spatial pattern of rainfall distribution is presented in Figure 6, which shows that rainfall exceeding 2000 mm per year covers most of the regency. This widespread high-rainfall regime underscores the importance of precipitation as a dominant driver of landslide susceptibility in Padang Lawas.

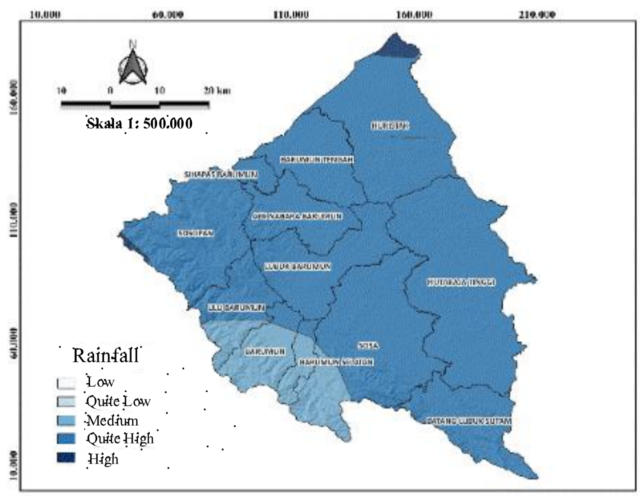

Figure 6. Rainfall Map

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4.5. Drainage density

River density analysis indicates that 68.74% of Padang Lawas falls within the high drainage density class, reflecting a landscape characterized by numerous active surface and subsurface water pathways. Such hydrological conditions intensify erosional processes, promote the removal of slope-supporting materials, and accelerate long-term slope degradation particularly along river valleys and dissected terrains where hydraulic action is strongest.

Areas with high drainage density are therefore more vulnerable to landslides due to the combined effects of continuous erosional undercutting and increased infiltration, both of which weaken slope stability over time. The spatial distribution shown in Figure 7 illustrates that the central and southern parts of the regency exhibit the highest drainage density. The GIS-based mapping confirms that these zones correspond closely with areas of moderate to high landslide susceptibility, emphasizing the critical role of drainage networks in shaping slope instability patterns across Padang Lawas.

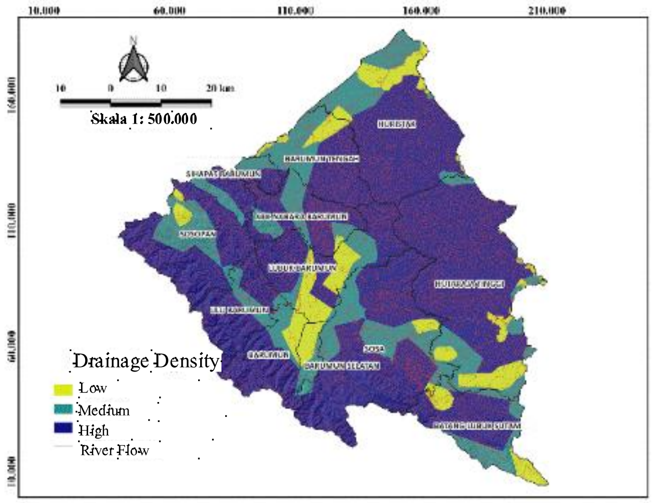

Figure 7. Drainage Density Map

4.6. Seismicity

The seismicity assessment reveals that 39.11% of Padang Lawas falls within the high seismicity class. Elevated seismic activity poses a significant landslide hazard because earthquake-induced ground shaking can rapidly reduce soil strength, disrupt slope equilibrium, and trigger mass movement. These effects are particularly pronounced in areas characterized by steep gradients, highly weathered materials, or saturated soils, where even moderate seismic events may initiate slope failure.

Figure 8 illustrates the spatial distribution of seismicity across the regency, showing that nearly 39% of the area is classified as highly seismic. The GIS-based mapping underscores the importance of seismic loading as a contributing factor to landslide susceptibility, especially in regions where tectonic forces interact with geomorphological and hydrological conditions that already predispose slopes to instability.

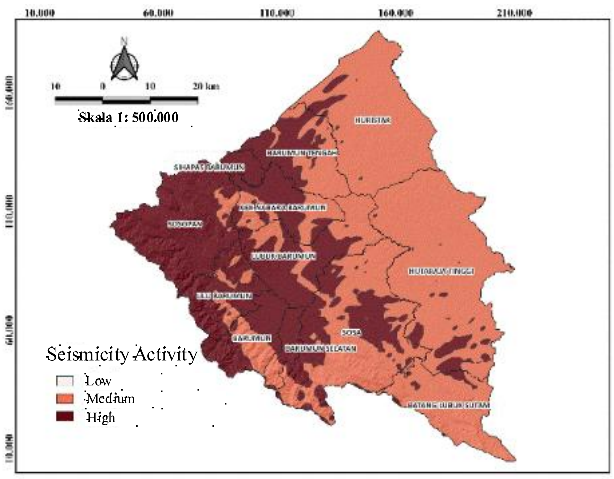

Figure 8. Seismicity Map

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4.7. Vegetation

Vegetation cover plays an important role in regulating slope stability by providing root reinforcement, enhancing soil cohesion, and reducing surface erosion. In Padang Lawas, most of the region (81.45%) is dominated by forest and plantation cover, both of which contribute positively to slope stability through dense root systems and reduced surface runoff. However, areas undergoing agricultural expansion including mixed dryland farming (12.51%), dry fields, open land, and settlement zones form localized pockets where vegetation cover is substantially weaker. These land-use types are generally associated with reduced root binding capacity and higher exposure to erosional forces, thereby increasing landslide susceptibility, particularly on steep or highly dissected terrain.

Figure 9 presents the spatial distribution of vegetation classes, including Pm (settlements), Tt (open land), T (transmigration areas), H (forests), P (plantations), Pk (dry fields), B (shrubs), Sw (rice fields), and Pkc (mixed dryland farming). The GIS-based vegetation map clearly illustrates the dominance of forest and plantation areas across the regency, while patches of dry agricultural land are scattered within steeper physiographic zones. This pattern reinforces the role of vegetation loss as an important contributing factor to localized increases in landslide susceptibility.

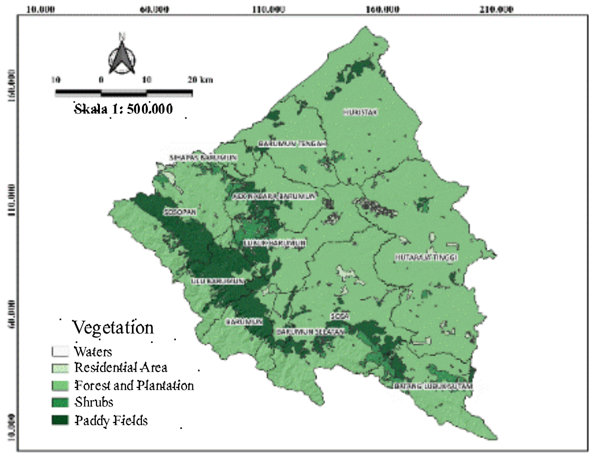

Figure 9. Vegetation Map

The final stage of the analysis involved performing a weighted overlay of all parameters to produce the Landslide Vulnerability Index (LVI), which was subsequently classified into five categories following the Jenks natural breaks method (Table 2). The results indicate that Padang Lawas is predominantly characterized by *moderate vulnerability*, covering 51.30% of the total area. High vulnerability zones constitute an additional 28.54%, reflecting the substantial influence of steep slopes, moisture-sensitive soils, and highly weathered sedimentary formations.

Table 2. Landslide Vulnerability Index

Class	Area (km^2)	Percentage (%)
Very Low	1.998	0.05
Low	378.72	9.58
Moderate	2028.6	51.30
High	1128.47	28.54
Very High	416.76	10.53

Areas classified as very high vulnerability (10.53%) are primarily concentrated in locations where steep terrain coincides with high annual rainfall and weak lithological units. These zones represent the most critical areas for hazard mitigation and land-use regulation. In contrast, the very low and low vulnerability classes collectively account for less than 10% of the regency, suggesting that only a small proportion of the landscape is inherently stable under current environmental conditions.

The spatial distribution of the LVI is illustrated in Figure 10, which presents the comprehensive landslide vulnerability map for the regency. Figure 10 further summarizes the distribution of vulnerability levels at the district scale, highlighting variations in susceptibility driven by differing geomorphological and hydrological

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characteristics. The complete vulnerability mapping based on natural factors, generated using QGIS 3.22.16, is shown in Figure 9.

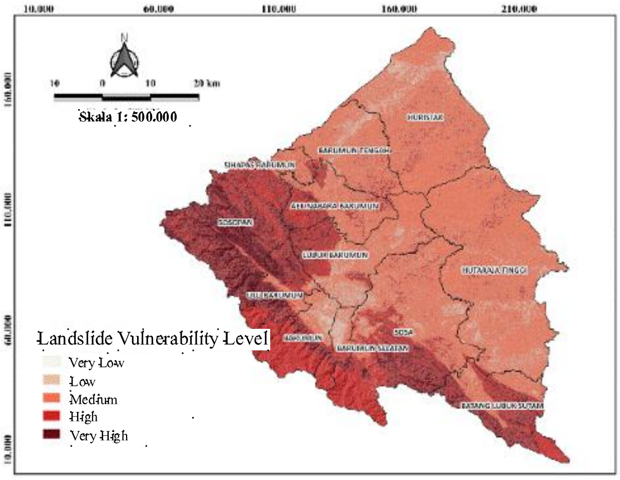

Figure 10. Landslide Vulnerability in Padang Lawas Regency

Figure 10 illustrates the final landslide vulnerability distribution in Padang Lawas Regency, derived from a weighted overlay of seven natural parameters. The map clearly shows the dominance of moderate to high vulnerability classes, particularly in the central and eastern districts, where steep slopes coincide with clay-rich soils and highly weathered sedimentary formations. Overall, the spatial configuration of susceptibility is primarily governed by the interplay between slope steepness, high rainfall intensity, and weak lithological units. These relationships validate the weighting scheme applied in the model and emphasize the need for focused mitigation interventions in specific high-risk districts.

This spatial pattern is consistent with global findings. Reichenbach et al. (2018) highlighted that slope gradient, lithology, and hydrological saturation repeatedly emerge as the strongest predictors of landslide susceptibility across diverse geomorphic environments [4]. The clustering of high and very high vulnerability along ridge zones and river valleys in Padang Lawas mirrors the observations of Saha et al. (2005) [5], who demonstrated that river incision and toe erosion substantially accelerate slope failure in monsoonal landscapes. Likewise, the predominance of weakly consolidated sedimentary rocks in these zones supports the conclusions of García-Rodríguez et al. (2008), who noted that such formations exhibit reduced shear resistance and become highly susceptible when saturated [6].

The correspondence between model results and recorded landslide events further strengthens the reliability of the vulnerability map. Similar strong agreement between susceptibility outputs and historical inventories has been reported in Turkey [7], Nepal [8], and Iran [9], confirming that GIS-based weighted overlay techniques represent robust tools for regional-scale hazard assessment. The contribution of high rainfall (>2000 mm/year) to increased susceptibility aligns with findings from Pourghasemi et al. (2012) and Pham et al. (2018), both of whom identified precipitation intensity as one of the most influential triggering factors in data-driven landslide models [10],[11]. In Padang Lawas, prolonged or extreme rainfall events likely intensify soil saturation, decrease cohesion, and initiate slope failures particularly in steep and geomorphologically dissected terrain.

4.8. Recommendation for mitigation strategies

Based on the spatial distribution observed in Figure 9 and supported by international studies, several targeted mitigation strategies are recommended:

a. Slope Stabilization and Structural Measures
   - Installation of reinforced retaining structures, as demonstrated to be effective in steep terrains [12].
   - Terracing and controlled regrading to reduce shear stresses acting on unstable slopes.

b. Hydrological Management
   - Enhancement of surface drainage and subsurface water interception, consistent with practices proven effective in Himalayan regions [5].

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- Construction of check dams and riverbank reinforcement to reduce toe erosion in areas with high drainage density.

c. Vegetation and Bioengineering Approaches
- Reforestation and bioengineering treatments to improve root cohesion and reduce surface erosion, as supported by Guzzetti et al. (2012) [13].
- Restricting agricultural expansion into steep, highly susceptible zones where vegetation cover is insufficient.

d. Land-Use Regulation and Planning
- Integration of the vulnerability map into regional zoning regulations, reflecting approaches encouraged by Reichenbach et al. (2018) [4].
- Designation of high-risk slopes as restricted development zones to prevent exposure of settlements and infrastructure.

e. Monitoring and Early Warning Systems
- Implementation of rainfall-threshold-based early warning systems, which have shown success in Nepal and Japan [14].
- Community-based monitoring programs focused on detecting early indicators of slope movement, such as ground cracks and deformation.

In summary, the spatial pattern shown in Figure 9 interpreted in conjunction with global empirical evidence demonstrates that the weighted overlay method successfully identifies the principal physical controls of landslide occurrence in Padang Lawas Regency. These findings provide a strong foundation for targeted mitigation, informed land-use regulation, and future improvement of regional landslide hazard assessments. A comparison between documented landslide events in the regency and the dominant vulnerability classes over the past three years is presented in Table 3.

Table 3. Comparison of Landslide Occurrences with Analysis Results

District	Landslide Occurrences			Landslide Vulnerability
	2021	2022	2023	
Sosopan	0	0	1	High
Ulu Barumun	0	0	1	High
Barumun	0	0	0	High
South Barumun	0	0	0	High
Lubuk Barumun	0	0	0	Moderate
Sosa	0	0	0	Moderate
Batang Lubuk Sutam	0	0	0	High
Hutaraja Tinggi	0	0	0	Moderate
Huristak	0	0	0	Moderate
Barumun Tengah	0	0	0	Moderate
Aek Nabara Barumun	0	0	0	Moderate
Sihapas Barumun	0	0	0	Moderate

Figure 11. Site Condition in Sosopan District

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Using Google Earth satellite imagery, several landslide occurrences in Padang Lawas Regency were identified, as illustrated in Figures 11 and 12.

Figure 2. Site Condition Ulu Barumun District

Qualitative validation was performed by examining these areas through high-resolution satellite imagery. Two confirmed landslide locations in the Sosopan and Ulu Barumun sub-districts display characteristic geomorphic signatures of slope failure, such as arcuate scarps, tension cracks, displaced soil masses, and disturbed vegetation patterns. Both sites fall within the model-generated high-vulnerability zones, providing strong support for the validity of the susceptibility mapping results. This validation approach is consistent with verification techniques commonly recommended for regional-scale studies where official landslide inventories are incomplete.

A comparison between recorded landslide occurrences during 2021–2023 and the modeled vulnerability classes is summarized in Table 2. Although Padang Lawas Regency lacks a comprehensive landslide inventory, the available evidence shows clear spatial agreement between documented landslides and the high-susceptibility areas identified in this study. Districts categorized as highly vulnerable particularly Sosopan, Ulu Barumun, and Batang Lubuk Sutam correspond to locations where visible landslide scarps and slope disturbances were detected through satellite imagery.

Figures 11 and 12 provide visual confirmation of recent slope failures in these districts. Distinct morphological indicators, including semicircular scarps, displaced colluvial deposits, and disrupted vegetation cover, are readily observable. These features are typical of shallow to moderately deep landslides and affirm the reliability of the GIS-derived vulnerability zoning.

Qualitative satellite-based verification is widely applied in susceptibility assessments, especially in regions lacking systematic landslide documentation. Previous studies such as those by Guzzetti et al. (2012), Yalcin (2008), Dou et al. (2015), and Kornejady et al. (2017) have demonstrated the effectiveness of remote-sensing reconnaissance for validating model outputs when field access is limited or historical archives are incomplete [13],[15],[9].

Nevertheless, this validation approach has inherent limitations. The absence of a complete landslide inventory precludes the application of quantitative accuracy measures, including Receiver Operating Characteristic (ROC) curves, Area Under the Curve (AUC), and Kappa statistics, all of which require comprehensive presence–absence datasets. Despite this constraint, the strong spatial correspondence between high-vulnerability zones and observed slope failures indicates that the model effectively captures the dominant controlling factors at the regional scale.

Overall, this study provides a reliable first-order approximation of landslide-prone areas in Padang Lawas Regency. The results can support land-use planning, slope hazard mitigation, and prioritization of monitoring and early-warning efforts. Future research should focus on developing a more complete landslide inventory through field surveys, UAV photogrammetry, or multi-temporal satellite analysis to enable more rigorous statistical validation and the development of predictive models with higher accuracy.

5. Conclusion

This study developed a GIS-based landslide vulnerability map for Padang Lawas Regency using seven natural parameters: slope gradient, soil type, lithology, rainfall, drainage density, vegetation cover, and seismicity. The results indicate that the regency is predominantly characterized by moderate and high

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vulnerability levels, driven primarily by the combination of steep slopes, clay-rich and highly weathered soils, weak sedimentary lithology, dense drainage networks, and high annual rainfall. These controlling factors are consistent with well-established global determinants of landslide susceptibility in tropical environments. Qualitative validation using Google Earth imagery and a comparison with documented landslide occurrences from 2021–2023 confirm that observed slope failures predominantly occur within high-vulnerability zones. Although the absence of a comprehensive landslide inventory restricted the application of quantitative validation metrics such as ROC, AUC, or Kappa statistics, the strong spatial correspondence between modeled susceptibility and observed failures increases confidence in the reliability of the resulting map. The vulnerability map produced in this study offers a valuable decision-support tool for local governments, particularly for spatial planning, zoning regulation, slope management, and disaster mitigation. High-risk areas should be prioritized for slope stabilization measures such as surface drainage improvement, terracing, toe protection, and retaining structures, especially where steep terrain coincides with high rainfall intensity. The map is also suitable for integration into the Regional Spatial Plan (RTRW) to delineate restricted or non-cultivable zones and regulate land-use changes in hazardous areas. Future research should incorporate a more complete multi-temporal landslide inventory, supported by field surveys, UAV photogrammetry, or high-resolution satellite imagery. In addition, the application of advanced modeling techniques such as machine learning, logistic regression, or probabilistic susceptibility models would allow for more robust quantitative validation and improved predictive performance. Overall, the findings demonstrate that landslide vulnerability in Padang Lawas is primarily governed by the interaction of steep topography, high rainfall, weak sedimentary rock formations, and concentrated drainage networks, aligning closely with international studies on landslide processes in tropical regions.

This study has several limitations. First, the absence of a comprehensive historical landslide inventory restricts the use of quantitative validation techniques such as ROC curves, AUC, or Kappa statistics, limiting the assessment to qualitative verification through satellite imagery. Second, the analysis relies on secondary datasets with resolutions of approximately 30 meters, which may generalize micro-topographic variations and reduce spatial precision in highly heterogeneous terrain. Additionally, the weighting of parameters, while based on established literature, retains an element of subjectivity inherent to weighted-overlay approaches. Future research should address these limitations by compiling a detailed landslide inventory, employing higher-resolution datasets, and applying advanced statistical or machine-learning models to enhance predictive accuracy and validation robustness.

6. Acknowledgements

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7. Conflict of Interest

The authors assert that there is no conflict of interest associated with the publication of this manuscript.

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