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LANDSLIDE VULNERABILITY ANALYSIS OF TOURISM SITES IN THE TOBA CALDERA UNESCO GLOBAL GEOPARK AREA

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Abstract: The geological hazard that frequently occurs at geological tourism sites in North Sumatra is landslides. The most famous geological tourism site in North Sumatra is the Lake Toba Caldera UNESCO Global Geopark (TC UGGp). Several studies and media reports have mentioned that several tourist areas in the Lake Toba region are prone to landslides. One effort to reduce disaster risk is to determine the level of landslide vulnerability at sites managed by the TC UGGp. Given that the TC UGGp area has received worldwide attention and significant support from investors, assessing landslide vulnerability based on spatial aspects and field conditions is crucial to improving sustainable management in the TC UGGp area. The objective of this study is to determine the distribution of landslide vulnerability levels at tourist sites in the TC UGGp. Landslide vulnerability mapping in this study was conducted using a spatial model with assessment and weighting methods. The variables used to assess landslide vulnerability include slope gradient, lithology, soil type, and land use. This study found that most of the Toba Caldera UNESCO Global Geopark (TC UGGp) area is classified as having very high vulnerability. Several Geosite locations in the TC UGGp area, including Bakkara-Tipang, Tele Efrata, Silahisabungan, Haranggaol, Sipiso-piso, Taman Eden, Hutaginjang, and Sibaganding, are located in areas with high to very high landslide vulnerability. The landslide vulnerability map produced using a spatial model with the natural break classification method shows good accuracy. The results of the landslide vulnerability classification accuracy test show that the overall accuracy value reaches 90.20% and the Kappa accuracy reaches 69.02%, indicating that most of the data on the landslide vulnerability classification map corresponds to the actual conditions in the field. Most landslides occur on steep slopes and in areas with evidence of past land fires. We recommend that Geosite areas with high to very high vulnerability levels implement strict visitor safety standards, adopt infrastructure designs that minimize landslide risk, and strengthen efforts to prevent land burning activities.

Keywords: landslide mitigation, landslide vulnerability map, sustainability tourism, Sustainable Development Goals, Toba Caldera UNESCO Global Geopark

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INTRODUCTION

Natural disasters are phenomena that can occur anytime and anywhere, posing risks and hazards to human life, including both material losses and human casualties (Bukit et al., 2025). Landslides are one of the geological natural disasters that can cause significant loss of life and extensive material damage, such as sedimentation, disruption of transportation routes, destruction of agricultural land, settlements, and bridges (Susanti et al., 2017). A landslide occurs when masses of soil, rock, or a combination of both move downward. This often takes place on slopes, whether natural or man-made (Çellek, 2020). A landslide represents a natural phenomenon in which the earth seeks a new balance as a result of disturbances or external factors that trigger soil movement (Thoha et al., 2023).

The frequency of landslides or soil movements in Indonesia has been increasing, particularly during the rainy season (Polemio & Petrucci, 2000). Steep slopes, heavy rainfall, and unstable soil conditions are the main causes of landslides in Southeast Asia, which has a humid tropical climate (Lee & Talib, 2005). Furthermore, unplanned land-use changes in recent years have exacerbated the situation, resulting in an increasing frequency of landslide disasters (Quevedo et al., 2023). A combination of human activities and natural conditions often triggers landslides, leading to loss of life and material damage,

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especially in mountainous and valley areas (Wu et al., 2020). Ongoing deforestation, population growth, and infrastructure development in high-risk slope areas further increase vulnerability. Excess water in the soil is the main factor causing slope imbalance, while soil saturation and steep gradients contribute significantly to landslide risk (Zamroni et al., 2020).

One of the provinces with a high risk of landslides in Indonesia is North Sumatera (BNPB, 2023). Landslides frequently occur in geological tourism areas of North Sumatera, particularly within the Toba Caldera UNESCO Global Geopark (TC UGGp). A study by Sitompul et al. (2024) found that most of the geotourism areas in TC UGGp, particularly in Baktiraja, Humbang Hasundutan Regency, fall within zones of high to very high landslide susceptibility. Some of these landslide-prone areas in Baktiraja even triggered flash floods that resulted in casualties at the end of 2023. The steep topography and degraded land dominating several regencies in North Sumatera represent natural conditions with high landslide potential (Thoha et al., 2020; Thoha et al., 2021). Research conducted by Setiawan et al. (2010), also indicated that climate change is expected to increase landslide risks in North Sumatera, particularly during the month of September. Most of these high-risk areas are located within the TC UGGp region. Currently, specific efforts toward early warning systems and landslide disaster mitigation have not yet become a major focus in the sustainable tourism management of the TC UGGp area. Landslide vulnerability assessments that integrate geotourism management have not been widely explored or published.

Therefore, mapping landslide vulnerability in this internationally recognized tourism area is necessary to enhance management quality and support global efforts in preserving this important World Heritage site. The objective of this study is to determine the distribution of landslide vulnerability levels at tourist sites in the Toba Caldera UNESCO Global Geopark.

LITERATURE REVIEW

Indonesia is a country that is highly vulnerable to various types of natural disasters that can threaten lives and cause significant material losses (Bukit et al., 2025). The BNPB Disaster Information and Communication Data Center recorded a drastic increase in the number of disasters in Indonesia, from 3,544 incidents in 2022 spread across all regions of Indonesia, dominated by both dry and wet hydrometeorological disasters (BNPB, 2023). Among the various types of disasters that occurred, extreme weather, floods, and landslides ranked highest in frequency after forest and land fires (Lacasse & Nadim, 2009). Landslides are the displacement of soil mass caused by the loss of soil stability due to various triggering factors such as steep slopes, high rainfall intensity, changes in land cover, soil characteristics, and anthropogenic activities such as tree felling and poorly planned cutting of hillsides (Sultana & Tan 2021). The impact of landslides will be even more severe if they occur simultaneously with flash floods, which can worsen environmental conditions in the disaster area. Landslides are one of the geological natural disasters that can cause many casualties and significant material losses such as siltation, disruption of traffic routes, damage to agricultural land, settlements, and bridges (Susanti et al., 2017). Landslides occur when masses of soil, rock, or a combination of both undergo movement. This often occurs on slopes, both natural and man-made (Çellek, 2020). Landslides are actually a phenomenon in which nature seeks a new balance caused by disturbances or influencing components, resulting in increased ground movement (Thoha et al., 2023). According to BNPB, one of the regions with a high risk of landslides in Indonesia is North Sumatra Province (BNPB, 2023). The steep topography that dominates several districts in North Sumatra is a natural condition that has the potential for landslides (Thoha et al., 2020; Thoha et al., 2021).

Research conducted by Setiawan et al. (2010) states that climate change is predicted to increase the risk of landslides in North Sumatra, especially in September. One of the districts in North Sumatra Province that is prone to landslides is Humbang Hasundutan District. Other landslide-prone areas are located in North Tapanuli, Toba, Asahan, Simalungun, Dairi, Karo, Deli Serdang, Langkat, West Pakpak, and Padang Lawas Districts (Kurniawan, 2008). Landslides in Indonesia tend to increase over time, especially during the rainy season when rainfall intensity peaks (Polemio & Petrucci, 2000).

Southeast Asia, with its characteristic wet tropical climate, has a high vulnerability to landslides, caused by a combination of steep slopes, high rainfall, and unstable soil structures (Lee & Talib, 2005). In recent decades, land use changes that ignore land suitability aspects have exacerbated this situation and contributed to an increase in the frequency of landslides (Quevedo et al., 2023). The complex interaction between anthropogenic activities and natural geomorphological conditions is a major trigger for landslides that cause substantial loss of life and economic damage, especially in hilly and valley areas (Wu et al., 2020). Development pressures characterized by deforestation, settlement expansion due to population growth, and infrastructure development in landslide-prone slopes continue without adequate conservation efforts. Saturated water content in the soil profile is a dominant factor that causes loss of soil shear strength and triggers slope instability, while high slope gradients significantly increase the probability of mass movement (Isnaini, 2019). The geological hazard that frequently occurs at geological tourism sites in North Sumatra is landslides. Landslides often occur with very high risk because they are located in geological tourism areas that are densely populated with visitors and vital infrastructure. A well-known geological tourist site in North Sumatra is the Toba Caldera UNESCO Global Geopark (TC UGGp). The Toba Caldera not only possesses unique natural potential but is also capable of fostering new businesses and local product innovation in the form of geotourism and geoproducts, as outlined by Eder & Patzak (2000) Research by Sitompul et al. (2024) found that most of the tourist areas in Baktiraja, Humbang Hasundutan Regency, are located in areas with high to very high landslide risk. Most of these landslide-prone areas are part of the TC UGGp, which was established in 2021 (TCUGGp, 2021).

One effort to reduce disaster risk is to determine the level of landslide vulnerability at management sites in the TCU GGp area, which has gained worldwide attention and significant investment support, requires serious protection against various potential natural disasters. Although landslides occur relatively frequently in this area, this risk has not been a major concern in the management of tourist destinations. The availability of spatial information and field conditions regarding landslide-prone areas is essential so that tourism managers can mitigate impacts that could threaten visitor safety and managed assets, while also supporting safe, sustainable, and disaster-resilient tourism management.

Geological tourism areas have complex activities and high asset values, requiring a more specific approach to disaster mitigation (Farsani et al., 2014). One of the main components of landslide mitigation is an effective early warning system, especially in areas with high tourist visitation rates (Intrieri et al., 2012). This system includes real-time monitoring of rainfall, ground movement, and slope conditions with the support of sensor and telemetry technology (Michoud et al., 2013). In addition to the technological aspects, increasing human resource capacity through the active involvement of local communities and tourism managers in disaster response training and evacuation simulations also plays an important role in improving preparedness. Research by Mutaqin et al. (2021) shows that mountain tourism areas that have structured disaster education programs demonstrate a much higher level of community preparedness compared to areas without similar programs.

In the context of internationally recognized geoparks, the implementation of disaster mitigation strategies not only aims to protect visitors and tourism assets, but also forms part of a global commitment to sustainable geological heritage management (Dowling, 2013). The integration of spatial-based landslide vulnerability studies, the implementation of early warning systems, and community capacity building are important foundations for safe and disaster-resilient geotourism management. Therefore, this study aims to identify and formulate landslide disaster mitigation strategies at tourist sites in the TCU GGp area to support sustainable and globally-standardized area management.

METHODOLOGY

Research Location

This research was conducted in the Toba Caldera UNESCO Global Geopark (TC UGGp), which spans across seven regencies, from May to September 2025. Field surveys were carried out at 16 Geosites within the study area, including the Batak Museum Simanindo, Muara–Situbandang, Balige, Pusuk Buhit, and Haranggaol.

Other surveyed sites include Parapat Sibaganding, Silalahi Sabungan, Ambarita Tuktuk Tomok, Bakkara Tipang, Huta Ginjang, Huta Tinggi Sidohoni, Sipinsur, Situmurun, and Tele Eferata Sihotang. Additionally, the geosites with iconic natural attractions include Sipiso-piso Tongging and Taman Eden.

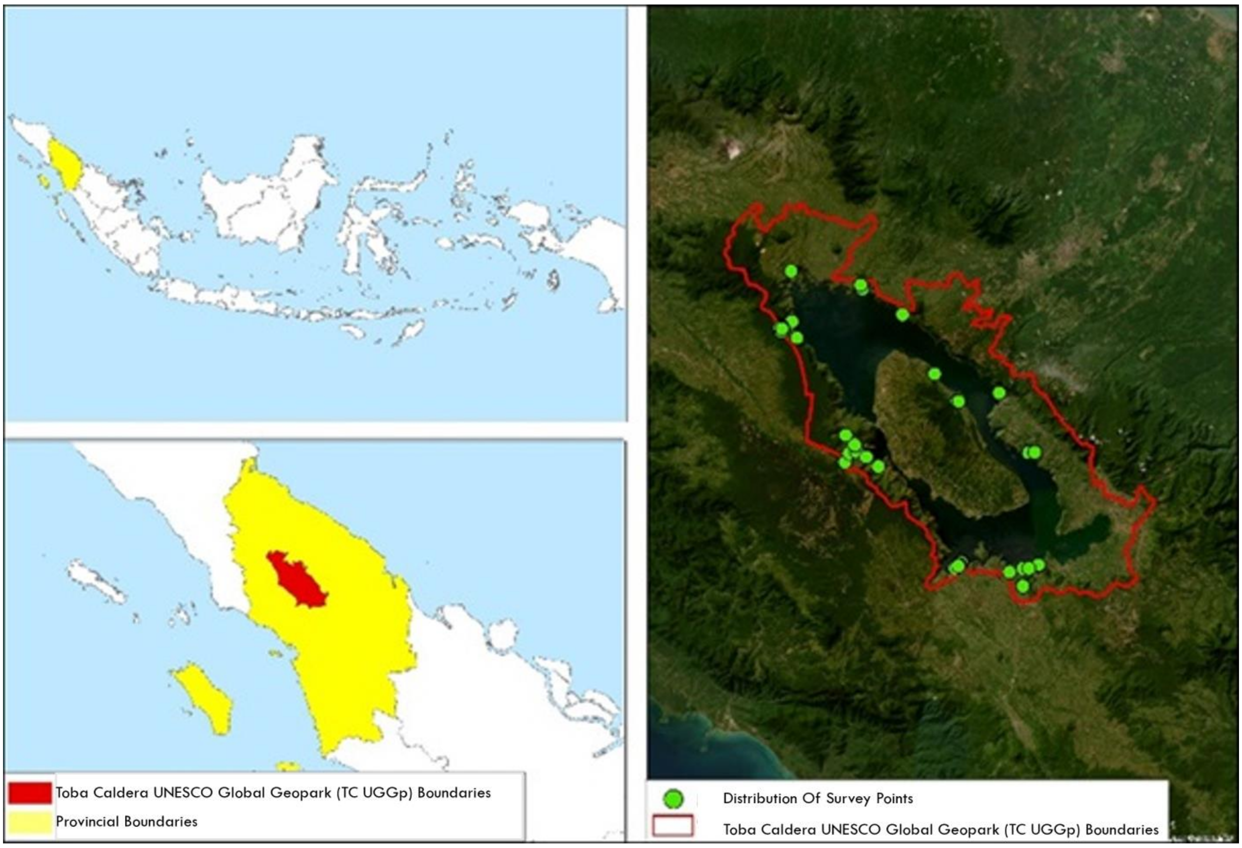

Figure 1. Research Location (Source: Authors Analysis, 2025)

Tools and Materials

The materials used in this study include land cover maps, slope maps, soil type maps, rock type (lithology) maps, and land-use maps. The tools employed for field data collection were a Global Positioning System (GPS) device, camera, tallysheet, and writing instruments. For data analysis, the spreadsheet and GIS tool were utilized.

Data Analysis

The mapping of landslide vulnerability in this study employed a quantitative approach, based on the method proposed by Wati et al. (2010) with several modifications to suit the characteristics of the study area. This approach was chosen because it enables a systematic and measurable assessment of landslide risk by integrating multiple physical parameters that influence slope stability. Data collection was carried out comprehensively through literature review, analysis of official maps, and direct field observations with visual documentation. The four main parameters, including slope gradient, lithology, soil type, and land use, were selected as they are scientifically proven to have a significant influence on landslide occurrence. The details of parameters, weights, and variable scores used in determining landslide vulnerability are presented in Table 1.

The landslide vulnerability map was created using a simple overlay method with weighted scoring, combining various environmental parameters that influence landslide events (Thoha et al., 2021). Each parameter was assigned a score ranging from 1 to 4, where higher values indicate greater influence on landslide potential. The determination of scores and weights was based on relevant literature and regional characteristics analysis. All spatial analyses were conducted using Geographic Information System (GIS) software. Vulnerability classes were categorized into five levels: very low, low, moderate, high, and very high, based on the accumulated weighted scores. Classification was conducted using equal interval and natural breaks methods. The resulting landslide vulnerability map was then overlaid with 16 tourism site (geosite) locations within the TC UGGp area. Field surveys were conducted to verify and test the accuracy of the landslide vulnerability mapping in TC UGGp. The spatial analysis produced a distribution map of vulnerability levels across the TC UGGp region. The final step in the classification process was accuracy testing using a confusion matrix. This test was conducted to determine the accuracy level of the spatial model compared with field observation results (Rini, 2018). The error matrix technique was applied, comparing classified data with reference data or actual field conditions. Based on this analysis, values for producer accuracy, user accuracy, and overall accuracy were obtained. These values serve as key indicators to evaluate how accurately the classification model represents real field conditions and to determine the reliability level of the landslide vulnerability mapping results.

Table 1. Parameters, Weights, and Scores of Landslide Vulnerability (Source: Wati et al., 2010 modified)

Parameters and Factor Weights	Score
Slope (weight: 40.8)	
Flat and undulating (0- 8%)	1
Moderately sloping (8-15%)	2
Hilly and moderately steep (15-45%)	3
Steep (> 45%)	4
Lithology (weight: 24.2)	
Andesite	1
Lava rock	2
Breccia	3
Volcanic rock	4
The soil type (weight: 19.2)	
Alluvial,	1
Andosol, latosol	2
Regosol, Litosol	3
Brown forestsoil	4
Land use (weight: 15.8)	
Area limestone, wetland, paddy field, pine plantation	1
Shrubs and bush, mixed garden, forests	2
Mixed paddy fields and vegetable garden	3
Settlement, vegetable garden, sparse vegetation in forest region	4

RESULTS AND DISCUSSION

Four main factors were used in this assessment. First, slope gradient: the steeper the slope, the higher the likelihood of landslides because the soil becomes less stable. Second, rock type (lithology): volcanic rocks generally have stronger resistance to weathering, making areas with this type of rock more stable. Third, soil type: fine-textured soils, such as clay, absorb water more easily and become heavier when saturated, increasing the risk of landslides. Fourth, land use: areas covered with dense vegetation, such as forests, tend to be more stable because plant roots help hold the soil in place. Conversely, open land or residential areas with little vegetation are more prone to landslides.

Slope

One of the most important factors to consider in determining the vulnerability of an area to landslides is the slope. The steeper the slope, the higher the probability of soil movement and landslide occurrence. In the TC UGGp area, information on slope steepness is crucial for identifying regions with higher risk. This data is also useful for preventive planning, such as spatial zoning, constructing infrastructure suitable for local soil conditions, and planting vegetation that can help stabilize slopes (Chowdhury & Flentje, 2003). The conditions and distribution of slope are presented in Figure 2 and Table 2.

Table 2. Slope Gradient Levels (Source: Authors, 2025)

Slope	Notes	Area (ha)	Persentage
0 – 8 %	Flat and Undulating	6,631.09	2.68
8 – 15 %	Moderetly Sloping	10,682.81	4.31
15 – 25 %	Hilly and moderately steep indutan	48,101.68	19.43
25 – 45 %	Hilly and moderately steep	30,011.98	12.12
> 45 %	Steep	152,179.91	61.46
Total Area		247,607.47	100

Based on Figure 2 and Table 2, the lowest slope is found in the 0–8% class, categorized as flat and undulating. This class covers an area of approximately 6,631.09 hectares, or about 2.68% of the total region. Areas within this slope range generally have stable conditions with a very low likelihood of landslides, making them suitable for settlements, agriculture, and other infrastructure without the need for special engineering treatments. Communities typically use land for cultivation on slopes with a maximum gradient of 15%. This finding aligns with the Toba Caldera Master Plan, which states that land available for community activities within the TC UGGp area accounts for only about 20%, while more than 70% consists of hilly and mountainous areas that are prone to landslides (BPGKT, 2018).

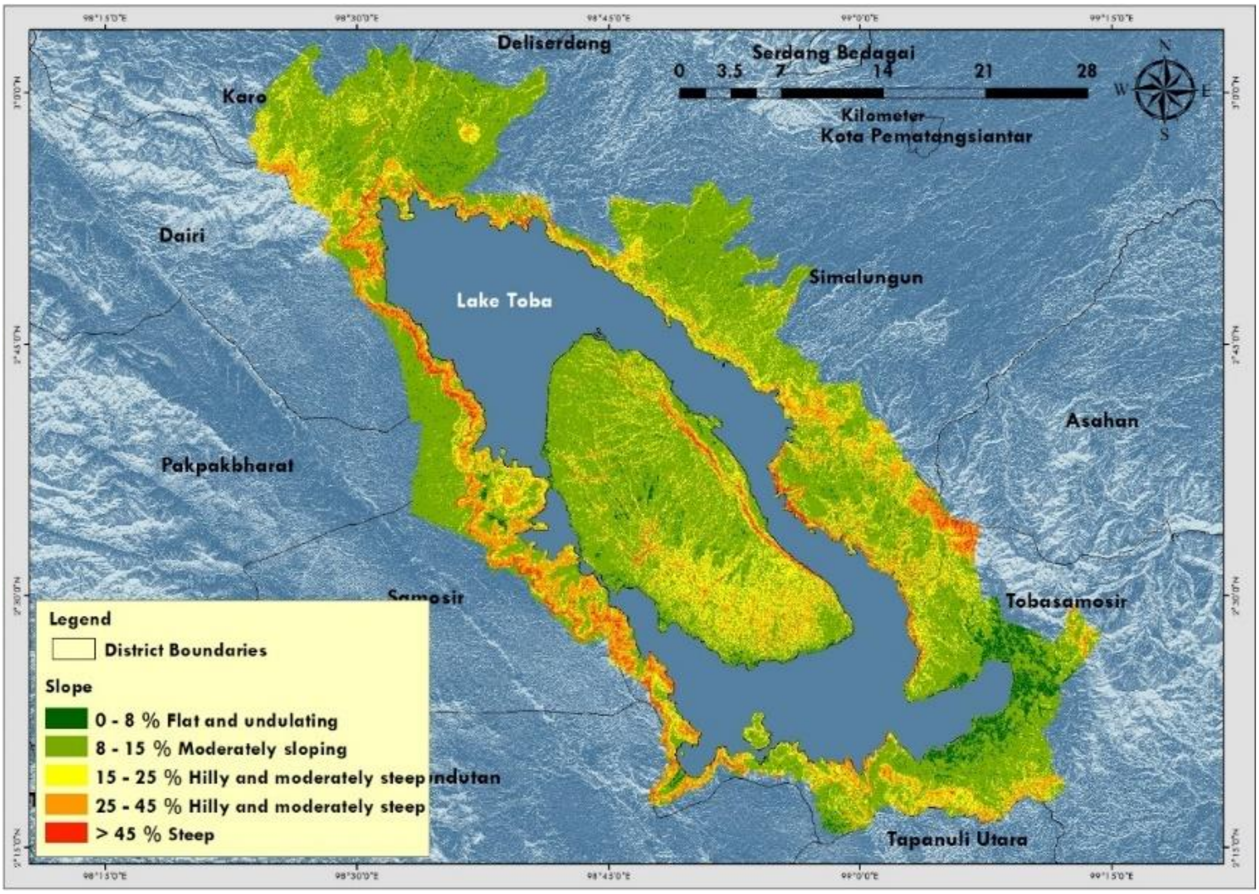

Figure 2. Slope Gradient Levels (Source: Authors Analysis, 2025)

Meanwhile, the steep to hilly and moderately steep slopes represent the highest slope class, covering approximately 70% of the total TC UGGp area. Areas with moderately steep slopes account for around 30,011.98 hectares, or 12.12% of the total region. Although their coverage is relatively smaller, these areas exhibit very high landslide potential, particularly if vegetation cover decreases or soil stability weakens. Therefore, these zones should be carefully managed and avoided for residential development or any activity that may exacerbate slope instability.

Lithology

In landslide vulnerability studies, lithology or rock type is one of the key factors influencing slope stability. Figure 3 and Table 3 show the distribution of rock types and their respective areas within the study region, which serve as one of the parameters in the landslide vulnerability analysis. Based on Figure 3 and Table 3, the most dominant rock type in the study area is volcanic rock, covering approximately 167,504.06 hectares, or 67.65% of the total area. Volcanic rocks are generally stable. However, once weathered, they may become weak and increase the risk of landslides (Rakhman & Maulana, 2021). Another rock type, andesite, occupies 21.26% of the study area and is known for its high strength, making it relatively resistant to landslides (Rakhman & Maulana, 2021). Meanwhile, breccia, which constitutes about 10.67% of the region, and lava, covering 0.42%, have varying characteristics. Breccia tends to be more fragile than massive rock formations and is therefore more susceptible to landslides, especially when located on steep slopes (Hidayat et al., 2016).

Table 3. Area Distribution of Rock Types (Source: Authors, 2025)

Lithology	Area (ha)	Percentage (%)
Andesite	52,638.60	21.26
Breccia	26,415.40	10.67
Lava Rock	1,049.42	0.42
Volcanic Rock	167,504.06	67.65
Luas Total	247,607.47	100

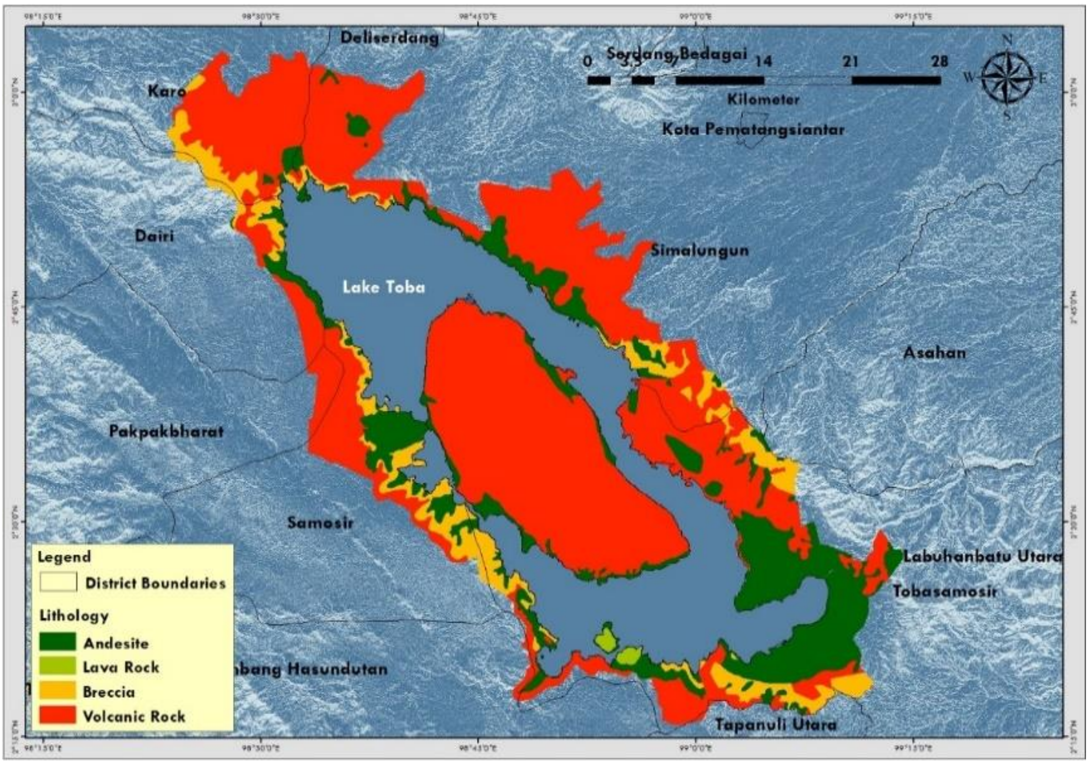

Figure 3. Rock Type Distribution Map (Source: Authors Analysis, 2025)

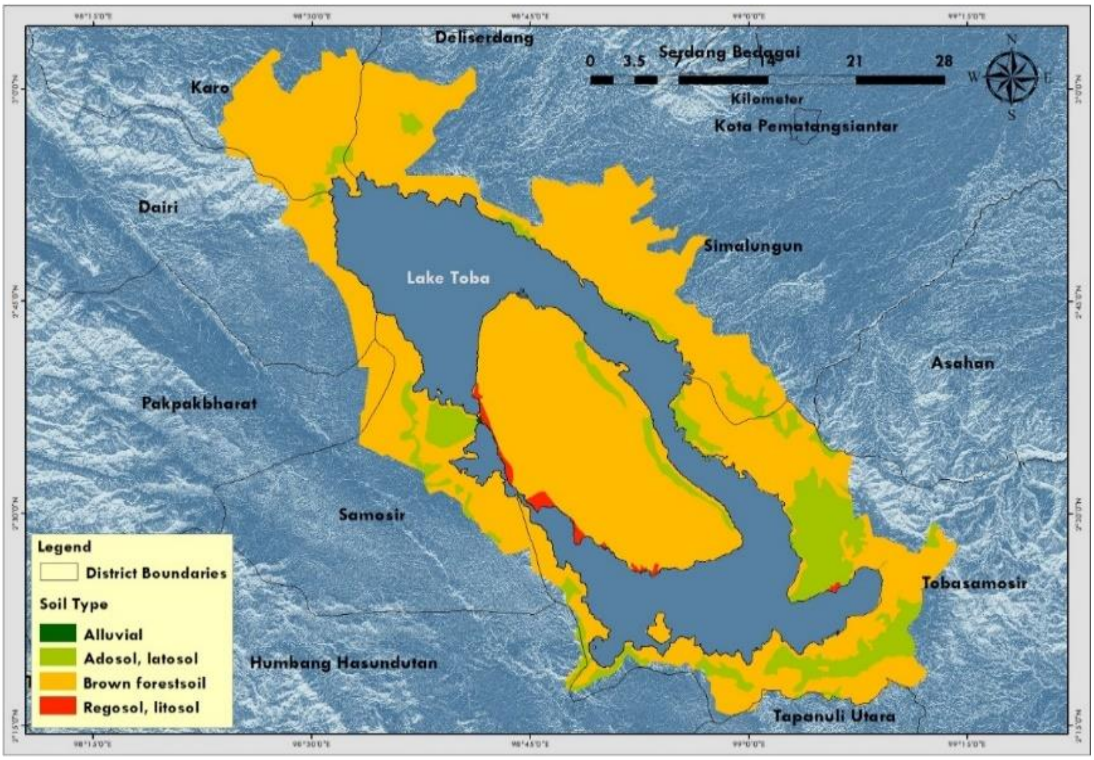

Figure 4. Soil Type Distribution Map (Source: Authors Analysis, 2025)

Soil Type

Soil type is another important parameter in assessing landslide vulnerability because the physical properties and structure of the soil, including texture, horizon stratification, and infiltration rate, greatly affect a slope's ability to remain stable (Kitutu et al., 2009). Figure 4 and Table 4 present the distribution of soil types within the study area, which are used in the spatial analysis of landslide vulnerability. Each soil type has distinct physical characteristics that determine slope stability levels. Based on the classification, the most dominant soil type in the study area is brown forest soil, which covers approximately 210,345.83 hectares, or 84.95% of the total area.

This soil type is generally formed in hilly regions with considerable depth, allowing it to support vegetation well under normal conditions. However, when saturated with large amounts of rainwater, it can lose its strength and become unstable, triggering landslides. The next types are Andosols and Latosols, covering a total of 3,511.35 hectares. Both are derived from volcanic material and are characterized by loose texture and high water absorption capacity.

While these properties enable them to hold large amounts of water, they also make the soils highly susceptible to saturation during heavy rainfall. This condition makes Andosols and Latosols relatively vulnerable to landslides, especially when located on steep slopes or when land use changes occur without proper management.

This analysis highlights that understanding soil types is crucial for assessing potential landslide-prone areas and determining appropriate mitigation strategies (Arham & Wibowo, 2024).

Table 4. Area Distribution of Soil Types (Source: Authors, 2025)

Soil Type	Area (ha)	Percentage (%)
Andosol, latosol	35,311.35	14.26
Alluvial	50,86	0.02
Brown forest soil	210,345.83	84.95
Regosol, litosol	1,899.43	0.77
Total Area	247,607.47	100

Land Use

Land use plays a significant role in influencing the level of vulnerability of an area to landslides. Therefore, an analysis of land cover is essential to assess how different land uses contribute to landslide potential. The distribution of land-use types in the study area is presented in Figure 5 and Table 5.

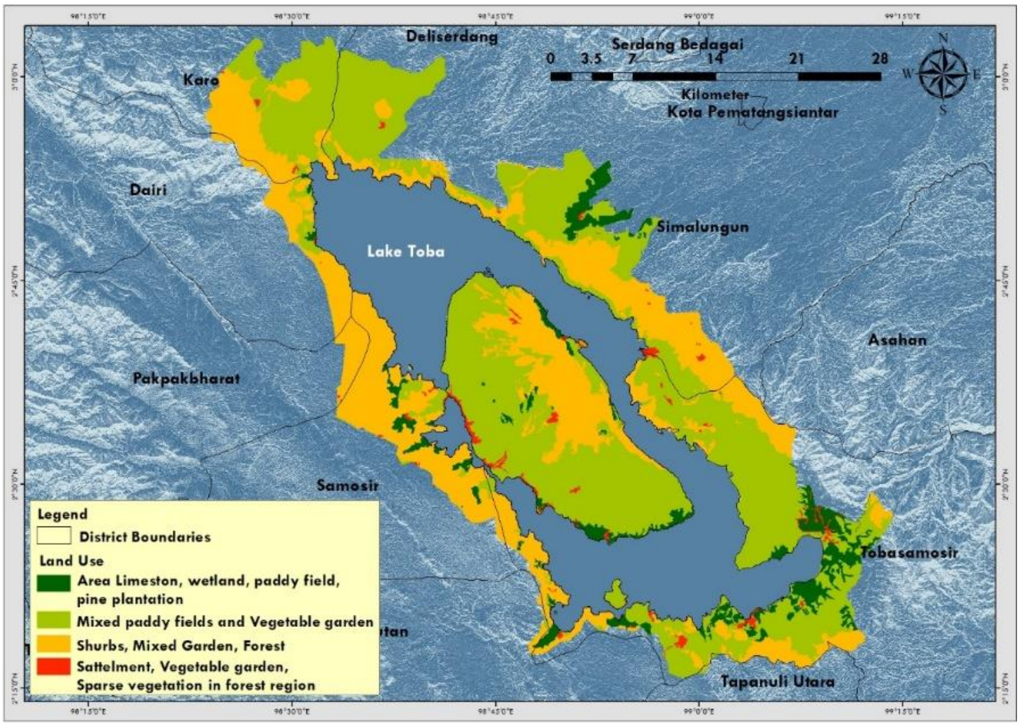

Figure 5. Land Use Map (Source: Authors Analysis, 2025)

These data help identify vulnerable areas, such as settlements on steep slopes or open lands without vegetation, so that preventive measures and spatial planning can be implemented more effectively.

The type and intensity of activities on land surfaces can either strengthen or weaken slope stability. Based on available data, the most dominant land use is mixed rice fields and vegetable gardens, covering 134,811.07 hectares or 54.45% of the total area. This type of land use is generally found on moderately to steep slopes and, if not properly managed, can increase landslide risk due to limited permanent vegetation cover (Suwarsito et al., 2020). The second most extensive land use consists of bushes, mixed plantations, and forests, with a total area of 92,937.59 hectares, or 37.53%. This category emphasizes the important role of vegetation in maintaining ecosystem balance in the region. Moreover, the presence of shrubs, plantations, and forests serves as a natural buffer that can reduce the risk of environmental disasters such as erosion and landslides.

Table 5. Land Use Area Distribution (Source: Authors, 2025)

Land Use	Area (ha)	Percentage (%)
Area Limeston, wetland, paddy field, pine plantation	16,375.09	6.61
Mixed paddy fields and vegetable garden	134,811.07	54.45
Settelment, vegetable garden, sparse vegetation in forest region	3,483.71	1.41
Shurbs, mixed garden, forest	92,937.59	37.53
Luas Total	247,607.47	100

Landslide Vulnerability Zone

The classification results using the natural break method produced the area distribution for each landslide vulnerability level. The natural break method is widely applied in landslide vulnerability classification, as used in studies by Wati et al. (2010), Thoha et al. (2021) and Basofi et al. (2018), because it effectively represents data distribution based on attribute values and the geometric structure of map features. Based on Table 6, most areas of the TC UGGp are dominated by high to very high vulnerability zones, covering more than 80% of the total area. Spatially, regions with high landslide vulnerability are present in almost all regencies within the TC UGGp area (Figure 6). Areas with low to very low vulnerability are distributed around the edges of Lake Toba. These areas are generally composed of irrigated farmland (rice fields), dryland agriculture, settlements, and tourism zones. The regions categorized as very low to low vulnerability constitute only 9% of the total area. This means that more than 90% of the TC UGGp area falls within moderate to very high vulnerability classes, indicating that most of the region is unsafe from landslide risk. Areas with low to very low vulnerability are generally found on flat slopes within the TC UGGp zones located in Toba Regency and North Tapanuli Regency. Meanwhile, TC UGGp regions in Dairi, Karo, Samosir, Humbang Hasundutan, and Simalungun Regencies are predominantly classified as moderate to very high vulnerability zones.

Table 6. Area of Landslide Vulnerability Classes Using Natural Breaks (Source: Authors, 2025)

Vulnerability Level	Area (ha)	Percentage (%)
Very Low	3,232.41	1.31
Low	19,811.18	8.00
Moderate	24,122.32	9.74
High	143,367.16	57.90
Very High	57,074.41	23.05
Luas Total	247,607.47	100

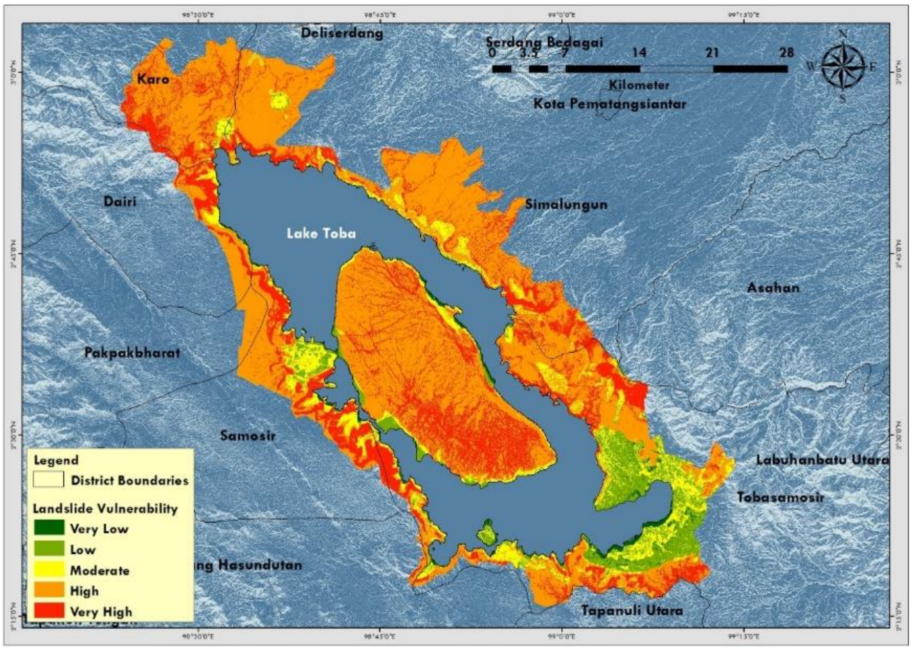

Figure 6. Landslide Vulnerability Map Using Natural Breaks (Source: Authors Analysis, 2025)

Accuracy Test

The accuracy test results of the landslide vulnerability classification show that the overall accuracy reached 90.20%, and the Kappa accuracy was 69.02% (Table 7). These figures indicate that the majority of areas on the landslide vulnerability classification map correspond well to actual field conditions. In other words, the classification model demonstrates a very good level of accuracy, as over 90% of the data were correctly classified. Nevertheless, some discrepancies remain, particularly within the moderate vulnerability category. Therefore, it is recommended that the map be regularly updated and revalidated to ensure that the results continue to reflect real conditions as accurately as possible.

Table 7. Accuracy Test Results Using Confusion Matrix (Source: Authors, 2025)

Vulnerability Class	Field Observation			Total	User Accuracy
	High-Very High	Moderate	Low-Very Low		
High-Very High	39	1		40	97.50
Moderate	4	5		9	55.56
Low-Very Low			2	2	100
Total	43	6	2	51	
Producer Accuracy	90.70	83.33	100		
Overall Accuracy	90.20				
Kappa Accuracy	69.02				

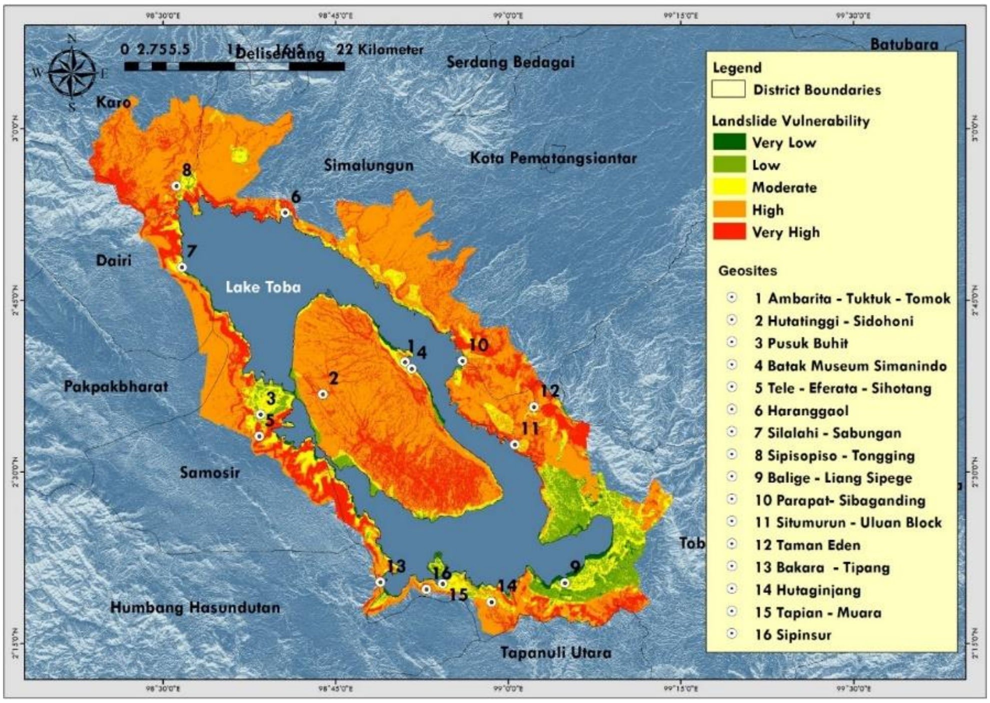

Figure 7. Map of Tourism Locations with Landslide Vulnerability (Source: Authors Analysis, 2025)

Figure 7 illustrates the distribution of geosites within the TC UGGp area based on the level of landslide vulnerability. There are 16 geosite locations situated at varying levels of landslide risk. The degree of landslide vulnerability at each tourism geosite within the Toba Caldera UGGp is presented in Table 8.

Based on the distribution of geotourism sites in the Toba Caldera UGGp shown in Table 8, there are seven locations classified as having high vulnerability levels. This condition aligns with the overall characteristics of the TC UGGp area, where most regions fall within the high vulnerability category. Field surveys identified actual landslide occurrences at seven geosite locations, including Ambarita Tuktuk-Tomok, Bakkara Tipang, Hutaginjang, Huta Tinggi Sidohoni, Sipinsur, Situmurun, and Tele Efrata Sihotang. Additionally, several geosites with very high vulnerability, such as Sipiso-piso Tongging and Taman Eden, were found to have multiple landslide points during field observation.

Table 8. Landslide Vulnerability Levels at Geosite Locations in the Toba Caldera (Source: Authors, 2025)

No	Geosites Name	Villages	Vulnerability Level
1	Batak Museum Simanindo	Tomok/Tomok Parsaoran	Very Low
2	Muara - Situbandang	Hutanagodang	Very Low
3	Balige	Hutaginjang	Low
4	Pusuk Buhit	Sianjur Mula-Mula	Low
5	Haranggaol	Haranggaol	Moderate
6	Parapat Sibaganding	Kelurahan Tiga Raja	Moderate
7	Silahi Sabungan	Silalahi	Moderate
8	Ambarita Tuktuk Tomok	Ambarita	High
9	Bakkara Tipang	Tipang	High
10	Huta Ginjang	Hutaginjang	High
11	Huta Tinggi Sidohoni	Huta Tinggi	High
12	Sipinsur	Pearung	High
13	Situmurun	Situmurun	High
14	Tele Eferata Sihotang	Sosor Dolok	High
15	Sipisopiso Tongging	Tongging/Pengambatan	Very High
16	Taman Eden	Sionggang Utara	Very High

Landslide Events at Geosite Locations

Landslides occur quite frequently in geosite areas and have a significant impact on the environment and surrounding communities, including in geotourism management. These impacts include damage to productive land, the decline of ecosystem functions, and the destruction of vital infrastructure such as roads, bridges, and public facilities that support tourism and community activities (Tunas et al., 2020). Moreover, the threat to residents' safety is a major concern since landslides can occur suddenly without warning. In August 2025, a field survey recorded landslide points and visual documentation across the geosite areas. Based on the collected data, 49 landslide points were identified in various locations. These findings serve as concrete evidence that the study area is predominantly composed of zones with high landslide vulnerability, posing repeated risks of damage if not properly mitigated.

The survey also revealed several areas with land damage, including Bakkara–Tipang, Tele Efrata, Silahisabungan, Haranggaol, Sibaganding, and Balige (Figure 8). In these locations, extensive slope damage, landslide material blocking main roads, and disruptions to daily community activities were observed. The blockage of roads due to landslide debris hindered residents' mobility, isolated several settlements, and disrupted local economies dependent on transportation access. Furthermore, damage to agricultural land, which is the main livelihood of local communities, resulted in significant economic losses. This indicates that landslides in the study area are not incidental but rather recurring disasters closely linked to geological conditions and land-use patterns. Fragile rock formations and the loss of dense vegetation, which serves as a natural stabilizer, increase the likelihood of landslides, especially during periods of heavy rainfall. Therefore, serious attention and comprehensive mitigation strategies are urgently required, including slope stabilization at critical points, rehabilitation of degraded land, improvement of drainage systems, and community empowerment to recognize early warning signs of landslides (Wati et al., 2010).

Field observations at high and very high vulnerability geosites revealed landslide occurrences often associated with previous forest and land fires. Many landslides were found in burned areas located on steep slopes. This suggests that burned land on steep terrains significantly increases landslide risks due to the loss of vegetation that protects the soil and stabilizes slopes. This finding aligns with Thoha et al. (2020), who noted that parts of the TC UGGp in Dairi Regency are among the regions with the highest landslide potential in North Sumatera. In addition to Dairi, landslide-prone areas are also spread across the Lake Toba Catchment Area, characterized by complex geomorphology and high rainfall intensity. Landslides in Dairi Regency have had wide-ranging impacts, including social, physical, economic, and environmental. Furthermore, Setiawan et al. (2010) emphasized that climate change is expected to exacerbate landslide risks in North Sumatera. Changes in rainfall patterns, especially short-duration extreme rain, can accelerate soil weathering and trigger mass soil movement on steep slopes, thereby increasing the likelihood of future landslides, particularly in vulnerable regions (Christanto et al., 2009).

Figure 8. Landslide Events at Geosite Locations: (a) Bakkara Tipang, (b) Tele Efrata, (c) Silahisabungan, (d) Haranggaol, (e) Sibaganding, (f) Balige (Source: Authors Documentation, 2025)

Considering the mapping results and field surveys, comprehensive mitigation efforts are needed to reduce disaster risks in the TC UGGp area, which serves as an international-scale tourist destination. Recommended measures include building proper drainage systems to minimize surface water flow, planting vegetation on steep slopes to reinforce soil stability, and educating local communities and tourists about potential hazards and evacuation procedures to enhance disaster preparedness. Mapping the landslide risk level is one of the important points in developing sustainable tourism in TC UGGp. As stated in the research by Mulyadi et al. (2024), attention to environmental sustainability and disaster prevention are important programs in the management of TC UGGp. The results of this study also show that geotourism attractions in TC UGGp have fragile characteristics, requiring serious attention in the development of world-class tourism. The same results were also revealed by a study by Hutagalung, et al. (2024), which emphasized that with highly fragile geological elements, the development of TC UGGp through sustainable geotourism needs to receive attention from all sectors.

CONCLUSION

Approximately 80% of the TC UGGp area falls within high to very high vulnerability zones based on the natural break method. Of the 16 geosite locations in TC UGGp, nine fall within the high–very high vulnerability categories. The geosites of Ambarita Tuktuk Tomok, Bakkara Tipang, Huta Ginjang, Huta Tinggi Sidohoni, Sipinsur, Situmurun, Tele Efrata Sihotang, Sipiso-piso Tongging, and Taman Eden are located in high to very high landslide risk zones. These sites are characterized by steep slopes, dry agricultural land, and areas frequently affected by land fires. Accuracy testing indicates that the landslide vulnerability map developed using slope, lithology, soil type, and land use variables achieved high reliability, both in overall accuracy and Kappa accuracy. Therefore, the map can serve as a valuable reference for landslide mitigation and sustainable tourism management in the TC UGGp area. Management authorities must address the increasing landslide risks driven by both the region's natural vulnerability and intensified land-burning activities that weaken slope stability.

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