Journal of Asian Scientific Research
ISSN(e): 2223-1331
ISSN(p): 2226-5724
DOI: 10.55493/5003.v16i1.5864
Vol. 16, No. 1, 57-78.

URL: www.aessweb.com

Geospatial modeling-based assessment of landslide hazards along the Medan–Berastagi Route, North Sumatra

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Article History
Received: 30 June 2025
Revised: 9 December 2025
Accepted: 22 December 2025
Published: 2 February 2026

Keywords
AHP
GIS
Landslide hazard mapping
North Sumatra
Slope stability.

ABSTRACT

Landslides are a recurrent problem in hilly regions, particularly during the rainy season, causing fatalities, infrastructure damage, and socio-economic disruption. Landslide hazard mapping is therefore essential for identifying vulnerable areas and developing effective mitigation strategies. This study aimed to create a landslide hazard map for the Medan–Berastagi road using the Analytic Hierarchy Process (AHP) integrated with Geographic Information Systems (GIS). Eleven parameters were selected, including slope angle, slope height, slope aspect, rainfall, drainage, lithology, soil type, land use, distance to faults, seismic activity, and proximity to rivers. Data were compiled through field surveys, GPS verification, and secondary sources, then processed with QGIS. Hazard levels were classified into five categories: very low, low, moderate, high, and very high. Results show that 44% of the road segments (19 km) fall under moderate hazard, 46% (29 km) under high hazard, and 9% (3 km) under very high hazard. Field validation using 71 landslide inventory points yielded an accuracy of 97.6%. The most influential factors were slope angle, slope height, rainfall intensity, and land use. Prolonged heavy rainfall on steep slopes underlain by fractured volcanic rocks contributed significantly to slope instability. The developed hazard map demonstrates that most of the Medan–Berastagi corridor is vulnerable to landslides, emphasizing the need for targeted disaster risk mitigation. These findings provide a scientific basis for regional planning and sustainable infrastructure management in mountainous terrains.

Contribution/ Originality: This study contributes to the existing literature on landslide risk by applying AHP–GIS to the Medan–Berastagi route. It is one of the few studies that have investigated this corridor. The primary contribution of the paper is identifying slope angle, rainfall intensity, and land use as the most dominant triggers.

1. INTRODUCTION

Indonesia frequently encounters natural disasters, including landslides. A landslide refers to the gravitational movement of materials, including soil, rocks, and organic matter, down a slope, leading to alterations in landforms, frequently observed in hilly regions [1]. In Indonesia, landslides are one of the deadliest natural disasters, often occurring during the rainy season [2]. Various types of landslides occur in Indonesia, such as soil slides, rockfalls, and debris flows. According to the National Disaster Management Agency, from 2010 to mid-2019, there were 5,822 recorded landslide incidents in Indonesia, with 73 occurring in North Sumatra, resulting in 119 fatalities [3]. Generally, landslides are caused by natural factors such as rainfall, seismic activity, volcanic activity, slope steepness, soil conditions, rock composition, and slope drainage. Human factors include activities such as deforestation, settlements on steep slopes, and inappropriate land use, which increase the risk in landslide-prone areas [4]. Sometimes, a combination of these factors can exacerbate landslide risk. Studies indicate that the most critical triggers for landslides are rainfall, human activities altering land use, geological conditions such as soil and rock types, and geomorphology [5].

A hazard is an event or condition that has the potential to cause fatalities, injuries, health problems, property loss, disruption of livelihoods, economic and social disturbances, or environmental harm [6]. Mitigating the impact of landslide disasters can be minimized with risk management, which is part of land-use planning in high landslide-risk areas. This involves providing information on the division of regions and their rankings according to the level of landslide hazard. Methods that can be used to assess landslide-prone areas include qualitative and quantitative approaches [7]. In Indonesia, a semi-quantitative approach combining elements of both qualitative and quantitative methods can be applied. This method offers more reliable results than purely qualitative assessments while avoiding the complexity of full quantitative analyses. Semi-quantitative evaluations of landslide hazards have previously been implemented in both Indonesia [8] and India [9].

The Analytical Hierarchy Process (AHP) is one of the semi-quantitative methods widely used for landslide hazard analysis [10, 11]. This method, introduced by Saaty, relies on expert opinions to estimate landslides based on several triggering parameters [12]. This method is based on the belief that the relationship between parameters and landslide vulnerability has been determined through modeling [13]. Landslide hazard research is supported by GIS (Geographic Information System) technology, which can process spatial and non-spatial data, enabling the creation of more efficient and accurate maps [14]. The application of Geographic Information Systems (GIS) for landslide hazard mapping has been widely adopted by researchers in Indonesia. Several studies have demonstrated the effectiveness of GIS-based approaches in assessing landslide-prone areas. For instance, Suriadi and Arsjad [15] utilized geospatial information for spatial planning in landslide-prone regions [15] while Hadmoko et al. [16] conducted a comprehensive landslide hazard and risk assessment in the eastern flank of the Menoreh Mountains, integrating the results into land-use planning and disaster risk management [16].

The condition of a country's road network significantly affects its socio-economic development, with landslides and slope failures commonly occurring in hilly terrains. The Medan–Berastagi route, which traverses such landscapes, is crucial to the region's economy and connects two regencies, Deli Serdang and Karo. The Sibolangit highlands along this road feature steep, rugged terrain with slopes ranging from 60° to 90°, making the area particularly susceptible to landslides [17]. Furthermore, geological data indicate that both Sibolangit in Deli Serdang and Berastagi in Karo Regency lie near active fault lines, increasing their vulnerability to seismic activity.

Historically, many major earthquakes have occurred in Sumatra, including one in Karo Regency in 1936. Karo Regency experienced a devastating earthquake on September 9, 1936, with a magnitude of 7.2 on the Richter scale [18]. According to the Directorate of Volcanology and Geological Hazard Mitigation, this earthquake caused severe damage in Berastagi and Parapat, reaching level VIII on the Mercalli scale, two levels lower than the damage scale of the Aceh earthquake on December 26, 2004. The earthquake also caused ground cracks from Kabanjahe to Kutacane and shook the Renun-Toru fault line. Although the epicenter was in Kutacane (Southeast Aceh), the strongest tremors were felt in Karo compared to other areas along the Renun Fault line.

Several landslide studies have been conducted in North Sumatra, including landslide hazard zone maps based on rainfall and soil movement parameters in North Sumatra, slope height, slope angle, rainfall, land-use parameters, land cover, soil type, geological formation (parent rock), identification of landslide characteristics, land, dominant landslide causes, and landslide hazard distribution mapping in parts of Karo Regency (Dolat Rakyat, Berastagi, Merdeka, Kabanjahe, Simpang Empat, and Naman Teran) [19, 20]. Landslide hazard mapping has also been conducted based on population density, rainfall, soil type, rock type, slope angle, land use, and earthquakes in Sibolangit [20].

Considering previous studies and the slope characteristics along the Medan–Berastagi road, it is essential to develop a landslide hazard map or zoning plan. This study aimed to identify the spatial distribution and types of landslides using a semi-quantitative AHP (Analytical Hierarchy Process) method to help reduce the impact of landslide-related disasters. The resulting hazard map can provide fundamental data for disaster risk mitigation and inform regional planning in mountainous areas. Model validation is conducted by comparing the hazard map outputs with actual field observations.

2. RESEARCH METHODS

2.1. Primary Assumptions

Based on previous research, slope failures that have occurred will affect the stability of the slopes in the future. The assumptions regarding landslide triggering parameters remain consistent over time according to the studies conducted [16, 21]. The selection of landslide causative parameters is based on literature studies and their relevance to the conditions of the Medan-Berastagi road [22, 23]. These studies concluded that parameters such as slope angle, slope height, slope aspect, soil type, rock type, drainage, and land use are landslide causative factors. Rainfall is also a significant factor causing landslides, as landslides always occur during the rainy season. The fault structure is a crucial parameter for the Medan–Berastagi road since it is located along the Bukit Barisan. The Sumatra Fault forms the Barisan Mountains and is classified as a highly active fault. One cause of earthquakes is faults, so in this study, earthquakes are used as a factor causing landslides. Based on these research results, the data used for the landslide-prone area model in this study include slope height, slope angle, slope aspect, rainfall, drainage conditions, rock type, soil type, land use, faults, earthquakes, and river proximity.

Landslide hazard mapping through GIS can be conducted using three main approaches: qualitative, quantitative, and semi-quantitative methods [24]. The quantitative approach involves mathematical modeling and numerical analysis, whereas the qualitative method relies on descriptive assessments to evaluate landslide susceptibility [25, 26]. The semi-quantitative approach integrates elements of both, employing techniques like the Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), and fuzzy-AHP for more balanced and structured evaluations [27]. The overall research workflow is summarized in Figure 1, illustrating the process from primary and secondary data acquisition, parameter weighting via AHP, spatial data standardization, overlay integration in GIS, to the final classification and validation of landslide hazard zones.

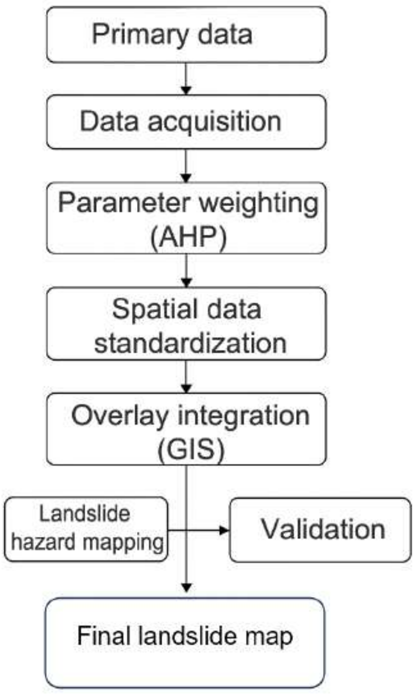


Figure 1. Workflow of the research methodology, from data acquisition to landslide hazard mapping using AHP and GIS integration.

2.2. Research Sites

The research site is located along road sections extending from the initial point at the Medan City border, Simpang Tuntungan, (Point A coordinates 98.6004; 3.4909) to Simpang Tiga Ujung Aji (Point B coordinates 98.5109; 3.1788), covering a distance of approximately 51 km. The road sections were segmented into roughly 1 km each, with an additional ±500 m on both sides, totaling 45 segments. Segments exceeding 1 km in length consist of winding roads. The study area traverses through Pancur Batu, Namu Rambe, Sibolangit, Berastagi, and Dolat Rayat regions. Sibolangit and Berastagi are well-known tourist spots in North Sumatra, situated at elevations of about 1,300 meters above sea level. The elevation change across the research site predominantly exceeds 600 m. Precipitation levels are notably high, ranging from 2001 mm/year to 2500 mm/year, with numerous minor faults (unidentified faults). Soil compositions in the study site include latosol and andosol, while lava and pyroclastic breccia are the primary rock types. The presence of multiple fractures in the partially weathered andesite lava rocks facilitates water permeation, elevating the slope load and inducing slope instability, ultimately resulting in landslides. The primary land utilization consists of dryland farming and residential areas, contributing to frequent landslides along this route during the rainy season. Figure 2 illustrates the research site along the Medan–Berastagi road corridor, highlighting 45 segmented sections between Simpang Tuntungan and Simpang Tiga Ujung Aji. The figure also presents the location of the study area within North Sumatra Province, Sumatra Island, and Indonesia, providing geographical context for the landslide hazard analysis.

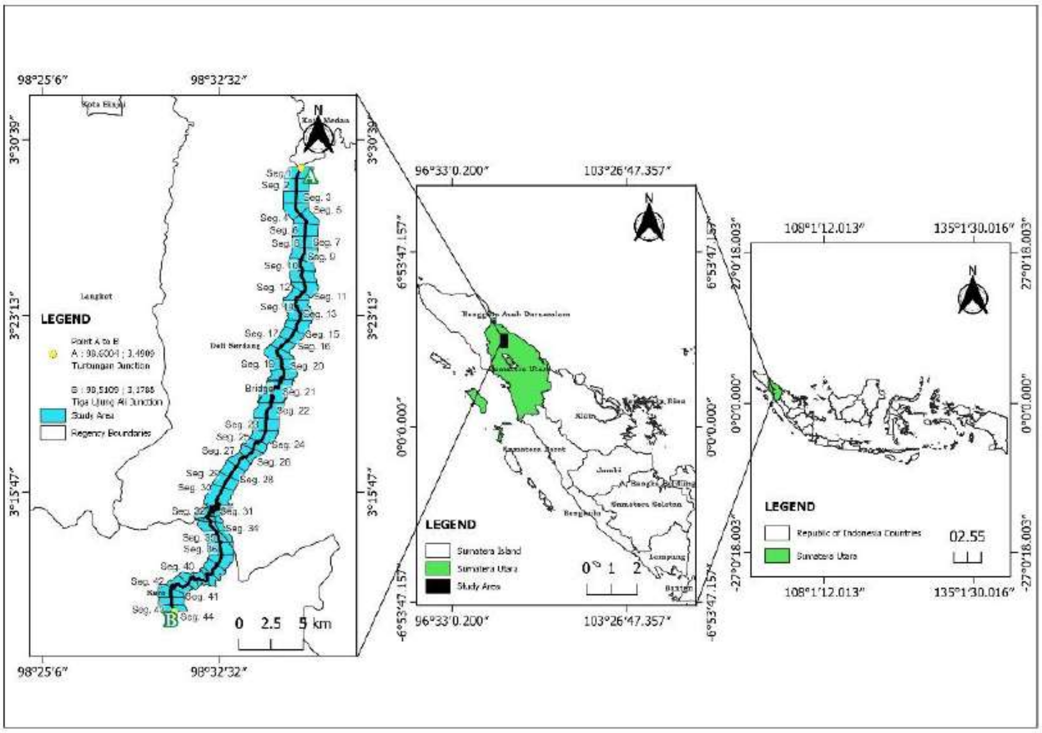


Figure 2. Research sites.

2.3. Landslide Data Inventory

Based on data from the National Road Implementation Center Medan, 21 landslide incidents occurred in the research location from 2017 to 2019, as depicted in Figure 3.

Figure 3. Landslide and landslide-prone locations charts on the Medan-Berastagi route [28].

2.4. Data Acquisition

The study utilized both primary and secondary data sources. Primary data were obtained through field surveys, focusing on existing landslide locations using GPS and observations of drainage conditions at the slope base. Secondary data included topographic maps, geological maps, rainfall records, earthquake data, and land-use maps. Topographic data were derived from the Shuttle Radar Topography Mission (SRTM) DEMNAS (https://tanahair.indonesia.go.id/) with an 8-meter resolution at a 1:25,000 scale. Geological information such as soil type, rock type, and proximity to fault lines was obtained from the North Sumatra Geological Sheet at a 1:100,000 scale, which provides simplified geological details due to its relatively small scale. The land-use map was also scaled at 1:25,000. Earthquake data, covering the period from 1900 to 2022 and within a 30 km radius of the study area, were sourced from the USGS website (https://earthquake.usgs.gov).

2.5. Analytical Hierarchy Process Algorithm

The Analytical Hierarchy Process (AHP) is a decision-making technique developed by Thomas L. Saaty. It aims to assess decision alternatives and identify the optimal choice when decision-makers face several objectives or criteria. This methodology can manage both qualitative and quantitative data, allowing for the measurement of qualitative aspects, thus categorizing it as partially qualitative. The application of AHP in this study requires structuring a hierarchy that begins with the basic research objective of developing a landslide hazard map and extends to the essential elements that induce landslides. Additionally, it involves evaluating the importance of each indicator and converting qualitative data concerning landslide causative elements into numerical values from 1 to 9. This technique is considered sufficiently indicative of perceptions due to the implementation of expert answer consistency analysis.

2.6. Overlay Technique

To process maps using Geographic Information Systems (GIS), each map must first be standardized to ensure a uniform scale, converted into shapefile (SHP) format, and supplemented with complete attribute information, such as location names and village names. In the case of hardcopy maps, such as geological or fault maps, digitization is required. Digitization refers to the process of converting analog map data into digital format. All spatial and attribute data must be accurately entered to transform raster maps into vector-based objects, including polygons, lines, and points.

The integration of all thematic maps comprising eleven parameters is commonly referred to as the overlay process, which represents the final stage in generating a landslide hazard map. As illustrated in Figure 4, this process involves summing the weighted scores at corresponding spatial locations across all parameters.

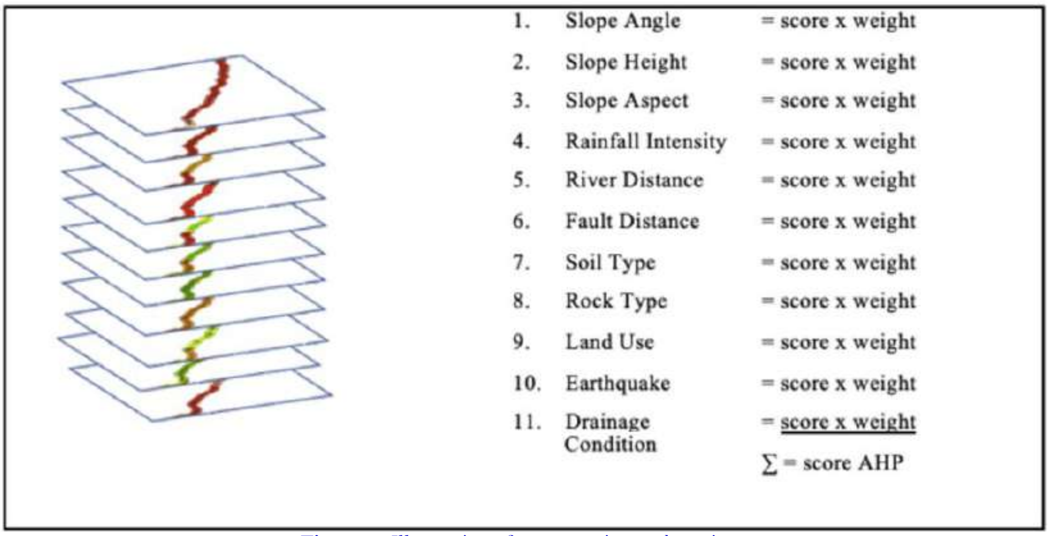


Figure 4. Illustration of map merging and scoring.

Before creating the landslide hazard map, ranking and weighting all factors through AHP is the first step that must be completed. In this study, each factor is weighted against the others using the pairwise comparison method, and the results are shown in Table 1.

Table 1. Landslide hazard parameter.

Parameter	Verification	Weight (%)	Score
Slope Angle (%) (SA)	Flat (0 – 8)	14	1
	Slightly Sloping (8 – 15)		2
	Sloping (15 – 25)		3
	Very Sloping (25 – 45)		4
	Steep – Very Steep (>45)		5
Slope Height (m) (SH)	< 150	12	1
	150 – 300		2
	300 – 450		3
	450 – 600		4
	> 600		5
Aspect (A)	North, Northeast, East	7	1
	East, Southeast		2
	South, Southwest		3
	Southwest, West		4
	West, Northwest, North		5
Rainfall Intensity (mm) (RI)	< 500	18	1
	501 - 1000		2
	1001 - 1500		3
	1501 - 2000		4
	>2000		5
River Distance (m) (RD)	>1000	10	1
	800-1000		2
	500-800		3
	300-500		4
	<300		5

Parameter	Verification	Weight (%)	Score
Fault Distance (FD)	>10000	5	1
	5000 – 10000		2
	3000 – 5000		3
	1000 – 3000		4
	< 1000		5
Soil Type (ST)	Regosol	5	1
	Entisol		2
	Latosol		3
	Inceptisol		4
	Andosol		5
Rock Type (RT)	Alluvial Deposits	5	1
	Sedimentary Rock 1 (Argillic-altered tuff)		2
	Volcanic Rock 1 (breccia lava)		3
	Sedimentary Rock 2 (breccia and conglomerate)		4
	Volcanic Rock 2 (lava and pyroclastic breccia)		5
Land Use (LU)	Protected Forest, Dense Forest	10	1
	Mixed Forest		2
	Plantation		3
	Wet Agriculture, Flat Land		4
	Dry Agriculture, Settlements		5
Earthquake (g) (E)	<0.05 g	5	1
	0.05 – 0.14		2
	0.15 – 0.34		3
	0.35 – 0.50		4
	>0.50		5
Drainage Conditions (DC)	Very adequate drainage system	9	1
	Slightly adequate drainage system.		2
	Inadequate drainage system		3
	Poor drainage system		4
	No drainage		5

The hazard map is obtained from the score and weight calculation as shown in Equation 1.

$$Hazard = (14\% * SA) + (12\% * SH) + (7\% * A) + (18\% * RI) + (9\% * RD) + (5\% * FD) + (5\% * ST) + (5\% * RT) + (10\% * LU) + (5\% * E) + (9\% * DC) \quad (1)$$

Description: As SA is slope, SH is altitude, A is aspect, RI is rainfall intensity, RD is distance of river, FD is distance of fault, ST is type of soil, RT is type of rock, LU is land-use, E is earthquake, and DC is condition of drainage. The hazard map uses a classification of five levels of landslide risk: very low, low, medium, high, and very high.

3. RESULT AND DISCUSSION

3.1. Landslide Inventory

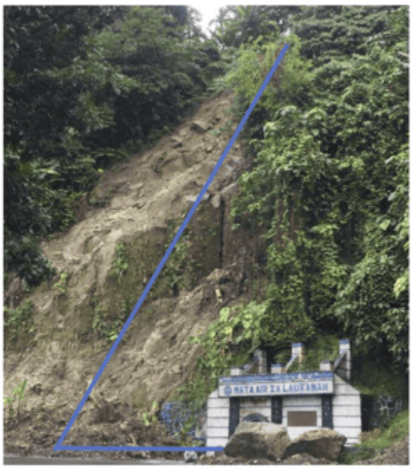
Based on direct field observations, there are three locations where landslides repeatedly occur, causing both material and human losses. The three sampled locations along the Medan-Berastagi road are Site-1 in Batu Layang Village, Sibolangit; Site-2 in the PDAM Tirtanadi Sibolangit area; and Site-3 in Doulu Village, Berastagi District. The results of the landslide inventory are shown in Figures 5,6, and 7.

(a)

Slope Calculation for Site-1	
Path Length (Climb)	14.78 m
Min Elevation on Path	471.75 AMSL
Max Elevation on Path	486.53 AMSL
Average Slope/Tilt	76.68°
Max Slope/Tilt	83.11°
Area Calculation	245.94 m2
Type of landslide	translational slide
Soil type	Silt inorganic, gravel-sand-silt mixture, rock flour

(b)

Figure 5. Site-1 Batu Layang Village (Longitude 98.5789° and Latitude 3.3266°). (a) Observed slope angle, and (b) slope calculation.



(a)

Slope Calculation for Site-2	
Path Length (Climb)	23.18 m
Min Elevation on Path	501.63 AMSL
Max Elevation on Path	524.81 AMSL
Average Slope/Tilt	67.84°
Max Slope/Tilt	89.59°
Area Calculation	224.15 m^2
Type of landslide	topples
Soil type	Silt inorganic, *gravel-sand-silt mixture, rock*

(b)

Figure 6. Site-2 in the PDAM Tirtanadi Sibolangit area (Longitude 98.5789° and Latitude 3.3340°). (a) Observed slope angle, and (b) Slope calculation.

(a)

Slope Calculation for Site 3	
Path Length (Climb)	31.65 m
Min Elevation on Path	1430.67 AMSL
Max Elevation on Path	1442.34 AMSL
Average Slope/Tilt	51.39°
Max Slope/Tilt	58.11°
Area Calculation	847.27 m^2
Type of landslide	translational slide
Soil type	Silt inorganic, gravel-sand-silt mixture, rock flour

(b)

Figure 7. Site-3 in Doulu Village, Berastagi District (Longitude 98.5414° and Latitude 3.2130°). (a) Observed slope angle and (b) slope characteristics calculation.

The field-based landslide inventory along the Medan–Berastagi route indicates that slope angle, soil type, and rainfall intensity are significant factors in landslide incidence, corroborating existing theories and previous studies.

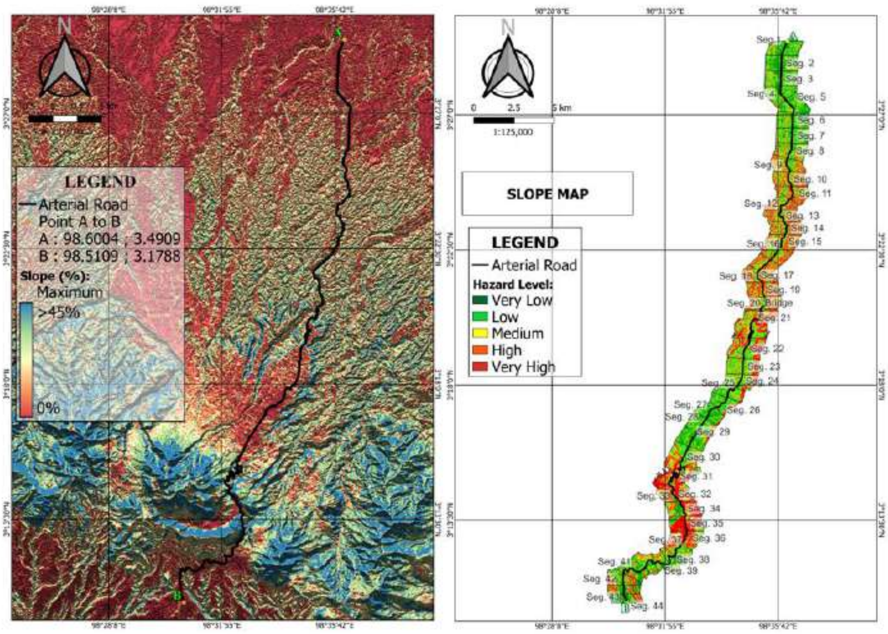
The high inclines at Site-1 and Site-2, above 75°, significantly exceed the typical threshold of 45° for slope instability in tropical areas. This corroborates the findings of other studies, Çellek [29], which highlight slope gradient as a primary component in landslide susceptibility mapping. The prevalence of silt and gravelly sand combinations in weathered volcanic formations corresponds with findings from landslide-prone regions in Central Java and India, where lithology was recognized as a crucial feature [29, 30]. The identified failures, translational slide at Site-1 and toppling at Site-2, align with the soil mechanics principles that dictate slope failure modes in colluvial deposits and volcanic tuffs.

Moreover, precipitation and proximity to active faults substantially affect the onset of landslides. The proximity of faults within 1 km of all three locations heightens seismic susceptibility, as earthquakes can diminish soil cohesiveness and induce collapses, especially in already compromised slopes. The AUC value of 0.711 from the AHP-based hazard model signifies acceptable prediction accuracy, akin to findings from analogous semi-quantitative research in India [30]. These findings corroborate the application of AHP for landslide hazard assessment and emphasize the necessity of incorporating topographic, geological, hydrological, and anthropogenic elements into slope stability analysis.

3.2. Evaluation of Landslide Triggering Parameters

Landslide triggering parameters are evaluated using eleven factors: slope angle, slope height, slope aspect, rainfall, river distance, fault distance, soil type, rock type, land use, earthquake, and drainage condition. Landslide susceptibility levels are classified into five categories: very low (green), low (light green), moderate (yellow), high (orange), and very high (red).

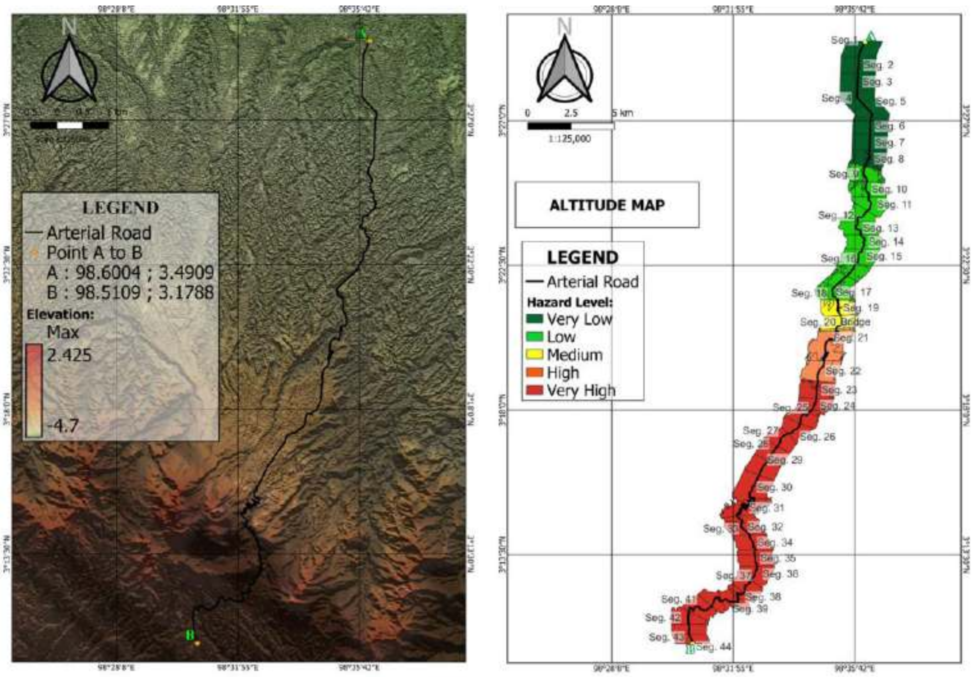
From topographic maps, data layers for altitude (slope height), slope angle, and slope aspect will be obtained. The geographic and topographic conditions are based on the Digital Elevation Model (DEM). The DEM is generated by contour interpolation. The topographic map is obtained from DEMNAS data issued by the Geospatial Information Agency (BIG) with a contour interval of 50 meters at a scale of 1:25,000. The slope angle parameter significantly influences landslide susceptibility because areas with steep slopes are primary contributors to the movement of weathered materials or rocks down the slope. The slope chart data is shown in Figure 8.



(a) **(b)**

Figure 8. The slope charts. (a) slope angle and (b) classification of slope angle.

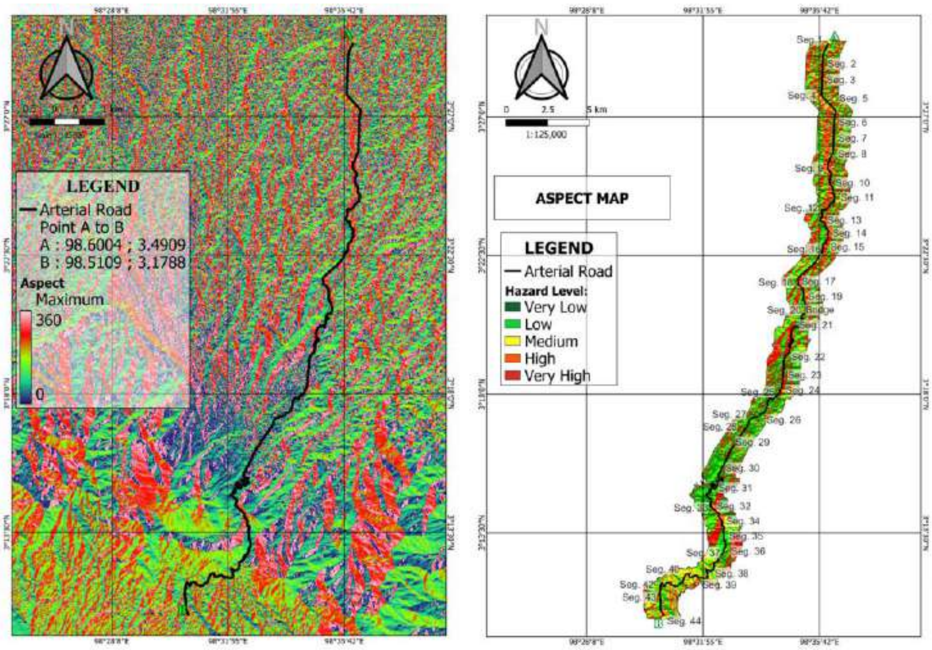
The altitude parameter is also a determining factor for the possibility of landslides because it is influenced by several geological and geomorphological processes. Different altitudes result in varying climates, temperatures, and pressures. Altitude (slope height) is useful for classifying relief and determining areas with maximum and minimum elevations. Therefore, slope height is one of the topographic factors affecting landslides. Higher slopes tend to have lower safety levels. The data for altitude (slope height) is illustrated in Figure 9.



(a) (b)

Figure 9. The slope height charts (a) height maps and (b) classification.

Slope direction (aspect) is considered one of the factors causing landslides, where aspect is defined as the compass direction (e.g., East, Southeast, South, Southwest, West, Northwest, North, and Northeast). The data for slope direction is illustrated in Figure 10.



(a) (b)

Figure 10. (a) Slope aspect map and (b) slope classification.

Rainfall intensity in this mapping is expressed in millimeters per year. Rainfall data was obtained from the annual rainfall distribution map from the Geoportal Bappeda from 2010 to 2020. Rainfall intensity at the research location consists of two categories: high intensity (1501-2000 mm/year) and very high intensity (2001-2500 mm/year). Throughout the research location, rainfall with very high intensity (2001-2500 mm/year) predominates. The data for rainfall intensity is illustrated in Figure 11.

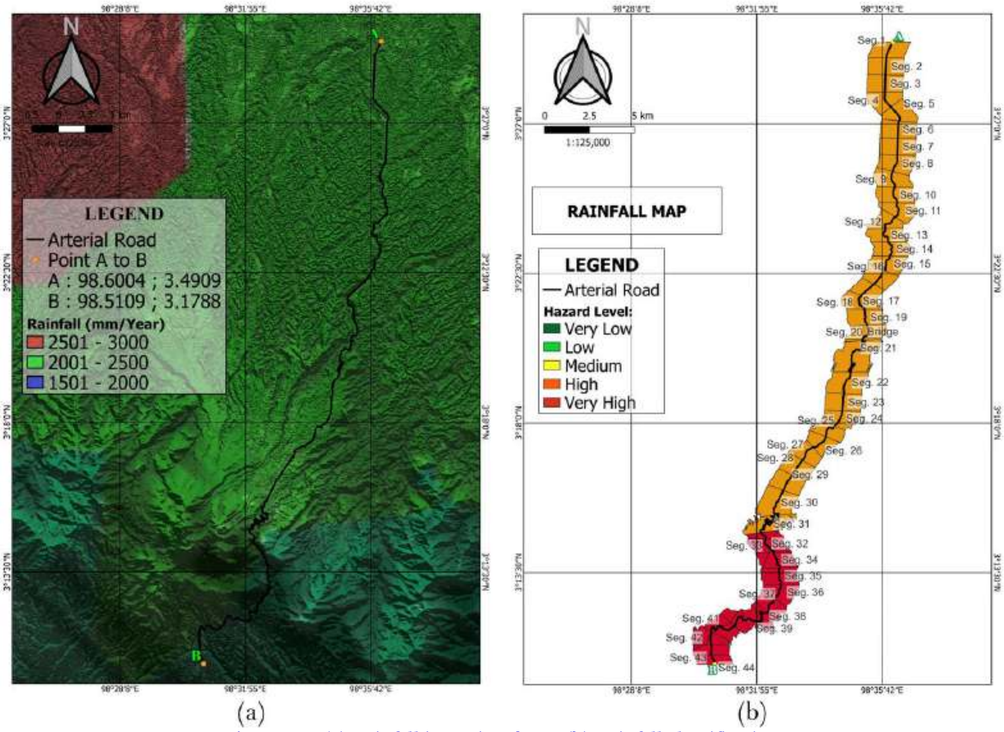


Figure 11. (a) Rainfall intensity charts (b) Rainfall classification.

In general, areas closer to rivers are more prone to erosion, increasing the likelihood of landslides. The distance to the river is represented by river proximity. The data for river proximity is illustrated in Figure 12.

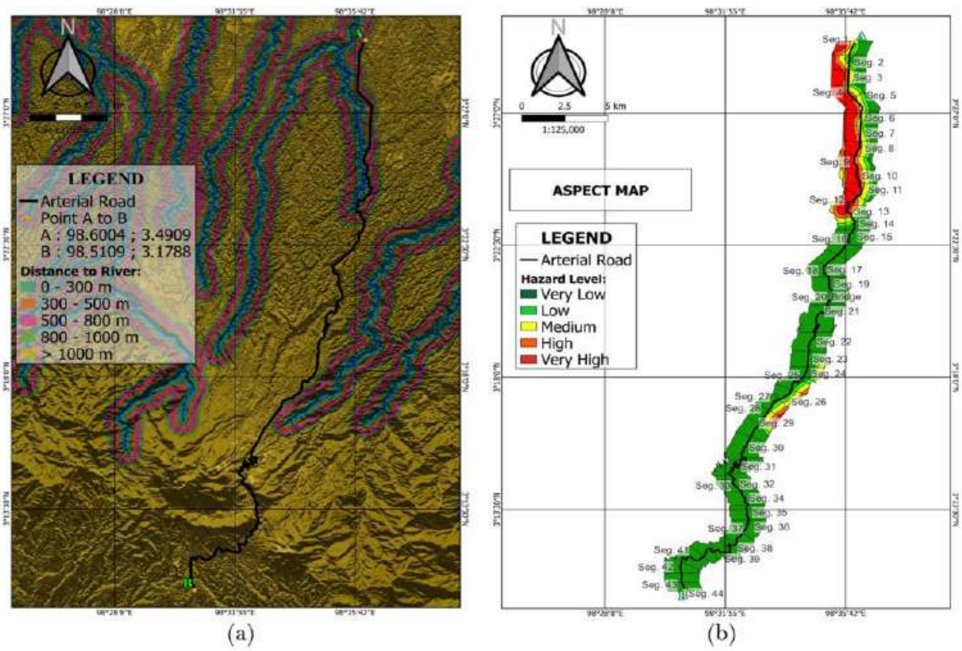


Figure 12. River charts (a) River distance map and (b) Classification.

The geological structure factor affects slope stability. The distance to faults relates to an area's location in an active geological zone, where areas in active geological zones have a high frequency of ground movements. The data is presented in Figure 13.

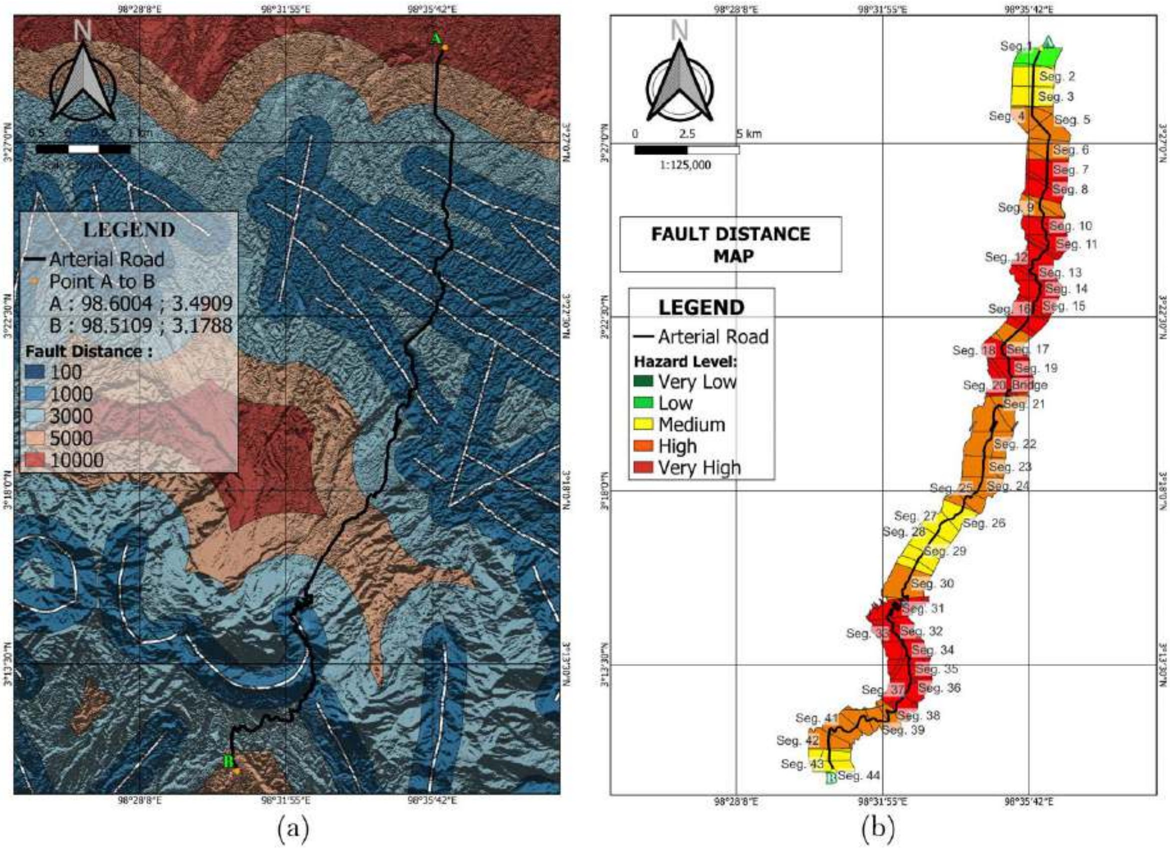


Figure 13. Fault distance map (a) Distance to minor faults and (b) Classification.

Soil type is a significant factor contributing to the occurrence of landslides on a slope due to its role in determining the mass involved in a landslide event. The properties of soil type play a crucial role in influencing the stability of slopes. Slopes characterized by soil with low cohesion and high permeability are more inclined to experience landslides. The classification of soil types in this investigation is in accordance with the Technical Guidelines for National Soil Classification, 2014, which draws upon the Soil Map of the World [31] and Soil Taxonomy from the United States Department of Agriculture (USDA) [32], adapted to suit the soil conditions in Indonesia. The findings of the research reveal that the soil types identified at the study site include Latosol and Humic Andosol, both falling within the classification of mineral soil. Latosol soil is a product of incomplete rock weathering processes, resulting in the preservation of the original rock structure. Latosol soil layers are characterized by limited thickness, encompassing gravel, sand, and small rocks with low nutrient levels, diverse texture, and fertility, formed through volcanic activities. Latosol soil is highly vulnerable to erosion. Humic Andosol is typically present in elevated regions formed by volcanic eruptions. Humic Andosol, or Mollic Andosol, is rich in humus content, though its color is predominantly dark brown rather than black. The primary formation mechanism of Andosol soil involves weathering and alteration, typically situated on volcanic inclines. Andosol soil is highly fertile and conducive to agricultural practices, yet it poses risks of land degradation and environmental harm, rendering it susceptible to erosion and landslides. Soil type data is presented in Figure 14.

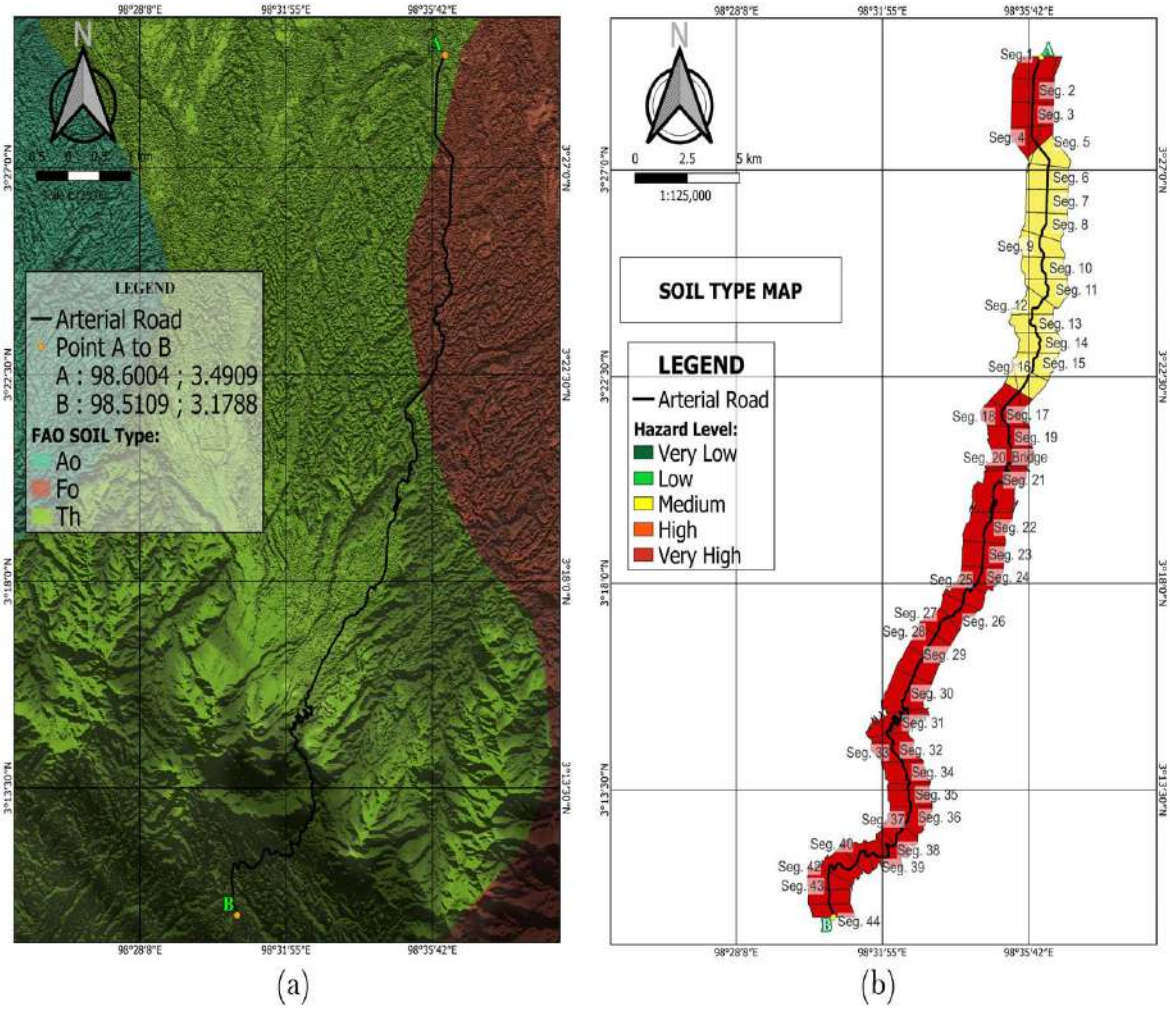


Figure 14. Soil type map (a) Soil charts and (b) its classification.

The rock types present in the study area are MtkQh, QTvm, and Qvbj. As stated in the North Sumatra Geological Sheet, Mtk represents the Kuala formation, which is composed of shale, sandstone, and siltstone. Qh denotes alluvium, a sedimentary rock formed by the transportation and deposition of materials such as gravel, sand, and clay by rivers. The formation of MtkQh is attributed to alluvial deposits with remarkably low susceptibility, characterized by a combination of clay, silt, sand, and gravel, making it one of the most recent rock formations. Alluvial deposits are predominantly located along riverbanks, particularly in floodplains and river deltas. QTvm, known as the Mentare unit, is identified as lahar breccia or pumice with an andesite to dacite composition, categorized as volcanic rock (volcanic rock-1). This rock type, QTvm (volcanic rock-1), is comprised of lahar breccia resulting from volcanic reworking and exhibits a moderate susceptibility. Breccia lava is susceptible to expansion and contraction due to variations in moisture content. Qvbj, referred to as the Binjai unit, is characterized by andesite to dacite flow breccia, classified under volcanic rock (volcanic rock-2). Within the study area, this particular rock type falls into the classification of very high susceptibility (volcanic rock-2) and is commonly situated near volcanic eruption centers. Lava and pyroclastic breccia (volcanic rock-2) encompass a range of materials discharged during volcanic eruptions, varying from solid fragments to large boulders. Data for rock type is presented in Figure 15.

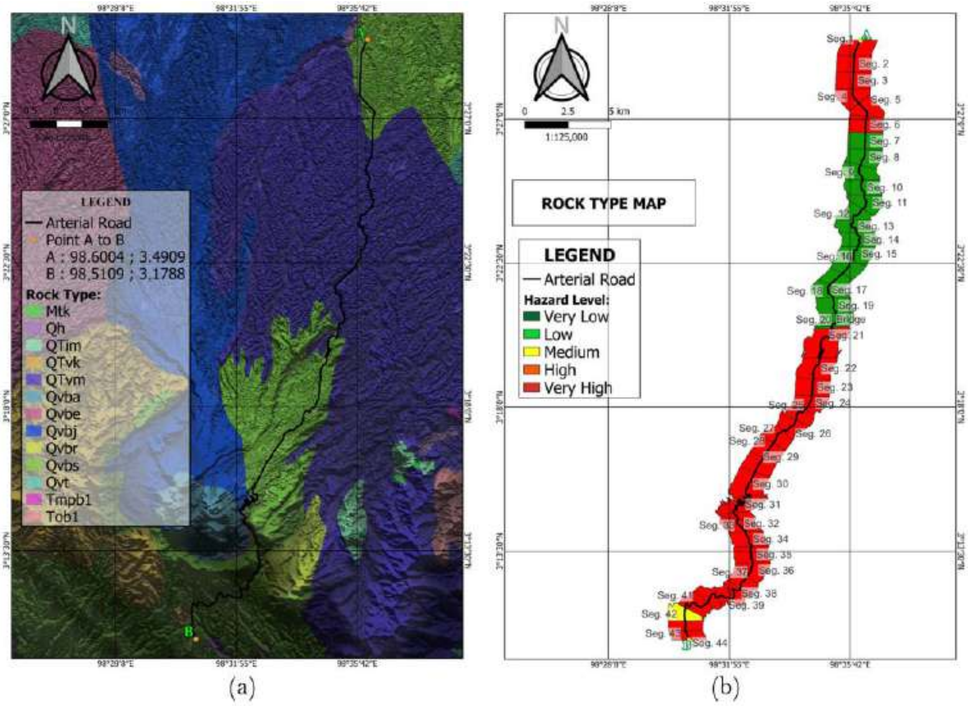


Figure 15. Rock type map (a) Rock type charts and (b) its classification.

Human activities are closely related to slope stability. Rainfall and human activities are among the factors triggering landslides that relate to geomorphological conditions. Land cover can be a controlling factor for soil movement and increase the risk of soil movement due to land use changes. One way to mitigate soil movement is through land-use regulation. Land use in an area should serve as a guideline for managing all activities in the area under consideration. The research area consists of protected forests/dense forests, mixed forests, plantations, wet agriculture or flat land, and dry agriculture/settlements, predominantly dry agriculture/settlements. Data is presented in Figure 16.

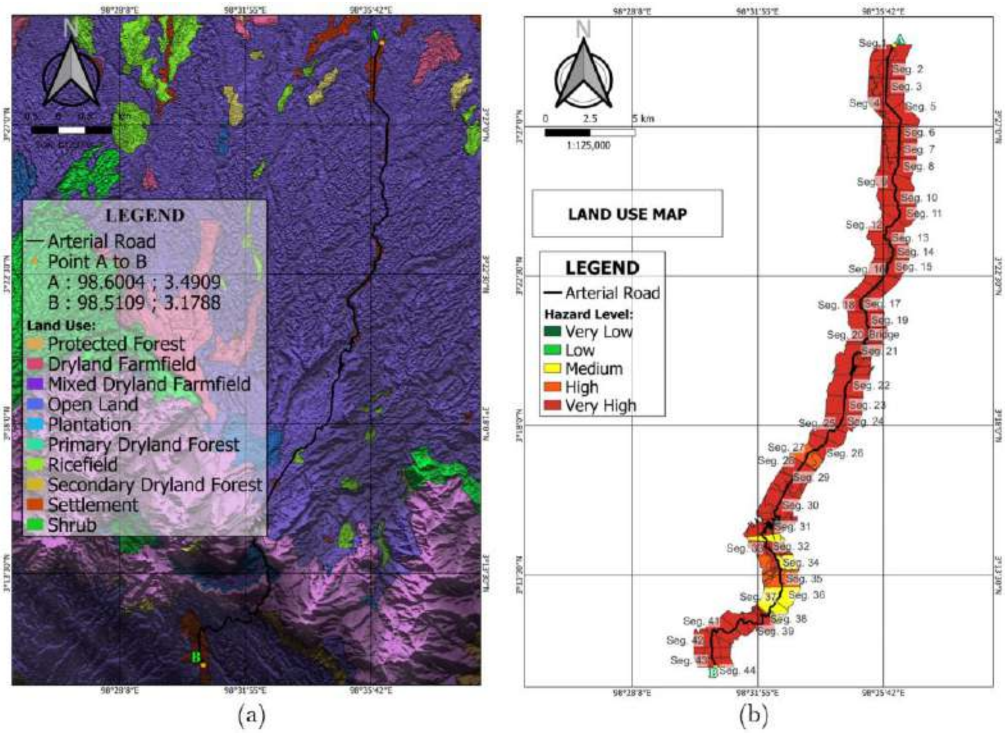


Figure 16. Land use map (a) Land use charts and (b) its classification.

Earthquakes can trigger mass movements on slopes. Periodic vibrations caused by earthquakes can reduce the stability of soil or rock on slopes. In this study, earthquake information used is the peak ground acceleration (PGA) data from the Indonesian Seismic Hazard Map (Puskim PU) based on coordinate points by creating a 5 km grid to produce an earthquake acceleration contour map.

The website accessed is https://rsa.ciptakarya.pu.go.id/2021/. By inputting the latitude and longitude coordinates of the earthquake location and assuming a moderate soil type, the PGA (g) value at the bedrock is obtained. Calculations show that the PGA (g) value at the research location ranges from 0.15 – 0.24g (moderate susceptibility) and 0.35 – 0.50g (high susceptibility).

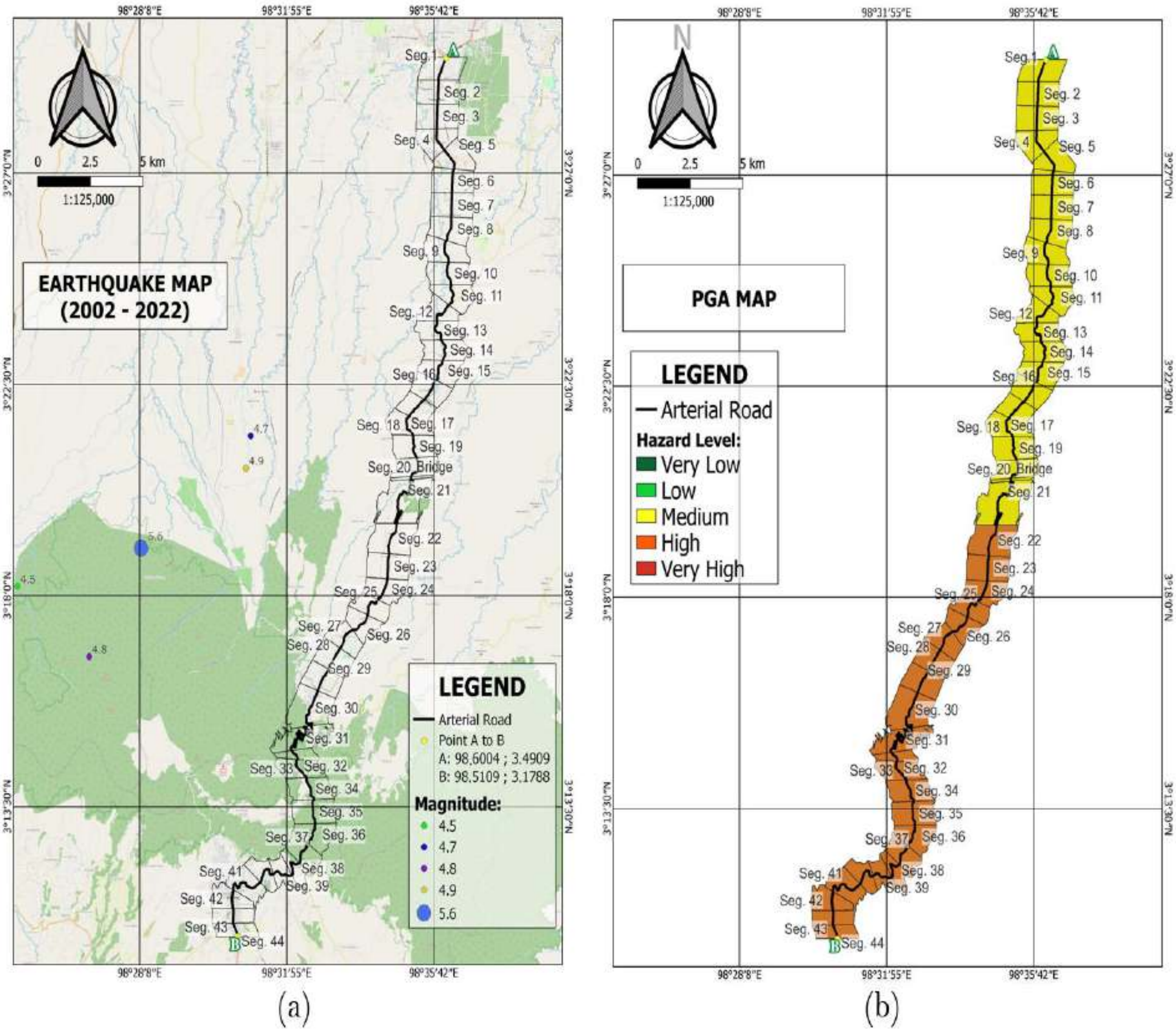


Figure 17. Peak ground acceleration map (a) The earthquake chart (b) its classification.

Drainage conditions affect slope stability because water flows through lower areas. Rainwater infiltrating the soil can accumulate at the slope foot. If the slope drainage system is poor, water at the slope foot increases hydrostatic pressure on the slope and reduces soil strength. Poor drainage conditions cause water from catchment areas to lack flow space, leading to landslides. In the research area, drainage conditions were surveyed directly. The analyzed drainage system is located below the slope (roadside). Most drainage conditions at the research location are classified as low, with 23 segments totaling 19 km.

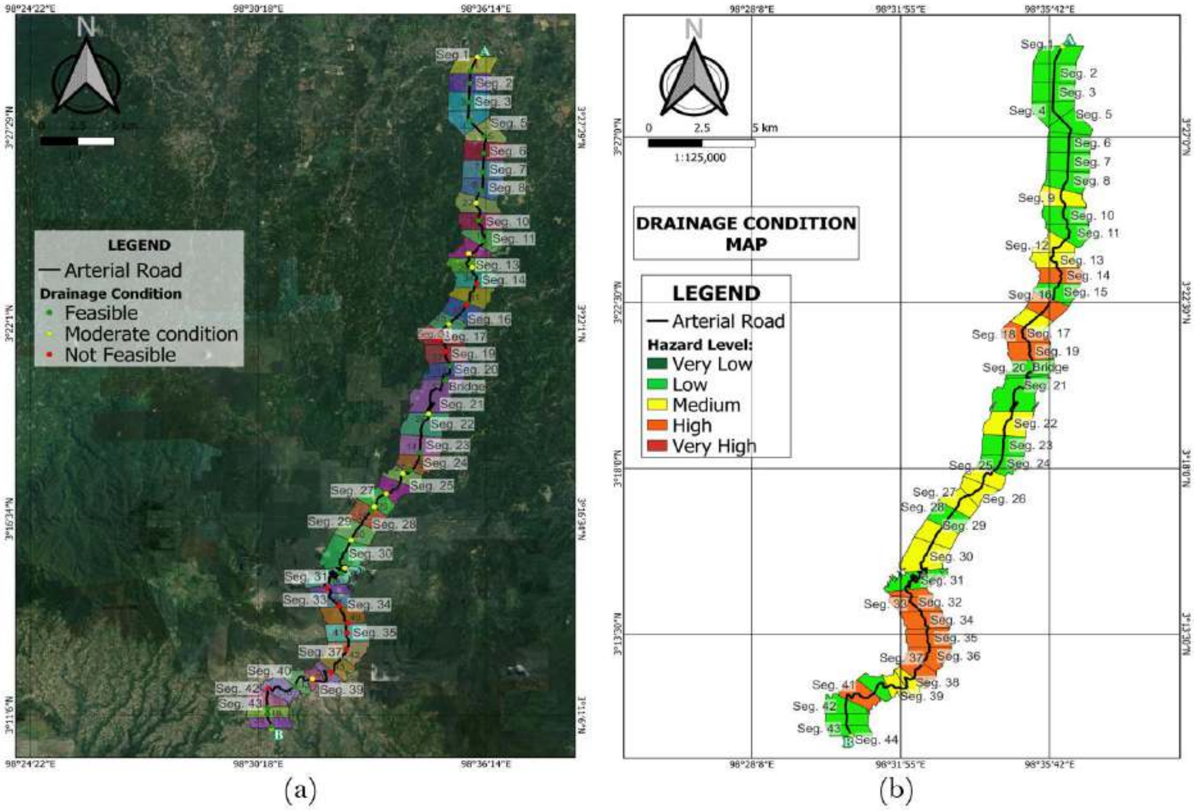


Figure 18. Drainage map (a) Drainage condition and (b) its classification.

The classification of the landslide hazard map comprises five levels of hazard: very low, low, moderate, high, and very high. Analysis of the study findings reveals that the predominant hazard levels for landslides along the Medan-Berastagi route are high, encompassing 20 segments totaling 19 km (representing 46% of the overall segment length), and very high hazard levels, with 4 segments totaling 3 km (9% of the total segment length). The highest proportion in terms of segment length falls under the moderate category at 44%, followed by high at 46%, and very high at 9%. The villages susceptible to landslides are identified in Table 2.

Table 2. Potential Landslide-Prone locations by district and village.

No.	Hazard level	Segment number	Districts	Villages
1	Very low	-	-	-
2	Low	-	-	-
3	Moderate	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 14, 15, 16, 17, 20, 22, 23, 26, 27	Pancur Batu, Sibolangit,	Baru, Lama, Namo Simpur, Hulu, Pertampilen, Durin Simbelang, Namo Riam, Tiang Layar, Rumah Sumbul, Ketangkuhen, Suka Makmur
4	High	10, 12, 13, 18, 19, 21, 24, 25, 28, 29, 30, 31, 32, 36, 37, 39, 40, 41, 42, 43, 44	Pancur Batu, Sibolangit, Berastagi	Sugau, Bintang Meriah, Rambung Baru, Bingkawan, Sembahe, Batu Mbelin, Puang Aja, Sibolangit, Batu Layang, Ketangkuhen, Suka Makmur, Bandar Baru, Daulu, Martelu, Dolat Raya, Sempajaya, Tambak Lau Mulgab I, Tambak Lau Mulgab II, Gundaling I, Gundaling II, Rumah Berastagi
5	Very High	33, 34, 35, 38	Berastagi, Dolat Rayat	Daulu, Dolat Rayat

The hazard classifications/zones of very low and low depict stable regions devoid of landslide probabilities, located on slopes not exceeding 300 m in height, featuring slope inclinations under 15%, and fault separations surpassing 10 km. Within this hazard classification, the rock varieties consist of alluvial sediments and argillic-altered tuff, while the soil compositions include regosol and entisol, with land utilization designated as protected forest or mixed forest. Furthermore, the Peak Ground Acceleration (PGA) value remains below 0.14 g. Moderate hazard levels delineate regions exhibiting landslide potentials, identifiable by alterations in vegetation and leaning trees. In the event of landslides, the resulting damages are localized and can be mitigated through straightforward measures. The moderate hazard category is typified by slope gradients ranging from 15% to 25%, slope elevations spanning from 300 m to 450 m, and land usage for plantations, with an annual rainfall intensity of 1001-1500 mm. The proportion of moderate hazard levels is recorded at 44%, encompassing 20 segments. Conversely, the percentage of high hazard levels is 47%, represented by 21 segments, while the very high hazard levels constitute 9%, distributed across 4 segments. Predominantly observed in the study area are high and very high hazard levels, distinguished by slope altitudes surpassing 450 m, slope inclinations exceeding 25%, rainfall intensities surpassing 1500 mm/year, fault distances less than 1 km, and soil types categorized as andosol. Landslides in these specified zones are anticipated to recur, resulting in substantial damages, economic losses, and human casualties. The result landslide hazard map is presented in Figure 19.

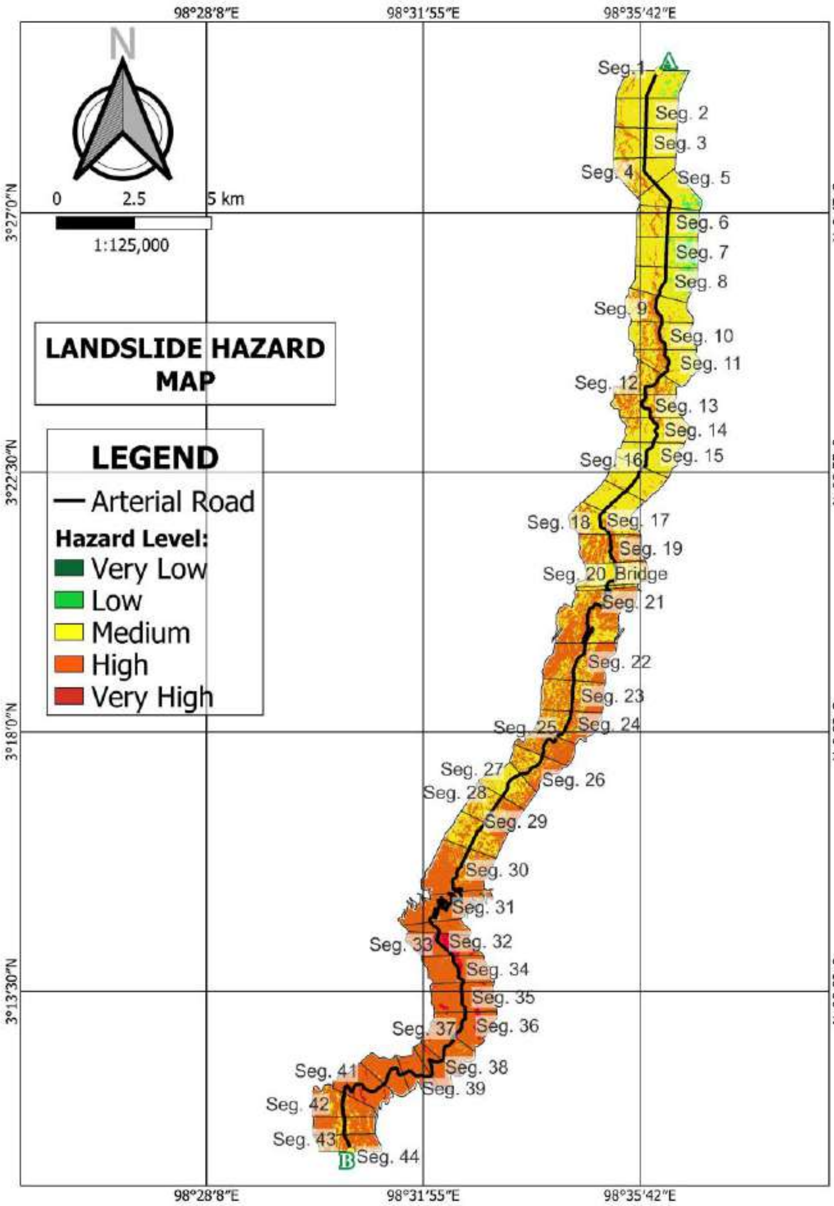


Figure 19. Landslide hazard map.

Our results underscore that slope angle, slope height, and aspect are primary influences on landslide susceptibility, consistent with applied research in Xi'an, China. In that study, AHP was used to generate susceptibility maps across a similar set of parameters: elevation, slope, aspect, curvature, river density, soil, lithology, and land use, and successfully classified 82.6% of historical landslides into "moderate-to-very-high" zones [33]. The spatial distribution and performance of their model closely mirror our findings, suggesting that integrating these topographic variables within a GIS-based AHP framework yields robust hazard delineation, especially when validated against field data. In addition, an AHP–Frequency Ratio hybrid model applied in Northwestern Ethiopia highlighted rainfall intensity, proximity to faults and rivers, soil type, and lithology as key trigger roles echoed in our study [34]. Like the Ethiopian study, we found that zones with slope >25 %, rainfall >2000 mm/yr, and volcanic lithologies cluster in the "high" and "very high" hazard classes. Moreover, our AUC score of 0.711 aligns with the Xi'an (AUC ≈ 0.82) and Ethiopia (AUC ≈ 0.76) models, indicating that semi-quantitative methods retain predictive reliability across diverse geologic and climatic settings. Altogether, these comparative analyses affirm the validity of our parameter selection, while pointing to future enhancements such as optimized rainfall indexing and hybrid statistical-AHP workflows that could further refine model accuracy.

3.3. Map Validation

To assess the efficiency of the model, model validation is performed using the ROC curve method by calculating the AUC (Area Under Curve) value. The AUC value indicates the predictive quality of the loose risk model. AUC values ranging from 0 to 1 indicate that the model's performance level varies from low to high. A ROC chart is a two-dimensional graph that shows the relationship between True Positive Rate (TPR) or Sensitivity (Y-axis) and False Positive Rate (FPR), or 1 - Specificity (X-axis). From the slide spread data, using field data, as many as 68 slide points along the road corridors are used as validation data sets (Figure 20). Field data uses high classification and very high data.

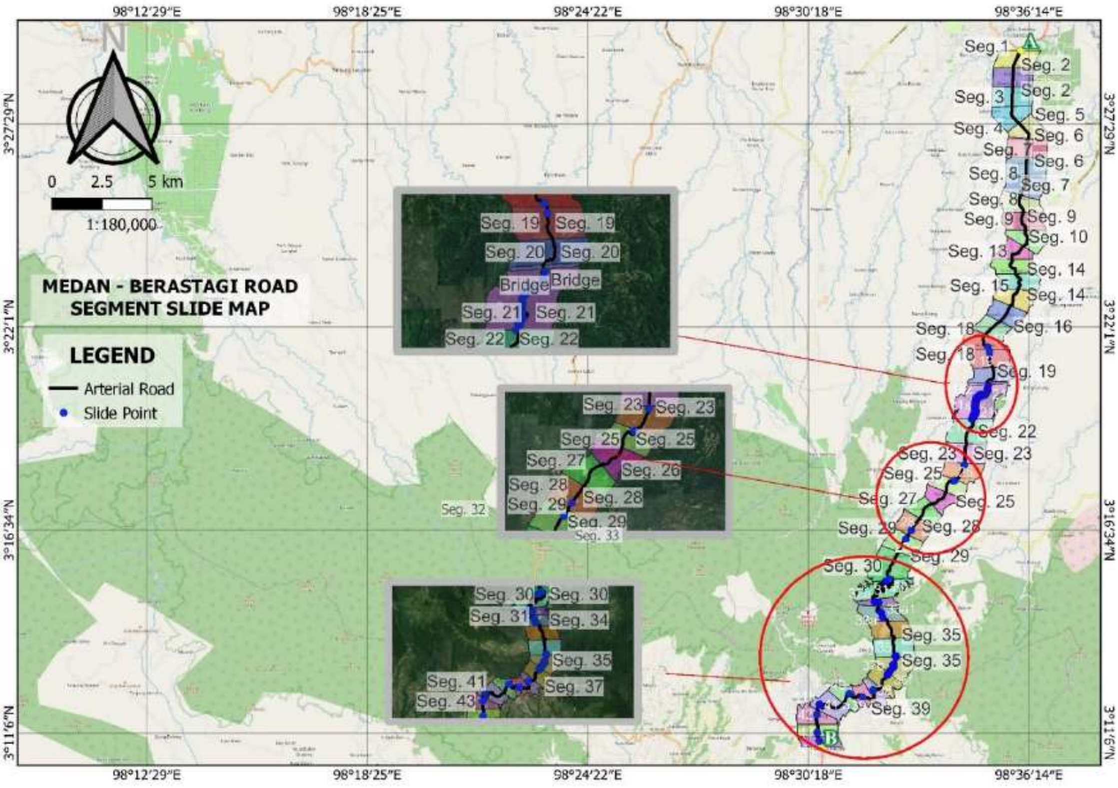


Figure 20. Map of existing slide incidents at the research site from 2019 to 2023.

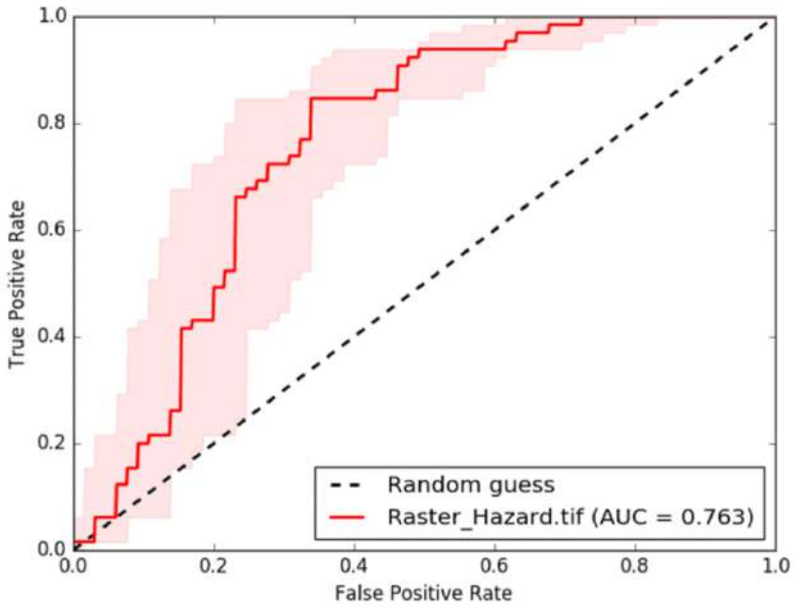


Figure 21. ROC Curve with training data set.

Model performance was evaluated using the Receiver Operating Characteristic (ROC) curve in Figure 21, with the Area Under the Curve (AUC) serving as the primary metric for predictive accuracy [35]. The model achieved an AUC of 0.763, indicating "sufficient" discriminatory power based on conventional thresholds where 0.7–0.8 is deemed fair, with values below 0.7 generally considered poor and those above 0.8 considered good to excellent. A total of 68 landslide occurrences along the Medan–Berastagi corridor, comprising 13 "very high" and 55 "high" hazard points based on field observations, were used for model validation (Figure 19). These validation points show the model reliably identified high-risk zones, demonstrating strong spatial consistency between predicted hazard levels and observed landslide incidents. The ROC plot (Figure 21) confirms this alignment, with the curve significantly exceeding the 45° line (AUC = 0.5), further affirming the model's capability to correctly classify landslide-prone areas. While the model's performance is categorized as "sufficient," there is still room for improvement, especially by incorporating additional conditioning factors or leveraging higher-resolution datasets. However, in its current form, the semi-quantitative AHP model provides a robust tool for hazard identification and supports targeted disaster mitigation strategies in hilly terrains like the Medan–Berastagi corridor.

4. CONCLUSION

The study identified that 44% (19 km) of the road segments were classified as moderate hazard, 46% (29 km) as high hazard, and 9% (3 km) as very high hazard. Field data showed an increase in landslide occurrences, from 21 incidents between 2017–2019 to 52 incidents between 2019–2023. The landslide susceptibility model yielded an AUC value of 0.711, indicating acceptable predictive accuracy. Prolonged heavy rainfall was the main triggering factor, especially in areas underlain by the Singkut Formation, which is composed of fractured and weathered andesite and dacite lava, allowing water infiltration and increasing slope instability. Contributing factors include steep slopes (>25%), elevations above 600 m, proximity to faults (<1 km), Latosol and Humic Andosol soils, land use dominated by agriculture and settlements, and peak ground acceleration (PGA) values exceeding 0.35 g. It is recommended to further investigate local fault structures (direction, depth, and type) and assess the influence of vehicular loads on slope stability.

Future research could focus on testing hybrid models that combine AHP with other statistical or machine learning approaches, as well as integrating real-time monitoring data from sensors and remote sensing platforms to further improve landslide hazard prediction accuracy and timeliness.

Funding: This study received no specific financial support.
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
Disclosure of AI Use: The author used OpenAI's ChatGPT (GPT-4) to edit and refine the wording of the Introduction and Literature Review. All outputs were thoroughly reviewed and verified by the author.

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