



Multi-Criteria Landslide Susceptibility Assessment in a Tropical Volcanic Environment: An Integrated GIS–AHP and Geotechnical Approach from the Cameroon Volcanic Line

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: <https://doi.org/10.9734/jgeesi/2026/v30i71071>

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://pr.sdiarticle5.com/review-history/159532>

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Abstract

Landslides are complex geomorphological hazards driven by multiple interacting geological, hydrological, and environmental factors, and they cause significant socio-economic and environmental impacts. Therefore, landslide susceptibility mapping is essential for effective hazard assessment and risk management. This study assesses landslide susceptibility along the Cameroon Volcanic Line, characterized by steep terrain, intense rainfall, and active tectonics. Remote sensing data, geotechnical investigations, and Geographic Information Systems (GIS) were integrated using the Analytic Hierarchy Process (AHP) to identify and map areas prone to slope instability. The analysis considered rainfall, soil characteristics, morphology, surface lineament density, deep lineament density, weathering thickness, drainage density, and vegetation cover. Geotechnical investigations revealed the presence of silty clay soils that may contribute to slope instability under high moisture conditions. The results indicate that rainfall is the dominant controlling factor, followed by soil properties, topography, and drainage density, whereas vegetation cover and fracture density exert a comparatively lower influence. The resulting susceptibility map highlights high-risk zones that are consistent with previously reported landslide occurrences. These findings demonstrate that integrating remote sensing, GIS, and geotechnical data within an AHP framework provides a reliable approach for landslide susceptibility assessment and risk management in tropical volcanic environments.

Keywords: Landslides; remote sensing; analytic hierarchy process; Geographic Information Systems (GIS); Cameroon volcanic line; geotechnical testing.

1. Introduction

Landslides are a major category of mass movements. (Dai & Lee, 2002; Clerici et al., 2002; Dai & Lee, 2002; Guzzetti, Reichenbach, Cardinali, & Gall, 2005; Pande, Khadri, Moharir Kanak, & Patode, 2017) and (Sivakumar & Ghosh, 2021) identify debris flows and rockfalls as significant geological hazards with strong geomorphological impacts, leading to severe socio-economic and environmental consequences. (Garcia-Rodriguez, Malpica, & Benito, 2008) demonstrated that landslides occur predominantly in mountainous terrains and often cause more damage than other natural disasters such as earthquakes, floods, and windstorms. As a result, landslides remain a major societal and environmental concern, particularly in developing countries where vulnerability is high. However, identifying triggering factors and understanding their environmental impacts remain significant scientific challenges. Previous studies (Moradi et al., 2012; Park et al., 2013; Zhang et al., 2016; Pande et al., 2017, 2021; Shu et al., 2021) have shown that several factors contribute to landslide occurrence, including geology (rock types, faults, and structural features), soil characteristics (type, depth, and geotechnical properties), orography (slope, aspect, curvature, and relief amplitude), hydrology (drainage density, groundwater flow, and proximity to rivers), geomorphology, land use (vegetation cover), and seismic activity. These factors interact in complex ways and are considered key drivers of slope instability. The prediction of mass movements and the use of landslide susceptibility maps have been widely demonstrated as effective tools for hazard assessment (Clerici et al., 2002; Szen & Doyuran, 2004; Zhu et al., 2014; Pande et al., 2017, 2021).

In the Cameroon Highlands Plateau (CHP), particularly along the Cameroon Volcanic Line (CVL), numerous landslides have been recorded (Table 1). Several studies have been conducted in different localities of the Western Cameroon region, including Dschang (Tchoua, 1984), Wabane, Kekem (Aboubakar et al., 2013), Santa (Guedjeo et al., 2017), Bamenda (Aboubakar et al., 2013; Guedjeo et al., 2017), Bafoussam (Aretouyap et al., 2021), and Santchou (Ndonbou et al., 2022). These studies concluded that the CVL is developed on a Precambrian to post-Cambrian basement composed of metamorphic and plutonic rocks, overlain by Phanerozoic volcanic formations forming high plateaus and collapse plains. The region is characterized by altitudes ranging from 800 m to 2700 m, dense human occupation, and a complex geomorphological setting consisting of irregular volcanic mountains, alternating hills and deep valleys, and steep slopes (often exceeding 30°) that are

intensively cultivated. Despite these previous works, there is still a lack of integrated approaches combining remote sensing, geotechnical investigations, and multicriteria analysis to comprehensively assess landslide susceptibility in this region. This gap constitutes the main motivation of the present study, especially given the increasing human pressure and the recurrent occurrence of landslides reported by the Civil Protection Directorate of Cameroon, which records annually numerous fatalities, homeless populations, and significant damage to infrastructure such as houses, schools, and hospitals (Déruelle et al., 2007; Fanyu et al., 2012).

Therefore, the main research problem addressed in this study is how to identify landslide-prone areas and produce a susceptibility map in a complex volcanic and tropical environment by integrating multiple conditioning factors. This leads to the following research questions: (i) What are the most influential factors controlling landslide occurrence in the study area? (ii) How can remote sensing, GIS, and geotechnical data be effectively combined to improve landslide susceptibility mapping? and (iii) To what extent does the Analytic Hierarchy Process (AHP) provide reliable results for landslide susceptibility assessment in the Cameroon Volcanic Line?

The general objective of this study is to assess and map landslide susceptibility in a portion of the Cameroon Volcanic Line using an integrated approach. Specifically, the study aims to: (1) identify and analyze the main factors controlling slope instability; (2) generate thematic maps using remote sensing and GIS techniques; and (3) apply a multicriteria analysis method AHP to produce a landslide susceptibility map.

The remainder of this paper is organized as follows: Section 1 presents the study area, including its geological, geomorphological, and environmental characteristics. Section 2 describes the materials and methods used, including data sources and the AHP approach. Section 3 presents the results and discussion, focusing on susceptibility mapping and interpretation. Finally, Section 4 concludes the study and provides recommendations for landslide risk management (Saaty, 1979, 1990, 2008, 1993a, 1993b, Guzzetti et al. 1999).

2. Materials and Methods

2.1 Study Area

2.1.1 Geological and Tectonic Setting

The study area is located along the Cameroon Volcanic Line (CVL), (See Fig. 1), one of the most prominent geological features in Central Africa. This approximately 1,600 km long alignment of volcanic massifs and plutonic complexes extends across the Pan-African fold belt and reaches the northwestern margin of the Congo Craton. The CVL is generally oriented N30°E and comprises volcanic formations ranging from the Cenozoic to the present day (Le Maréchal, 1976; Deruelle et al., 1991, 2007). The geological framework of the study area is characterized by considerable lithological heterogeneity resulting from the interaction between volcanic activity, tectonic deformation, and basement evolution. Volcanic formations, including basaltic, rhyolitic, and trachytic lava flows as well as pyroclastic deposits of Tertiary age, unconformably overlie a Pan-African granito-gneissic basement (Tchoua, 1974). The lithological assemblage consists of metamorphic rocks such as migmatites and anatexites, extensive basaltic formations represented by lava flows and volcanic ash deposits, localized acidic volcanic rocks, particularly within the Messongo massif northwest of Bagam, and unconsolidated alluvial deposits occupying valley bottoms and floodplains. Structurally, the area is affected by a dense fracture network oriented predominantly between N20° and N40°, partly concealed beneath volcanic formations. These discontinuities are associated with major regional tectonic structures, notably the Fouban Shear Zone, which represents one of the principal brittle deformation corridors in Central Africa. The influence of volcanism on landscape evolution remains evident, particularly within the Foubot–Bamendjin peneplain and the southern part of the study area, where thirteen volcanic vents have been identified. Most of these vents are associated with limited lava flows, whereas three exhibit a Vulcanian eruptive style characterized by significant ash emissions. The combined effects of lithological contrasts, tectonic discontinuities, and volcanic activity have played a major role in controlling the geomorphological evolution of the region and constitute important predisposing factors for slope instability.

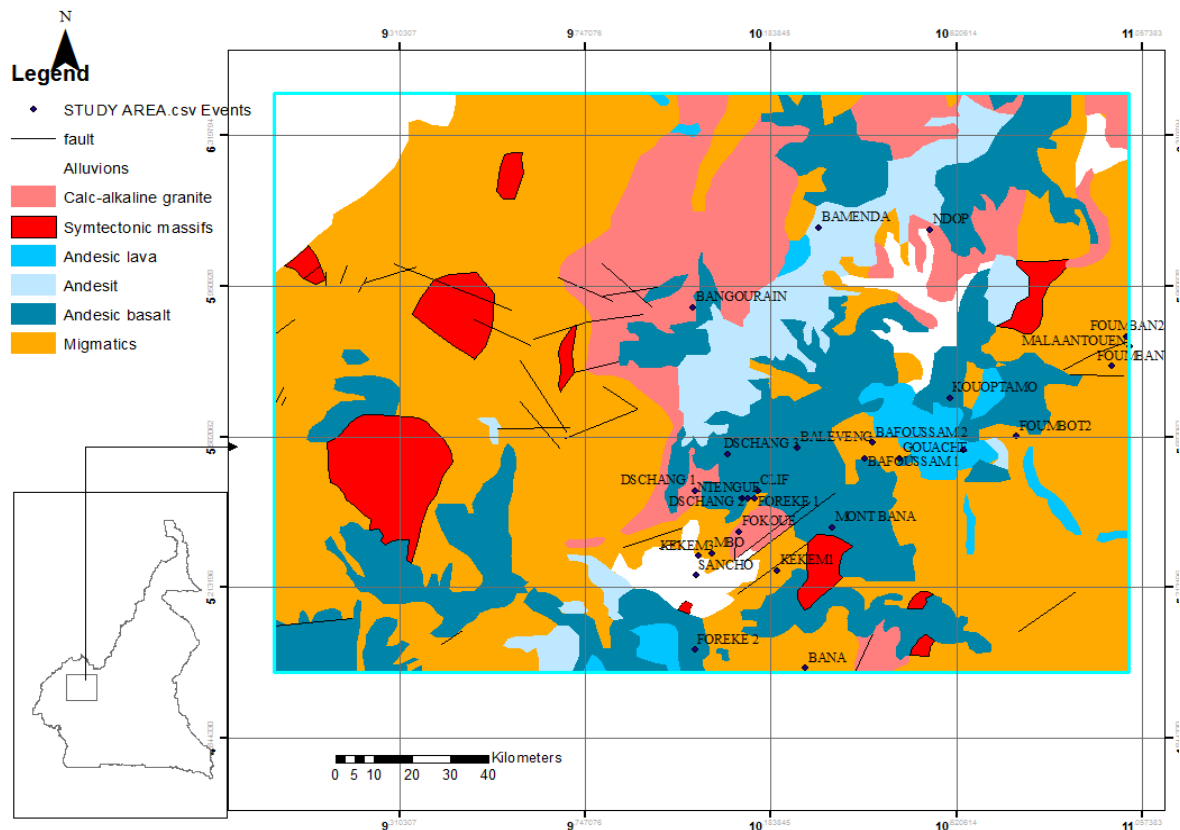


Fig. 1. Geological map of the study area

2.1.2 Topography and Hydrographic Network

The present-day topography reflects the combined influence of tectonic uplift, volcanic construction, and long-term erosional processes. Elevations generally range between 1,200 and 1,400 m above sea level, forming a volcanic plateau that terminates abruptly to the east through steep escarpments overlooking the Noun and Mifi-Sud valleys by approximately 100 to 200 m. In contrast, the northern and northwestern sectors display a more gradual topographic transition toward the Bamendjin–Foumbot peneplain, which is characterized by gently undulating relief and elevations generally below 1,200 m. The hydrographic network is deeply incised into both volcanic and basement formations and contributes significantly to landscape dissection. The entire study area belongs to the Noun River basin and is drained primarily by the Noun River and its main tributaries, the Mifi-Nord and Mifi-Sud rivers. The Noun River follows a predominantly north–south course before forming a broad westward concave loop near Foumbot and exhibits a torrential regime marked by numerous waterfalls developed on both resistant gneissic formations and basaltic lava flows. The Mifi-Nord River joins the Noun south of Batié and receives tributaries originating from the Bamendjin plateau and the western highlands, while the Mifi-Sud River originates south of Bafoussam and follows a broad arcuate course between the basaltic plateau and the Baleng–Bapi gneissic massif before joining the Noun northeast of Baleng. Several tributaries descend abruptly from elevated volcanic surfaces, forming waterfalls and deeply entrenched channels. This dense and locally steep drainage network promotes surface runoff concentration, channel incision, and toe erosion of slopes, thereby contributing to the development of landslide-prone conditions throughout the region.

2.1.3 Climate, Vegetation and Land Use

The climate of the study area is generally temperate and is controlled by several factors, including altitude, regional atmospheric circulation, geographic position, and distance from the Atlantic coast (Tsalefac, 1999). Rainfall constitutes one of the dominant environmental controls on slope processes. Average annual

precipitation is approximately 1,670 mm, with most rainfall occurring between April and October. September is the wettest month, receiving about 281 mm of rainfall on average, whereas a slight decrease in precipitation is observed during June, July, and August. In the neighboring high-altitude area of Dschang, annual rainfall reaches approximately 1,897 mm while maintaining a similar seasonal distribution. These climatic conditions favor intense weathering of volcanic materials and periodic saturation of surface soils, particularly during prolonged rainfall episodes. The natural vegetation cover has undergone significant modification as a result of agricultural expansion and increasing human pressure. Remnants of the original vegetation are mainly confined to wetlands and lowland areas where swamp forests persist. Elsewhere, the landscape is dominated by secondary vegetation consisting of wooded savannas, raphia palm groves, food crops, and scattered arabica coffee plantations. The progressive replacement of natural vegetation by agricultural land has locally reduced root reinforcement and soil protection against erosion, thereby increasing the susceptibility of slopes to degradation and mass movement processes. Consequently, the interaction between abundant rainfall, weathered volcanic materials, and land-use changes creates favorable conditions for landslide occurrence across the study area.

2.1.4 Historical Landslides

The combined effects of steep slopes, weathered volcanic materials, tectonic discontinuities, intense rainfall, and anthropogenic activities make the study area highly prone to landslides. Several events reported in recent decades have caused significant human and material losses. The landslide inventory summarized in Table 1 is used to characterize past failures and validate the susceptibility assessment developed in this study.

Table 1. Inventory of landslides in the study area (Aboubakar, 2013; ONACC, 2024)

No.	Location	Damage	Date	Reference
1	Fossong-Wentcheng (SW of Dschang)	6 deaths and destruction of plantations	08/1978	Tchoua (1984, 1989)
2	Fondonera (SW Dschang)	Destruction of plantations	2008	Aboubakar (2013)
3	Dschang cliff	12 deaths, road cut	05/11/2024	University of Dschang
4	Bafoussam, Gouaché	43 deaths	29/10/2019	Tangmouo Tsoata, F (2020)
5	Bana	Destruction of plantations	10/09/2002	Aboubakar (2013)
6	Bafou	2 deaths	2003	Zogning et al. (2007)
7	Kekem	1 death	20/10/2007	Aboubakar (2013)
8	Bamenda	Destruction of plantations and road	2009	Aboubakar (2013)
9	Chomba, Bamenda	3 deaths	27/09/2024	ONACC (2024)
10	Koutaba	2 deaths	23/10/2011	Aboubakar (2013)
11	Mbo and Ndop plains	Flooding and infrastructure damage	Seasonal (Aug–Oct)	Bandji (1994)

2.2 Materials

This study was based on the integration of remote sensing, topographic, climatic, geological, and geotechnical datasets. Remote sensing data consisted of Landsat-8 Operational Land Imager (OLI) imagery acquired in 2020, which provided multispectral information for environmental characterization and landslide-related analyses. Topographic information was derived from the Shuttle Radar Topography Mission (SRTM-1) Digital Elevation Model (DEM) with a spatial resolution of 30 m, obtained from the United States Geological Survey (USGS) Earth Explorer database.

Climatic data consisted of rainfall records covering the period 2000–2024. These data were obtained from radar-based precipitation datasets available through the International Research Institute for Climate and Society (IRI) Climate Data Library and complemented by observations collected by the Cameroon Meteorological Service in western Cameroon. Geological information was obtained from existing geological maps and supplemented by field observations conducted throughout the study area.

Field investigations were carried out to collect geotechnical data and ground-truth observations. The equipment used included a Garmin eTrex Vista GPS receiver with an accuracy of approximately 3 m for georeferencing field observations and a digital camera for site documentation. Geotechnical investigations involved heavy dynamic penetrometer tests (NF P 94-115), Menard pressuremeter tests (NF P 94-110), and undisturbed soil sampling using PVC tubes for laboratory analyses. These investigations provided the geotechnical parameters required for slope stability assessment. Spatial data processing and map production were carried out using ArcGIS 10.4, ENVI, ERDAS Imagine, Geomatica, Oasis Montaj v8.4, Surfer 16, and Adobe Illustrator CS6.

2.3 Method

Landslide susceptibility was assessed using the Analytic Hierarchy Process (AHP) developed by Saaty (1980). This multicriteria decision-making approach enables the integration of several conditioning factors to identify areas potentially prone to landslides without explicitly considering the temporal probability of occurrence (Dai et al., 2002). AHP has been widely applied in landslide susceptibility studies and can be combined with expert knowledge, statistical analyses, and landslide inventory data to evaluate the relative influence of conditioning factors. In the present study, the method was implemented within a GIS environment through the successive stages described below.

2.3.1 Determination of Conditioning Factors and Thematic Mapping

The first stage consisted of selecting the main factors controlling landslide occurrence based on field observations, historical landslide records, and the environmental characteristics of the study area. The selected factors were subsequently transformed into thematic layers for susceptibility analysis. The relative importance of these factors was evaluated using Saaty's pairwise comparison scale (Table 2).

Table 2. Saaty's pairwise comparison scale used for the weighting of landslide conditioning factors

Intensity	Definition	Description
1	Equal importance	Two criteria contribute equally to the objective
3	Moderate importance	One criterion is slightly more important than the other
5	Strong importance	One criterion is strongly more important than the other
7	Very strong importance	One criterion is strongly dominant and its importance is demonstrated in practice
9	Extreme importance	The dominance of one criterion over another is absolute
2, 4, 6, 8	Intermediate values	Used to express compromise between two adjacent judgments

2.3.2 Weight Determination (Weighting)

The pairwise comparison matrix was used to determine the weights assigned to the selected conditioning factors. The priority vector (V_p) was calculated from the geometric mean of each row of the matrix according to Equation (1):

$$V_p = (w_1 \times w_2 \times \dots \times w_k)^{\frac{1}{k}}, \quad (1)$$

where k is the number of criteria and w_i represents the comparison value assigned to each criterion. Furthermore, the resulting vector must be normalized so that the sum of its components equals unity. This normalization is achieved by dividing each element by the total sum of all elements, as expressed in Equation (2).

$$T = \left(\frac{V_{p1}}{\sum_k V_{pk}}, \dots, \frac{V_{pk}}{\sum_k V_{pk}} \right). \quad (2)$$

The consistency of the pairwise comparison matrix was evaluated using the Consistency Ratio (CR), which should not exceed 0.10 to ensure acceptable consistency of the judgments. The Consistency Ratio was calculated as:

$$CR = I_c/I_a \quad (3)$$

Where I_c is the consistency index and I_a is the random index. The consistency index was determined using:

$$I_c = \frac{\lambda_{max} - k}{k-1} \quad (4)$$

Where λ_{max} is the principal eigenvalue of the pairwise comparison matrix, computed as:

$$\lambda_{max} = \max(T/W). \quad (5)$$

where W is the normalized weight vector, found by summing the columns of the normalized pairwise comparison matrix. The values of I_a depend on the number of criteria considered and are presented in Table 3.

Table 3. Random Index (RI) values according to the number of criteria (Saaty, 1980)

N Number of criteria	2	3	4	5	6	7	8
I_a	0	0.58	0.9	1.12	1.24	1.32	1.41

2.3.3 Preparation of Thematic Layers

After determining the relative weights of the conditioning factors, thematic layers representing their spatial distribution were generated within a GIS environment. These layers were subsequently classified according to their contribution to landslide occurrence and used as inputs for the susceptibility assessment. Based on field observations, the landslide inventory, and the environmental characteristics of the study area, eight conditioning factors were considered: Rainfall, Soil characteristics (Safety factor, Clay index); Morphology (Slope, Elevation); Surface lineament density; Deep lineament density; Weathering thickness (roughness index); Drainage density; Vegetation cover.

2.3.3.1 Rainfall

This parameter was derived from rainfall data collected in the West Region, provided by the National Meteorological Directorate of the Ministry of Transport (2000–2024), as well as rainfall radar data available from the IRIDL database.

2.3.3.2 Geotechnical Safety Factor

Except for flood-related cases, most landslides in the study area were recorded on hillslopes characterized by significant heights and steep gradients.

This parameter, which plays a key role in slope stability, was estimated using the geotechnical safety factor based on the method proposed by Fellenius (1936). This method considers slope geometry, soil cohesion, unit weight, and internal friction angle.

Undisturbed soil samples were carefully collected using cylindrical plastic samplers (height = 25 cm; diameter = 18 cm). The samples were sealed with paraffin, properly labeled, and transported to the laboratory for geotechnical testing.

$$F = \frac{\sum Cl_i + (W_i \cos \alpha_i) \tan \phi}{\sum W_i \sin \alpha_i} \quad (6)$$

With: C : cohesion of soil; W : weight; α : slope angle; ϕ : friction angle; and l : length

2.3.3.3 Weathering Thickness

Weathering thickness is an important conditioning factor in landslide occurrence because it directly influences the mechanical behavior of slope materials. Most inventoried landslides in the study area occurred on hillslopes covered by thick weathered formations, where prolonged weathering processes have reduced soil strength and increased susceptibility to erosion and failure. Intense rainfall, combined with anthropogenic activities such as

deforestation, road construction, and agricultural practices, accelerates soil degradation, surface erosion, and slope undercutting, thereby promoting instability. Consequently, areas characterized by greater weathering thickness are generally more prone to landslide occurrence. In this study, weathering thickness was estimated by integrating the terrain roughness index with the geological formations of the study area.

2.3.3.4 Drainage Density

Surface water dynamics constitute a major triggering factor for landslides, particularly in volcanic environments where impermeable substrata limit infiltration and promote runoff concentration. Drainage density, defined as the total length of stream channels per unit watershed area, provides an indirect measure of the capacity of a landscape to concentrate surface flow. High drainage density generally reflects enhanced erosion processes and increased soil saturation potential, both of which contribute to slope instability. According to Gökçeoğlu and Aksoy (1996), rising groundwater levels and rock saturation significantly increase landslide susceptibility. The drainage network was extracted from SRTM-derived DEM data using the Hydrology tools available in ArcGIS 10.4. Subsequently, drainage density was computed using the Line Density function.

2.3.3.5 Structural Controls and Lineament Density

Geological structures constitute important conditioning factors in landslide occurrence because they influence rock fracturing, groundwater circulation, and mechanical discontinuities within slopes. The study area is located within an active volcanic environment characterized by numerous tectonic structures and fault systems that contribute to slope failures, rockfalls, and mass movements.

Surface lineaments were extracted from Landsat 8–9 imagery through image enhancement and directional filtering techniques implemented in ENVI and Geomatica software. Deep-seated structural discontinuities were identified from gravity data by calculating the maxima of the horizontal gradient of the residual gravity anomaly after regional-residual separation and upward continuation processing. The horizontal gradient magnitude (HGM) was computed using:

$$MHG(x, y) = \sqrt{\left(\frac{\partial g(x, y)}{\partial x}\right)^2 + \left(\frac{\partial g(x, y)}{\partial y}\right)^2} \quad (7)$$

where $g(x, y)$ represents the residual gravity anomaly. Surface lineament density was derived from Landsat 8–9 imagery processed using ENVI DL and Geomatica, followed by cartographic refinement in ArcGIS. Major fault systems were identified through the integration of surface and deep lineament datasets, providing a comprehensive representation of the structural framework of the study area.

2.3.3.6 Land cover and Vegetation Density

Vegetation plays a fundamental role in slope stabilization through root reinforcement, reduction of surface runoff, and protection against soil erosion. Consequently, areas characterized by dense vegetation generally exhibit lower landslide susceptibility than sparsely vegetated or bare surfaces. Land-cover mapping was performed using Landsat 8 OLI satellite imagery and a supervised classification approach based on the Maximum Likelihood algorithm. To quantify vegetation density and evaluate its influence on slope stability, the Normalized Difference Vegetation Index (NDVI) was calculated according to:

$$*NDVI = \frac{I_R - R}{I_R + R} \quad (8)$$

Where

- NDVI is the normalized difference vegetation index;
- I_R is the Near infrared (NIR, band 5);
- R is the red (band 4).

The resulting NDVI map was used to characterize the spatial distribution of vegetation cover across the study area and to assess its contribution to landslide susceptibility.

2.3.3.7 Slope Gradient

Slope gradient is widely recognized as one of the most influential factors controlling landslide occurrence. Steeper slopes are generally associated with greater gravitational forces acting on soil and rock masses, thereby increasing the likelihood of failure. Numerous studies, including those of Dai et al. (2002), Yalcin (2008), and Feizizadeh and Blaschke (2013), have demonstrated the strong relationship between slope angle and landslide susceptibility.

In this study, the slope gradient map was derived from SRTM digital elevation data using the Slope function available within the Spatial Analyst extension of ArcGIS 10.4.

2.3.4 AHP-based Landslide Susceptibility Assessment

The landslide susceptibility assessment adopted in this study is based on the Analytic Hierarchy Process (AHP) developed by Saaty (1980). This multicriteria decision-making technique allows the relative importance of conditioning factors to be quantified through pairwise comparisons and weighted aggregation. The methodological framework consists of two main stages.

2.3.4.1 Selection and Mapping of Conditioning Factors

The first stage involves the identification, justification, and spatial representation of the principal factors influencing landslide occurrence. Thematic maps corresponding to each conditioning factor were generated and standardized for subsequent integration within the susceptibility assessment framework.

2.3.4.2 Landslide Susceptibility Index Calculation and Classification

The final susceptibility map was produced through the weighted combination of all thematic factors. Each factor was assigned a relative importance weight (W_j) derived from the AHP procedure, while each class within a factor was attributed a rating value (w_{ij}). The overall Landslide Susceptibility Index (LSI) was calculated using:

$$S = \sum_{j=1}^n W_j w_{ij} \quad (9)$$

With: W_j : the weight of parameter j , and w_{ij} : the weight of class i within parameter j , which can be expanded as (Equation 10):

$$S = 0.15\text{Rain} + 0.15\text{Soity} + 0.15\text{MORP} + 0.1\text{SLD} + 0.1\text{DLD} + 0.1\text{Weat} + 0.15\text{DrD} + 0.1\text{VC} \quad (10)$$

Where: Rain: Rainfall; Soity: Soil type; MORP: Morphology; SLD: Surface lineament density; DLD: Deep lineament density (tectonic activity); Weat: Weathering; DrD: Drainage density; VC: Vegetation cover.

The resulting susceptibility values were subsequently classified into different hazard levels ranging from very low to very high susceptibility, allowing the identification of areas most vulnerable to future landslide events.

3. Results and Discussion

3.1 Pairwise Comparison Matrix and Consistency Analysis

The results of the AHP analysis are presented in Tables 4 and 5. The pairwise comparison matrix (Table 4) yielded a consistency ratio of 0.085, indicating that the pairwise judgments satisfy the consistency requirements commonly adopted in AHP-based studies.

Table 4. Pairwise comparison matrix, factor weights, eigenvectors, and consistency ratio (CR)

Factors	Rain	Soity	MORP	SLD	DLD	Weat	DrD	VC	Weight	VP	CP
Rain	1.00	1.00	1.00	1.50	1.50	1.50	1.00	1.50	0.15	1.22	0.14
Soity	1.00	1.00	1.00	1.50	1.50	1.50	1.00	1.50	0.15	1.22	0.14
MORP	1.00	1.00	1.00	1.50	1.50	1.50	1.00	1.50	0.15	1.22	0.14
SLD	0.67	0.67	0.67	1.00	1.00	1.00	0.67	4.00	0.1	0.97	0.11
DLD	0.67	0.67	0.67	1.00	1.00	1.00	0.67	1.00	0.1	0.82	0.10
Weat	0.67	1.00	1.00	0.67	1.00	1.00	0.10	1.00	0.1	0.68	0.08
DrD	1.00	1.00	1.00	1.50	1.50	10.00	1.00	1.50	0.15	1.55	0.18
VC	0.67	0.67	0.67	1.00	1.00	1.00	0.67	1.00	0.1	0.82	0.10
Rc	0.085										

Table 5 presents the classification of the conditioning factors and the corresponding class rankings used in the susceptibility assessment. The consistency ratios obtained for the individual factors range from 0.001 to 0.021, remaining below the recommended threshold value. These results indicate satisfactory consistency in the ranking of the different classes within each conditioning factor. The resulting weights and class rankings were subsequently integrated into the computation of the Landslide Susceptibility Index and the generation of the susceptibility map.

Table 5. Pairwise comparison matrix, principal eigenvectors, and consistency ratio

Factors		Classes	Weights	Performance scores	Vp	Cp	Rc
Rainfall (mm/year)		Rain $\geq$ 250	0.1	Susceptibile	0.55	0.10	0.013
		200 $\leq$ Rain $\leq$ 250	0.150	Susceptibile	0.82	0.15	
		150 $\leq$ Rain $\leq$ 200	0.30	Susceptibile	1.64	0.29	
		100 $\leq$ Rain $\leq$ 150	0.30	Moderate	1.89	0.34	
		100 $\geq$ Rain	0.15	Low	0.72	0.13	
Soil characteristics	Safety factor	FS $\geq$ 3	0.150	Highly Susc.	0.77	0.15	0.021
		1.5 $\leq$ FS $\leq$ 3	0.20	Highly Susc.	1.03	0.20	
		1 $\leq$ FS $\leq$ 1.5	0.25	Susceptibile	1.28	0.24	
		0.5 $\leq$ FS $\leq$ 1	0.25	Moderate	1.53	0.29	
		$\leq$ FS $\leq$ 0.5	0.15	Low	0.65	0.12	
	Clay index	1.37 – 1.94	0.3		1.77	0.3	0.002
		1.28 – 1.37	0.25	Susceptibile	1.47	0.25	
		1.16 – 1.28	0.25	Susceptibile	1.47	0.25	
		0.89 – 1.16	0.15	Moderate	0.94	0.16	
		0.285 – 0.89	0.05	Low	0.28	0.3	
Soil morphology	Slope	Slope $\geq$ 40	0.2	Highly Susc.	1.48	0.2	0.018
		30 $\leq$ Slope $\leq$ 40	0.2	Highly Susc.	1.26	0.17	
		20 $\leq$ Slope $\leq$ 30	0.30	Susceptibile	2.62	0.35	
		15 $\leq$ Slope $\leq$ 20	0.20	Susceptibile	1.48	0.20	
		10 $\leq$ Slope $\leq$ 15	0.05	Moderate	0.37	0.05	
		Slope $\leq$ 10	0.05	Low	0.37	0.05	
	Level curve (Elevation)	El $\geq$ 1883	0.20	Susceptibile	1.05	0.20	0.006
		1412 $\leq$ El $\leq$ 1883	0.2	Susceptibile	1.05	0.20	
		941 $\leq$ El $\leq$ 1412	0.25	Moderate	1.31	0.25	
		470 $\leq$ El $\leq$ 941	0.25	Moderate	1.44	0.27	
		El $\leq$ 470	0.1	Low	0.48	0.09	
Fracturing (lineament density, km/km ²)		Lin.sup $\geq$ 3.83	0.3	Susceptibile	2.25	0.30	
		3.16 $\leq$ Lin.sup $\leq$ 3.83	0.25	Susceptibile	1.87	0.25	

Factors	Classes	Weights	Performance scores	Vp	Cp	Re
	$2.59 \leq \text{Lin.sup} \leq 3.16$	0.2	Moderate	1.50	0.20	0.001
	$2.09 \leq \text{Lin.sup} \leq 2.59$	0.15	Low	1.18	0.16	
	$1.625 \leq \text{Lin.sup} \leq 2.099$	0.05	Very low	0.36	0.05	
	$\text{Lin.sup} \leq 1.625$	0.05	Very low	0.37	0.05	
Tectonic activity (Deep lineament density, km/km ²)	$\text{Lin.if} \geq 0.1219$	0.3	Susceptible	2.25	0.30	0.001
	$0.106 \leq \text{Lin.if} \leq 0.1219$	0.25	Susceptible	0.87	0.25	
	$0.091 \leq \text{Lin.if} \leq 0.106$	0.20	Moderate	1.50	0.20	
	$0.0457 \leq \text{Lin.if} \leq 0.091$	0.15	Low	1.18	0.16	
	$0.015 \leq \text{Lin.if} \leq 0.0457$	0.05	Very low	0.36	0.05	
	$\text{Lin.inf} \leq 0.015$	0.05	Very low	0.37	0.05	
Weathering (Roughness index)	$(-0.29) - 0$	0.2	Highly susc.	1.05	0.20	0.01
	$(-0.4) - (-0.4)$	0.25	Susceptible	1.31	0.25	
	$(-0.48) - (-0.4)$	0.25	Low	1.31	0.25	
	$(-0.5) - (-0.48)$	0.20	Low	1.21	0.23	
	$(-0.998) - (-0.5)$	0.1	Very low	0.46	0.09	
Drainage (Drainage density, km/km ²)	$\text{Dens} \geq 1105$	0.002	Very low	0.18	0.02	0.018
	$416 \leq \text{Dens} \leq 1105$	0.030	Very low	0.28	0.03	
	$138 \leq \text{Dens} \leq 416$	0.30	Very high	2.77	0.29	
	$70 \leq \text{Dens} \leq 138$	0.30	Very high	3.26	0.35	
	$27 \leq \text{Dens} \leq 70$	0.20	High	1.57	0.17	
	$\text{Dens} \leq 27$	0.15	Moderate	1.38	0.15	
VC (Vegetation cover)	Dense vegetation	0.15	Very low	0.92	0.15	0.002
	Shrubland	0.25	Low	1.54	0.25	
	Bare soil	0.40	Highly susc.	2.47	0.40	
	Water bodies	0.15	Very low	0.98	0.16	
	Cropland	0.05	Low	0.29	0.05	

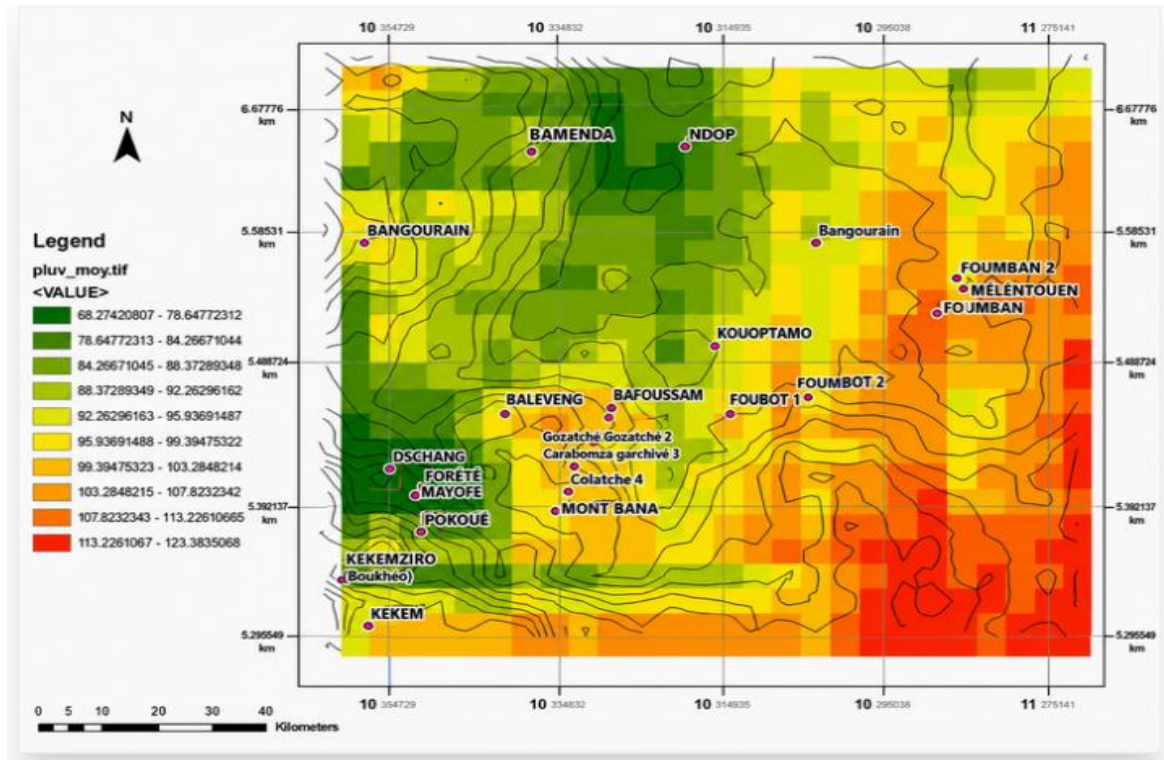
3.2 Thematic Maps of Landslide Susceptibility Factors

3.2.1 Rainfall

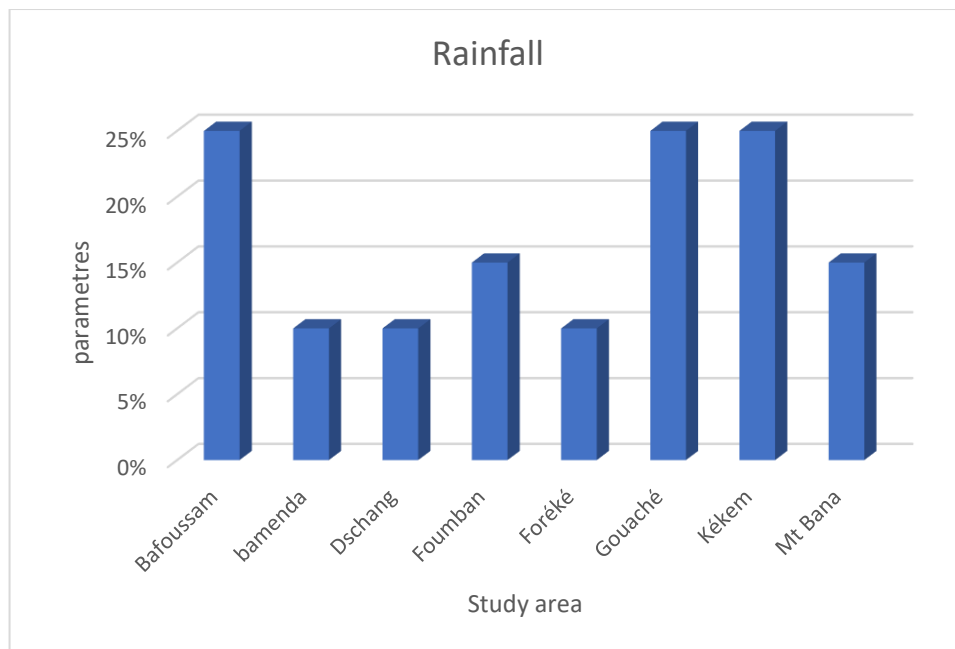
Rainfall is one of the main triggering factors of landslides in the study area. As shown in Fig. 2, rainfall distribution exhibits significant spatial variability during the September–November period, corresponding to the season when most recorded landslides occur. Average rainfall ranges from 68 to 123 mm, whereas October, the wettest month, records precipitation values between 152 and 316 mm. The areas receiving the highest rainfall generally coincide with sectors identified as highly susceptible to landslides. Intense precipitation promotes infiltration, groundwater recharge, and soil saturation, leading to a reduction in shear strength and the development of potential slip surfaces within weathered materials. These observations are consistent with previous studies conducted along the Cameroon Volcanic Line (El Fanchou et al., 2015; Moradi et al., 2012; Aboubakar et al., 2013; Aretouyap et al., 2021).

3.2.2 Clay Index

The clay index map (Fig. 3) highlights the spatial distribution of clay-rich materials within the study area. Clayey soils play an important role in landslide development because their mechanical behavior is strongly influenced by water content. Infiltration processes modify the physicochemical properties of clay minerals, reducing soil strength and increasing susceptibility to deformation. Repeated wetting–drying cycles induce shrinkage and swelling phenomena, which favor cracking, loss of cohesion, and progressive slope weakening. Consequently, areas characterized by high clay-index values are more vulnerable to slope instability, particularly under prolonged rainfall conditions. The predominance of weathered clay-rich formations therefore constitutes a significant predisposing factor for landslide occurrence.



(a)



(b)

Fig. 2. Spatial distribution of rainfall in the study area: (A) average rainfall; (B) average rainfall distribution across the investigated localities

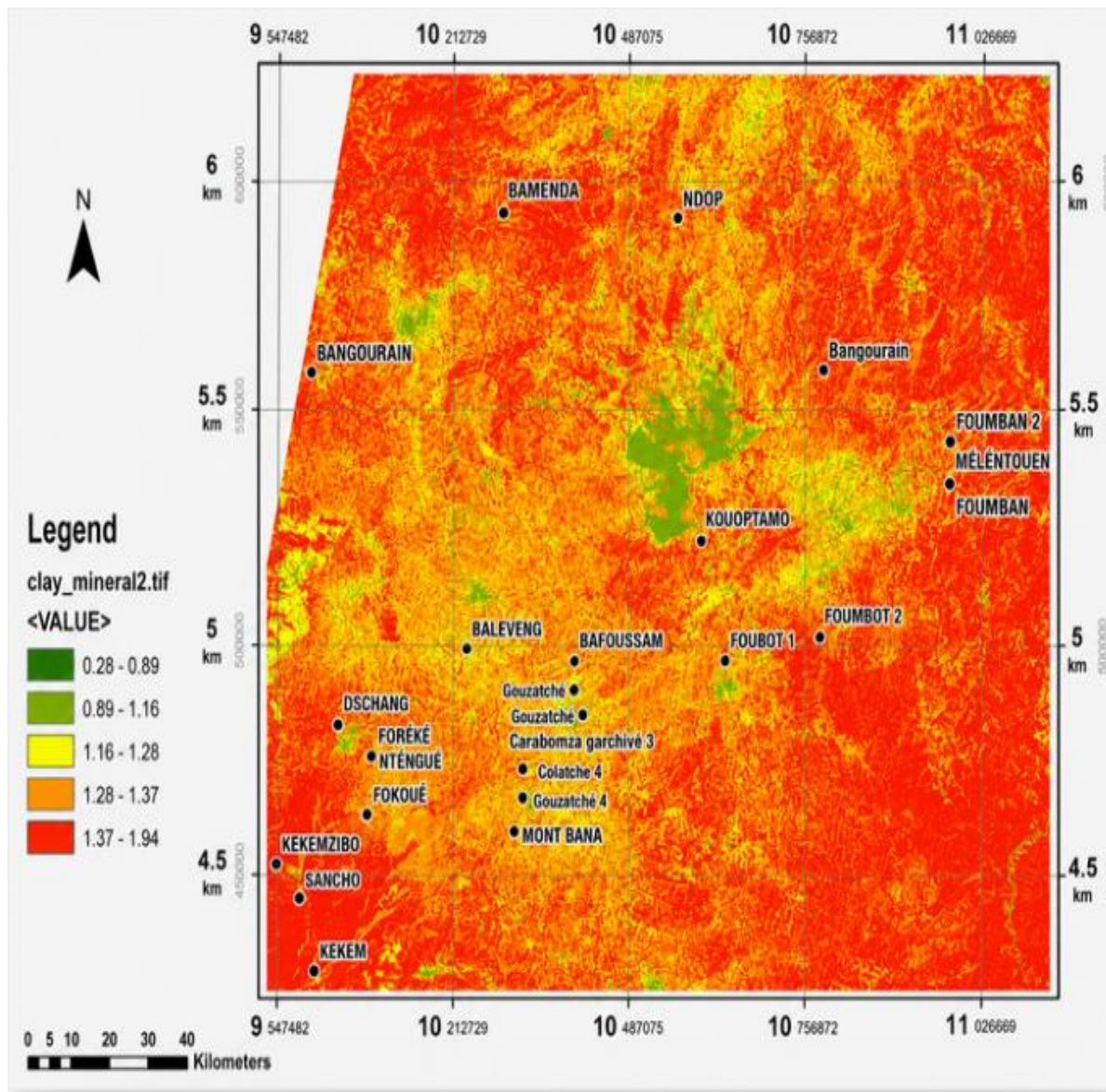


Fig. 3. Spatial distribution of the clay index in the study area

3.2.3 Elevation Map

The elevation map (Fig. 4) shows the topographic variability of the study area. Elevations above 1883 m represent approximately 20% of the area, while the ranges 1412–1883 m and 941–1412 m account for 20% and 25%, respectively. Areas below 941 m cover nearly 35% of the region. The distribution of documented landslides indicates that approximately 65% of the affected zones occur within the intermediate and low-elevation classes. Elevation indirectly influences slope instability by controlling surface runoff concentration, weathering intensity, and hydrological conditions. Similar observations have been reported by Nohani et al. (2019) and Shirzadi et al. (2018), who identified elevation as an important conditioning factor in landslide susceptibility assessment.

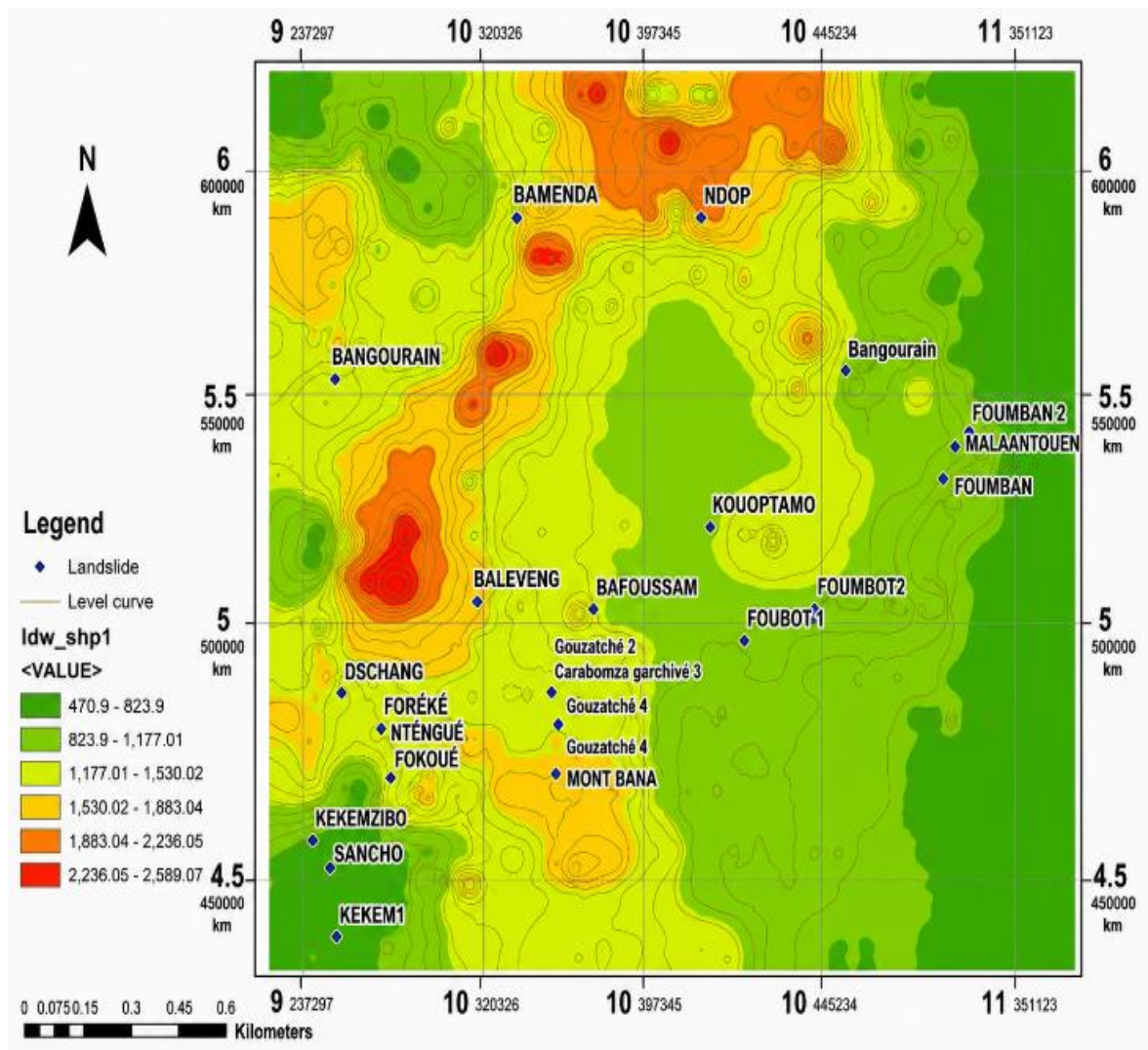


Fig. 4. Elevation (contour) map of the study area

3.2.4 Slope Gradient

Slope gradient is one of the most influential factors controlling landslide occurrence because it directly affects the balance between gravitational driving forces and the resisting forces of slope materials. As illustrated in Fig. 5, the study area is characterized by three main slope classes. Gentle slopes ($\leq 15^\circ$) occupy approximately 10% of the area and are mainly distributed along river valleys and low-relief zones. Moderate to steep slopes ($15\text{--}30^\circ$) cover about 50% of the study area and correspond to sectors where numerous landslides have previously been reported. Very steep slopes ($\geq 40^\circ$) account for nearly 40% of the area and constitute the most landslide-prone zones. These steep terrains favor rapid runoff, increased erosion, and the accumulation of pore-water pressure during intense rainfall events, resulting in reduced soil shear strength and enhanced slope instability. This observation agrees with the findings of Sivakumar and Ghosh (2021), who identified slope angle as a major conditioning factor in landslide susceptibility assessments.

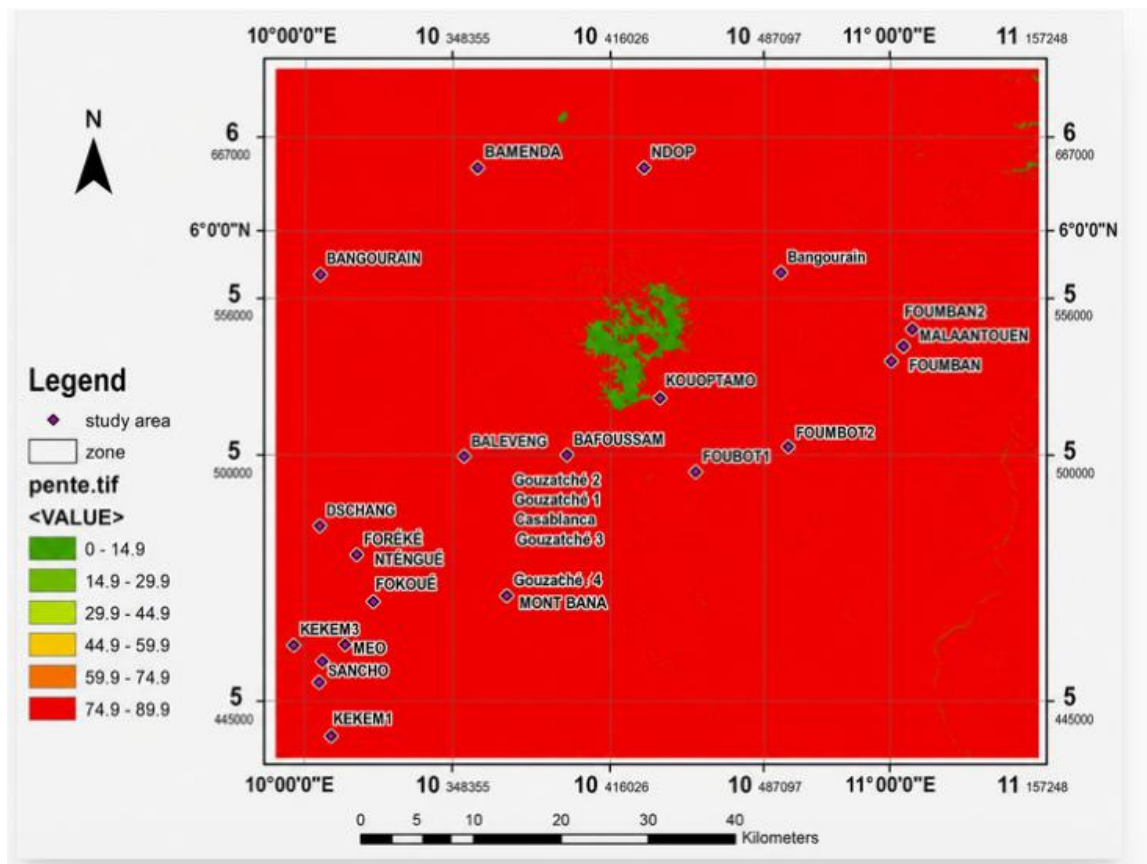


Fig. 5. Slope gradient map of the study area

3.2.5 Surface Lineament Density

Surface lineaments represent geological discontinuities such as fractures and faults that influence groundwater circulation and the mechanical behavior of slope materials. The surface lineament density map (Fig. 6) reveals a dominant NE–SW orientation, approximately 45°, reflecting the regional tectonic framework. Very high lineament densities (3833–5390 km/km²) occupy about 20% of the study area, while high densities (3163–3833 km/km²) account for another 20%. Moderate densities (2098–3163 km/km²) cover approximately 40% of the area and correspond to zones where landslides are most frequently reported. In contrast, low-density areas (364–2098 km/km²) represent about 20% of the study area. High fracture densities facilitate water infiltration, accelerate weathering processes, and reduce rock mass strength, thereby increasing susceptibility to slope failure. Furthermore, the rose diagram highlights a preferential structural orientation that reflects the influence of regional tectonic stresses, in agreement with the observations of Ngapna et al. (2023) and Ntomba et al. (2020).

3.2.6 Deep Lineament Density

Deep lineaments reflect major tectonic discontinuities that influence rock mass fracturing, groundwater circulation, and the overall stability of slopes. As shown in Fig. 7, the deep lineament network exhibits a dominant NE–SW orientation, approximately 45°, consistent with the regional tectonic framework of the Cameroon Volcanic Line. Very high lineament densities (≥ 0.1219 km/km²) cover about 30% of the study area, while high densities (0.106–0.1219 km/km²) account for 25%. Moderate densities (0.0457–0.106 km/km²) occupy approximately 35% of the area and coincide with sectors where landslides are most frequently reported. In contrast, low-density zones (≤ 0.0457 km/km²) represent only 10% of the study area. The concentration of deep structural discontinuities promotes water infiltration and weathering processes while reducing the mechanical integrity of geological formations, thereby increasing slope susceptibility to failure. Consequently, deep tectonic structures constitute an important predisposing factor for landslide occurrence in the region.

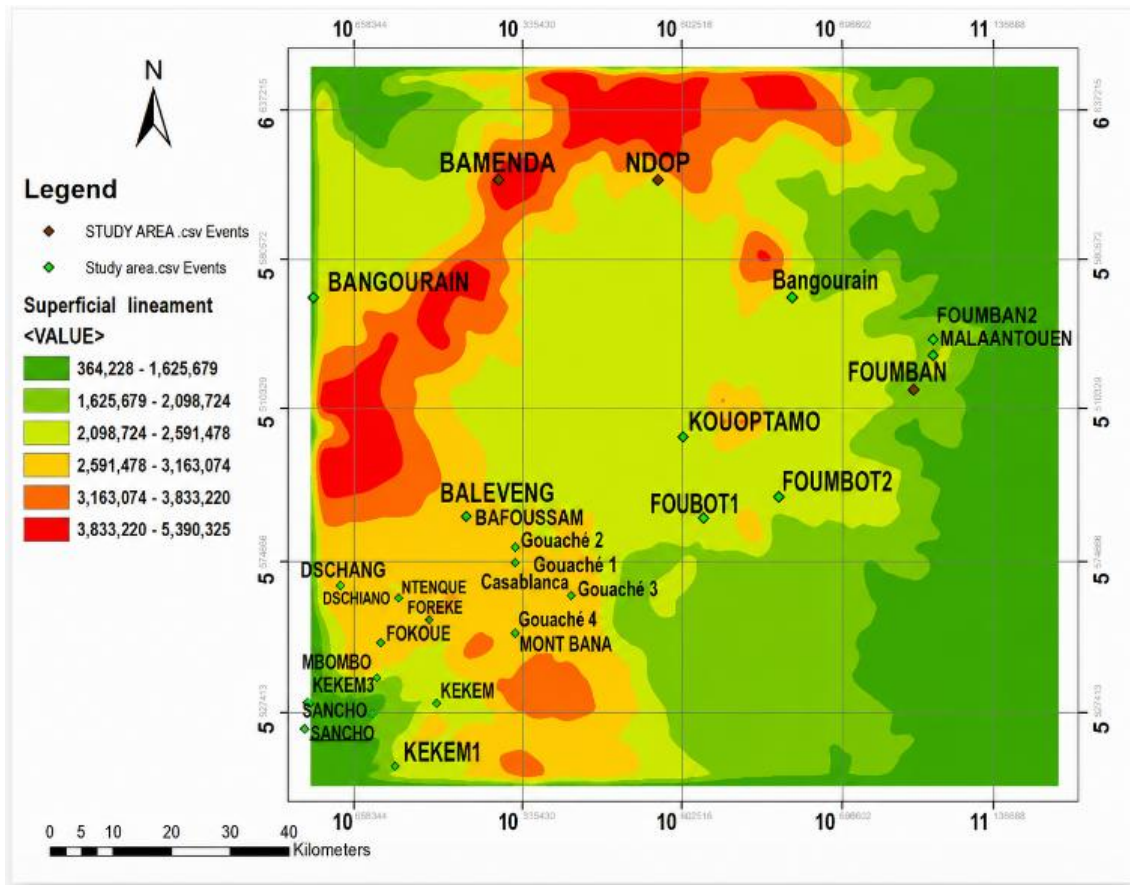


Fig. 6. Surface lineament density map and associated rose diagram showing the dominant structural orientations in the study area

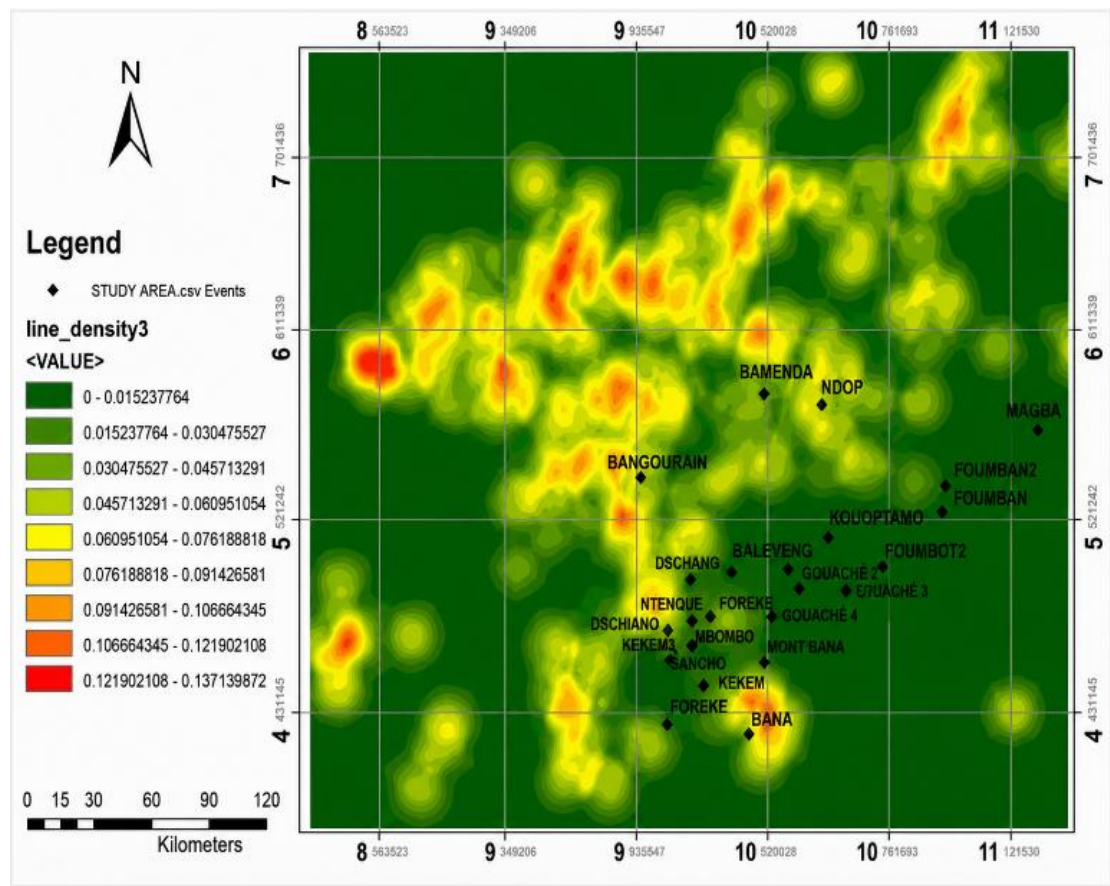


Fig. 7. Deep lineament density map at a depth of 1 km, highlighting the main tectonic discontinuities of the study area

3.2.7 Roughness Index

Terrain roughness is an indirect indicator of weathering intensity and geomorphological variability. The roughness index map (Fig. 8) reveals significant spatial variations across the study area, reflecting differences in surface morphology and the degree of rock alteration. Areas characterized by low roughness values generally correspond to highly weathered materials, where prolonged chemical alteration has transformed primary minerals into clay-rich products. Processes such as hydrolysis of feldspars and hydration of susceptible minerals contribute to the progressive weakening of rock masses and the development of thick weathered profiles. These altered materials exhibit reduced mechanical strength and increased sensitivity to water infiltration, making them more vulnerable to erosion and slope failure. Consequently, zones displaying low roughness and advanced weathering conditions are considered more susceptible to landslides than areas underlain by fresh and resistant rock formations.

3.2.8 Drainage Density

Drainage density is an important conditioning factor in landslide occurrence because it controls the concentration of surface runoff and the intensity of erosion processes. As shown in Fig. 9, three drainage-density classes were identified in the study area. Low drainage density (≤ 70 km/km²) covers approximately 35% of the area and is mainly concentrated along the Mifi River. Moderate drainage density (70–416 km/km²) represents about 60% of the study area and corresponds to zones where streams and runoff channels are most densely developed. These areas are frequently associated with landslide occurrences because concentrated runoff promotes soil saturation, slope undercutting, and gully erosion. High drainage density (≥ 416 km/km²) occupies only 5% of the study area and occurs locally. Overall, the results indicate that areas characterized by moderate to high drainage densities are more susceptible to slope instability due to the combined effects of runoff concentration, erosion, and increased pore-water pressure during intense rainfall events.

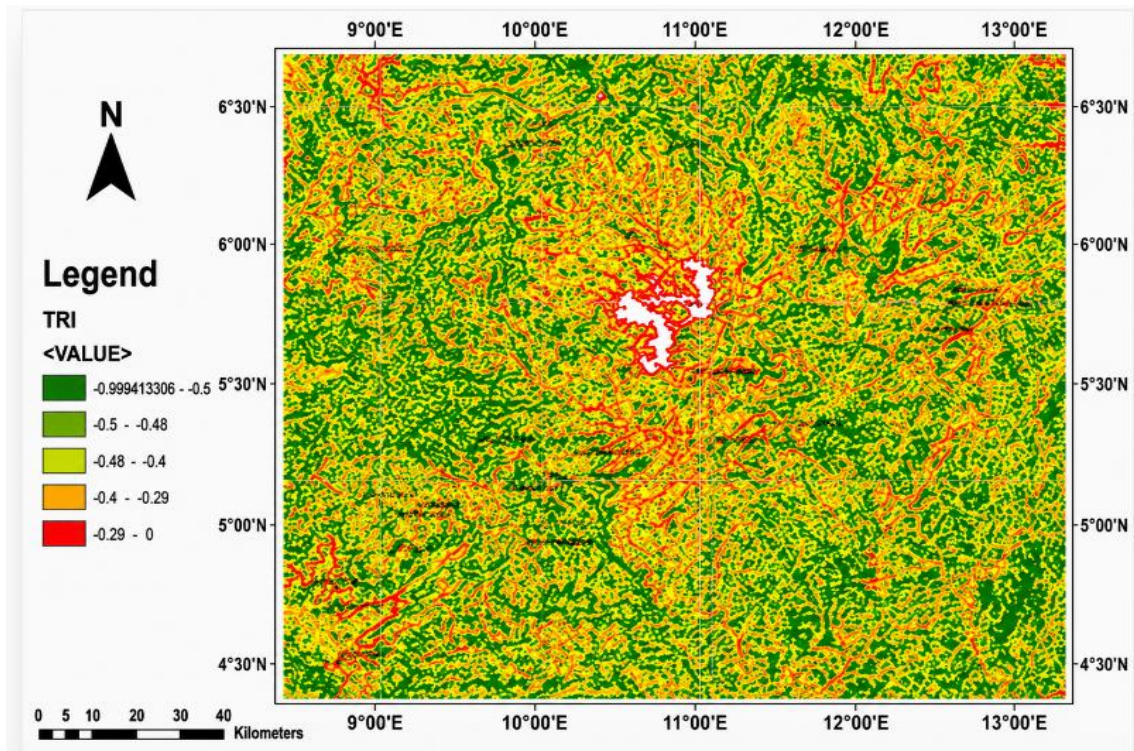


Fig. 8. Relative roughness index map showing the spatial distribution of weathering intensity and terrain irregularity within the study area

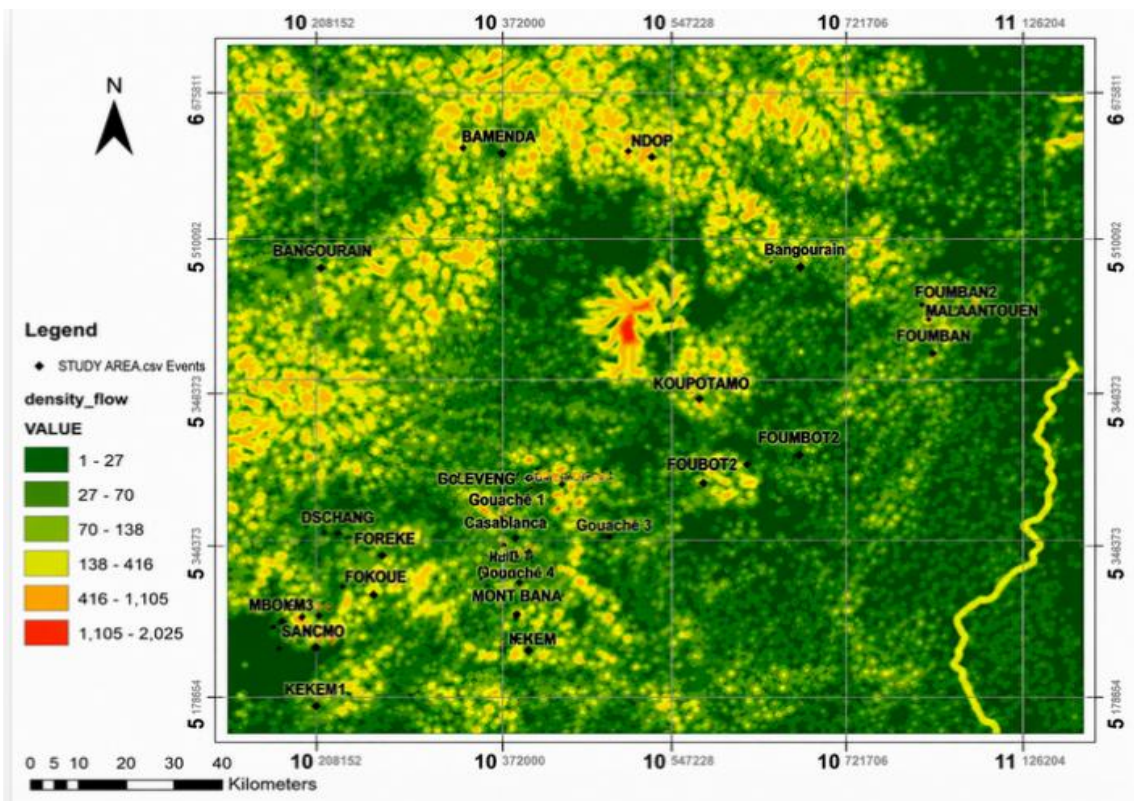


Fig. 9. Drainage density map of the study area showing the spatial distribution of surface runoff concentration zones

3.2.9 Vegetation Cover (VC)

Vegetation cover plays a crucial role in slope stabilization by reducing surface runoff, limiting soil erosion, and reinforcing soil structure through root systems. The vegetation cover map (Fig. 10) was derived from the Normalized Difference Vegetation Index (NDVI), with values ranging from 0.134 to 0.625. Low NDVI values (≤ 0.249), corresponding mainly to water bodies and cultivated lands, represent approximately 20% of the study area. Areas covered by shrubs and dense vegetation, characterized by NDVI values ≥ 0.325 , account for about 40% of the area and generally exhibit lower susceptibility to landslides. Bare or sparsely vegetated surfaces, with intermediate NDVI values between 0.29 and 0.325, also represent nearly 40% of the study area and coincide with sectors identified as landslide-prone in previous studies. The degradation of vegetation cover resulting from agricultural expansion, urbanization, and other human activities reduces soil protection against erosion and enhances vulnerability to intense rainfall. Consequently, poorly vegetated areas are more exposed to runoff, soil saturation, and slope failure, confirming the important role of vegetation cover in landslide susceptibility within the study area (Che et al., 2011; Zogning et al., 2007).

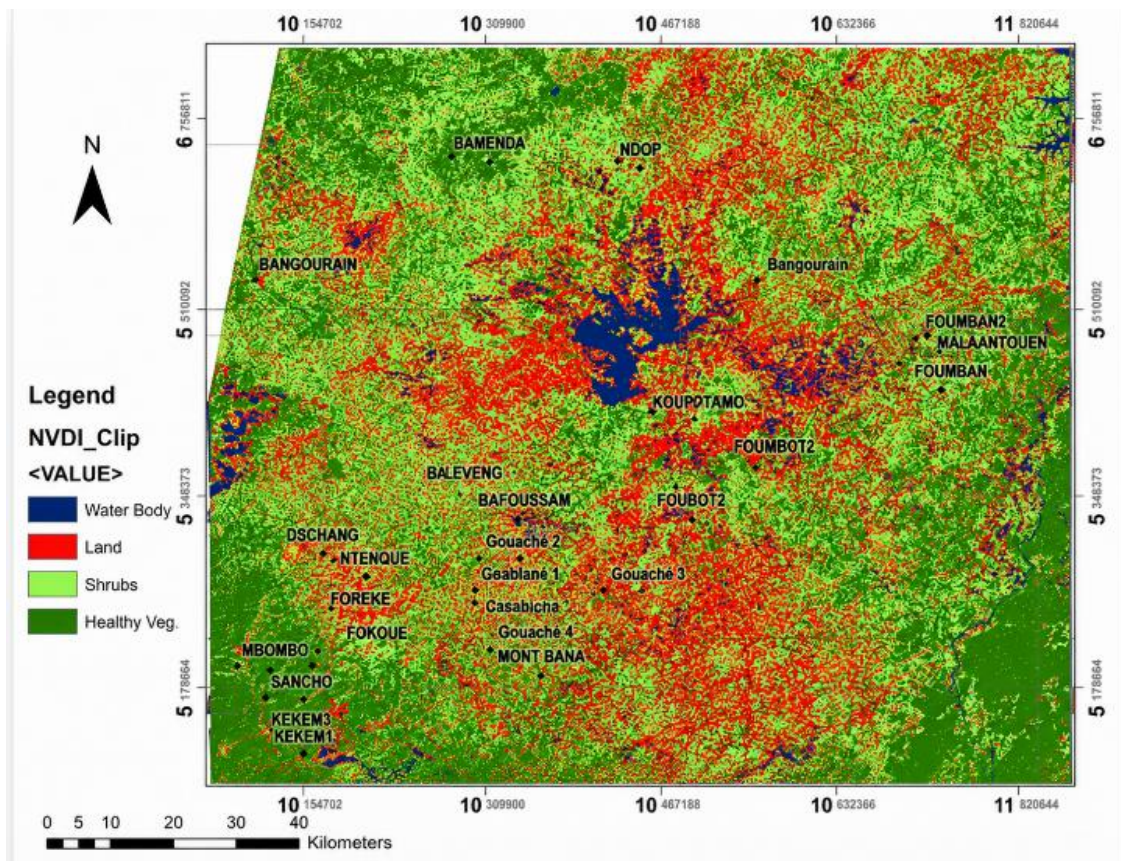


Fig. 10. Vegetation cover (NDVI) map illustrating the spatial distribution of vegetation density and land-cover conditions in the study area

3.3 Geotechnical Investigation

3.3.1 Pressuremeter and Dynamic Cone Penetration Tests

The geotechnical investigations conducted at representative locations within the study area provide valuable information on the subsurface conditions controlling slope stability. Borehole logs and in-situ tests reveal relatively shallow refusal depths, approximately 7.0 m and 7.2 m, indicating a limited thickness of unconsolidated materials overlying the bedrock. Both profiles are characterized by a superficial clay-rich horizon and the presence of a groundwater table encountered at an average depth of about 1.4 m. Dynamic penetration results show a progressive increase in soil resistance with depth, reaching values close to 1 MPa at

approximately 5 m depth. The shallow groundwater level, combined with the predominance of clayey materials, creates favorable conditions for water retention and pore-pressure development during intense rainfall events, thereby increasing slope instability.

The lithological succession observed at the Gouaché site further confirms the predominance of weathered clay-rich formations overlying more competent materials at depth (Fig. 11). These weathered horizons exhibit high moisture retention capacity and reduced mechanical strength, making them particularly sensitive to saturation and deformation. The alternation of clayey, silty, gravelly, and lateritic layers reflects the heterogeneous nature of the subsurface and strongly influences groundwater circulation and slope behavior.

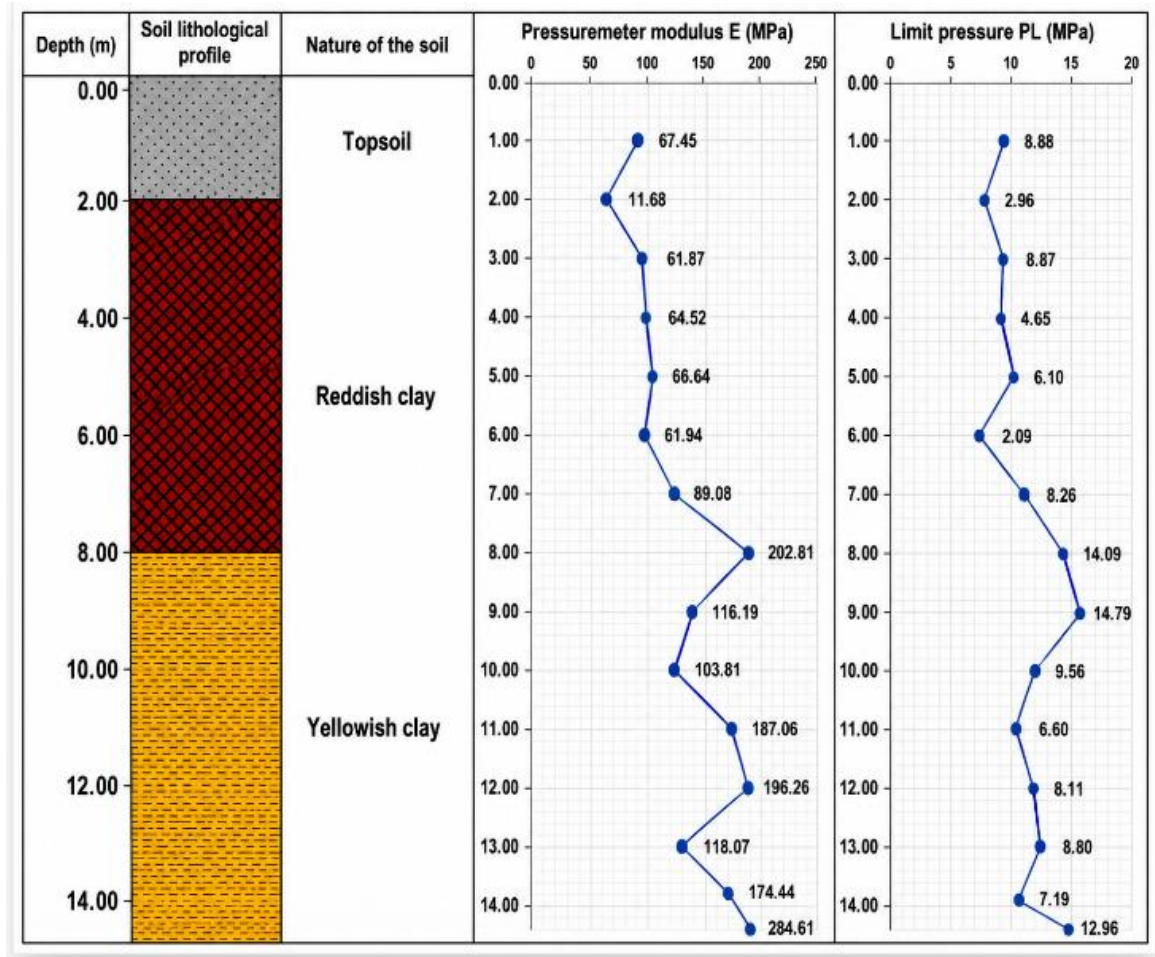


Fig. 11. Lithological profile of the Gouaché landslide site

The dynamic cone penetration profiles (Fig. 12) reveal significant vertical variations in penetration resistance associated with changes in lithology. Low-resistance zones generally correspond to highly weathered silty and clayey materials, whereas higher resistance values are associated with compact lateritic horizons and competent substrata. Several profiles indicate the presence of expansive clay layers, including montmorillonitic clays, which are characterized by high water absorption capacity, swelling potential, and reduced stability under saturated conditions. Refusal depths recorded between approximately 7 and 9 m indicate the occurrence of a relatively competent geological substratum beneath the weathered cover. These results highlight the important role of clay-rich weathered materials in controlling slope instability within the study area.

3.3.2 Soil Shear Strength Parameters

The mechanical properties of the soils were assessed through direct shear tests performed on representative samples collected throughout the study area. According to the Mohr–Coulomb failure criterion, soil shear

strength is governed by cohesion (c) and the internal friction angle (ϕ), which together control the resistance of the material to failure under loading conditions. The results presented in Table 6 indicate relatively homogeneous mechanical behavior, although three distinct geotechnical groups can be identified. Group I corresponds to low-strength plastic clays characterized by cohesion values of approximately 12 kPa, friction angles around 14° , and maximum shear stresses ranging from 42 to 45 kPa. Group II includes soils of intermediate strength, generally composed of compact clayey materials, with cohesion values close to 22 kPa, friction angles of about 20° , and maximum shear stresses between 59 and 64 kPa. Group III exhibits the highest shear resistance and is mainly composed of clay-sand mixtures and lateritic materials, characterized by cohesion values around 30 kPa, friction angles of approximately 27° , and maximum shear stresses ranging from 65 to 73 kPa.

The predominance of Groups II and III suggests that most soils possess moderate to relatively high shear resistance under natural conditions. However, the abundance of clay-rich materials and the shallow groundwater table indicate that soil strength may decrease significantly under saturated conditions. This reduction in shear strength can favor slope failure during prolonged rainfall periods, particularly on steep slopes. Consequently, the geotechnical parameters obtained from laboratory testing constitute essential input data for the calculation of safety factors and the assessment of landslide susceptibility within the study area.

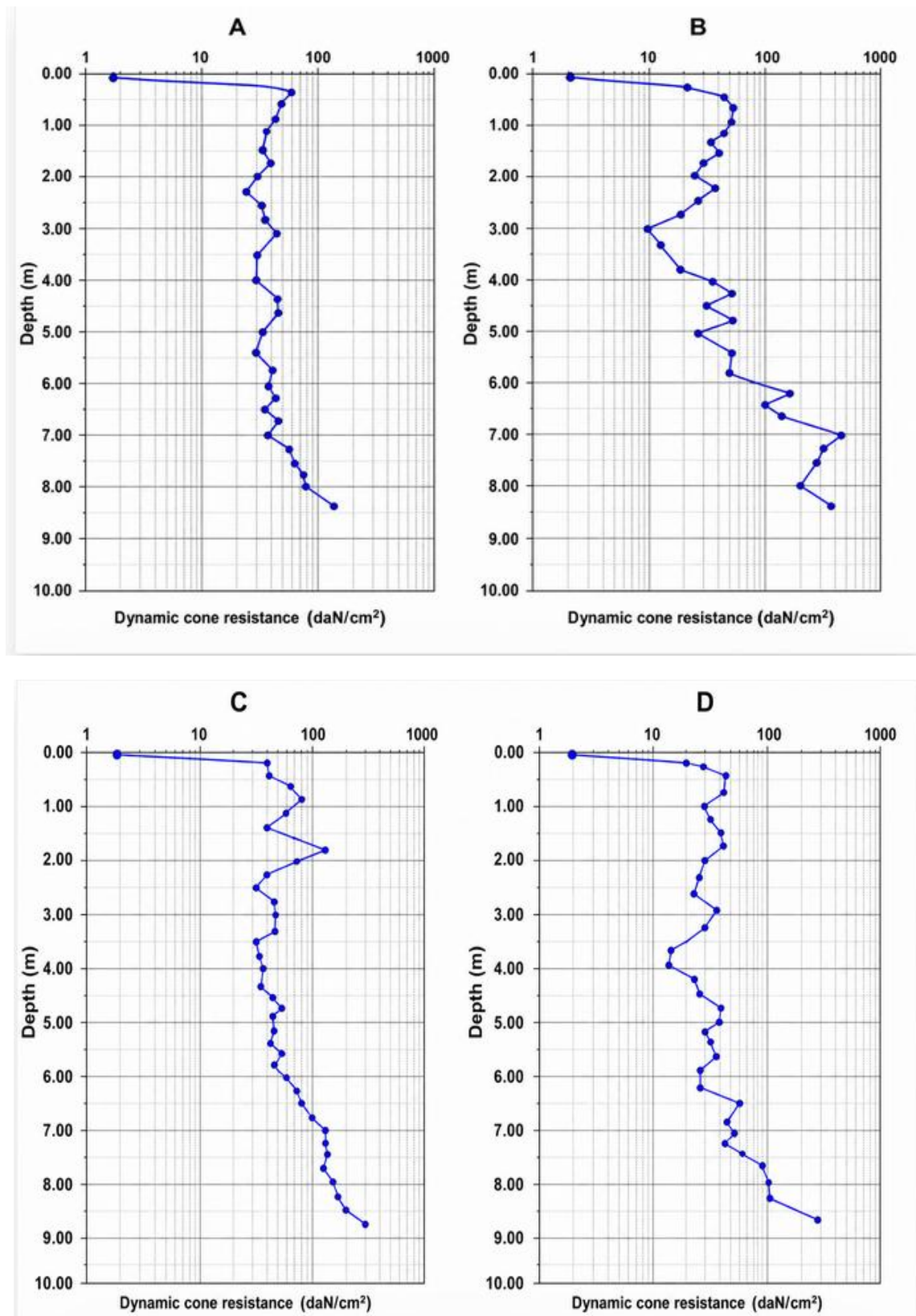
Table 6. Soil shear strength parameters obtained from direct shear tests, including cohesion (c), internal friction angle (ϕ), and maximum shear stress (τ_{max}) for the different geotechnical groups

Sample	Geotechnical group	Cohesion c (kPa)	Friction angle ϕ ($^\circ$)	Maximum shear stress, τ_{max} (kPa)
Test No. 1	III	30	27	67
Test No. 2	II	22	20	63
Test No. 3	III	30	27	67
Test No. 4	II	22	20	60
Test No. 5	III	30	27	73
Test No. 6	III	30	27	66
Test No. 7	I	12	14	42
Test No. 8	II	22	20	64
Test No. 9	III	30	27	66
Test No. 10	II	22	20	59
Test No. 11	I	12	14	44
Test No. 12	I	12	14	45
Test No. 13	III	30	27	68
Test No. 14	II	22	20	63
Test No. 15	II	22	20	64
Test No. 16	III	30	27	65
Test No. 17	II	22	20	61
Test No. 18	II	22	20	60
Test No. 19	II	22	20	62
Test No. 20	III	30	27	67

The dynamic cone penetration profiles presented in Fig. 12 reveal significant vertical and lateral variations in the geotechnical characteristics of the subsurface materials, and the interpretation is found through the Mohr-Coulomb failure curves as shown in Fig. 13. In profile A, a superficial crust extending from 0 to 1 m exhibits low penetration resistance due to limited rod friction. Between 1 and 2 m depth, resistance increases as a result of the presence of silty clay, a material characterized by high water-retention capacity and sensitivity to settlement. From 2 to 8.8 m, the profile is dominated by unweathered clay with high plasticity and moisture absorption capacity, making it particularly susceptible to swelling. Refusal occurs at 8.8 m upon reaching the bedrock substratum.

Profile B consists of topsoil overlying a succession of montmorillonitic and stiff clay layers. The increase in penetration resistance observed between 3 and 5 m reflects the presence of compact clay horizons with enhanced shear strength. Below this interval, another montmorillonitic clay layer is encountered, followed by

unweathered moraine clay extending to a depth of 7.8 m. These materials exhibit relatively high mechanical properties but remain sensitive to variations in moisture content.



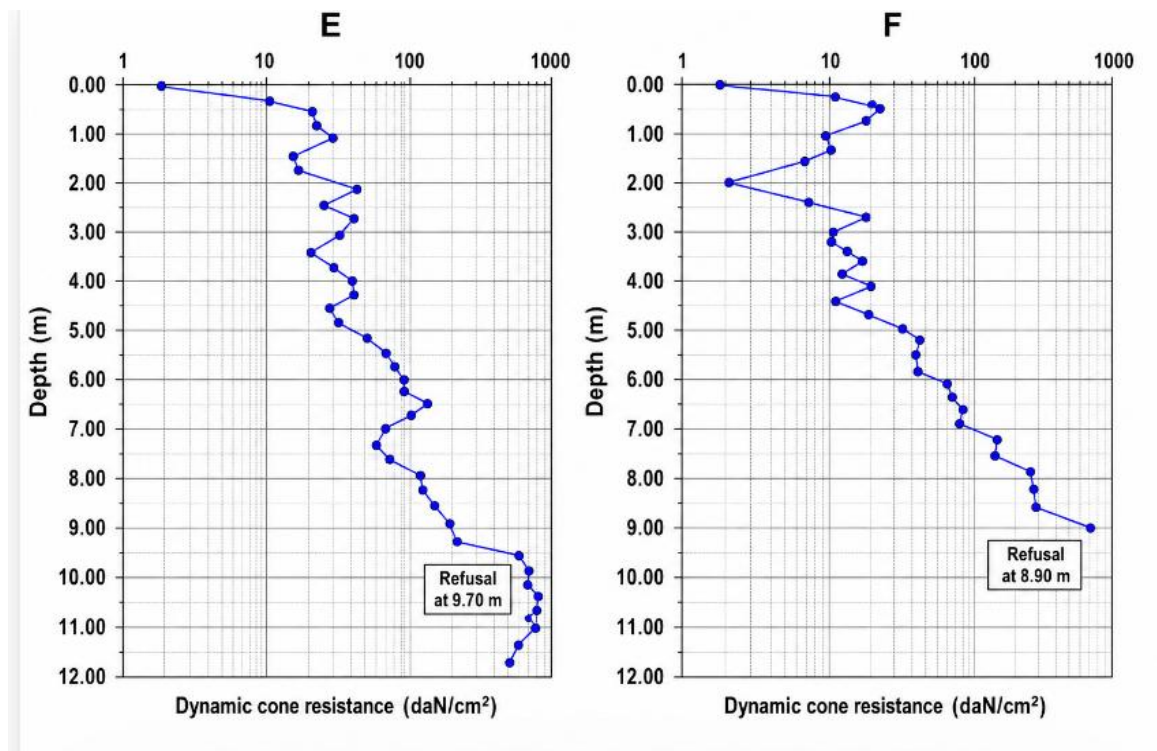


Fig. 12. Dynamic cone penetration profiles of the Gouaché site showing the variation of penetration resistance with depth and the corresponding geotechnical horizons

Profile C is characterized by silty gravels between 0.2 and 2.0 m depth, followed by silt and lateritic marls extending to approximately 9 m. The coarse-grained materials exhibit larger fluctuations in penetration resistance than fine-grained soils, highlighting the influence of particle size distribution on mechanical behavior. Although compact, these gravelly horizons may experience a reduction in bearing capacity under excessive moisture conditions.

In profile D, unweathered clay extends from 0.2 to 4.0 m beneath a thin surface crust. This clay layer is characterized by high plasticity, swelling potential, and strong water absorption capacity. It is underlain by sandy gravels and slightly clayey sandy silts exhibiting relatively good shear strength and favorable engineering properties. Lateritic gravels are encountered below 9 m depth, marking a transition toward more competent materials.

Profile E is dominated by weathered clay from the ground surface to approximately 5 m depth. This material exhibits a high moisture retention capacity resulting from intense physicochemical alteration processes. A groundwater table is encountered between 5 and 6.2 m depth, below which sandy gravelly silts are present until refusal. The occurrence of groundwater within highly weathered clayey formations constitutes a critical factor that may reduce soil strength and promote slope instability.

Finally, profile F comprises a thin weathered clay horizon overlying sandy gravelly silts, gravels, and fine sandy silts. The progressive increase in coarse-grained materials with depth results in improved mechanical resistance compared with the clay-dominated profiles. Overall, the penetration tests indicate a predominance of clay-rich weathered formations interbedded with gravelly and lateritic horizons. The widespread occurrence of expansive and moisture-sensitive clays, combined with shallow groundwater levels, provides favorable conditions for the development of landslides, particularly during periods of intense rainfall.

3.3.3 Geotechnical Safety Factor of the Study Area

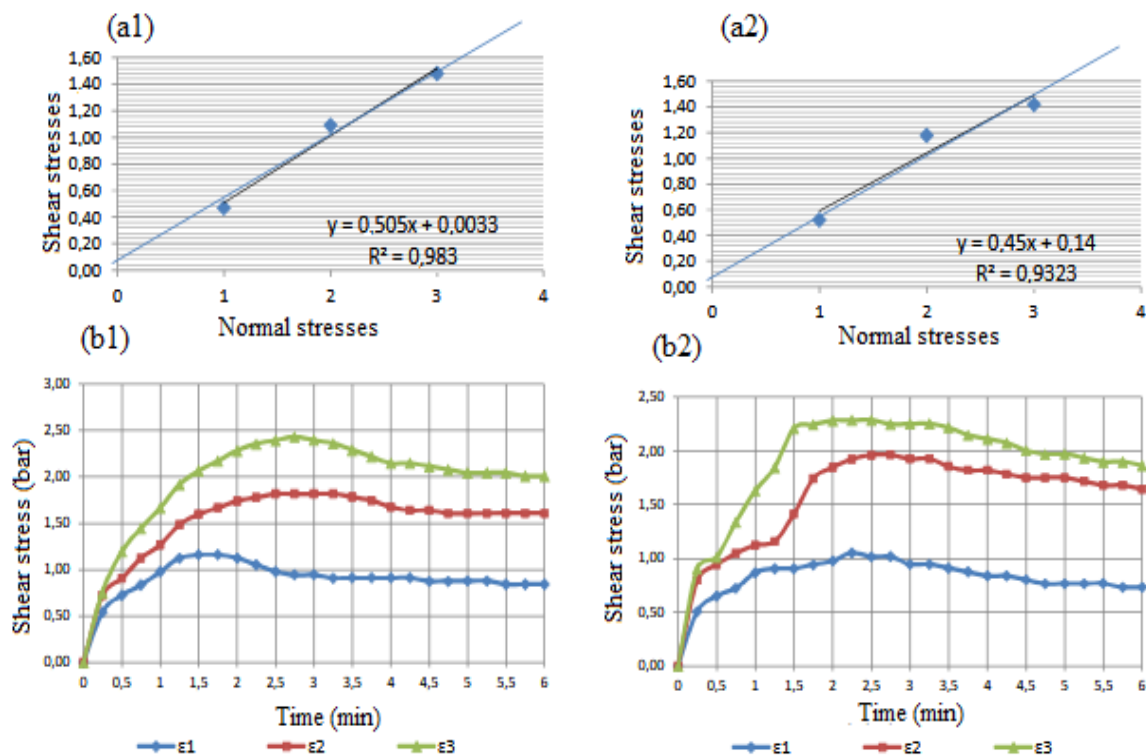
The spatial distribution of the geotechnical factor of safety (FoS), presented in Fig. 14, reveals significant variations across the study area, with values ranging from approximately 0.5 to 1.8. This variability reflects

differences in soil properties, slope geometry, and groundwater conditions. Several sectors exhibit FoS values lower than unity, indicating critical instability conditions and a high probability of slope failure. These unstable areas are mainly associated with clay-rich formations identified during the geotechnical investigations, particularly plastic and montmorillonitic clays characterized by low shear strength parameters (cohesion ≈ 12 kPa and friction angle $\approx 14^\circ$) and a high capacity for water retention. The presence of a shallow groundwater table, encountered at an average depth of approximately 1.4 m, further reduces the effective stress within the soil mass and promotes instability.

Conversely, the highest safety factors ($\text{FoS} \geq 1.5$) are observed in zones underlain by lateritic soils and sandy-gravelly formations. These materials exhibit higher cohesion (≈ 30 kPa), larger friction angles ($\approx 27^\circ$), and better drainage characteristics, resulting in greater resistance to failure. A substantial portion of the study area is characterized by intermediate FoS values ranging from 1.0 to 1.3, corresponding to marginally stable conditions. These sectors are generally composed of moderately compact clayey and silty materials (cohesion ≈ 22 kPa and friction angle $\approx 20^\circ$), which remain stable under normal conditions but become highly vulnerable when subjected to prolonged rainfall infiltration or anthropogenic disturbances.

The geotechnical investigations further revealed the widespread occurrence of expansive clays, whose behavior is strongly influenced by variations in moisture content. The Casagrande plasticity analysis indicates liquid limit values ranging from approximately 50% to 65.3%, highlighting the high plasticity and compressibility of these materials. Under saturated conditions, these clay-rich horizons may behave as weak slip surfaces, facilitating downslope movement. In addition, the fractured and heterogeneous structure of the weathered formations promotes water circulation and deep infiltration, accelerating the degradation of mechanical properties. The resulting decrease in cohesion and shear resistance significantly contributes to slope instability. Similar observations have been reported by Robitaille and Tremblay (1997), Aboubakar et al. (2013), and Mayer (2003), who emphasized the critical role of expansive clay minerals, groundwater infiltration, and weathering processes in landslide initiation.

Overall, the distribution of the factor of safety demonstrates that slope stability in the study area is controlled by the combined influence of soil mechanical properties, groundwater conditions, and geomorphological factors. The predominance of low to moderate FoS values confirms the high susceptibility of the region to landslides and is in good agreement with the results obtained from the AHP-based susceptibility assessment.



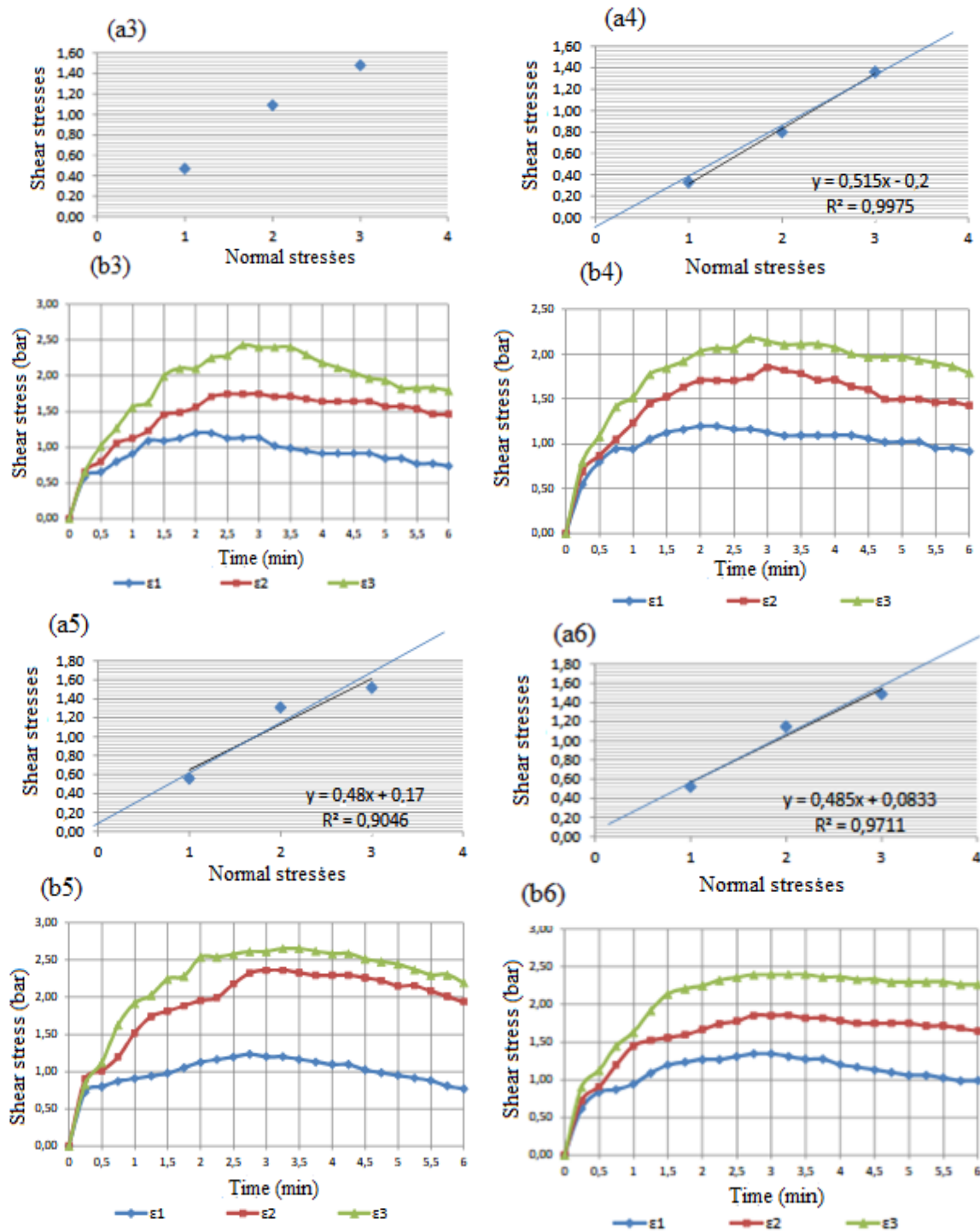


Fig. 13. (a1-a6) Mohr–Coulomb failure envelope showing shear stress as a function of normal stress; (b1-b6) shear force as a function of time

3.4 Scientific Implications of the Study

This study contributes to the advancement of landslide susceptibility assessment by demonstrating the effectiveness of integrating geotechnical investigations, remote sensing data, Geographic Information Systems (GIS), and the Analytic Hierarchy Process (AHP) within a unified framework. Unlike many previous studies

conducted along the Cameroon Volcanic Line (CVL), which mainly focused on geomorphological or remote-sensing indicators, the present approach incorporates field-derived geotechnical parameters, thereby improving the physical interpretation of slope instability processes. The resulting susceptibility assessment provides new insights into the relative influence of rainfall, soil properties, slope morphology, drainage conditions, and structural controls on landslide occurrence in tropical volcanic environments.

Beyond its regional significance, this work contributes to the limited scientific literature on landslide susceptibility mapping in Central Africa and provides a methodological reference for similar data-scarce mountainous regions. The generated database and susceptibility framework may also serve as a baseline for future developments using advanced methodologies such as Artificial Intelligence (AI), Machine Learning algorithms, and Interferometric Synthetic Aperture Radar (InSAR) techniques. The integration of these emerging approaches with geotechnical and environmental datasets could further enhance landslide monitoring, deformation detection, susceptibility modelling, and early-warning systems in the Cameroon Volcanic Line and other tropical volcanic regions.

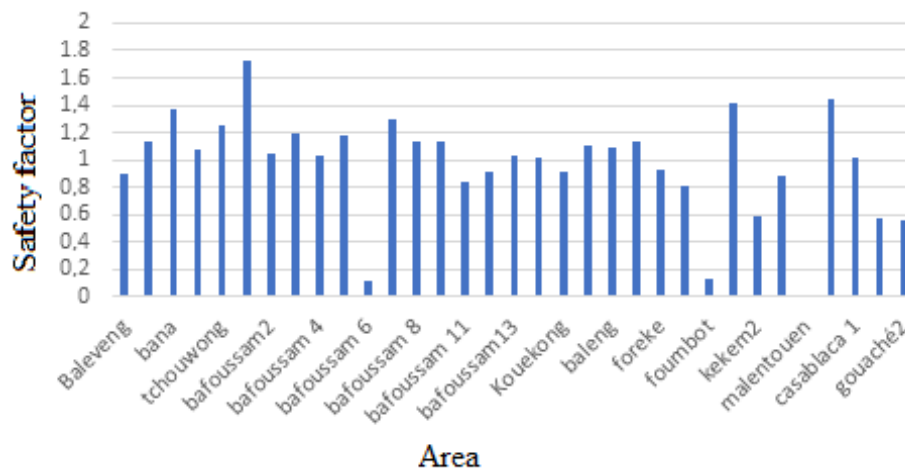


Fig. 14. Spatial distribution of the geotechnical factor of safety (FoS) across the study area, highlighting stable, marginally stable, and unstable slope sectors

4. Conclusion

This study assessed landslide susceptibility in a portion of the Cameroon Volcanic Line through the integration of remote sensing data, geotechnical investigations, Geographic Information Systems (GIS), and the Analytic Hierarchy Process (AHP). The adopted methodology combined eight conditioning factors, namely rainfall, soil characteristics, slope, drainage density, vegetation cover, weathering, surface lineament density, and deep lineament density, to identify and map areas prone to slope instability. The AHP analysis produced a satisfactory consistency ratio ($CR = 0.085$), confirming the reliability of the weighting procedure and the robustness of the susceptibility assessment. The results indicate that rainfall, soil characteristics, slope, and drainage density are the dominant controlling factors, each contributing 15% to the susceptibility model. High-susceptibility zones are characterized by rainfall ranging from 152 to 316 mm during the critical rainy season, slopes exceeding 30° and occupying approximately 65% of the study area, and clay-rich soils exhibiting low shear strength parameters, with cohesion values ranging from 0.22 to 0.30 bars (22–30 kPa) and friction angles between 20.72° and 23.86° . In contrast, vegetation cover, tectonic activity, weathering, and fracturing exert a comparatively lower influence, each contributing 10% to landslide susceptibility.

The geotechnical investigations revealed the predominance of weathered clay-rich formations, including expansive clays characterized by high liquid limits (50–65.3%) and strong water-retention capacities. The presence of a shallow groundwater table, encountered at an average depth of approximately 1.4 m, together with locally low factor-of-safety values ($FoS < 1$), highlights the unfavorable hydrogeological and mechanical conditions prevailing in several parts of the study area. These conditions promote the degradation of soil strength under saturation and favor the development of slope failures. The resulting susceptibility map identified

areas of high and very high susceptibility that largely coincide with previously documented landslide events, demonstrating the effectiveness of integrating environmental and geotechnical parameters within a GIS-based multicriteria framework. The study therefore provides a comprehensive understanding of the mechanisms controlling landslide occurrence in this tropical volcanic environment.

The findings constitute a valuable decision-support tool for land-use planning, infrastructure development, and disaster-risk management in the mountainous regions of western Cameroon. The identification of high-risk zones can assist decision-makers in implementing appropriate mitigation measures for roads, settlements, and agricultural areas, thereby reducing the human, economic, and environmental impacts of landslides. Nevertheless, some limitations remain, particularly regarding the availability and spatial resolution of environmental and geotechnical datasets. Future research should focus on the integration of higher-resolution satellite imagery, detailed geophysical investigations, and advanced modelling approaches, including statistical and machine-learning techniques. Furthermore, incorporating temporal analyses of rainfall variability and landslide inventories would improve the understanding of triggering mechanisms and enhance the predictive capability of susceptibility models within the geological and climatic context of the Cameroon Volcanic Line.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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