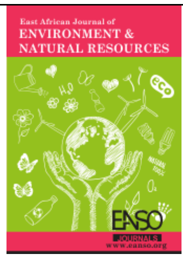


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*Original Article*

# Landslide Vulnerability Zones and Their Driving Factors in Rwanda: A Case of Gakenke District

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*Landslide, GIS, Remote Sensing, AHP, Vulnerability, Gakenke District, Rwanda.*

**ABSTRACT**

Landslides are recognised as devastating and deleterious natural disasters which are contemporary substantial threats to communities, exerting profound impacts on human lives, infrastructure, and the environment. In this line, Gakenke is one of the districts in Rwanda that has experienced landslide events damaging ample property, infrastructure, and the environment. Hence, this study aimed at geo-modelling and visualising the landslide vulnerability zones and determining the local factors that mostly drive landslide vulnerability. Primary data were collected through field observation and expert knowledge. In contrast, secondary data were collected from historical landslide records, meteorological institutions, and satellite images, where a set of factors was deduced. Using an integrated approach, this study integrated remote sensing techniques, Geographic Information Systems (GIS), and the Analytical Hierarchy Process (AHP) to model and geo-visualize landslide vulnerable zones, determining the risk levels considering a set of independent variables subdivided into topographical, meteorological, geological, hydrological, and land use factors. The results of the first objective revealed slope (26.83%), rainfall (21.23%, soil texture (15.51%, and distance from roads (11.21%) as the most influential factors to landslide vulnerability in the study area. In addition, distance from the river (8.47%) and land use land cover (5.74%) exhibited moderate influence, while normalised difference vegetation index (4.03%), topographic wetness index (3.01%), aspect (2.1%), and curvature (1.59%) disclosed a low influence. The study results for the second objective showed that 18.12% of the area was classified as very high and highly vulnerable zones, mainly western and northern regions. Moderately vulnerable areas covered 60.7% of the central and eastern regions, while low and very low vulnerable zones comprised 21.2%, mainly in southern and south-eastern regions. This highlights the heterogeneous distribution across the district, emphasising the need for tailored mitigation

 

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strategies. These findings informed the development of tailored, community-driven resilience planning strategies that address the specific vulnerabilities and leverage local resources and knowledge. Therefore, a reforestation program, toe protection walls, terraces, and provision of proper drainage with check dams in very high and highly vulnerable areas, accompanied by relocating residents from these areas, particularly those living on hilltops, roads, and river sides, are recommended. These measures are essential for protecting vulnerable populations and enhancing community resilience against natural disasters in the district.

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## INTRODUCTION

Natural hazards are considered to be one of the major drivers causing immense loss of human lives and serious damage, particularly in developing countries [1,21]. Among these hazards, landslides globally resulted in approximately 55,997 deaths across 4,862 distinct events from 2004 to 2016, with Asia being the most affected region, accounting for about 54% of these occurrences [1,2]. Notable regions include the Himalayan Arc in South Asia, where monsoon rains are a significant trigger, and Central America, particularly between Costa Rica and southern Mexico, which also experiences high landslide activity due to heavy rainfall [3]. The primary causes of these landslides are often linked to extreme weather events, particularly intense rainfall, as well as anthropogenic factors such as deforestation and urbanisation that destabilise slopes [4]. This combination of natural and human-induced factors has led to increased vulnerability and fatalities in many low- and middle-income countries where populations reside in precarious locations prone to landslides [3,4]. The increasing world population, the gradual expansion of human activities, increasing levels of disturbance, unsustainable land use, and extreme climate events have caused landslides, which have damaged not only property but also claimed the lives of many people globally [5]. In Rwanda, landslides have had a devastating impact on the local community, particularly in terms of loss of life and property [6,18]. In May 2018, a catastrophic cluster of over 700 landslides in Rwanda resulted in 18 fatalities, primarily due to two months of continuous rainfall that saturated the soil on a steep slope [7,8].

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Recent statistics indicate that from 2019 to 2022, landslides resulted in at least 7 deaths and numerous injuries, with 27 fatalities recorded in 2020 alone [9,17]. The destruction extended to infrastructure, with 77 houses destroyed in 2023 and over 1,200 homes remaining in high-risk zones. The agricultural sector has also suffered significantly, with substantial losses of crops and livestock across multiple years; for instance, 119 hectares of crops were lost in 2019, and 208 hectares in 2020, contributing to increased poverty and food insecurity in the region. In Gakenke District, landslides have become a critical issue exacerbated by heavy rainfall and challenging topography characterised by steep slopes and high elevation [9,10,18].

Recent incidents have resulted in significant destruction, including the demolition of 26 houses and the loss of crops, with reports indicating that urgent evacuations were necessary to prevent casualties as early signs of danger were observed [11]. The region's susceptibility to landslides is attributed to factors such as poor land management and deforestation, which have intensified soil erosion during torrential rains [11,12,19]. Over the years, landslides have caused extensive damage, including the destruction of hundreds of homes and numerous fatalities, highlighting the urgent need for effective risk mitigation strategies to protect the local communities [13,21].

## METHODOLOGY

### Study Area Description

Gakenke District, situated in the Northern Province of Rwanda, encompasses a diverse geographical landscape characterised by high-inclined hills and marshlands, with elevations ranging from approximately 1,700 meters to 2,648 meters at Mont Kabuye. The district spans an area of 704.06 km² and is divided into 19 administrative sectors, housing a population of around 345,487 people [11,12]. The climate in Gakenke is predominantly humid, with average annual temperatures fluctuating between 16°C and 29°C [14]. This region experiences substantial rainfall, ranging from 1,100 mm to 1,500 mm annually, distributed across four distinct seasons: a small dry season (January-February), a high rain season (March-May), a high dry season (June-August), and a small rain season (September-December). The abundant precipitation supports various agricultural activities, particularly in the marshlands, which are exploited during the dry season for crops like maize and beans. However, the district faces challenges such as soil erosion due to its hilly terrain and the need for effective soil conservation measures to maintain agricultural productivity and protect water resources flowing into major rivers like Mukungwa and Nyabarongo, which ultimately feed into the Nile River [8,16].

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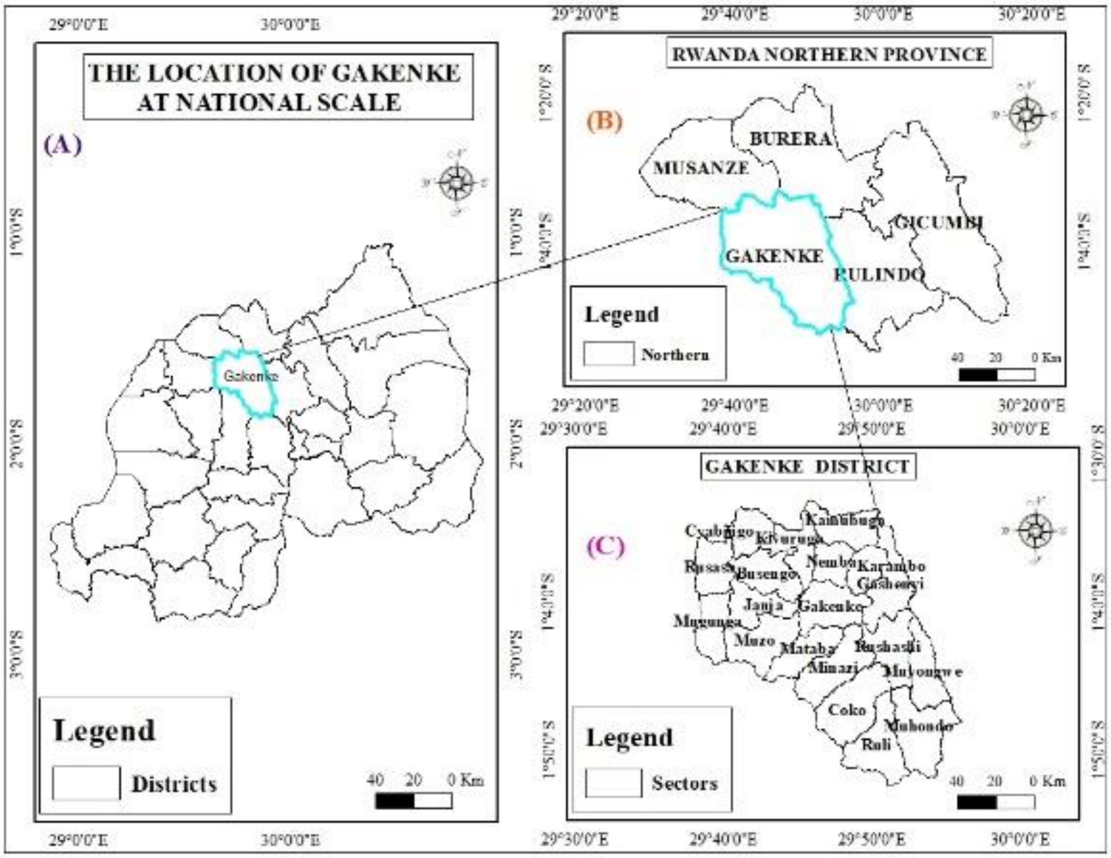
**Figure 1: Map of the Study Area**




## Data Collection and Analysis

The data to be utilised for this study will encompass a diverse array of geospatial datasets, remote sensing information, and traditional geospatial datasets. High-resolution satellite imagery from providers such as Digital Globe will be accessed to capture detailed terrain characteristics, land cover, and land use patterns, providing a foundational understanding of the physical landscape. Multispectral data from sources like Landsat will be incorporated to monitor terrain stability, vegetation (NDVI), and surface, among other factors, which are crucial factors influencing landslide vulnerability.

The project will also leverage topographic and cartographic sources, including digital elevation models (DEMs) and topographic maps from the United States Geological Survey (USGS) retrieved from (https://www.usgs.gov/). This will add valuable insight into slope gradient, elevation, curvature, and TWI, contributing to a comprehensive assessment of landslide vulnerability factors. Furthermore, the road network and river system datasets will be obtained from the Ministry of Infrastructure (MININFRA) of Rwanda, representing the official transportation infrastructure and hydrological networks. These vector datasets will be integrated with DEM data to generate proximity maps that account for topographic variations. The latter will be done to show the proximity of any location to the nearest road and river features. This integration will enable more accurate surface distance calculations rather than simple planar distances, providing crucial parameters for assessing landslide vulnerability, as both road cuts and river erosion can significantly influence slope stability. Furthermore, meteorological data, in the form of rainfall records, will be obtained from the Rwanda Meteorology Agency (https://meteorwanda.gov.rw/index.php?id=2),

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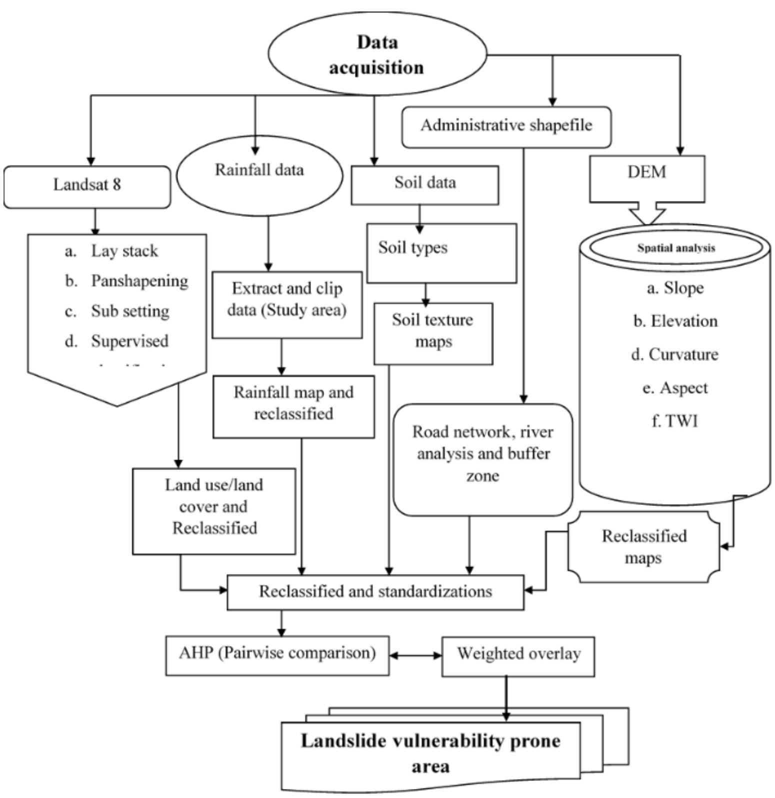
interpolated to produce a spatial distribution of rainfall to assess the influence of climatic patterns on landslide vulnerability.

To evaluate the soil type and geological conditions, soil maps, geotechnical surveys, and geological reports from the Ministry of Natural Resources of Rwanda (https://www.environment.gov.rw/) and academic institutions will be incorporated. Historical landslide inventories and reports from the Ministry of Emergency Management (MINEMA) will also be compiled to analyse past events and identify high-vulnerable areas, providing crucial insights into historical landslide occurrence. Moreover, LULC maps and spatial datasets from the National Land Centre and Mapping in Rwanda (https://www.lands.rw/land-use-and-mapping) will be considered to evaluate the exposure and vulnerability of human settlements to landslide hazards. Hence, this study will encompass existing literature on landslide vulnerability assessment, GIS-based landslide risk modelling methodologies, and empirical studies on landslide vulnerability and current mitigation measures

These secondary data will provide valuable insights into conceptual frameworks, analytical methods, and best practices for assessing and mitigating landslide risks in similar geographic contexts. To complement the secondary datasets, this research will incorporate observational methods to gather primary data for ground-truthing, ensuring a nuanced understanding of the local context. Field observations will be conducted across the Gakenke district to capture the physical landscape, infrastructure, and settlement patterns that can be affected. Structured visits will be made to targeted areas, systematically documenting relevant features. Photographic and video documentation will accompany these observations, aiding in data analysis. Primary field data is utilised for the validation of the model, which will provide a comprehensive understanding of landslide risks and characteristics of the Gakenke district.

**Figure 2: Methodological Framework**



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The data processing and analysis will involve a combination of techniques, considering the capabilities of the Analytical Hierarchy Process (AHP) and Geographic Information Systems (GIS). The AHP, a multi-criteria decision-making method, will be employed to determine the landslide-vulnerable areas by systematically evaluating and weighting various landslide conditioning factors.

These factors will be identified based on a comprehensive literature review and expert knowledge. Through a series of pairwise comparisons, the relative importance of each factor will be quantified, and corresponding weight values will be calculated using the AHP method. Within the ArcGIS 10.8 environment, the landslide conditioning factor maps will be generated from the pre-processed geospatial data, including remote sensing imagery and digital elevation models.

## RESULTS

### Criteria for Locational Suitability for Residential Development

In assessing landslide vulnerability in the Gakenke district of Rwanda, several key factors have been identified as significant contributors to landslide occurrences. These factors include slope, which directly influences gravitational forces on soil; elevation, affecting climate and rainfall patterns; rainfall, a crucial trigger for landslides; and soil type, which determines the stability of the ground. Curvature and aspects of the terrain impact water drainage and erosion, while land cover/land use influences vegetation stability. The Topographic Wetness Index (TWI) assesses moisture accumulation, and soil texture affects water retention capabilities. Furthermore, the Normalised Difference Vegetation Index (NDVI) provides insights into vegetation health, and the distance to road networks can alter drainage patterns and human activities that exacerbate landslide risks. Mapping these parameters is essential for understanding their interactions and developing effective regional risk management strategies.

### Land Cover/Land Use

Poor land management practices, including deforestation, agricultural activities on steep slopes, and settlement expansion on steep slopes, significantly elevate an area's susceptibility to landslides by disrupting the ecosystem's natural balance. Deforestation removes vital vegetation that stabilises soil through root systems, increasing erosion and reducing soil cohesion.

Unsustainable agricultural practices, such as overgrazing and improper tillage, can lead to soil degradation and compaction, further destabilising slopes and enhancing runoff during rainfall events.

The results reveal a significant variation in vegetation and land utilisation within the Gakenke district, with the low-class, forest covering 27.9 % of the area; the medium-class, vegetation covering 10.7%, the high-class, crop covering 39.5%; and areas of very high-class, built-up areas covering 21.9%. This distribution is crucial for understanding the landscape's susceptibility to landslides, as areas with lower vegetation cover may be more vulnerable to erosion and instability, particularly in light of the district's challenging topography and rainfall patterns.

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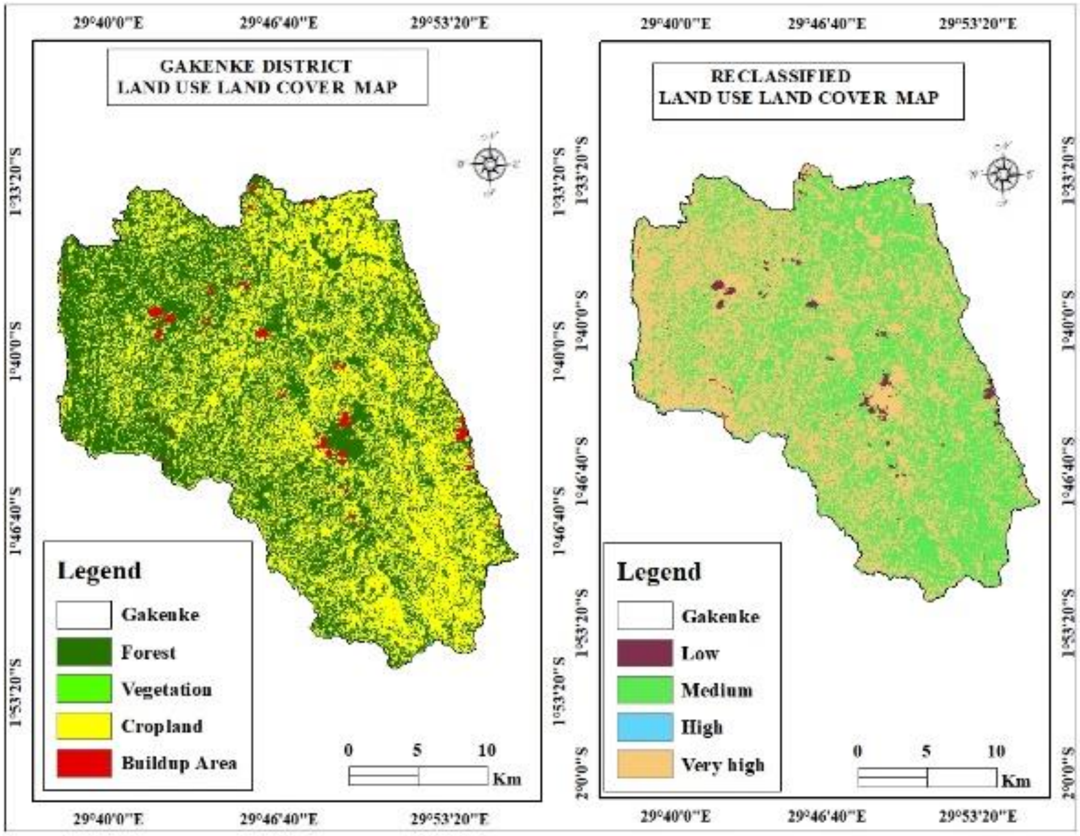
**Figure 3: Thematic Layer of Land Use Land Cover Map and Its Reclassification, 2018**




**Topographic Factors**

Slope steepness and aspect play vital roles, with steeper slopes and certain orientations more prone to landslides due to heightened gravitational forces and varying erosion patterns. Natural depressions, such as valleys or concave terrains, can exacerbate this risk by collecting water, increasing pore pressure, and saturating soils, further destabilising slopes.

***Slope***

Slope factors are critical determinants of landslide susceptibility, with steeper slopes more prone to instability due to increased gravitational forces. The angle of repose, beyond which materials are prone to failure, plays a significant role. Slope gradient interacts with factors like soil cohesion and water content, influencing landslide occurrence. The area's slope vulnerability analysis, derived from a Digital Elevation Model (DEM), reveals a significant distribution of landslide susceptibility across four classes. From the analysis of DEM data, the very high slope ($>60^0$) covers 2.4%, the high slope ($40^0$-$60^0$) covers 6.1%, the medium slope (200-400) covers 55%, and the low slope ($<20^0$) covers 36.5%. This classification underscores the importance of slope steepness in assessing landslide risks and highlights the need for targeted mitigation strategies in the most vulnerable regions.

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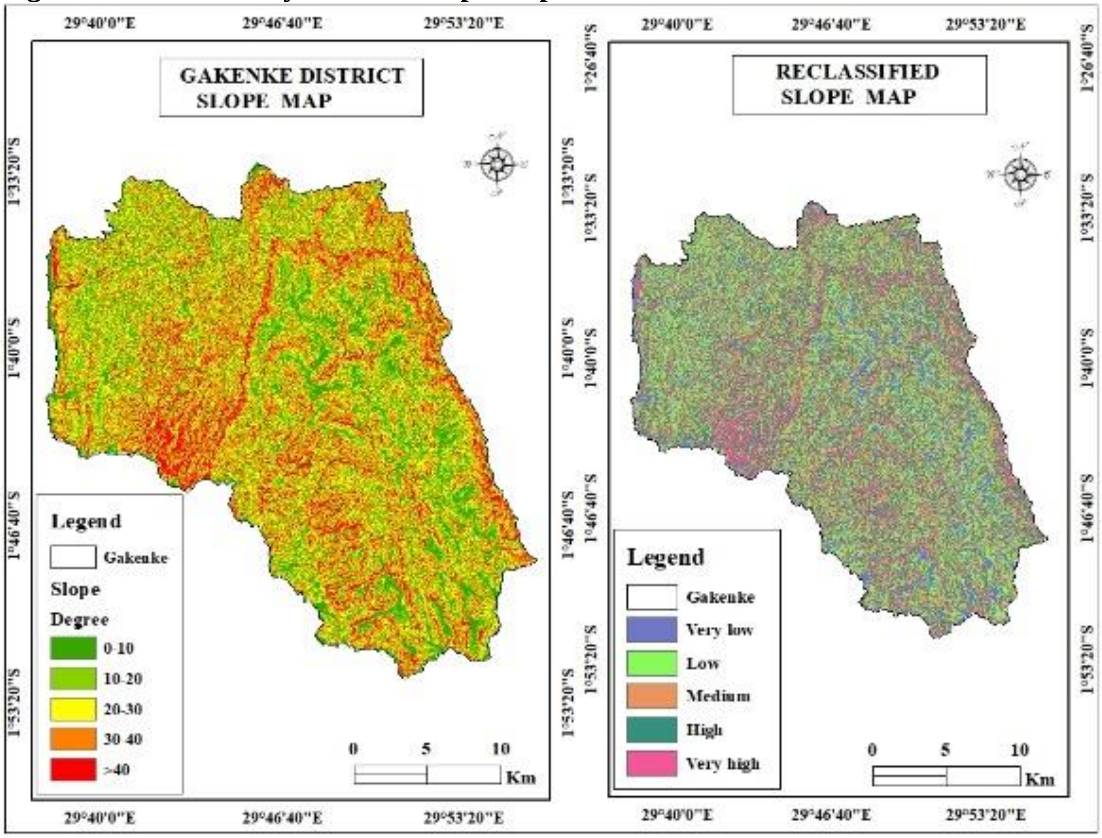
**Figure 4: Thematic Layers of the Slope Map and Its Reclassification**




### *Curvature*

Curvature pointedly influences landslide vulnerability by affecting the hydrological dynamics and stability of slopes. Specifically, both plan curvature and profile curvature play crucial roles; concave slopes tend to accumulate water, increasing pore pressure and soil saturation, which can lead to instability and landslide occurrences. Conversely, convex slopes are often associated with rapid drainage but can also be prone to erosion and rock falls. Research indicates that extreme curvature values, whether positive or negative, correlate with higher probabilities of landslide events, highlighting the importance of understanding these topographic features in assessing landslide risk.

The reclassified curvature map reveals a diverse distribution of landslide vulnerability across the area, with the very highly vulnerable class accounting for 7.3 % of the total landscape, indicating regions at significant risk due to unfavourable curvature characteristics. The highly vulnerable class comprises 25.04%, representing the largest portion and suggesting substantial landslide vulnerability. Meanwhile, the medium vulnerable class covers 37.8%, indicating a moderate level of risk, the low vulnerable class encompasses only 23.6%, reflecting areas with comparatively lower vulnerability, and the very low vulnerable class covers 6.3%.

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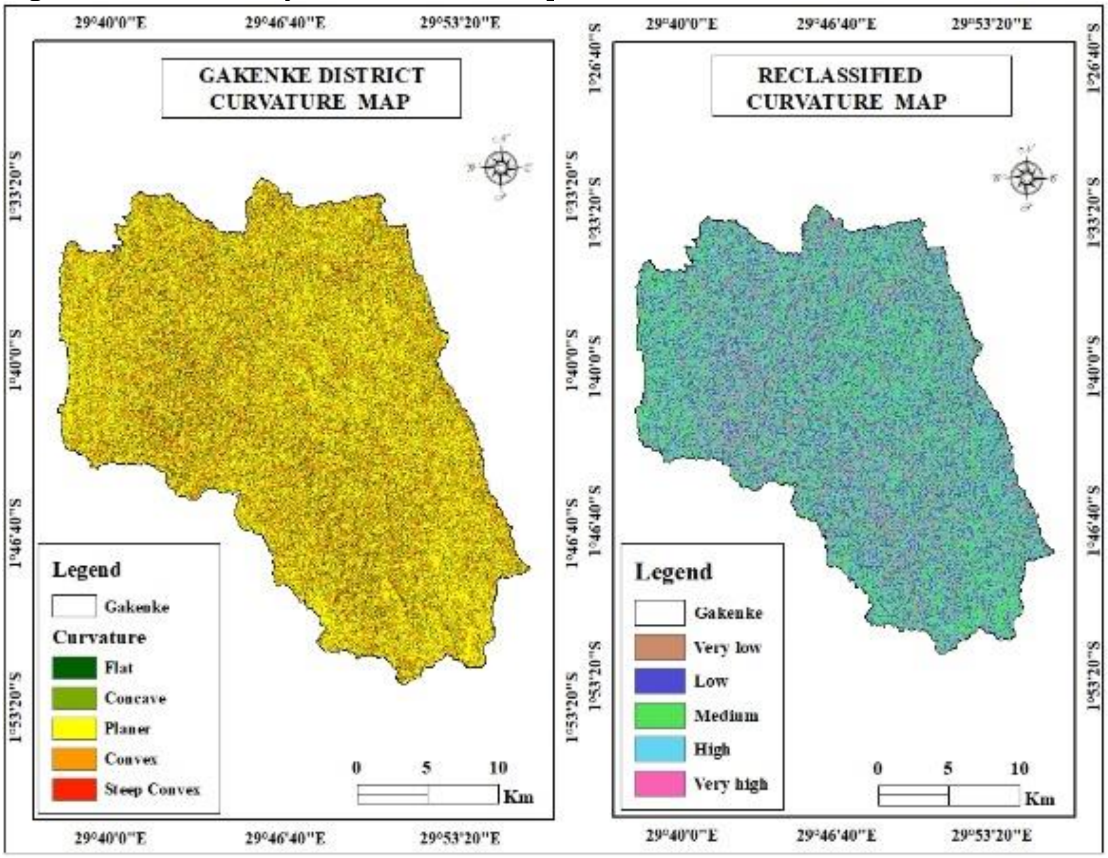
**Figure 5: Thematic Layer of Curvature Map and Its Reclassification**




### *Aspect*

Aspect plays a significant role in landslide vulnerability by influencing microclimatic conditions and slope moisture distribution. The direction of slope aspect affects exposure to sunlight, rainfall patterns, and wind, which in turn impact soil moisture content and vegetation health. Areas with certain aspects may retain more moisture due to reduced sunlight exposure, leading to increased soil saturation and decreased stability, thereby heightening the risk of landslides. The slope aspect map indicating landslide vulnerability in Gakenke District reveals a significant distribution across various susceptibility levels. The slope aspect map indicating landslide vulnerability in Gakenke District reveals a significant distribution across various susceptibility levels. Specifically, areas classified as very low vulnerability cover 17.5%, low vulnerability covers 20.4%, medium vulnerability covers 19.0%, high vulnerability covers 22.7%, and very high vulnerability covers 20.5% of the district. This distribution underscores the varying degrees of risk associated with landslides in Gakenke, highlighting the need for targeted risk management strategies to address the most vulnerable zones effectively.

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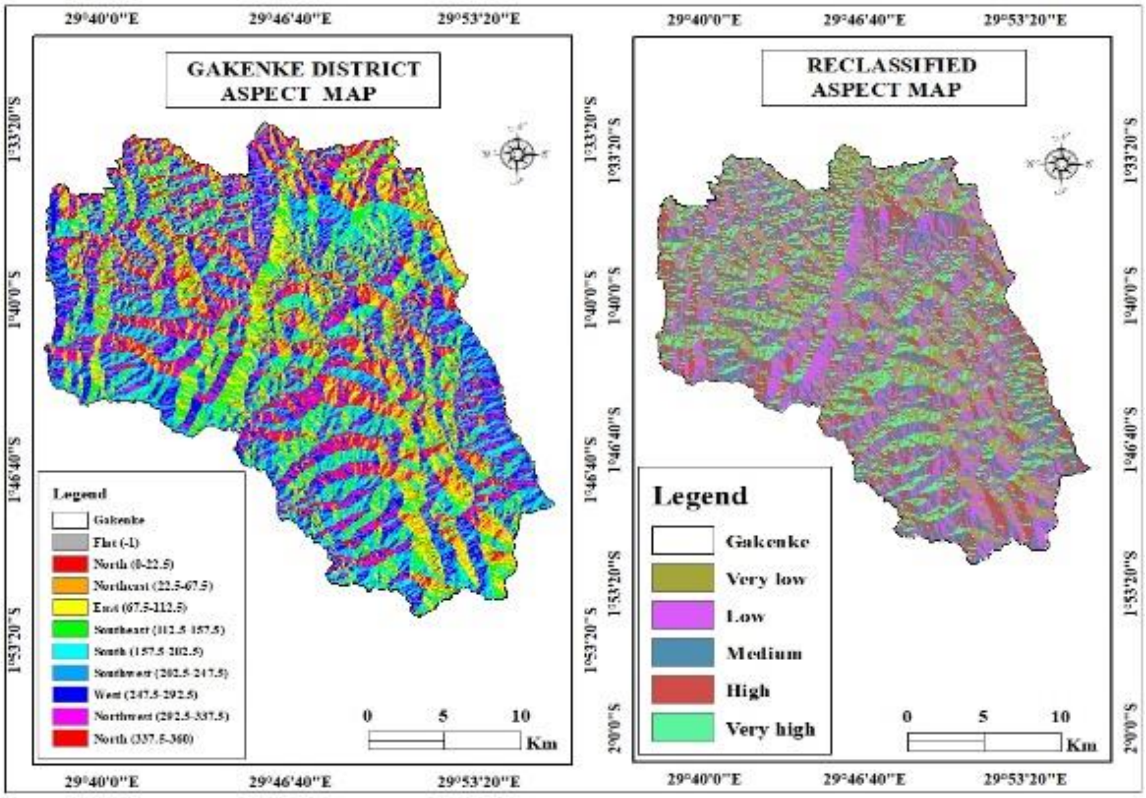
**Figure 6: Thematic Layer of Aspect Map and Its Reclassification**




### *Topographic Wetness Index*

The Topographic Wetness Index (TWI) significantly influences landslide vulnerability by quantifying the propensity of water to accumulate on slopes, thereby affecting soil saturation and stability. Higher TWI values indicate areas where water is likely to collect, increasing pore pressure within the soil, destabilising slopes, and triggering landslides. This index helps identify regions more susceptible to landslides, particularly in areas with gentle slopes where water retention is more pronounced.

Understanding TWI is essential for effective landslide risk assessment and developing targeted mitigation strategies, as it provides insight into hydrological processes that contribute to slope instability reclassification.

The TWI map reveals a distribution of land occupancy across five classes within the study area. Specifically, the very low class covers 44.2%, the low class covers 35.5%, the medium class covers 13.7%, the high class covers 4.9%, and the very high class covers 1.6%. This gradient of occupancy suggests a significant prevalence of lower slope areas, which may influence land use and ecological dynamics in the region. This gradient of occupancy suggests a significant prevalence of lower slope areas, which may influence land use and ecological dynamics in the region.

**Figure 7: Thematic Layer of Topographic Wetness Index Map (TWI) and Its Reclassification**

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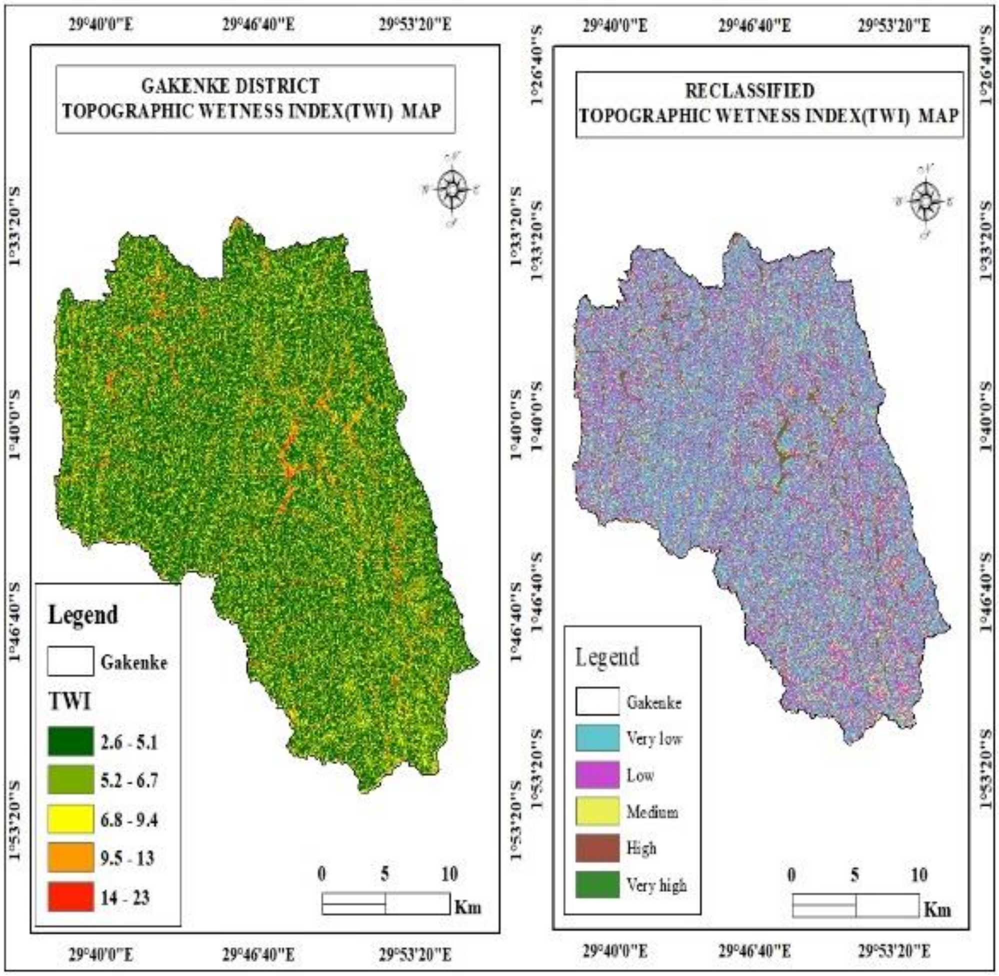


### *Climate Factor*

Climate factors significantly influence landslide vulnerability through precipitation patterns, temperature fluctuations, and seasonal changes. Increased frequency and intensity of heavy rainfall can saturate soils, reducing stability and heightening landslide risk, particularly in areas already prone to saturation from snowmelt or prolonged wet conditions.

### *Rainfall*

Rainfall is one factor that has been found to activate landslides, as high rainfall events result in high water saturation in soils, decreasing the soil's strength. The rise in water content increases pore water forces. The impact of rain is extremely high because landslides are more common when precipitation is continuous and the soil is saturated.

In Gakenke District, rainfall significantly influences landslide vulnerability, with levels below 1200 mm considered to exert a low influence on triggering landslides, while rainfall exceeding 1500 mm poses a greater risk. The analysis reveals that the area is categorised into different vulnerability classes: very highly vulnerable (13.8%), highly vulnerable (17.7%), medium vulnerable (21.1%), low vulnerable (26.3%), and very low vulnerable (21.1%). This distribution indicates that as rainfall increases, the probability of landslides increases, highlighting the critical role of precipitation in shaping the landscape's susceptibility to such disasters in this region.

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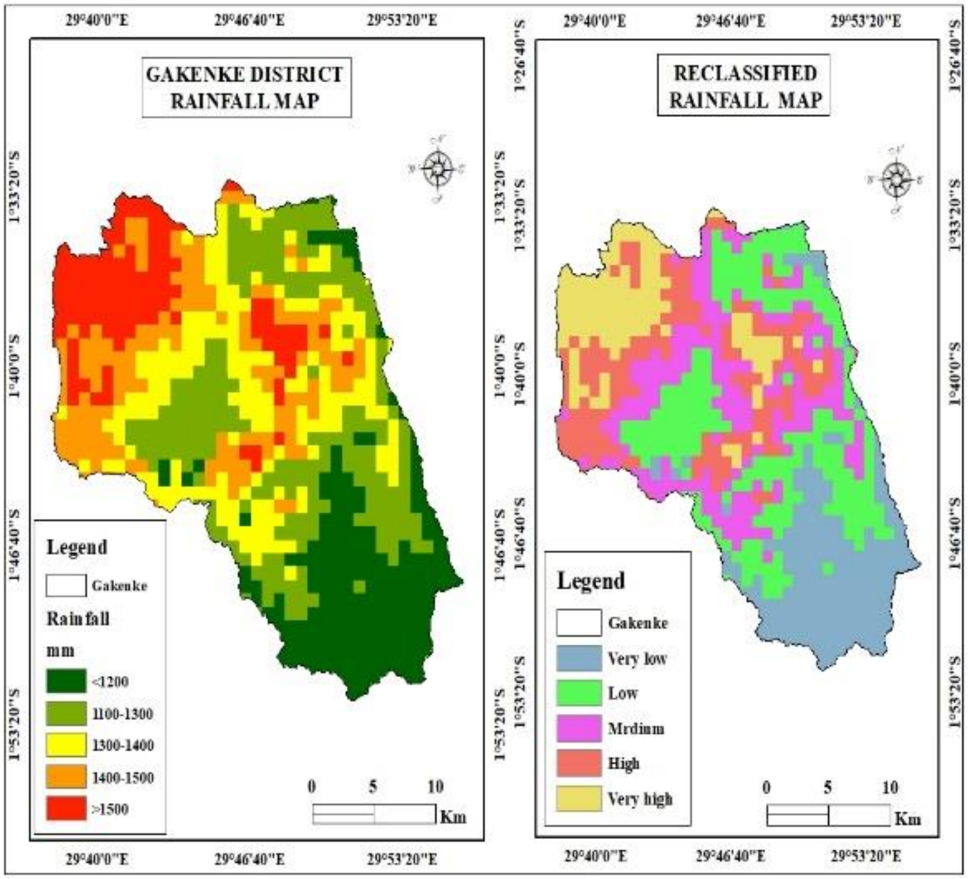
***Figure 8: Thematic Layer of Rainfall Map and Its Reclassification***




***Soil Texture***

Landslide risk is greatly influenced by soil texture, with different varieties showing differing levels of instability and erosion susceptibility. Under some circumstances, clay soils, which are renowned for their cohesive qualities and high water-holding capacity—can reduce the risk of landslides; yet, when they become saturated, their increased pore water pressure may also exacerbate instability.

On the other hand, clay loams and sandy soils are more prone to erosion and quick drainage due to their higher permeability and lesser cohesiveness, which can cause landslides during periods of intense rainfall. Because of their expansive clay content, Vertisols can also be dangerous since they can crack and even cause slope failures because they expand when wet and shrink when dry. The stability of alluvial soils, which are frequently found in river valleys, can vary according to their moisture content and composition.

A diverse distribution throughout the study area is revealed by the table, which groups soil types according to their importance in landslide incidence. The most common type of soil, clay, makes up about 32.0% of the total area and has a significant influence on determining the dynamics of landslides. Sandy clay loam covers 21.7%, sandy clay covers 18.6%, clay loam covers 13.5%, and loam covers 14.2% of the study area. This classification emphasises how crucial it is to comprehend soil composition when determining the risk of landslides because different types of soil contribute significantly to the region's overall vulnerability.

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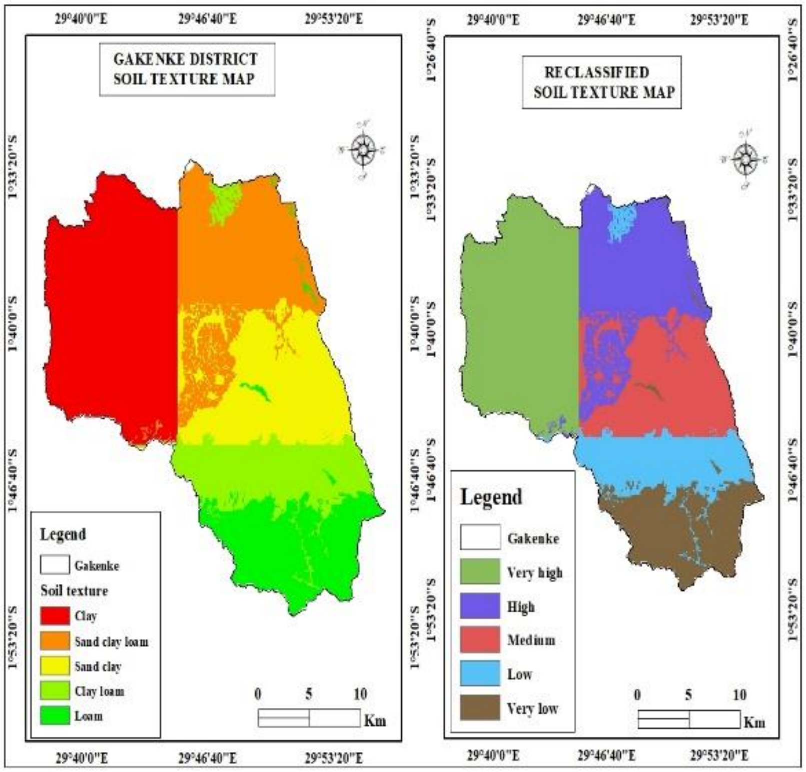
**Figure 9: Thematic Layer of the Soil Type Map and Its Reclassification**




## NDVI

The Normalised Difference Vegetation Index (NDVI) is a valuable tool for assessing landslide vulnerability, as it provides insights into vegetation cover and health, which are critical factors in slope stability. High NDVI values generally indicate dense and healthy vegetation, which can help stabilise slopes by reducing soil erosion and increasing cohesion. Conversely, low NDVI values suggest sparse or stressed vegetation, creating conditions conducive to landslides. Studies have shown that incorporating time-varying NDVI data captured through remote sensing enhances the accuracy of landslide susceptibility models by reflecting changes in vegetation due to climatic variations and human activities. This dynamic assessment allows for better identification of vulnerable areas, ultimately aiding disaster risk management and mitigation strategies in susceptible regions.

A varied distribution of vegetative health and its relationship to landslide risk is revealed by the findings of the NDVI evaluation for landslide vulnerability in the study region. Therefore, the very low class covered 1.9%, the low class covered 16.9%, the medium class covered 33.8%, the high class covered 32.6%, and the very high class covered 14.9% of the study area. This classification emphasises how important vegetation is for determining and controlling the landscape's vulnerability to landslides. On the other hand, 23% of the study region is made up of low-vulnerability areas, which emphasise areas with healthier vegetation that can successfully reduce the risk of landslides.

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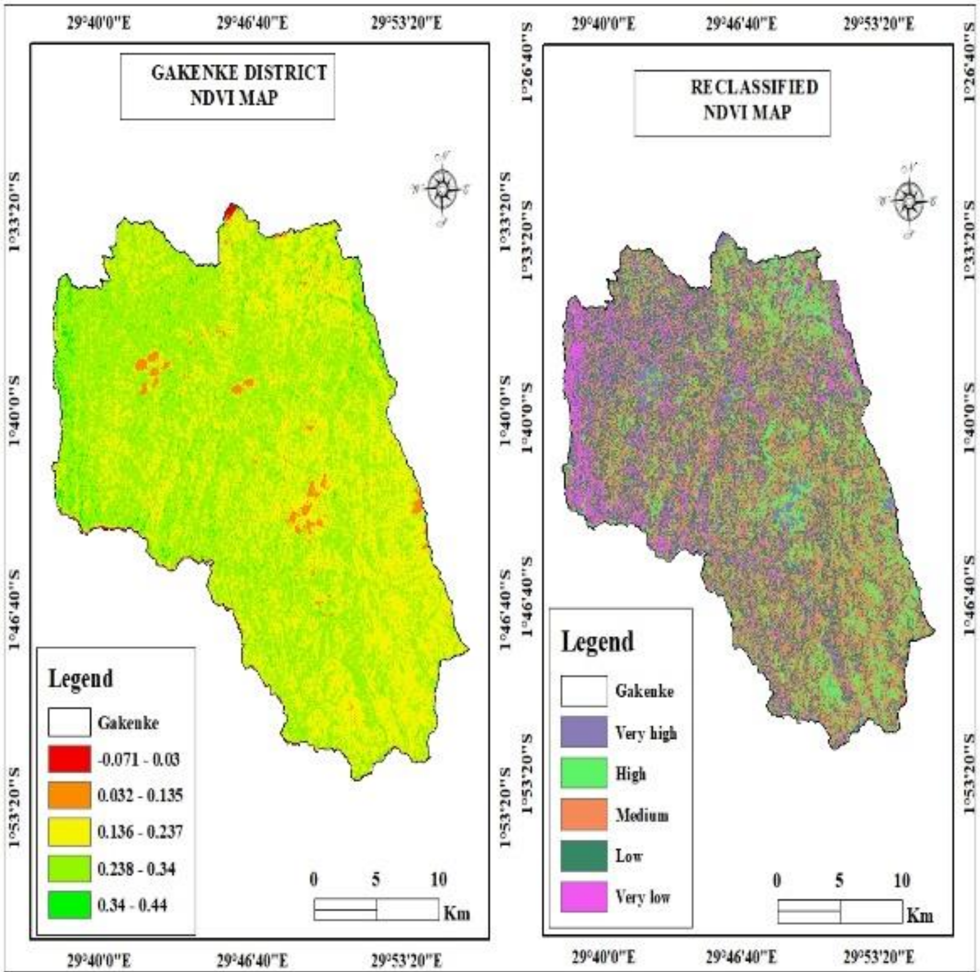
**Figure 10: Thematic Layer of NDVI Map and Its Reclassification**




***A Thematic Layer of Distance from the River and Its Reclassification***

Distance from rivers is a critical factor in assessing landslide vulnerability zones in Gakenke, Rwanda, as proximity to water bodies can increase soil saturation and erosion, leading to higher landslide risks. The study utilises hydrological data and river network maps sourced from the Rwanda Water Resources Management Authority, which provide insights into river locations and their influence on local topography.

This information is integrated with rainfall data from the Rwanda Meteorology Agency and elevation data derived from Digital Elevation Models (DEMs) using Geographic Information Systems (GIS) to create vulnerability maps. Findings indicate that areas closer to rivers are more prone to landslides, particularly during periods of heavy rainfall when runoff increases. This relationship is essential for developing effective land management strategies that mitigate risks associated with landslides in vulnerable regions like Gakenke, highlighting the need for community awareness and proactive measures to manage water flow and soil stability.

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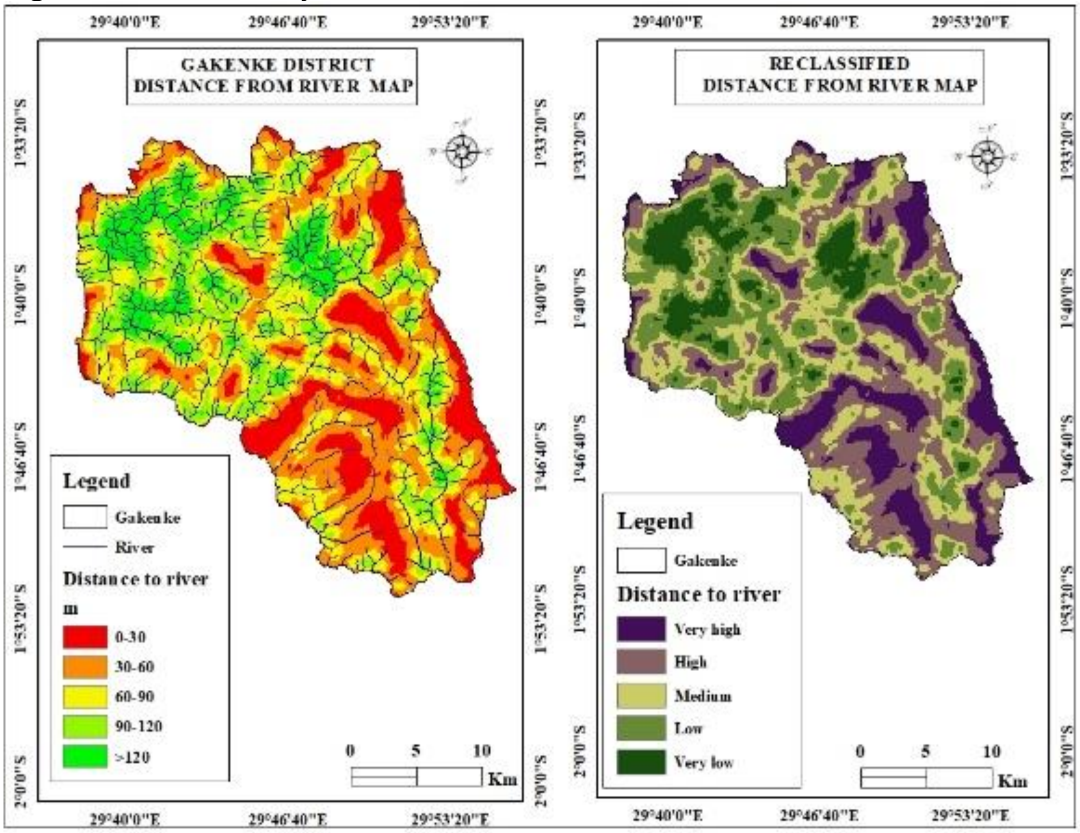
**Figure 11: Thematic Layer of Distance from the River and Its Reclassification**




According to the data, the distance from the river shows the different levels of landslide susceptibility in the region. The very high class covers 17.2%, the high class covers 30.2%, the medium class covers 28.9%, the low class covers 19.5%, and the very low class covers 4.3% of the entire terrain. This distribution highlights how landslide dynamics affect erosion and deposition processes in particular, underscoring the necessity of close observation and management in the areas that are most at risk.

***Distance from the Road Networks***

Distance from road networks significantly influences landslide vulnerability zones in Gakenke, Rwanda, as proximity to roads can exacerbate soil erosion and destabilise slopes. Roads often alter natural drainage patterns and increase runoff, leading to higher vulnerability to landslides, particularly in areas with steep terrain and heavy rainfall. Data sources for this analysis include road network maps from MININFA and landslide inventories obtained through Global Positioning System (GPS) tracking of past landslide events, combined with Geographic Information Systems (GIS) to assess spatial relationships.

The study utilises historical rainfall data from the Rwanda Meteorology Agency and elevation data from Digital Elevation Models (DEMs) to create comprehensive vulnerability maps. Findings indicate that regions closer to road networks are at greater risk of landslides, underscoring the need for integrated land management practices that consider both infrastructure development and environmental stability to mitigate risks in vulnerable areas like Gakenke.

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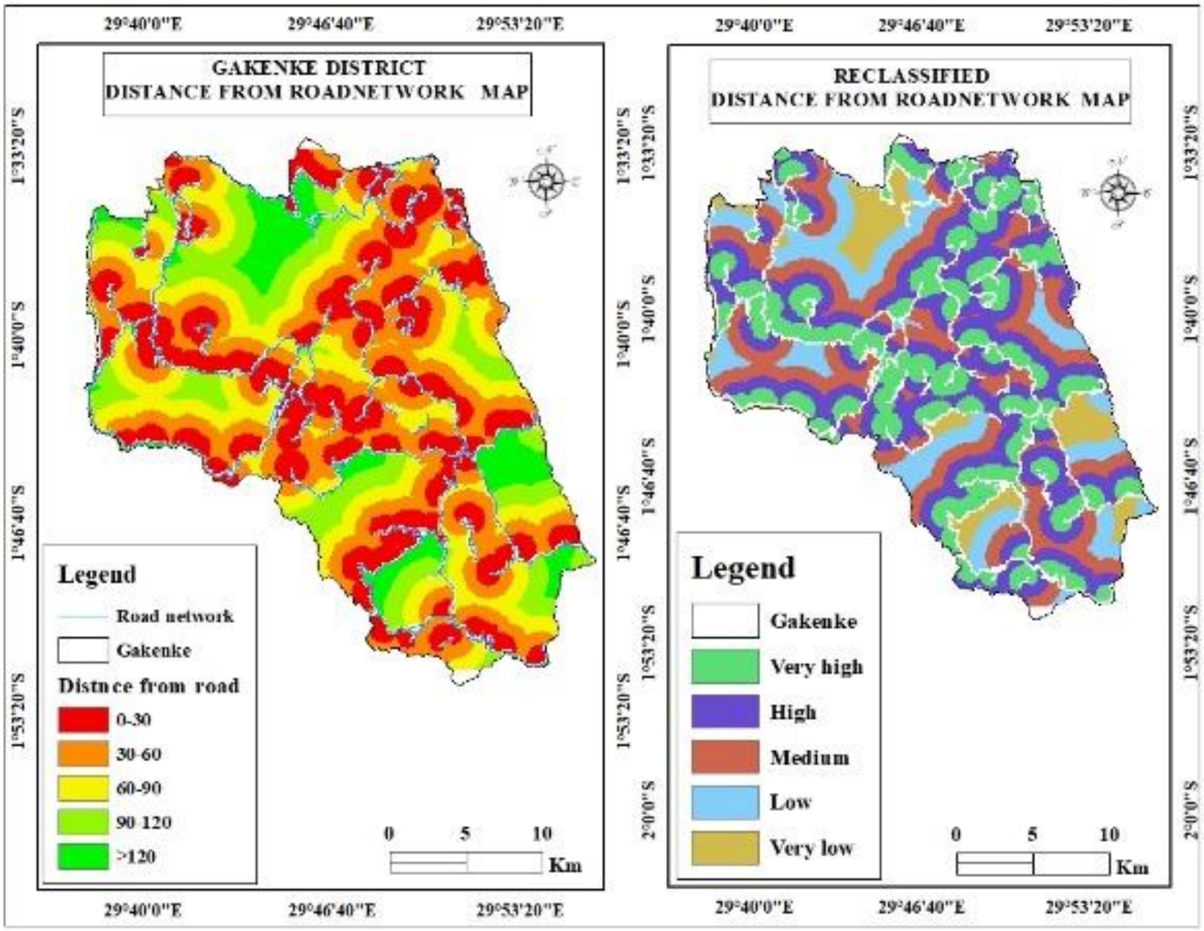
**Figure 12: Thematic Layer of the Distance from Road Networks and Its Reclassification**




The analysis of distance from the road network in Gakenke District reveals a clear correlation between proximity to roads and landslide vulnerability. Areas classified as very high risk, located within 0 to 30 meters from roads, are significantly affected by human activities contributing to slope destabilisation. The high-risk zone extends from 30 to 60 meters, while the medium-risk zone covers 60 to 90 meters. In contrast, areas situated >120 meters from roads experience very low landslide effects due to their greater distance from potential disturbances associated with road construction and maintenance. This gradient underscores the importance of considering road proximity in landslide risk assessments and management strategies within the district.

***Landslide Vulnerability Area***

Due to its ability to absorb large amounts of precipitation and the current soil conditions, which are dominated by clay and Vertisols, Gakenke District, which is located in Rwanda's hilly and mountainous regions, is especially susceptible to landslides. High infiltration rates and water accumulation are made possible by this combination, which eventually causes slope collapses.

To create a landslide vulnerability map for the district, a thorough examination of numerous parameters was carried out using Spatial Multi-Criteria Evaluation in ArcMap. Slope, Rainfall, soil texture, land use/cover, distance from the road, distance from the river, aspect, elevation, topographic wetness index (TWI), NDVI and curvature, and distance from the road were the ten

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important elements taken into account in this study. The results show a clear distribution of landslide risks throughout the Gakenke District, highlighting the need for focused risk management techniques that take into account the particular:

**Table 1: Pair-wise Comparison Matrix for Criteria**

| Factor | Criteria | Slope | Rainfall | Soil Texture | Distance from Roads | Distance from River | LULC | TWI | NDVI | ASPECT | Carvature |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Slope | 1 | 2 | 3 | 4 | 3 | 6 | 7 | 6 | 7 | 9 |
| 2 | Rainfall | 0.50 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 3 | Soil texture | 0.33 | 0.50 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 4 | Distance from Road | 0.25 | 0.33 | 0.50 | 1.00 | 2 | 3 | 4 | 5 | 6 | 7 |
| 5 | Distance from River | 0.33 | 0.25 | 0.33 | 0.50 | 1 | 2 | 3 | 4 | 5 | 6 |
| 6 | LULC | 0.17 | 0.20 | 0.25 | 0.33 | 0.50 | 1 | 2 | 3 | 4 | 5 |
| 7 | TWI | 0.14 | 0.17 | 0.20 | 0.25 | 0.33 | 0.50 | 1 | 2 | 3 | 4 |
| 8 | NDVI | 0.17 | 0.14 | 0.17 | 0.20 | 0.25 | 0.33 | 0.50 | 1 | 2 | 3 |
| 9 | Apect | 0.14 | 0.13 | 0.14 | 0.17 | 0.20 | 0.25 | 0.33 | 0.50 | 1 | 2 |
| 10 | Carvature | 0.11 | 0.11 | 0.13 | 0.14 | 0.17 | 0.20 | 0.25 | 0.33 | 0.50 | 1 |
|  | Total | 3.15 | 4.83 | 7.72 | 11.59 | 14.45 | 22.28 | 29.08 | 34.83 | 43.5 | 54 |

**Table 2: Normalised Pairwise Matrix in Decimal Value and Assigned Weights to Factors**

| Factor | Criteria | Slope | Rainfall | Soil Texture | Distance from Roads | Distance from River | LULC | TWI | NDVI | ASPECT | Carvature |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Slope | 0.31778058 | 0.41 | 0.38870893105 | 0.345040049 | 0.207612457 | 0.269259536 | 0.240687679 | 0.172248804 | 0.16091954 | 0.166666667 |
| 2 | Rainfall | 0.16 | 0.21 | 0.25913928737 | 0.258780037 | 0.276816609 | 0.224382947 | 0.206303725 | 0.200956938 | 0.183908046 | 0.166666667 |
| 3 | Soil texture | 0.11 | 0.10 | 0.12956964368 | 0.172520025 | 0.207612457 | 0.179506358 | 0.171919771 | 0.172248804 | 0.16091954 | 0.148148148 |
| 4 | Distance from Road | 0.08 | 0.07 | 0.06 | 0.09 | 0.138408304 | 0.134629768 | 0.137535817 | 0.14354067 | 0.137931034 | 0.12962963 |
| 5 | Distance from River | 0.11 | 0.05 | 0.04 | 0.04 | 0.069204152 | 0.089753179 | 0.103151862 | 0.114832536 | 0.114942529 | 0.111111111 |
| 6 | LULC | 0.05 | 0.04 | 0.03 | 0.03 | 0.03 | 0.044876589 | 0.068767908 | 0.086124402 | 0.091954023 | 0.092592593 |
| 7 | TWI | 0.05 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.034383954 | 0.057416268 | 0.068965517 | 0.074074074 |
| 8 | NDVI | 0.05 | 0.03 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 | 0.028708134 | 0.045977011 | 0.055555556 |
| 9 | Apect | 0.05 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.022988506 | 0.037037037 |
| 10 | Carvature | 0.04 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.018518519 |
|  | Total | 1.00 | 1.00 | 1.00 | 1.00 | 1 | 1.00 | 1.00 | 1.00 | 1 | 1 |

**Table 3: Weighted Overlay, Lambda Calculation, and Normalised Pairwise Matrix in Decimal Value, and Assigned Weights to Factors**

| Factor | Rows Sum | Rows sum /10 | Weighted overlay(%) | λ |
|---|---|---|---|---|
| 1 | 2.71 | 0.27 | 27.06 | 11.02 |
| 2 | 2.12 | 0.21 | 21.23 | 11.15 |
| 3 | 1.55 | 0.16 | 15.51 | 11.06 |
| 4 | 1.12 | 0.11 | 11.21 | 10.87 |
| 5 | 0.85 | 0.08 | 8.47 | 10.53 |
| 6 | 0.57 | 0.06 | 5.74 | 10.41 |
| 7 | 0.40 | 0.04 | 4.03 | 10.34 |
| 8 | 0.30 | 0.03 | 3.01 | 10.08 |
| 9 | 0.21 | 0.02 | 2.10 | 10.19 |
| 10 | 0.16 | 0.02 | 1.59 | 10.34 |
| Total | 10.00 | 1.00 | 100.0 |  |

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The next step is to calculate the criterion weights (CW) by averaging the entire element in the row and dividing it by the number of criteria. For example, the requirements weights for slope are as follows: CW (0.318+0.41+0.389+0.345+0.208+0.269+0.241+0.172+0.161+0.167)/10 = 0.2706. After obtaining the weights for each criterion, we have calculated the Eigenvalue (Lambda max), which will help us to determine the consistency index and the consistency ratio. The consistency index (CI) is expressed by (λ max-n)/n-1 where n is the number of criteria. The consistency ratio can be interpreted as the probability that the croak is completed randomly. The responses often have a certain degree of incoherence. The AHP method does not require that judgments are consistent or transitive, indeed, Saaty (1980) has defined the value of the consistency ratio. The consistency ratio equals the consistency index divided by the random index. If the CR is equal to or less than 0.1, the comparisons are considered consistent, otherwise, they would be revised. Since the value of CR is less than 0.1, which is standard, we have to conclude that the matrix is reasonably consistent. The table below is a clear check for the matrix.

**Table 4: Matrix Checking Parameters**

| | |
|---|---|
| λmax | 10.60 |
| λmax | **11.13** |
| CI | **0.13** |
| CR | **0.08** |
| RI | 1.49 |

***Weighted Overlay***

The weighted overlay tool is found in the spatial analyst tools under the overlay. It allows the calculation of multiple criteria analysis between several rasters. In the weighted overlay table, the input was the raster being weighed. The raster's influence compared to the criteria is expressed as a percentage of 100. Values are rounded down to the nearest integer. The sum of influence must be equal to 100. I specify the weights calculated for each parameter in the scale value place.

***Landslide Vulnerability Area***

The mapping of landslide susceptibility in Gakenke District, Rwanda, incorporates various parameters such as slope, distance from rivers and roads, soil texture, curvature, aspect, NDVI (Normalised Difference Vegetation Index), TWI (Topographic Wetness Index), land cover, and rainfall. A weighted overlay function was utilised to analyse these factors, assigning a slope a significant influence weight of 28.7%, marking it as the primary trigger for landslides. In contrast, curvature was deemed to have a minimal influence at approximately 1.6%.

The resulting landslide hazard map categorises areas into four classes: low, moderate, high, and very high hazard zones, effectively illustrating regions susceptible to landslide hazards based on the combined analysis of these parameters. This research illustrates the application of GIS tools and the Analytical Hierarchy Process (AHP) method to create a map identifying landslide-vulnerable areas in the northern region of Rwanda, especially the Gakenke district.

Key factors influencing landslides were analysed, including rainfall, slope, soil texture, distance from roads and rivers, TWI, NDVI, aspect, curvature, and land use/land cover (LULC). This research illustrates the application of GIS tools and the Analytical Hierarchy Process (AHP) method to create a map identifying landslide-vulnerable areas in the northern region of Rwanda, especially the Gakenke district. Key factors influencing landslides were analysed as slope (26.83%), rainfall (21.23%), soil texture (15.51%, and distance from roads (11.21%) as the most influential factors to landslide

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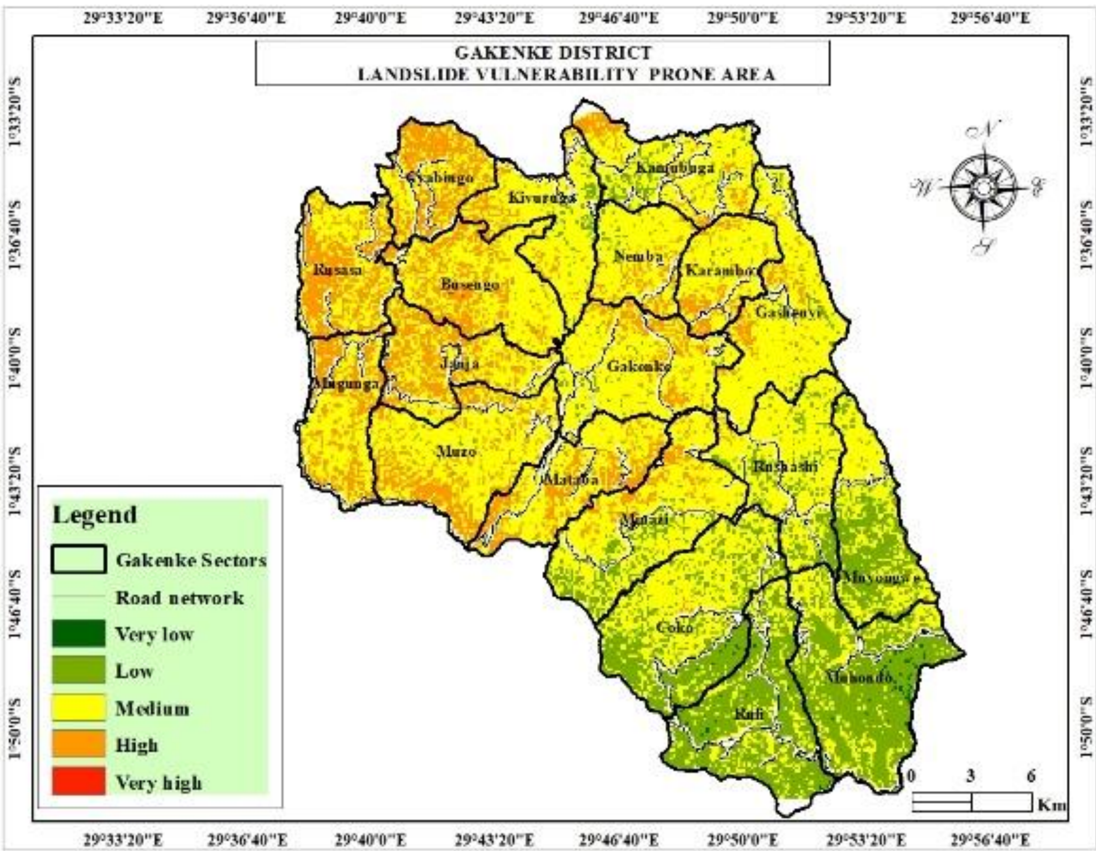
vulnerability in the study area. In addition, distance from the river (8.47%) and land use land cover (5.74%) exhibited moderate influence, while normalised difference vegetation index (4.03%), topographic wetness index (3.01%), aspect (2.1%), and curvature (1.59%) disclosed a low influence.

The resulting landslide coverage map showed that 18.12% of the area was classified as very high and highly vulnerable zones, mainly western and northern regions. Moderately vulnerable areas covered 60.7% of the central and eastern regions, while low and very low vulnerable zones comprised 21.2%, mainly in the southern and south-eastern regions. Despite some modelled results being deemed insignificant due to limitations in representing manual landslide management interventions, the methodology proves robust for developing shelter site maps for effective landslide management strategies.

**Figure 13: Landslide Susceptibility-prone Area of Gakenke District**




### *Slide Inventory Landslide Vulnerability Zones*

During the data inventory in the Gakenke District, landslide vulnerability zones were visited, including the Gakenke, Kivuruga, Nemba, and Kamubuga sectors, where several areas near the roads were identified as prone to landslides. The results indicate that landslides in these areas are primarily caused by human activities, such as providing steep cut slopes and farming on steep slopes, which destabilise the soil. The presence of moisture-retaining soils and scattered tree cover contributes to soil instability, increasing the risk of sliding, especially during heavy rainfall. To create a landslide vulnerability map for the district, a thorough examination of numerous parameters was carried out using Spatial Multi-Criteria Evaluation in ArcMap. Slope, Rainfall, soil texture, distance from the road, distance from the river, land use/cover, NDVI, topographic wetness index (TWI), aspect, and curvature were the ten important elements considered in this study.

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**Table 5: Slide Inventory Landslide Vulnerability Zones**

| S/ N | Longitude (Y) | Latitude (Y) | Soil type | LULC | Distance from road (m) | Distance from River (m) | Moisture |
|---|---|---|---|---|---|---|---|
| 1 | 29.796984 | -1.6569225 | vertisols | cropland | 10 | 50 | saturated |
| 2 | 29.779635 | -1.6456217 | vertisoil | grass | 10 | 50 | wet |
| 3 | 29.774922 | -1.6454331 | vertisol | scattered tree | 100 | 10 | wet |
| 4 | 29.770412 | -1.6280072 | vertisols | bare land | 10 | 80 | dry |
| 5 | 29.769792 | -1.6126094 | vertisoil with shist rock | Forest | 10 | 200 | wet |
| 6 | 29.766471 | -1.6020715 | vertisol | cropland | 10 | 200 | wet |
| 7 | 29.785318 | -1.5777379 | vertical | cropland | 10 | 200 | wet |
| 8 | 29.642942 | -1.6067363 | vertisol | cropland | 10 | 50 | saturated |
| 9 | 29.679443 | -1.5840396 | vertisoil | grass | 10 | 50 | wet |
| 10 | 29.684859 | -1.5654640 | vertisoil | scattered tree | 100 | 10 | wet |
| 11 | 29.703286 | -1.5741413 | vertical | bare land | 10 | 50 | dry |
| 12 | 29.766001 | -1.5897040 | vertisoil with shist rock | cropland | 100 | 50 | wet |
| 13 | 29.761249 | -1.557098 | vertisoil | grass | 10 | 50 | wet |
| 14 | 29.832088 | -1.5869259 | vertical | scattered tree | 10 | 10 | wet |
| 15 | 29.848402 | -1.5859057 | vertical | bare land | 10 | 80 | saturated |
| 16 | 29.861117 | -1.6184290 | vertisoil with shist rock | Forest | 10 | 200 | wet |
| 17 | 29.831987 | -1.6205207 | vertisols | cropland | 10 | 200 | wet |
| 18 | 29.815341 | -1.6124428 | vertical | cropland | 10 | 200 | dry |
| 19 | 29.710711 | -1.6190113 | vertisoil with shist rock | cropland | 10 | 200 | wet |
| 20 | 29.738530 | -1.6048292 | vertisols | grass | 10 | 200 | wet |
| 21 | 29.722676 | -1.5815272 | vertisoil with shist rock | Forest | 10 | 200 | wet |
| 22 | 29.767122 | -1.6082370 | vertisol | cropland | 10 | 200 | wet |
| 23 | 29.770843 | -1.5783828 | vertical | cropland | 10 | 200 | wet |
| 24 | 29.807184 | -1.5935479 | vertisol | cropland | 10 | 50 | saturated |
| 25 | 29.808289 | -1.5838130 | vertisoil | grass | 10 | 50 | wet |
| 26 | 29.81841414 | -1.5706505 | vertisoil | scattered tree | 100 | 10 | wet |
| 27 | 29.833972 | -1.5618848 | vertical | bare land | 10 | 50 | dry |
| 28 | 29.843845 | -1.5981694 | vertisoil with shist rock | cropland | 100 | 50 | wet |
| 29 | 29.762722 | -1.6683740 | vertical | cropland | 10 | 200 | wet |
| 30 | 29.769561 | -1.6561107 | vertisol | cropland | 10 | 50 | saturated |
| 31 | 29.840009 | -1.6597071 | vertisoil | grass | 10 | 50 | wet |

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| S/N | Longitude (Y) | Latitude (Y) | Soil type | LULC | Distance from road (m) | Distance from River (m) | Moisture |
|---|---|---|---|---|---|---|---|
| 32 | 29.876274 | -1.6534280 | vertisoil | scattered tree | 100 | 10 | wet |
| 33 | 29.865574 | -1.6324883 | vertical | bare land | 10 | 50 | dry |
| 34 | 29.677415 | -1.6465257 | vertical | cropland | 10 | 200 | wet |
| 35 | 29.796622 | -1.6367000 | vertisol | cropland | 10 | 50 | saturated |
| 36 | 29.672966 | -1.5837088 | vertisoil | grass | 10 | 50 | wet |
| 37 | 29.670638 | -1.6673891 | vertisoil | scattered tree | 100 | 10 | wet |
| 38 | 29.872408 | -1.6767598 | vertical | bare land | 10 | 50 | dry |
| 39 | 29.696732 | -1.6716553 | vertical | bare land | 10 | 50 | dry |
| 40 | 29.648167 | -1.636998 | vertisoil with shist rock | cropland | 100 | 50 | wet |

| Previous Slide Spot at the Gakenke Sector | Previous Slide Spot at the Nemba Sector |
|---|---|
|  |  |
| Previous Slide Spot at the Nemba Sector | Previous Slide Spot at the Kivuruga Sector |
|  |  |

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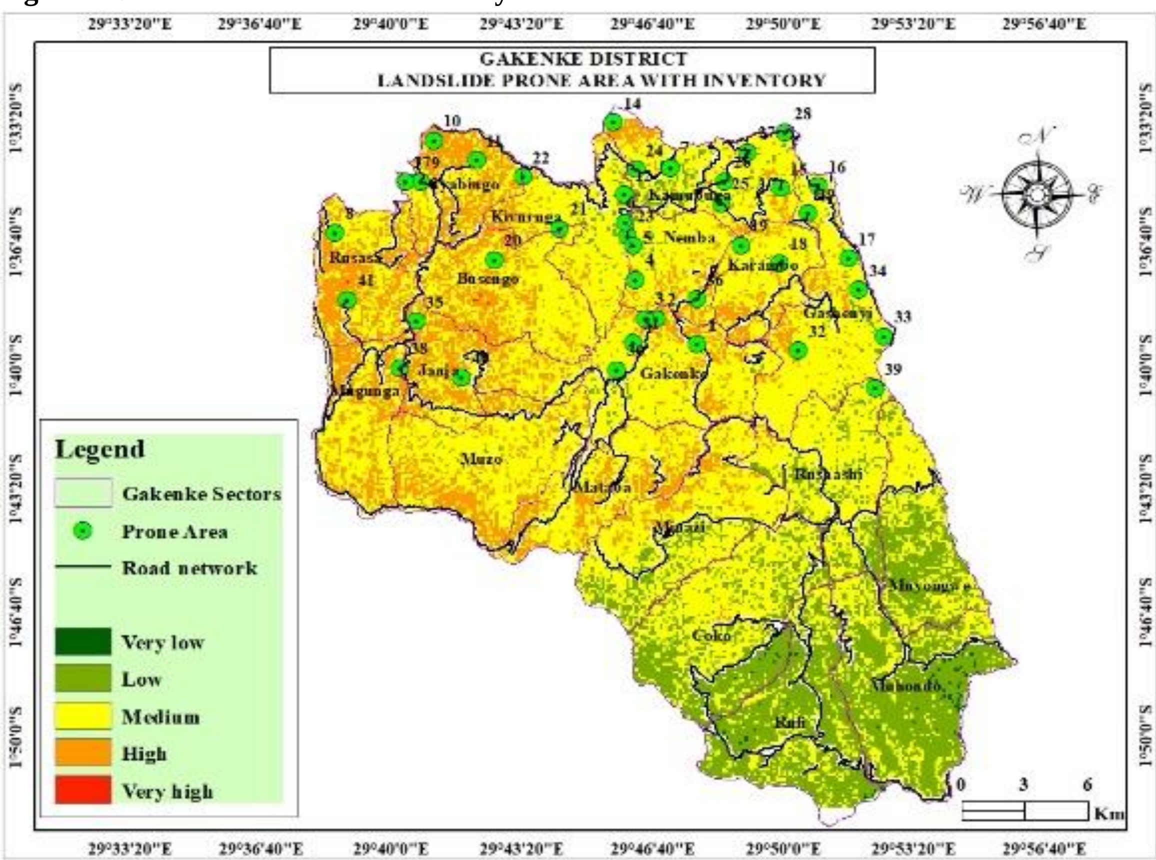
| Previous Slide Spot at the Kivuruga Sector | Previous Slide Spot at the Kamubuga Sector |
|---|---|
|  |  |

**Figure 14: Gakenke Landslide Inventory- Prone Area**




## Discussion

The results of this study reveal a nuanced pattern of landslide vulnerability across the Gakenke district of Rwanda. With 60.7% of the total area falling within the medium vulnerability category, the district exhibits a predominant moderate risk profile. However, the presence of high (18.1%) and

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very high (0.016%) vulnerability zones demands particular attention from disaster management authorities. The limited extent of very low vulnerability areas (0.2%) underscores the district's overall vulnerability to landslides, which aligns with historical records of landslide events in the region.

The spatial distribution of vulnerability zones corresponds strongly with the topographical characteristics of Gakenke, particularly its slope gradient, which emerged as the most influential factor (26.83% weight) in our AHP analysis. This finding is consistent with studies by Yalcin (2008) and Guzzetti et al. (2008), who identified slope as a primary trigger for landslides in mountainous regions. The steep terrain that characterises much of Gakenke creates ideal conditions for mass movements, especially when compounded by other destabilising factors.

Rainfall emerged as the second most influential factor (21.23%), highlighting the critical role of precipitation in landslide initiation within the district. The seasonal rainfall patterns in Rwanda, characterised by two rainy seasons, create cyclical patterns of soil saturation that reduce cohesion and increase pore water pressure in slope materials. This finding corroborates research by Dewitte et.al (2021) on rainfall thresholds for landslide occurrence in the East African Rift. The high weight assigned to rainfall suggests that climate change-induced alterations in precipitation patterns could potentially exacerbate landslide vulnerability in Gakenke in the coming decades.

Soil type (15.51%) and proximity to roads (11.21%) ranked third and fourth in influence, respectively. The significance of soil type reflects the varying mechanical properties of different soil formations in the district, with clay-rich soils presenting higher landslide susceptibility due to their water retention properties and lower shear strength when saturated. The influence of road proximity indicates the substantial impact of anthropogenic modifications on slope stability. Road cuts often destabilise slopes by removing lateral support and altering drainage patterns, creating artificial trigger points for landslides. This finding aligns with observations by Van Westen et al. (2016) on the relationship between infrastructure development and landslide occurrence in developing regions.

Hydrological factors, represented by distance to streams (8.47%) and TWI (4.03%), collectively contributed significantly to the vulnerability assessment. Stream networks in Gakenke often follow topographic lows, where they can undercut slopes and reduce stability, particularly during high flow periods. The moderate influence of land use/land cover (5.74%) reflects the protective role of vegetation in slope stabilisation through root reinforcement and reduction of surface runoff. Areas with reduced NDVI values (3.01% weight) showed increased vulnerability, confirming the importance of vegetation cover in landslide risk reduction. The relatively lower weights assigned to curvature (1.59%) suggest that while morphological characteristics of slopes influence water flow directions and concentrations, they play a secondary role compared to primary factors like slope gradient and rainfall intensity. This hierarchical relationship among factors demonstrates the complex, multi-dimensional nature of landslide vulnerability in the district.

The vulnerability patterns identified in Gakenke align with regional studies in the East African highlands. Research by Bizimana (2015) in northern Rwanda and Nsengiyumva et al. (2018) in the Western Province identified similar vulnerability factors, with topographical and meteorological variables consistently ranking highest in influence. This regional consistency suggests that the methodological approach employed in this study could be applicable to other districts in Rwanda with similar physiographic characteristics. The very high vulnerability zones (0.016%) identified in this study, while limited in spatial extent, coincide with areas that have historically experienced landslide events, validating the predictive capacity of the integrated AHP-GIS approach. These zones

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primarily occur at the convergence of multiple risk factors such as steep slopes, road cuts, stream proximity, and susceptible soil types, creating compound vulnerability scenarios that exceed individual factor thresholds.

The medium vulnerability classification for the majority of Gakenke (60.7%) presents both challenges and opportunities for regional planning. While not immediately critical, these areas could transition to higher vulnerability categories under changing environmental conditions or land use practices. The differential spatial distribution of vulnerability classes offers a scientific basis for prioritising risk reduction interventions, with immediate attention focused on the high and very high vulnerability zones.

The findings emphasise the need for the integration of landslide vulnerability assessments into broader land use planning frameworks in Rwanda. The identification of road construction and proximity as significant vulnerability factors suggests that infrastructure development projects in Gakenke should incorporate comprehensive geotechnical assessments and slope stability measures as standard practices. This aligns with Rwanda's Vision 2050 development goals, which emphasise sustainable infrastructure development and disaster resilience.

The significant vulnerability identified along settlement corridors, particularly on hilltops and near waterways, highlights the need for community-centred risk reduction strategies. The recommended measures should align with both engineering best practices and traditional Rwandan land management approaches. This integration of technical solutions with local knowledge creates a more sustainable and culturally appropriate risk reduction framework.

Relocation strategies for residents in very high and high-vulnerability zones must be approached with sensitivity to community attachments to place and livelihood dependencies. Successful implementation would require participatory approaches that engage community members in vulnerability mapping, solution design, and implementation monitoring.

The integrated approach combining remote sensing, GIS, and AHP represents a methodological advancement in landslide vulnerability assessment in the Rwandan context. The multi-criteria framework enabled the quantitative evaluation of diverse factors while accommodating expert knowledge through the pairwise comparison process. However, the subjective nature of factor weighting in AHP introduces potential bias, which could be addressed in future studies through sensitivity analysis or comparative application of alternative multi-criteria decision analysis methods. The resolution of available data, particularly for soil and geological factors, represents a limitation that could be addressed through more detailed field surveys and higher-resolution remote sensing. Additionally, the static nature of this assessment does not account for temporal dynamics in vulnerability factors, particularly rainfall patterns and land use changes, which could be incorporated through time-series analysis in follow-up studies.

Despite these limitations, the study provides a robust baseline for understanding landslide vulnerability in Gakenke and demonstrates the efficacy of integrated geospatial approaches for disaster risk assessment in developing regions with limited historical data and monitoring infrastructure.

## CONCLUSION

The comprehensive assessment of landslide vulnerability in Gakenke district, Rwanda, through the integration of remote sensing, GIS, and AHP methodologies, has yielded significant insights into the spatial distribution of landslide risk zones. The resulting landslide coverage map revealed that very high vulnerability areas accounted for 28.6%, medium vulnerability for 15%, low vulnerability for 6.9%, and high vulnerability for 49.4% of the total area. These findings are particularly crucial given the district's history of destructive landslide events and their impacts on local communities and infrastructure. The multi-factorial analysis, incorporating topographical, meteorological, geological, hydrological, and land use parameters, has enabled a detailed understanding of the complex interplay of factors driving landslide vulnerability in the region. This comprehensive approach has facilitated the development of a robust vulnerability assessment framework that can serve as a valuable tool for disaster risk reduction and spatial planning.

The study's findings underscore the urgent need for targeted intervention strategies, particularly in areas classified as high and very high vulnerability zones. The recommended measures, including reforestation initiatives, construction of toe protection walls, implementation of terracing systems, and installation of proper drainage infrastructure with check dams, represent practical steps toward enhancing community resilience. Moreover, the recommendation for relocating residents from high-risk areas, especially those residing on hilltops, emphasises the critical importance of proactive risk management. This research contributes significantly to the body of knowledge on landslide risk assessment and management in Rwanda, offering a methodological framework that could be adapted for similar studies in other regions. The findings provide a scientific basis for informed decision-making in disaster risk reduction and spatial planning, ultimately supporting the development of more resilient communities in landslide-prone areas.

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