SUSCEPTIBILITY MAPPING OF RAINFALL INDUCED LANDSLIDES: A CASE STUDY OF TCHODA MOUNTAIN, CHIRADZULU MALAWI.

BY

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A DISSERTATION SUBMITTED TO NDATA SCHOOL OF CLIMATE AND EARTH SCIENCES OF THE MALAWI UNIVERSITY OF SCIENCE AND TECHNOLOGY IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE BACHELOR OF SCIENCE DEGREE IN DISASTER RISK MANAGEMENT

(21 May, 2025.)

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DECLARATION

I CHISOMO PRINCE MAHAMBA hereby declare that this research has been written by me and is a record of my research work. All borrowed ideas have been properly acknowledged. None of the present work has been submitted previously for my degree or examination in other university.

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ABSTRACT

Landslides are among one of the greatest destructive hazards which result in a lot of fatalities and financial losses all over the word the world every year. The central objective of this research was to develop a landslide susceptibility map of rainfall induced landslides, a case study of Tchoda mountain Chiradzuru district. Different landslides triggering factors were identified namely aspect, slope angle, elevation, land use/land cover (LULC), lithology, proximity to streams and rainfall which were assessed and processed in a GIS platform to come up different maps that were overlayed to develop a landslide map. Landslide hazardous areas are analyzed and mapped using the landslide occurrence factors through the heuristic approach i.e. Analytical Hierarchical Process (AHP) to determine how each factor contributes to landslides occurrence. The integration of different landslide causative factors in GIS platform help in identifying susceptible areas that assist in managing land-use planning of susceptible development. The study encountered a number of implications as it relied on a lot of secondary data which was difficult to find. This study showed how value it is to come up with a landslide susceptibility using GIS and RS which could help in managing sustainable highland development by monitoring the hazard-susceptibility area.

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Specia thanks should as well go to my friend's disaster risk management class fourth year students for the support and my roommate Vincent Malongo not forgetting my family for the prayers that kept me going so as to achieve the desired goal.

LIST OF ABBREVIATIONS

RS…… Remote Sensing

GIS…… Geographic Information System

LSM…… Landslide Susceptibility Mapping

HI…… Hypsometric Integral

DEM…… Digital Elevation Model

DCCMS…… Department of Climate Change and Meteorological services

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Landslides are one of the most devastating geo-hazards across the globe (Abuzied & Alrefaee, 2019). They are responsible for 1,000 deaths per year and damage to property of about US4 billion globally (Pradhan, 2010). Landslides are downward movement of slope masses under the influence of gravity the masses include the rocks, mud, and debris (Poudel et al., 2020). These cause a lot of serious threats to populations and infrastructure such as buildings, roads and the transport sector, natural resource management and tourism (Lee & Pradhan, 2007). Due to rapid population growth especially in developing countries and unplanned settlements and changes in climate has accelerated the risk of different natural hazards including landslides (Vakhshoori & Zare, 2016).

Landslides happen in most mountainous terrain of tropical and subtropical environments (Vakhshoori & Zare, 2016). These landslides are triggered by a number of predisposing factors, some of them are; slope angle, slope aspect, landcover and use, lithology, altitude, distance to faults and streams as well as rainfall (Zahor & Yamungu, 2023a). Landslides have cause a lot of havoc globally, some of the catastrophic consequences of landslides globally include the 1966 Aberfan landslide in Wales, the 1972 Calabria landslide in Italy and the 1985 Armero landslide in Colombia (Msilimba & Holmes, 2010). Other documented devastating effects of landslides are the 1958 Kanogawa slides and mud/debris flow in Japan that caused 1094 deaths, the 1963bVaiont rockslide that claimed 2000 lives, the 1987 Reventador landslides in Ecuador that killed 1000 people, the 1994 Paez landslides in Colombia were 271 people lost their lives, that 2008 Cairo landslides claiming 119 lives, and the 2010 Gansu mudslides in China that took 1471 souls, these are some of the international areas where landslides lead to extensive effects (Moses, 2019a).

Africa has not been spared with the occurrence of landslides, although they happen almost in every region, they occur frequently in Sierra Leone, DR Congo, Nigeria, Cameroon, Ivory Coast, Kenya, Uganda, Rwanda, Ethiopia, and Tanzania. Highlands of East Africa such as

Ruwenzori in Uganda, Elgon in Kenya, Aberdare Ranges in Kenya and Bakavu in the Democratic Republic of Congo, landslides happen frequently and have impacted the environment and society (Moses, 2019a). The 2010 landslide in Uganda killed over 300 people and the 2008 Cairo landslides claiming 119 lives (Moses, 2019a). A number of similar landslides that have happened in East African region have not left Malawi out(Msilimba & Holmes, 2010).

Literature indicates that Malawi has also experienced significant impacts from landslides, for example the 1946 Zomba mountain (21 fatalities), the 1991 Phalombe district landslide (500 deaths and extensive damage) and the 2019 cyclone IDAI which resulted in loss of life and massive destruction in the southern (4 fatalities) and northern (3 deaths, 5 missing and 12 injured) regions. (Thiery et al., 2021). The recently documented landslide effects is that caused by cyclone Freddy in 2023, 14 districts were affected across the country, the southern region being the most affected region. This caused 511 deaths, 533 missing persons, 563771 displaced people and 126511 displaced households(*Malawi*, 2023). A lot of landslides studies have been conducted across the world using different probabilistic approaches (Lee, 2004). Some of these probabilistic methods of landslide susceptibility mapping include; heuristic methods, landslide density approach and physical based landslide models(Msilimba & Holmes, 2010).

Tchoda mountain is located in Chiradzulu district in southern Malawi. According to (*Malawi*, 2023) landslides caused by cyclone Freddy affected the residents of Tchoda and resulted in devastating consequences like property damage and crops and livestock being washed away. It is against this background this study tries to develop a landslide susceptibility map of Tchoda, which will be carried out with the help of GIS and RS incorporating WoE model.

1.2 PROBLEM STATEMENT

In all regions of Malawi, limited research on landslide has been done (Msilimba & Holmes, 2010). Moreover, the absence of spatial and temporal information on landslide events and triggering factors, especially rainfall induced landslide exacerbates this challenge(Thiery et al., n.d.). Although there have been limited research in the country, some research has been

conducted focusing mainly in Chiweta, and Ntchenachena, Zomba, Phalombe and Banga just to mention a few(Msilimba & Holmes, 2010; Thiery et al., 2024). So, based on the available literature it has been observed there no research has been done in Tchoda mountain Chiradzulu concerning landslide susceptibility mapping and there is a knowledge gap in this area. In reference to cyclone Freddy in 2023 in which Tchoda mountain was affected by the impacts of landslides, communities around Tchoda are vulnerable to similar event as they reside in steep slopes which contribute greatly to the occurrence of landslides. And this study attempts to bridge this knowledge gap by providing an in-depth analysis of landslide susceptibility mapping of rainfall-induced landslide which crucial for decision making, risk reduction and mitigation strategies.

1.3 OBJECTIVES

1.3.1 MAIN OBJECTIVE

The objective of this study is to develop a landslide susceptibility map of Tchoda mountain Chiradzulu using GIS and RS technologies that will be essential for decision-making, risk reduction and mitigation strategies.

1.3.2 SPECIFIC OBJECTIVES

This studies specificity is to;

I. Map landslide inventory of Tchoda mountain.
II. Analyze conditioning factors for rainfall-induced landslides.
III. Generate a detailed landslide susceptibility map to identify high risk zones.

1.4 RESEARCH QUESTIONS

This research will be based on the following questions;

I. What is the spatial distribution of landslides in Tchoda mountain?
II. Which factors influenced rainfall induced landslides in the area?

III. How can AHP be used to map landslide susceptibility in Tchoda mountain?

1.5 SIGNIFICANCE OF THE STUDY

Conducting landslides susceptibility mapping in Tchoda mountain using GIS and RS techniques together with statistical methods is of great importance. GIS and RS technologies will help in timely landslide detection, mapping, monitoring and analyzing landslide prone areas (Zahor & Yamungu, 2023b), AHP model helps in assigning ranks as how each of the predisposing factors contributed to the occurrence of landslides ((Othman et al., 2018). This will help in developing policies that can protect human activities that may trigger landslides occurrences and use this generated information to mark areas so that deaths and other economic or environmental impacts are minimized, this information can also be useful in choosing the best suitable areas for settlement and economic activities to reduce damage (Sarkar et al., 2008).

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Landslides can be defined as the movement of rock, soil or debris fall from a slope under the influence of gravity (Zahor & Yamungu, 2023b). Landslides are common in most mountainous regions of the world. These are counted as the most catastrophic geohazards that cause severe impacts throughout the world every year. Landslides can be categorized as in various forms as fall topple, rotational sliding, transitional sliding, lateral spreading etc. they slow down development processes in the country. They also cause death of 1000 people per year and monetary losses of US4 billion (Murthy et al., 2023). Before advancement of RS and GIS technologies, landslide susceptibility mapping relied on field surveys and visual interpretation of superimposed maps. These technologies are becoming widely used in undeveloped countries and has shown substantial evidence in reducing landslides, as they can process huge number of datasets (Sahana & Sajjad, 2017). This literature review will give an account of Landslide Susceptibility Mapping Tchoda mountain Chiradzulu district articulating methodologies, framework data requirements and challenges.

2.2 LANDSLIDES DISTRIBUTION AND TRENDS

Landslides are one of the most devastating geohazards causing deaths and property damage all over the world (Hategekimana et al., 2021). Literature reveals that a total of 3,876 landslides have occurred between 1994 and 2014 leading to 163,658 fatalities and 11,689 injuries. These events occur at different times of the year across the globe. In Northern Hemisphere they occur between June and December while in southern Hemisphere it is between December and February. In Latin America and the Caribbean landslides are most reported leading to many deaths and biodiversity losses mostly caused by the effects of El Nino and La Nina. The mostly affected are Haiti, Central America and Brazil. About 611 landslides incidence occurred between 2004 to 2013 with about 11,631 death as well as property and environmental destruction (Zahor & Yamungu, 2023b). Other examples of landslides incidences that have occurred across the globe include the 1972 Calabria landslide

in Italy, the 1970 Hauscaran landslide in Peru, the 1966 Aberfan landslide in Wales and the 1985 Armero landslide in Colombia (Msilimba & Holmes, 2010).

In Africa, landslide incidences are reported. Despite occurring in regions, they are common most common in Sierra Leone DR Congo, Uganda, Nigeria, Cameron, Ivory Coast, Kenya, Rwanda, Ethiopia, Tanzania and Malawi. Most East African highlands are different in terms of physiograph, geomorphology and rainfall but their susceptibility to landslides is common. Although there have been limited research across the African region but by the year 2018 literature 18,050 were reported (Zahor & Yamungu, 2023). According to Zahor & Yamungu, (2023), More than 500 people were killed and 2000 lost their homes as a result of such events in Sierra Leone, 1200 deaths in Burundi and 8000 have been accounted in Kivu GR Congo but its consequences remains a mystery.

Landslides incidences happening in Malawi are not different from those that happen across the region (Moses, 2019b; Zahor & Yamungu, 2023b). A lot of landslides have been documented across the country, the impacts of these incidences are catastrophic, the chiweta landslide (Moses, 2019), the Ntchenachena landslide (Msilimba & Holmes, 2010), the 1946 Zomba mountain landside that killed 21 people, the 1991 Phalombe district landslide that led to 500 death and extensive damage (Thiery et al., 2021). It is also reported about the 2023 cyclone Freddy which affected 14 districts causing 511 fatalities, 533 missing persons, 563,711 displaced persons and 126,511 displaced household (*Malawi*, 2023).

2.3 FACTORS INFLUENCING LANDSLIDES

Landslides occurrences depends on a number of factors including; lithology, slope angle, slope aspect, land use land cover, distance to roads and streams and rainfall (Shahabi et al., 2012). Literature reveals that about 94.2% of landslides happening in China are a result of heavy rainfall. A lot of these events happening from 1995 to 2014 in the world are caused by heavy amount of rainfall (Zahor & Yamungu, 2023b). (Poudel et al., 2020b) argued that slope and land cover are the biggest contributors of landslide occurrence. They identified that grounds with a slope of 10-degree to 90-degree are susceptible to landslides. In terms of land cover

land use, it explains that areas whose proximity to rivers is of short distance are at high risk of landslide as compared to those areas covered by forest, built-up area and snow-covered land are less susceptible to landslide (Zahor & Yamungu, 2023b). In different study, Othman et al., (2018) discusses that HI and lithology contributes greatly to the occurrence of landslides. As highlighted earlier the contributing factors are different in accordance with places. These factors represent the geological, climatic, hydrological and topographic factors of the area in question. Because of differences in geomorphology and landscape characteristic factors that contribute to the occurrence of landslides differently globally. That is why it is important to rank such factors in accordance to percent contribution (Zahor & Yamungu, 2023b).

2.4 GIS AND RS IN LANDSLIDE MANAGEMENT

Great amount of work has been made in the advancement of landslide susceptibility mapping, this being the case most of the work is carried out by GIS and RS techniques (Zahor & Yamungu, 2023b). According to Chen et al., (2010) these techniques were used in Iran, this applied weight to weighted overlay layers. RS is mainly used in acquiring visual images and other physical characteristics of the surface. Whilst GIS technology gives a room for processing datasets which is used in developing and managing social-economic environment. The use of such techniques is becoming widely used across the globe as it is important for timely landslide detection, mapping, monitoring, and analyzing landslide prone areas (Zahor & Yamungu, 2023b). In this study of Tchoda mountain GIS and RS techniques will be used to detect landslide-susceptible areas. This will rank different landslide predisposing factors using the AHP approach as to how each factor contributes to the occurrence of landslides.

2.5 ANALYTICAL HIERARCHICAL PROCESS (AHP)

Analytical hierarchical process (AHP) is a very useful method in landslide susceptibility mapping. This method was devised by Saaty. AHP is based upon three principles i.e. decomposition of problem, comparative judgement and synthesis of relative importance or ranking. AHP works on the principle of breaking the problem in hierarchical order and then ranking the criterion according to their relative importance. The weights can be assigned by

expert advice to the factors on which occurrence of landslide events depends upon. The weights purely depend upon the user's perception. So, the accuracy of the expert driven approach depends upon the accuracy of the weight that are assigned to each factor. The factors on which the occurrence of landslide events depends upon are compared in the pairwise comparison matrix and the ranking of each factor is calculated according to the relative importance.

2.6 RESEARCH GAP

RS and GIS have been widely used in LSM. And different methods have been used in assessing landslide causative factors (Murthy et al., 2023). A number of predisposing factors like slope angle, slope aspect, elevation, lithology, proximity to the road and streams and rainfall have been used (Moses, 2019b). Despite a lot of studies being conducted across the country, some only focus on the mechanisms and generations (Msilimba & Holmes, 2010), others susceptibility mapping using few contributing factors (Moses, 2019b). Although, the methods used in most studies have limitations in capturing spatial evidence (Zahor & Yamungu, 2023b). That is why this study will be conducted in Tchoda mountain to bridge the so that it develops LSM incorporating several causative factors using GIS, RS and AHP models taking into consideration spatial and temporal data.

CHAPTER 3.0 METHODOLOGY

3.1 RESEARCH DESIGN

This study will utilize both quantitative and qualitative research design. Specifically, AHP model whereby data on several predisposing factors those review in the literature will be collected with the purpose of ranking the factors to find out how each factor contribute to the occurrence of landslides.

3.2 ANALYTICAL HIERARCHICAL PROCESS (AHP)

Analytical hierarchical process (AHP) is a very useful method in landslide susceptibility mapping. This method was devised by Saaty. AHP is based upon three principles i.e. decomposition of problem, comparative judgement and synthesis of relative importance or ranking. AHP works on the principle of breaking the problem in hierarchical order and then ranking the criterion according to their relative importance. A numerical index called consistency ratio is also calculated to check the accuracy of the results. If λ_max is the maximum value of the pairwise comparison matrix and **n** is the number of the factors responsible for landslide occurrence, then consistency index is given by equation:

$$C.I = \frac{\lambda_max_{1}}{n-1}$$

The consistency ratio i.e. the ratio of consistency index and the randomness index. If the consistency ratio is less than 10%, then the weightages calculated are fairly accurate and can be used for deriving of susceptibility map. If the consistency index is more than 10% the weightages are to be calculated again.

$$LSM_{AHP} = \{(Rainfall*W_{AHP}) + (Slope*W_{AHP}) + (Aspect*W_{AHP}) + (Lithology*W_{AHP}) + (Elevation*W_{AHP}) + (Proximity\ to\ streams*W_{AHP}) + (LULC*W_{AHP})\}$$

Where W_{AHP} is the weightage for each landslide conditioning factor (Pourghasemi et al., 2012).

Table 1:Scale of preference between two parameters in AHP

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favor one element over another
5	Strong importance	Experience and judgement slightly favor one element over another
7	Very strong importance	One element is favored very strongly over another, its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	Used to represent comparisons between the preferences in weights 1,3,5,7,9
Reciprocals	Opposites	Used for inverse comparison

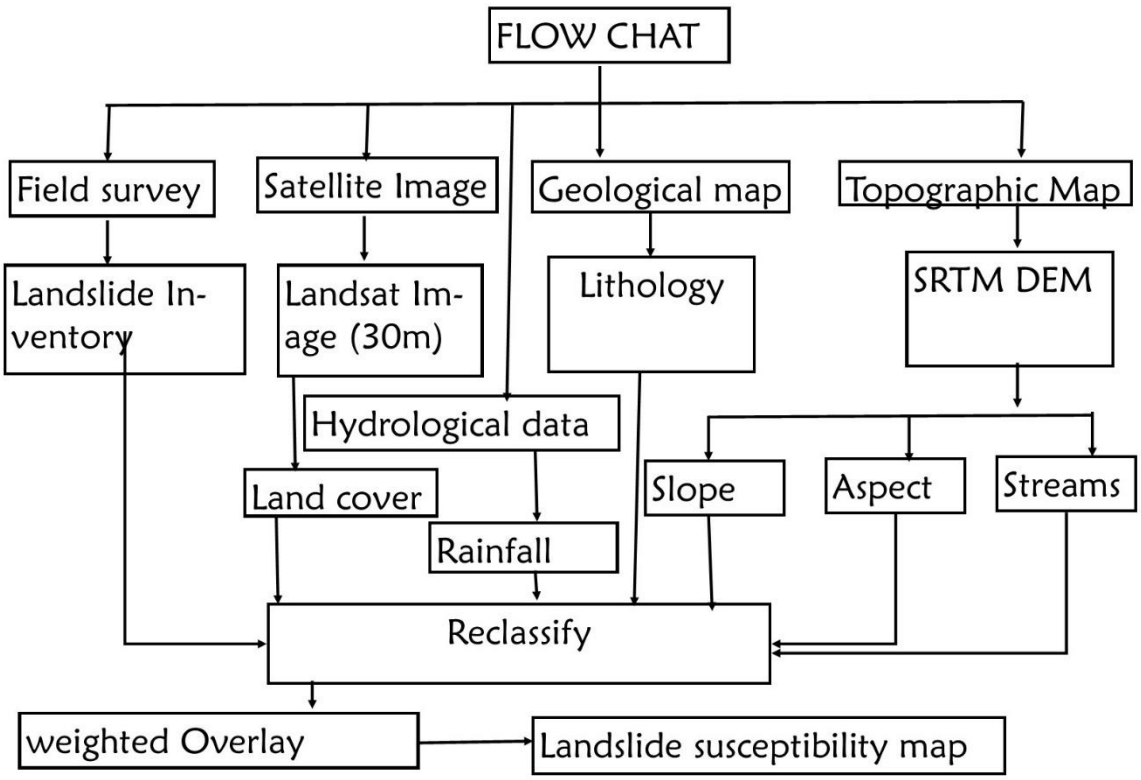


Figure 1: shows the methodology flow chart

NUMBER	DATA TYPE	DATA SOURCE
1	Geological map 1. Lithology	Geological Survey Department (GSD)
2	Satellite Image (Landsat image) Landcover	USGS
3	Topographic map Aster Dem) 1. Slope 2. Aspect 3. Streams 4. Elevation	USGS
4	Hydrological data 1. Rainfall	DCCMS (Department of climate change and meteorological services)

Table 2: showing sources of data

3.3 STUDY AREA

This study will be conducted in Tchoda mountain (Chiradzulu district), southern Malawi. It is located at an elevation of 830 meters above sea level and it lies at the latitude of 15°5260S and longitude of 35°1360E.

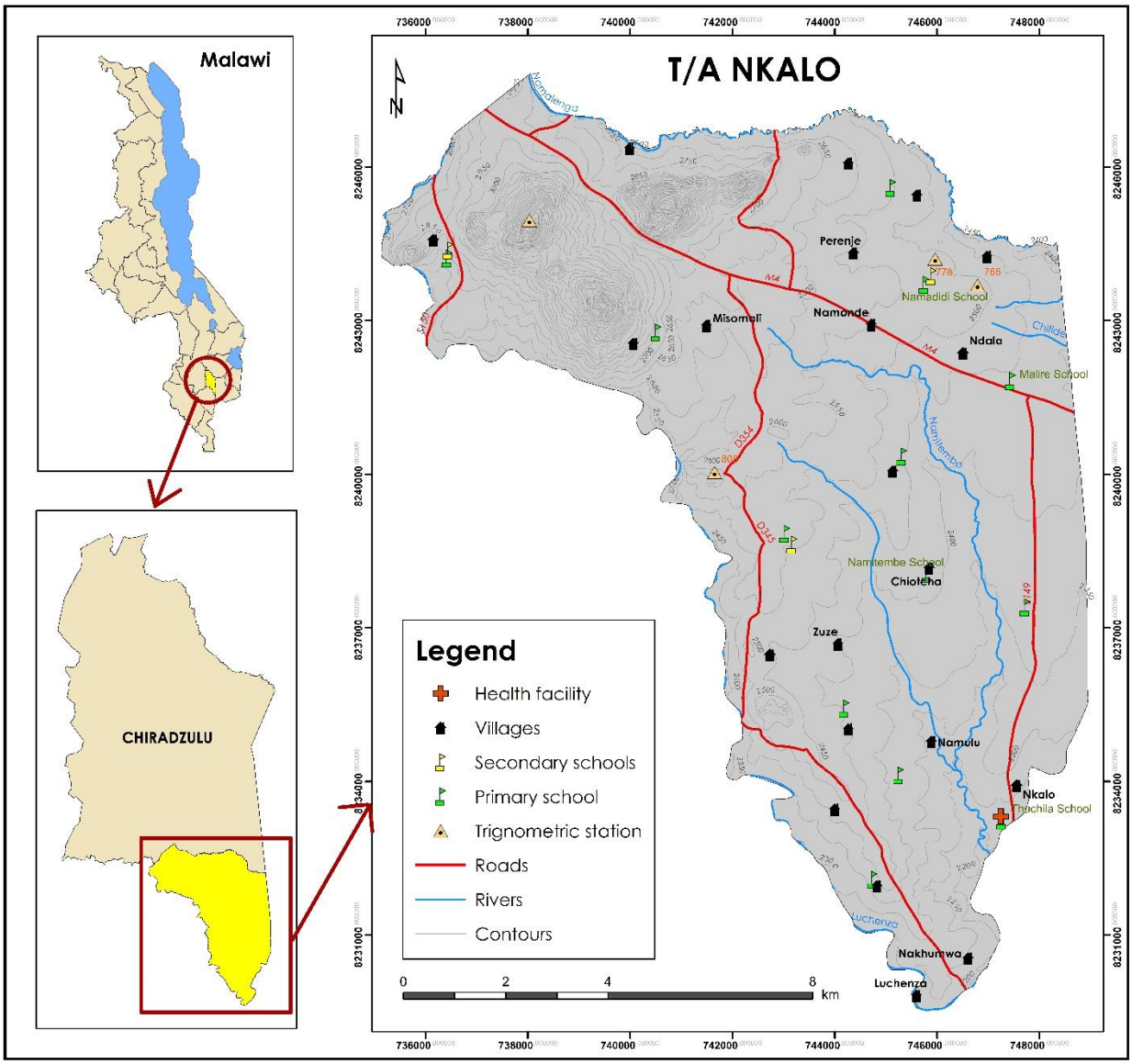


Figure 2: Map of study area

3.4 SITE SELECTION

This area has been chosen for this study because, as a hilly area it is prone to the occurrence of landslides based on different characteristic conditions, making the residents around the mountain vulnerable to the impacts of such hazard.

3.5 DATA COLLECTION AND SOURCES

This study will not involve direct collection of data but will use secondary data. The DEM will be used, geological map, topographic maps and rainfall data will be used that will be collected from DCCMS.

3.5.1 HISTORICAL LANDSLIDE/LANDSLIDE INVENTORY

Landslide inventories can be prepared from physical observation, by interpretation of remotely sensed images such as those based on spectral characteristics, shape, contrast, and the morphological expression or aerial photographs and google image interpretation (Rasyid et al., 2016). The key starting point in all versions of susceptibility mapping is to prepare landslide map as the first step of data production (Solaimani et al., 2013). Although there is no any agreement on the techniques for the preparation of landslide inventory map, researchers use different sampling strategies to prepare landslide inventory map including (I) drawing the main scarp of each landslide distinguished from the accumulation/depletion zone or rupture zone as polygon feature. (ii) showing landslides as seed cells.

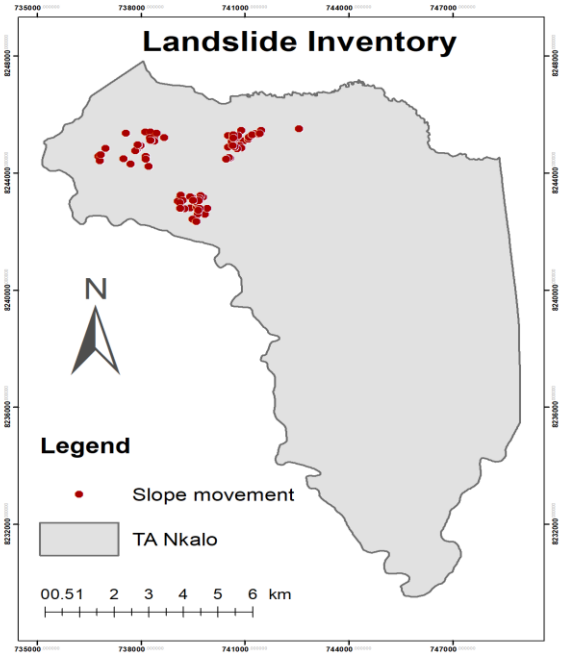


Figure 3:Inventory Map of Tchoda Mountain

3.5.2 2023 ANNUAL PRECIPITATION

Precipitation data is a key factor in analyzing and predicting landslides susceptibility. In this study, annual rainfall was chosen as a primary rainfall-related factor for analysis. By looking at yearly precipitation patterns, researchers can gain a broad understanding of rainfall distribution and identify areas that consistently receive high rainfall amounts, making them prone to landslides (Piciullo et al., 2018).

For this analysis, monthly rainfall from Thuchira weather station was gathered from the Department of Climate Change and Meteorological Services (DCCMS) for the year 2023. The annual rainfall was the calculated by adding up recorded monthly precipitation using Excell.

3.5.2.1 PRECIPITATION MAP PREPARATION

To analyze landslide susceptibility based on rainfall, a thematic data layer is created by generating classified precipitation map for the area (Tsaparas et al., 2002).

In this study, the process of creating a precipitation map began by converting the annual rainfall data into a CVS (Comma Separated Value) file using excel. This file was then imported into ArcGIS (ArcMap) to further analysis. To estimate rainfall in areas without stations, the Inverse Distance Interpolation method was used in ArcGIS. this technique predicts precipitation levels at unknown locations based on the rainfall data from nearby known stations.

Distance Interpolation process uses the following formula;

$A(x_o, y_o) = \sum w_i . P(x_i, y_i)$, Where: A = unknown precipitation at location (x_o, y_o), while P = precipitation at location (x_i, y_i) and w_i = weights (inverse of the distances). Thereafter, the resulting map was sliced to give a raster map with five classes: 1030-1055, 1055-1073, 1073-1088, 1088-1102 and 1102-119 (mm).

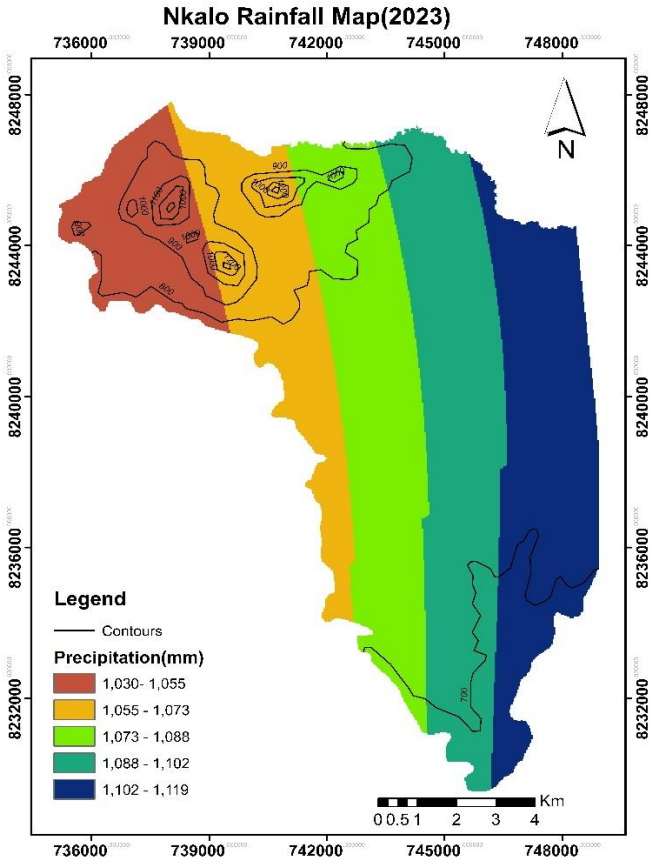


Figure 4:Rainfall Map

3.5.3 LANDSLIDE PREDISPOSING FACTORS

Different predisposing factors were studied based on the presence of other maps available in the country. In this study, the contributing factors of landslides were considered for the purpose of WOE modelling and preparation of susceptibility map. These factors are slope angle, lithology, land use/cover, elevation, slope aspect, rainfall and distance to rivers.

I. Slope angle

Slope is often used to study landslide probability, and all studies into the likelihood of landslides consider slope. Highly sloped areas and cleared areas receive exposure to direct

sunlight, thereby accelerating landslides occurrences. The slope angle is arguably considered one of the most predisposing factors for landslide modelling (Nurdin & Kubota, 2018). The slope angle data was collected from the Copernicus Global Digital Elevation model distributed by open Topography. https://doi.org/10.5069/G9028PQB.

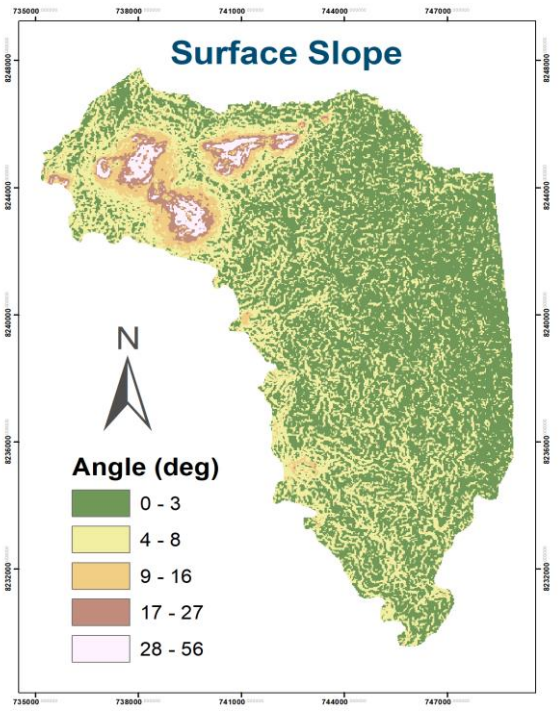


Figure 5:Slope angle map

II. Slope aspect

The slope aspect describes the slope direction. The influence of aspect on the occurrence of landslides can be direct or indirect; direct in the sense that the amount of water absorbed by soil or evaporated; indirectly because a correlation could be found between other landslide factors and the aspect factor model (Nurdin & Kubota, 2018). The slope aspect data was collected from the Copernicus Global Digital Elevation model distributed by open Topography. https://doi.org/10.5069/G9028PQB.

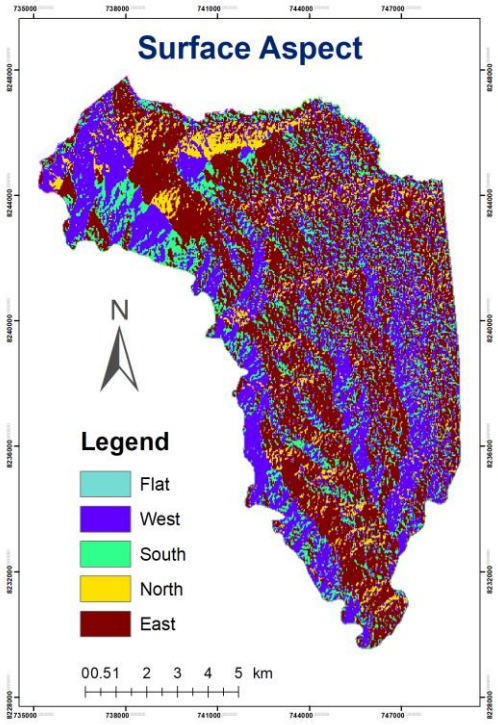


Figure 6:Aspect map

III. Land use/cover

Land use/cover is another triggering factor for the occurrence of landslides, since bare slopes are more prone to landslides. Conversely, vegetative areas tend to reduce action of climatic agents such as rain etc., thereby preventing the erosion due to anchorage provided by the tree roots thus less prone o landslides. A sentinel-2 image for land use/ cover was downloaded in Copernicus Data Space Ecosystem | Europe's eyes on Earth that was used in this study.

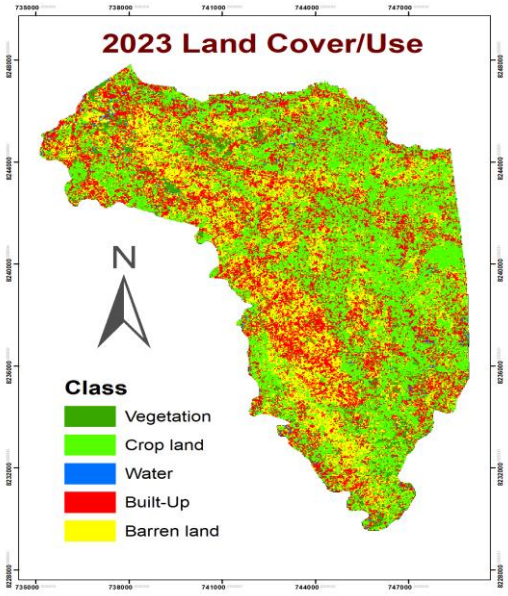


Figure 7:Land use land cover map

IV. Distance to streams

An important parameter that controls the stability of a slope is he saturation degree of the material on the slope. The closeness of the slope to the river is another aspect in terms of stability. Streams may adversely affect stability by eroding or by saturating the lower part of material until resulting increase in water level (Onagh et al., 2012). For it was obtained from open street map then doing Euclidean distance computation.

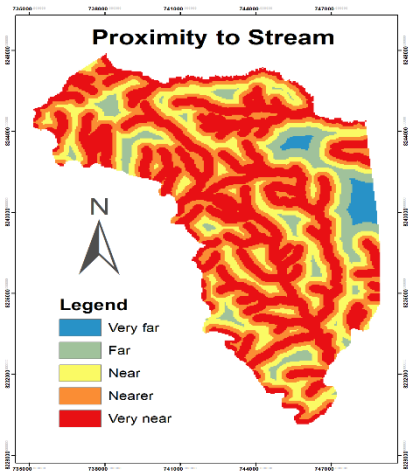


Figure 8:Proximity to streams map

V. Lithology

Lithology is considered to be one of the most significant triggering factors (Murthy et al., 2023).most of the landslide are concentrated in area where there is fine grained sediments and stones including Mable, sandstone etc. In this the lithology was obtained https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/60803da0-a15f-4cc5-9cb5-172fa2460af3.

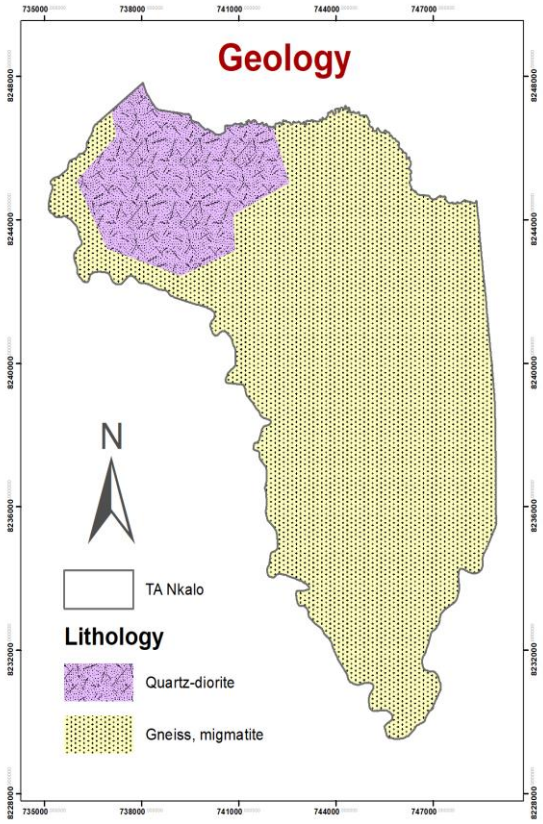


Figure 9:Geology map

VI. Elevation

Elevation is commonly used to assess landslide susceptibility. The variation in elevation may be related to several environmental settings such as rainfall and vegetation variety. A digital elevation model (DEM) can categorize the local relief and locate points of maximum and minimum heights within the terrain (Nurdin & Kubota, 2018). The likelihood of a landslide happening decreases as the elevation increases, this can be mainly imposed by the fact that as the elevation increases rocks are more resistant to weathering process landslides (Vakhshoori & Zare, 2016). Elevation data was collected from the Copernicus Global Digital Elevation Model, distributed by Open Topography https://doi.org/10.5069/G9028PQB.

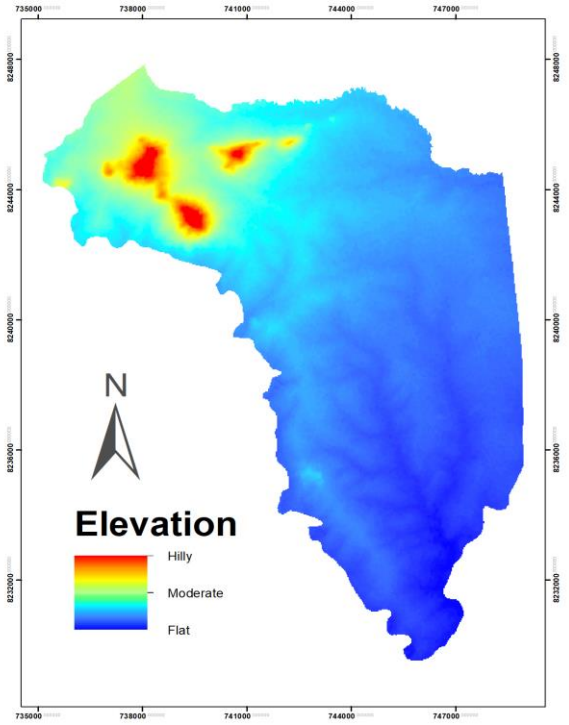


Figure 10:Elevation map

3.6 PREPARATION OF PREDISPOSING FACTOR MAPS

All the predisposing factors were prepared and analyzed in ArcGIS. The results of the classified maps were reclassified in different classes each representing its contribution in landslide occurrence. Those represented with numbers for exapmle five showed that it has higher occurrence of landslides while some were indicated with hilly, moderate flat for elevation, very far, fair, near, and nearer for proximity to streams and Quartz-Diorite and Gneiss-Migmatoite for geology.

3.6.1 PREDISPOSING FACTOR MAPS PREPARATION

All the predisposing factors were prepared and analyzed in ArcGIS. The results of the classified maps were reclassified in different classes each representing its contribution in the landslide occurrence. The higher factor class number shows it has a higher impact on landslide occurrence based on understanding and literature review.

Table 3:class factors with their categories

FACTOR	CLASS	CATEGORY
Land use/land cover	1	Vegetation
	2	Crop land
	3	Water
	4	Built up
	5	Barren land
Slope (degree)	1	0°-3°
	2	4°-8°
	3	9°-16°
	4	17°-27°
	5	28°-56°
Proximity to streams	1	Very far
	2	Fair
	3	Near
	4	Nearer
	5	Very near
Rainfall (mm)	1	1030-1055
	2	1055-1073
	3	1073-1088
	4	1088-1102
	5	1102-11919
Geology	1	Gneiss-Migmatite
	2	Quartz-Diorite
Elevation	1	Flat
	2	Moderate
	3	Hilly

3.7 DATA ANALYSIS

3.7.1 SUSCEPTIBILITY ANALYSIS

All the reclassified and rasterized factor maps were standardized to have the same coordinate system, **WGS 1984 UTM Zone 36S.** This standardization is crucial because differences in projection can cause misalignment of feature, leading to errors in analysis. Additionally, variations in pixel sizes can create biases in the results for instance a factor map with larger pixels may exaggerate its influence compared to one with smaller pixels. To analyze landslide prone areas a rasterized training landslide dataset was used. A tabulated area analysis was then conducted in ArcGIS where the number of pixels containing landslides in each factor class was calculated using a field calculator. This process helped quantify the relationship between landslides and different influencing factors

3.7.2 MAP VALIDATION

Validation of the landslide susceptibility map was physically verified in the field at few locations particularly at the very high and high susceptible zones. It was observed that the areas of very high and high susceptible zones are marked by slope stability signatures such as landslides, slope erosion, and road subsidence damage (Sarkar et al., 2008). Validation is essential for evaluating how well the model performs in generating the susceptibility map. It ensures the accuracy and reliability of the results. A well validated map supported by strong scientific evidence is more credible and useful for decision makers and stakeholders.

In this study, the susceptibility map was tested using existing landslide location data for the study area which were derived from field survey and satellite images. Spatial landslide sites that were collected using a handheld GPS was overlaid with landslide susceptibility map and most of the landslides matched with high to very high landslide susceptibility zones. This shows the accuracy of the results.

CHAPTER FOUR 4.0 RESULTS AND DISCUSSION

4.1 Results

Table 4:Analytical Hierarchical Process

Factor	Rainfall	Slope	Aspect	Elevation	LULC	Lithology	Prox. streams	Row sum	Weight
Rainfall	1	2	3	4	2	2	3	1.995	0.285
Slope	0.5	1	2	3	2	2	3	1.477	0.211
Aspect	0.33	0.5	1	2	1	1	2	0.831	0.119
Elevation	0.25	0.33	0.5	1	0.5	0.5	1	0.457	0.065
LULC	0.5	0.5	1	2	1	1	2	0.881	0.126
Lithology	0.5	0.5	1	2	1	1	2	0.881	0.126
Prox. streams	0.33	0.33	0.5	1	0.5	0.5	1	0.481	0.069

Table 5:Landslide Weights

Ranking	Factor	Weight
1	Rainfall	0.285
2	Slope	0.211
3	Lithology	0.126
4	LULC	0.126
5	Aspect	0.119
6	Proximity to streams	0.069
7	Elevation	0.065

4.1.1 Analytical Hierarchical Process

In this study, the Analytic Hierarchy Process (AHP) was employed to evaluate and assign relative importance to seven key factors that influence landslide susceptibility. These factors included Rainfall, Slope, Aspect, Elevation, Land Use/Land Cover (LULC), Lithology, and Proximity to Streams.

Comparing the seven factors in pairs according to how important they were in causing landslides was the first stage. Saaty's fundamental scale of preferences with values ranging from 1 (equal importance) to 9 (extreme importance), was used for this. Where one aspect was deemed less significant than another, reciprocal figures such as 1/3, 1/5, were employed. For instance, rainfall was given a value of 5 in that comparison since it was thought to be far more significant than elevation. In contrast, elevation received a score of 1/5 when compared to rainfall. Until the entire 7 by 7 matrix was filled, this procedure was repeated for every pairwise combination that might possibly exist, since each factor is equally important to itself, all 1s were found on the diagonal of the matrix.

Normalization came next after the comparison matrix was finished. To do this, the values in each column were summed up each matrix element was then divided by the sum of the values in its corresponding column. Bringing all values into a uniform scale, usually between 0 and 1 is the aim normalization. The original matrix is changed into a normalized matrix by this process with each cell denoting the relative contribution of a factor in a particular comparison. This makes it easy to compare components directly across several relevance scales. following normalization, the average of each row in the normalized matrix was used to determine the weights for each criterion. The sum of all consecutive normalized values was then divided by the total number of criteria, which in this case is seven. The weight of each component in determining landslide susceptibility is shown by this average, rainfall for example was given the highest weight suggesting that it has the greatest impact of all the variables. Because slope is also important to the stability of the landslide it also carried a lot weight. Elevation and proximity to streams on the other hand had lower weights indicating a more indirect contribution to landslide in the study area.

To ensure that the judgements made in the pairwise comparisons were logically consistent, a consistency check was performed. This involved calculating the weighted sum vector by multiplying each element in the original matrix by the corresponding weight from the criteria weight vector and summing across each row, each row total was then divided by the respective factor's weight to produce a consistency ratio estimate known as λ (lambda). The average of all λ values was taken as λ_max. with λ_max obtained the consistency Index (CI) was calculated using the formula:

CI= (λ_max-n)/ (n-1), where **n** is the number of criteria.

The consistency Ratio (CR) was computed by dividing the Consistency Index by the Random Index (RI) value corresponding to n=7. The resulting CR was well below the threshold of 0.1% (10%), confirming that the pairwise comparison were acceptably consistent and the derived weights were reliable. Through this structured AHP process, each factor was objectively assigned a weight based on its influence on landslide occurrence. Rainfall was identified as the most dominant factor, followed by slope, which is consistent with both literature and local observations. Other factors like LULC, lithology and aspect also showed moderate influence while elevation and proximity to streams had a lower but still notable impact.

4.2.2 Landslide weights

Using the landslide predisposing factors were calculated and changed into weights to represent landslide susceptibility. These values range from 0.065 to 0.285. The higher the weight, it indicates a relatively high susceptibility, rainfall has the highest weight followed by slope whilst elevation has the least. Based on the results from this process we can conclude that the occurrence of landslide in this study area was highly contributed to rainfall and slope.

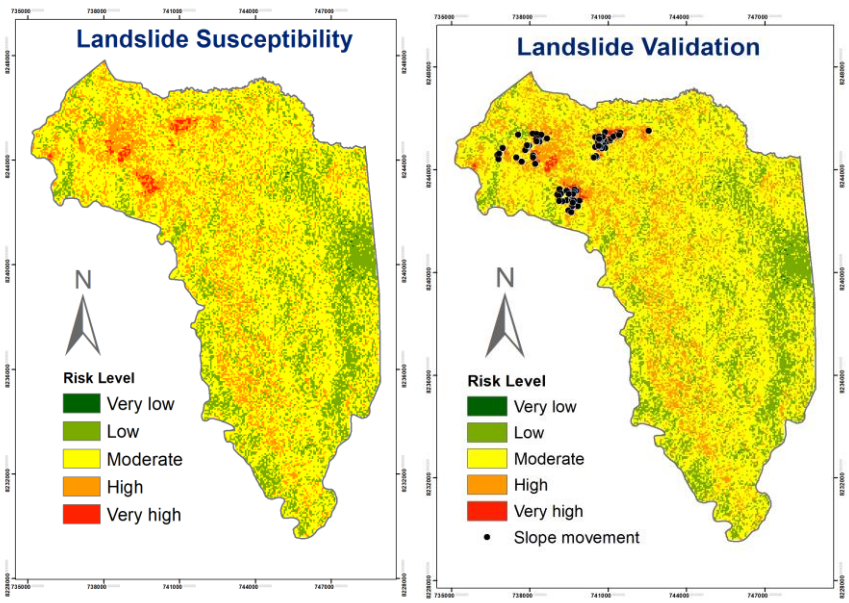


Figure 11:Susceptibility map (a) Validated map (b)

4.2 Discussion

The findings of this study underscore that landslide in Tchoda mountain was highly facilitated by extreme rainfall. According to reported Zahor & Yamungu,(2023), landslides in places like Makanya, Mlola and Mcheza Ngulu in Tanzania were caused by high amounts of rainfall due to water infiltration. In contrast, he also indicated that elevation played a significant role in the occurrence of landslides unlike in this study where it was found that elevation contributed indirectly to the occurrence of landslides. The research findings also closely agrees with (Abuzied & Alrefaee, 2019; Vakhshoori & Zare, 2016) who researched that most landslides are caused by extreme rainfall in infiltration of rainfall leading to increased pore water pressures in the subsurface and reduced shear strength, this is also in line with the findings in Virunga ranges (North Rwanda) that most landslides are concentrated in rainy season . With a different view, Akbari et al., (2020.) argued that a lot of landslides are concentrated in steep slopes which also agrees with these findings that after rainfall slope also contributes to the occurrence of landslides in this study area. It is also correlated that landslides lithology plays a role in the occurrence of landslides. It is also evidenced in the study by

Abuzied & Alrefaee, (2019) that landslides in El-Qaa area in Egypt were caused by the distance to faults followed by lithological units.

As evidenced from the findings of this study that landslides in this area were greatly caused by rainfall followed by slope angle and it was least contributed by elevation unlike in other studies where it was found out that some of these factors contributed more to the occurrence of landslides. This can only mean that the occurrence of landslides depends on several predisposing factors and with spatial and temporal aspects.

The findings of this study highlight that the landslide susceptibility map produced will prove to be vital if it will be incorporated into development plans of the area so that human loses, livelihoods, property and infrastructure is protected from the impacts of landslides. This study also brings into light that there should be enforcement of building codes so that communities members area restricted from building in areas that are prone to landslides occurrences to safeguard themselves and their properties. As it has been seen that the area is vulnerable to landslides caused by extreme rainfall there is need to come up with reliable early warning systems that will help in making sure that once rainfall amounts has reached a specific threshold the residence should know that its best they evacuate the area to minimize damages and losses and the findings will also make sure that there is proper awareness to the community members in the dangers of living in landslide prone areas and will also make it possible to incapacitate them with proper training on how the evacuation should be conducted in the event of the hazard and also lessons will incorporated in school curriculum so that children are not left behind and also training of specialist in these fields, and these will make sure that policy are in places so that the most vulnerable groups are not left like women, children, elderly and people with disability.

CHAPTER FIVE 5.0 CONCLUSION AND RECOMMENDATIONS

5.1 LIMITATIONS

There are limitations in the process of coming up with a susceptibility map, though interesting a lot of challenges are faced. The limitation is related to landslide inventory data. The data did not include the total number of the landslides within Tchoda mountain. In addition, the output landslide susceptibility map shows only spatial predicted landslides and not the temporal probability. Despite the mentioned limitations, the produced landslide susceptibility map could be useful to community and local officials. It could help design future land-use plans and implementation of developments. The results of this research could be helpful for explaining the known existing landslide, making emergency decisions and supporting the efforts of reduction and mitigation of future landslide hazard. Landslide hazard by excluding development in highly susceptible areas.

5.2 RECOMMENDATIONS

Utilize landslide susceptibility mapping in land use planning. Local authorities should adopt the susceptibility maps generated in this study to guide infrastructure development, agricultural activities and settlement planning. High risk areas should be avoided.

Enhance community awareness and preparedness. Communities living near Tchoda mountain need to be sensitized to landslide risks through target awareness campaigns. Training on emergency response early warning signals and safe construction practices should be introduced in vulnerable areas.

Develop a comprehensive landslide inventory system. There is a lack of centralized and consistent landslide records. Establishing a digital, GIS based inventory system managed by relevant government agencies would enable better hazard monitoring, support academic research and inform future susceptibility assessments.

Rainfall monitoring systems. Given the dominant role of rainfall in triggering landslides, real time rainfall monitoring stations should be installed in and around Tchoda mountain area. This will help in activating warning systems when thresholds are reached.

Reforestation and afforestation. Vegetation plays a critical in stabilizing the slopes, efforts should be made to plant more tress and avoid deforestation. This can be achieved by the community taking part in afforestation projects and sustainable land management practices that can significantly reduce landslide occurrences.

5.3 CONCLUSION

Landslides are among the most hazardous natural disasters. Government and research institutions worldwide have attempted for years to assess landslides hazards and risk to show their spatial distribution. This study successfully produced with the of RS and GIS a susceptibility map of rainfall induced landslides. Different predisposing factors namely aspect, slope angle, lithology, land use/land cover (LULC), elevation proximity to streams and rainfall were studied to find out which of the factors contributes more to the occurrence of landslides and how different strides can be taken so that landslides occurrence should not impact people, livelihoods, property and buildings. To come up with how each factor contributes to the occurrence of landslides AHP was used which uses pair wise comparison so that each factor shows how it contributes to landslide occurrence in Tchoda mountain Chiradzuru district. The contents of the susceptibility map identify factors that contributes to occurrence of rainfall induced landslide.

The main objective of this project was to come up with a landslide map by integrating remote sensing and GIS technologies, hazard and risk zonation helps to divide different areas according to their degree of hazards or risk. The core purpose of hazard and risk assessment is to facilitate decision-making concerning new developments within sloping areas susceptible to landslides. Through the similar application of RS and GIS it advises decision makers (e.g. local authorities) to identify where landslide might occur to minimize the impact of development.

References

Abuzied, S. M., & Alrefaee, H. A. (2019). Spatial prediction of landslide-susceptible zones in El-Qaá area, Egypt, using an integrated approach based on GIS statistical analysis. *Bulletin of Engineering Geology and the Environment*, *78*(4), 2169–2195. https://doi.org/10.1007/s10064-018-1302-x

Akbari, A., Yahaya, F. B. M., Azamirad, M., & Fanodi, M. (n.d.). *Landslide Susceptibility Mapping Using Logistic Regression Analysis and GIS Tools*.

Chen, Y., Khan, S., & Paydar, Z. (2010). To retire or expand? A fuzzy GIS-based spatial multi-criteria evaluation framework for irrigated agriculture. *Irrigation and Drainage*, *59*(2), 174–188. https://doi.org/10.1002/ird.470

Hategekimana, F., Nsengiyumva, C., & Edmond Rwabuhungu Rwatangabo, D. (2021). Review on the Geomorphological Approaches to the Landslide Susceptibility Analysis in Rwanda. *Academia Letters*. https://doi.org/10.20935/AL4197

Lee, S. (2004). Application of Likelihood Ratio and Logistic Regression Models to Landslide Susceptibility Mapping Using GIS. *Environmental Management*, *34*(2), 223–232. https://doi.org/10.1007/s00267-003-0077-3

Lee, S., & Pradhan, B. (2007). Landslide hazard mapping at Selangor, Malaysia using frequency ratio and logistic regression models. *Landslides*, *4*(1), 33–41. https://doi.org/10.1007/s10346-006-0047-y

Malawi: Tropical Cyclone Freddy - Department of Disaster Management Affairs (DoDMA) Situation Report No 9 (as of 23-24 March 2023) - Malawi | ReliefWeb. (2023, March 25). https://reliefweb.int/report/malawi/malawi-tropical-cyclone-freddy-department-disaster-management-affairs-dodma-situation-report-no-9-23-24-march-2023

Moses, D. N. (2019a). *Landslides Mapping and Susceptibility Analysis Using RS and QGIS Techniques in Chiweta Area, Northern Malawi*. *2*(1).

Moses, D. N. (2019b). *Landslides Mapping and Susceptibility Analysis Using RS and QGIS Techniques in Chiweta Area, Northern Malawi*. *2*(1).

Msilimba, G. G., & Holmes, P. J. (2010). Landslides in the Rumphi District of Northern Malawi: Characteristics and mechanisms of generation. *Natural Hazards*, *54*(3), 657–677. https://doi.org/10.1007/s11069-009-9495-8

Murthy, T., Yusoff, I. M., Samsudin, S. H., Majid, T. A., Abir, I. A., Yong, C. H., & Ismail, M. A. M. (2023). Geographical Information System (GIS)-Based Landslide Susceptibility Mapping in Malaysia: A Review of Past, Current and Future Trends. *Academic Journal of Interdisciplinary Studies*, *12*(3), 162. https://doi.org/10.36941/ajis-2023-0069

Nurdin, P. F., & Kubota, T. (2018). GIS-BASED LANDSLIDE SUSCEPTIBILITY ASSESSMENT AND FACTOR EFFECT ANALYSIS BY CERTAINTY FACTOR IN UPSTREAM OF JENEBERANG RIVER, INDONESIA. *Geoplanning: Journal of Geomatics and Planning*, *5*(1), 75. https://doi.org/10.14710/geoplanning.5.1.75-90

Onagh, M., Kumra, V. K., & Rai, P. K. (2012). LANDSLIDE SUSCEPTIBILITY MAPPING IN A PART OF UTTARKASHI DISTRICT (INDIA) BY MULTIPLE LINEAR REGRESSION METHOD. *International Journal of Geology*, *2*.

Othman, A. A., Al-Jaff, A. U., & Al-Manmi, D. A. (2018). *LANDSLIDE SUSCEPTIBILITY MAPPING USING REMOTE SENSING AND GIS APPLICATION: A CASE STUDY IN QALA DIZA AND SURROUNDING AREA, KURDISTAN REGION, NE IRAQ*.

Piciullo, L., Calvello, M., & Cepeda, J. M. (2018). Territorial early warning systems for rainfall-induced landslides. *Earth-Science Reviews*, *179*, 228–247. https://doi.org/10.1016/j.earscirev.2018.02.013

Poudel, K. R., Hamal, R., & Paudel, N. (2020a). Landslide Susceptibility Assessment: Identification and Hazard Mapping of Gandaki Province, Nepal. *Prithvi Academic Journal*, *3*, 11–21. https://doi.org/10.3126/paj.v3i0.29555

Poudel, K. R., Hamal, R., & Paudel, N. (2020b). Landslide Susceptibility Assessment: Identification and Hazard Mapping of Gandaki Province, Nepal. *Prithvi Academic Journal*, *3*, 11–21. https://doi.org/10.3126/paj.v3i0.29555

Pourghasemi, H. R., Pradhan, B., & Gokceoglu, C. (2012). Application of fuzzy logic and analytical hierarchy process (AHP) to landslide susceptibility mapping at Haraz

watershed, Iran. *Natural Hazards*, *63*(2), 965–996. https://doi.org/10.1007/s11069-012-0217-2

Pradhan, B. (2010). Landslide susceptibility mapping of a catchment area using frequency ratio, fuzzy logic and multivariate logistic regression approaches. *Journal of the Indian Society of Remote Sensing*, *38*(2), 301–320. https://doi.org/10.1007/s12524-010-0020-z

Rasyid, A. R., Bhandary, N. P., & Yatabe, R. (2016). Performance of frequency ratio and logistic regression model in creating GIS based landslides susceptibility map at Lompobattang Mountain, Indonesia. *Geoenvironmental Disasters*, *3*(1), 19. https://doi.org/10.1186/s40677-016-0053-x

Sahana, M., & Sajjad, H. (2017). Evaluating effectiveness of frequency ratio, fuzzy logic and logistic regression models in assessing landslide susceptibility: A case from Rudraprayag district, India. *Journal of Mountain Science*, *14*(11), 2150–2167. https://doi.org/10.1007/s11629-017-4404-1

Sarkar, S., Kanungo, D. P., Patra, A. K., & Kumar, P. (2008). GIS based spatial data analysis for landslide susceptibility mapping. *Journal of Mountain Science*, *5*(1), 52–62. https://doi.org/10.1007/s11629-008-0052-9

Shahabi, H., Ahmad, B. B., & Khezri, S. (2012). Landslide Susceptibility Mapping Using Image Satellite and GIS Technology. *International Journal of Engineering Research*, *1*(6).

Solaimani, K., Mousavi, S. Z., & Kavian, A. (2013). Landslide susceptibility mapping based on frequency ratio and logistic regression models. *Arabian Journal of Geosciences*, *6*(7), 2557–2569. https://doi.org/10.1007/s12517-012-0526-5

Thiery, Y., Kaonga, H., Mtumbuka, H., & Rohmer, J. (2021, March 4). *Landslide hazard assessment and mapping for Malawi (Southeastern Africa): From susceptibility to hazard by integration of temporal exceedance probabilities related to tropical meteorological events*. https://doi.org/10.5194/egusphere-egu21-6636

Thiery, Y., Kaonga, H., Mtumbuka, H., Rohmer, J., & Terrier, M. (n.d.). *Quantitative landslide hazard assessment at 1:250 000 scale for Malawi (Southeastern Africa)*.

Thiery, Y., Kaonga, H., Mtumbuka, H., Terrier, M., & Rohmer, J. (2024). Landslide hazard assessment and mapping at national scale for Malawi. *Journal of African Earth Sciences*, *212*, 105187. https://doi.org/10.1016/j.jafrearsci.2024.105187

Tsaparas, I., Rahardjo, H., Toll, D. G., & Leong, E. C. (2002). Controlling parameters for rainfall-induced landslides. *Computers and Geotechnics*, *29*(1), 1–27. https://doi.org/10.1016/S0266-352X(01)00019-2

Vakhshoori, V., & Zare, M. (2016). Landslide susceptibility mapping by comparing weight of evidence, fuzzy logic, and frequency ratio methods. *Geomatics, Natural Hazards and Risk*, *7*(5), 1731–1752. https://doi.org/10.1080/19475705.2016.1144655

Zahor, Z., & Yamungu, N. E. (2023a). Geographical Information Systems (GIS) and Remote Sensing (RS) Analysis for Landslides Susceptibility Mapping. *University of Dar Es Salaam Library Journal*, *17*(2), 72–93. https://doi.org/10.4314/udslj.v17i2.6

Zahor, Z., & Yamungu, N. E. (2023b). Geographical Information Systems (GIS) and Remote Sensing (RS) Analysis for Landslides Susceptibility Mapping. *University of Dar Es Salaam Library Journal*, *17*(2), 72–93. https://doi.org/10.4314/udslj.v17i2.6