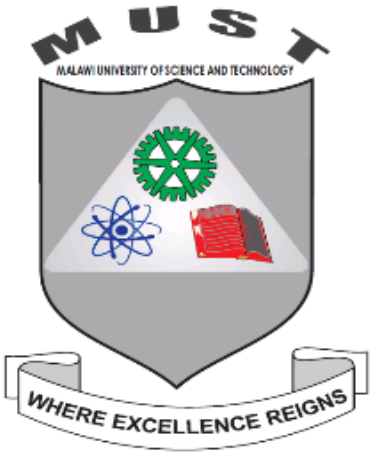


LANDSLIDE SUSCEPTIBILTY ASSESSMENT USING GIS MODELING - The case study of Zomba Mountain areas

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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 Earth Sciences

30 JULY, 2021

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ABSTRACT

Landslide susceptibility mapping is a practical tool in natural and urban planning. It can be applied for determining land use zone, in construction design, and planning of a variety of projects. In this study, GIS based landslide susceptibility map were generated in the mountainous parts of Zomba district at the Southern part of Zomba Mountain plateau which has helped in determining the slope effects that can induces landslides in the study area. This was accomplished by using the weight of evidence (WoE) method for correlating the causative factors which have an effects on landslide occurrences. The instability factors taken into account were lithology, slope angle, slope aspect, distance to stream, curvature and land use. These factors were integrated in GIS environment for constructing the thematic layers of factor dataset. For this bivariate statistical approach, significant assumptions were emphasized prior to the study to establish conditional independence between each pair of components. In addition, a detailed landslide inventory map was constructed through field investigation and Google earth image interpretation process at a scale of 1:125,000. The thematic layers and landslide map were overlapped to obtain a spatial statistical relationship. The produced susceptibility map were classified into four zones: Very Low, Low, Moderate, and High susceptible zones and validated using the other half number of the landslide events of the area. The map indicates that more than 90% of the landslides were in categories of high and moderate susceptibility zones. The causative factor classes incl uding the slope class >55, the north facing slopes, the highly weathered Syenites and superficial deposits of Dambo soils and the bare lands were identified to considerably influence the landslide in the study area.

ACKNOWLEDGEMENTS

I am greatly indebted to my supervisor Mr. Mzee .W. Nyirongo for his unreserved guidance and general expert hand rendered throughout proposal writing up to completion of this reaserch. Thanks to Geological Survey Department for providing with the geological dataset for use in this research. Deep thanks to my brother Dr. Bosco Rusuwa and sister Benelita Rusuwa for all the support and kindness they have been giving me throughout my University education. May the good Lord bless you and reward you for your unreserved support and kindness. To my family, friends and

colleagues, I am grateful for your moral and material support. Finally, I give thanks to Almighty God

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ACRONYMS/ABBREVIATIONS

Cw:	Contrast Weight
DoDMA:	Department of Disaster Management Affairs
DEM:	Digital Elevation Model
GIS:	Geographic Information System
GPS:	Geographic Positioning System
GSD:	Geological Survey Department
LSI:	Landslide Susceptibility Index
SM:	Slope movement

SRTM: Shuttle Radar Topographical Mission

USGS: United States Geological Survey

UTM: Universal Transverse Mercator

W+: positive weight

W-: negative weight

WGS: World Geodetic System

WOE: Weight of Evidence

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1.0. INTRODUCTION

1,1. Background of the Study

In many parts of the World, mass wasting have caused damages in the natural and built environment. It may occur in various forms such as landslides, rock falls, soil creep, and mudflows. Landslides have been described as the most significant damaging events in mountainous regions of the world (Mersha & Meten, 2020). The term “landslide” is defined as the movement of a mass of rock, debris or earth down a slope under the influence of gravity (Bell, 2007). This can involve flowing, sliding, toppling or falling movements and many landslides exhibit a combination of two or more types of movements (Crozier, 1986); (Cruden & D.J, 1996); (Dikau, et al., 1996). Mountainous areas are vulnerable to mass movements due to conditional and triggering causal factors. Triggering causal factors (e.g. rainfall, tremors and land use) are external stimuli responsible for the actual initiation of mass movements. Whereas the conditional factors such as geology, weathering, soils, topography are responsible for inducing slope instability. Anthropogenic activities in mountainous regions commonly cause the formation of unstable areas in the earth material on hill slopes (Nugraha, et al., 2014).

Landslide hazard zonation have been found as an effective way of managing landslides and is defined as the mapping of areas with an equal probability of occurrence of landslides within a specified period of time (Varnes, 1984). Normally, a landslide hazard zonation consists of two different aspects: (a) the assessment of the susceptibility of the terrain for landslides, expressing the likelihood that a landslide might occur under the given terrain conditions or parameters. (b) The determination of the probability that a triggering event occurs, such as a major rainfall event or an earthquake. A relation is made between the magnitude and return period of the triggering event and the occurrence of landslides, either through historical studies or through physical models (Western & Rengers, 2003),

A number of methods for slope movement susceptibility zonation using GIS have

been proposed in the susceptibility literature (Ayonghe & Ntasin, 2003) (Mwenelupembe & Mylius,

1.2. Problem statement

Landslides have caused havoc on Malawi's natural and built environments. When these geo-hazards occur, they take lives and destroy valuable assets such as livestock, buildings, and housing utilities worth millions of Kwacha. Furthermore, crops become destroyed, which results in severe famine throughout the country. As a result, the Malawian government has lost a large amount of money that have been spent on recovery and response. In the current study area, a number of landslides have been recorded, including the 1946 debris flow that killed at least 22 people and destroyed two villages, 24 bridges, roads, crops, and water supplies, as well as the 1997 and 1999 landslides that blocked Kuchawe road (World Bank, 2019). However, no studies have been conducted in the area to correlate landscape's characteristics and its susceptibility to landslides occurrence. Such occurrences emphasize the need for adequate slope movement hazard reduction techniques in these mountainous terrains.

Furthermore, despite the fact that landslides are one of the most dangerous geo hazards in the world, they are not taken seriously in Malawi since people are still building houses and settling on mountain slopes. For example, following the 1946 debris flow, a number of development projects below the mountain slopes, such as the Kuchawe Hotel and various camping grounds, as well as the Mulunguzi dam, have taken place in the current study area. These existing settlement patterns, as well as anthropogenic activity, have the potential to affect significant cataclysmic events.

Therefore, a complete systematic mapping was required for this area in order to identify the high-risk zones and generate susceptibility maps. This will help to reduce and mitigate the risk of future landslides.

1.3. Objectives of the study

1.3.1. Main Objective

The main purpose of this research was to assess the susceptibility of the area to landslides occurrence and create a reliable landslide susceptibility map for the Zomba district in the southern part of Zomba Mountain plateau, Malawi, to mitigate potential landslide hazards.

1.3.2. Specific Objectives

- To produce structural and geomorphological map of the area.
- To relate landscape characteristics to landslide occurrence in Zomba Mountain areas.
- To produce susceptibility map of the study area.

1.4. Research Questions

- Are there susceptibility map of Zomba area?
- What geomorphologic structural parameters on slopes in the study area can possibly facilitate landslides?
- What is the relationship between landscape characteristics and landslide occurrence in the study area?

1.5. Significance of the Study

The results of this study are critical because they shall enable users (planners, engineers, and property owners) to assess levels of risk and make appropriate precautions and decisions for the proper allocation of socioeconomic development projects on land, such as hotels, roads, and reservoir dams. The susceptibility map produced for the area can be employed in the environmental planning of landslide-prone areas as a decision support system for decision makers and public managers. A thorough landslide investigation aids in the reduction of damage to infrastructure, homes, and cultivated areas, as well as the loss of lives. When these landslide susceptibility maps are used by decision-makers in regional land use planning, landslide prevention, and mitigation activities, their relevance will be recognized.

1.6. General Setting

The study was conducted in Zomba Mountain areas within Zomba plateau in Zomba district Southern part of Malawi. Zomba Mountain is located to the South of the Zomba plateau (Zomba massif). It is a Mountain of the Shire highlands in the Southern Malawi. The study area covers a total area of about 130 square kilometers (50sq mi), with the highest elevation of 2,087 meters (6,847ft).The area is bounded within $15^0$00S and $15^0$30^0 S parallel of latitude, the 35^0 00E parallel of longitude and Western shores of Lake Chilwa (Bloomfield, 1965).

Zomba Mountain is composed of a Mesozoic syenite pluton that intruded Precambrian high-grade metamorphic gneisses and granulites. The Southern and Eastern scarps of Zomba Mountain attain a maximum height of 914.4 meters and have been formed by the differential erosion of the syenites making up the Massif and the surrounding Basement Complex gneisses. Weathering erosion and uplift have left the syenite standing at an elevation of 2000 meters while surrounding area is between 700 and 1000 meters above sea level. Zomba town is located at the foot of the Mountain. The slopes of the plateau above the inhabited locations have experienced erosion and landslides. As a consequence, the top soil was removed, exposing rocks and making the slopes unstable. The topography of Zomba is further dominated by several hills surrounding the city and some within the city. From these hills (mainly in the north towards Zomba Plateau and south), small streams connect to the main Likangala River, which flows through the city centre from west to east. Meanwhile, the Mulunguzi River, which originates from Zomba Plateau, flows through two of the wards in the north-east of the city. During the rainy season, increased water run-off in up-hill areas into the rivers flowing through the city causes flooding. In particular, Likangala River is the source of most floods and disasters, as it flows through densely populated areas. The risk profile of Zomba includes flooding, cyclones and strong winds. Since the city is located in the African Rift Valley, it is prone to earthquakes. Bush fires are also common, especially in the woods of the Zomba Plateau. Soil erosion, gully development, landslides and rock avalanches are common and to a certain extent linked to deforestation, which causes land degradation.

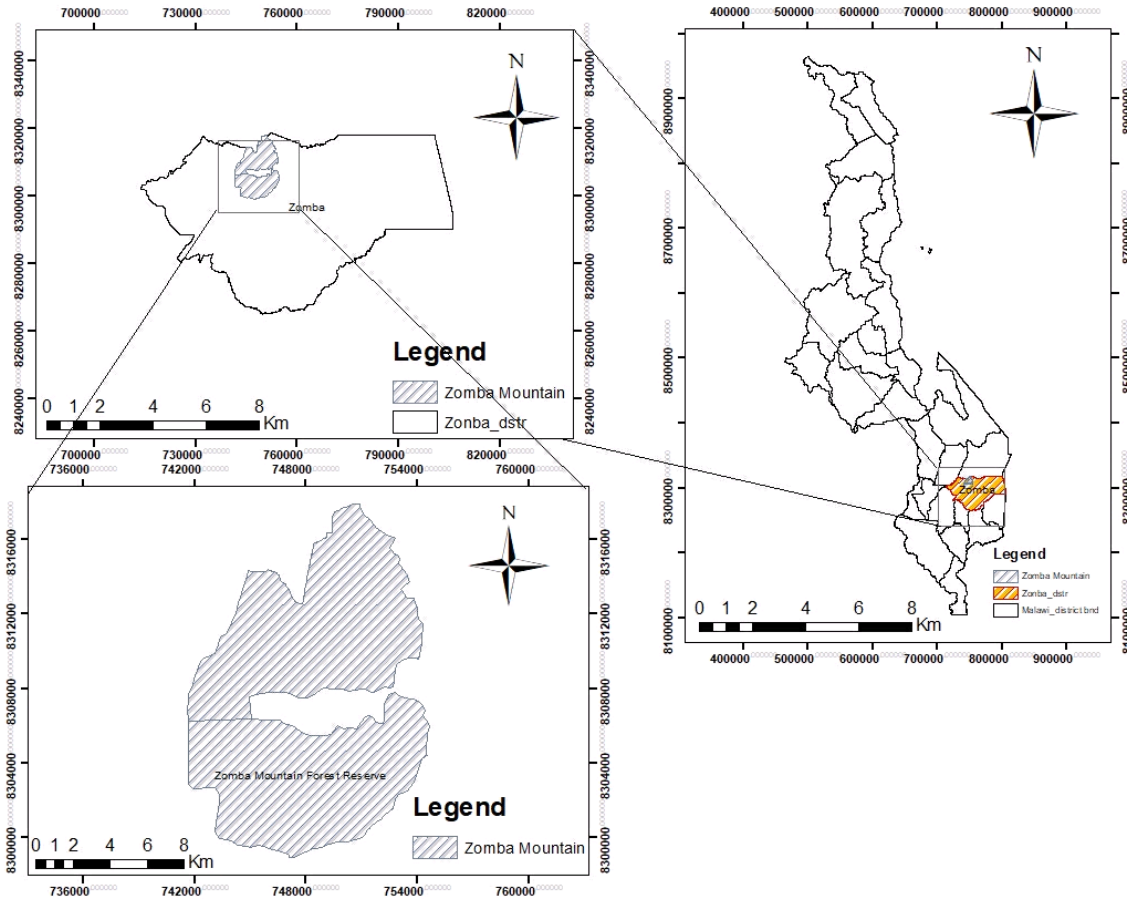


Figure 1: Map of Malawi showing the study Area (Zomba Mountain).

2.0. LITERATURE REVIEW

2.1. Slope Instability

Slopes are a remarkable feature of the landscape not only true of mountainous and hilly areas but also of many plains. However their pronounced nature within the mountainous and hilly areas makes them dynamic landscapes that are often mentioned as high energy landscapes of vast instabilities (Gumisiriza, 2014). The high altitude, steep slopes, extreme climatic conditions and above all gravity combine to make these areas a dynamic mechanism where geomorphic processes are often rapid and at times reach catastrophic extents. Slope instability is one of the major problems in geotechnical engineering where loss of life and property can and do occur (Soeters & Westen, 2007). These can occur on both man-made and natural slopes around the world (for example, hilly regions, embankments, road cuts, open-pit mining, excavations, riverbanks, and landfills). Slope instability therefore is a problem of either increased shear stress on a slope or reduced shear resistance of material covering a slope and its climax is shear failure manifested as slope failure. This kind of situation is a reflection of destruction of natural slope stability which is as a result of both natural as well as human inducing factors (Soeters & Westen, 2007). Although slope instability can occur on any inclined surface, the physical conditions as well as human activities in the hilly and mountainous areas make them susceptible to rapid movements which are often disastrous. As a result, not only are significant financial costs spent, but huge ecological and environmental issues also arise across wide geographic areas (Li, 1994; Larsen and Torres-Sanchez, 1998). In hilly settings, mapping or designating areas prone to slope failures is critical for land-use planning.

2.2. Factors that influence slope failures

There are several factors that influence slope failures. These include; climatic conditions, such as precipitation and evaporation, geological factors including soil and rock properties, topographical factors including slope gradient, aspect and angle, riparian vegetation (grasses/woody species), and land use/cover factors, including infrastructures.

2.3. Occurrences of Landslides in Africa

In Africa, various researchers have reported landslide problems in highland and mountainous environment, for instance in Kenya ((Davies, 1996) (Ngecu & Ichang, 1999) (Westerberg & Christiansson, 1999), Cameroon (Zogning, Ngouanet, & Tiafack, 2007) (Ayonghe & Ntasin, 2003), Rwanda (Bizimana, 2015) and Ethiopia (Broothaerts, et al., 2012). Although the East African highlands are a very heterogeneous region in terms of physiography, geomorphology and rainfall (Knapen et al., 2006), they have a high vulnerability to slope instability in common. The high annual rainfall, high weathering rates, deforestation and slope material with a low shear resistance or high clay content are often considered the main preconditions for landslides (Psomiadis, Papazachariou, Soulis, & Alexiou, 2020). Malawi has experienced a number of landslides, the causes of which are comparable to those in the East African region (Cheyo, 1999; Mwenelupembe, 1999; and Msilimba and Holmes, 2005). The 1946 Zomba Mountain debris flow (Cheyo, 1999), the 1991 Phalombe Landslide (Poschinger et al., 1998), and the 1997 Banga Landslide (Poschinger et al., 1998) are all examples (Msilimba, 2007; and Msilimba and Holmes, 2005).

2.4. The Landslide Susceptibility Assessment and Mapping

Landslide susceptibility is defined as the possibility of a mass movement (landslide) occurring in an area given the local geo-environment. Past landslides and various conditioning factors such as slope morphology, weathering conditions, land use, and geology of the area are the main parameters used to assess and evaluate landslide susceptibility in a GIS environment (Cao, et al., 2021). Landslide susceptibility assessment and mapping has been found to be a very useful tool in landslide hazard management as it shows the degree of susceptibility of an area to landslide occurrence (Mersha & Meten, 2020). The landslide susceptibility maps can be generated based on the assumption that future landslides will occur under the same conditions as in the past. This requires understanding the variables and processes that regulate slope instability in the research area, which is necessary for interpreting future landslide events (Cruden & D.J, 1996).

Different methods for landslide susceptibility zonation using GIS have been proposed in the susceptibility literature and are classified as qualitative techniques and

quantitative techniques. Qualitative techniques include geomorphological analyses and inventory m

In terms of prediction capability, several studies have employed the WOE model in comparison to a few methodologies such as frequency ratio, fuzzy gamma, and landslide index models. The weight of evidence (WoE) method has been successfully applied in hazard mapping due to its predictive power of each causative factor and considers the relationship among both the presence of each factor class and the absence of remaining sub-classes and the landslide events. WoE method employs the Bayesian probability model in a log-linear form, and each factor can be linearly superposed in the GIS environment (Cao, et al., 2021). Other reasons for adopting the WoE method rely on the independent characteristics of each variable of landslide factor. Thus, the effect of each causative factor can be independently considered and a decreasing number of variables can be ascertained in a slope susceptibility analysis, compared with other statistical methods, for avoiding possible existence of mutual correlated factors, otherwise, which might derive unreliable results. Therefore an optimal set of slope instability causative factors can be selected in this analysis by introducing an additional procedure of testing the conditional independence for each pair of factors, avoiding impacts from mutually correlated factors, and was thus adopted in this research.

3.0. METHODOLOGY

3.1. Reseach design

To produce and validate the landslide susceptibility map, data collection and organization, compilation of landslide inventory datasets, database construction of landslide causative factors, and application of WoE models were all used to meet the research's goals.

3.2. Data Collection and Organization

The necessary data for this study were collected from various sources. These include collecting relevant literatures from published and unpublished papers, free online DEM data was downloaded from USGS website, a regional geological map from the Malawi Geological Survey Department at a scale of 1:250000 and Google Earth image from Google Earth. During field work, data collection was carried out on different rock types by describing their character, the relative degree of weathering, slope steepness, location of springs and swamps, landslide inventory mapping, land use and manmade activities including farming practice. After compilation of the actual field investigation, the data has been systematically processed and analysed in ArcGIS.

3.3. Database for Landslide causative factors

To undertake landslide susceptibility assessment in the study area, a spatial database for the causative components was initially created using ArcGIS 10.3.1 software's spatial analysis tools. The database constitute the landslide inventory datasets (training and validation) and the SM causative factors (slope, aspect, curvature; land use, lithology, and distance from stream). The weights of these components were calculated from the relationship between the landslide and the landslide causative factors, and the results were then validated. During the fieldwork, locations were identified and marked with GPS, land use (land cover) types around the landslide scar, drainage networks and spring locations, lithological units and human activities were explored to prepare the landslide susceptibility maps.

Generally, the choice of landslide causative factors should consider the

character of the study area and the availability of data. In this regard, a total of six parameters were

Geomorphological elements like slope, aspect, curvature and distance to stream maps were derived from Digital Elevation Model (DEM) with a cell size of 30 m by 30 m. Fieldwork and Google Earth image interpretations were used to create lithology and land use maps.

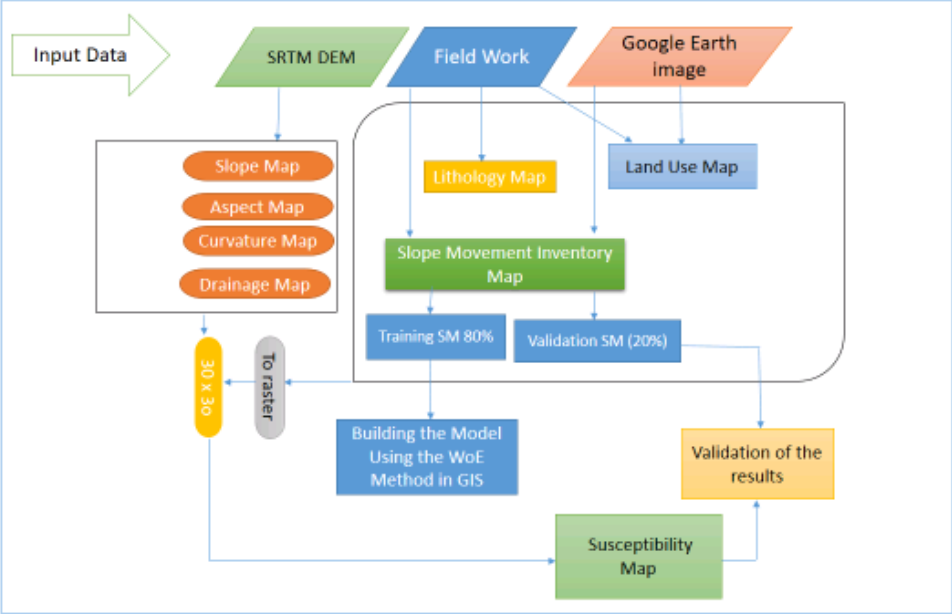


Figure 2: Flowchart of the research work

3.4. The Weight of Evidence Model (WOE)

WoE model is a log-linear kind of the Bayesian probability model for landslide susceptibility assessment that uses landslide occurrence as a training point to drive prediction outputs. It calculates both unconditional and probability of landslide hazards. This method relies on the calculation of positive and negative weights to define the degree of spatial association between landslide occurrence and every explanatory

variable class (Cao, et al., 2021). The positive weights (W+) indicate the occurrence of an occurren

- Nmap = total number of pixels within the map
- Nslide = number of pixels with landslides within the class
- Nclass = number of pixels within the class

The values needed for the weight of evidence formula are:

- Number of class pixels
- Number of Landslide pixels
- % of class pixels
- % of landslide pixels

Then the positive and negative weights are calculated as follows;

W^{+}= ln ( ) . . . . . (Equation 1)

W^{-}=ln (. . . . . (Equation 2)

Where P is the probability, B is the presence of landslide predictive factor, is the absence of a landslide predictive factor, □□ is the presence of a landslide, and is the absence of a landslide. W^{+} and W^{-} are the weights-of-evidence when the factor B is present and absent, respectively. A positive weight (W^{+}) indicates the present of spatial association between conditioning factor (B) and landslides (S) while the magnitude of this weight indicates the positive correlation between the presence of the predictive factor and the landslides. A negative weight (W^{-}) indicates an absence of the spatial association between predictive factor (B) and landslides (S) while the magnitude shows the level of negative correlation. The calculation of positive and negative weights in GIS was implemented by combining the landslide (estimation set) with each factor class individually giving a result of four possible combinations of which the frequency is expressed in number of pixels.

The values of the weight are then used to calculate a weight of contrast value (C) for the particular susceptibility variable.

$C= W^{+}–W^{-}$ . . . . . (Equation 3)

The contrast value (C) measures the strength of a relationship between the causative factors and landslides. If the contrast value is positive, it will have a positive spatial association while the negative one will have a negative spatial association. The weighted map (Wmap) for every SM causative factor is prepared by summing the

weights of contrast(C) values of every factor class. Similarly, the ultimate landslide susceptibility inc

$$Wmap = \sum C \quad \text{(Equation 4)}$$

$$LSI = \sum Wmap \quad \text{(Equation 5)}$$

4.0. RESULTS AND DISCUSSION

4.1. LANDSLIDE INVENTORY

The landslide inventory was developed through the interpretation of aerial photographs (composed of three views on a 1:20,000 scale, UTM 36S WGS84) and satellite images (Land Sat8). By using a GPS, the SM locations have been accurately determined, and so verified. The inventory map provided the geographic locations, and the geometrical characteristics. The dependent variables were identified in keeping with the SM inventory as featuring points. This map was rasterized into grids with 30*30m sub area, and those events were identified within this grid. For slope movement susceptibility mapping SM polygons are often divided into training and validation datasets. The training dataset is employed for constructing the predictive model while the validation dataset is employed for validating the model. Hence, the SM polygons were randomly split into two classes with 80% for training and 20% for validation by keeping their spatial distribution into consideration. The inventory data was mapped as vector-based polygon data so converted to the raster format with a pixel size of 30m by 30m in ArcGIS 10.3.1.

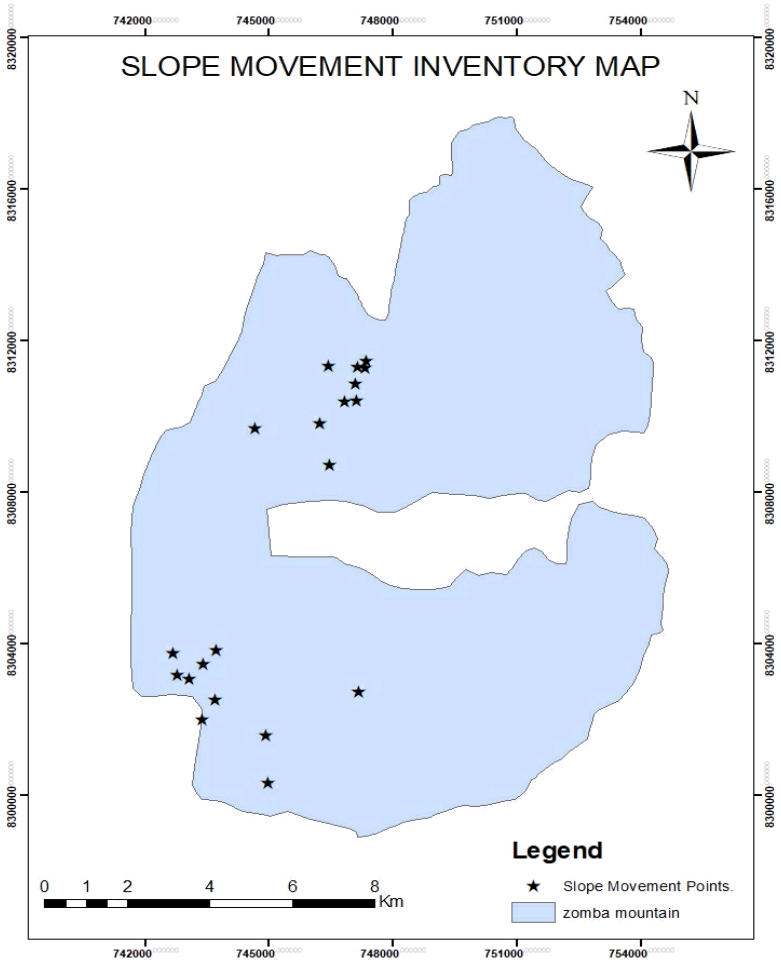


Figure 3: Map showing landslide points

In the current study area, a total of 22 landslides that contain 5693 pixels were identified and divided randomly into training and validation landslides by keeping their spatial distributions into account. Landslide locations are predominantly distributed in

the north, in the south and in the western parts of the study area with decreasing order of landslide

4.2. Slope Movement Causative Variables

4.2.1. Preparation of Lithology Map from regional geology map of Zomba

The geo-referenced geology map of Zomba area was obtained from the Geological survey department at a scale of 1:25,000. This map was obtained as a geo-tiff and it was imported into ArcGIS. The picture was digitized and the result was the Lithology map of Zomba Mountain. The process of digitizing was done by firstly creating shape files of lithological units, then drawing each unit as a polygon. Furthermore, the polygons were merged using geo-processing tool in the software. The map was in vector representation, so it was also converted to raster dataset.

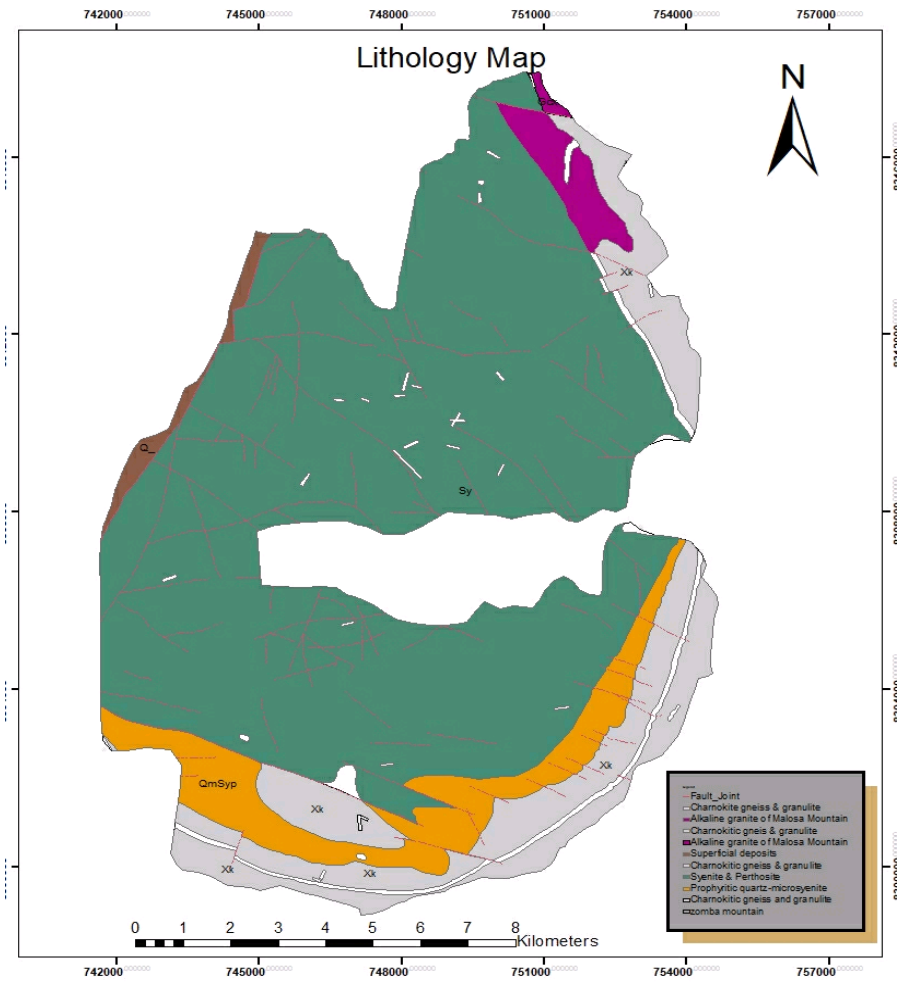


Figure 4: Lithology Map of Zomba Mountain Areas

4.3.2. Preparation of Geomorphologic Factor Maps from DEM

Digital Elevation Model (DEM) is the digital representation of the land surface elevation with respect to any reference datum, it is frequently used to refer to any digital representation of the topographic surface (Rakesh L. & et al, 2015). The SRTM DEM that covers Zomba district were downloaded from USGS explorer in raster format of 30 x 30m. Thereafter, the coordinate system for Malawi, WGS_1984_UTM_Zone_36S, was assigned. These DEMs were imported into ArcGIS for processing. From the DEM, four geomorphologic factor maps (slope, aspect, curvature, and distance to stream maps) were produced. Evaluating the impact of these causative factors on the spatial distribution of slope movement is very important in order to understand their failure me chanism and to prepare the landslide susceptibility map. The roles played by each geomorphologic factor has been discussed in the following sections.

4.2.2.1. Slope

Slope is a critical parameter in landslide studies since it has a direct relationship with the occurrence of landslides. As a result, it's commonly utilized to make slope susceptibility maps (Yalcin and Bulut 2007). It is well known that slope movements occurs more frequently on steeper slopes due to gravity stress. The slope map of the study area from DEM was prepared by first, loading the DEM data into the ArcGIS software where it was processed using spatial analyst tools found in arc tool box. The slope was divided into five classes such as $0^0 – 10^0$, $10^0 – 20^0$, $20^0 – 30^0$, $30^0 – 45^0$, $45^0 – 55^0$ and $> 55^0$. For slope classes above 55^0, the weight value was increasing which indicate the higher probability of landslide occurrence in these classes.

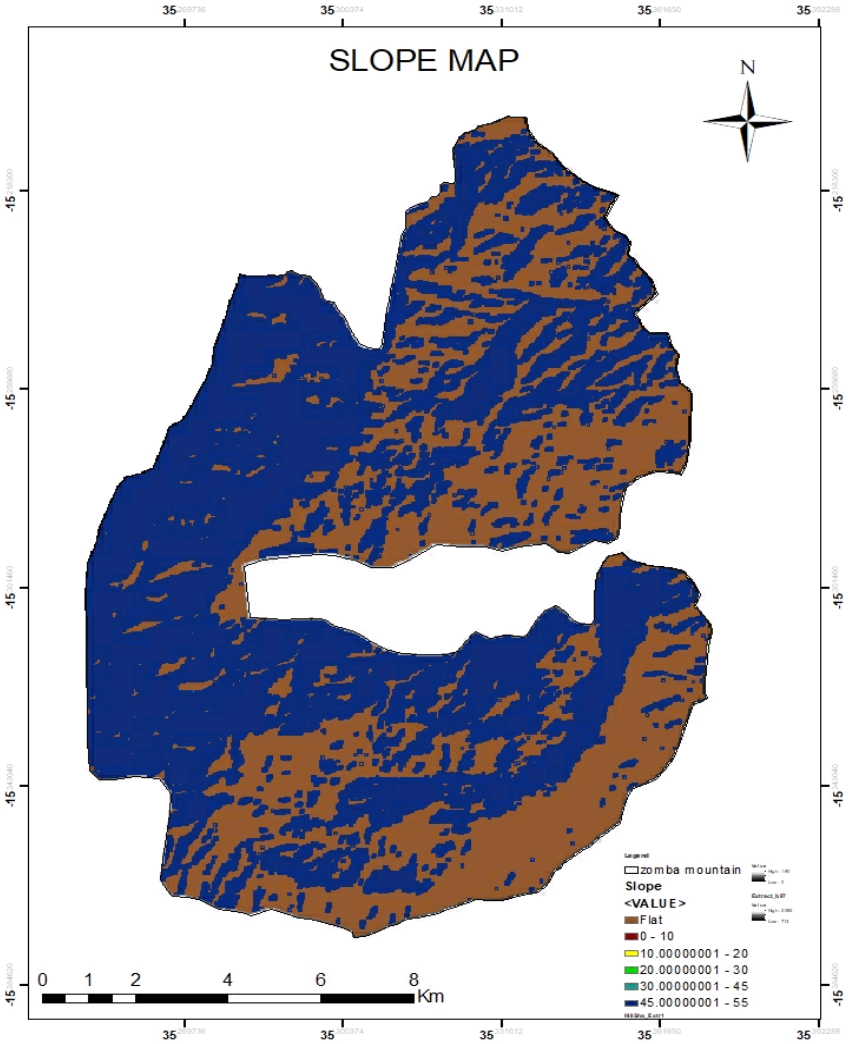


Figure 5: Slope map of Zomba Mountain areas.

4.2.2.2. Aspect

Aspect refers to the slope orientation which is generally expressed in terms of degree from 0^0 – 360^0. It is considered as an important factor in landslide studies as it controls slope's exposure to sunlight, wind direction, rainfall (degree of saturation) and discontinuity conditions. Preparation of the Slope aspect map in this study area from DEM data was done using spatial analyst tools in arc tool box. Firstly, the shape file of Zomba Mountain was added into the ArcGIS and then the Zomba DEM data was also added as another layer. Thereafter, the DEM was extracted by masking, a tool which is found in the arc tool box. The extraction was done so that the DEM aligns with the area of interest which is Zomba Mountain. The slope aspect was divided into nine classes, namely; north (0 – 22.5), northeast, east, southeast, south, southwest, west, northwest, and North (337.5- 360).

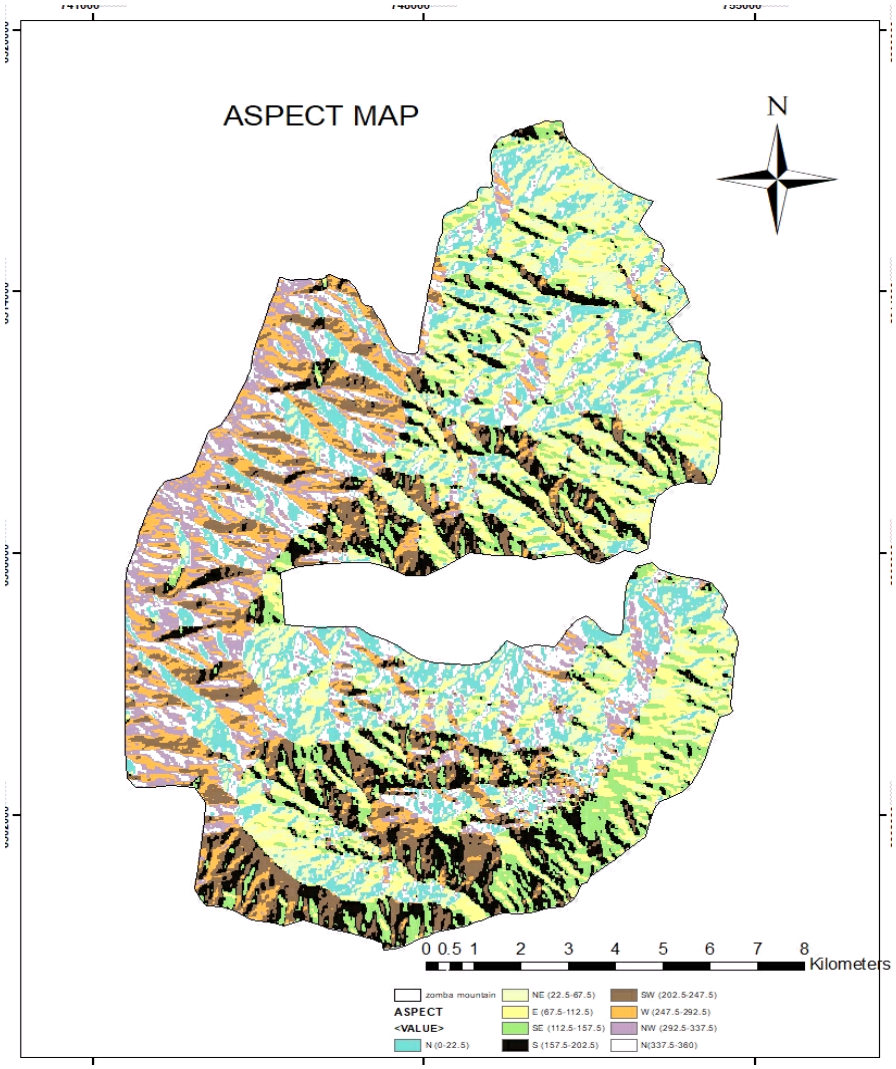


Figure 6: Aspect Map of Zomba Mountain Areas

4.2.2.3. Curvature

Curvature map of the study area was generated from DEM data and it was classified into 2 classes of concave and convex surfaces as shown in the figure below. Following heavy rainfall, a convex or concave slope contains more water and retains this water for a longer period (Skilodimou, et al., 2018). The higher the positive or negative value, the more likely slope movement will occur. The likelihood of a landslide occurring in a flat terrain is extremely low. A positive curvature indicates that the surface at that grid was upwardly convex. A negative curvature suggests that the surface at that grid was upwardly concave.

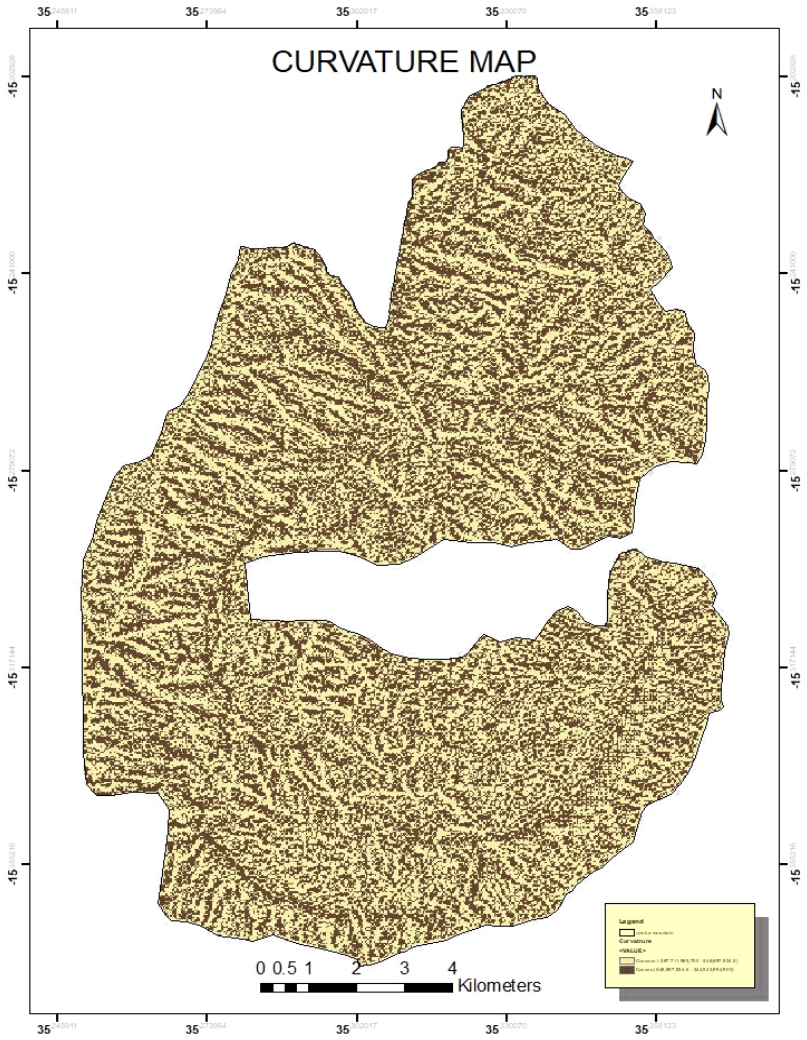


Figure 7: Curvature Map of Zomba Mountain areas

4.2.2.4. Distance to stream

The slope's proximity to the stream course is an important component that influences the area's landscape evolution and serves as a predictor of landslides and related erosional issues. Highlands with a number of drainage networks have a high probability of landslide occurrence as they erode the slope base and saturate the underwater section of the slope forming material (Akgun & Turk, 2011). Since there are many streams in the study area which flow into Likangala River, slope failures may occur in the close vicinity of this river. Hence, this parameter was considered as one causal factor in landslide susceptibility analysis. Drainage frequently contributes to the development of pore water pressure, which lowers the shear strength of slope materials. The DEM data was used to derive streamlines, which were then categorised based on stream order. Landslide in this area is most likely to be associated with 1st, 2nd, and 3rd order streams. Distance from stream map was developed from Euclidean distance buffering method in the spatial analyst tool of ArcGIS 10.3.1. This map was classified into five classes: 100, 200, 300, 400 and > 1200 meters.

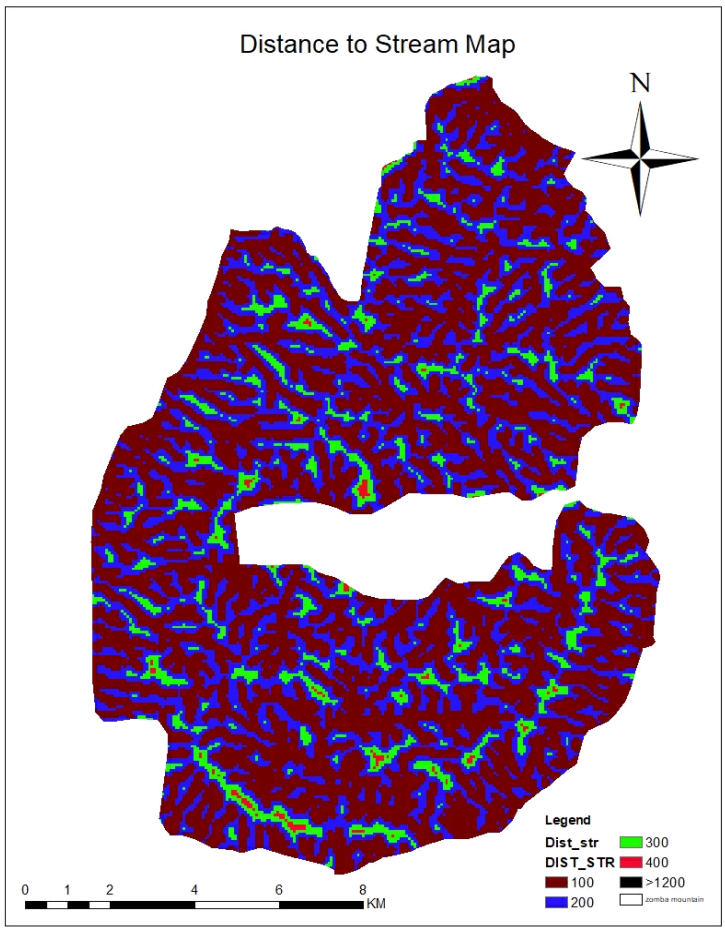


Figure 8: Distance to stream map of Zomba Mountain Areas

4.2.3. Preparation of Land Use/ cover map from Google earth satellite images

Land-use change has been recognized throughout the world as one of the most important factor influencing the occurrence of rainfall-triggered landslides. Changes in land use/cover resulted from man-made activities such as deforestation, overgrazing,

intensive farming and cultivation on steep slope can initiate slope instability (Glade, 2003). Vegetat

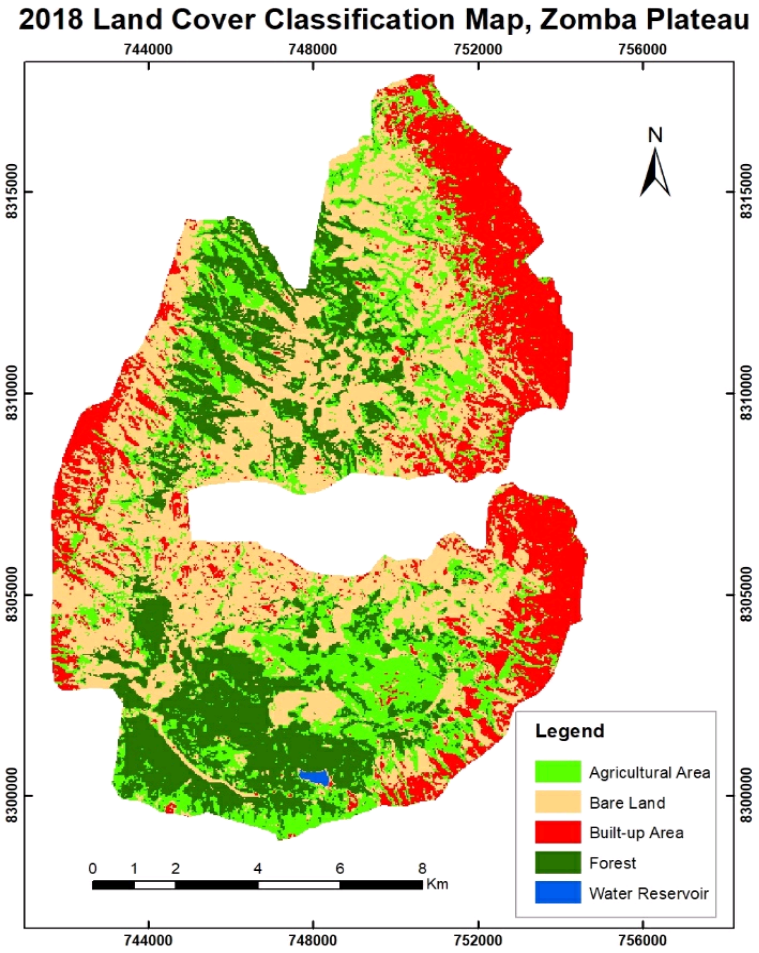


Figure 9: Land use map of Zomba mountain areas

4.2.3. Relationship between landslides and slope instability causative factors

This study has analysed the relationship between six causative factors and landslide occurrence. Using the WoE model, the weights of values were calculated respectively. The Causative factors were classified into different classes and weights

were assigned to them as presented in table 1 respectively. These results showed that the relative

The slope classes > 45^0 have higher susceptibility for landslide occurrence. The area with a slope class > 55^0 is the most landslide prone class while the area with a slope class < 30^0 is the least one. Generally, as the slope increases, the probability of landslide occurrence also increases. In case of aspect classes, the WOE values of slope classes facing towards the north (0 – 22.5), northwest and southwest are greater than one indicating a higher probability of landslide occurrence. The north facing aspect class has got the maximum weight followed by the northwest facing ones. The curvature range of (-2.8) - (5.4) has a greater contribution to the slope failures. In case of lithology, two units' i.e highly weathered syenite and the superficial deposits of dambo soils at top of the mountain have high probability of landslide occurrence. Superficial deposits and weathered syenite have less strength and hence susceptible to landslides. Syenite rocks in the study area formed a cliff underlying thin residual soils. As a result, the landslides may occur at the contact between syenite and thin residual soils. The type of land use also controls the occurrence of landslide in the study area. The highest weights were observed in the land use types of bare lands and agricultural land areas indicating a high probability of landslide occurrence. The highest weighted value of bare land is due to its exposure to erosion and weathering. In case of the relationship between landslide occurrence and the distance from stream, as the distance from stream increases, the occurrence of landslide generally decreases. Landslide occurrence is higher in the first three classes of 100m, 200m and 300. Generally, slope classes >55^0, land use classes of bare lands and agricultural areas; lithology of superficial deposit and highly weathered syenite and distance to stream classes of <200 m buffers are the most contributing factor classes among the six landslide factor classes.

4.2.4. Landslide susceptibility mapping using Weight of Evidence model

The landslide susceptibility map of the study area by WoE model was produced based on the weighted values from the seven causative factors and the training landslide (Table 1). The difference between W^+ and W^- is known as the weight of contrast which is designated by $C = W^+ - W^-$. This reflects the overall spatial association between the causative factors and landslides. LSI map of the study area was prepared

by summing the weight of contrast values (C) of all the six causative factors using a raster calculato

$$LSI = C_{sl} + C_{as} + C_{CU} + C_{li} + C_{lu} + C_{ds} \quad \text{(Equation 6)}$$

Where LSI = landslide susceptibility index; Csl = weight contrast value of slope, Cas = weight contrast value of aspect, Ccu = weight contrast value of curvature, Cli = weight contrast value of lithology, Clu = weight contrast value of land use, Cds = weight contrast value of distance to stream.

The LSI values for the WoE model in the study area ranged from 1.67 to 8.59. The LSI map was reclassified by the natural breaks method of classification technique in order to prepare the landslide susceptibility map of the study area (Fig. 10). Then, the LSI values were classified into four susceptibility zones of very low (1.67 - 3.63), low (3.63 - 4.94), moderate (4.94 – 6.27), and high (6.27 – 8.59).

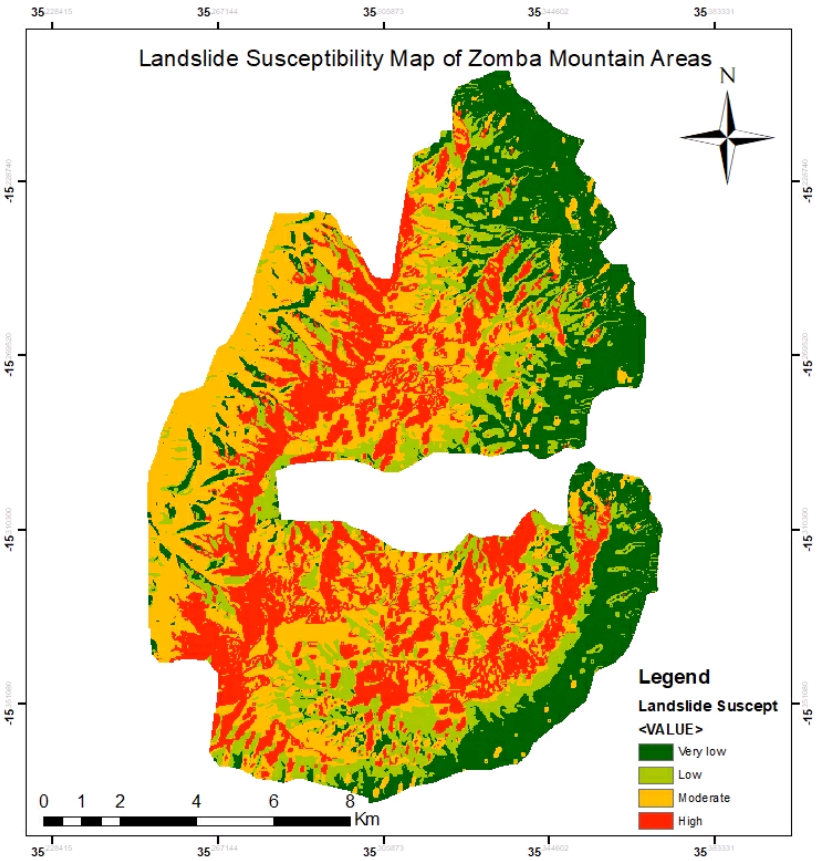


Figure 10: Landslide Susceptibility map of Zomba Mountain Areas

Table 1; Data analyses and results obtained from Weight of evidence model

Factor	Class	Class pixels	Landslide pixels	W+	W–	C
Slope (degree)	0-10	83	4	–1.2140	0.1677	–1.3816
	10-20	220	23	–0.6856	0.2505	–0.9361
	20-30	483	105	–0.1205	0.1203	–0.2408
	30-45	1557	115	0.0138	–0.0305	0.0443
	45-55	189	30	1.445	–0.672	2.1231
	>55	63	16	0.657	-0.022	0.67813
Curvature	Concave	294	976	0.52	0.65	-0.13
	Convex	276	510	0.89	0.34	0.55
Aspect	N (0-22.5)	7106	1466	-2.602	-2.665	0.063
	NE(22.5-67.5)	1856	1226	0.230		-0.036
	E (67.5-112.5)	699	261	-0.322		0.035
	SE(112.51-57.5)	1166	636	-0.076		0.010
	S (157.5-202.5)	762	591	-0.182		0.022
	SW(202.5-247.5)	2029	522	0.266		-0.037
	W (247.5-292.5)	1940	261	0.146		-0.020
	NW(292.5-337.5)	457	68	-0.117		0.015
	N (337.5-360)	254	94	0.359		-0.061
Distance to Stream(m)	0-100	2768	940	-1.875	0.18	0.59
	100-200	4940	1028	0.578	0.20	0.05
	200-300	3290	632	0.134	0.14	0.08
	300-400	6063	349	-0.498	0.07	–1.19
	>1200	9467	2177	-0.214	0.21	–0.54

Land use	Agricultural area	9754	1477	0.31	0.36	0.15
	Bare land	9910	3091	0.36	0.65	0.60
	Built-up area	4047	54	0.14	0.01	–2.6
	Forest	3481	121	0.12	0.03	–1.39
	Water reservoir	0	0	0	0	0
Lithology	Syenite & Perthosite			0.684	-0.090	0.77386
	Superficial deposits			0.294	-0.005	0.29886
						-0.09745
	Porphyritic quartz-microsyenite			-0.091	0.006	
						-0.13625
	Charnokite gn & granulite			-0.134	0.003	

4.2.5. Validation of the Susceptibility Map

Landslide susceptibility maps will be useless without model validation. As a result, landslide susceptibility mapping requires validation of the predictive model (Bui,et aal., 2012). The landslide points that were collected in the field were overlaid with the susceptibility map. By overlaying 80% of the landslides (training) over the causative elements, a predictive model map was created. It was observed that few landslides were in very low and low regions and a lot fall within the moderate and high landslide susceptible areas as shown in the figure.

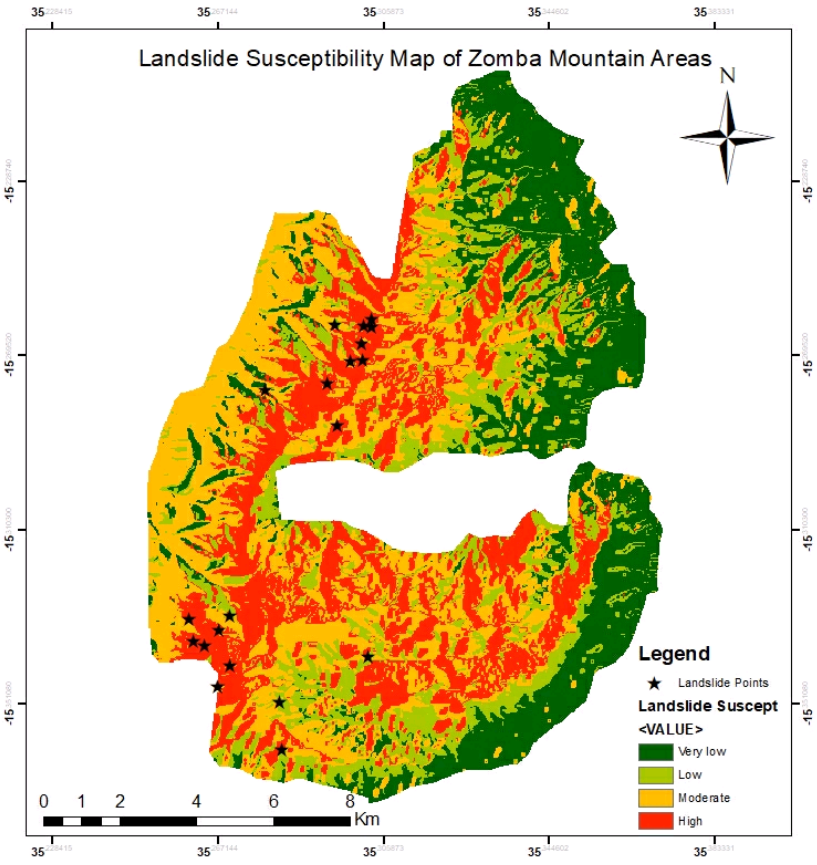


Figure 11: Validated Susceptibility map for Zomba Mountain areas

5.0. CONCLUSION

GIS modelling provides a very convenient platform for the evaluation of landslide hazards. The advantage of this approach is that regional geological, geomorphological, and elevation data can be readily combined within the GIS model and then can be analysed using statistical slope stability analysis methods. In this study, the GIS- based landslide susceptibility assessment using Weight of Evidence method for the Zomba district of the Zomba Mountain areas was successfully conducted, which could be further processed for regional landslide risk evaluation. Multiple slope instability causative factors were collected and compared for the aim of quantifying each independent contribution to the slope failure initiation. Compared with the frequency ratio, the predictive power of the WoE method can be further identified for each causative factor, through determining the correlation between each factor class and past occurred landslides. A certain range of factors, including the slope angle >55, lithological units of the highly weathered syenite and the superficial deposits of dambo soils and land use types of bare lands and agricultural areas have presented high probabilities of landslide prone areas and, thus, geomorphological factors, lithology and external triggering factors including anthropogenic activities significantly determine regional landslide distribution in the study area. However, the selection of landslide samples, resolution of DEM data, and the scale of the study area are also crucial reasons for the derived outcomes of the susceptibility map.

5.1. Recommendations

The landslide susceptibility map generated in this study has managed to categorize the study area into very low, low, moderate, and high susceptible zones. This resulting map supports the observation that landslides are likely to be more common in the Northern and Western part of the Zomba Mountain. Therefore, the land planners should seriously consider these areas to plan appropriate locations for implementing new facilities in these Mountain terrains. The study also establish a great change in land use. It was observed that people's settlement and agricultural practices are trending towards the foothills and hill slopes creating predisposing interference that

may lead to fatal landslides. People are constructing their structures within 0-100 m away from stee

5.2. Limitations of the study

Lack of funds to collect all the necessary data to complete this study. Field visits for verifying landslide event points was mostly done in the Southern part of the Mountain. There was need to visits all the parts of the Mountain from north to south and east to west but this was not achieved. The other limitation is the poor quality of the data. The DEM data that was used for this analysis was of lower quality such that other derivatives such as slope and curvature that were supposed to be used in the analysis were only being classified into two classes which affected the data analysis process.

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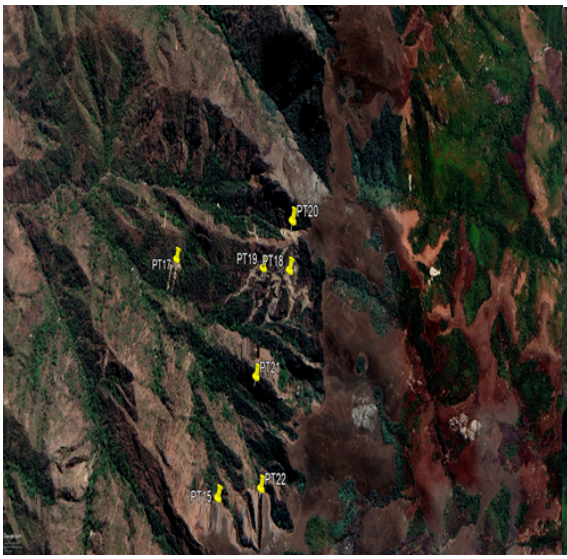
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7.0. APPENDICES





(a) (b)





(c)

Figure 12 (a), (b) and (c): Showing landslide points in Zomba Mountain Areas.



Figure 13: A picture showing a highly weathered syenite Profile in Zomba

Mountain