

**GIS-Based Statistical Analysis for Evaluation of Landslide
Susceptibility Mapping: A Case Study in Blue Nile Gorge,
Gohatsion-Dejen Road Section, Central Ethiopia**

Yechale Ali Beza
A Thesis Submitted to
School of Earth Sciences



**Presented in Partial Fulfillment of the Requirements for the Degree of
Master of Science (Engineering Geology)**



ADDIS ABABA UNIVERSITY

Addis Ababa, Ethiopia

September, 2021

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SIGNATURE PAGE

Addis Ababa University

School of Graduate Studies

This is to certify that the thesis prepared by **Yechale Ali Beza** entitled: GIS-Based Statistical Analysis for Evaluation of Landslide Susceptibility Mapping: A Case Study in Blue Nile Gorge, Gohatsion-Dejen Road Section, Central Ethiopia and submitted in partial fulfillment of the necessities for the Degree of Master of Science (Engineering Geology) complies with the regulations of the university and meets the accepted standards with regards to originality and quality.

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ABSTRACT

The present study was conducted in Blue Nile Gorge Gohatsion - Dejen road section about 185 km from the capital city Addis Ababa. It has been well recorded that the Blue Nile Gorge Gohatsion-Dejen section road corridor was sufferer in different landslides and slope failures. The main objective of the present study was to evaluate landslide susceptibility of the road corridor and produce its landslide susceptibility map. To realize the objectives of this research statistical information value model was basically followed. Seven causative parameters: namely; lithology, elevation, slope, aspect, land use/land cover, proximity to road and proximity to streams were considered for landslide susceptibility evaluation and map preparation. The landslide inventory mapping in the corridor was administered through field observations and Google Earth image interpretations. For statistical information value model the inventory landslide and causative factor maps were converted into the same pixel size raster format then depending on the influence of causative factors on past landslide the information values were calculated. After the statistical information value calculation, distribution of landslide over each causative factor maps was obtained and analyzed. Weights for the class within these causative factor maps were obtained by using statistical information value model. Causative factors are classified into various classes; based on landslide concentration, topographic condition, geology and land cover types in the road corridor/study area. As the statistical information value analysis result; causative factor classes of colluvium deposit, 1575–2100m elevation, $> 45^{\circ}$ slope, east facing slope aspect, bare land, 0-0.5km distance from road and 0-50m distance from streams have maximum contribution for a landslide occurrence. The landslide susceptibility map, thus produced in the study area clearly indicates that 43.2km² (17.0%), 96.8km² (38.1%) and 113.9km² (44.9%) falls in low, moderate and high susceptible classes respectively. Validation of the prepared susceptibility map revealed that 87.1% of past landslides fall in high susceptible class of the prepared landslide susceptibility map (LSM). Thus, the landslide susceptibility map (LSM) validation provided acceptable results and the different classes those delineated can be safely applied for future developmental planning in the present study area.

Key words: Blue Nile Gorge, Information Value Model, Landslide, Landslide Susceptibility, Landslide susceptibility index

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LIST OF ACRONYMS

DEM	Digital Elevation Model
GERD	Grand Ethiopian Renaissance Dam
EBCS	Ethiopian Building Code Standard
EIGS	Ethiopian Institute of Geological Survey
ERA	Ethiopian Roads Authority
GIS	Geographic Information System
GPS	Global Positioning System
GSE	Geological Survey of Ethiopia
HS	High Susceptible
ITCZ	Inter-tropical Convergence Zone
IV	Information Value
JICA	Japan International Cooperation Agency
LS	Low Susceptible
LSI	Landslide Susceptibility Index
LSM	Landslide Susceptibility Mapping
LULC	Land-use Land-cover
MOA	Ministry of Agriculture
MS	Medium Susceptible
NMSA	National Meteorological Services Agency
OJEC	Oriental/Japan Engineering Consultants
OLI	Operational Land Imagery
SRTM	Shuttle Radar Topographic Mission
TCDSCo	Transport Construction Design Share Company
USGS	United States Geological Survey
VLS	Very low Susceptible
Yrs	Years

CHAPTER ONE**INTRODUCTION**

1.1 Background

Landslide is one, among the most destructive natural or man induced hazards that commonly lead to serious problem, through its occurrences especially in hilly and mountainous regions (Martha et al., 2010; Filagot Mengistu et al., 2019). Landslides cause significant effect on livelihood, property, infrastructures, farmlands, and natural environments (Lulseged Ayalew, 1999; Lulseged Ayalew and Yamagishi, 2004; Tenalem Ayenew and Barbieri, 2005).

To minimize landslide associated risks, identifying, evaluating and delineating landslide susceptibility prone areas are very crucial for proper strategic planning and mitigation measures (Anbalagan, 1992; Raghuvanshi et al., 2014; Fikre Girma et al., 2015). Therefore, in order to demarcate landslide susceptibility prone slopes over large area, landslide susceptibility mapping (LSM) techniques could be functional (Anbalagan, 1992). Landslide susceptibility maps have maximum value to developmental planning as they present a spatial division of the ground into areas of various levels of potential landslide hazard zones and it provides the essential framework for land use planning and development of proper engineering practices (Anbalagan, 1992; Gemechis Chimidi et al., 2017). Since, these landslide susceptibility maps are important to predict where landslides are likely to occur in the future (Guzzetti et al., 2005a).

Several landslide susceptibility mapping (LSM) techniques were developed in the past and these techniques were widely classified as qualitative, semi-quantitative and quantitative approaches (Varnes, 1984; Guzzetti et al., 1999; Fall et al., 2006; Kanungo et al., 2006 and Lulalem Shano et al., 2020). Each of these landslide susceptibility mapping (LSM) techniques have their own advantages and disadvantages owing to certain uncertainties on account of factors considered or methods by which factor data are derived (Carrara et al., 1995).

In order to prepare a landslide susceptibility map for the present study area statistical information value model with the association of GIS-software were used. Among those various statistical landslide susceptibility mapping techniques, statistical information value model was basically followed for the present study; because of two things. One, this technique was not followed by previous researchers in the study area and the second is

having of minimum degree of subjectivity like other statistical techniques. This statistical technique was used by many researchers such as; [Yin and Yan, \(1988\)](#); [Sarkar et al., \(2013 & 2006\)](#); [Filagot Mengistu et al., \(2019\)](#); [Sharma and Mahajan \(2019\)](#); [Azemeraw Wubalem and Matebie Meten, 2020](#)) for the purpose of landslide susceptibility mapping.

1.2 Statement of the Problem

As stated by many researchers [Lulseged Ayalew and Yamagishi, \(2004\)](#); [Tenalem Ayenew and Barbieri \(2005\)](#); [Bekele Abebe et al. \(2010\)](#); [Raghuvanshi \(2014a; 2014b\)](#); [Matebie Meten et al. \(2015\)](#) landslides are common geo-environmental hazards in northern, southern and western highlands of Ethiopia. From the past experience landslide hazards have resulted into damaging infrastructure as well as human's life all over the world ([Dai et al., 2002](#); [Raghuvanshi et al., 2014a](#)).

The present study is conducted in northwestern Ethiopian plateau; which is undulated, mountainous and dissected terrain. The area is known by landslide activities which cause immense damage on infrastructures, natural environment, house and agricultural land. Especially, the Addis Ababa - Bahir Dar highway corridor crosses this gorge, and it is vulnerable to this problem.

In mountainous terrain developmental measures especially, road construction covers large area of slope therefore, it needs detailed slope stability assessment work ([Raghuvanshi et al., 2014a](#)). Due to this; landslide susceptibility mapping (LSM), forecasting, monitoring of landslide is necessary to inform government and the public about the spatial probability of landslide for safer land use planning and developmental activities and to minimize emanation impacts.

Even though the present study road corridor/area is known which is highly affected by landslide and various published and unpublished study by individuals and institutions using various techniques were reported from the area before the present study but still now the problem is not solved sustainably. Therefore, this study is focused on the evaluation of the landslide susceptibility mapping for the proposed study to reform the current spatial plan and to give insight for local government in managing present and future land use practices.

1.3 Objective

The general objective of the study is to evaluate the landslide susceptibility using GIS-based statistical analysis and prepare landslide susceptibility map of Gohatsion-Dejen section road corridor, Blue Nile Gorge.

Specific objectives which are designed to attain the major objective are listed as follows:-

- To conduct landslide inventory in the study area;
- To evaluate possible causative factors in the study area; and
- To evaluate and zone landslide susceptibility in the study area

1.4 Scope and Limitations

The investigation was conducted between Gohatsion and Dejen towns along the main road corridor with 1: 50,000 scale, northwestern part of central Ethiopia.

The possible limitation of this research was data quality because statistical information value method is highly dependent on the quality of the data. For the present study the quality of the data was limited due to accessibility problem, resource and limited time constraints. The study area has various valleys and undulating terrains due to that it was difficult to address all corners of the area during field visit.

1.5 Significance of the study

The present study Gohatsion-Dejen section main road corridor is frequently damaged by landslides. To tackle this problem preparing a landslide susceptible map is very essential. Landslide susceptibility map (LSM) is useful for land planning, natural risks management and to develop mitigation measures (Catani et al., 2013). In this study landslide susceptibility map is prepared, which is used for planners with a practical and effective way for demarcation of areas suitable to landslide. Further, it is important to do safer strategic planning for future developmental activities like; selection of appropriate sites for road construction, agriculture and other development activities. In addition, it may be helpful to minimize the upcoming impact in landslide prone areas by providing updated information for concerned bodies and local government in managing present and future land use.

1.6 The Outcome of the Study

The final outcome of the present study is producing a landslide susceptibility map at a scale of 1:50,000 and making appropriate recommendations based on the susceptibility class map to tackle damages which could be induced by a landslide.

1.7 Thesis outlines

This research has seven separate chapters. The first chapter is an introduction which contains background, statement of the problem, expected output and significance, scope and limitations of the study area. The second chapter is literature review which states about the previous study of the area and the general overview of the landslide conditions. Chapter three it includes, location and accessibility, physiography, climate condition, seismicity, land use land cover, regional and local geological of the area, geological structures and hydrogeology of the present study area. The fourth chapter is the methodology part under this chapter the methods, data collection procedures, materials and software's followed to conduct this research work are discussed. The fifth chapter is landslide inventory and landslide distribution evaluation of the study area. In this chapter the different past landslides and their distributions on different localities are discussed, seven causative factors evaluation are included within this chapter. Chapters six is result and discussion part of the study. Under this the causative factors weight are assigned. Based on the assigned causative factors class the final landslide susceptibility map was produced. Further the correlation relationships between the landslide and the causative factors have been analyzed. The last chapter is chapter seven which summarizes the research. In here based on the final out put conclusions and recommendations are explained.

CHAPTER TWO**LITERATURE REVIEW**

2.1 An Overview of Landslides

Landslides are the most destructive geological hazards throughout the world, threatening both human beings and property (Lee, 2019). Landslides are signs of slope instabilities which are defined as the tendency for a slope to undergo morphologically and structurally disruptive landslide processes. They could be manifested individually and combinations of various forms, including emergence or ceases of springs, seeps or saturated ground in areas that have not typically been wet before, new cracks or unusual bulges in the ground, street pavements or sidewalks, soil slide away from foundations, tilting of ancillary structures from the main house, cracking of concrete floors, structures and walls, disrupted drainage ditches, leaning telephone or electric poles, trees, retaining walls or fences, offset fence lines, sunken or down-dropped road beds, bulging and cracking of the ground, sudden decrease in stream water level in while under rain are all surface manifestations indicating emergence of landslides (Leulseged Ayalew et al., 2003; Rotaru et al., 2007).

Landslides/slope failures are not costly as earthquakes, major floods, hurricanes or some other natural catastrophes. Slope failures are more widespread, and over the years they may cause more damage to properties than any other geological hazards (Varnes, 1984). As mentioned by Aleotti and Chowdhury (1999) the study of landslides drawn worldwide attention because of two things: - (1) to create awareness about socio-economic impacts of landslides and (2) increment of urbanization on the mountain environment.

2.2 Types of landslides

According to Cruden and Varnes (1996) landslides can occur as falling, flowing, toppling, sliding or as a combination of two or more slope failures. A landslide means the phenomenon which some or all of a slope slowly or rapidly moves down the slope under the influence of groundwater and gravity. Landslides can be differentiated due to (1) materials involved and (2) mode of movement. Based on the materials involving during the movement and the type of movement Cruden and Varnes, (1996) have classified landslides into five types these are: - fall, topple, slide, spread, flow and combination of two or more type of landslide with different types of materials involved (soils, bed rocks, mud and debris).

Table 2.1 Types of landslide according to Cruden and Varnes, 1996

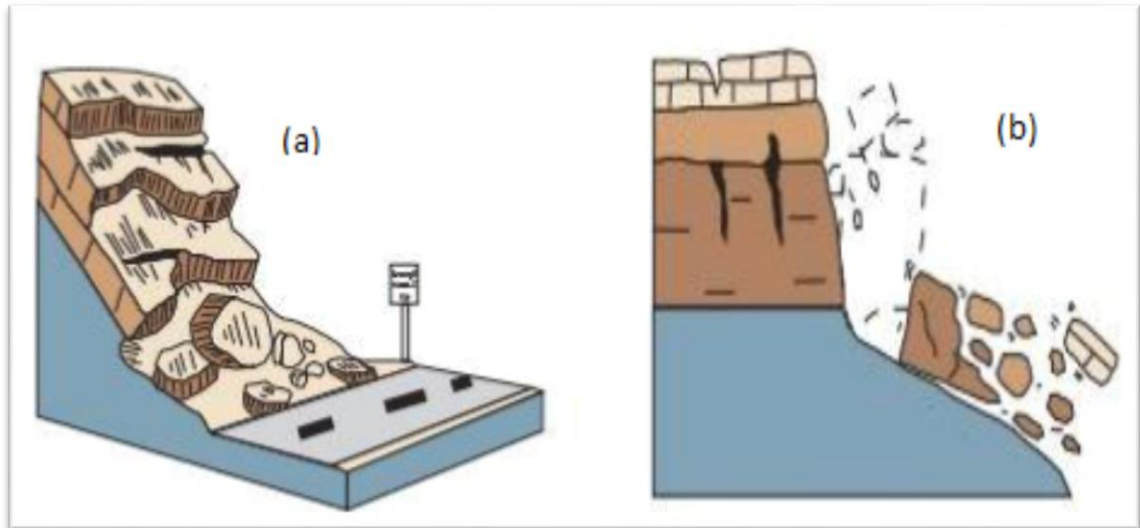
Types of movement		Types of materials involved		
		Engineering soils		
		Predominantly coarse	Predominantly fine	
Falls	Bedrock	Rock fall	Debris fall	Earth fall
Topple		Rock topple	Debris topple	Earth topple
Slide	Rotational	Rock slide	Debris slide	Earth slide
	Translational			
Lateral spread		Rock spread	Debris spread	Earth spread
Flow		Rock flow	Debris flow	Earth flow
Complex slope movements		Combination of two or more principal types of movement		

2.2.1 Falls

Falls are an abrupt down ward movement of slope materials (soil, rock or both) that are detached from their parent materials at steep slopes or cliffs when elevated masses are separated along discontinuities (Highland and Bobrowsky, 2008). In this type of movement, the detached materials move by bouncing, falling or rolling (Hung et al., 2014) (Figure 2.1a). It is fast down ward movement of slope material. In such, type of failure there is no interaction between one failure and the next failure.

2.2.2 Topples

This type of slope failure is usually downward movement of large pieces of rocks. It is forward rotation and movement of rock out of the slope. This type of slope failure occurs around an axis at or near the base of rock (Figure 2.1b). The cause for this type of slope failure may be gravity, ice or water occurring within discontinuities or weak zones like cracks or joints that weaken the rock mass. The rate of failure ranges from extremely fast to extremely slow movement (Highland and Bobrowsky, 2008).



(Source: Highland and Bobrowsky, 2008)

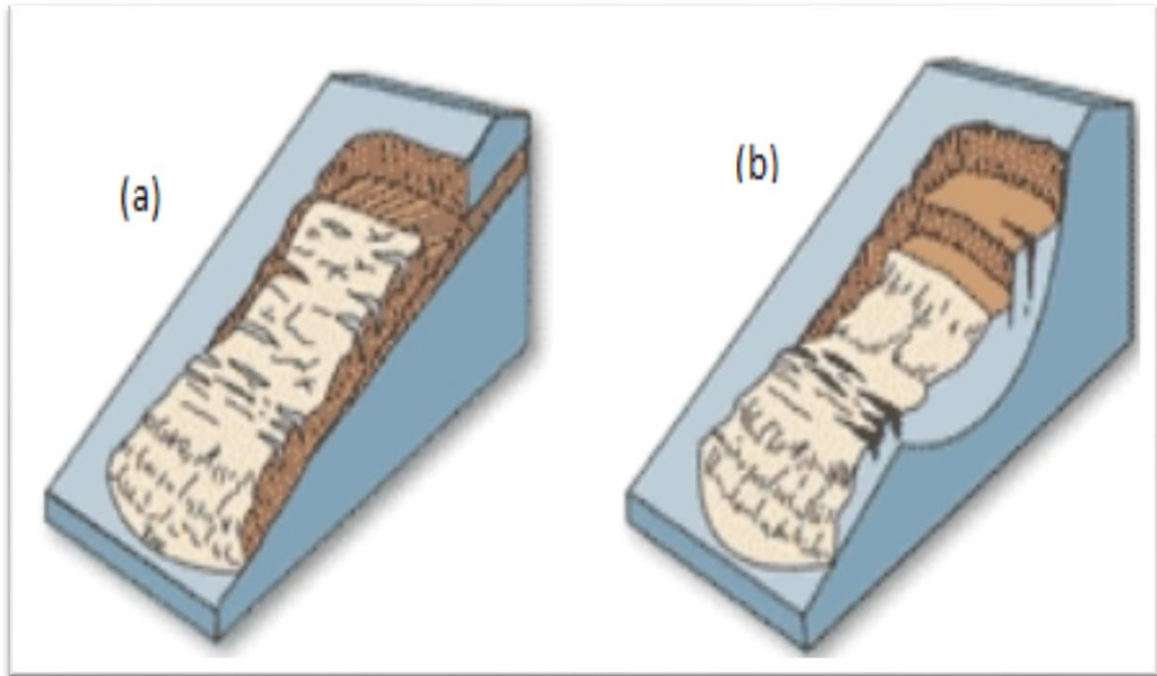
Figure 2.1 Schematic representations of a) Rock fall and b) Topple

2.2.3 Slide

Slide is a quite mass movement whereas the sliding material breaks away from underlying stable material. This type of slide movement could be translational or rotational.

a) Transitional slide: slide may be a slide during which a mass moves along a roughly planar surface with little rotational or backward tilting (Figure 2.2a). This type of failure happens with little rotation or back ward tilting (USGS, 2004).

b) Rotational slide: rotational slide is one type of slide in which broken/rupture surface is curved concavely upward following the contour and thus the mass movement is roughly rotational about an axis that is parallel to rock bottom surface and transverse across the slide (Varnes, 1978) (Figure 2.2b). It occurs when the inside strength of slope material is overcome by its own weight (USGS, 2004). Rotational and translational slides are kinds of slides, they are common in unconsolidated soils and their rate of movement ranges from extremely slow to moderately fast and mostly they will damage structures but not life if their movement is slow (Highland and Bobrowsky, 2008).

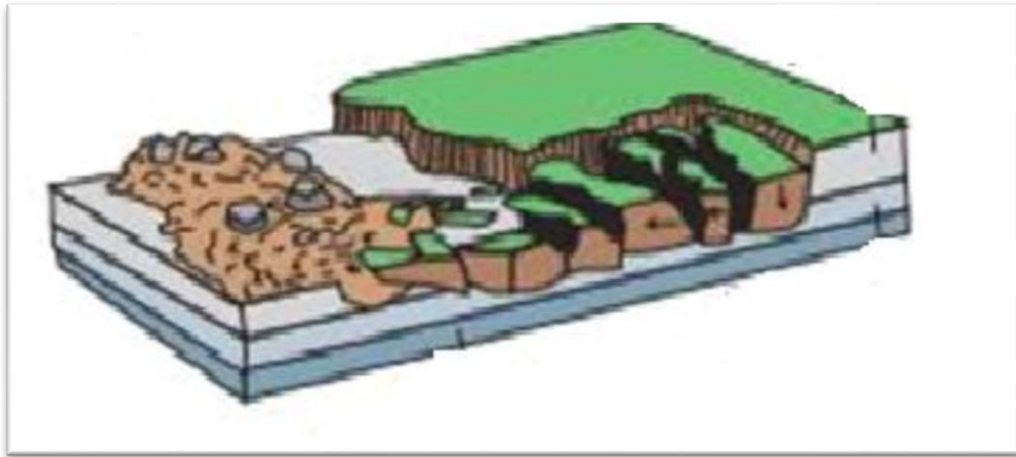


(Source: Highland and Bobrowsky, 2008 and USGS, 2004 online)

Figure 2.2 Schematic representations of a) translation and b) rotational slides

2.2.4 Lateral Spread

This type of movement is unusual because it occurs on a very gentle slope or a flat terrain. The mode of movement is lateral extension accompanied by shear/tensile fractures (Figure 2.3). The failure is caused by liquefaction. When loose and cohesion less sediments (sands and silts) will be saturated they will be liquefied or changed liquid state. Failure is usually triggered by rapid ground motion, which will be induced by natural and artificial ground motions. When coherent fine grained materials, either bedrock or soil, rests on materials that liquefy, the upper units may undergo fracturing, extension then subside, translate, rotate, liquefy and flow off. Lateral spreading is usually progressive in fine-grained materials on a shallow slope. Lateral spreads typically damage pipelines, utilities, bridges, roads and other structures having shallow foundations (Highland and Bobrowsky, 2008).

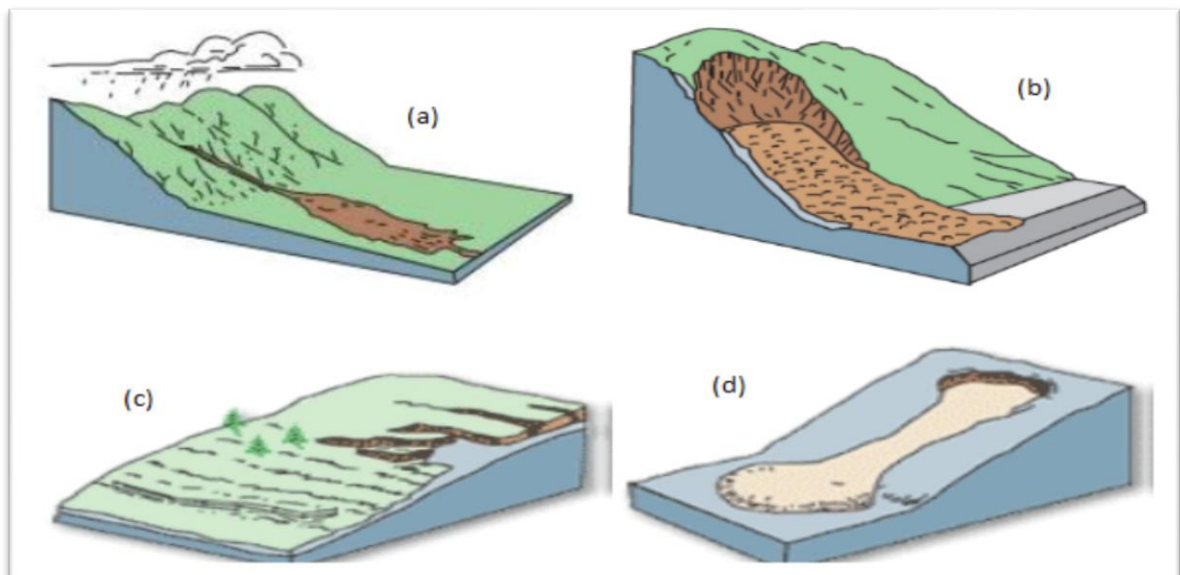


(Source: Highland and Bobrowsky, 2008)

Figure 2.3 Schematic representation of lateral Spread

2.2.5 Flow

Regards to the (1) materials involved and (2) speed of movement flow type landslide can be divided as debris flow, debris avalanche, creep and earth flow (Figure 2.4a, b, c & d) respectively. Even if each type of flow has its own characteristics dominantly the materials involved are water saturated with fine grain dominated and running out leaving a basin shaped depression. They are unconsolidated at the time of flow but may contain various types of materials like rock fragments, fine material, and debris (USGS, 2004).



(Source: USGS, 2004)

Figure 2.4 Schematic representations of a) Debris flow, b) Debris avalanche, c) Creep and d) Earth flow

2.2.6 Complex type slope movement

Sometimes a combination of two or more types of failures will happen in a single slope. This type of combination failures could happen at the same time or during the life time of a slope failure (Cruden and Varnes, 1996).

2.3 Landslide Susceptibility Mapping Techniques

Landslides are the main devastating hazards in different parts of the world; therefore some rapid slope stability analysis techniques are required. For the purpose of delineation of an area with different degree of susceptibility for a landslide different analysis techniques could be applied (Anbalagan, 1992). These landslide susceptibility mapping techniques can be classified as expert (qualitative), quantitative (statistical and deterministic) approaches (Leroi, 1997; Fall et al., 2006). The detailed description of each method is discussed separately as follows.

2.3.1 Expert evaluation technique

This technique is a type of qualitative method which is classified into inventory and heuristic (geomorphic) approach (Fall et al., 2006). Landslide inventory mapping is a method used to identify the past landslide affected area and record the position/location, date of failure, dimension, triggering factor, frequency of occurrence and mode of failure of landslide (Dai and Lee, 2001; Fall et al., 2006). It represents an existing landslide on the map in the form of a polygon or a point (Kanungo et al., 2009). Landslide inventories show the susceptibility for those areas where landslides are observed. This method doesn't provide information about the degree of susceptibility for the future landslide activity (Tilahun Mersha and Matebie Meten, 2020). However, this method provides firsthand information for many susceptibility analysis studies (Dai and Lee, 2002; Tilahun Mersha and Matebie Meten, 2020).

Whereas heuristic approach includes his or her experience to determine the type and degree of hazard (Dai and Lee, 2001; Aleotti and Chowdhury, 1999). For this technique various causative factor maps are prepared (Dai and Lee, 2002). During this technique numerical ratings are assigned based on logical judgment of geoscientists from their past experiences on the relation between those causative factors and slope instability (Anbalagan, 1992). Nevertheless, this method is subjective; it is simple in application by utilizing much field data which are supported by experience of geoscientists (Fall et al., 2006; Raghuvanshi et al., 2014a; 2014b).

2.3.2 Statistical analysis technique

Statistical analysis techniques are a type of quantitative techniques. These techniques are carried out based on statistical determination of combination of causative variables in a given area. These methods are indirect and the landslide hazard technique is based on rule evolved statistically with the relative contribution of each causative parameter (Carrara et al., 1992). For this statistical analysis GIS tools are quite useful. Statistical method can be bivariate and multivariate (Dai and Lee, 2001). In this method the major problem is collection of data over large area and identification of causative factors which needs large time and more cost (Van Westen et al., 1997). The other limitation of statistical method is the result is highly dependent on the quality of data (Van Westen et al., 1997). Even though statistical methods have this limitation, this technique is developed for reducing the subjectivity of expert evaluation.

2.3.2.1 Bivariate statistical method

This technique is one type of statistical method. In this method individual factor maps are overlaid on past landslide inventory map to workout relative contribution of each factor class in inducing landslide. Then, weights are calculated to each factor class to deduce landslide susceptibility. Weights to each causative factor are assigned based on landslide density. This method includes various statistical techniques; like information value method, frequency ratio method, weight of evidence method, weighted overlay method, fuzzy logic method, certainty factor method, statistical index method and density area (Aleotti and Chowdhury, 1999; Kanungo et al., 2009). These all bivariate statistical type techniques were developed for landslide susceptibility mapping.

2.3.2.2 Multivariate statistical method

A multivariate statistical model forecasts the spatial occurrence of landslides. This method takes into consideration relative contribution of each thematic data layer to total landslide susceptibility (Ayalew and Yamagishi 2005; Kanungo et al., 2009; Lulalem Shano et al., 2020). The percentage of landslide affected area for each pixel and non-landslide affected area data layer is created followed by the purpose of multivariate statistical method for reclassification of hazard for the given area. Logistic regression method, discriminant method including artificial intelligence methods, artificial neural network method, support vector

machines, probabilistic approach and deterministic approach are among the common method for landslide hazard zonation method ([Lulalem Shano et al., 2020](#)).

2.3.3 Deterministic approach

This technique is a kind of quantitative approach. As stated by [Raghuvanshi et al. \(2014a\)](#) this approach is an empirical method provides hazard in definite quantity within the sort of factor of safety. This approach provides quantitative result which serves for direct engineering designs ([Fall et al., 2006](#)). Application of such method is more practical and straightforward. This technique is applied for landslide hazard zonation which is performed in small to medium size areas through large or medium scale mapping. However, deterministic approach requires the availability of more detailed geotechnical and hydrological data ([Raghuvanshi et al., 2014a](#); [Van Westen et al., 2006](#)). The most limitation of this approach is that it can be applied at large scales only, due to the necessity of detailed geotechnical data from individual slopes ([Barredo et al., 2000](#)).

2.4 Previous Landslide Study in Ethiopia

Different researchers have stated that landslide hazard is crucial environmental problem for the development of the country like Ethiopia, especially within the three physiographic regions which are; the northern, western and southern highlands. The distribution of landslides within the area depends on various factors which are complex and weathered geology, unstable soil cover, undulated morphology, high rain fall, high relief energy, hydrogeology, seismicity and anthropogenic activities generally. As stated by the following researchers [Leulseged Ayalew \(1999\)](#); [Lulseged Ayalew and Yamagishi \(2004\)](#); [Tenalem Ayenew and Barbieri \(2005\)](#); [Kifle Woldearegay \(2013\)](#); [Fikre Girma et al. \(2015\)](#); [Tilahun Hamza and Raghuvanshi \(2017\)](#) the increased man-made activities in the recent past years such as road, building and other construction works have resulted increment of landslides in Ethiopian highlands. Various research works have been conducted using different qualitative and quantitative techniques to assess the causes that induce landslides in the different highland of Ethiopia. A summarized description of various studies on landslides in Ethiopia is presented as follows.

[Leulseged Ayalew and Yamagishi \(2002\)](#) have conducted their research entitled by land sliding and landscape development in northern Ethiopia. The final discovery of this research show nine types of slopes based on concavity and convexity of horizontal and vertical

profiles; the type of landslides in these slopes were explained. Further they have discussed the important contributions of landslides to landscape development and they have determined principal phases for landscape evolution.

[Tenalem Ayenew and Barbieri \(2005\)](#) carried out a research on landslides in Dessie area entitled by inventory of landslides and susceptibility mapping within the Dessie area, northern Ethiopia. In this study, four wide landslide susceptibility zones and 22 specific active landslide sites were identified. The final discovery of this study suggests that the type of landslides that occurred within the area including debris slide, earth and soil slump, rock and debris falls and sophisticated. As the author mentioned that during this paper work large-scale landslides are triggered mostly by surface water and groundwater during the wet or rainy season.

[Shiferaw Ayele \(2009\)](#) has conducted a research in Abay Gorge, central Ethiopia by using remote sensing and GIS to delineate landslide hazard zones. He considered different causative factors including geology, groundwater condition, land use land cover, drainage, structure, aspect and slope. During this work, a comparison of the landslide hazard map was made with actual landslide events of the area. He found that 67% of the area falls under maximum hazard zone.

[Kifle Woldearegay \(2013\)](#) reviewed the occurrences and influencing factors of landslides within all highlands of Ethiopia - With implications for infrastructural development. According to a review of this work hilly and mountainous areas of Ethiopia are commonly suffering from rainfall triggered landslides of various types and sizes. These landslides caused loss of human lives, failure of engineering structures, damage on agricultural lands and on the natural environments generally. The last conclusion according to the review is that, since Ethiopia is currently involved in massive infrastructural development, landslides & landslide-generated ground failures need attention to reduce losses from such hazards and to make safe Geo-environment.

[Matebie Meten et al. \(2015\)](#) carried out a study in Debresina GIS-based frequency ratio and logistic regression modeling for landslide susceptibility mapping of Debresina area central Ethiopia. To discuss this and to prepare landslide susceptibility mapping landslide inventory and nine causative factors including lithology, land use, distance from river and fault, slope, aspect, elevation, curvature and annual rainfall were considered. After various rasterization of

causative factor thematic maps and landslide inventories for both LR and FR model the success and prediction rates 75.7%, 74.5% and 74.8%, 73.5% were produced respectively. The prediction rate and therefore the validation rates are almost similar, therefore based on this they concluded that the model is acceptable.

[Gemechis Chimidi et al. \(2017\)](#) conducted landslide hazard zonation mapping in Gimbi town; western Ethiopia using GIS based statistical approach entitled which was by landslide hazard evaluation and zonation in Gimbi town and its surroundings, western Ethiopia – a GIS-based statistical approach. In this study, nine causative factors were considered for the LHM preparation including slope material, elevation, slope, aspect, curvature, land-use/land-cover, groundwater, and distance to road and distance stream. From this study, five hazard zones and fifty past landslide sites were identified. The authors concluded that 75% of the past landslides fall within very high and high hazard zones; as a result future planning and development of the town should consider this hazard.

2.5 Landslide Monitoring Measurements in the Study Area

Previously landslide monitoring devices were installed for detail slope instability counter measures identification and investigation along the main road corridor Gohatsion-Dejen section by [JICA and GSE \(2012\)](#). These monitoring devices were two types which are inducing factor monitoring and landslide displacement monitoring. Inducing factor monitoring includes precipitation observation, surface water observation, ground water observation and seismic observation, whereas landslide displacement monitoring includes on the ground surface and under the ground surface monitoring systems. Generally, the following type (borehole and surface extensometer, borehole inclinometer, groundwater level and rain gauge) devices were installed.

2.6 Previous Landslide Studies and Gaps of the Present Study Area

No more detail landslide work is conducted anywhere in Ethiopia, except in Blue Nile Gorge along Gohatsion-Dejen section road corridor slope instability investigation. This road corridor is very important due to that various individuals and institution conduct detail investigations more than anywhere in Ethiopia. It is obvious, as stated by different authors the three physiographic units: the northern, western and southern highlands of Ethiopia are more prone to landslides. The current study area Blue Nile Gorge falls on a landslide prone physiographic region, western highland. Due its physiographic condition this area is

frequently affected by landslide hazards and this reason makes a particular interest to many researchers. Summarized different individual and institutional previous research works on the present study area are presented as follows;

According to [Samuel Molla \(2011\)](#), [ERA \(1967\)](#) investigated the area between the Filiklik village and Washa Mikael church. The purpose of investigation was to identify slope stability condition that the road passes. According to the ERA investigation, weathered basaltic rock and the colluvial moving materials under the pier foundations were responsible for the failure of the viaduct. Based on this work investigation result realignment of the road avoiding the problematic slope section along the viaduct was suggested.

[EIGS \(1994\)](#) conducted a detailed engineering geological investigation by utilizing an integrated approach between Gohatsion - Dejen towns to determine the depth to the hard rock material and the quality of the rock defined; to locate any linear features like faults, fractures, contacts and lineaments.

The material characteristics along the proposed new realignment road section using geophysical methods were explained by [Mesfin Wubshet *et al.*, \(1994\)](#).

According to the report produced by staff members of EIGS, [Almaz Gezahegn and Tadesse Dessie \(1994\)](#) four types of slope instabilities or geological problems in the Abay River Gorge and its tributaries related to landslides were identified. These slope instabilities are presented in numbers as follows; (i) continuously moving granular deposits from the slopes of basalt escarpments, (ii) rotational failure of colluvial soil, (iii) gully erosion and (iv) rock fall and toppling. The presence of marl and shale within hard rocks are considered as the cause for slope instabilities. Based on the results of their investigation road realignment was recommended.

Further, as cited in [Henok Woldegiyorgis *et al.* \(2014\)](#), the TCDSCo has carried out detailed geotechnical investigation project along the Gohatsion-Dejen-Debre Markos road corridor in 2003 ([TCDSCo, 2003](#)). According to their findings, they describe unconsolidated colluvial soil mass was the cause for the distortion of the northern parts of the road.

[Lulseged Ayalew and Yamagishi \(2004\)](#) have investigated some slope failures on the Abay Gorge that stretched from Gohatsion to Yet Nora, a small village about 8-km north of Dejen.

In their study, their goal was to relate topographical characteristics with the process of mass movement. Finally they concluded that slope instability was a part of the mega-forces that shaped the entire Blue River Basin and that mega-force also contributed to general landscape evolution.

According to [Henok Woldegiyrgis et al. \(2014\)](#), [Jemal Saed in 2005](#) studies slope stability analysis on the sides of the road from Gohatsion to Dejen towns. During his study He has identified 17 critical slope sections. Among 17 critical slope sections 9 were taken for detail slope stability analysis to suggest suitable remedial measures.

[OJEC \(2008\)](#) conducted a research for instant counter measures to against landslides. During that time different landslide mitigation measurements like subsurface tube strain gauge, borehole extensometers and also automatic ground water level recorder were installed. In addition 5 boreholes were drilled to obtain samples of subsurface material to recognize the formation of stratum. According to [Samuel Molla \(2011\)](#), among the investigations which have been conducted still this one was detail.

[JICA and GSE \(2012\)](#) conducted a vast detail study to countermeasures against landslide in the Abay River Gorge. The study was carried out cooperatively with [JICA and GSE in 2012](#) by technical assistance of JICA. They made an extensive survey on landslide hazards by using integrated topographical and geophysical methods. According to the report obtained during their study more than 60 boreholes were drilled for the testing purpose, sampling purpose of subsurface material to recognize the formation of stratum and to install underground monitoring equipment's. The main goal of the study was generating well organized comprehensive data to monitor a landslide hazard along Gohatsion–Dejen section road corridor. During their study they have identified four major landslide susceptible zones; these were landslide in Amist kuter asphalt (at the entry of the gorge in Gohatsion side), landslide in Marba locality, landslide in Chifinchif locality and landslide in Kurar Gebriel locality. Based on the results of the study, they made recommendation and install various landslide monitoring instruments like surface extensometer, borehole extensometer, surface and borehole inclinometer, strain gage, and also horizontal borehole drainage were done along Gohatsion-Dejen section main road corridor. According to their recommendation groundwater was crucial factor for slope instabilities.

[Mulugeta Beyene \(2013\)](#) has carried out his MSc thesis research work entitled by “assessment of slope stability using combined probabilistic and deterministic approach for selected sections along Gohatsion – Dejen route”. During his research work he has evaluated stability condition for existing and anticipated worst conditions to which the slopes would be subjected. During the study he has identified four critical slope sections; two from failed colluvium sections and two from rock slopes for further analysis. According to his research findings he suggests remedial measures for critical slope sections in the area.

[Henok Wolde Giorgis et al. \(2014\)](#) have conducted a landslide hazard zonation by utilizing a technique expert evaluation between Gohatsion town and Abay River. In this study, they have attempted to delineate the area into LHZ by utilizing LHEF rating scheme. The considered causative factors were relief, slope morphometry, geology, groundwater and land use/ land cover. Based on the causative factor scheme the hazard has low, moderate and high levels. According to the final overlay analysis hazard zonation result the main road passes through moderate and high hazard zones. According to these authors detail investigation was recommended to suggest the remedial measures or to realign of the main road.

[Shiferaw Ayele et al. \(2014\)](#) have conducted a research to delineated landslide hazard zones in the Gohatsion - Dejen section road corridor using Remote Sensing and Geographic Information System approach. To carry on this landslide delineation work weighted linear combination method was followed. For the study, the triggering factors, which were considered, were: slope, structures, aspect, geology, groundwater condition, drainage, and land use/ land cover. Validation was done by overlying past landslide activities in study area. The past landslide locations laid on the maximum hazard zone.

The most recent work entitled by the effects of causative factor combinations prediction correctness of landslide susceptibility zonation maps in the Abay Gorge, central Ethiopia was conducted by [Matebie Meten et al. \(2015\)](#). To conduct his research work he was followed the frequency ratio and logistic regression models. The selected causative factors were; slope, aspect, profile-curvature, plan-curvature, lithology and land-use, proximity to lineament & proximity to river. Using correlation matrix of logistic regression he has ascertain the independence among each causative factors before producing a landslide susceptibility index map by using mathematical combination theory. Joining of slope, lithology, land-use and proximity to lineament causative factors and except distance from the river combination

landslide causative factors show the same prediction accuracy. Based on the prediction similarity, he has concluded four landslide causative factors have more influence relative to the remaining landslide causative factors.

Generally, different and several type researches were conducted in the Abay Gorge by individuals and institutions. More or less all are doing in regional and medium scales, except OJEC in (2008, as stated by Samuel Molla, 2011) and a recent and vast detail landslide counter measure work by JICA and GSE, (2012).

To carry out the present study detail review work was essential to identify the gaps that were not used by the previous researchers. After detail review, a technique which was not followed by a previous researcher is obtained. This technique which was not used by a previous researcher is information value method. Therefore the current study was conducted by using a technique information value method that fall on bivariate statistical approach.

This is an important technique to prepare the landslide susceptibility mapping. This landslide susceptibility map has various susceptible level classes. Based on these susceptible class level land use management systems will be planned and also important to conduct detail investigations before different infrastructures development according to the susceptibility class levels or recommendations.

2.7 Genesis of Methodology for the Present Study

The methodology followed in the present study is part of a bivariate statistical approach. Bivariate statistical approach proposes that if a situation holds in all observed cases then the situation holds in all cases (Lulalem Shano et al., 2020). Thus, the techniques are based on the general assumption that “the past and the present are the key for the future” (Dai and Lee, 2001). A statistical approach information value method which falls under bivariate statistical analysis was basically followed in the present study Gohatsion-Dejen section main road corridor. Statistical approach is the most popular technique (Raghuvanshi et al., 2014a, Lulalem Shano et al., 2020). Many authors agree that statistical methods are more appropriate for hazard zoning, because of having minimum degree of subjectivity (Lulalem Shano et al., 2020). In this method result of the inventory data are compared with the causative factors which influence landslides. Statistical analysis techniques are based on statistical determination of combination of causative variables in a given area. Based on the analysis

relations of causative factors and the inventoried landslide activities quantitative estimations are made. For statistical information value analysis each causative factor classes information values are decided through the combination of landslide raster to causative factor raster based on the presence of landslide in a given thematic map. After the statistical IV obtained then the weight rate is assigned for each causative factor classes. These weighted factor maps were rasterized by using lookup tool in spatial analysis of Arc Toolbox. Then, after rasterization the landslide susceptibility index (LSI) maps were produced by the sum-up of all raster maps using a raster calculator in Map Algebra. Thus, a landside susceptibility map for the given study area could be produced.

CHAPTER THREE

THE STUDY AREA

3.1 Location and Accessibility

The present study area is located about 185kms northwestern of Addis Ababa along the main road that connects Addis Ababa to Bahir-Dar through Debre Markos. The area coverage is 254km² and it extends from Gohatsion to Dejen towns, central Ethiopia, which lies in the two regional states of Amhara and Oromia (Figure 3.1). The area forms a part of the Abay River Basin and is geographically defined by co-ordinates 406036 E – 420001E to 1105982N – 1124003N.

The road corridor which passes through Blue Nile Gorge is very important because it connects northwestern part of the country along Addis Ababa-Debre Markos-Bahir Dar-Gondar-Metema, Gondar-Kafta Humera and across the country Eritrea and Sudan. Further, along Addis Ababa-Debre markos-Injibara-Metekel-Grand Ethiopian Renaissance Dam (GERD).

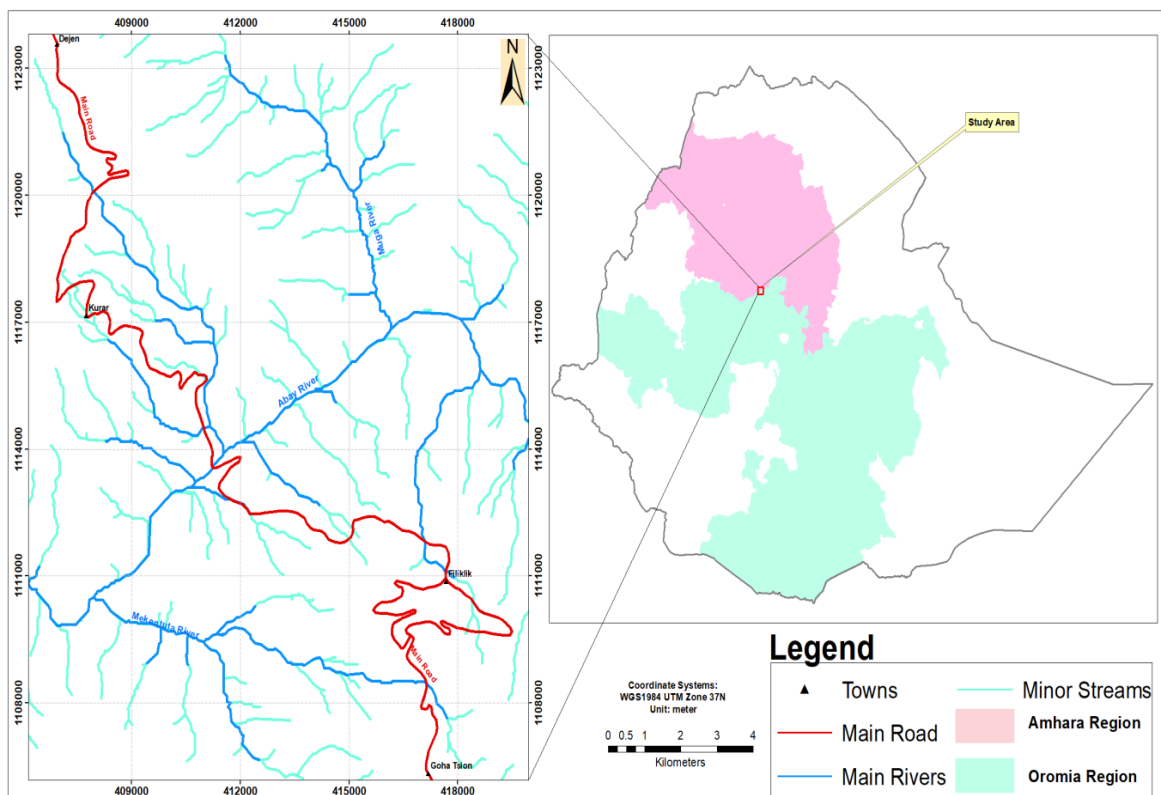
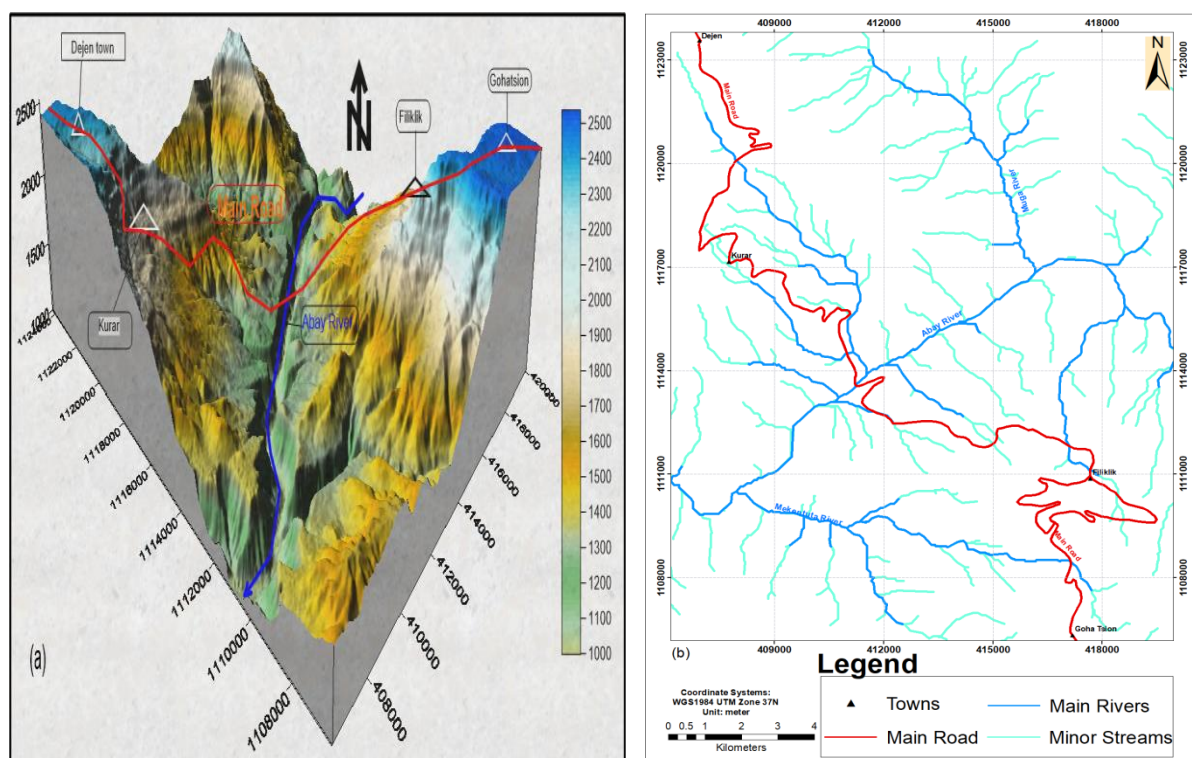


Figure 3.1 Location and accessibility map of the study area

3.2 Physiography and Drainage Pattern

The study area is situated in the northwestern plateau of Ethiopian highland. The lowest and the highest peak elevation of the study area is 1023m a.s.l and 2542m a.s.l respectively (Henok Woldegiorgis et al., 2014) and (Figure 3.2a) below is a good illustration. The elevation difference is more than 1500m. It ranges from the highland in Gohatsion and Dejen side to Abay River valley. The physiography of the Blue Nile Gorge is undulated, which is extensively eroded and dissected by the deep gorges. This physiographic feature is mainly a result of erosion, rock fall, toppling and associated landslide processes. The main road corridor which passes through this terrain is frequently damaged by landslides. In this area most of the rivers originate from the highland plateau and characterized by dendritic to sub parallel drainage patterns. They drain towards Abay River (Figure 3.2b).



a) 3D view physiographic map and b) Drainage map

Figure 3.2 General physiography of the study area

3.3 Climate

Ethiopian climate is mostly controlled by the seasonal variation of the Inter-tropical Convergence Zone (ITCZ) following the position of the sun regards to earth and the associated atmospheric circulation (NMSA, 2001). Not only that the climate is also highly

influenced by the complex topography of the country. There are five traditional climate classes in the country Ethiopia (Table 3.1).

Table 3.1 Traditional climatic zone and their physical characteristics of Ethiopia

(Source: MOA, 2000)

Zone	Altitude (meters)	Rain fall (mm/yr)	Average temperature ($^{\circ}$ c)
Wurch (upper high lands)	3200 plus	900-2200	11.5 plus
Dega (high lands)	2300-3200	900-1200	11.5-17.5
Weynadega (mid land)	1500-2300	800-1200	16.0-20.0
Kola (low land)	500-1500	200-800	20-27.5
Bereha (desert)	Under 500	Under 200	27.5 plus

According to this classification shown in Table 3.1, the present study area lies in three different climate regions; Kola, Dega and Weyinadega. Large part of the area lies on Kola climate region (Figure 3.3).

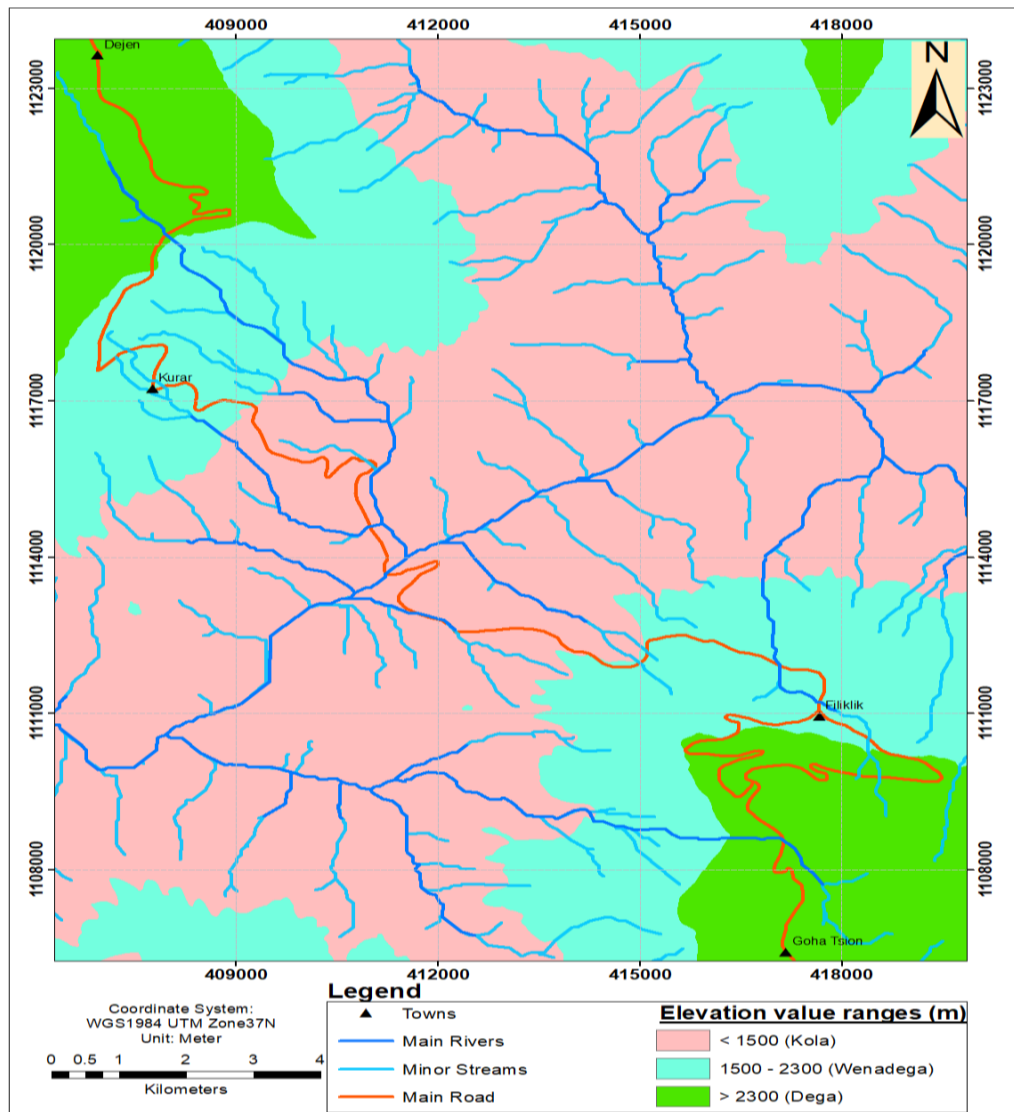


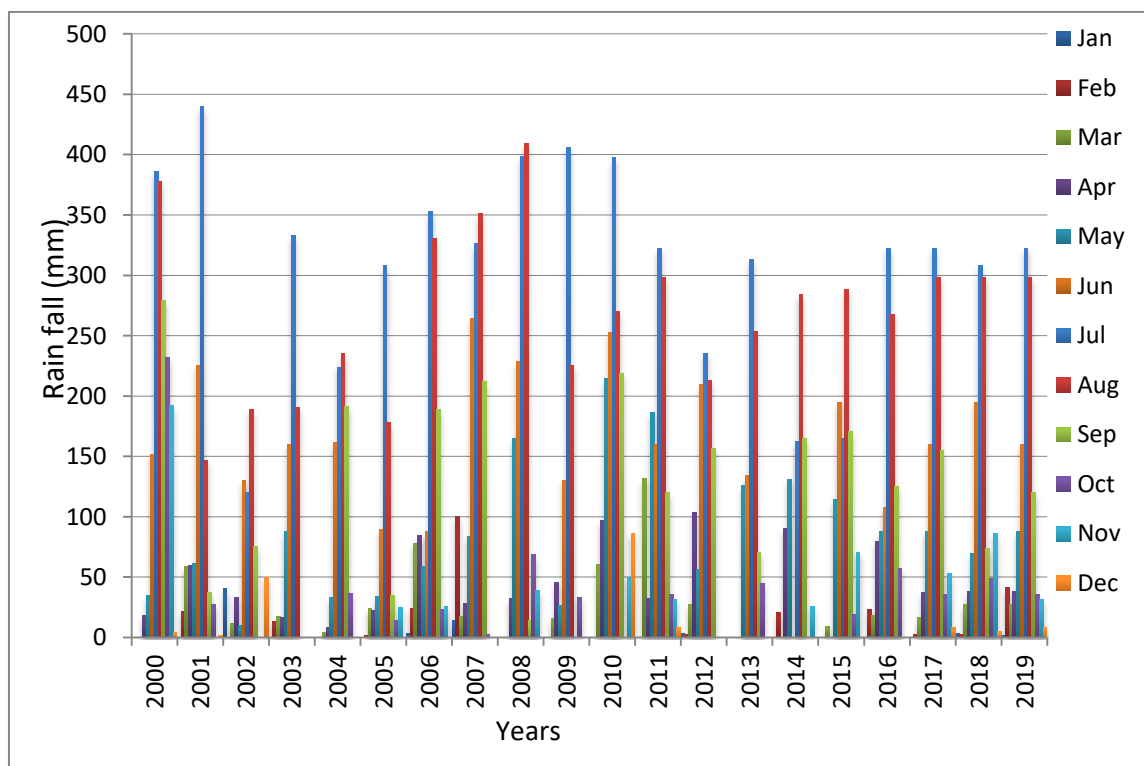
Figure 3.3 Climate map of the study area based on elevation

3.3.1 Rainfall Distribution

A landslide means the phenomenon which some or all of a slope slowly or rapidly moves down the slope under the influence of groundwater and gravity. Therefore, the most important mechanism that triggers landslides is fluctuation of the groundwater level. Generally, changes to groundwater level are due to rainfall in many cases. The frequent landslides occur mainly in rainy seasons July to September (JICA, 2010). Landslides occur most easily when about 10 mm/day of rain continues for about five days; in the study area such kind rain is recorded especially in two months July and August (Takano, 1960). Landslide and rain fall have close relations.

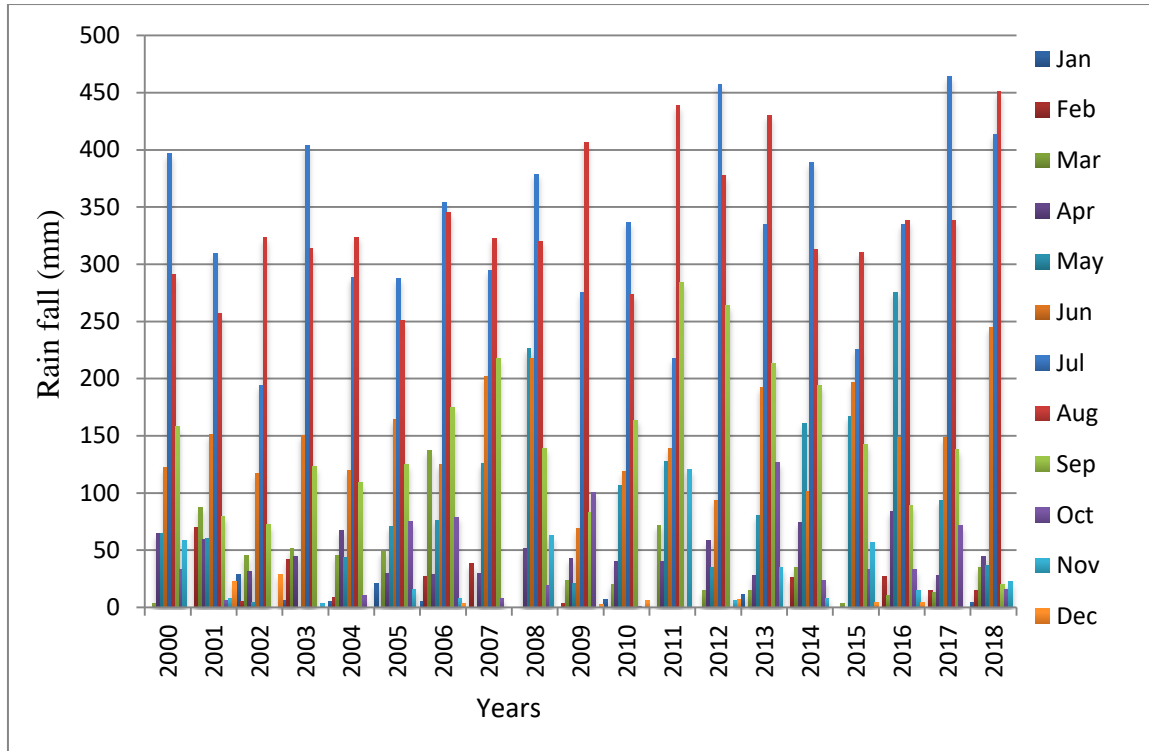
Increasing and decreasing of precipitation can have its own impact in slope stability. When precipitation will have decreased the consequences are lowering of the water table, decrease the weight of the soil mass and decreased solution of materials while precipitation will have increased the following results like, raise the level of the groundwater table, reduce shear strength, increase the weight of the soil mass and may increase erosion will be occurred.

In the present study area there are three metrological stations. These metrological stations are installed in Filiklik, Gohatsion and Dejen towns and the mean annual rainfall recorded at these stations were 1110.1mm/20yrs, 1219.3mm/19yrs and 1321.9mm/18yrs, respectively (Apendix-1a,1b & 1c). For the assessed various years data on Filiklik, Gohatsion and Dejen station the maximum monthly rainfall were 439.7mm in 2001, 464.3mm in 2017 and 645.4mm in 2001 respectively which were recorded in the month of July (Figure 3.4a, b & c). In the months July and August the rainfall reaches at peak.



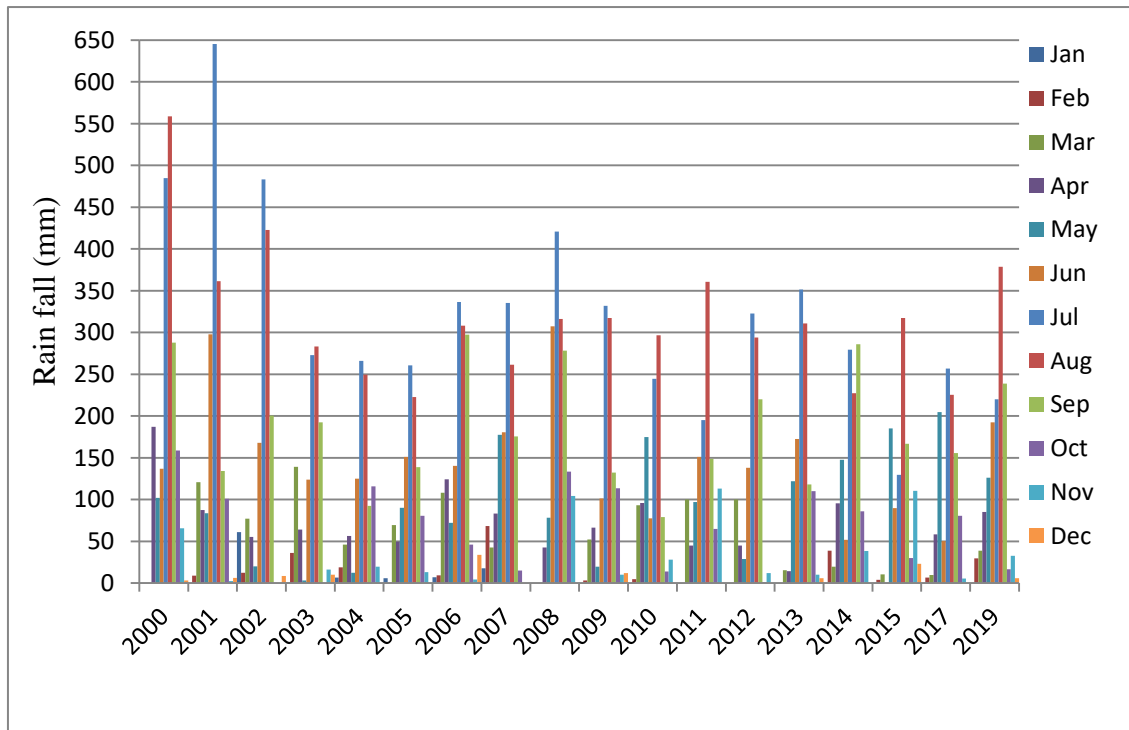
(Source: Metrological Agency of Ethiopia)

Figure 3.4a Monthly rainfall distributions on Filiklik station



(Source: Metrological Agency of Ethiopia)

Figure 3.4b Monthly rainfall distributions on Gohatsion station



(Source: Metrological Agency of Ethiopia)

Figure 3.4c Monthly rainfall distributions on Dejen station

3.3.2 Temperature

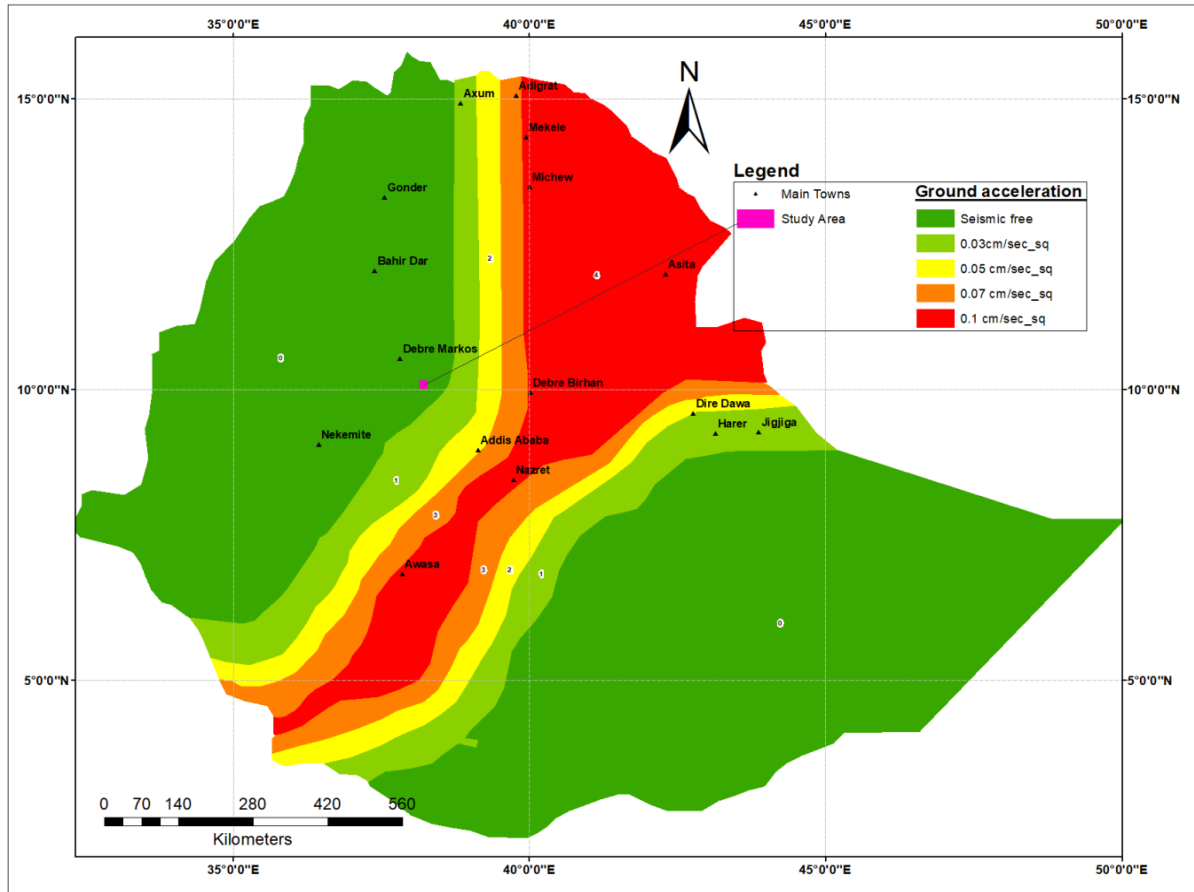
Temperature changes can affect the stability of a slope in several ways. Increasing and decreasing of temperature can cause changes in vegetation cover and groundwater.

According to Ethiopian Metrological Agency record, the maximum mean annual temperature was recorded from February up to June in the present study area. The minimum mean and the maximum mean annual temperature nineteen years data of the area are 12.8°C and 27.5°C respectively (Appendix2).

3.4 Seismicity

Seismicity refers to earthquake ground motion at the earth's surface, and likely it has effects on existing natural conditions, man-made infrastructures and public safety. Earth quakes are common in the active plate boundaries and rift marginal areas. Ethiopian Building Code Standard (EBCS, 1995) released seismic hazard zoning by classifying the country into four major seismic hazard zones (figure 3.5). Areas that fall in Zone 4 are the most prone to seismic hazards. This zone comprises all areas in the Main Ethiopia Rift and Afar Depression. Areas that fall in zone 1 are least prone to the hazard. According to the seismic hazard map, the present study area falls in zone 0 which is seismic free, which implies that the Abay Gorge (the present study area) lies in no seismic hazard zone. The ground acceleration that should be considered in each seismic zone is described here under in Table 3.3.

Table 3.2 Ground acceleration of earth quake that should be considered in each seismic zone of Ethiopia					
Zone	4	3	2	1	0
g (cm/sec ²)	0.1	0.07	0.05	0.03	Seismic free



(Source; EBCS, 1995)

Figure 3.5 Seismic hazard map of Ethiopia for 100-year return period

3.5 Land-Use/Land-Cover

As a result obtained from supervised classification system of Landsat 8 OLI data processing using Arc GIS v 10.7, percent of area coverage and land use land cover types were identified (Figure 3.6 and Table 3.2). Much of the area is covered by agricultural land followed by bush land with area coverage of 46.6% and 41.7% respectively. Valleys around Abay River and its tributaries are mostly covered by bushes but the flat and gentle slope areas are covered by agricultural crops. The remaining bare land includes river sediments, cliffs, river wall banks

and existing quarry sites. The dominant crop produced in the area is sorghum, wheat, maize, teff and sugarcane (Samuel Molla, 2011).

LULC	Area (km ²)	% of area coverage
Agricultural land	118	46.4
Bare land	24	9.4
Built up area	6	2.2
Bush land	107	41.7

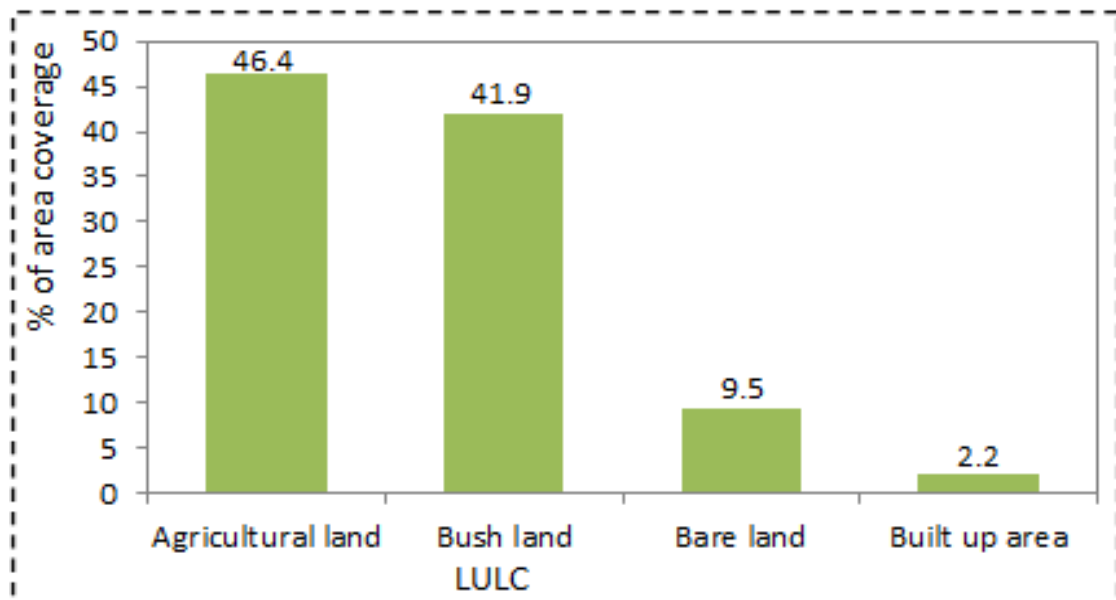


Figure 3.6 % of area coverage and LULC type

3.6 Geology

3.6.1 Regional Geology

The present study area Blue Nile Basin is one of the main East African sedimentary basins found in Ethiopia in addition to Mekele, Ogaden, Gambela and Rift basins (Getaneh Assefa, 1991). According to Wolela Ahmed (2008) these five basins cover 33% of the Ethiopian Surface. Among these basins the northwestern part sedimentary basin covers most part of the country and characterized by highland relatively 1500m to 4000m and the southeastern plateau occupied by Ogaden Basin relatively lies below 1000m which is characterized by descending to the Indian Ocean (Getaneh Asefa, 1991). The history of Mesozoic

sedimentation related to the beginning of break-up of Gondwanaland during Paleozoic-Jurassic times which were largely fault-controlled (Lulseged Ayalew and Yamagishi, 2004). Abay Gorge (Blue Nile Basin) is created during the intra-continental rift stage which related to the beginning of Gondwanaland break-up (Russo et al., 1994). According to Russo et al. (1994) Blue Nile River Basin is 1200 meters thick and capped by Tertiary flood basalt, includes five units from bottom to top: lower sandstone (Adigrat Sandstone)- represents post rift deposition which was fluvial sedimentation, shale and gypsum unit also called Gohatsion Formation (Getaneh Asefa, 1981) - deposited at the beginning of marine transgression, Antalo limestone – represents the product of a major transgression, muddy sandstone (Mugher sandstone), and upper sandstones (Debra libanos sandstone) - formed by regression of the sea from the main water body.

These formations contain different rock units with long cliffs of sandstone, limestone interceded with shale and marl and gypsum intercalated with relatively soft units of mudstone, shale, and marl (Getaneh Asefa, 1981), which are susceptible for mass movement.

3.6.2 Local Lithological Units of the Study Area

Abay Gorge has stratified sedimentary rocks capped by Tertiary basaltic volcanic rock. The stratigraphic sequence starts with the oldest being Paleozoic sedimentary rocks at the bottom followed by subsequent younging upward sequence of Mesozoic sedimentary rocks and Tertiary basaltic rocks. As stated by Wolela Ahmed (2008) the central part of the Blue Nile Basin (Gohatsion-Dejen area) has a maximum thickness of 3000m and 200 m at the extreme west margin. Within this thicker succession there are different formations. The Paleozoic sedimentary rocks are Abay Sandstone; the sandstone at its top part alternates with siltstone and/or shale and mudstone; the siltstone/shale and mudstone sediments occupy the top most part while the sandstone occupies the lower part in terms of the stratigraphic succession. The Mesozoic sedimentary rocks from the oldest to the youngest are: (1) lower sandstone unit (Adigrat Sandstone); sandstone with lenses of conglomerate and siltstone or shale, and at the top most part contains about 40m thick blue mudstone, (2) gypsum unit; gypsum beds alternate with limestone, blue shale, dolomite and minor sandstone, (3) limestone unit; fossiliferous limestone occasionally alternates with black shale, impure limestone and very minor sandstone, (4) upper sandstone unit; sandstone alternates with shale and contains lenses of conglomerate. The Tertiary rocks are dominated by basalt lava flows, which are

non-conformably overlaid on the Mesozoic sedimentary rocks. The sedimentary and volcanic rocks in the area are exposed largely as symmetrical stratigraphy on both sides of the Abay River; the detailed sequences are unevenly distributed (JICA and GSE, 2012). The Tertiary rocks overlying the Mesozoic units. Quaternary age recent deposits are extensively found in the form of alluvial sediments and as slope deposits.

Sandstone; Adigrat Formation

Sandstone is the oldest unit within the study area and belongs to Adigrat formation which unconformably overlies on Paleozoic sediments. It is exposed on each side of the Abay River. This unit is intercalated with mudstone, siltstone and shale within the lower part, and conglomerate within the upper part. It is 270 meters thick (Almaz Gezahegn and Tadesse Dessie, 1994) well cemented fine to medium grained. The rock is brownish red in color, but because of weathering effect it is changed in to white grey and brownish dark (Plate 3.1). No fossils are reported within the unit. This unit is underlain by upper Paleozoic sediments and has gradational contact with the overlying mud rock. Most of this unit is horizontally bedded, but also locally show cross bedding. The upper part of the sandstone is thickly bedded whereas the lower part is thinly bedded. Structurally this unit has three well- developed joint sets, the bedding plane which is horizontal and other two sets trending NW and NE (JICA and GSE, 2012). It forms a vertical cliff, leading to rock falls due to the intersection of those three joint sets.



Plate 3.1 Sandstone exposure along Gohatsion-Dejen road section in the study area

Murdock; Abay Formation

The mudstone forms flat-lying, gentle slope to moderate slope topography with occasional steep slope topography and has about 40m maximum thickness on top of the sandstone. The mudstone is massive, partly laminated and bedded vertically jointed and faulted (JICA and GSE, 2012; GSE, 2015). This unit is dominantly represented by fine grained silici-clastic rocks and subordinate evaporite beds. It is bounded by sandstone and gypsum beds at the lower and at the top respectively. This mud rock unit comprises two well-developed joint sets trending N30W and N70E, respectively (Henok Woldegiorgis et al., 2014).

Gypsum; Abay Formation

The gypsum member represents evaporite dominated facies forming cyclic intercalations of gypsum, dolostone, limestone, shale and subordinate silt and mudstones. The dominant lithology within this member is gypsum. Gypsum forms flat-lying, moderately steep topography. The gypsum unit is composed of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. It has intercalation of thinly bedded shale. This unit has 180 meters thickness (Almaz Gezahegn and Tadesse Dessie, 1994). The gypsum is bounded between the lower mud rock unit and the overlying upper mud rock unit. It is generally white in color, but varies to grey, bluish grey and black. The

variation in color is attributed to several ferruginous minerals and organic impurities. Generally gypsum is susceptible to weathering and erosion, this phenomenon is evident on the Gohatsion side where the gypsum is exposed along the road side (JICA and GSE, 2012). The weathering in the gypsum contributed to the change of color on the surface and along the joint plane. In the gypsum unit, two sets of joints which are N30W and N70E as well as a horizontal bedding plane are observed (JICA and GSE, 2012). Although the rock itself is hard and strong, the two joint sets and the bedding plane would result in huge rock failure due to intersections.

Limestone; Antalo Formation

The limestone is usually horizontally bedded and is topped by the trap series basalts. The colour is pale grey, yellowish grey and brownish grey but the weathered color is dark and typically its grain size is fine to medium (Plate 3.2). The unit comprises of dolomite and mudstone.

This unit has 400 meters thickness (Almaz Gezahegn and Tadesse Dessie, 1994). It overlies on the upper shale unit. Fine to medium grained limestone is widely spread out within the area. The form of limestone layer creates steep slope cliffs and escarpments. Even though, the dominant unit is limestone but there are shale, carbonated clay and marl intercalations within the unit. The unit is reported as fossiliferous. It is generally white in color, but due to weathering effect it varies to yellowish grey, and brownish grey color.

In general, this unit is horizontally bedded and has three well-developed joint sets; bedding plane which is almost horizontal and two other joint sets trending NW and NE (JICA and GSE, 2012). The joints of the limestone are crammed with calcite, marl or both fragments. The three joint sets with both closely and widely spaced fractures would lead to huge rock failure due to the intersection. The upper part of the limestone is thickly bedded whereas the lower part of it is thinly bedded.



Plate 3.2 Limestone exposure along Gohatsion-Dejen road section in the study area

Basalt; Ashangi Formation

The thickness of the formation is over 380m on both sides of Gohatsion and Dejen towns and occurs intercalated with pyroclastic layers (JICA and GSE, 2012). The lower part of this unit is characterized by a massive basaltic lava flow associated with colluvium deposit with thickness reaching 70m while the middle part is composed of basaltic lava and pyroclastic rocks with thickness over 70m (JICA and GSE, 2012). This unit on the top is columnar jointed (20-30cm), whereas at the bottom flows are massive with huge blocks. The columnar joints are partly concealed and the bottom is composed of more than (15-20m³) weighting considerable tons. Rock fall is associated with both columnar and massive basalt ((Almaz Gezahegn and Tadesse Dessie, 1994).

These joints often conduit water from surface to pass down to the less jointed and softer volcano clastic intercalations. In this volcanic unit columnarily jointed rocks water flow is moderate therefore vegetation does not developed in a well manner (JICA and GSE, 2012).

Residual Soils

Residual soil deposits are formed from weathering and decomposition of parent rock material. These soils cover most of the plateau and the step like terraces formed by basalt and

completely flat lands. The residual soil developed from the basalt plateau is red in color due to higher iron oxide content in clay; whereas down the gorge it changes its color into brownish and yellowish as the rock unit changes into limestone and shale. In general, the residual soils reflect colors pertinent to the parent rocks.

Alluvial soils

The alluvial soils are found in low lying areas like, valleys, gullies, river channel of Abay River and tributaries of Abay River such as Muga and Mekentuta Rivers. These soil deposits contain Coarse grained gravels and sands are also present along major stream channels and gullies.

Colluvial soil

Colluvial soils are deposits displaced from their original location of formation or deposition by gravity force. Colluvium soil is found all along the valley with varying thickness but are mainly concentrated on the terraces of volcanic units, gypsum beds, Abay limestone and at the foot of the cliffs. The colluvial deposits are accumulation of thin soil layers, rock cobbles and boulders. They come from denudation terraces on the top of the cliff and fall off cliff suspended blocks. Their thickness is more than 20m especially on the Dejen side of the valley where numerous unstable landslides are concentrated (Almaz Gezahegn and Tadesse Dessie, 1994; JICA and GSE, 2012).

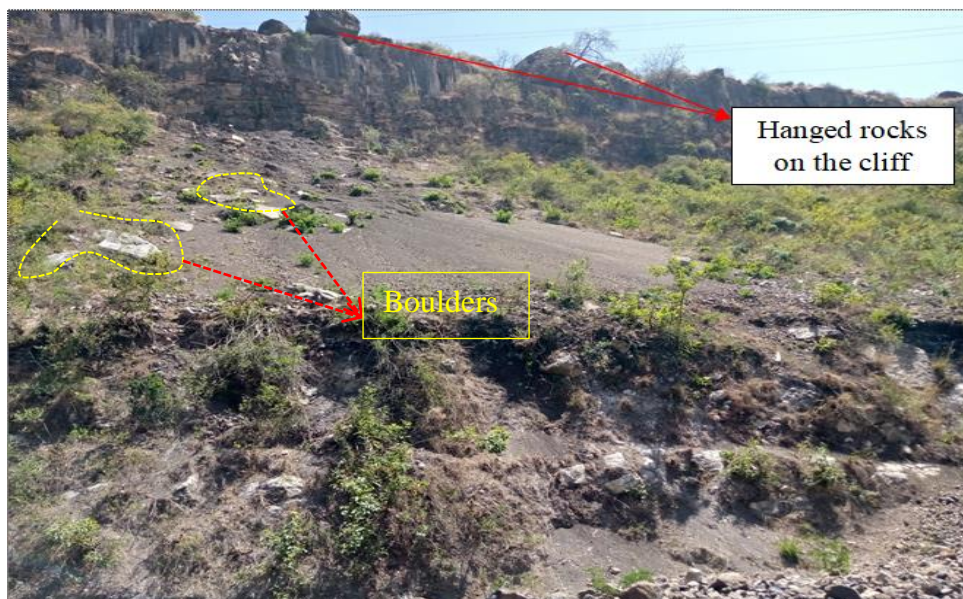
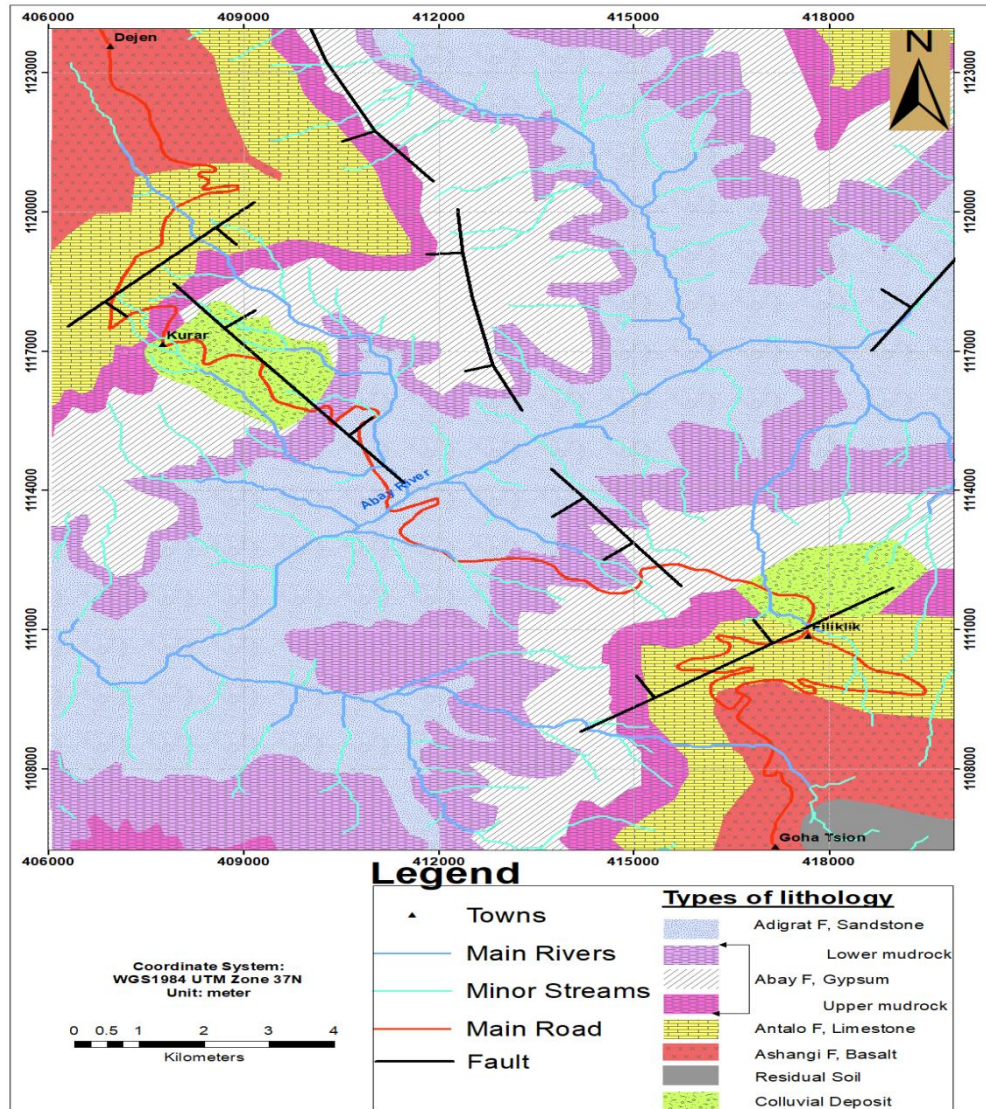


Plate 3.3 Thick colluvial deposit on the foot of limestone cliff along the main road in the study area



(Source: Modified after, GSE, 2015)

Figure 3.7 Geological map of the study area

3.7 Geological Structures in the Study Area

Normal faults that strike generally towards NE-SW and NW-SE are distributed in the study area. These structures are clearly observed in gypsum beds of the study area. Many part of the study area consists three well-developed joint sets; the bedding plane, which is nearly horizontal, and two other joint systems (j_1 and j_2). Most of them are trending to NW and the other NE, respectively.

Many columnar joints in the study area are observed in basalt rock mass. Surface cracks are also observed in the study area on colluvial deposit around Filiklik and Kurar vilages.



a) Ground crack on the Church compound in Kurar village, b) Normal fault on gypsum bed & c) columnar jointed basalt

Plate 3.4 Geological structure in the study area

3.8 Hydrogeology

3.8.1 Surface Hydrology

The rain absorbed by soil reaches ground water while the rain that is not absorbed by soil remains on the surface of the ground, fills small depressions, and eventually spills over and runs quickly down slope in to streams as over land flow, which generates floods. The absorbed water seeps in to the soil by the process of infiltration and is held there as a soil moisture. If the soil moisture content is raised sufficiently, infiltrating water will displace older water, which may percolate laterally through the top soil into streams as subsurface

storm runoff or vertically to the ground water zone where the pores of the soil or rock are completely filled with water. From this zone, water moves slowly in to streams, swamps or lakes providing surface runoff during dry weather. Runoff is water that flows on the surface in to the stream channel as over land flow and from the ground water contribution to the stream as base flow. Most of the runoff in the study area flows from Gohatsion and Dejen side to the low laying valley Abay River. The study area is bounded by the Abay, Mekentuta, Muga and unnamed rivers. In the study area there are many streams and gullies which are joining the Abay, Mekentuta and Muga and unnamed rives. All flows are finally accumulated to Abay River. The presence of various rivers and streams exposed the area for gully erosion especially in the lower slopes, which are mainly formed by unconsolidated colluvium and alluvial deposits.

3.8.2 Groundwater Hydrology

The groundwater condition is the most important factor in slope stability problems. The way groundwater flows, its pressure and gradient at any point with in a slope depend on local geology ([Abramson, 1996](#)). Water is among the main triggering factors that makes instable hill slopes. Theoretically, when groundwater increases, pore water pressure increases and effective stress will decrease. As a result, shear resistance decreases, triggering a landslide.

Identification of water source, water movement, amount of water and pressure has further importance for the identification of the material constituting the slopes and the type of structures. An area having highly jointed rocks and thick overburden soil, surface and ground water plays a crucial role in the initiation of landslides. The presence geological structures like faults and lineaments in high slopes, bigger pressure head and seepage velocity than the surrounding area, the impact on slope instability will be higher ([Mahajan and Virdi, 2000, as cited in Tilahun Hamza, 2014](#)).

The present study area falls in Kola, Weynadega and Dega climatic zones (Figure 3.3). The Subtropical (Weynadega) and Temperate (Dega) climatic zones are the areas where there is relatively an excess of rain for ground water recharge. Despite the fact that the low-laying parts of the study area are relatively hot, this surplus of rain assumed to have a contribution to ground water recharge for the study area. Though groundwater hydrology can be affected by many factors such as; the permeability of local geology, structures like joints, faults, fractures

and lineaments this can be depicted from the surface water flow direction and springs which all of the streams and gullies springs run towards the low-laying valley of the study area.

Groundwater - ground water condition at the surface certainly can be observed from spring located and available precipitation records (Varnes, 1984). Therefore, ground water condition of the study area should be observed by the presence of springs, algal growth on shadow areas, gully development, slope toe erosion, stream bank erosion and other water marks on slopes face (Plate 3.5). The springs face towards the downslope. It is assumed that the intensive fracturing favors a higher amount of water to infiltrate downwards and emerges through the fractures of the impermeable horizontally bedded limestone with shale's and sandstones.



a) Spring at the left flank kola Jemo landslide b) Spring at Chifinchi locality

Plate 3.5 springs at various locations

Springs - even no more spring data's have been collected throughout the study area due to accessibility problems but some spring data's along the main road corridor are collected and the relationships of landslide with the spring has been analyzed. There are 8 springs and 2 hands dug wells (Table 3.4) some of them serve for drinking and bathing purposes and some are developed randomly along the landslide areas. Most springs in the study area have a contribution for the occurrence of the landslide and the landslide itself also have contribution for emerging new springs due to these new spring development an old springs have been disappear and changed the flow out directions. As the results analyzed from the respondents

interviewed and as observed at the landslide locations many springs were emerged after the landslide and some of the springs were also disappeared after the landslide occurrence. The red arrow on the photo locates spring point.

Table3.4 Location and description of collected spring data

ID	Easting	Northing	Elevation	Description	Locality
SP1	417212	1108499	2391	A pond like spring which is found around at 1km distance from the entry of the gorge in Gohatsion side. At this spring lignite coal is developed.	Around amidst kuter asphalt
SP2	416972	1110361	2131	Drivers used it for washing purpose. This was drain down in borehole pipe.	Marba
Sp3	417043	1111972	1714	Which serves for animals drinking purpose	Around Filiklik
Sp4	410995	1114594	1154	A spring which serves for drinking and bathing and which at the left flank of chifinchif landslide	Chifinchif
Sp5	411020	1114737	1154	Newly developing spring at chifinchif locality it comes up due to a landslide	Chinchif
Sp6	406961	1118194	1887	A spring which is used for drinking in the locality people around it a new landslide s developed	Kurar
Sp7	416424	1112332	1756	seasonal spring	-----
Sp8	407346	1119176	1920	A pond which is developed on the landslide area	Dembeza Mariyam
Sp9	407915	1120255	2062	shallow hand dug well which serves for locality people drinking purpose	-----
Sp10	408466	1121227	2323	shallow hand dug well which serves for locality people drinking purpose	Kurar

CHAPTER FOUR**METHODS AND MATERIALS**

4.1 General

Among the various techniques which have been used for landslide susceptibility mapping statistical approach is widely used (Leulalem Shano et al., 2020). Statistical methods are preferred by many authors for hazard zoning, because of having minimum degree of subjectivity (Raghuvanshi et al., 2014a; Leulalem Shano et al., 2020). In statistical method the inventory data were compared with the causative factors which influence landslides. Statistical analysis techniques are determined based on the combination of causative variables and past landslides in a given area. According to the statistical analysis for the relations of the causative factors and the invented landslide activities quantitative estimations are made.

4.2 Methodology Adopted for Landslide Susceptibility Mapping**4.2.1 Information value model**

It is a statistical method for spatial prediction of an event based on the parameter and event relation. In this model, statistical information values of causative factors are used to characterize the possibility of landslide occurrence. The statistical information values are decided for each class of landslide related parameter on the basis of presence of landslide in the given mapping unit. The causative factor maps were combined with landslide map in order to get weight of each class.

The statistical information value model is very important to analyze landslide susceptibility in a quantitative way. The method gives the quantified prediction of susceptibility by means of a score, even on terrain units not yet affected by landslide occurrence. The considered instability causative factor are integrated with the landslide distribution, and weighting values based on landslide densities are calculated for each parameter class, as it happens with all bivariate statistical methods. When the statistical information value becomes negative the presence of the variable does not have relevant contribution in landslide development but if the statistical information value is positive a variable has a relevant contribution in landslide development (Yin and Yan, 1988).

Landslides are governed by several indigenous and exogenous factors; however it is not always possible to obtain the data. In the present study seven causative factors were considered for the evaluation of landslide susceptibility mapping. Further, these causative

factors were classified into forty four classes based on landslide concentration, topographic condition; geology and land cover types. The current causative factor classes' classification for elevation, slope, proximity to road and proximity to stream were made on the basis of land condition and the concentrations of landslides, while the class for land use/land cover was made on the basis of land cover. And also the lithological classes were also obtained from the type of lithology's which have been found within the study area according to the scale of the study and the aspect classes were also considered based the facing directions of slopes in the study area.

The considered causative factors for the present study are; lithology, elevation, slope angle, aspect, land use land cover, proximity to road and proximity to streams. Groundwater was identified as crucial causative factor for slope instability as reported by [JICA and GSE \(2012\)](#). But due to lack of well-organized data it is not considered for the present study. The considered causative factors were selected based on the relative importance in inducing instability to slopes based on the nature of the study area, literature, field evaluation and local people's interview, since there are no universal guidelines regarding the selection of factors in landslide susceptibility mapping ([Shahabi and Hashim, 2015](#)).

According to [Yin and Yan \(1988\)](#) the statistical information values (IV) can be computed as the equations shown on (eq.4.1 to 4.5). Using eq.4.1 the conditional probability is calculated. That calculated value of conditional probability is important to tell how much the class is probable for landslide. The prior probability which is indicated at eq.4.2 indicates the total area probability for landslide. It is simply calculated by division of total landslide pixels to the pixels of total area. The value is fixed for each class because in the same study area the pixel amount is the same. Weight of factor class and statistical information values are also easy to calculate by substituting the values obtained from eq.4.1 and eq.4.2.

$$\text{Conditional probability (Con_prob)} = \frac{\text{Number of landslide pixels within factor class (Nslpix)}}{\text{Number of factor class pixel (Ncpix)}} \text{-----eq. (4.1)}$$

$$\text{Prior probability (Prior_prob)} = \frac{\text{Sum of landslide pixels of the whole study area}}{\text{Sum of pixels of the whole study area}} \text{-----eq. (4.2)}$$

$$\text{Weight of factor class} = \frac{\text{Conditional probability (Con_prob)}}{\text{Prior probability (Prior_prob)}} \text{-----eq. (4.3)}$$

$$\text{Information value} = \log(\text{Con_prob})/(\text{Prior_prob}) \text{-----eq. (4.4)}$$

Statistical information values are assigned to each factor class to obtain weighted factor maps. These weighted factor maps were rasterized using look-up tool in a spatial analysis of Arc Toolbox. After rasterizing all causative factor maps the landslide susceptibility index map for each pixel were formed by summing-up using a raster calculator in Map Algebra (eq. 4.5):

$LSI = IV \text{ lithology} + IV \text{ elevation} + IV \text{ slope} + IV \text{ aspect} + IV \text{ LULC} + IV \text{ proximity to road} + IV \text{ proximity to stream}$ ---- (eq. 4.5). Where; IV = information value

Finally, the landslide susceptibility map was classified into three landslide susceptibility class levels low, moderate and high.

4.3 Data Collection and Processing

This is the basic step in landslide susceptibility mapping. In this step relevant landslide conditioning factors are extracted to construct a spatial database. In order to accomplish the aforementioned objectives of the present study the necessary data's are collected from various sources. These various data's are collected from field visit and Remote Sensing image analysis. These are the initial steps for the landslide study. Sources and types of data are presented in Table 4.1.

Type of data	Source of data
Literature	Published and unpublished paper
DEM (SRTM) and Landsat8 (30m*30m resolution)	USGS
Geological map	GSE, (2015)
Metrological data	NMAE
Topographic map (1:50,000)	Geospatial Information Agency (GIA)
Google Earth image	Google Earth

4.3.1 Pre-Field Investigation

During pre-field investigation stage various secondary data and required materials were gathered from different organizations and sources. The activities which have been conducted during this stage are listed under here;

- Literature review, articles and websites related to landslide and landslide hazard susceptibility, both unpublished and published written materials and maps were collected and studied in order to have a general background and a conceptual framework about the thesis.
- Various types of base maps including lithological map and land use/ land cover map of the study area with the scale of 1: 50,000 were prepared. Due to limited time constraint and areal extent the study was conducted at medium /semi-detail scale.
- Metrological data has been collected from metrological agency to acquire good understanding about climatic conditions of the study area.
- Slope, elevation, aspect, proximity to road and proximity to stream were prepared from Digital Elevation Model (DEM) at a resolution of 30m*30m obtained from SRTM data set by using Arc GIS v 10.7.

4.3.2 Field Investigation

During field visit validation of the pre-field work and relevant data collection for the present study was conducted. Basically, this field investigation has been conducted in order to collect different types of primary data and to validate causative factor maps which were prepared from secondary data sources. The activities that were carried out during field investigations are:-

- Related data to locations, mode of failure and volume of past landslide were collected using topographic maps and GPS.
- Photographing for the failed past landslides, quarry sites, geology and topography of the area
- Surface manifestation of groundwater (springs) were recorded and documented. For this GPS point data at each spring site was collected.
- Data on artificial manmade activities like road or building construction, quarrying slope cut, slope stabilization and excavation were observed and recorded.
- Pre-existing geological map has been verified during field investigation.
- Land use and land cover types were observed and validated.

4.3.3 Post-Field Investigation Data Processing and Analysis

After compilation of both the pre-field work investigation and field observation, the data has been systematically grouped and analyzed using available techniques and computer programs. The following activities were done during post field investigation.

- Landslide inventory polygon was created by overlaying field GPS failure point data on Google Earth image for accessible areas and demarcation of landslides from Google Earth image for inaccessible areas were made. For accessible areas a landslide inventory was made by GPS bounding.
- Thematic map layers of causative factors were prepared using secondary and primary data in Arc GIS v 10.7. Later, all these maps were transformed into raster by using look-up tool analysis of Arc GIS v 10.7.
- All parameters, possibly responsible for past landslides, have been quantified by overlay analysis
- After rasterizing the factor maps by using look up tool, the landslide susceptibility index (LSI) maps generated by the sum-up of all raster maps using a raster calculator in Arc GIS v 10.7.
- Finally three landslide susceptible class levels (low, moderate and high) map was prepared.
- At the end landslide susceptibility map was validated through inventoried landslide map.

4.4 Materials and Software's

4.4.1 Materials

Different materials were used before, during and after field investigations. These various type materials: camera, laptop, topographic map, GPS and stationery materials including (note book, pen and pencil). GPS was used to locate landslides, lithological contacts and springs on a topographic map. Laptop and stationery materials were used to write and draw different activates from starting to the end of research work. To capture various photo types sonny camera was applicable.

4.1.2 Software's

Various software's were utilized for this task including Microsoft office Excel 2010 and Microsoft office Word 2010 version for data processing and report writing. ESRI'S Arc GIS v 10.7 was used for various thematic maps layout preparation. Supervised classification system LULC was also prepared using ArcGIS v 10.7. Global mapper 11, to visualize and process Digital Elevation Model (DEM) from Shuttle Radar Topographic Mission (SRTM) data of 30m*30m resolution and Surfer 10 to produce 3D model physiographic map of the study area from SRTM 30m*30m resolution DEM.

CHAPTER FIVE LANDSLIDES INVENTORY AND CAUSATIVE FACTOR EVALUATION

5.1 Landslide Inventory

Having information about landslides that have occurred in the past is basic for landslide susceptibility assessment and to prepare the landslide inventory map (Guzzetti et al., 1999). Identifying and knowing the distribution and location of past and present landslides in a certain area is very important to predict the future probability of landslide occurrence (Guzzetti et al., 1999).

Landslide inventory is the simplest method to determine the condition of future landslide. This is to mean that future landslides will occur under similar conditions as past landslides (Lee and Talib 2005). Further, landslide inventory indicates the location, distribution and types of past landslides. Therefore, compiling landslide features are the basic requirement before performing any slope stability analysis and landslide inventory map preparation. To prepare a landslide susceptibility map, landslide distribution was properly identified and mapped. Landslide distribution or landslide inventory map of the study area was prepared from the field observations and the Google Earth satellite image interpretations. From the accessible area landslide data's were identified by field survey but inaccessible area landslides like gorges, valleys, high cliffs and the river wall banks were identified using Google Earth image interpretation (Google Earth version 2021) as shown in Plate 5.1.

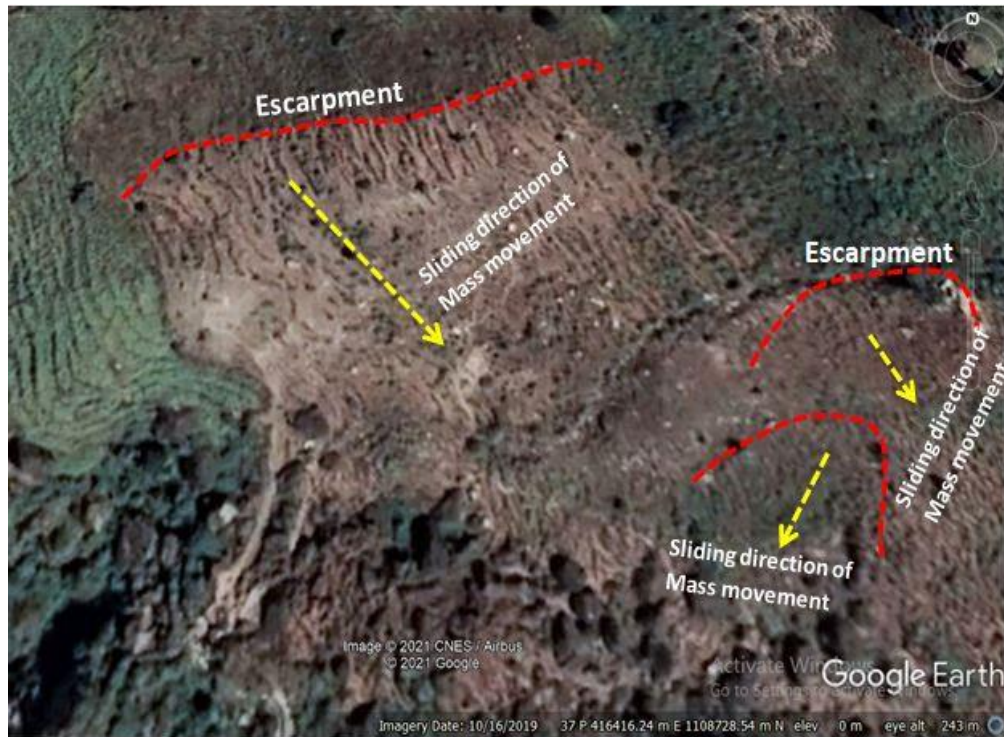


Plate 5.1 Image used to represent inaccessible areas for landslide inventory

Based on these two ways of data collection technique Google Earth image interpretation and field survey totally 101 active different type landslides (Appendix 3) were recorded. These inventoried landslides area coverage's are 3,213, 875m². Among these 101 active landslides almost fifty percent were collected from Google Earth image interpretation. These landslide data were used as the dataset for statistical information value model. Landslide inventory map of the study area (Figure 5.1) was prepared by the combination of a field survey data and Google Earth image interpretation data.

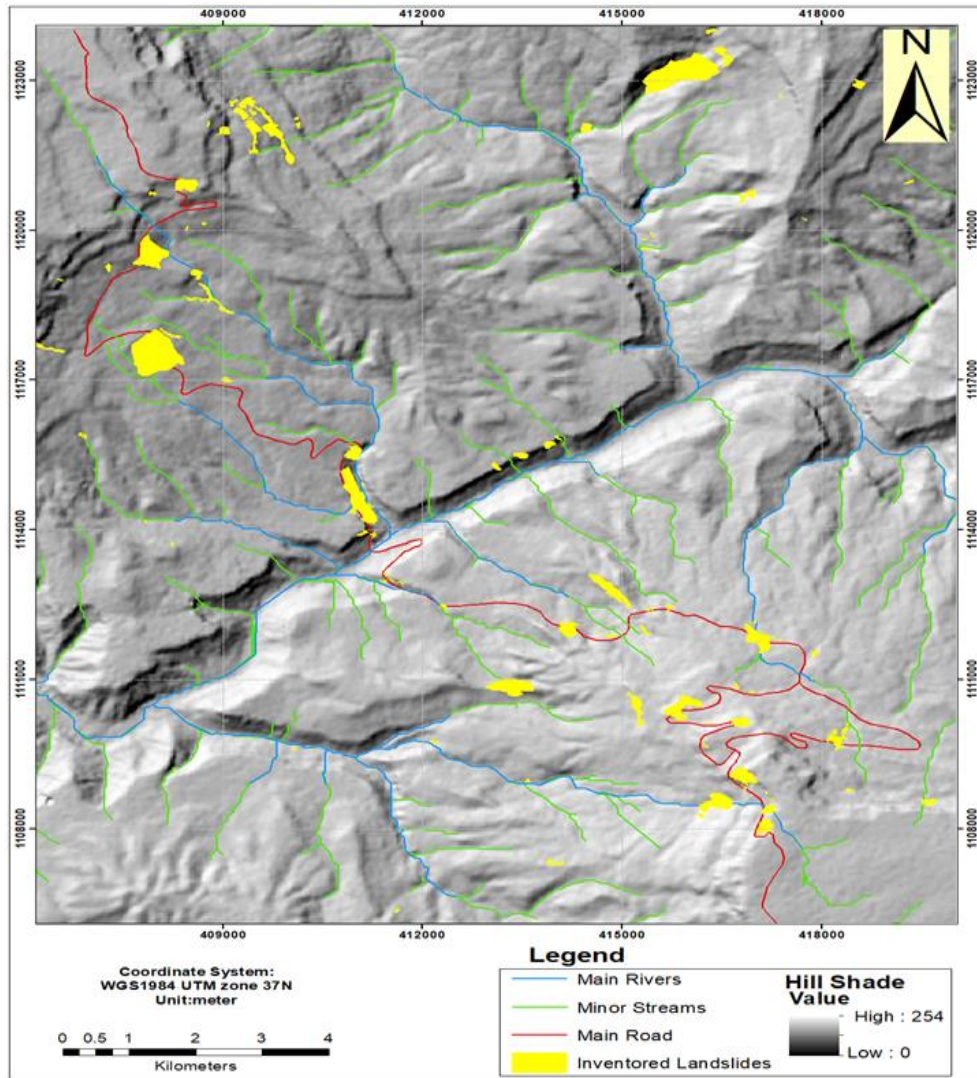


Figure 5.1 Landslide inventory map

5.2 Landslides in the Study Area

On field survey in March, 2021 several active landslides were identified. Most of them are distributed along and around Gohatsion- Dejen section road corridor NW to SE and NE of the study area. Among these several landslides, currently five extremely damaged sites which hinder the traffic movement and also which are the causes for dwelling damage landslide susceptible sites are observed. These five extremely damaged sites; landslide in Kurar Gebriel locality, landslide in Turet locality, landslide in Chifinchif locality, landslide in Kola Jemo Gidara Kebele and landslide in Dembeza Mariam locality along Gohatsion - Dejen section road corridor were selected for a detail discussion because of the magnitude of the damage.

Even though all inventoried landslides have their own effect for the locality people and infrastructures, but it is impossible to discuss all. Among those several landslides five extremely damaged sites are discussed separately.

Landslide in Kurar Gebriel locality - is a wide extent landslide with about 800m width and 1.2Km length from head to toe. Kurar village and Gebriel church are resting near to the crown of the landslide along the main road from Gohatsion to Dejen segment. In this area a number of landslide scarps and individually moving blocks of shallower landslides and deeper landslides were identified by [JICA and GSE \(2012\)](#). Further, an extensive monitoring instrument like water level and displacement sensors were installed in the boreholes and on the surfaces in the landslide area ([JICA and GSE, 2012](#)).

The area is comprised of sedimentary successions of cretaceous age overlain by Cenozoic volcanic series above 2,100 m a.s.l. In particular the landslide is located on carbonaceous formation of limestone. The dominant geological material of this locality landslide is thick colluvium deposit.

The landslides are mostly noted to be deeper in extent and recurrent in nature following rainy seasons. No activity of the landslide has been witnessed during the field visit to the area in March, 2021, since the season was dry. Nevertheless, the remnants of the recent landslide damages like demolished roads are still evident from the last rainy season. The place is outstayed with a landslide and still a landslide activity is going on. As witnessed from the locality people and damage variation evidence (Plate 5.2a & b), this locality landslide has long history. The photo shown in the Plate 5.2a is an already collapsed church before 20yrs; the newly constructed church shown in Plate 5.2b is also highly cracked.

Landslide in Turet locality - is translational active landslide developed on a gentle slope of lower marl cliff. This lithological unit is found at gradational contact of gypsum bed along the main road corridor.

At the foot of this cliff various grain size soils and fallen rock fragments are accumulated. These accumulated soils and fallen fragmented rock materials were formed thick colluvium deposit. This thick unconsolidated colluvium deposit material slide down towards the main road corridor and close the main road corridor.

Even though its extent (50m length and 100m width) is relatively small but the magnitude of the damage is high. Currently traffic flow is hindered due to this locality landslide effect. The main cause for this landslide occurrence is groundwater presence within this thick colluvium deposit. On the body of the slide the newly developing spring flows out and old spring which were flowing at the left flank of the current landslide are ceased because of newly developed landslide. Previously a landslide mitigation measurement, a concrete retaining wall was built but the sliding material slides over on it (Plate 5.2c).

In order to mitigate this slide making longer and thicker retaining wall is essential. In order to reduce the ground water impact making a horizontal drainage to bring the ground water flow in one direction is another option, since water reduces the cohesion of cementing material within grains and that reduces shear strength.

Landslide in Chifinchif locality – is developed at the foot of sandstone cliff. It is a debris avalanche type landslide. This locality landslide currently affects the main road corridor. The left and right side of this road corridor is bounded by valleys and steep cliff. This landslide is mainly caused by loading on the cliff and lack of support at the valley side makes easy to slope failure continuous. Further, groundwater facilitates the landslide, since various groundwater manifestations (spring and drips) are developed along the failed section slopes. Currently, Ethiopian Road Authority is on the progress to mitigate this damaged road. The retaining wall is built at the bottom side of the main road to support failed road and to protect the road from another failure (Plate 5.2d). Traffic flow is highly hindered at this current situation rather it is difficult for the future also since the road passes through the foot of the cliff and at down side there is a valley. When vehicles travel along this road the load is increased, therefore the road will slide towards the valley side of the road.

Further, in addition to retaining wall making a drainage system is essential, because the landslide triggering manifestations like springs and drips are developed and which triggers a landslide.

Landslide in Kola Jemo Gidara Kebele - this landslide area is located near to filiklik village towards Dejen, along Gohtsion-Dejen section main road corridor. It is a wide extent landslide with about 600m width and 1.5 Km length.

The dominant geological material of this locality landslide is thick colluvium deposit. The lithological units are various like silt and clay soil, basalt and limestone boulders, cobbles and gravels. Dominantly it affects main road, farming land, gabion and ditch.

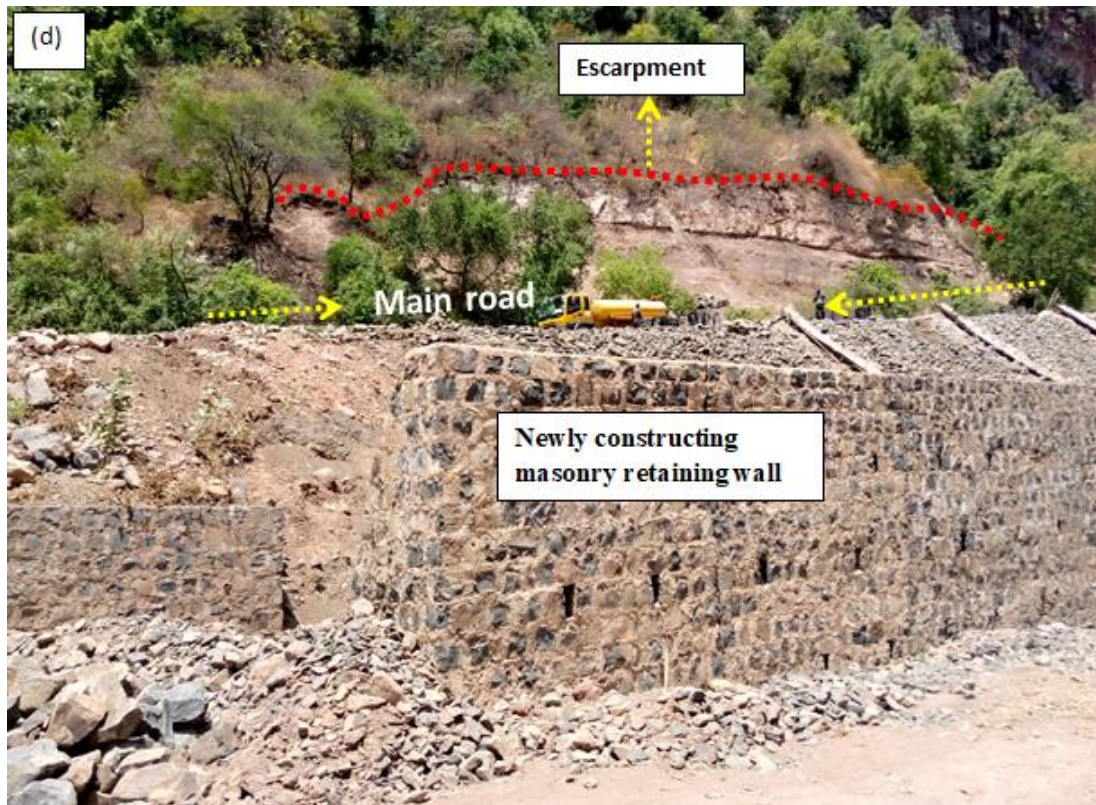
Landslides are frequently reactivated by rain. For the present study area field visit was conducted in sunny season. During that field visit, no activity of the landslide has been witnessed but there are recent rain effect landslide remnants which are good evidence for the presence of landslide. These remnants are offset landslide blocks and demolished roads (Plate 5.2e). As witnessed by the locality people common mitigation measurement like selected material filling was done, but without long time service filled materials sink down when vehicles travel through it. Mostly the traffic flow is hindered at this locality landslide.

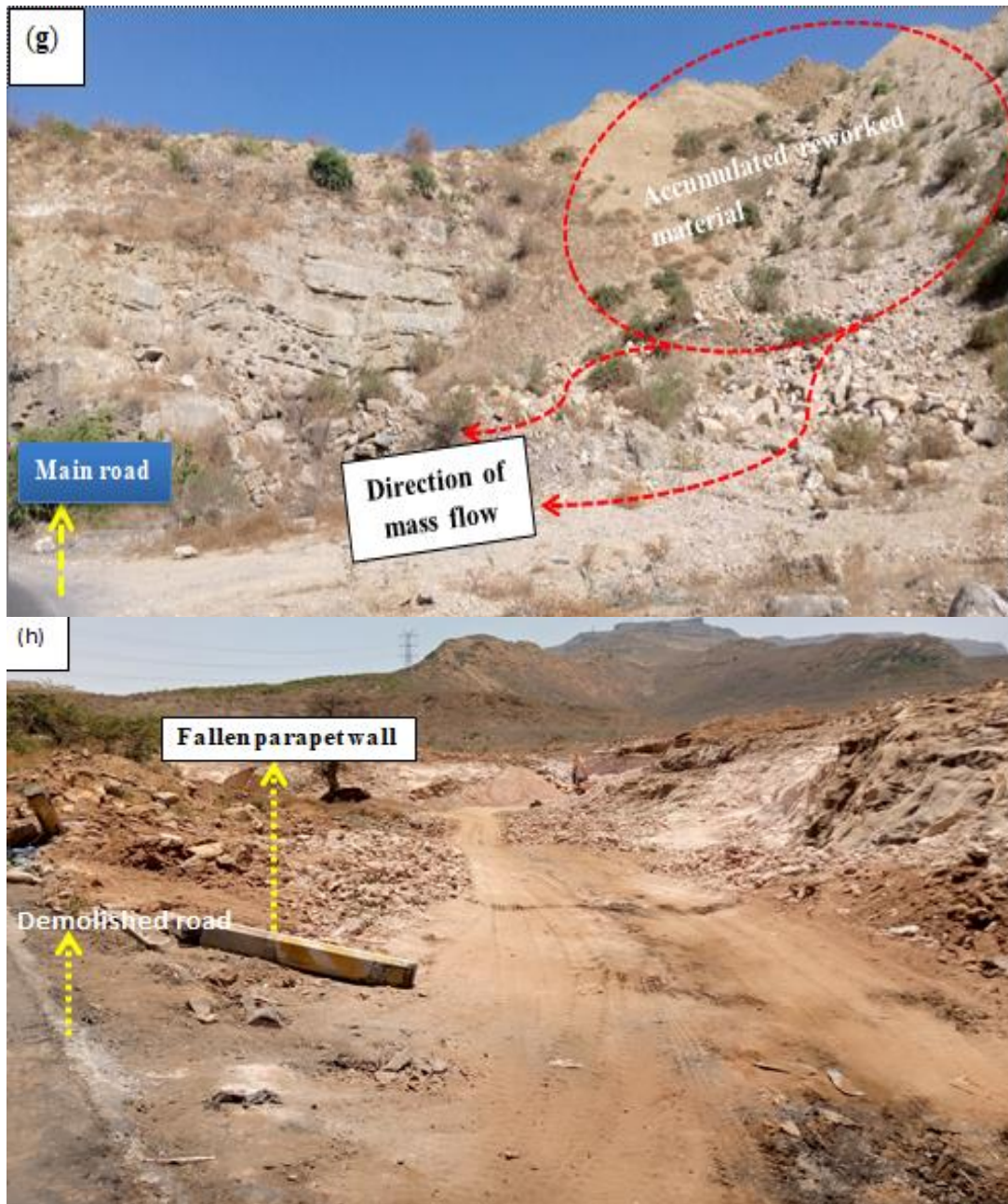
Landslide in Dembeza Mariam locality - this active landslide is developed at the contact of Tertiary basalt and Antalo limestone. The Dembeza Mariam village rests around the escarpment of the landslide. This locality landslide affects the main road, houses, farming land and ditches. It is wide and currently Ethiopian Road Authority is on the progress to mitigate the road corridor by making retaining wall support at the down side of the main road. Due to this landslide the houses are sunk and the inhabitants are displaced from their residence (Plate 5.2f).

As observed on field survey and locality peoples witness in the study area another the current main demolishing cause to the main road corridor is accumulating reworked or excavated materials and quarrying at inappropriate distance from the main road corridor (Plate 5.1 g & h). Quarrying and accumulation of reworked materials at appropriate distance from the main road makes safe the road from such damage. In order to mitigate this kind hazard making public awareness is very important.

The plates listed from 5.2a up to plate 5.2h are good illustrations for the current situation of the present study area.



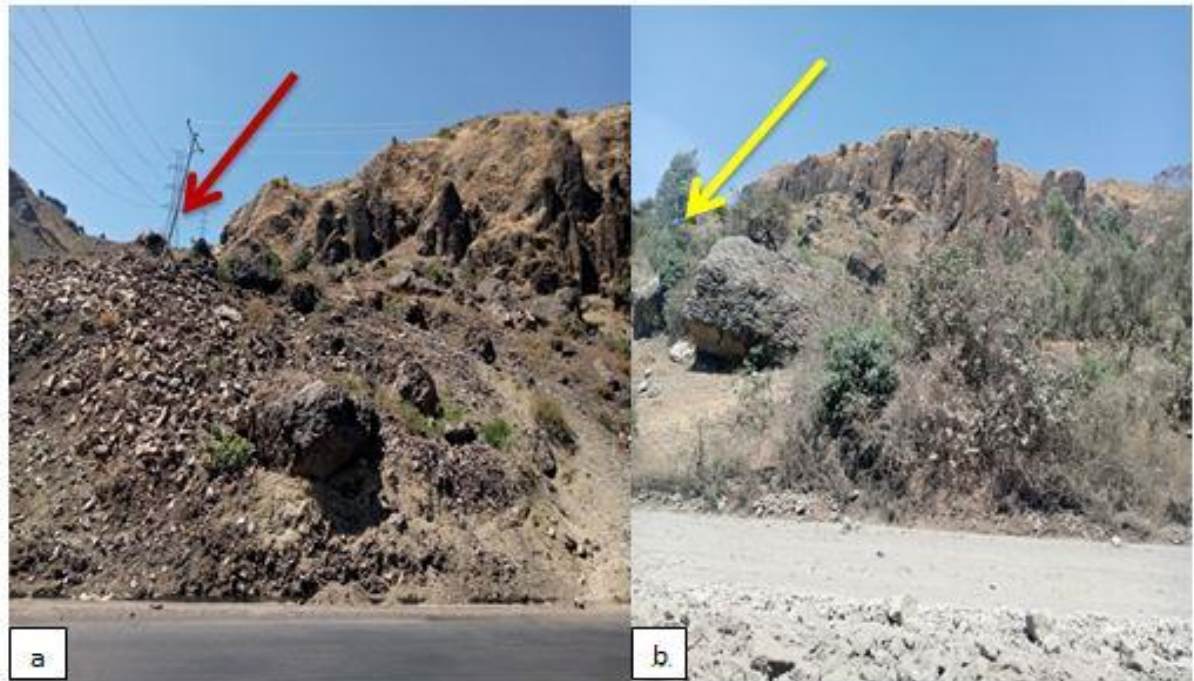




a) Already collapsed Church (source: JICA & GSE, 2012), b) Macro-cracked newly constructed Church in Kurar Gebriel locality, c) Landslide in Turet locality, d) Newly constructing masonry retaining wall below the main road at Chifinchif locality landslide, e) Offset landslide block and demolished road in Kola Jemo Gidara kebele, f) Sunked and tilted house in Dembeza Mariam locality, g) Accumulated excavation material & h) quarry site in the study area

Plate 5.2 Landslide hazards in different locations of the study area

During field survey various landslide manifestations were observed. Some of these are; tilting of trees and electric poles, hanging of rocks on high cliffs, presence of tension cracks, houses sank and failure of road. For instance Plate 5.3a & b with red and yellow arrow of tilted electric pole and tilted tree respectively are illustrations of landslides presence in the study area.



a) Tilted electric pole & b) Tilted tree

Plate 5.3 Manifestation of landslide in the area

5.3 Main Causes of Landslide within the Study Area

Most landslides in the study area are induced due to shallow groundwater conditions, rugged topographical conditions, weak geological materials and intense rainfall, active surface processes including gully erosion, stream, over-steeping or undercutting of the slope, river under cutting, over load and removal of trees.

Shallow ground water- triggers sliding by reducing the shear strength of soils and adds weight of the overburden material leading to lower shear strength than shear resistance. After a detail slope failure investigation [JICA and GSE, \(2012\)](#) have concluded groundwater is a decisive factor to slope instability occurrence for this area.

Intense rainfall- which results in slope saturation, increase in the level of ground water, increase in the weight of overburden material and pore water pressure, and decrease in the

shear resistance of the slope. In the study area frequent landslides are occurred in rainy seasons.

Slope undercutting by streams- when foot of the slope is cut by streams the slope is devoid of support and prone to failure. The study area is rich in perennial and seasonal streams. When streams flow the supporting material at the abutment of the valley and the gorge are eroded.

Over-steeping or undercutting of the slope – steep slopes are highly susceptible to sliding due to gravity. During road construction and quarrying the natural slopes are modified and they become steep. The present study area was exposed by such cause and more landslides developed at the foot of steep slopes.

Deforestation- this is also another cause for slope instability for the present study area. Lack of deep root plant facilitates slope movement. More landslides are recorded in bare land relative to plated land.

Nature of material involved- loose and unconsolidated materials are highly prone to collapse and sliding. Unconsolidated colluvium deposits, highly weathered, closely spaced joints and fractured volcanic rocks exposed along the main road. Frequent slope failures are recorded along the road.

Poor drainage system- during construction of infrastructures like roads, the drainage system was not considered deeply. Groundwater does not drain out in one direction it washes the cementing material and cause for slope failure to happen.

Intense human interventions/anthropogenic effects- which involves improper excavation such as steep and deep cut in loose unconsolidated material without support and slope protection are the main triggering factors of natural and anthropogenic landslide hazards in the study area. In the study area intensive agricultural activities are conducted on gentle slope areas. When a farming activity is conducted the slope stability is disturbed and causes to slope failure.

However, these causes are commonly enhanced by man-made activities like deforestation and plowing of unstable areas because of population growth and anticipated land scarcity. Generally, the main causes of landslide in the study area are a combination of natural

processes and anthropogenic activities. As observed on the field survey and literature most of the landslides are anthropogenic cause, since most landslides are developed along and around the road cut and in plowing areas. The descriptions of various causative factor layers and the data source that have been used to prepare these causative factor maps are presented in (Table 5.1) as follows;

Causative factors	Data	Data type	Data source
Elevation, slope, aspect and proximity to road	SRTM DEM	30m grid	USGS
LULC	Landsat 8 OLI 2020 Image	30m grid	USGS
Lithology	Geological map 1:50,000	Polygon	Ethiopian Geological Survey

5.4 Landslide Causative Factor Evaluation

For landslide studies assuming the combination of conditions pertaining to various causative factors may possibly lead to landslide in a given area. Evaluation of these factors and their relation with the past landslides in the area may form the basis for the prediction of potential areas where landslides may occur in future ([Gemechis Chimidi et al. 2017](#); [Fikre Girma et al., 2015](#); [Leulalem Shano et al., 2020](#)).

The spatial distribution and density of landslides are dependent on the surrounding topography, weather condition, geology, land use/land cover and anthropogenic factors ([Khan et al., 2019](#)). Consequently, evaluating the impact of these causative factors on the spatial distribution of the landslides is significantly important in order to know their operating technique, and subsequently develop a landslide susceptibility map. In the current study, the considered causative factors that have been used for the preparation of landslide susceptibility mapping are; lithology, elevation, slope angle, aspect, land use land cover, proximity to road and proximity to streams. The contribution of each causative factor a landslide occurrence will be explained in detail as follows.

5.4.1 Lithology

For the present study geological map was modified from the geological map compiled by Geological Survey of Ethiopia (GSE, 2015). The majority of the study area is covered by stratified sedimentary rocks and capped by Tertiary basaltic plateau on the top at Gohatsion and Dejen side (Figure 5.2).

Lithology is one among different influential parameters on slope stability since each class of materials has different shear strength and permeability characteristics (Yalcin and Bulut, 2007). Different rock and soil types have varied composition and structural discontinuities which contribute to the strength of the material. The stronger rock units have more resistance to the driving forces when compared to the softer/ weaker rocks. According to GSE (2012) the present study area lithological units were classified in to three rock mass strength units these were; high rock mass strength (basalt), medium rock mass strength (sandstone and lime stone) and low rock mass strength (gypsum and mud rock). The probability of slope instability is higher in low rock mass strength than medium and high rock mass strengths. Further, lithological contact zones are weak, along this weak zones water percolates easily. Water also washes cementing materials within grains and grain to grain contact becomes less, then the materials eroded and fall easily because its shear strength becomes weak. Therefore along weak lithological zone the probability of landslide occurrence is high.

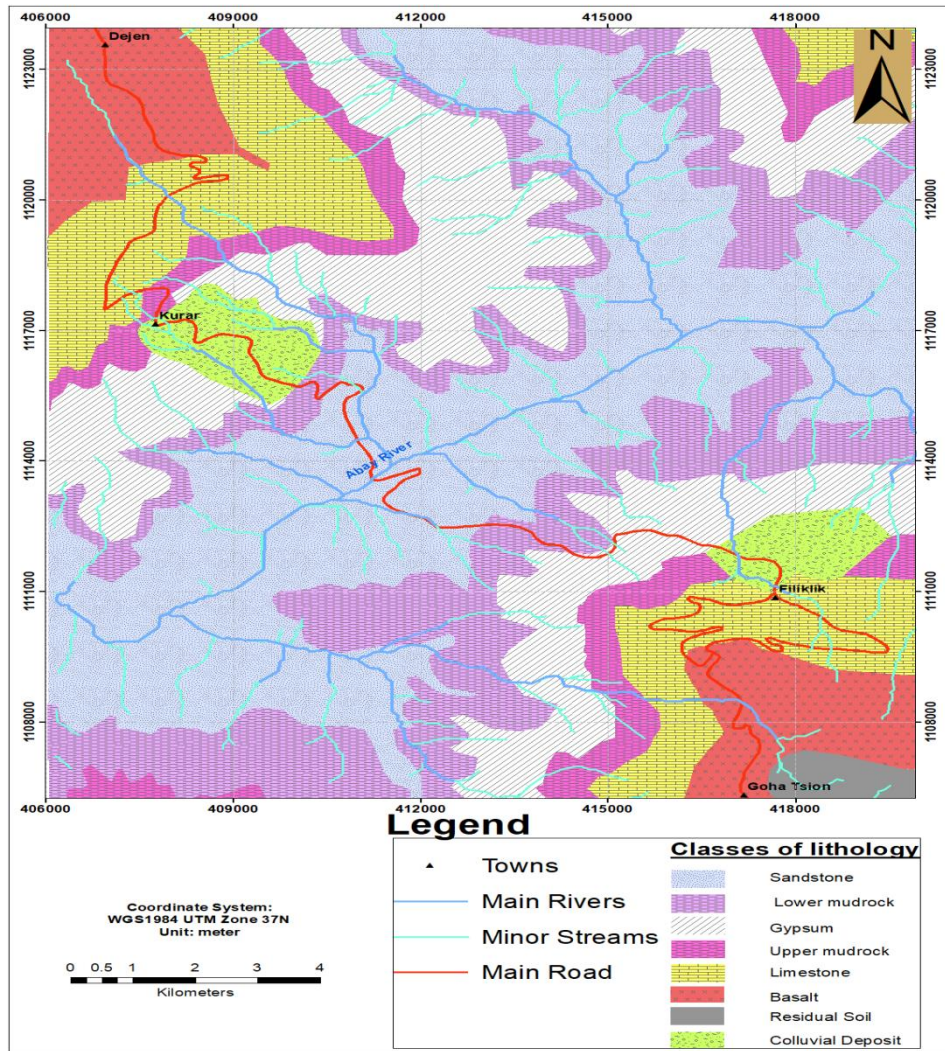


Figure 5.2 Geological map of the area

5.4.2 Elevation

Elevation is a significant causative factor that has an obvious role in landslide susceptibility assessment as considered by several researchers like (Dai et al., 2002; Yalcin et al., 2011; Dou et al., 2015, as cited in Asmelash Abay, 2019). Elevation variation may be related to different environmental settings such as vegetation types, temperature and rainfall (catani et al., 2013). The elevation is considered to be an important causative factor which may possibly affect the lithological material by weathering process (Raghuvanshiet al., 2015).

An elevation layer is obtained from the SRTM DEM of 30m*30m resolution. The elevation factor was classified into seven ranges based on rocks appearance. These class ranges and the incorporated lithological units are; < 1280(sandstone), 1280 – 1360 (lower mud rock), 1360 – 1430 (gypsum), 1430 - 1575 (upper mud rock), 1575 – 2100 (limestone), 2100 – 2480

(basalt) and > 2480 (residual soil) (Figure 5.3). One lithological unit colluvial deposit is found within the elevation class range 1575 – 2100). This colluvial deposit is developed on the areas of gentle slope limestone and shale, which are covered by colluvial deposits and several landslides are also appear at these slopes (JICA and GSE, 2012).

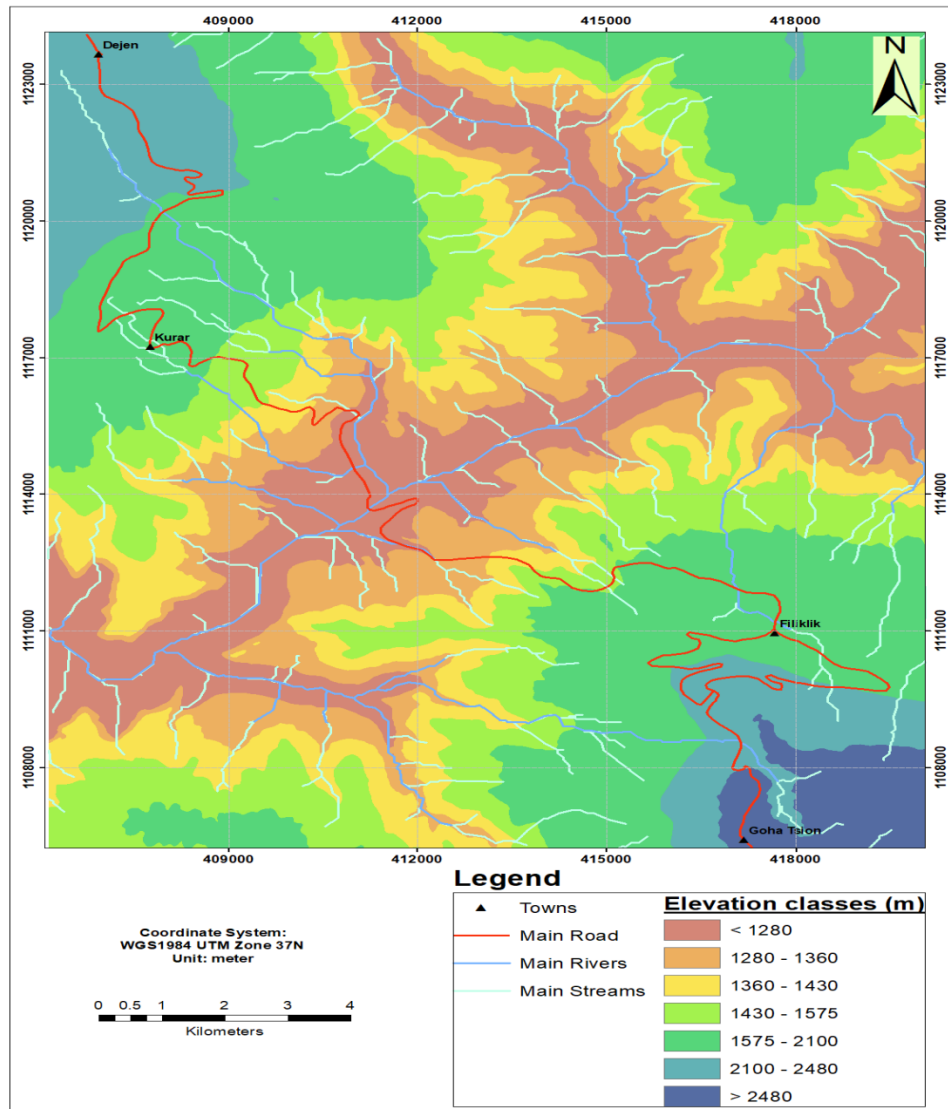


Figure 5.3 Elevation map of the area

5.4.3 Slope

The slope angle is a very important factor for landslide study. It is directly related to landslide which is frequently used in preparing a landslide susceptibility map (Yalcin and Bulut, 2007). If the slope angle is high the probability of landslide occurrence is high which it means that if the slope angle is high the probability of landslide susceptibility is also high due to gravity stress.

Relative to steep slope, gentle slopes have low frequency landslide occurrence because they possess lower shear stresses/shear force associated with low gradients (Raghuvanshi *et al.*, 2015). In general, if the slope is steeper it will be more susceptible to instability as compared to gentle slope (Tilahun Hamza and Raghuvanshi, 2017).

The slope map (Figure 5.4) of the study area was prepared from DEM of 30m*30m resolution SRTM. It is divided into five classes; $0^{\circ} - 5^{\circ}$, $5^{\circ} - 12^{\circ}$, $12^{\circ} - 30^{\circ}$, $30^{\circ} - 45^{\circ}$ and $> 45^{\circ}$. Slope classes $30^{\circ} - 45^{\circ}$ and $> 45^{\circ}$ have highest contribution for landslide occurrence, since this class ranges dominate foot of the cliff, cliffs and lithological contact zones. On the foot of the cliff unconsolidated materials are accumulated which are easy to slide. The erosion resistant cliffs start sliding because of exposing it into weathering variation for a long period of time, the presence of intercalated weak material and the erodibility of supporting materials. It is obvious when the slope angle increase the probability of landslide occurrence will be higher.

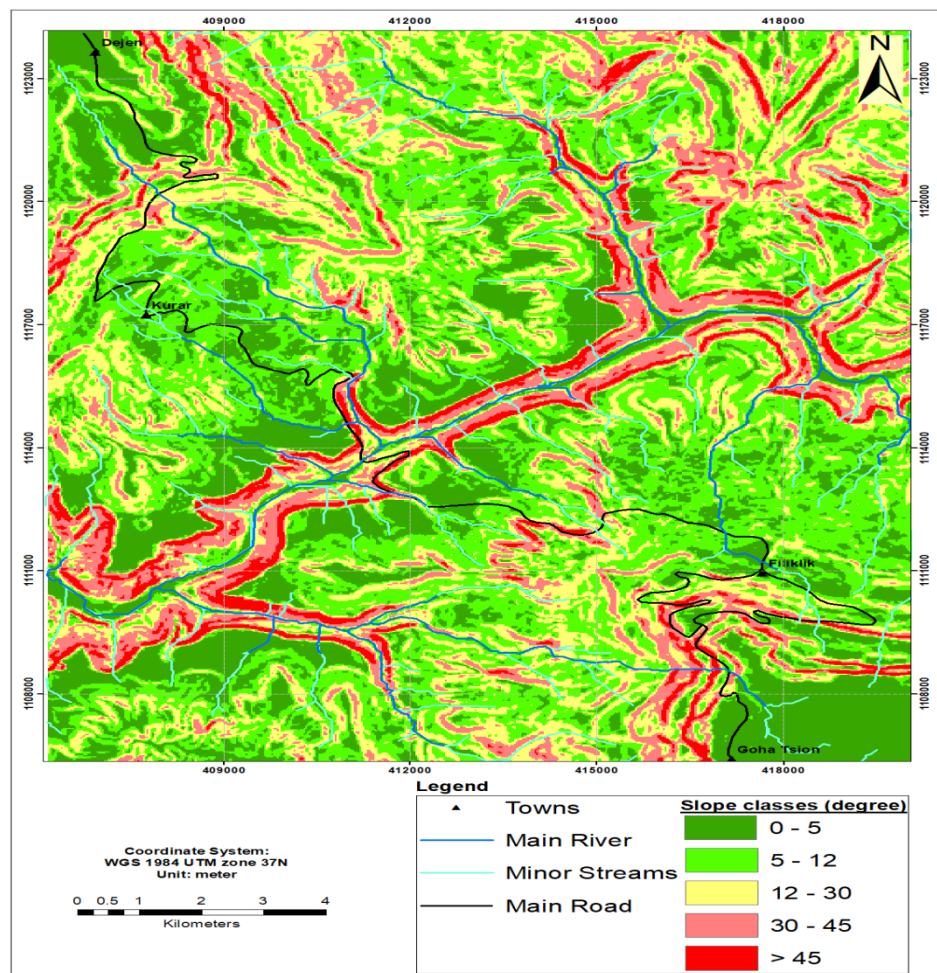


Figure 5.4 Slope map of the area

5.4.4 Aspect

According to *Xu et al., (2012)* aspect is the direction of the maximum slope of the terrain surface. Aspect shows the slope orientation and it is also mostly expressed in terms of a degree from $0^{\circ} - 360^{\circ}$ (*Tilahun Mersha and Matebie Meten, 2020*). The aspect of a slope can influence landslide initiation; because it affects moisture retention and vegetation cover (*Raghuvanshi et al., 2015*).

The aspect map (Figure 5.5) of the study area was derived from at SRTM 30m*30m resolution DEM. The aspect of the study area is split into ten classes namely: Flat (-1 – 0), North ($0-22.5^{\circ}$), Northeast ($22.5-67.5^{\circ}$), East ($67.5-112.5^{\circ}$), Southeast ($112.5-157.5^{\circ}$), South ($157.5-202.5^{\circ}$), Southwest ($202.5-247.5^{\circ}$), West ($247.5-292.5^{\circ}$), Northwest ($292.5-337.5^{\circ}$) and North ($337.5-360^{\circ}$). Aspect classes represent the orientation of the slopes throughout the study area.

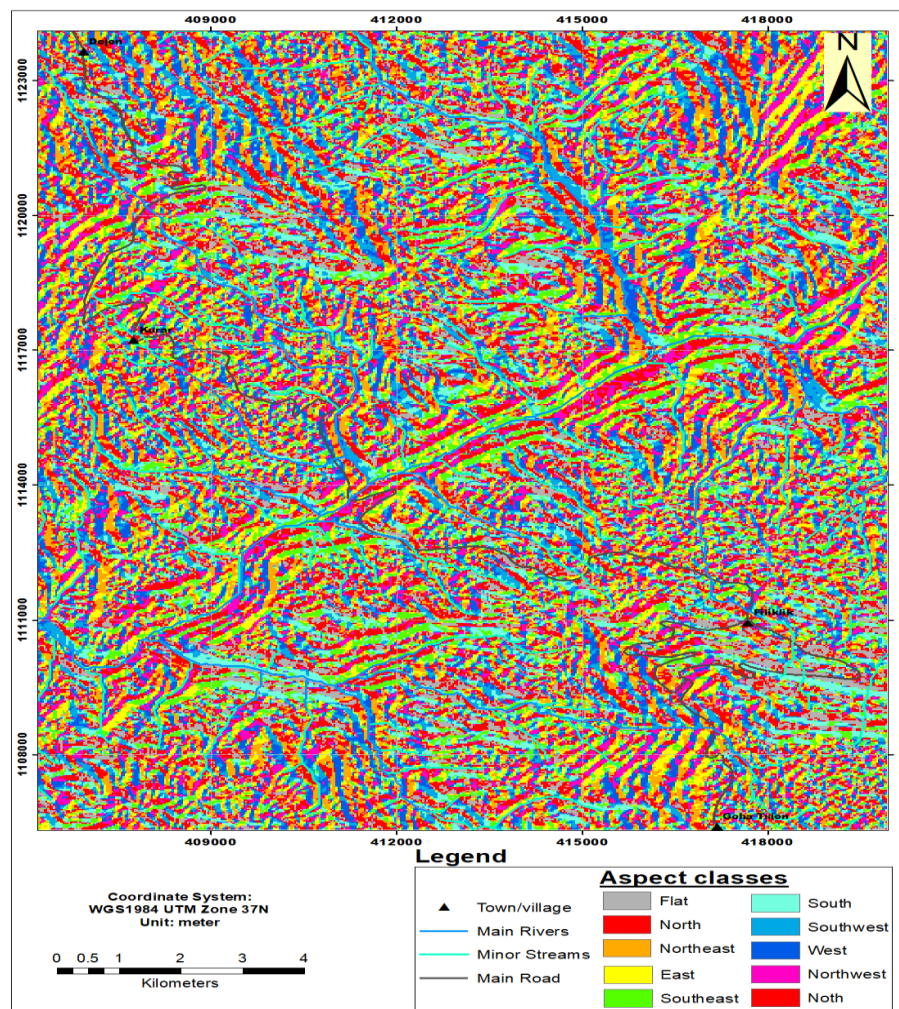


Figure 5.5 Aspect map of the area

5.4.5 Land-use / Land-cover

Land-use changes are recognized as one of the most important factors influencing the occurrence of rainfall-triggered landslides throughout the world (Tilahun Mersha and Matebie Meten, 2020). Changes in land use and land cover resulted from human activities, such as deforestation, overgrazing, intensive farming and cultivation on a steep slope which can initiate slope instability (Glade, 2003).

Vegetation's have maximum contribution to withstand slope movement, since a well-spread network of root system increases the shearing resistance of the lithology. This is due to the natural anchoring nature of the rock. Further that, it reduces the activity of erosion and adds the stability of the slope.

In another way, barren or sparsely vegetated slopes are usually exposed to erosion and thus it has the effect of increasing slope instability (Dikau et al., 1996; Sharma et al., 2012). In the present study area most landslides are exposed in barren lands. In fact bare lands are located on existing and abandoned quarry sites, along different erosion resistance cliff foots and stream embankments.

The land use/land cover map (Figure 5.6) was prepared from the landsat8 image data through supervised classification using the Maximum Likelihood classifier in ArcGIS 10.7 tool. In the current study area there are four land-use/land cover types including crop land, bush land, bar land and built up area. Most landslides are distributed on bare land areas. Along these areas landslides are higher than other land use land cover types.

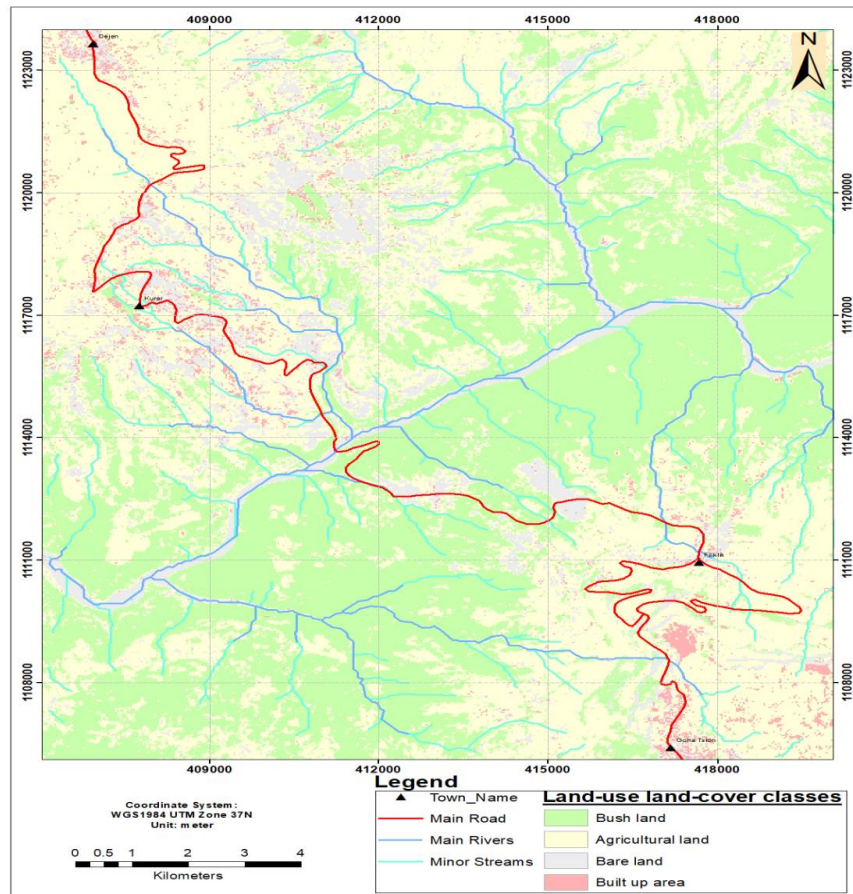


Figure 5.6 Land-use and land-cover map of the area

5.4.6 Proximity to Road

During construction of infrastructures like roads, the drainage system was not considered deeply. When groundwater does not drain out in one direction it washes the cementing materials between the grains and it will be a cause for slope failure by reducing shear strength.

Many landslides in the study area are found along and around the main road corridor which passes through Blue Nile Gorge, Gohatsion – Dejen section. Proximity to road has five classes, which are < 0.5km, 0.5 -1.0km, 1.0 – 1.5km, 1.5 – 2km and > 2km (Figure 5.7). The most landslides are concentrated < 0.5km range from the main road, since over steeping of slope cut have increased this sliding event.

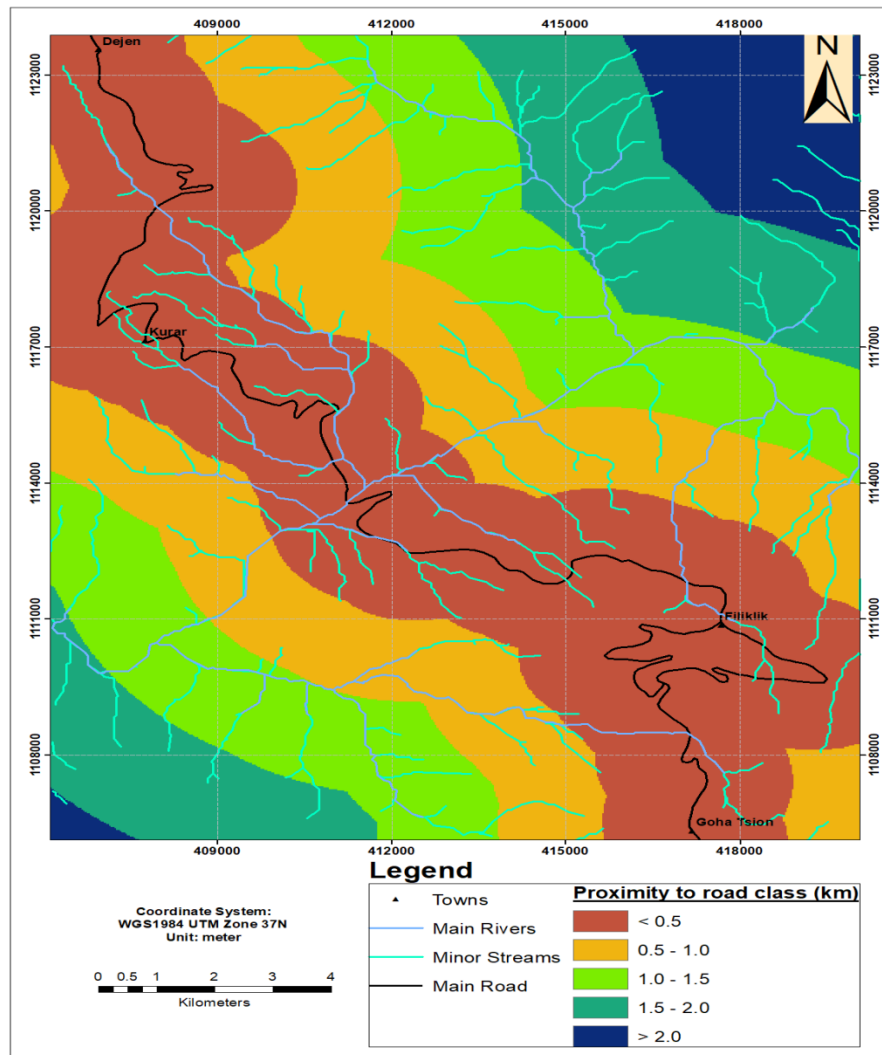


Figure 5.7 Proximity to road map of the area

5.4.7 Proximity to Streams

The proximity to streams is taken in to consideration as an influential controlling factor for several landslides in the region when streams undercutting a slope base (Che et al., 2011). Rivers with dense drainage networks have higher possibility of landslide occurrence, since they erode the slope base and saturate the slope forming materials (Akgun and Turk, 2011).

The study area has many streams which flow into Abay, Mekentut, and Muga Rivers; many landslides occurred within the close vicinity of those rivers and with to other unnamed streams. Hence, this parameter was considered together determinant in landslide susceptibility analysis. Zones with parallel pattern of drainage in steep slopes are the foremost probable landside sites.

Drainage is often a decisive factor as it plays an important role pore-water pressure development which has an effect of reducing the shear strength of rocks and soils. Streamlines were derived from SRTM of 30m*30m resolution DEM.

Distance from stream map (Figure 5.8) was developed using Euclidean distance in the spatial analysis tool of Arc GIS v 10.7. The map was classified into five subclasses: 0 – 50m, 50m – 100m, 100m – 200m, 200m – 500m and 500m – 1000m.

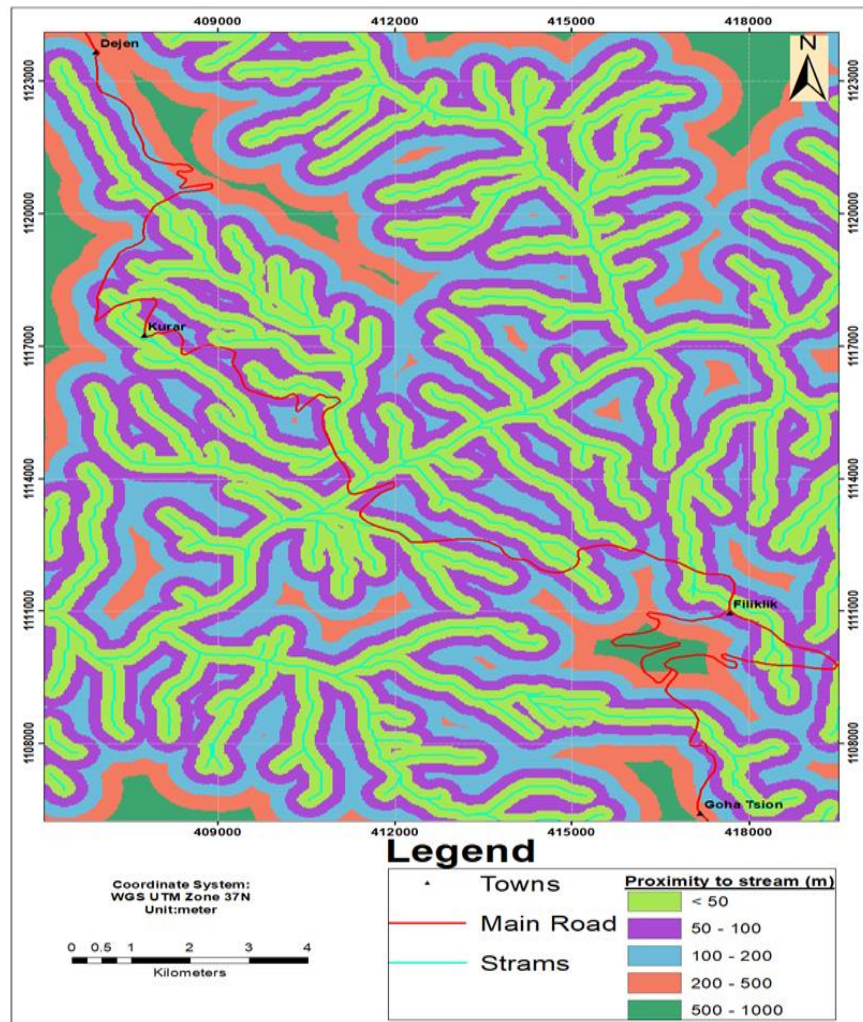


Figure 5.8 Proximity to stream map of the area

CHAPTER SIX**RESULTS AND DISCUSSION**

6.1 Relations of Landslide Occurrence and Causative Factors

This study has analyzed the relations between seven causative factors and landslide occurrence using the statistical information value model. The causative factors were classified into different forty-four classes. The weights assigned for each causative factor classes of statistical IV models are presented in Table 6.1. The weight values derived from statistical IV model shows the spatial relation of the causative factor class contribution for the landslide occurrence. The calculated statistical IV values of the classes are negative or positive. When the statistical IV value is negative the causative factor has no contribution for a landslide occurrence whereas if the statistical IV value of the causative factor is positive the causative factor has contribution for landslide occurrence (Yin and Yan, 1988). The statistical IV method values are calculated and its results are presented in Table 6.1.

6.2 Causative Factors Influence on Landslides

For the present study, the seven causative factors were selected based on the nature of the study area, literature review of previous works, field evaluation and local people's interview, since there are no universal instructions/principles according to selections of factors in landslide susceptibility mapping (Shahabi and Hashim, 2015). These selected causative factors including; lithology, elevation, slope, aspect, land use – land cover, proximity to road and proximity to stream were recognized as primary causative factors for landslide occurrence.

Table 6.1 Data used for the analysis and results obtained by the statistical IV method

Factor	Class	Ncpix	Ncpix %	Nslpix	Nslpix %	Con_prob	Prior_prob	Con_prob/ Prior_prob	IV
Lithology	Residual soil	3105	1.1	0	0	0	0.012	0	0
	Basalt	21559	7.6	263	8	0.012	0.012	1.04	0.02
	Limestone	33769	12	936	28.3	0.028	0.012	2.37	0.37
	Upper mud rock	17736	6.3	323	9.8	0.018	0.012	1.55	0.19
	Colluvial deposit	9293	3.3	444	13.4	0.048	0.012	4.08	0.61
	Gypsum	53744	19.1	412	12.5	0.008	0.012	0.65	-0.18
	Lower mud rock	54287	19.2	605	18.3	0.011	0.012	0.95	-0.02
Elevation (m)	Sandstone	88575	31.4	321	9.7	0.004	0.012	0.31	-0.51
	< 1280	32422	11.5	182	5.5	0.006	0.012	0.48	-0.32
	1280 - 1360	89609	31.8	214	6.5	0.002	0.012	0.2	-0.69
	1360 - 1430	60652	21.5	635	19.2	0.01	0.012	0.89	-0.05
	1430 - 1575	40359	14.3	1043	31.6	0.026	0.012	2.21	0.34
	1575 - 2100	27556	9.8	817	24.7	0.03	0.012	2.53	0.4
	2100 - 2480	14982	5.3	264	8	0.018	0.012	1.5	0.18
Slope (degree)	> 2480	16487	5.8	149	4.5	0.009	0.012	0.77	-0.11
	(0 - 5) ⁰	53053	18.8	145	4.4	0.003	0.012	0.23	-0.63
	(5 - 12) ⁰	85940	30.5	627	19	0.007	0.012	0.62	-0.21
	(12 - 30) ⁰	73679	26.1	747	22.6	0.01	0.012	0.87	-0.06
	(30 - 45) ⁰	44095	15.6	1039	31.4	0.024	0.012	2.01	0.3
Aspect	> 45 ⁰	25301	9	746	22.6	0.029	0.012	2.52	0.4
	Flat(-1- 0)	27275	9.7	271	8.2	0.01	0.012	0.85	-0.07
	N(0 - 22.5)	28924	10.3	319	9.7	0.011	0.012	0.94	-0.03
	NE(22.5 - 67.5)	29304	10.4	367	11.1	0.013	0.012	1.07	0.03
	E(67.5 - 112.5)	27156	9.6	443	13.4	0.016	0.012	1.39	0.14
	SE(112.5 - 157.5)	27278	9.7	316	9.6	0.012	0.012	0.99	0
	S(157.5 - 202.5)	29396	10.4	236	7.1	0.008	0.012	0.69	-0.16
	SW(202.5 - 247.5)	29356	10.4	319	9.7	0.011	0.012	0.93	-0.03
	W(247.5 - 292.5)	29496	10.5	342	10.4	0.012	0.012	0.99	0
LULC	NW(292.5 - 337.5)	26750	9.5	332	10	0.012	0.012	1.06	0.03
	N(337.5 - 360)	27133	9.6	359	10.9	0.013	0.012	1.13	0.05
	Bush land	117431	41.6	413	12.5	0.003	0.012	0.3	-1.93
	Agricultural land	130260	46.2	1503	45.5	0.011	0.012	0.98	-0.01
Proximity to road (km)	Bare land	27428	9.7	1173	35.5	0.043	0.012	3.63	0.56
	Built up area	6949	2.5	215	6.5	0.031	0.012	2.63	0.42
	< 0.50	98008	34.7	2236	67.7	0.023	0.012	1.95	0.29
	0.5 - 1.0	68954	24.4	349	10.6	0.005	0.012	0.43	-0.36
	1.0 - 1.5	56268	19.9	4	0.1	0	0.012	0.01	-2.22
Proximity to stream(m)	1.5 - 2.0	40159	14.2	511	15.5	0.013	0.012	1.09	0.04
	>2.0	18679	6.6	204	6.2	0.011	0.012	0.93	-0.03
	< 50	99935	35.4	1298	39.3	0.013	0.012	1.11	0.04
	50 - 100	86121	30.5	1041	31.5	0.012	0.012	1.03	0.01
	100 - 200	55170	19.6	589	17.8	0.011	0.012	0.91	-0.04
Proximity to stream(m)	200 - 500	29001	10.3	270	8.2	0.009	0.012	0.79	-0.1
	500 - 1000	11841	4.2	106	3.2	0.009	0.012	0.76	-0.12

Note; Ncpix= Factor class pixel count, Nslpix= Landslides pixel within factor, Con_prob =Conditional probability, Prior_prob=Prior probability, Con_prob/ Prior_prob =Weight of factor classes, IV=information value

6.2.1 Lithology

Lithology is taken as a causative factor for landslide susceptibility assessment. In the present study area with the distribution of limestone, siltstone and shale in the Antalo Formation, followed by the area with distribution of basalt and pyroclastic rock the landslide frequency is high and in the area with the distribution of gypsum, siltstone and shale in the Abay Formation and the area with sandstone and conglomerate in the Adigrat Formation the frequency of a landslide is low. Both Abay and Adigrat Formations are located at low altitudes in Abay Gorge ([JICA and GSE, 2012](#)).

Within the lithological causative factor there are eight classes; these are residual soil, basalt, limestone, upper mud rock, colluvial deposit, gypsum member, lower mud rock and sandstone. Upper mud rock and lower mud rock are also named as upper clay stone and lower clay stone. The landslide occurrence and the causative factors lithological relation are shown in Figure 6.1a.

Basalt, limestone, upper mud rock and colluvium deposit have the statistical information values of 0.02, 0.37, 0.19 and 0.61 respectively, while gypsum member, lower mud rock and sandstone have the statistical IV value of -0.18, -0.02 and -0.51 respectively. These statistical IV values of positive lithological units have a correlation for landslide occurrences while the lithological unit with the statistical IV value negative does not have a significant contribution for a landslide occurrence. In here it is possible to deduce that the lithological classes with higher statistical IV values have higher contribution for the landslide occurrence, whereas the lithological class with lower statistical IV values has lower contribution for the landslide occurrence.

Limestone has a maximum landslide occurrence 28.3% among the eight classes and its statistical IV is 0.37. Limestone rests on a gentle slope and capped by basalt. The load of basalt is exerted on limestone, since limestone is an immediate contact of basalt. Further, the presence of basalt load and intercalated weak materials like marl and shale makes limestone to be more susceptible to landslide. Upper mud rock is one of lithological causative factor class with its statistical IV value of 0.19. The upper mud rock is soft and weathered. Therefore it is easy for slope instabilities. The other lithological unit with the statistical IV value 0.02 is basalt. It has contribution for landslide occurrence, since within this unit weak materials like pyroclastic tuff and highly weathered basalts are intercalated. These weak

materials are very soft and easy to expose for liquefaction and collapse. Among the lithological factor classes' sandstone covers 31.4% of the total study area which is the highest. The total landslide area covered by this sandstone class is 9.7% and its statistical IV value is -0.51. This causative factor class statistical IV value is negative because the ratio of landslide pixel within this class to the causative factor class pixel is too small therefore its weight class log becomes negative. Most colluvium deposits are accumulated under scarps and on gentle slopes of limestone and upper mud rock units. The highest statistical IV value is recorded in colluvium deposit, so the probability of landslide occurrence is high. This lithological unit is unconsolidated and the susceptibility for landslide is higher. In residual soil there is no recorded landslide occurrence. It rests on the flat terrain on Gohatsion side of the study area.

6.2.2 Elevation

Elevation is a causative factor which is frequently utilized in landslide hazard assessment ([Raghuvanshi et al., 2014](#); [Tilahun Hamza and Raghuvanshi, 2017](#); [Fliagot Mengistu et al, 2019](#)).

The elevation class has seven ranges related to different lithological unit's appearance with a consideration of thickness differences on both Abay River to Gohation and Abay River to Dejen sides. These classes range and the incorporated lithological units are; < 1280 (sandstone), 1280 – 1360 (lower mud rock), 1360 – 1430 (gypsum), 1430 - 1575 (upper mud rock), 1575 – 2100 (limestone), 2100 – 2480 (basalt) and > 2480 (residual soil). One lithological unit colluvium deposit is found within the elevation class range 1575 – 2100m, where it lies on at the contact between upper mud rock and limestone.

The elevation classes 1430 – 1575, 1575 – 2100 and 2100 – 2480 have positive statistical information values of 0.34, 0.4, and 0.18 respectively. These three causative factor class ranges have contributions for landslide occurrence. While the remaining elevation class ranges statistical IV values are negative, therefore they did not have contribution for a landslide occurrence.

The highest landslide occurrence percentages are recorded on 1430 – 1575m class range and followed by 1575 – 2100m class ranges (Figure 6.2b). These class ranges dominate lower mud rock and limestone respectively. 1430 – 1575m class range includes the upper mud rock and limestone contact, since the contact zones are weak that's why more landslides are

recorded. The elevation class range 2100 – 2480m dominates basalt and pyroclastic materials. Further, limestone and basalt unit contacts are also included within this elevation class range. The lithological unit contact zones are weak that initiates the landslide. At this unit the landslide is developed due to the presence of intercalated weathered basalts and pyroclastic materials.

Generally, the number of landslides related to elevation is highest in 1430m to 1575m, 1575m to 2100m followed by 1360m to 1430m, while few are observed at other elevations.

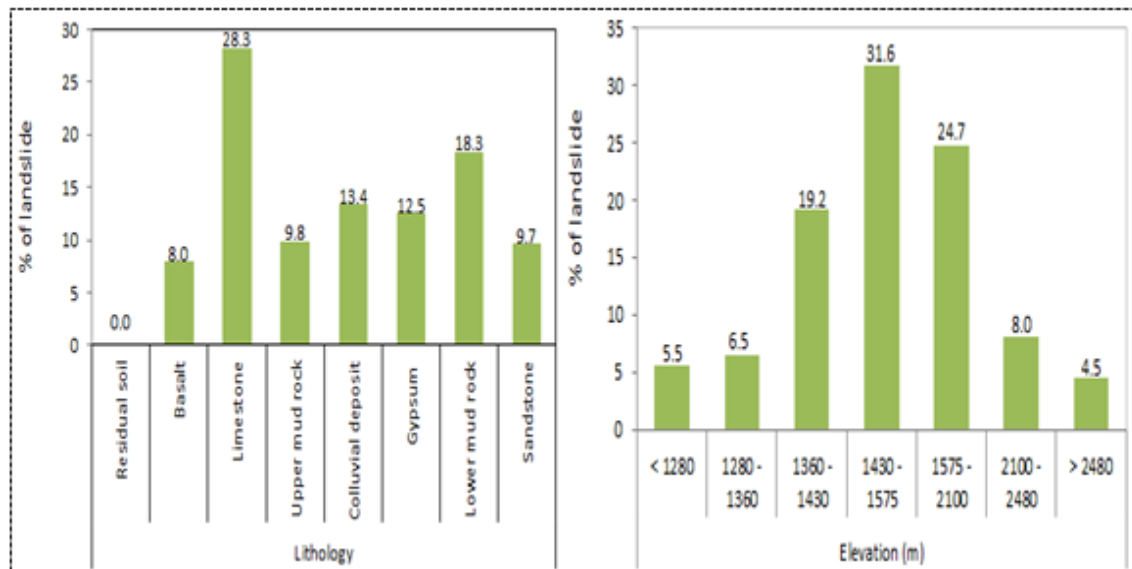


Figure 6.1 Relations between the percentage of landslide distribution with causative factor classes a) Lithology and b) Elevation

6.2.3 Slope

Slope is considered as an important factor for landslide occurrence (Anbalagan, 1992; Raghuvanshi *et al.*, 2014). The study area was classified into five slope classes. According to Table 6.1 4.4%, 19.0%, 22.6%, 31.4% and 22.7% of landslides occurred in $0 - 5^{\circ}$, $5 - 12^{\circ}$, $12 - 30^{\circ}$ and $30^{\circ} - 45^{\circ}$, respectively (Figure 6.2a). The slope classes $0 - 5^{\circ}$, $5 - 12^{\circ}$, $12 - 30^{\circ}$, $30 - 45^{\circ}$ and $> 45^{\circ}$ show statistical information value (IV) of -0.63 , -0.21 , -0.06 , 0.30 and 0.40 respectively. Among these slope classes $0 - 5^{\circ}$, $5 - 12^{\circ}$ and $12 - 30^{\circ}$ shows negative statistical information value (IV), this indicates that these classes have low contribution for the probability of landslide occurrence. However, the slope classes $30 - 45^{\circ}$ and $> 45^{\circ}$ have positive statistical information value (IV) 0.30 and 0.40 , respectively. These classes have a contribution for landslide occurrence, since according to Yin and Yan, (1988) if the statistical information value is positive that class has a contribution for a landslide occurrence. Based

on the statistical information values (IV) the slope classes $30^{\circ} - 45^{\circ}$ and $>45^{\circ}$ are more susceptible for instability. The possible reason for instability in 30° - 45° and $>45^{\circ}$ slope classes are related to the poor characteristics of the slope material within these slope classes. The slope materials, which predominantly occupy these slope classes, are highly weathered basalt and limestone, colluvial and pyroclastic deposit. Such slope materials are highly disintegrated and have poor shear strength, high porosity and are relatively more permeable (Raghuvanshi *et al.*, 2015). Thus, slopes which are formed by weakly consolidated masses are more susceptible for instability (Shadfar *et al.*, 2005). The slope angle $0 - 5^{\circ}$ range is less prone to landslides in the present study area.

Generally, as seen from the statistical IV values in Table 6.1, it is possible to deduce that the relationship of landslide and slope shows a positive correlation for slope classes $> 30^{\circ}$. The progressive increment in information values shows landslide occurrence increases as the slope angle increases.

6.2.4 Aspect

Slope orientation (aspect) affects the exposure to sunlight and winds, affecting indirectly other factors that contribute to landslides, such as precipitation, soil moisture, vegetation cover and soil thickness (Clerici *et al.*, 2006 as cited in Matebie Meten, 2015). In the present study area aspect has an important role for landslide occurrence. The aspect classes facing to north-east, east, north-west and north-west, with statistical information values of 0.03, 0.14, 0.03 and 0.05 have shown the highest probability contribution of the landslide occurrence. This may be the east-facing slopes get high amount of sunlight and rainfall. This favors land sliding due to increased rate of saturation and weathering particularly in loose pyroclastic rock masses and disintegrated slope material.

Further, the overlay analysis showed that 13.4% landslides occurred in slopes that are oriented towards east, 11.1% occurred in slopes that are oriented towards northeast, 10.9% occurred in slopes that are oriented towards north northwest, 10.4% occurred in slopes that are oriented towards west, 10.0% occurred in slopes that are oriented towards southeast direction and the remaining 9.7%, 9.7%, 9.6%, 8.2% and 7.1% landslides occur in slopes oriented towards north, southwest, southeast, flat and south respectively (Table 6.1 and Figure 6.2b).

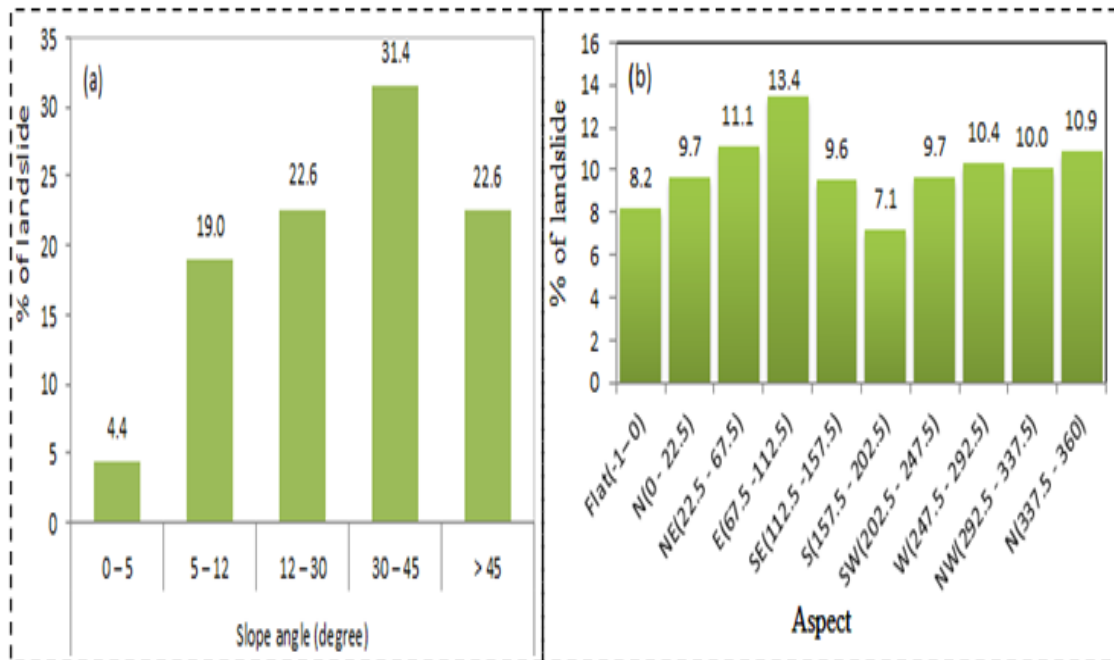


Figure 6.2 Relations between the percentage of landslide distribution with causative factor classes a) Slope and b) Aspect

6.2.5 Land-use and Land-cover

The land-use/land-cover type of the study area was classified into four. These are; bush land, agricultural land, bare land and built up area. The statistical information value is positive in bare lands and built up area (Table 6.1). Thus, bare land and built up area shows highest probability contribution for landslide occurrence. Bare lands include cliffs, river sediments, river wall banks and existing quarry sites. Bare lands devoid of deep rooted vegetation, particularly on the steep wall river banks and a cliff is more highly susceptible to land sliding than the other land use types.

The statistical information value is negative in bush lands and agricultural lands (Table 6.1). Thus, bush lands and agricultural lands show lowest probability for a landslide occurrence. These four land-use land-cover classes and percentage of landslide occurrence is presented (Figure 6.3)

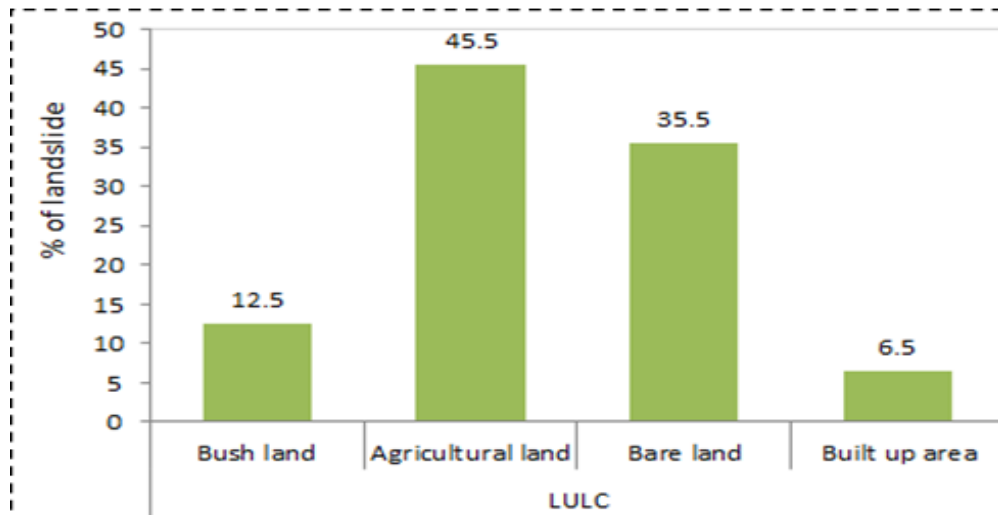


Figure 6.3 Relations between the percentages of landslide distribution with causative factor classes LULC

6.2.6 Proximity to Road

Proximity to road is also considered as an important factor because road construction is usually accompanied by excavation in some areas and the addition of material to the slope in other areas. Traffic load and the cutting of steep slopes during road construction are another factor influencing landslide occurrence. As observed on field survey most landslides are concentrated around the road. This is developed due to over increasing of slope cut, traffic load and lack of proper drainage system during road construction. This is verified by the statistical information values calculated in Table 6.1. It has five classes these are < 0.5km, 0.5km – 1.0km, 1.0 – 1.5km, 1.5km – 2km and >2.0km. The maximum landslide occurrence is observed on < 0.5km class which is 67.7% and its IV value 0.29. The lowest landslide occurrence is recorded in 1.0 – 1.5km class because this class encompasses lowest altitude and slightly weathered Adigrat sandstone. For the classes < 0.5km, 1.5km – 2km the statistical information values are positive which are 0.29 and 0.04 respectively. The causative factor class ranges (< 0.5km and 1.5 – 2km) have highest contribution for the probability of a landslide occurrence. The IV values for distance from a road are relatively higher in the first class (< 0.5km). Many landslides are recorded near to the main road in < 0.5km range (Figure 6.4a).

5.4.7 Proximity to Streams

Slope failure probability is higher around streams because streams will erode slopes. Proximity to stream was classified into five subclasses: 0 – 50m, 50m – 100m, 100m – 200m, 200m – 500m and 500m - 1000 meter. In case of proximity to streams, the classes 0 – 50 and 50 – 100m have higher probability for a landslide occurrence, while the class 100 – 200, 200 – 500 and 500 – 1000m have low probability of a landslide occurrence because of statistical information value results (Table 6.1). The higher landslide occurrence contribution is noted within the two class ranges 0 - 50m and 50 – 100m proximity to the river. The present study area is dissected by various perennial and seasonal streams like, Abay, Mekentuta, Muga Rivers and other unnamed streams. Close to these streams dense landslides are occurred, since foot of the slope is eroded by streams the slope is devoid of support and prone to failure. The percentage of landslides against proximity to stream class of causal factor is presented in Figure 6.4b.

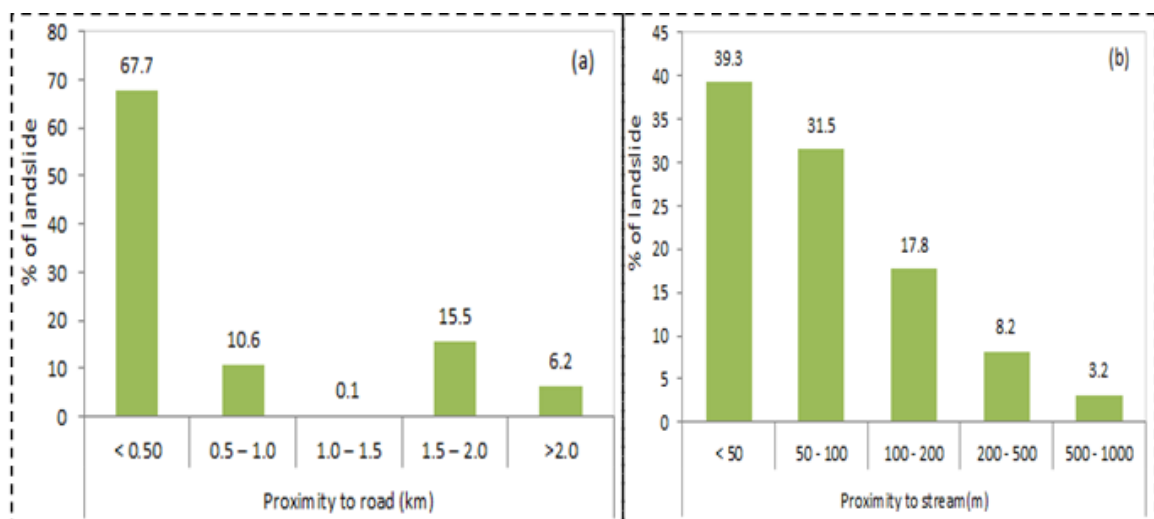


Figure 6.4 Relations between the percentage of landslide distribution with causative factor classes a) Proximity to road and b) Proximity to streams

6.3 Prominent Classes among Various Causative Factor Class

Landslide is a complex process and various causative factors are contributed in its occurrence. In the present study seven causative factors were considered namely; lithology, elevation, slope, aspect, LULC, proximity to road and proximity to streams. From the past landslide data relational statistical correlation with various causative factors was established and prominence of various causative factor classes was worked out with the help of statistical information value. Table 6.2 presents the highest statistical information value in respective factor class. Table 6.2 clearly shows that the slope angle $>45^{\circ}$ and the slopes which are

trending towards east are more prone for landslide susceptibility. Similarly, slopes falling within elevation class 1575 to 2100m, proximity to road < 0.5km class and proximity to stream < 50m class are more susceptible for slope instability. And also, a landslide probability is higher in colluvium deposits and bare lands.

Causative factor	class	Information value
Lithology	Colluvium deposit	0.61
Elevation (m)	1575 - 2100	0.4
Slope ($^{\circ}$)	> 45 $^{\circ}$	0.4
Aspect	East (67.5 -112.5)	0.14
LULC	Bare land	0.56
Proximity to road (km)	< 0.50	0.29
Proximity to stream (m)	< 50	0.04

6.4 Landslide Susceptibility Mapping

Landslide susceptibility analysis in the present study area was implemented by using statistical information value method. For thematic causative factor maps preparation and for statistical IV pixel calculation ArcGIS v 10.7 was used. The weight for all the landslide causative factor classes was assigned statistically. Then the weight assigned causative factor maps were rasterized using lookup tool in spatial analysis. After rasterizing the factor maps, the landslide susceptibility index (LSI) map was generated by the sum-up in ArcGIS v 10.7 of all raster maps using a raster calculator in Map Algebra, then the final landslide susceptibility map was prepared. For the calculated values of statistical IV for each pixel in the LSI indicates the relative susceptibility to landslide occurrence. According to [Yin and Yan \(1988\)](#) when the information value is positive the causative factor class has a great contribution for the landslide occurrence while the information value is negative it has low contribution for the landslide occurrence.

The landslide susceptibility index value for each pixel was obtained by summing up all causative factor maps using raster calculator in map algebra in the study area and ranges from (-6.24) up to 2.22. The LSI map was reclassified by the natural break classification method to develop a landslide susceptibility map. Because this method creates classes from natural

breaks based on groupings inherent in the data with similar values by searching depressions in a frequency distribution and it sets class breaks to classify values into different classes by minimizing the variance within classes and maximizing the variance between classes (Matebe Meten et al., 2015). Further, this method works well with unevenly distributed data.

The relation analysis is the statistical information value of the area where landslides occurred to the total area, if the value is higher relative to other classes, it shows a higher correlation; if lower, it indicates a lower correlation. The least LSI value obtained for the study area is -6.24 and the maximum is 2.22. Based on the LSI distribution the landslide susceptibility level in the present study area was divided in to three class levels: these are; low, moderate and high susceptible classes. Further, on trial basis LSI values were distributed into different susceptible classes and landslide susceptibility map (LSM) was produced. For each of such attempt the prepared landslide susceptibility map was validated with the past landslide data. Thus, the best landslide susceptible classes obtained by this procedure are presented in Table 6.3 and the landslide susceptible map thus prepared is presented in Figure 6.3.

Table 6.3 Landslide susceptibility class based on landslide susceptibility index

Landslide susceptibility class	Landslide susceptibility index range	Landslide susceptibility class coverage			Past landslide coverage			Landslide density (b/a)
		Pixel count	Area (km ²) (a)	Area (%)	Pixel count	Area (km ²) (b)	Area (%)	
Low (LS)	-6.24 - -3.49	47974	43.2	17.0	8	0.007	0.23	0.0002
Moderate (MS)	-3.49 - -1.10	107531	96.8	38.1	323	0.29	9.73	0.003
High (HS)	-1.10 – 2.22	126563	113.9	44.9	2973	2.68	89.9	0.024

The landslide susceptibility map (Figure 6.3) and (Table 6.3) clearly shows that in the study area 43.2km² (17.0%) falls in low susceptible class (LS) and 96.8km² (38.1%) of the area falls in moderate susceptible (MS) class. While the remaining 113.9km² (44.9%) of the study area falls in high susceptible class. Out of total study area coverage 210.7km² (83.8%) falls under moderate and high class level susceptible classes. Only, 43.2km² (17.0%) falls in low susceptible class levels. As shown in Figure 6.3 all parts of the road corridor passes through

moderate and high susceptible class levels. This will be the possible cause for frequent failure of the road corridor.

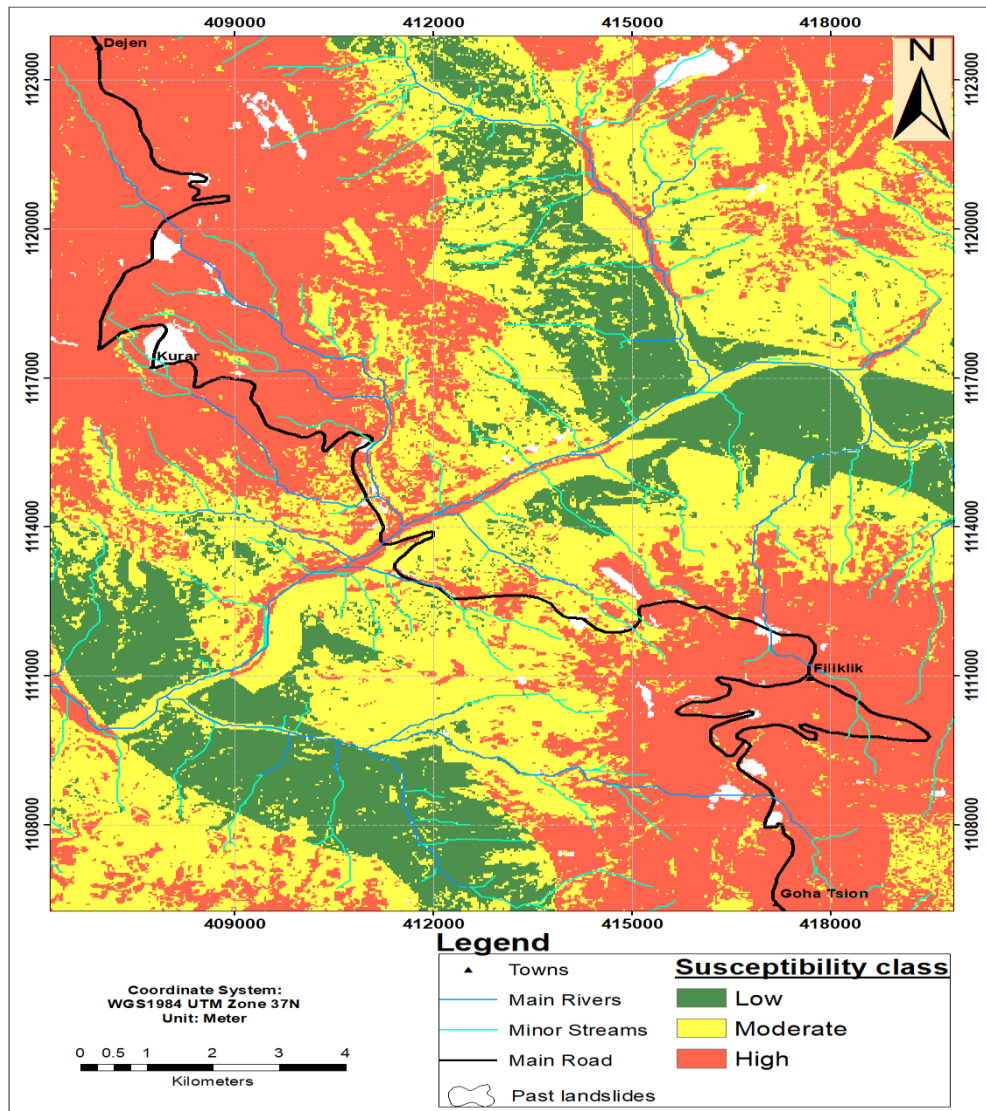


Figure 6.3 Landslide susceptibility map of the study area

6.5 Validation of Landslide Susceptibility Class Map

Validation of the derived LSM is essential to ascertain the applicability of the method used for practical purposes (Chung and Fabbri, 2003). Unless validated, the produced landslide susceptibility map is meaningless. In order to validate the landslide susceptibility map produced in the study area an overlay analysis was made with the past landslides inventory data.

The overlay analysis (Figure 6.3) clearly shows that out of 101 past landslide inventory data 88 (87.1%) falls in high susceptible (HS) class, 15(14.9%) falls in moderate susceptible (MS) class and 1(0.99%) falls in low susceptible (LS) class. In addition validation of the LSM showed that 87.1% of the past landslides fall in high susceptibility (HS) class. Then based on this, it can be safely deduce that the landslide susceptible class demarcated in the present study validated with the past landslide data and the potential class described can reasonably be applied for safe planning of the area. Further, according to the landslide density value as shown in Table 6.3 column nine the landslide density of low, moderate and high susceptible classes are 0.0002, 0.003 and 0.024 respectively. When the landslide density increases the landslide susceptibility level also increase (Sarkar et al., 2008). In the current study the landslide density value has increased from low landslide susceptibility class level to high landslide susceptibility class levels and vice versa. As also verified on the field the high susceptible areas are more of with landslides, slope erosion, road subsidence etc.

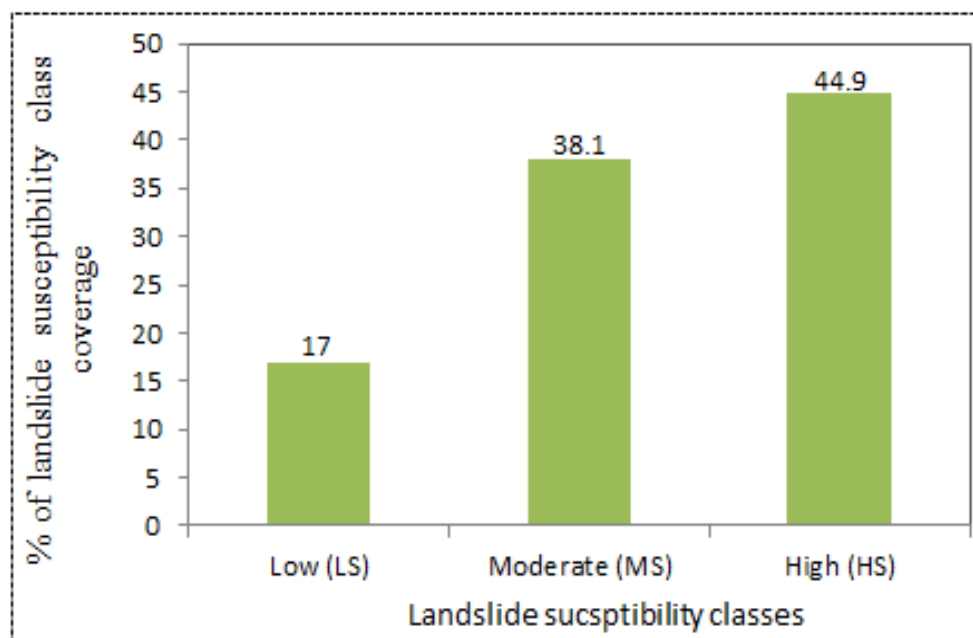


Figure 6.4 Distribution of landslide susceptibility classes

CHAPTER SEVEN**CONCLUSION AND RECOMMENDATION**

7.1 Conclusion

The landslide susceptibility map provides basic information for hazard assessment and monitoring strategies. For inaccessible areas like gorges and valleys, direct ground based landslide causative factor mapping and evaluation is expensive and impossible to address within a limited short period of time. GIS-based statistical technique and remote sensing system provides powerful alternatives for detecting, identifying and monitoring landslides and their related factors. Regarding on the results and discussion this research has been concluded as follows:

- To demarcate landslide susceptible classes in the present study area seven causative factors were considered. These are: - lithology, elevation, slope, aspect, land use/land cover proximity to road and proximity to streams. The thematic maps of causative factors including slope, aspect, elevation, proximity to road and proximity to streams were prepared from the SRTM DEM at 30m*30m resolution and land use land cover was also prepared from Landsat8 OLI image. Lithological map layer of the study area was extracted from the geological map of Ethiopian Geological Survey with the scale of 1:50,000 and through field observations during the present study. Later, all vector maps were transformed into raster data for further analysis.
- In order to establish relational statistical correlation of various causative factors with past landslides in the area landslide inventory was made through field observations and Google Earth image interpretation. In total 101 past landslides were identified in the study area. Further, statistical information value was applied in which information values of predisposing causative factors were used to characterize the possibility of landslide occurrence.
- The statistical information values are determined for each class of landslide related parameters on the basis of presence of landslide in the given mapping unit. The causative factor maps were combined with landslide map in order to get weight of each class. Thus, spatial relationship between the occurrence of landslides and each landslide causative factor class was derived.
- Statistical information values were important to identify the contribution of causative factor classes for a landslide occurrence. From statistical information value analysis the

positive values of statistical information values are found in causative factor classes lithology of basalt, limestone, upper mud rock and colluvial deposit; elevation of 1430-1575, 1575-2100 and 2100-2480 meters; Slope of 30° - 45° and $> 45^{\circ}$; aspect of NE, E, NW and N facing slopes; LULC of bare land and built up area; proximity to road of $< 0.5\text{km}$ and $1.5\text{-}2\text{km}$ and proximity to stream of $< 50\text{m}$ and $50\text{m-}100\text{m}$.

- The relation analysis is the statistical information value of the area where landslides occurred to the total area, if the value is higher relative to other classes, it shows a higher correlation; if lower, it indicates a lower correlation. Therefore, the pixels of landslide susceptibility values were divided in to three classes low susceptible (LS), moderate susceptible (MS) and high susceptible (HS) by natural break method of classification system.
- The landslide susceptibility map, thus produced clearly indicates that in the study area 43.2km^2 (17.0%) falls in low susceptible class (LS), 96.8km^2 (38.1%) of the area falls in moderate susceptible (MS) class and 113.9km^2 (44.9%) of the study area falls in high susceptible class. Further, validation of landslide susceptibility map with past landslide inventory data shows that 87.1% of the existing landslides falls in high susceptible (HS) class. Therefore, it can be safely deduced that the susceptible classes demarcation in the present study validates with the past landslide data and the potential areas described can reasonably be applied for safe planning of the area.

7.2 Recommendations

Based on the present study findings the following recommendations are listed under here:

- Much of the road corridor passes through high landslide susceptible class. This is one possible reason for the frequent failure of the road corridor at various places. More detailed slope stability studies are required along the main road corridor which falls in the high landslide susceptible class to suggest the remedial measures or to realign the main road corridor.
- The road corridor is exposed for suspended blocks and slope failure, therefore continuous follow-up is essential.
- Detailed surveys should be made using existing and previously recorded landslide data, since for the present study only active landslide data were used.
- High susceptible class has the probability for future slope instability problems. Prior to any future infrastructure development and settlements in this class more detailed slope stability study is recommended.
- Landslide susceptibility map can be used for optimum land management by decision makers, land use planners and engineers to tackle losses caused by current and also future landslides.
- Quarrying and accumulation of excavated materials along and around the road corridor closes and damages the road corridor, so that quarrying and accumulating of excavated materials at appropriate distance from the road corridor is recommended to protect the safety of the road corridor.

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APPENDIX**Appendix-1a Precipitation on Filiklik station**

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2000	0	0	0	18.4	34.8	152.1	386.2	377.6	279.3	231.9	192.5	4.6	1677.4
2001	0	21.4	59	59.5	61.7	225.6	439.7	146.9	37.1	27.1	0	2.1	1080.1
2002	40.7	0	11.8	33.3	10.1	130	120.6	188.7	75.7	0	0	49.8	660.7
2003	0	13.6	17.2	17	88	160.2	333	190.5	0	0	0	0	819.5
2004	0	0	4	8.2	33.3	161.6	224.1	235.7	191.7	36.5	0	0	895.1
2005	0	1.8	24.1	22.6	33.7	89.4	308	178	35.1	14.3	24.8	0	731.8
2006	3.2	24.5	78.1	84.8	59.3	87.5	352.9	330.3	188.7	23.5	26	0	1258.8
2007	13.8	100.1	17.6	28.1	84.1	264.2	326.6	351.4	211.9	2.4	0	0	1400.2
2008	0	0	0	32	165.2	228.9	398.2	409.6	14	68.9	39.1	0	1355.9
2009	0	0	16.1	45.3	26.8	129.9	406.1	225.2	0	33.6	0	0	883
2010	0	0	60.7	96.8	214.6	252.8	397.6	270.5	218.6	0	50.1	86.3	1648
2011	0	0	131.9	32.3	186.4	160.2	322.7	298.2	120.6	35.8	31.6	8.7	1328.4
2012	3.3	2.5	27.4	103.3	56.3	210	235.6	213.3	156.6	0	0	0	1008.3
2013	0	0	0	0	126	134.2	313.2	253.3	70.8	45.1	0	0	942.6
2014	0	20.7	0	90.2	131.3	0	162.6	284.5	165.2	0	25.7	0	880.2
2015	0	0	9.3	0	114.5	194.6	165	288.5	171	18.8	70.2	0	1031.9
2016	0	22.9	18.7	79.3	88	107.6	322.7	267.3	125.6	57.5	0	0	1089.6
2017	0	2.5	16.7	37.2	88	160.2	322.7	298.2	155	35.8	53	8.7	1178
2018	3.3	2.5	27.4	37.8	69.7	194.8	308.4	298.7	74.2	48.8	86.6	5.3	1157.5
2019	1.4	41.8	27.4	37.8	88	160.2	322.7	298.2	120.6	35.8	31.6	8.7	1174.2
Average													1110.1

Appendix-1b Precipitation on Gohatsion station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2000	0	0	3	64.6	64.7	122.7	397.1	291.3	158.4	33.4	58.8	0	1194
2001	0	69.7	87	59.5	60.6	150.9	309	256.6	79.7	6.3	8	22.8	1110.1
2002	28.6	5.2	45.5	31.1	4.1	116.8	193.8	323.4	72.8	0	0	28.4	849.7
2003	6	41.8	51.7	44.6	0	150.7	403.9	313.4	123	0	3	0	1138.1
2004	5.1	8.3	45	66.9	43.2	119.5	288.1	323.7	108.9	10.1	0	0	1018.8
2005	20.5	0	49.1	30	70.4	164.5	287.5	250.8	124.6	75.2	16	0	1088.6
2006	5	27.4	136.9	29	76	124.9	354.3	345.3	174.9	79	7.5	3	1363.2
2007	0	38	0	29.6	125.8	201.9	294.6	322.8	217.4	8	0	0	1238.1
2008	0	0	0	51.7	226.5	217.9	378.9	320.3	139.3	18.7	62.7	0	1416
2009	0	3.2	23.4	42.4	20.5	69.2	275.1	406.8	83	100.3	0	2.1	1026
2010	7.1	0	20.2	40.4	106.4	118.7	336.2	273.7	163.8	1.1	0	6	1073.6
2011	0	0	71.8	40.4	127.2	138.8	217.4	438.8	283.8	0	120.3	0	1438.5
2012	0	0	14.5	58.6	35.3	93.7	457.4	377.8	264	0	6.3	7.2	1314.8

2013	11	0	14.5	27.8	80.4	192.6	334.4	430.2	213.4	126.3	34.5	0	1465.1
2014	0	25.9	34.7	74.6	161.2	101.4	389.2	313.1	193.9	23.3	7.6	0	1324.9
2015	0	0	3.2	0	166.8	196.3	225.2	310.4	142.3	33.3	56.4	4.1	1138
2016	0	26.6	10.2	83.8	275.5	148.6	334.4	338.2	89.1	33.4	14.5	4.1	1358.4
2017	0	14.5	13.3	28.1	93.4	148.6	464.3	338.2	137.7	71.4	0	0	1309.5
2018	4.6	14.5	34.7	44.6	36.3	244.9	413.1	451.1	19.7	15.6	22.6	0	1301.7
Average													1219.3

Appendix-1c Precipitation on Dejen station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2000	0	0	0	187	101.9	136.9	484.7	558.8	288	158.8	65.8	3.2	1985.1
2001	0	9	120.8	87.5	83.7	298	645.4	361.5	134.3	100.9	2.4	6.1	1849.6
2002	60.9	12.3	77.2	55.1	20.2	168	483.4	422.7	200.5	0	0	8.6	1508.9
2003	0.8	36	139.3	64.1	3.3	123.9	273	283.3	192.5	0	16.1	9.9	1142.2
2004	6.5	19	46	56.4	12.5	125.2	266	249.6	92.3	115.8	19.6	0	1008.9
2005	6	0	69.3	49.4	90	151.2	260.8	222.7	139	80.5	13.3	0	1082.2
2006	7.1	9.2	108	124.4	72.3	140.5	336.6	308.2	297.4	46.1	4.4	33.7	1487.9
2007	17.6	68.2	42.8	83.4	177.7	180.7	335.2	261.4	175.5	15.2	0	0	1357.7
2008	0	0	0	42.6	78.1	307.4	420.9	316.3	278.4	133.3	104.5	0	1681.5
2009	0	3	52.2	66.2	19.8	101.1	331.8	317.36	132.4	113.5	9.9	12	1159.26
2010	0	4.7	93.3	95.8	174.7	77.6	244.6	296.7	79.2	13.7	28.2	0	1108.5
2011	0	0	100.3	44.8	96.98	151.2	195.2	360.6	148.6	64.84	113.1	0	1275.62
2012	0	0	100.3	44.8	28.7	137.9	322.8	294.1	220.1	1.4	11.8	0	1161.9
2013	0	0	15.4	14.1	122	172.4	351.4	310.7	118.1	110.1	9.9	6	1230.1
2014	0	38.8	19.6	95.6	147.6	52	279.3	227.4	286	86	38.4	0	1270.7
2015	0	4.1	10.4	0	185.2	89.9	129.6	317.36	166.7	29.9	110.4	23	1066.56
2017	0	6.5	9.7	58.2	204.9	50.3	256.7	225.3	155.5	80.5	5.5	0	1053.1
2019	0	29.6	38.9	85.1	126.1	192.3	220.2	378.5	239	16.6	32.55	6	1364.85
Average													1321.9

Appendix-2 Temperature Data of Filiklik Town Station (19yrs)

Temp(°C)	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max	2000	30.4	33.1	34.9	31.1	33.1	31	25.8	26.7	26	29.9	28.7	28.5
Min	2000	17.7	18.6	18.6	17.3	17.7	16.4	15.5	16.5	16.4	17.8	16.6	14.2
Mean		25.9	25.9	24.2	24.2	23.7	23.7	21.6	21.6	23.9	23.9	21.4	21.4
Max	2001	29.3	31.9	31.8	32	30.9	27.4	23.1	25.4	27.4	27.6	25.7	27.1
Min	2001	15	17.1	16.5	16.9	17.1	15.1	12.8	15.2	17.2	17.1	14.9	16.3
mean		24.5	24.2	24.5	24	21.3	18	20.3	22.3	22.4	20.3	21.7	21.7
Max	2002	27.1	33.2	31.3	30.6	35	28.5	24.5	23.9	28.1	30	30.6	29.3
Min	2002	16.3	17.6	16.5	16.4	18.3	15	13	13.2	14.4	15.6	14.2	14.5
Mean		21.7	25.4	23.9	23.5	26.7	21.8	18.8	18.6	21.3	22.8	22.4	21.9
Max	2004	28.9	31.3	30.6	34	34.4	31.4	23.5	21.1	21.4	22.4	24.7	27

Min	2004	15.7	19.6	17.8	18.6	18.1	15.7	14.7	14.5	15.7	15.4	16.6	16.5
Mean		25.5	25.5	26.3	26.3	23.6	23.6	17.8	17.8	18.9	18.9	21.8	21.8
Max	2005	29.9	31.3	34.1	34.1	32.1	31.2	26	25.1	26.5	26.7	23.6	26.3
Min	2005	18.2	18.4	18.6	18.7	18.5	18	15.1	15.7	16.4	17.2	13	15.6
Mean		24.1	24.9	26.4	26.4	25.3	24.6	20.6	20.4	21.5	22	18.3	21
Max	2006	30.3	31.1	30.6	29	32.2	29.5	22.9	21.8	23.5	21.9	24.2	26.5
Min	2006	18.1	18.6	16.7	17.4	19.2	17.4	13.2	13	14	14.5	14	14.2
Mean		24.2	24.9	23.7	23.2	25.7	23.5	18.1	17.4	18.8	18.2	19.1	20.4
Max	2007	28.3	27.3	31.8	35.2	30.7	26	22.1	23.4	26.1	29.7	21.8	26.4
Min	2007	15.4	17.2	17.7	17.7	16.8	15	12.8	13	15.3	17.7	14.4	16.1
Mean		21.9	22.3	24.8	26.5	23.8	20.5	17.5	18.2	20.7	23.7	18.1	21.3
Max	2008	30	33.3	33.7	29.4	28.7	26.5	21.7	23.7	26.1	28	26.5	27.9
Min	2008	19.1	20.9	21.2	18.2	16.7	16	12.2	11.8	14.9	17.9	14.6	15.5
Mean		24.6	27.1	27.5	23.8	22.7	21.3	17	17.8	20.5	23	20.6	21.7
Max	2009	30	33.5	34	33.1	30	28.1	24.5	22.6	28.9	27.2	25.8	28.1
Min	2009	17.7	18.9	18.8	17.8	16.6	16	11.2	15.7	17	16	16	16
Mean		23.9	26.2	26.4	25.5	23.3	22.1	17.9	19.2	23	21.6	20.9	22.1
Max	2010	31.9	33.1	32.1	32.5	28.4	24.9	25.5	24.7	25.6	31.3	28.9	24.8
Min	2010	18.6	18.4	17.9	17.2	14.5	13.6	14.2	13.1	13.1	17.8	15.8	12.9
Mean		25.3	25.8	25	24.9	21.5	19.3	19.9	18.9	19.4	24.6	22.4	18.9
Max	2011	27	33	29.3	29.3	29.5	28.5	24.5	23.9	25.7	26.7	25.6	26.6
Min	2011	16	17.7	15.5	16.3	15.9	15	13	13.2	14.4	15.6	14.2	14.5
Mean		21.5	25.4	22.4	22.8	22.7	21.8	18.8	18.6	20.1	21.2	19.9	20.6
Max	2012	27.9	30.3	31.7	30.5	31.9	28.5	24.9	23.2	23.4	24.4	23.6	23.3
Min	2012	15.7	17	17	12.2	12.9	11.8	10.9	10.8	11.1	13.2	13.5	13.6
Mean		21.8	23.7	24.4	21.4	22.4	20.2	17.9	17	17.3	18.8	18.6	18.5
Max	2013	21.9	23.6	32.1	33.5	28.3	24.5	21.8	20.5	21.1	21	19.1	17.5
Min	2013	12.1	13.5	16.6	14.2	12.3	11.6	11	10.9	12.4	12.1	9.5	8
Mean		17	18.6	24.4	23.9	20.3	18.1	16.4	15.7	16.8	16.6	14.3	12.8
Max	2014	16.8	17.5	21.4	23.4	21.3	26	24.2	19.1	20.6	24.1	22.8	27.3
Min	2014	9.2	10.3	12.3	12.2	11.5	14.5	12.5	9.7	12.1	14.3	12.6	15.1
Mean		13	13.9	16.9	17.8	16.4	20.3	18.4	14.4	16.4	19.2	17.7	21.2
Max	2015	26.4	28.6	29.7	31.1	30.1	30.8	28.2	26.3	25.2	26.7	25.6	26.6
Min	2015	14	14.1	14.2	15.2	14	15	13.3	13.6	13.4	15.5	14.6	14.7
Mean		20.2	21.4	22	23.2	22.1	22.9	20.8	20	19.3	21.1	20.1	20.7
Max	2016	27.9	30.3	32	31.6	31	30.4	26.2	26	26.2	28	28	28.4
Min	2016	15.6	15.8	16.1	15.9	16.1	15.2	12.9	13.1	13.3	13.7	13.8	13.6
Mean		21.8	23.1	24.1	23.8	23.6	22.8	19.6	19.6	19.8	20.9	20.9	21
Max	2017	29.5	30.3	34.3	35.2	31	28.5	24.5	23.9	27.9	26.7	27.1	26.6
Min	2017	14.5	17	16.9	17.6	16.1	15	13	13.2	13.8	15.6	13.5	14.5

Mean		22	23.7	25.6	26.4	23.6	21.8	18.8	18.6	20.9	21.2	20.3	20.6
Max	2018	27.9	30.3	31.7	31.7	32.9	29.5	25.4	24.5	30.7	28.8	27.7	29.7
Min	2018	15.7	17	17	16.4	16.4	14.7	12.6	12.2	15.1	14.3	13.6	14.9
Mean		21.8	23.7	24.4	24.1	24.7	22.1	19	18.4	22.9	21.6	20.7	22.3
Max	2019	28	31.2	33.1	32.2	33.4	30.1	27.4	26.4	28	26.7	25.6	26.6
Min	2019	14.1	15.2	16.4	15.9	16.7	14.7	13.5	13.1	13.9	15.6	14.2	14.5
Mean		21.1	23.2	24.8	24.1	25.1	22.4	20.5	19.8	21	21.2	19.9	20.6

Appendix-3 Landslide Inventory Data of the Study Area

FID	Name	Easting	Northing	Length (m)	Width (m)	Mode of failure
1	Df1	411113	1114027	60	189	Debris flow
2	Df2	413890	1115825	142	177	Debris flow
3	Df4	413110	1115364	185	88	Debris flow
4	Df5	414195	1112101	282	245	Debris flow
5	Df6	416303	1124086	88	157	Debris flow
6	Df7	414845	1112857	144	880	Debris flow
7	Df8	411536	1112041	62	212	Debris flow
8	Df9	413338	1110971	80	94	Debris flow
9	Df10	413346	1110898	77	122	Debris flow
10	Df12	415409	1112425	44	99	Debris flow
11	Df13	415713	1112557	145	75	Debris flow
12	Ls1	417113	1108161	41	35	Rotational
13	Ls3	417039	1108968	14	44	Translational
14	LS8	407900	1119662	427	446	Rotational
15	Ls100	409475	1122440	92	68	Rotational
16	Ls101	409374	1122305	146	23	Rotational
17	Ls102	409453	1122150	174	600	complex
18	Ls103	409012	1122108	136	154	Translational
19	Ls104	409806	1122114	209	1172	Translational
20	Ls106	410137	1122236	120	60	Rotational
21	Ls107	417210	1108482	45	62	Rock fall
22	Ls108	417210	1108702	98	22	Translational
23	Ls109	417169	1108816	39	46	Translational
24	Ls111	416955	1108973	72	23	Translational
25	Ls112	416706	1109202	108	317	Rock fall
26	Ls113	416849	1108922	35	83	Translational
27	Ls114	416817	1108970	56	23	Rotational
28	Ls115	416278	1109735	37	171	Translational
29	Ls116	416778	1110317	221	233	Rotational
30	Ls118	416312	1110243	21	94	Translational
31	Ls119	414622	1112004	16	127	Translational
32	Ls120	408244	1113811	89	43	Translational

33	Ls121	407849	1114276	64	34	Rotational
34	Ls122	407079	1115297	55	25	Rotational
35	Ls124	406850	1116004	72	127	Rotational
36	Ls125	410121	1122342	58	60	Rotational
37	Ls126	406538	1119117	89	30	Rotational
38	Ls128	408977	1118526	80	650	Rotational
39	Ls129	407824	1117291	708	803	Rotational
40	LS13	419628	1108641	120	205	Translational
41	Ls130	408196	1118005	61	351	Rotational
42	LS14	418411	1108903	95	114	Translational
43	Ls16	408557	1119247	154	169	Translational
44	LS17	408718	1120222	66	69	Translational
45	Ls18	414445	1122154	143	209	Translational
46	Ls19	416419	1108670	292	479	complex
47	Ls20	466370	1117722	514	36	Translational
48	Ls23	413920	1107411	125	248	Translational
49	Ls24	413584	1109064	78	79	Rotational
50	Ls25	412166	1109842	71	125	Translational
51	Ls27	411120	1115779	105	418	Translational
52	Ls30	412056	1113953	12	136	Toppling
53	Ls31	411451	1113190	51	317	Rock fall
54	Ls35	411712	1113052	30	56	Rock fall
55	Ls36	411428	1113063	99	69	Toppling
56	Ls37	411701	1112936	34	163	Translational
57	Ls39	411280	1113991	87	140	Rotational
58	Ls40	411215	1114581	35	158	Rotational
59	Ls41	411123	1114303	74	100	Rock fall
60	Ls43	411206	1114399	59	258	Rotational
61	Ls44	411172	1114391	31	113	Translational
62	Ls47	411026	1114761	30	122	Translational
63	Ls48	410889	1115104	89	33	Rotational
64	Ls49	411099	1115022	43	65	Debris flow
65	Ls50	409049	1117098	160	110	Rotational
66	Ls51	417384	1122803	39	80	Translational
67	Ls52	417746	1120323	31	102	Translational
68	Ls54	417363	1111885	55	45	Translational
69	Ls55	417100	1112054	31	56	Rotational
70	Ls56	417195	1111974	386	463	Rotational
71	Ls57	417897	1111614	66	165	Rotational
72	LS60	416968	1110812	76	69	Translational
73	LS63	416714	1111015	57	1061	Translational
74	Ls64	416563	1123572	175	368	Rotational

75	Ls65	415764	1123252	1189	484	Debris flow
76	Ls66	418563	1123030	161	150	Translational
77	Ls67	419884	1122089	62	147	Rotational
78	Ls68	419325	1121067	178	45	Translational
79	Ls69	415355	1119733	123	70	Translational
80	Ls70	415339	1119929	79	35	Translational
81	Ls71	415449	1120024	22	145	Translational
82	Ls74	416914	1120825	166	211	Rotational
83	Ls75	416822	1120739	60	146	Rotational
84	Ls76	414034	1115963	51	121	Debris flow
85	Ls77	411080	1114741	89	208	Rotational
86	Ls78	410962	1114663	82	43	Rotational
87	Ls79	410090	1109708	56	64	Translational
88	Ls82	416201	1108360	107	130	Rotational
89	Ls85	415228	1110597	157	582	Translational
90	Ls86	415074	1110791	32	63	Translational
91	Ls87	415914	1110605	105	262	Translational
92	Ls88	415904	1110379	37	115	Translational
93	Ls91	407858	1120838	136	73	Rotational
94	Ls92	408543	1120958	49	81	Translational
95	Ls93	408461	1120131	107	31	Translational
96	Ls94	417000	1112241	35	74	Translational
97	Ls95	411621	1106470	60	105	Translational
98	Ls96	409341	1122671	217	130	Translational
99	Ls97	409155	1122671	171	43	Rotational
100	Ls98	409269	1122436	95	272	complex
101	Ls99	409421	1122503	38	51	Translational
Where: Df = debris flow, Ls = landslide						