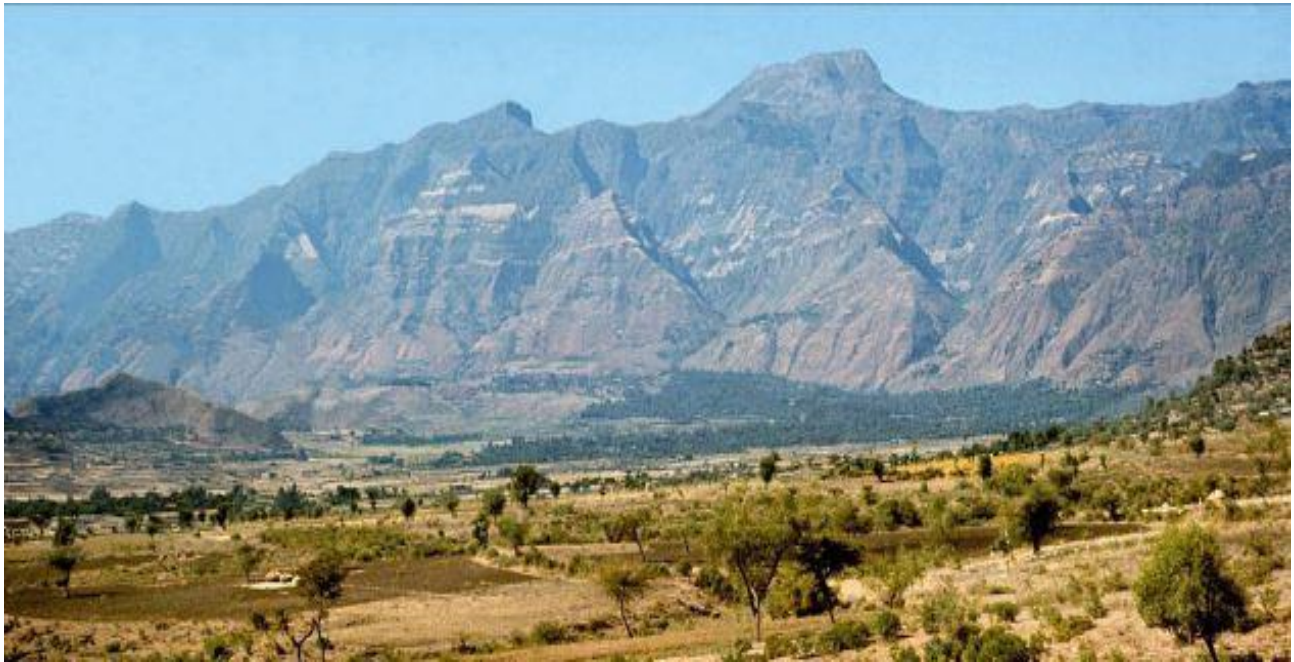


**REMOTE SENSING AND GIS-BASED LANDSLIDE SUSCEPTIBILITY
MAPPING OVER COMPLEX LANDSCAPES: A CASE OF BESHILO
WATERSHED, NORTHERN ETHIOPIA**

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A Thesis Submitted to

School of Earth Sciences



A thesis is submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the requirements for the Degree of Master of Science in (Remote sensing and Geoinformatics)



ADDIS ABABA UNIVERSITY

Addis Ababa, Ethiopia

September, 2020

DECLARATION

I hereby declare that the thesis entitled “Remote sensing and GIS-based landslide susceptibility mapping over complex landscapes: a case of Beshilo watershed, northern Ethiopia” has been carried out by me under the supervision of Dr. Tibebu Kassawmar and Co-Advisor: Dr. Tarun Kumar Raghuvanshi, School of Earth Sciences, Addis Ababa University during the year 2019 - 2020 as a part of Master of Science Program in Remote sensing and Geo-informatics. I further declare that this work has not been submitted to any other University or Institution for the award of any Degree or Diploma.

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ACKNOWLEDGMENTS

First of all I would like to thank Addis Ababa University for providing the opportunity to pursue my post graduate study at this University. This is a great opportunity to thank Addis Ababa University School of Earth Science staff members directly or indirectly for their support during my study period.

I would like to express my deep sense of gratitude to my advisor **Dr. Tibebu Kassawmar**. I don't believe as my word is enough strong to address my thankfulness to him. His golden word, advices, helpful discussions, comments and valuable suggestions were direct input of my work, the knowledge I held and also for my life. His knowledge and profession, is my always wish and dream!

I really want to give my thanks to my Co-advisor Dr. Tarun K. Raghuvanshi, for his guidance, encouragement, comments and teaching me the style of scientific writing and constructive comments.

I express my thanks to Ethiopian Mapping Agency, Geological Survey of Ethiopia, USGS and ESA for providing valuable data and information and free software access to carry out this research.

Finally, I would like to express my special thanks to my instructor, family and friends they were close to me in all aspect of my life. All names could not be mentioned separately because of their independent encouragement and cooperation. I passed enjoyable and memorable time. Thanks!

Andsera, Adugna

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
AUC	Area under the Curve
DEM	Digital Elevation Model
ENVI	Environment for Visualizing Images
ERDAS	Earth Resource Data Analysis System
ESA	European Space Agency
GIS	Geographic Information System
GSE	Geological Survey of Ethiopia
LHV	Landslide hazard susceptibility
LSI	Landslide susceptibility index
LULC	Land use land cover
MCDA	Multi criteria discussion analysis
OLI	Operational Land Imagery
PCA	Principal Component Analysis
ROC	Receiver Operating Characteristics
RA	Risk assessment
USGS	United State Geological Survey
WALRIS	Water and land resource information system
WLC	Weighted linear combination model

ABSTRACT

Remote sensing and GIS-based landslide susceptibility mapping over complex landscapes: A case of Beshilo watershed, Northern Ethiopia.

Andsera Adugna, MSc. Thesis

Addis Ababa University, August 2020

The need to predict possible occurrence of landslides is increasingly becoming a concern of governments and humanitarian bodies in developing countries. The occurrence of landslides and other related disasters requires an intervention towards a better approach where mitigation measures are planned before the disaster. This paper explores the suitability of the available spatial datasets as inputs into GIS-based landslide risk assessment in Beshilo watershed. The datasets used in this study included digital elevation model, slope, aspect, soils, fault, lineament, drainage, precipitation, land use land cover and lithology. The relative importance of factors was established by a combining literature review, expert opinion and pair wise comparison technique. Through GIS tools, a prediction map was generated that showed risk levels of various areas in Beshilo. The results from GIS analysis showed that the areas of highest risk included mountain slopes associated with high fault and lineament density. The result of the susceptibility mapping done for landslide hazard has been classified into five classes and their spatial area coverage also calculated. The study area shows the distribution of the five vulnerability/susceptibility classes ranking from very low (1) to very high (5). Areas with very high landslide susceptibility zones are found in the north eastern and eastern parts of Beshilo watershed. Comparatively, northern and western parts have very low vulnerability areas. From the calculations done, 9% (874.32km²) of the study area occupies very low, 24% (2362.71km²) low, 31% (2955.60km²) medium, 23% (2279.87km²) High, and the rest 13% (1215.28km²) very high hazard zones.

To validate landslide susceptibility map generated by Analytical Hierarchy Process technique, Receiver Operating Characteristics curve analysis was applied. From this; the result revealed that the performance of the model was acceptable. This research result demonstrates the need to incorporate the use of geospatial tools in the countries' disaster management strategies.

Keywords: GIS, landslide susceptibility, Beshilo, pair wise comparison.

CHAPTER ONE

INTRODUCTION

1.1 Background

Landslide is one of the geological hazards that cause damage to natural and social environment. From natural disasters in mountain areas that put lives and properties of the people at risk is the movement of a debris, rock, or soil mass down the slope which is one of the most frequently occurring called landslide [Ismail et al., 2017 as cited in \(Regmi A.D. et al, 2014\)](#). Landslides are the major mass wasting processes and landscape building factors in mountainous terrains. Community living within mountainous environment may be at risk due to a wide variety of geoenvironmental processes, which include geological, meteorological and human factors. Landslide hazard is becoming serious environmental constraints for the developmental activities in the highlands of Ethiopia. With the current infrastructure development, urbanization, rural development, and with the present landslide management system, it is predictable that the frequency and magnitude of landslide and losses due to such hazards would continue to increase ([Bekele Abebe et al., 2010](#); [Kifle Woldearegay, 2013](#); [Tilahun Hamza and Raghuvanshi, 2017](#)). [Varnes \(1984\)](#) and [Hutchinson \(1995\)](#) discussed the main factors which influence landslides. Most important inherent factors are bedrock geology (slope gradient, aspect, and relative relief), soil (depth, structure, permeability, and porosity), land use- land cover and hydrologic conditions. Local influence such as relative relief, proximity to drainage and proximity to lineament are very important for landslide trigger ([Anbalagan et al. 2014](#)). Landslides are triggered by many extrinsic causative factors such as earthquake, blasting and drilling, cloudburst, flash-floods ([Anbalagan 1992](#)).

According to [Bekele Abebe et al. \(2010\)](#), the rate of landslides has been increasing in the recent times due to rugged morphology, high relief energy and the nature of out-cropping rocks. The triggering factors are basically related with rainfall and human interventions, such as: the rapid step of developments in hilly regions, lack of proper engineering geological investigation, any construction activities: especially roads can be the cause of small or huge landslides, like in the case of the present study area, and subsequent damage to human life, general land form and properties.

Landslide susceptibility is defined as a quantitative or qualitative assessment of the classification, volume (or area), and spatial distribution of landslides, which exist or potentially may occur in an area. Whereas vulnerability is the level of population, property, economic activity, including public services, etc., at risk in a given area resulting from the occurrence of a landslide of a given type. Although it is expected that land sliding will occur more frequently in the most prone areas, in the vulnerability analysis, time-frame is explicitly not taken into account (Safaei et al., 2012).

Landslide hazard assessment and susceptibility maps are a basis for strategic and regional planning for landslide hazard mitigation work (Anbalagan, 1992; Raghuvanshi et al., 2014). Landslide hazard maps have a greater value to development planning as they present a spatial division of the ground in to areas of different level of potential landslide hazard zones and it provides the essential framework for land use planning and development of proper engineering practices (Anbalagan, 1992; Gemechis Chemindi et al., 2017). Landslide hazard analysis involves mapping and identifying future hazardous zones through the analysis of controlling parameters (Arnous, 2011).

Application of GIS and remote sensing is inevitable in large scale landslide inventory, landslide investigation and susceptibility mapping for landslide occurrence. Remote sensing, especially from the high-resolution satellite imagery is gaining the high importance due to its wide coverage (Delacourt et al. 2007). Landslide susceptibility mapping is the mapping of the probable landslide occurrence within the specific area considering specific contributing factor. Digital Elevation Model (DEM) of the study area was used for the extraction of terrain parameters like slope, aspect and elevation.

In this regard, remote sensing and GIS play great role in mapping and generating research evidence on the occurrence of landslide hazards. Therefore, the objectives of this study are to generate landslide susceptibility map of the area based on multi-criteria discussion method.

1.2. Statement of the problem

The Bashilo River watershed is located on the Northwestern Ethiopian Plateau (Fig. 3.1). Being part of Northwestern Plateau of Ethiopia, the Bashilo River watershed has experienced repeated

episodes of uplift since ~150 Ma (Ismail et al., 2017 as cited in Hofmann et al., 1997; Wolfenden et al., 2004; and Bonini et al., 2005), exposing sandstone and limestone at altitudes of ~2200 m within the major drainage networks of the plateau (Ismail et al., 2011 as cited in Gani et al., 2007).

According to many researchers (Lulseged Ayalew and Yamagishi, 2004; Tenalem Ayenew and Barrberie, 2005; Bekele Abebe et al., 2010; Raghuvanshi 2014a; 2014b), landslide is a common geo-environmental hazard in northern, southern and western highlands of Ethiopia. From the past experience landslide hazard have resulted into damaging infrastructure as well as human life all over the world (Dai et al., 2002; Raghuvanshi et al., 2014a).

The present identified study area is located in north western Ethiopian highland which is rugged mountainous terrain. The area is known by landslide activities which cause considerable damage on infrastructures and agricultural land.

In mountainous terrain developmental activity especially, road construction covers large area of slope therefore it needs detailed slope stability assessment (Raghuvanshi et al., 2014a). Due to this; landslide hazard susceptibility (LHS) mapping, 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 impact. Major slope failures have been noted in many parts of the uplifted northwestern Ethiopia Plateau, for instance near Dessie City that is located in the southwestern portion of the Bashilo River watershed (Ismail et al., 2017).

The Bashilo watershed was selected for this study because it is located in the uplifted part of the Northwestern Plateau. Slopes in the region are known for mass wasting processes, being bordered by Mount Guna (47,20 m) in the northwest, the elevated ridges of the western escarpments along its southern margins, and the elevated plateaus lying to the northeast (Ismail et al., 2017) and there is no enough research that shows the landslide hazard occurrence. Therefore, it is difficult to reduce the impact and develop management plan. So, to minimize the risk of landslide hazards and develop good management planning system, there is a need to map their occurrence and identify their intensity level. Researches related to landslide were done through geological survey, topographical survey, observational survey and geospatial survey.

Even if remotely sensed image for large area is not visible, mapping through integrated with indirect geospatial survey considering conditioning factor is appropriate. Even though the present study area is highly affected by the landslides, either published or unpublished study on landslide has not enough been reported from the area. In this regard to fill the gap remote sensing and GIS techniques play great role in mapping and generating research evidence on the occurrence of land slide hazards.

Therefore, in this study indirect mapping of landslide prone area is used. Indirect mapping uses Analytical Hierarchy Process (AHP) to predict landslide prone areas, based on information obtained from the interrelation between landslide conditioning factors and the possibility of landslide distribution. GIS is very suitable for indirect landslide susceptibility mapping, in which all possible landslide contributing terrain factors are combined with a landslide inventory map, using data-integration techniques. This study is used to generate information that helps to reform the current spatial plan and to give insight for local government in managing present and future land use practices.

1.3. Objectives of the study

1.3.1 General objective

The main objective of this study is to produce the landslide hazard susceptible area map of Beshilo watershed Northern Ethiopia through integrated remote sensing and GIS-based approach.

1.3.2 Specific objectives

To achieve the above general objective, remote sensing and GIS-based approach will be applied to address the following specific objective:

- To identify the causative and triggering factors responsible for landslide hazard occurrence and assess its relative contribution in the area.
- To model landslide occurrence using advance spatial analysis techniques and identify landslide susceptible area.
- To understand the use of remote sensing image and GIS techniques for landslide

vulnerable map production in the area.

- To verify the landslide susceptible area map with prepared general inventory of past landslide activities.
- To identify potential landslide risk areas like settlement, infrastructure and agricultural area.
- To propose some remedial and mitigation measures in order to mitigate landslides hazards.

1.4 Research questions

- What are the causative and the triggering factors which are responsible for landslides in the area?
- What are the relative contributions of causative factors on the landslides?
- What are the possible recommended remedial and mitigation measurements?
- What is the implication of GIS and Remote sensing approach to map landslide susceptible area?

1.5 Significance of the Study

Remote sensing and GIS techniques are a useful tool to identify, understand and mitigate landslide hazards by detecting the susceptible area. The significance of this study is to contribute in the guest of landslide hazards and risk facing area. The present study focuses on the most susceptible places to landslide hazards and produce valuable facts on landslide hazards which is a common environmental problem in Ethiopia highlands. The study show the application of geospatial technology in landslide hazard mitigation, both at pre and post risk management planning process. Generally, this study enables to identify hazard-prone areas in the study area, demonstrate significance of geospatial technology in landslide hazard studies, and provide relevant information that will contribute to the environmental management planners and disaster management activity.

This research will also build capacity of researchers in identifying and mapping landslide susceptible zone of the area at watershed and river basin levels by applying remote sensing and

GIS techniques.

1.6 Scope of the study

In Ethiopia, Most of the Natural hazards related to the geological phenomena like landslide have little attention in terms of vulnerability of natural resources, infrastructural property and human life. Given the fact of current and future geo-hazard susceptibility problems, there is a need to announce the area which is prone to landslide for decision making and planning to maintain at least some strategy for disaster management.

Remote sensing and GIS techniques can help to get up-to-date information to asses and monitor changes related to landslide hazard aspect with low cost. Therefore, this research will give insight to future researchers for landslide hazard susceptibility study using the science of remote sensing and GIS. In addition, this study will give a spot place to perform for future landslide hazard and risk monitoring.

1.7 Limitation of the study

The main limitation of this research is the weighting and ranking of factors which is highly subjective even if this is expert's opinion and software assisted not replaced of such opinions with researched parameters. And lack of detailed field survey to identify the type, location and time of the occurrence of landslide and lack of record to describe actual loess of element at risk to assess the risk assessment.

1.8 Organization of the thesis

This thesis is organized in to seven chapters. The first chapter is about the introduction which includes the background, the research problem, objectives and significant of the study. The second chapter covers an overview of the study area and landslide mapping techniques. The third Chapter includes work of previous researchers about the theoretical background for the landslide, landslide hazard zonation and remote sensing and GIS technique. The fourth Chapter describes the methodology, descriptions of the data collection, processing and analysis of different methods of the results. The fives Chapter covers the discussion of the results and the last chapter contains conclusions and recommendations made through the present study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Landslides overview

Landslide is one of the geological hazards that cause damage to natural and social environment. It is the movement of a debris, rock, or soil mass down the slope and is one of the most frequently occurring natural disasters in mountain areas that puts lives and properties of the people at risk (Regmi A.D. et al, 2014). Community living within mountainous environment may be at risk due to a wide variety of geoenvironmental processes, which include geological, meteorological and human factors. As defined by Kifle weldeargay (2013), landslide is the downslope movement of soil and rock under the influence of gravity without the primary assistance of a fluid transporting agent. Landslide hazard is becoming serious environmental constraints for the developmental activities in the highlands of Ethiopia.

Rainfall-induced landslides of different types and sizes are common in hilly and mountainous terrains of the highlands of Ethiopia. The major types of landslides reported which is a result of heavy rainfalls include debris/earth slides, debris/earth flows and, and medium to large-scale rockslides. Though rock falls are common in the Ethiopian highlands no association is made with rainfalls (Kifle weldeargay, 2013) see (fig 3.1).

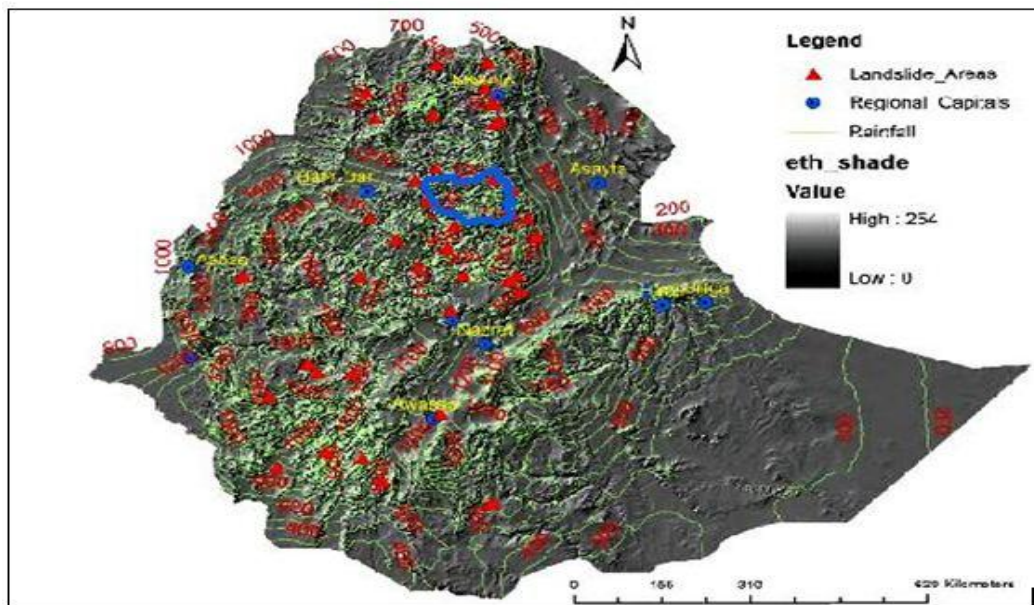


Fig 2.1: Location of landslide affected areas in the highlands of Ethiopia. (Source: Kifle weldeargay, 2013). The study area is highlighted in a blue color polygon.

2.1.1 Previous work of the study area

Various forms of mass movements can often be visually identified using topographic maps and other satellite-based imagery in combination with recognition protocols for anomalous topographic features [Ismail et al., 2017](#) as cited in ([Ahmed and Rogers, 2012, 2016](#)).

The study conducted in this area is tentatively identified large bedrock landslide features across the Beshilo River, a tributary of the upper Blue Nile River of Ethiopia, using a geospatial mapping approach ([Ismail et al., 2017](#)).

This previous research sought to identify and delineate landslides and related features by utilization of low- cost mapping techniques, including anomalous topographic protocols, contour patterns, and moderate-resolution satellite imagery ([Ahmed and Rogers, 2012, 2014, 2016](#)) in a GIS environment. These data were used to compile a cost-effective first-pass reconnaissance-level landslide map ([Ismail et al., 2017](#)) seeking to identify potential landslide features, based on expert knowledge, and to delineate the areal extents of such features on a regional scale (features >500 m long). The results of this inventory show several hundred landslides, including several landslide complexes likely induced by seismic excitation, composite bedrock landslides, retrogressive slumps, earth flows, and translational block slides having sizes generally >500 m in length ([Ismail et al., 2017](#)). Because of the resolution of the available data, a certain degree of error should be expected, even under the best conditions. The authors' intention was simply to identify "target sites" for more detailed evaluation of potential slope stability hazards, especially for under-developed countries like Ethiopia. This result suggests that the utilization of expert knowledge of anomalous geomorphic features and employment of low-cost satellite imagery data could be a very cost-effective method of making an initial, "first-pass reconnaissance" of large tracts of hilly terrain. In this case the identified landslide areas are located in (Fig 2.2).

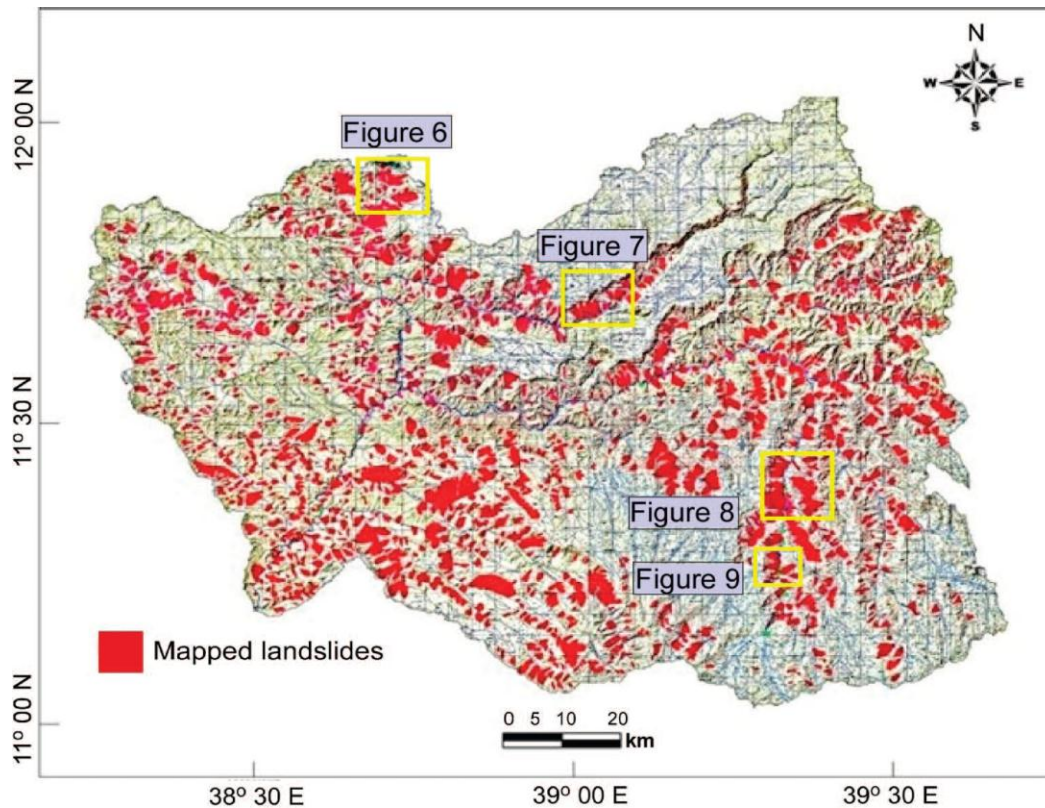


Figure 2.2 Previous work of the study area (source [Ismail et al., 2017](#))

2.2 Types of Landslide

Landslide may be classified into various categories based on mode of movement, material involved, speed of movement and other. According to ([Varnes, 1978](#)) landslide is classified based on the types of material involved (Rock, Earth, Soil, Mud and Debris) and types of movement (fall, topple, slide, spread, flow) and complex class of movement which contains two or more different mode movement acting downslope movement of the landslide mass (Table 2.1).

Table 2.1: Landslide classification (Varnes, 1978)

Types of movement	Types of material		
		Bed rock	Soil
		Coarse	Fine

Fall		Rock fall	Debris fall	Earth fall
Topple		Rock topple	Debris topple	Earth topple
Slide	Rotational	Rock slump	Debris slump	Earth slump
	Transitional	Rock block slide, rock slide	Debris block slide Debris slide	Earth block slide Earth slide
Lateral spread debris slide		Rock spread	Debris spread	Earth spread
Flow		Rock flow (deep creep)	Debris flow(soil creep)	Debris flow(soil creep)
Complex slope movements (combination of two or more movement type)				

2.2.1 Rock fall

Fall is freely down movement (the detachment) of either soil or rock or both soil and rock from a steep slope or cliff along a surface on which little or no shear displacement has occurred. Departure occurs along discontinuities for example fractures, joints, and bedding planes and movement occurs by free-fall, bouncing, and rolling. It is common in steep slopes, or vertical slopes also in coastal area, along rocky bank of river and streams, road cuts, and jointed, fractured and weathered bedrock (Wachal and Haduk, 2000). It triggered might be by natural process under cutting of slope, drainage erosion, weathering and human activity like excavation the toe of slope during road construction and repairs and increases agricultural practice along the landslide susceptible area (USGS, 2004).

2.2.2 Topple

Topple failure is a forward rotational movement of huge masses of soil, rock or debris and earth from a slope (Varnes, 1984). It is usually caused by cracks or fracture in the bedrocks. The rate of movement ranges from extremely slow to extremely rapid and it can be destructive especially when failure is sudden (Highland and Bobrowsky, 2008).

2.2.3 Slide

A slide is a downslope movement of a soil or rock mass occurring on surface of rupture due to

different factors. According to (Varnes, 1978) slide was classified as rotational and translational slide. In a translational slide the landslide mass moves along a roughly planar surface with little rotational or backward tilting. Whereas, In a rotational slide, a slide in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide (Varnes, 1978).

Rotational landslide

This type of landslide is occurs in the very weak rock mass or regolith material is moved slowly when due to rotational mechanism is self-stabilizing as the gravitational driving force weakening with increases displacement (Vernas, 2013). Rotational landslide is not controlled by structure. The structure is characterized by a prominent main scarp, a characteristic back-tilted bench at the head and limited internal deformation. Usually slow to moderately slow and may common in the area.

Translational landslide

In this type of landslide rock mass and soil is moved along the planar rupture surface. According to (Vernas, 2013) translational landslide is structurally controlled and has little or no internal deformation. Also he stated that planar sliding mechanism is not self-stabilizing and sliding is rapid when compared to rotation sliding and lead high damage to properties and natural environment.

2.2.4 Flow

In flows, the movement within the moved mass is such that the form taken by the moving material or the apparent spreading of velocities and displacements look like those of viscous fluids. The slide surfaces within the moving mass are usually not visible or are short-lived, and the boundary between moving and stationary material may be sharp or it may be a zone of plastic flow. The material is, by necessity, unconsolidated at the time of flow but may consist of rock fragments, fine granular material, mixed debris and water, or plastic clay (Varnes, 1984). Debris flow, debris avalanche, mudflow, creep and Earth flow are types of flow. Debris flow includes the rapid downhill movement of loose earth material usually with water. Debris Avalanche is similar to debris flow but unlikely to debris flow it has a more rapid flow. In an Earth flow, the earth material is finer and is washed away leaving a depression bowl at the head. Mudslides are composed of fine silt, sand and clay material saturated with water and flowing very rapidly.

Creeps are slower in nature and can be evident when electric poles and roads bend slightly. They are commonly caused by intense surface water flow, due to heavy precipitation or rapid snowmelt, which erodes and mobilizes loose soil or rock on steep slopes. They can move objects as large as houses in their downslope flow or can fill structures with a rapid accumulation of sediment and organic matter (Highland and Bobrowsky, 2008).

2.2.5 Lateral Spread

These types of landslide usually occur on very gentle slopes or flat terrain. These are distinctive and its dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is result of liquefaction, the process of saturated, loose, cohesion less sediments (usually sands and silts) are changed from a solid into a liquefied state. This Failure is usually triggered by rapid ground motion, such as that of experienced during an earthquake, but can also be artificially induced. Either bedrock or soil which is coherent material, rests on liquefied materials, the upper units may undergo fracturing, extension and then subside, translate, rotate, disintegrate, or liquefy and flow off.

Lateral spreading in fine-grained materials on shallow slopes is usually ongoing. Lateral spreads typically damage pipelines, utilities, bridges, and other structures having shallow foundations (Highland and Bobrowsky, 2008).

2.3.6 Complex type of movement

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

2.4 Causes of Landslides

The ultimate force behind any landslide and weathering is gravity. Land surfaces are held together by multiple forces. The most important of these is friction. Soil textures such as clay cling to each other tightly whereas sandy materials are only loosely joined. All landscapes are jointed together by friction between the sediment cover and the underlying bedrock. Landslides occur when gravity overcomes the force of friction. (<https://science.howstuffworks.com/enviromental/earth/geology/landslide2.htm>).

Several common causes of landslides are:

Water: the most common trigger of landslide, water reduces the friction between the bedrock and the overlying sediment, and gravity sends debris sliding downhill. The stability of soil increase by a small amount of water in sand and clay soils. When sediments gets heavier as more water is added and that can causes it to flow downhill. This is why landslide occurs after rainfall or rainstorms.

Earthquakes: if the earth crust vibrates enough to disrupt the force of friction holding sediments in place on an incline, a landslide can strike. Seismic activity can also make it easier for water to leach into the soil, further destabilizing the slope.

Wildfires: plants help keep the soil stable by holding it together like adhesive with their roots. When this adhesive is removed, the soil loosens, and gravity acts upon it much more easily. The loss of the vegetation after a fire makes the razed land susceptible to slides.

Volcanoes: several types of volcanoes make them productive starting points for especially destructive landslides. Volcanoes have unstable surfaces likely landslides even if the volcano is dormant. In addition to the fact that the surface is composed of mostly loose rock, the volcanic gases create acidic groundwater. This contributes to the rocks' collapse, making them more likely to be carried away. One of the types of volcanoes is pyroclastic flow which is amalgamation of ash, lava, rocks and gases that come barreling down volcanic mountains either during an eruption or when a volcano dome collapses.

Human activities: human make landslide more likely through activities like deforestation, overgrazing, mining and road-building. These activities rob that glue from the land, increasing the probability of landslides.

The structurally complexity and proximity and proximal to rivers increase the vulnerability to landslides. This study area has higher density of lineaments, high change in agricultural activities and population growth increasing the vulnerability of landslides. Remote Sensing and GIS tool are applicable in mapping landslide vulnerability in the highlands of Ethiopia.

<https://science.howstuffworks.com/enviromental/earth/geology/landslide2.htm>.

2.5 Landslide hazard mapping techniques

Landslide activities in different parts of the world require some rapid slope stability analysis technique. Identification of landslide susceptible area is necessary for further analysis of risk.

Landslide susceptibility mapping is a technique which helps to delineate areas with equal probability of landslide occurrence (Varnes, 1984). Landslide susceptible zone was evaluated by geomorphologic condition of the particular region (Kienholz et al. 1984). This is done by combining several causative factors.

Many different types of landslide hazard zonation techniques have been developed over the last decades (Van Westen et al., 2003). Most of the published literature on landslide hazard mapping actually only deals with landslide susceptibility mapping, or at best spatial probability assessment. Generally speaking landslide hazard zonation techniques can be subdivided into direct and indirect methods. In direct mapping the geomorphologist, based on his experience and knowledge of the terrain conditions using observational survey determines the degree of susceptibility directly. Indirect mapping uses either statistical models, deterministic models or the like to predict landslide prone areas, based on information obtained from the interrelation between landslide conditioning factors and the possibility of landslide distribution. The increasing popularity of Geographic Information Systems over the last decades has led to a majority of studies, mainly using indirect susceptibility mapping approaches (Van Westen et al., 2003). GIS is very suitable for indirect landslide susceptibility mapping, in which all possible landslide contributing terrain factors are combined with a landslide inventory map, using data-integration techniques (Van Westen et al., 2003).

GIS-multicriteria decision analyses (MCDA) provide a rich collection of techniques for landslide susceptibility mapping (Feizizadeh et al., 2012). The MCDA framework is primarily works with how to combine the information from several criteria to form a single index of evaluation (Yu et al., 2011; Feizizadeh and Blaschke, 2012). GIS-MCDA can be thought of as “a process that transforms and combines geographical data and value judgments (the decision-maker’s preferences) to obtain information for decision making. GIS and MCDA have synergetic capabilities one can see the benefit for advancing theoretical and applied research on GIS-MCDA” (Malczewski, 2006). GIS-MCDA based landslide analysis allows to combine information derived from heterogeneous sources to support landslide monitoring.

2.5.1 Analytical Hierarchy Process

One of the multi-attribute techniques which have been incorporated into the GIS-based landslide

analysis procedures is the Analytical Hierarchy Process (AHP) originally introduced by Saaty (1980). AHP builds a hierarchy of decision elements (factors) and renders comparisons possible between pairs of factors in form of a matrix. The results are weights for each factor and also a consistency ratio which quantifies the unambiguity of the pairwise weighting. AHP is a multiple criteria decision-making technique that allows subjective as well as objective factors to be considered in the decision-making process. It allows the active participation of decision-makers and gives managers a rational basis on which to make decisions.

The qualitative methods are based on individual or group expert opinions (Neaupane and antanakulchai 2006). Inventory and historical information has been helped Experts to evaluate landslides, determine the main actors inducing them, and identify sites that have similar geological and geomorphological features. Some qualitative methods become semi-quantitative by incorporating ranking and weighting (Ayalew et al. 2005), as is the case of the Analytic Hierarchy Process (AHP) (Saaty 1980; Yalcin, 2008;) and the weighted linear combination (WLC) (Ayalew et al. 2005).

In MCDM the AHP method is widely used to obtain the required weightings for different criteria (Saaty, 1977; 1980; Saaty and Vargas, 1991; Wu 1998), AHP has been successfully working in GIS-based MCDM since the early 1990s (Carver, 1991; Malczewski 1999; 2004; Makropoulos et al., 2003). It calculates the required weights associated with criterion map layers with the help of a preference matrix in which all relevant criteria identified are compared against each other on the basis of preference factors. The weights can then be aggregated. GIS-based AHP has gained popularity because of its capacity to integrate a large quantity of heterogeneous data, and because obtaining the required weights can be relatively straightforward, even for a large number of criteria. It has been applied to a variety of decision making problems (Tiwari et al., 1999; Nekhay et al., 2008; Hossain and Das, 2009). Finally, AHP as a multi objective, multi-criteria decision-making approach enables the user to specify preferences drawn from a set of alternatives. AHP gained wide application in site selection, suitability analysis and regional planning.

2.5.2 Weighted linear combination

The weighted linear combination model (WLC) is one of the common and effective methods for

landslide susceptibility mapping. In this method, involving multiple parameters is used to establish the relational importance and degree of influence of the selected parameters and Ranks and weights are assigned depending on their influence to enable a landslide event in a GIS environment ((Musigguzi M. and Asiiimwe I., 2014); Ladas et al. 2007). According to Ladas et al. 2007, there is no standard number of parameters or type of parameter but the parameter to be selected based on data availability.

Weighted linear combination (WLC) method was used to assess landslides vulnerability of a particular study area within the GIS environment of ArcGIS. This multi-criteria evaluation method allows flexibility and tradeoffs amongst all parameters used. Ranks and weights are assigned depending on their influence on the occurrence of landslides. Parameters to be select are different for different study area based on availability of data. The landslide susceptibility map provides valuable information of the risk (Michael E. A. and Samanta S., 2016).

CHAPTER THREE

OVERVIEW OF STUDY AREA

3.1 Description of the study area

The Beshilo River is located on the Northwestern Ethiopian Plateau and it extends around latitude $10^{\circ}50'00''$ to $11^{\circ}58'00''$ N and longitude $38^{\circ}12'00''$ to $39^{\circ}40'00''$ E in Amhara Regional State of Ethiopia (Fig 3.1). It originates west of Kutaber and initially flows northwest, where it convolves with the Tergiya tributary. Downstream of this location, it turns southwest, eventually joining the Abay River along a structurally controlled course (Ismail et al., 2017). The drainage area of Bashilo watershed is about 12,549 km², covering parts of the North Gondar, North Wollo, and South Wollo areas. Since the study area (Bashilo watershed) is located on the Northwestern Ethiopian Plateau the area is characterized by high temperature, erratic rainfall and sandy soil adopted from (Amhara region, 2007). Also it is seriously affected by landslide hazards. By nature, the area has very complex lithological character and complex farming system. The area is also very difficult or slopes are tilled and aggravate landslides.

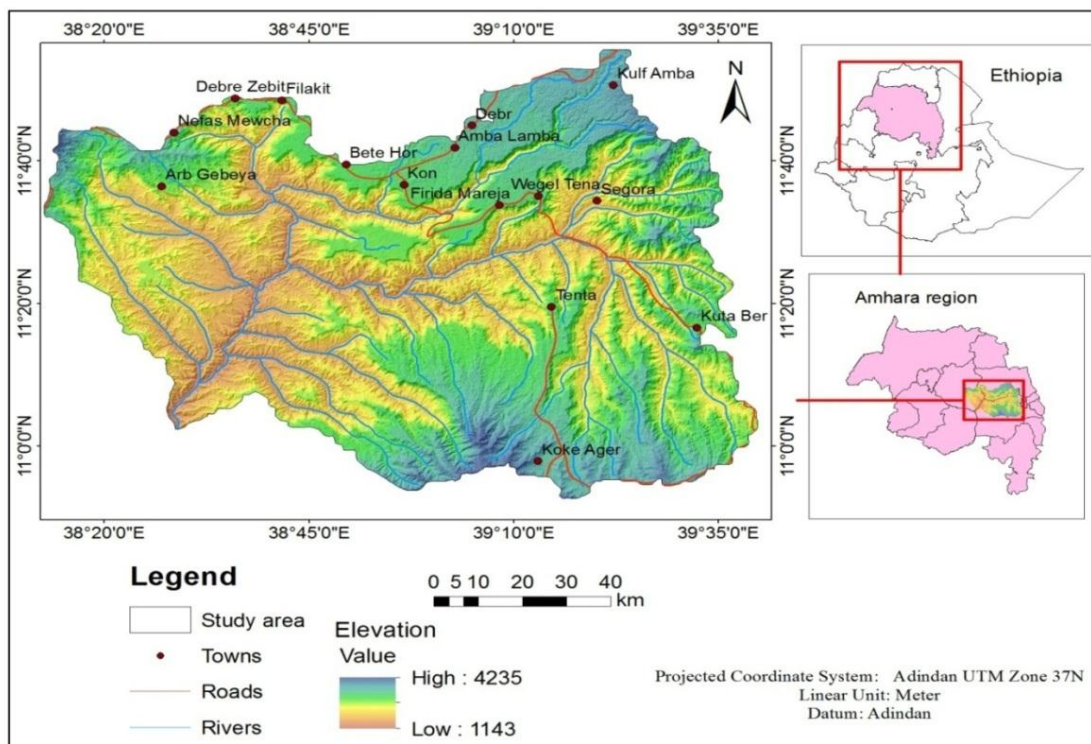


Fig 3.1: Location map of the study area

3.1.1 Topography of the study area

The Beshilo watershed is characterized by a complex topography with variable altitude, ranging from lowest elevation of 1,209 m in flat areas to the highest elevation reaches up to 4,260m (Fig 3.2). Hummocky topography, transverse ridges, isolated low-gradient channel profiles, isolated erosional knobs, and distal depositional fans are often direct manifestations of mass movements. The area is very difficult or slopes are tilled and aggravate landslides.

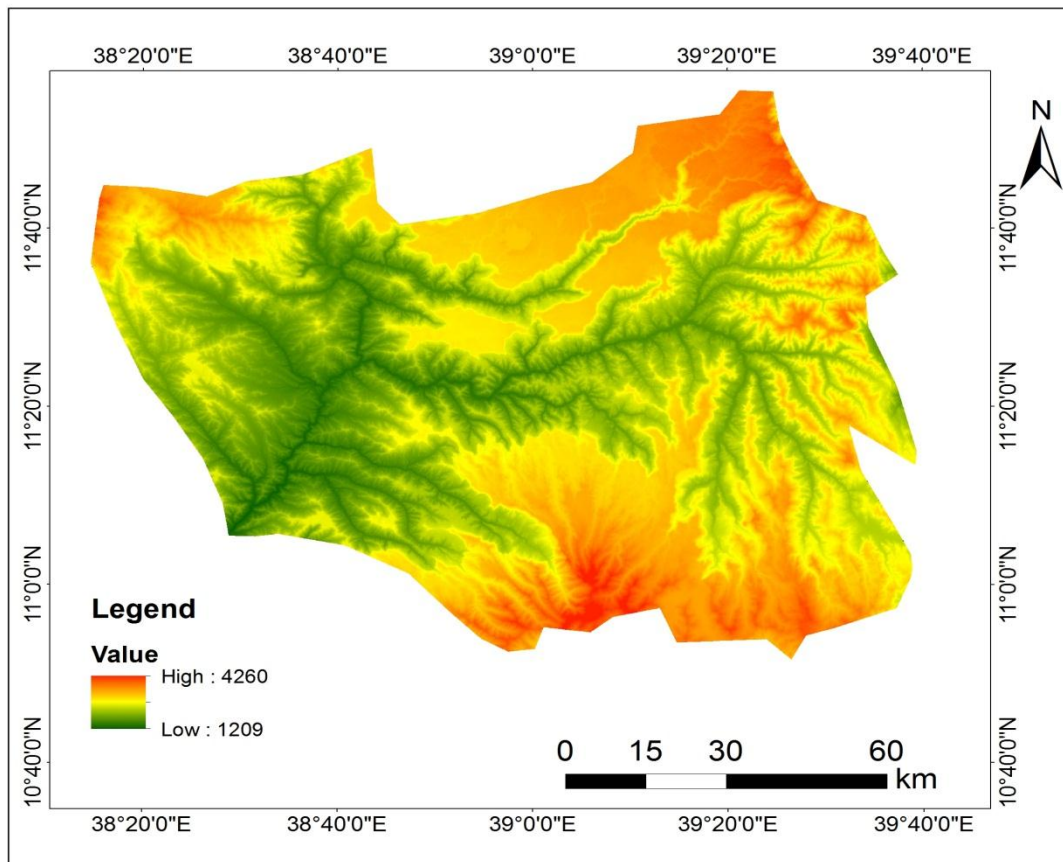


Figure 3.2 Topography of the area

3.1.2 Soil types of the area

For this study a soil data of the major soil groups of Beshilo watershed as FAO soil group were collected from Water and land resource information system (WALRIS) GIS department. The major soil groups found in the study area were Cambisol, Leptosol, and Vertisol (Fig 3.3).

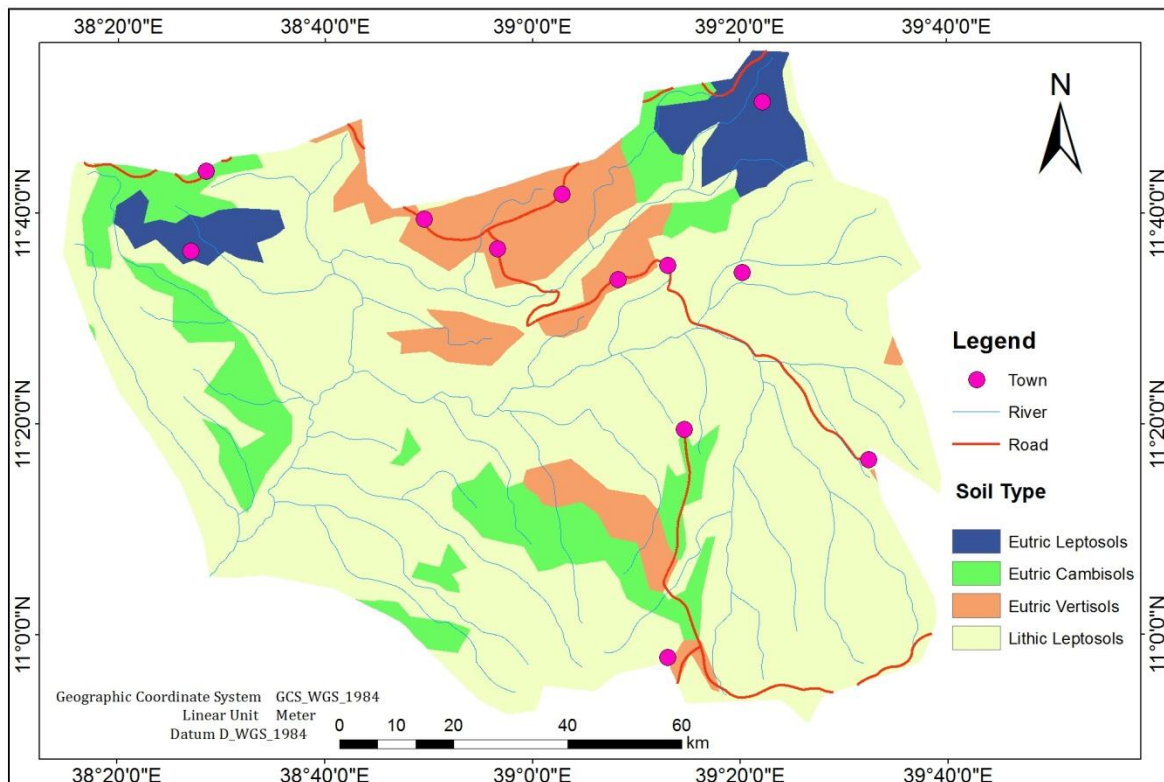


Figure 3.3 Soil type of the area

3.1.3 Drainage of the area

As we describe in the study area description the Beshilo River is located on the Northwestern Ethiopian Plateau and it originates west of Kutaber and initially flows northwest, where it convolves with the Tergiya tributary. There are also many rivers and streams which cross the study area. These streams and rivers start from the N and NE part of the study area and they drain to-wards SW and finally to the Abay River. Rivers drained from North and North East direction forms drainage pattern of the study (Fig 3.3). Downstream of this location, it turns southwest, eventually joining the Abay River along a structurally controlled course. The drainage area of Bashilo watershed is above twelve thousands km², covering parts of the North Gondar, North Wollo, and South Wollo areas. Also it is seriously affected by landslide hazards, by nature; the area has very complex lithological character and complex farming system.

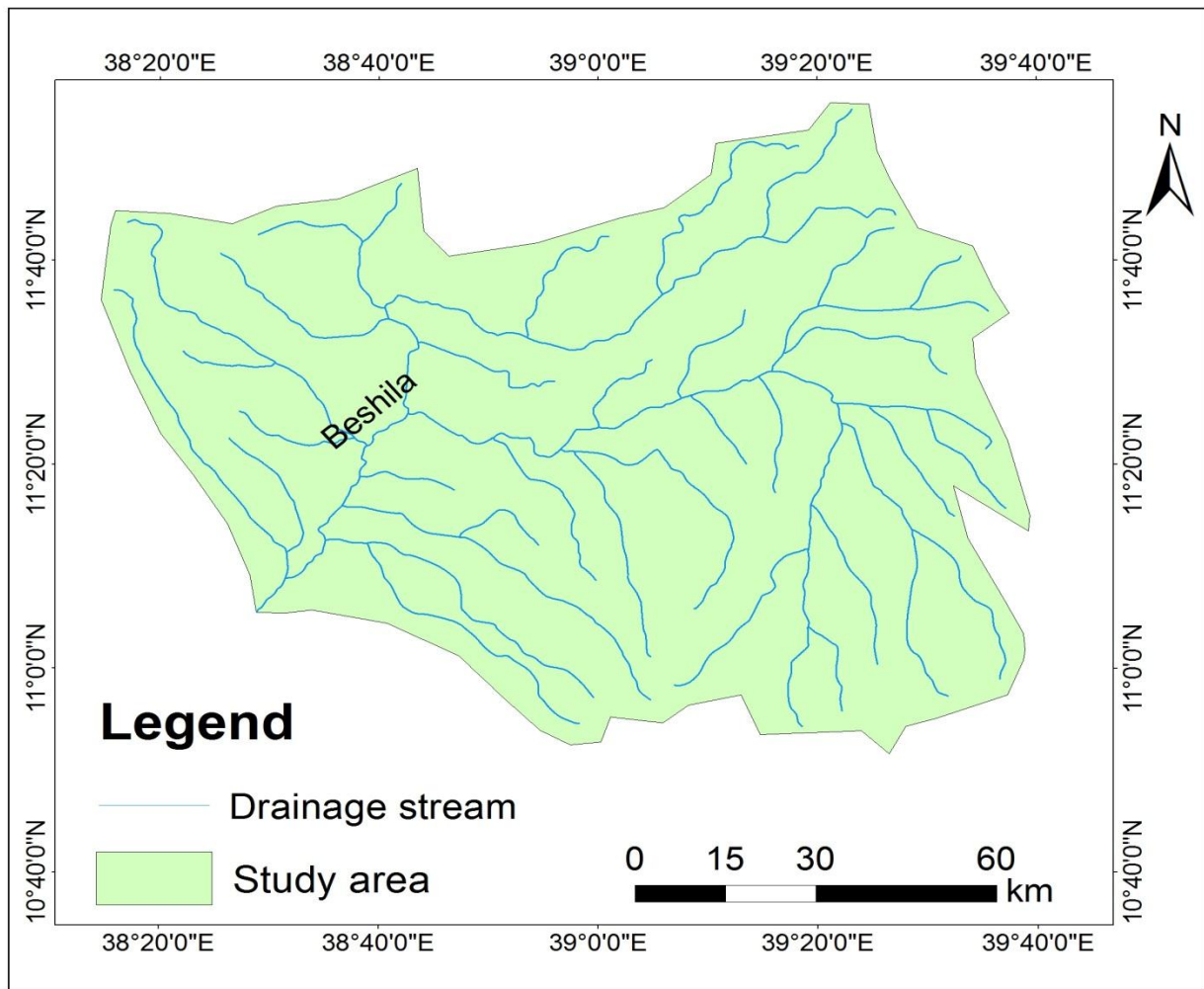


Figure 3.4 Drainage of the study area

3.1.4 Land use land cover of the area

For this study land use land cover of the area were done on ERDAS IMAGINE software using supervised classification from Landsat 8 images downloaded from USGS site. According to this classification land use land cover map of the Beshilo watershed is mostly dominated by agricultural land and pasture land (Fig 3.4).

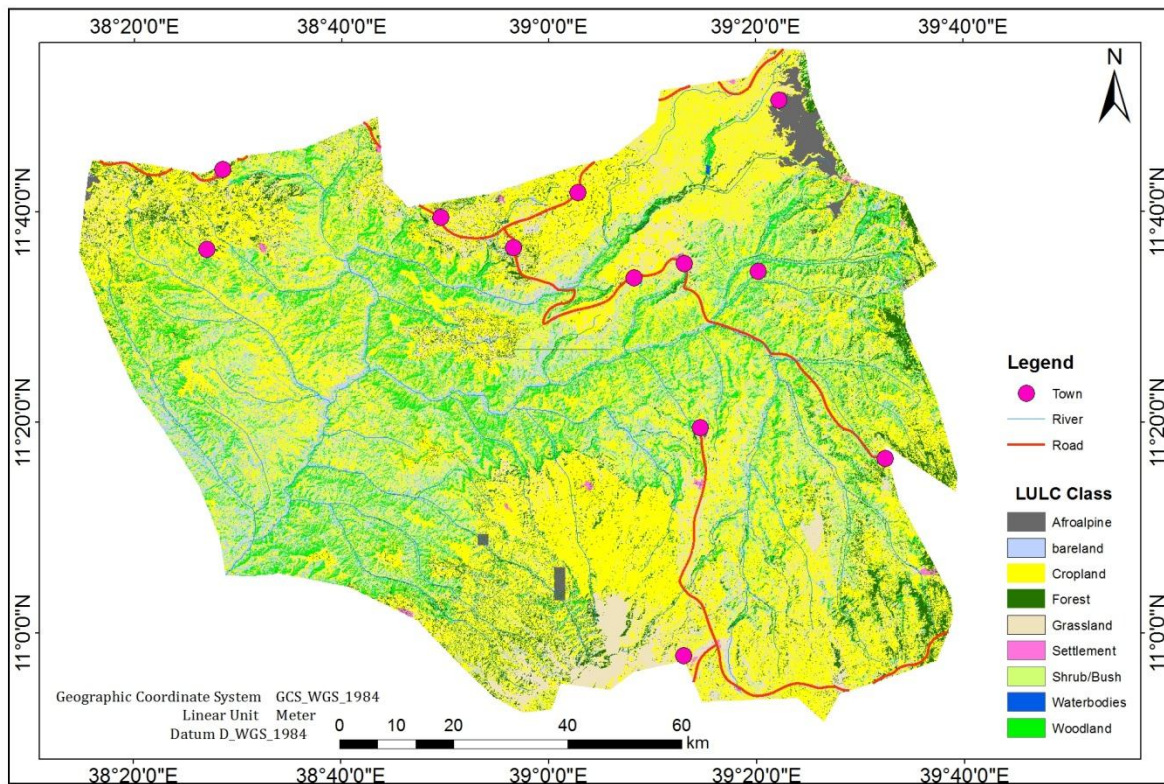


Figure 3.5 Land use land cover map of the area

3.1.5 Climate condition

The study area is characterized by extreme variation in topography. The study area lies in the humid to semiarid areas which are classified as having average annual rainfall up to 1404.9 mm during 2019 year (CHIRPS). The highest monthly average precipitation recorded was 198.4 mm in the month of May. From March to September the area receives high rainfall whereas from October to February it receives low rainfall. Generally, since the study area (Bashilo watershed) is located on the Northwestern Ethiopian Plateau the area is characterized by high temperature, erratic rainfall and sandy soil. The mean annual maximum temperatures for this area is 25.5 ° C and mean annual minimum temperature is 10.8 ° C (1988-2005).

3.2. Geology of the study area

The present study area is located in North Western Central Ethiopia. The regional geology of the area contains early Cenozoic extension/faulting accompanied by widespread volcanism mostly it's in tertiary period: i. Eocene-Oligocene, ii. Oligocene-Miocene, iii. Late Miocene and Quaternary

volcanic rocks and associated lacustrine and superficial sediments. Study area geology is from Dessie and Debretabor map sheet from geological survey of Ethiopia (Tesfaye Demsie et al., 2010).

3.2.1 Ashangie basalts (Tab)

The Ashangie basalts represent the earliest fissural volcanism (e.g. Mengesha Tefera et al., 1996). They are exposed in the western plateau and the western afar marginal area. The basalts attain a maximum thickness of around 1000 m along Beshilo river section. Its thickness decreases towards south east. These basalt flows represent the lower most parts of volcanic successions. They are exposed long the deep river gorges of NE-SW trending Beshilo and NW-SE trending Gerado rivers and their tributary streams in the western plateau area.

The Ashangie basalts are also exposed as faulted block along NW-SE trending escarpment. It is exposed as steep slopes of undulating mountain chains and low lying flat plains along road cut, stream bed and gentle slopes. The unit is uncomfortably overlain by the Wegel Tena rhyolite and / or ignimbrite and Dessie basalt formation.

Their contact with the Wegel Tena rhyolite is clearly observed on Wegel Tena and Gishen Mariam sections. The basalt is characterized by deeply weathered, greenish gray, dominated by columnar jointed aphanitic basalt, intercalated with different layers of vascular basalt, volcanoclastic sediment and agglomerate.

3.2.2 Wegel Tena rhyolitic ignimbrite (Twtr)

This rock is exposed on north of Wegel Tena town and Gishen Mariam and Ambassel sections. The ignimbrites like the mafic volcanic/basalt it forms typical plateau topography. North of Wegel Tena town it is extensively eroded and dissected by the deep gorges forming sharp cliffs. In the Mekdela and Gishen Mariam area it is found on the hill top with sharp slopes overlying the Ashangie basalts. Along Wegel Tena-Beshilo river road section it forms plains. It forms northwest southeast trending hill at the Ambassel section. The maximum thickness of the Wegel Tena ignimbrite is about 500 m. The rock characteristics are pink, white, light gray and fine to coarse grained. The individual layers show variation in texture, they are dominantly porphyritic with microlites or glassy matrix. Densely welded ignimbrites have a glassy appearance and exhibit a well-developed columnar jointing.

3.2.3 Dessie basalt formation (Tdb)

The name for this rock unit as Dessie basalt formation is adopted from [Wolfenden \(2003\)](#). It is exposed in the western plateau area forming chain of ridges like cliffs along the escarpment and river cuts. This unit is a package represented by association of different types of aphanatic and porphyritic, massive and vesicular basalts, with subordinates of pyroclasts and ash layers ([Tesfaye Demsie et al., 2010](#)). The aphanatic basalts are dominated by fine microcrystalline matrix with fine plagioclase microlites. They also contain traces of augite, olivine, plagioclase and opaque minerals with scarce vesicles. The porphyritic basalts are varying in composition ([Tesfaye Demsie et al., 2010](#)).

3.2.4 Tarmaber Megezez Formation (Ttb)

This unit is exposed in the northwestern and in the southwestern part of the Dessie map sheet. The name as tarmaber megezez formation is adopted from ([Zanettin et al., 1974](#); [Tefera et al., 1996](#)). The unit is exposed along plain road sections, gentle slopes and river beds.

In the north western part it forms elevated plains along Weldeya-Hamusit road. It has usually conformable contact with the Dessie basalt formation. This rock Formation attains a thickness greater than 1000 m and the unit is characterized by spatially distributed dark gray to black coarse grained, vesicular basalt and columnar jointed aphanatic basalt. It is associated with pink, columnar jointed ignimbrite, which comprises blocky outcrops of ignimbrite containing pumice rock fragments, glass shards and plagioclase phenocrysts ([Tesfaye Demsie et al., 2010](#)).

3.2.5 Middle basalt flows (TV2)

This unit is exposed in various localities lying above the Ashangie basalt with distinct unconformity. They are thin relative to the lower lava flows. The basal part of this unit is pyroclastic flow unit alternating with lava flow unit. The basal scoria flow changes to volcanic breccia often containing silica nodules (opal) and exposed in the deeply cut valleys of Beshilo rivers and their tributaries. This rock unit shows sharp topographic changes forming distinct cliff, from the underlying lower basalt. The basalts are variable in composition from aphanitic basalts to pyroxene plagioclase phyric basalts, vesicular basalts, plagioclase phyric basalts, olivine-plagioclase phyric basalts, olivine basalts and normal fine grained basalts.

The layered basalts forming cliffs are mostly deeply weathered on top of each layer giving

different weathering colors. Slope deposits cover the exposure of most basalt. When exposed the top of the basalt is marked by glassy trachytes or trachytic obsidians and/ or dark glassy basalts.

3.2.6 Bedded tuff (TV₃)

The bedded tuffs are exposed to the north part of the study area around steep slopes forming and cliffs topography. This loosely compacted and friable partly loose deposit is a thin layer that is bedded on middle basalt flow. Sometimes the stratigraphy shows trachytic obsidian lava often grading to ignimbrite intercalate the tuffs (Workineh Haro et al., 2010).

These grades down to pitchstone tuff also reworked and mixed with different rock fragments of gravels, conglomerate, cobbles which are more hard and compact. These are at the base intercalate with lapilli tuffs and lithic tuffs. Still as one descends the slope, diatomite beds lie below. The diatomite is light grey very fine grained, & massive rock. Still below the diatomite comes ignimbrite. This grades to greenish tuff ends with pyroclastic flow/ volcanic breccia's containing rock fragments of various sizes ranging from coarse sand to cobbles and boulders, cemented by ash flows. At this locality the middle basalt is eroded and becomes thin and decomposed to soil.

3.2.7 Guna tuff (TV₆)

This rock unit is named from guna mount and exposed in North West of the area with small extent. The Guna tuff is a sub aerial fall deposit originated within the locus of the mount Guna. The wide steep slopes of the mount are composed of massive structure less tuff of near source facies. The tuff is vertically variable and has also lateral variation.

Pulses of basalt and trachyte flows have flowed down slope of the volcano. Near the foot slope of the volcano, boulder tuff containing big boulders of basalt occur. These resemble spheroidal weathering from far, but the boulders are rock fragments cemented by ash-falls. The tuff is loosely compacted, softer and light colored. Except the boulder tuff which contains basalt fragments, rock fragments of the tuff are mainly pumice and tuffs. The Guna tuff is youngest eruption in the area and the volcanism is ended with trachyte flows.

3.2.8 Guna trachyte (TV₇)

This trachyte is exposed on Guna mountain peaks overlaid on guna tuff with small amount. The

rock is weakly columnar porphyritic sanidine trachyte. It is relatively fresh and shows dark greenish color. The trachyte is source facies and is originated from the mountain itself. The mountain is the source of volcanic in the nearest area including the Guna tuff, trachyte and the widely developed trachytic plugs.

3.2.9 Trachyte plug (TV_g)

This rock unit is exposed on guna tuff/guna Mountain as Conical hills. They are related to deep seated source (root of volcanic) giving raise to the Guna volcanic and they represent last phase of trachyte volcanism. Trachyte plugs are usually massive devoid of soil and are often columnar.

The trachyte plug at places cut across the tuff and at places overlain by the tuff. The plugs are rocky and resistant to erosion and form high rising hills. They are composed of sanidine and quartz crystals, but are generally fine to medium grained, pink to light grey. Xenoliths of earlier rock fragments are rarely associated within the rock mass.

3.2.10 lacustrine sediments (Qal)

These units are exposed in the eastern low land plain and in the south part of the area, they are characterized by black cotton and reddish brown silty to sandy soil with few outcrops of diatomite exposed along western marginal basins and on the top of the western plateau and eastern low land plain of the Afar rift floor, respectively (GSE, 2010).

3.3 Geological structure of the study area

The major plateau of Ethiopia is not affected by tectonics / faults. But there seems to be broad uplift which caused major tensional fractures / faults. Being part of Northwestern Plateau of Ethiopia, the Bashilo River watershed has experienced repeated episodes of uplift since ~150 Ma (Hofmann et al., 1997; Wolfenden et al., 2004; and Bonini et al., 2005). Shield volcanic eruptions of flood basalts impacted the study area, extending from the western escarpments of the Afar Depression and northwestern escarpment of the Main Ethiopian Rift during the late Holocene. The lava flow deposition took place in a series of intermittent events of early Eocene to late Miocene age (Mohr and Zanettin, 1988; Hofmann et al., 1997; Seng`or, 2001; Kieffer et al., 2004; and Beyene and Abdelsalam, 2005). The basalts tend to weather deeply, forming clay materials, including expansive smectite clays and kaolinites. The basaltic units in the study area

are thoroughly jointed and weathered. The block kinematics operating within the landslides are usually influenced by these discontinuities, and they are sufficiently continuous to perturb an entire slide mass. Most Faults in this area show different attitude at different localities. The east parts of the area show a strike of NW-SE and NE-SW, whereas west parts of the area show a strike of approximately NW-SE.

CHAPTER FOUR

METHODOLOGY AND DATA ANALYSIS

4.1 Data types and sources

4.1.1 Satellite Image archives

Landsat imagery of 2019 (OLI) with Path 168 and row 052/053 and 12.5m ALOS PLASAR Digital Elevation Model will be acquired from one source of free satellite imagery web: <<https://earthexplorer.usgs.gov/>>. The images will be used to generate different thematic data layers such as Land use land cover map while the 12.5m DEM from <<https://vertex.daac.asf.alaska.edu/>> will use to generate aspect, slope and elevation maps show in (Table 4.1).

Table 4.1: List of data and data sources

Data	Description	Source
Landsat 8 OLI Images	Downloaded	https://earthexplorer.usgs.gov
Aster DEM (Digital Elevation Model DEM) Resolution 12.5m	Downloaded	https://vertex.daac.asf.alaska.edu
Lithology	Digitized from geological map of Dessie and Debretabor map sheet	Geological survey of Ethiopia
Slope aspect	Derived from DEM 12.5m	DEM 12.5m
Slope angle	Derived from DEM 12.5m	DEM 12.5m
Elevation (m)	DEM 12.5m	ALOS PLASAR Satellite
Edaphic factor/soil properties	Soil map in Vector format	Water and land resource information system (WALRIS) Ethiopia and ministry of agriculture.
Land use land cover	Derived from Landsat 8 OLI image and Google earth imagery.	Landsat 8 OLI image from USGS
Faults	Digitized from geological map of Dessie and Debretabor map sheet	Geological survey of Ethiopia
Drainage/river	Extracted	Ethio-GIS from Water and land resource information system(WALRIS) Ethiopia
Precipitation	CHIRPS data raster format	https://vertex.daac.asf.alaska.edu

Software used in the process is ArcGIS, ERDAS IMAGINE, ENVI, IDRISI Selva and other open source software that are necessary for this research. The method for this research would be remote sensing and GIS based study to identify landslide susceptible area by applying GIS and remote sensing techniques.

4.1.2 Methods and data processing

The main activity to build spatial modeling of Landslide susceptibility is preparation of different thematic data layers. The entire data layers created were retrieved for the model input. These layers were Lithology, LULC, fault, lineament, Drainage, Slope aspect, slope degree, elevation, precipitation, soil depth and texture. (Fig 4.1) shows the general methodological flow chart.

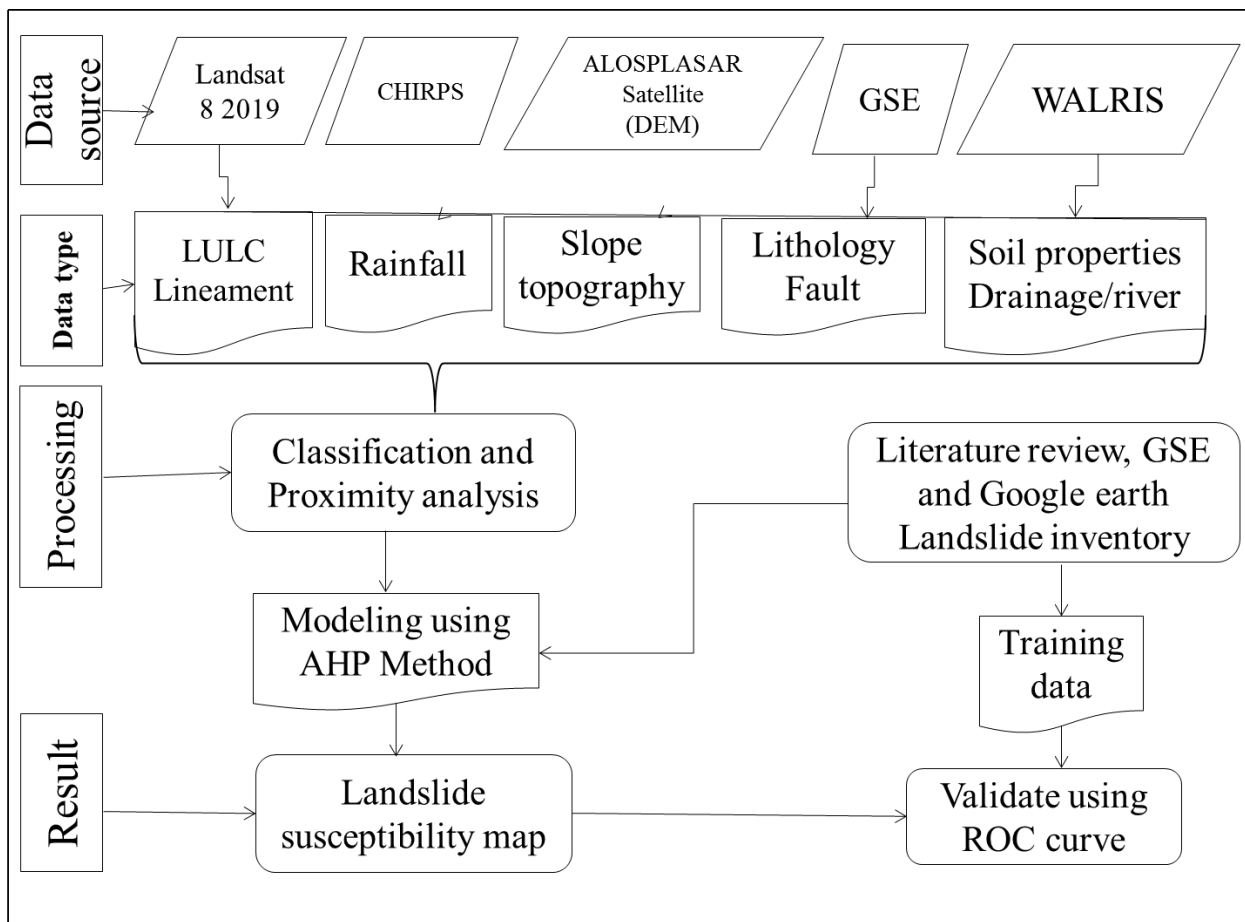


Fig 4. 1: Methodological flow chart

4.1.2.1 Processing of Landsat image

The digital image processing is largely concerned with four basic operations: image restoration, image enhancement, image classification, and image transformation (Lillesand et al., 2004). The image restoration is concerned with the correction and calibration of images in order to achieve a realistic representation of the earth surface as possible. Image enhancement is predominantly concerned with the modification of images to adjust their appearance to the visual system. To get a better-enhanced image, different image enhancement techniques are available with different digital image processing software (Lillesand et al., 2004). One of the image enhancement works done in Landsat image in this work was the spectral enhancement technique called principal component analysis.

4.1.2.2 Principal component analysis

Principal Component Analysis (PCA) is a statistical technique which aims to find the orthogonal basis that maximizes the variance of the projection for a given dimensionality of basis.

This process goes to maximize (statistically) the amount of information (or variance) from the original data into the least number of new components. These new components are linear combinations of the original image bands and are derived in decreasing order of importance so that, for example, the first principal component accounts for as much as possible of the variation in the original data (Lillesand et al., 2004).

PCA takes a dataset with a lot of dimension and flattens it to 2 or 3 dimensions so we can look at it. It tries to find a meaningful way to flatten/ reduce the data by focusing on the things that are different between bands. (Jensen, 1996) claims that, generally, the first component of the PCA consists of both near and middle-infrared information (e.g. Band 4, 5 and 7). Similarly Nama, (2004) argues that the geological information such as faults, lineaments and other subtle features can be easily identified using PCA of the Landsat image, which removes redundant information from visible and NIR multi-spectral data. So, We need to Transforms the original satellite bands into new 'bands' that express the greatest amount of variance (information) from the feature space of the original bands. In this study, the principal components (PCAs) were performed using Landsat 8 image. The first principal component analyses contain most of the pertinent information inherent to the scene so; lineaments were easily extracted using PCA1 band (fig 4.2).

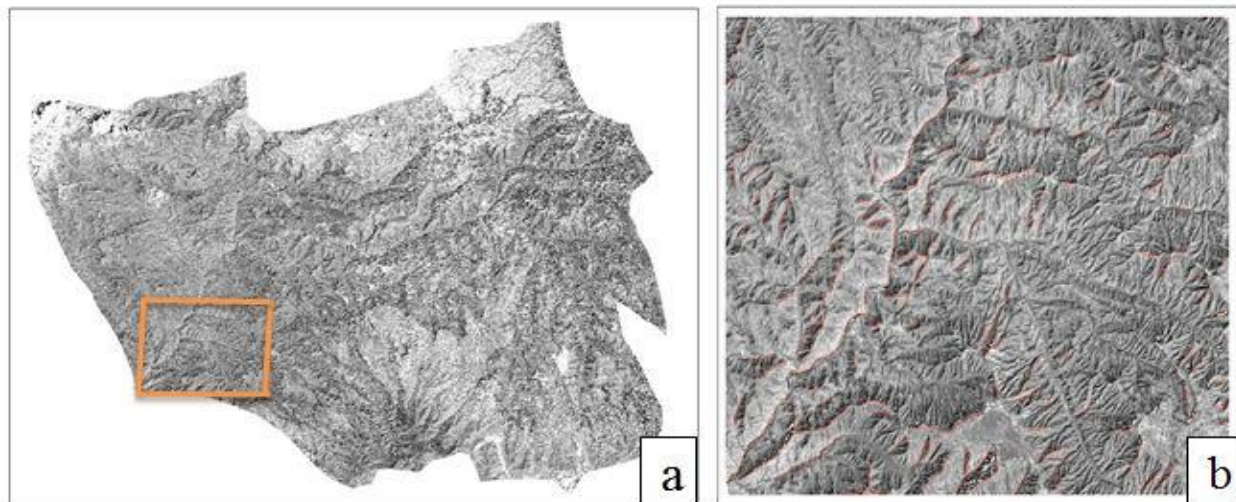


Fig 4.2: PC Analysis result; a) PCA1 image, b) zooming view from PCA1

4.1.2.3 Feature extraction

Feature extraction techniques are broadly being used in satellite imagery and getting impressive attention for remote sensing applications. The state of the art feature extraction methods are appropriate according to the categories and structures of the objects to be detected (Karim et al., 2017) means that algorithm used for extract different objects is different.

4.1.2.3.1 Lineament extraction

Lineaments and faults (structures) are defined as mappable linear surface features, which differ distinctly from the patterns of adjacent features and probably reflect subsurface phenomena (O'Leary et al., 1976). The subsurface effect is valid if the origin of the linear features is controlled by geological structures such as faults and fractures. Not faults, but lineaments could result from morphological effects (stream channels or drainage divides) or human effects (roads, field boundaries) can also exist in the region (Koike et al., 1995).

Lineaments were generated using an automatic feature extraction technique. Automated extraction was performed by using the Algorithm of Automated Lineament Extraction in Geomatica 2018 software. In Geomatica LINE module extracts linear features from an image and records the polylines in vector segments. The image used to extract the features was PCA1 band from Landsat 8 image. This method takes an advantage to perform operations in a short time and to extract lineaments which are not recognized by the human eyes over the manual extraction technique (Koçul, 2004). Fig 4.3, Shows the final map of lineaments generated from

the image.

Geological structures such as faults, folds, joints, bedding and shear zones have a greater influence on the stability of the slopes. The proximity of a slope to these features greatly influences its stability, increasing the susceptibility of landslides occurrence.

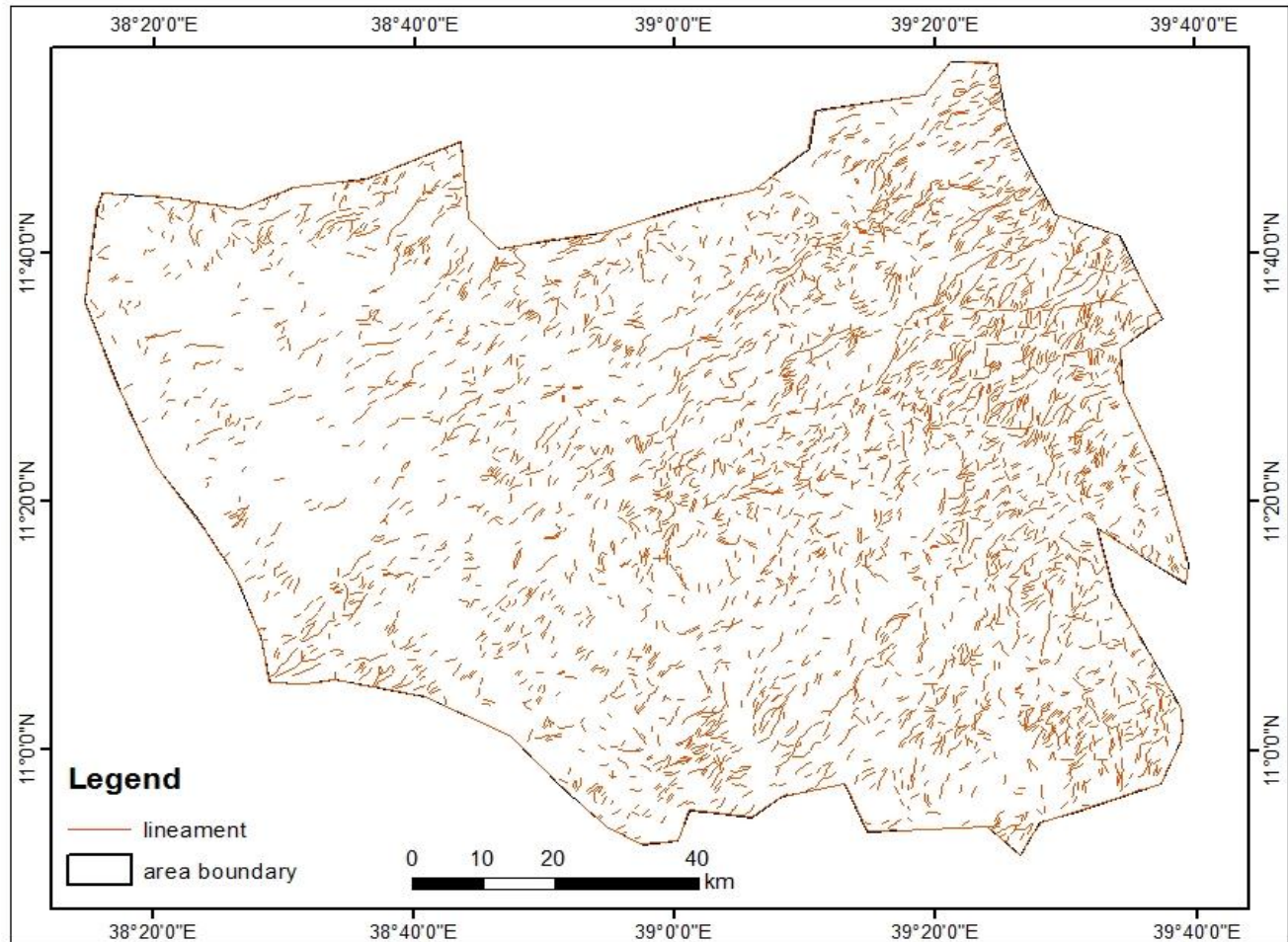


Fig 4.3: Extracted Lineament map

4.1.2.4 Topographic parameter feature extraction

The role of digital elevation model (DEM) has become very important with the invention of Geographical Information Systems (GIS), and effective tools in analytical Geo-hazard studies (Abolghasem et al., 2016). Spatial data used in GIS analysis come from a wide variety of sources. One of the data sources for GIS is Digital Elevation. To extract topographic parameters, digital elevation models (DEM) are often used to represent the bare-earth terrain, void of

vegetation and manmade features <https://learn.arcgis.com/>. Digital elevation models are essential for a number of topographic data analyses including slope and aspect computation etc. In this study, various derivations of digital elevation data were used to identify and model landslide hazard prone areas. The most important topographic parameters that were extracted from DEM include slope, aspect and elevation itself.

4.1.2.5 Manual digitizing

The geological map from geological survey of Ethiopia with a scale of 1:250,000 were used to generate lithological units which found in the study area. The (jpg) map first geo-referenced, then after using the user-defined database the rock units become converted to shapefile. Their topology was also build by using the editor tool in ArcGIS. And also landslide area were digitized based on literature review, Google earth imagery and landslide point I gained from Geological survey of Ethiopia to get the reference map for validation.

4.2 Approach/Method of landslide mapping

Appropriately selecting and implementing landslide mapping approaches require properly and explicitly defining the type of land slide issue the study will cover. Researches in the literature indicate that land slide related studies focused on land slide hazard mapping. However, landslide hazard only shows the probability of occurrence of land slide in a particular area. It doesn't show the risk or susceptibility of the society to that particular damage, which implies, the exposure of this likely affected society or any infrastructure is not included in a land slide hazard map. As far as concerned to the management and mitigation issues of land slide damages, the exposure or the susceptibility of society or any development structures need to be also included in the mapping endeavor. Landslide susceptibility assessment can be done in two ways;

Measuring or based on field assessment is i) Direct approach; modeling or prediction is ii) Indirect approach. The present study is limited on susceptibility map and wants to produce this map through indirect approach using multiple parameters.

4.2.1 Direct approaches

Before adopting GIS and RS technologies, landslide mapping is done by direct method, means that researcher went to the field and collecting data on their characteristics for all parameter in related to occurrence of landslides.

4.2.2 Indirect approaches; proxy indicators based landslide occurrence mapping

As indicated above, directly measuring the probability of landslide occurrence and the exposure and risk or the level of damage directly measuring or collecting primary data is very time consuming and resource demanding. Since the inception of GIS and RS technologies, it becomes quite common in mapping landslide hazard or probability of landslide occurrence in a given area. This is done by considering different parameters and sees the proxy of these factors for the occurrence of landslide in this particular area. This is an indirect method for landslide mapping after these technologies is adopted.

4.3 Factors determining the occurrence of Landslides and Vulnerability

Literature says that land sliding is an intricate process determined by several factors. In general the factors are categorized as inherent and triggering. Inherent factors are factors that govern the initiation of landslide whereas triggering factors are those factors that fuel the process of land sliding processes. Considering the nature of factors involved in the process, land sliding can be also categorized as geological/natural and anthropogenic driven. The former represents a natural process occurred due to natural conditions without any anthropogenic action involved in the process. The latter reflects a land slide largely initiated and aggravated by human activities. The inherent factors that determine the occurrence of land sliding are those environmental factors naturally exist in a particular area such as lithology, soil, slope, drainage, rainfall etc. Whereas triggering factors that determine the occurrence as well as the level of landslide are either climatic which is rainfall or anthropogenic/human activity which is land use land cover and land development activities (settlement, road construction, human and livestock movement etc...).

4.3.1 Landslide related terminology

We can describe different terminology related to land sliding as follows.

Landslide: The slope down movement of a mass of rock, debris, or earth. The inducing factors for landslide are earthquake shaking and other factors. These landslides are called submarine landslides. Submarine landslides sometimes cause tsunamis that disturb coastal areas.

Landslide inventory maps: This type of map shows the locations or outlines of landslides. A landslide inventory is a data set that may present a single event, a regional event, or multiple

events. Small-scale maps may show only landslide locations whereas large-scale maps distinguish landslide sources from which deposits, classify different kinds of landslides, and show other geological or geomorphological data.

Landslide susceptibility map - these maps go beyond an inventory map and depict areas that have the potential for land sliding. These areas are determined by correlating some of the principal factors that contribute to land sliding. These types of maps usually divide the study area into zones according to different degree or level of proneness (susceptibility) to slope movement.

Landslide hazard map: this map ideally indicates the probability of landslides occurring in a given area at a given time or with a given frequency. It is represented by susceptibility, which is the likelihood of a potentially damaging landslide occurring within a given area. Landslide hazard maps usually divide the study area into zones according to different levels of hazard to slope movement. They can also be called landslide hazard zonation maps (Varnes et al., 1984).

Vulnerability: the level of population, property, economic activity, including public services, etc., at risk in a given area resulting from the occurrence of a landslide of a given type.

Landslide risk is composed of many factors, such as those factors that enable the landslide process itself and those related to damages to people and man-made structures. Risk (specific): the expected degree of loss due to a particular landslide phenomenon potentially.

<https://www.usgs.gov/natural-hazards/landslide-hazards/science/landslides-glossary>

In this study landslide susceptibility mapping is conducted by adopting multi-criteria evaluation method which allows flexibility and tradeoffs amongst all parameters used and using existing metadata of the area.

4.4 Categories of factors related to landslide occurrence

4.4.2 Inherent factors

Intrinsically, landslide occurs when a mass of soil, rock or both moves from one place to the other. That implies this process can happen with soil/rock for that reason the process is lay on by top layer or geology/earth materials. According to [Raghuvanshi et al., 2014](#); [Van Westen et al.,](#)

2008; Anbalagan, 1992 environmental factors are a collection of factors that are expected to have an effect on the occurrence of landslide, and can be taken as causal factors in the prediction of future landslides. The variation of topographic feature (morphological) and geological material of the earth's surface is accountable for the occurrence of landslide and distribution due to different triggering and Inherent process which can affect the slope stability(R. Anbalagan, 1992). Many factors contribute to the instability of slopes, but the main controlling factors are; the nature of the underlying bedrock and soil, the configuration and geometry of the slope (Musinguzi M. and Asimwe I., 2014). Related to this factor different landslide mapping can produce. But this research is limited to landslide susceptibility mapping and potential risk mapping. Generally in this study we can classify inherent factors as Geologic, edaphic, Geomorphic/topographic, climatic and anthropogenic/human activity to produce landslide vulnerability map.

4.4.1.1 Geologic Factors

According to Varnes, 1984 particular attention should be given to the geological mapping to the deposits near and at the surface. Because Most of the slope failures are shallow this involves only the upper few meters of the surficial deposits. Different rock types (or lithology) have varied composition and structure, which contribute to the strength of the material. Therefore, the stronger rocks give more resistance to the driving forces as compared to the weaker rocks, and hence are less prone to landslides and vice versa (Kanungo et al., 2009).

The geological factors which induce the slope instability are based on:

i) Lithology

Lithology is often taken as the main controlling factors in Geo-hazard susceptibility assessment (Ismail et al., 2017). It is an immediate formation beneath the surface. Thus has great contribution to determine whether which are more prone or not to environmental hazards.

Studies by (Lulseged Ayalew et al., 2005; Dai et al., 2001; Yalcin, 2008) characterize the effect of geology on Geo-hazard assessment. It is one of the most important parameters in landslide studies because different lithological units have different vulnerability (Asmelash et al., 2019 as cited in Dai et al., 2001; Yalcin, 2007). Weak, incompetent rock is more likely to fail than strong, competent rock; general steeper slopes have a greater chance of land sliding, while

rainfall is considered as an important factor in slope stability, almost as important as gravity (Skilodimou et al., 2018).

In the present study, Lithological units were generated by digitizing the geological map sheets of the study area obtained from Ethiopian geological survey (GSE). These rock type includes; Ashangie basalts, Wegel Tena rhyolitic ignimbrite, Dessie basalt formation, Tarmaber Megezez Formation, Middle basalt flows, Bedded tuff, Guna tuff, Guna trachyte, Trachyte plug and lacustrine sediments(Fig 4.4).

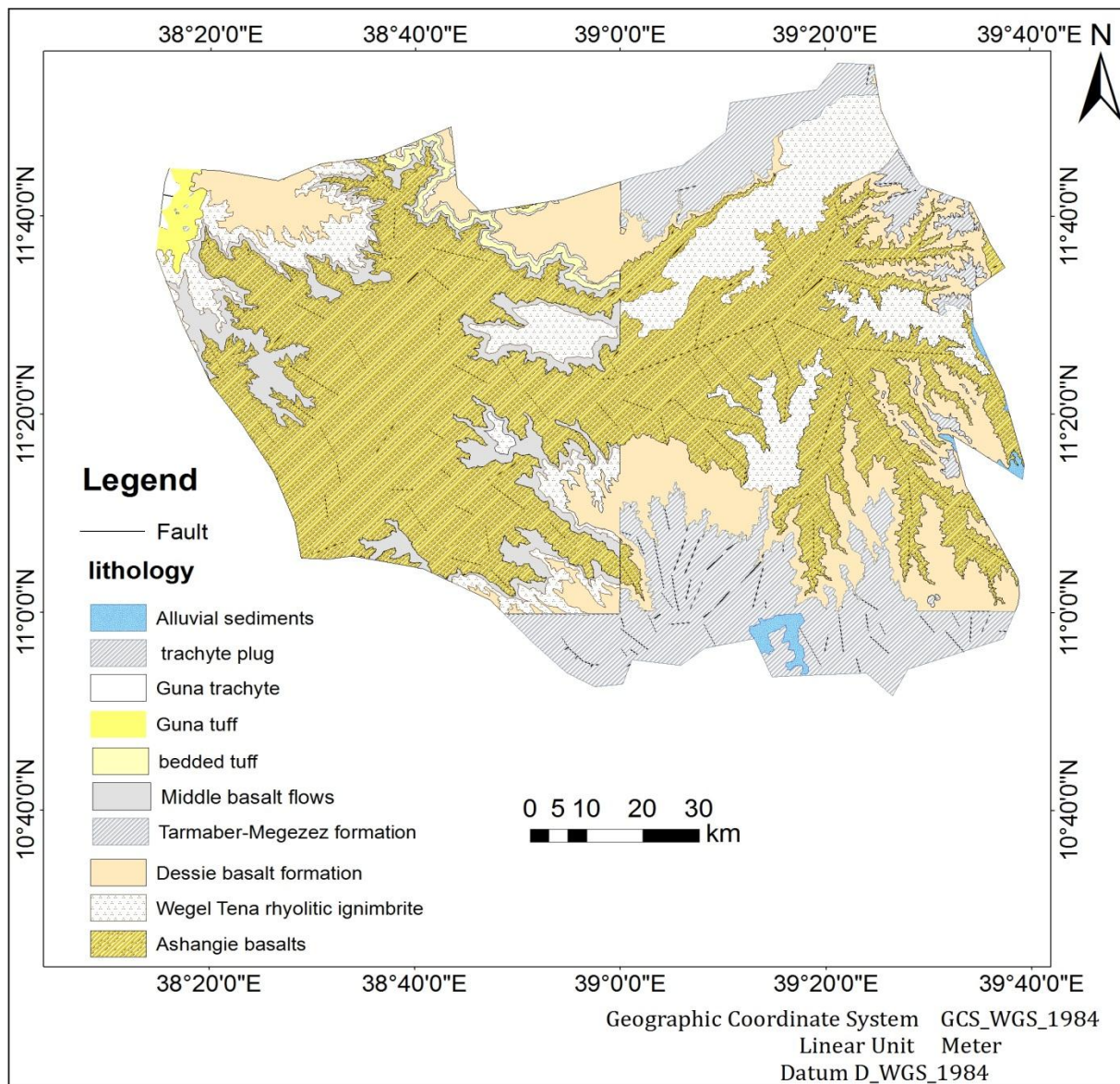


Fig 4.4: Geological map of the area (source: GSE)

ii) Fault

Faults have been considered as a critical factor in activating landslide in tectonically active areas (Tien et al., 2011). The main Ethiopian rift system and its escarpments are characterized by normal faults. Faults are very important factors for landslide initiations due to the fact that they are not only weak zones, but also mostly characterized with: (i) deeper weathering, resulting in greater thickness of soil masses; (ii) higher potential for concentrated groundwater flow, which can act as lubricant and also can produce water pressures causing landslides. Keeping this in view, fault density maps are produced to evaluate its contribution to the landslide.

Fault of the study area is digitized from geological map of the study area from (source: GSE) and calculate fault density map in ArcGIS environment (Fig 4.5).

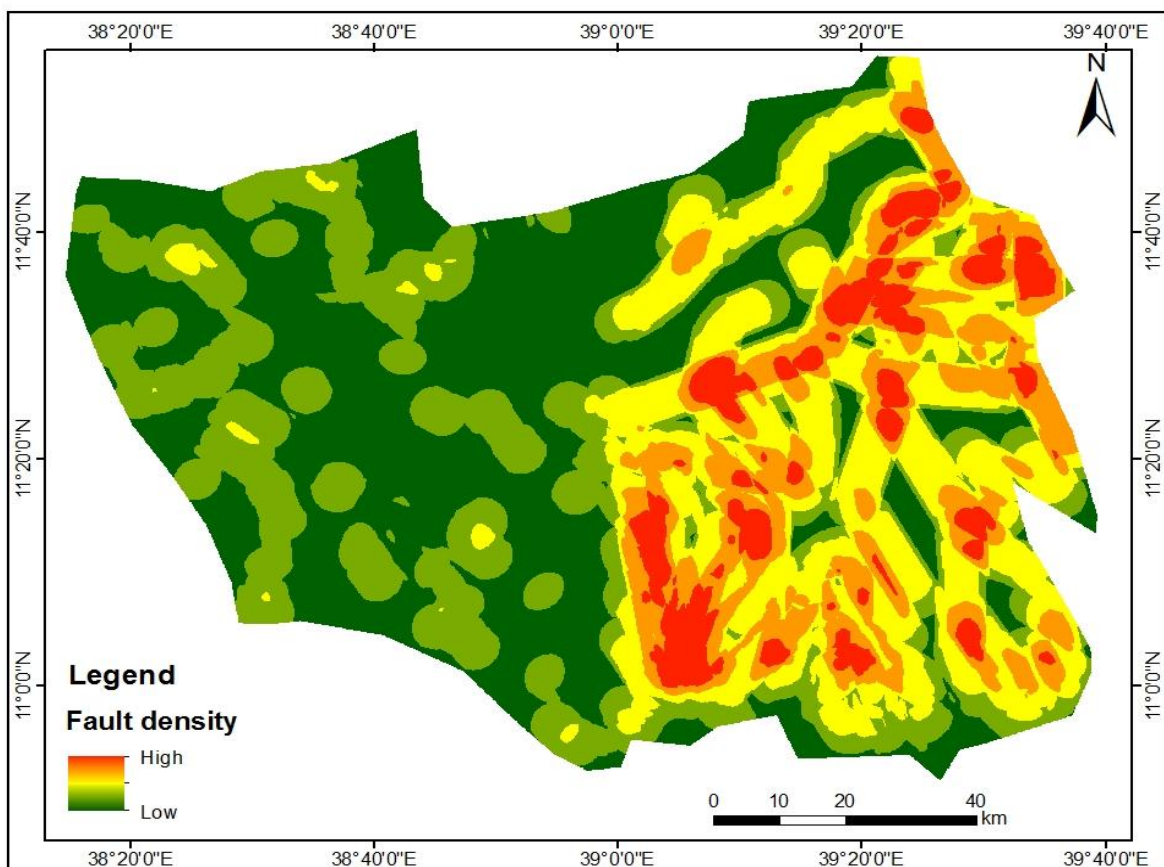


Fig 4.5: Fault map of the area

iii) Lineament

Geological structural features, such as the discontinuities that may be detected on satellite imagery as lineaments, in many cases control landslide occurrences. Lineament may represent the plane of weakness where the strength of the slope material has been reduced, eventually resulting in slope failure. The area with the high density level was suspected to be highly fractured due to the concentration of lineaments; this lead to the area is more vulnerable to landslide (Yusof N. et al., 2011).

Lineaments were generated using an automatic feature extraction technique (fig 4.3) and then calculate their density in ArcGIS environment (Fig 4.6).

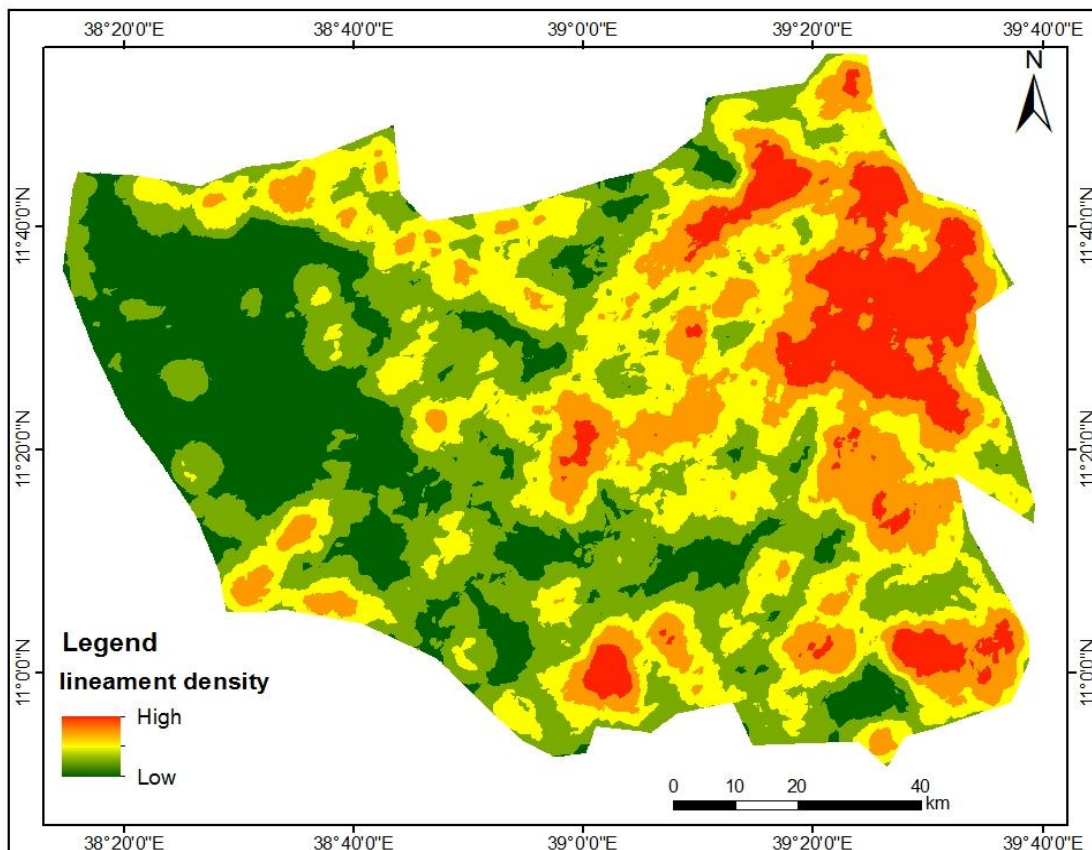


Fig 4.6: Lineament map of the study area

4.4.1.2 Edaphic factor

Soil properties influence on landslide occurrences. It could be happened when the soil moisture content exceeds the liquid limit in the field. This event generates the dangerous and

prospectively devastating results as a soil become visible to be stable and then when distressed can unexpectedly break away. Increase in soil moisture content decreases soil strength by diminishing capillary cohesion (Handy and Spangler, 2007). Another attributed effect is the presence of soils that contain a high proportion of a type of clay mineral called smectite or montmorillonite. Such clay minerals expand when they become wet as water enters the crystal structure and increases the volume of the mineral. When such clays dry out, the loss of water causes the volume to decrease and the clays to shrink or compact (Malik, 1996).

Important soil characteristics considered in this study are; soil depth and soil texture.

i) Soil Depth

Depth of the soil forms one of the important factors for assessing the stability of the soil and landslide susceptibility of the land. With the increase in soil depth, the tendency of the soil to absorb moisture is increased, resulting in reduced runoff rate. Hence, shallow soil is considered to be more unstable and prone to landslide than the deep soil. Soil depth of the study area from (WALRIS) shows (Fig 4.7).

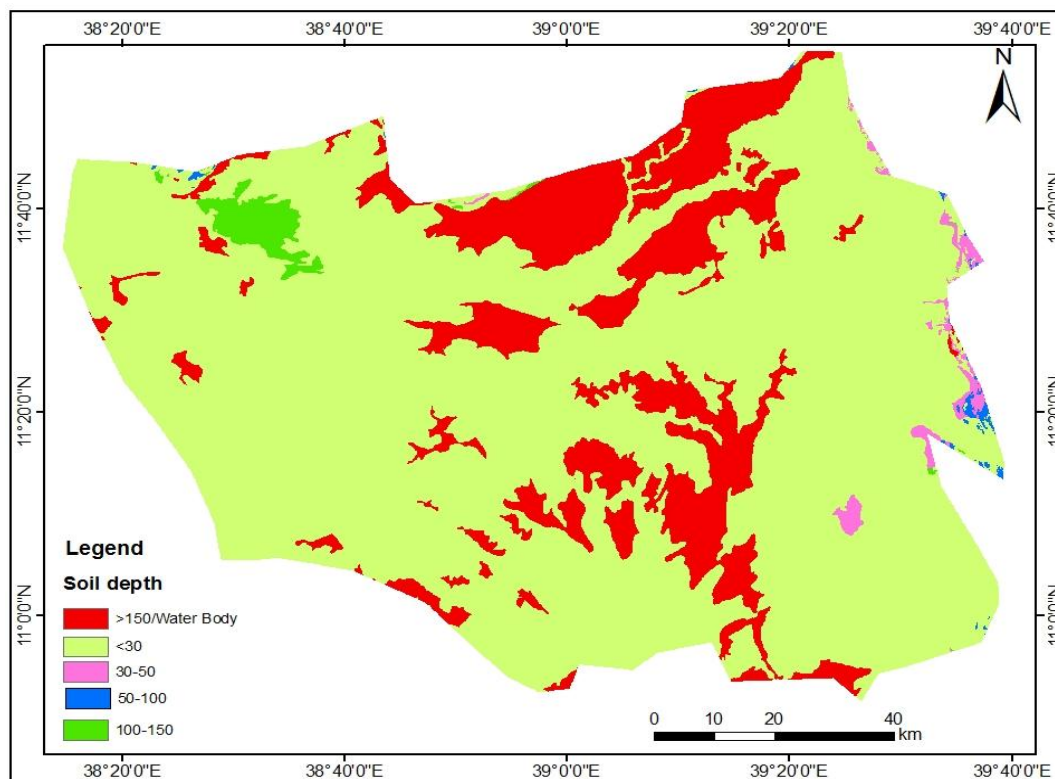


Fig 4. 7 Soil depth of the area

ii) Soil texture

The texture of soil represents the relative proportion of sand, silt, and clay content. Soils with high percentage of clay form very stable aggregates resistant to detachment. On the other hand, light soils like sandy or coarse loams are easy to detach as they have low organic matter content, resulting in their inability to form very stable aggregates (Das and Agarwal, 2002). Hence, soil with more sand, high slope, and intensive rainfall, which constitute most dominant factors of landslide, cause severe damage to the land (Patanakanog, 2001).

For the study area soil texture is only two types and the source is (WALRIS).

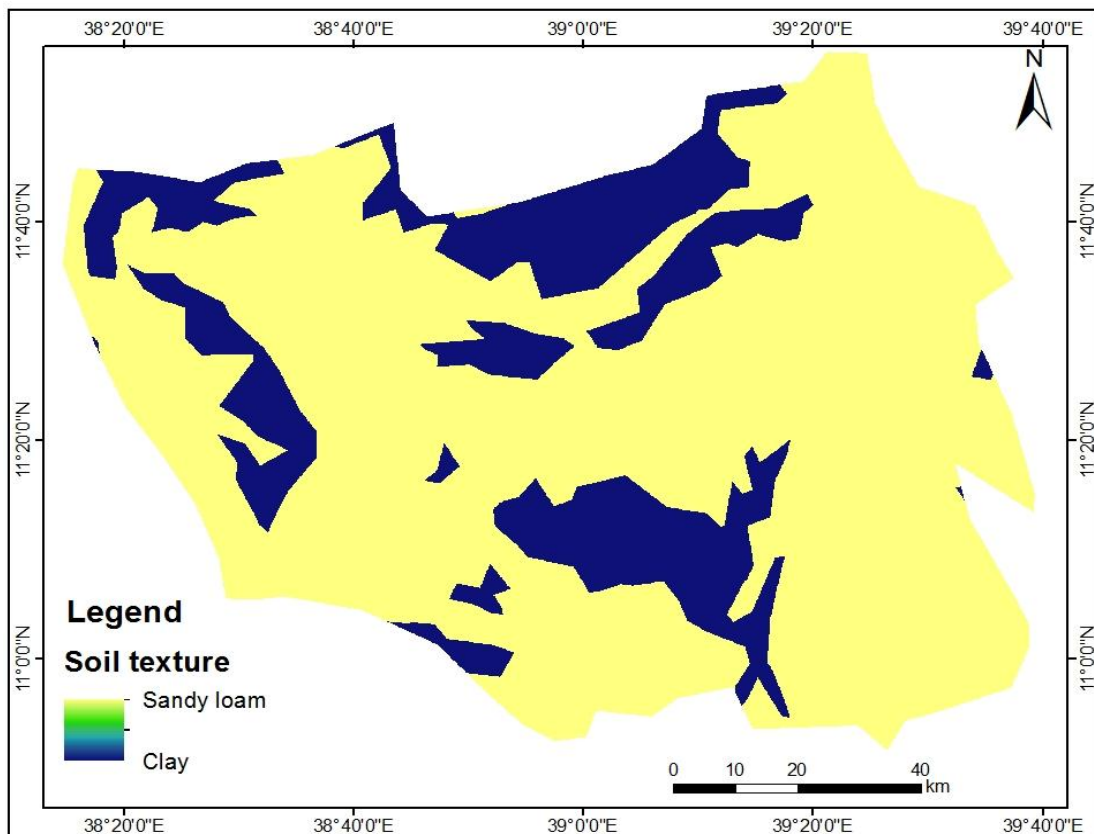


Fig 4.8: Soil map of the area

Table 4. 2: Soil type of the study area

	Soil type	Description
1	Eutric leptosol	Soils with a very shallow profile depth and expansive clay mineral.

2	Lithic leptosol	Soils with a very shallow profile depth and contain large amount of gravels. They typically remain under natural vegetation, being especially susceptible erosion, desiccation water logging, depending on climate and topography.
3	Eutric vertisol	Soils in which high content of expansive clay mineral, many of them known as montmorillonite that form deep crack in drier seasons.
4	Eutric cambisol	Sandy loam or finer and weekly to moderately developed soil.

4.4.1.3 Geomorphic/Topographic factors

It is known that the common force tending to generate movements on slopes is gravity. Review of the previous studies show that most of the reported debris/earth slides/flows and rockslides have taken place in areas with slope angles between 15 to 45 degrees. As indicated by different researchers (example: Tenalem Ayenew and Barberi, 2004; Kifle Woldearegay, 2005), the low probability of occurrence of landslides in low slope gradient is likely to be due to the corresponding increase in the factor of safety. On the other hand, absence of major debris/earth slides and debris/earth flows on terrains with slope gradients greater than about 50 degrees is related to the insignificant thickness or even absence of unconsolidated deposits on such terrains because most of the steep slopes are dominated by slightly weathered rocks. The moderately steep terrains are often covered by unconsolidated deposits, which are more vulnerable to rainfall triggered slope failures (Lohnes and Handy, 1968; Swanston, 1978).

Slope gradient is important with regard to landslide initiation. In most studies of landslides, the slope gradient is taken into account as a principal causative or trigger factor. Slope gradients are sometimes considered as an index of slope stability, and because of the availability of a digital elevation model (DEM) can be numerically evaluated and depicted spatially (O'Neill and Mark, 1987; Gao, 1993). Elevation is usually associated with landslides by virtue of other factors such as slope gradient, lithology, weathering, precipitation, ground motion, soil thickness and land use. For example; higher mountainous areas often experience larger volumes of precipitation, both rain and snow falls (Gao, 1993).

i) Slope degree

Slope gradient is very regularly used in landslide susceptibility studies since land sliding is directly related to the slope angle (Dai et al., 2001; Lee, 2005; Woldearegay, 2005; Yalcin, 2007; Long et

al., 2011). The slope angle directly affects landslide, thus it is used in preparing landslide susceptibility maps (Cevik et al., 2003; Clerici et al., 2002; Ercanoglu et al., 2004; Lee, 2005). Another study by Erden and Karaman, (2012) this parameter has been considered as one of the most important factors in landslide susceptibility assessment. Even today it is the leading parameter when landslide hazard assessment is considered.

Slope degree of the area is generated from DEM in ArcGIS software (Fig 4.9).

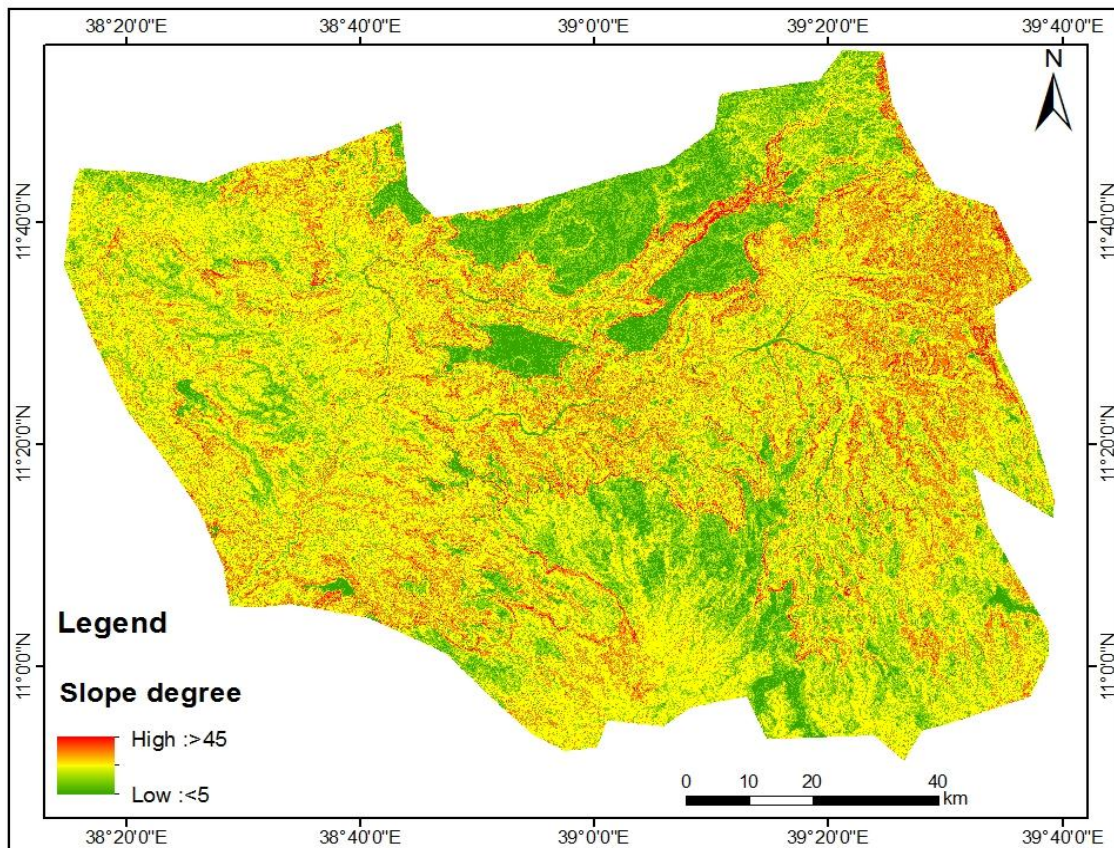


Fig 4.9: Slope degree map of the area

ii) Elevation

Elevation is usually associated with landslides by virtue of other factors such as slope gradient, lithology, weathering, precipitation, ground motion, soil thickness and land use. For example; higher mountainous areas often experience larger volumes of precipitation, both rain and snow falls (Gao, 1993). Digital elevation model (DEM) downloaded from ALOS PLASAR website for the area shows (Fig 4.10).

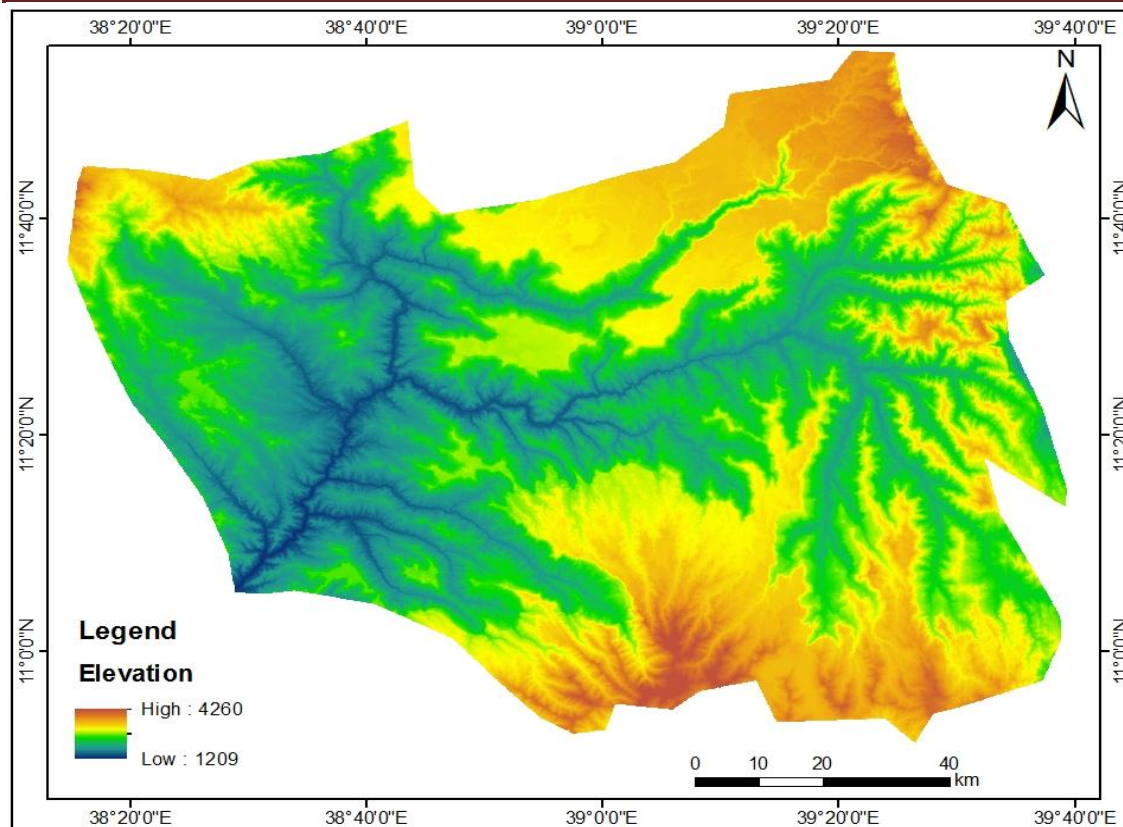


Fig 4.10 Elevation map of the study area

iii) Aspect

The aspect of a slope is defined as the horizontal direction to which a slope faces. In other words, it shows the direction of maximum slope of a surface. It can influence landslide initiation. The amount and distribution of precipitation received on a particular slope differs with respect to the various orientations it could have. Aspect related parameters such as exposure to sunlight, drying winds, rainfall (degree of saturation), and discontinuities may control the occurrence of landslides (Dai & Lee, 2002). This means that slopes similar in inclination, materials and geology may behave differently depending on their aspect which may control moisture, seepage and pore-water pressures and so on. However, the direct correlation between aspect and landslides is not yet clear (Van Westen, et al, 2006).

According to Xu et al., 2012 Aspect is defined as the direction of maximum slope of the terrain surface with reference to north. The aspect of a slope can influence landslide initiation, because it affects moisture retention and vegetation cover, and in turn soil strength and susceptibility to

landslides (Raghuvanshi *et al.*, 2015). The aspect map of the study area was generated from the DEM at 12.5m resolution and the aspect was classified according to the angles; Flat (-1–0°), North (0–22.5°), North-east (22.5–67.5°), East (67.5–112.5°), South-east (112.5–157.5°), South (157.5–202.5°), South-west (202.5–247.5°), West (247.5–292.5°), North-west (292.5–337.5°) and North (337.5–360°).

iv) Drainage

Streams may negatively affect slope stability by eroding the slopes or by saturating the lower part of the material (Dai *et al.*, 2001). Most of the recorded landslides have occurred close to stream/rivers cut by gully erosion. Density of stream channel is one of the controlling factors for the stability of a slope (Yalcin *et al.*, 2011). Most drainage system of the area is created following the geological structures. The tectonic morphology of the study area is greatly modified by stream incisions, which finally could influence slope stability through over steepening the lower sections of the slopes and removal of materials that provided support at the toe. For this reason the drainage density is considered as one causative factor in the landslide susceptibility study.

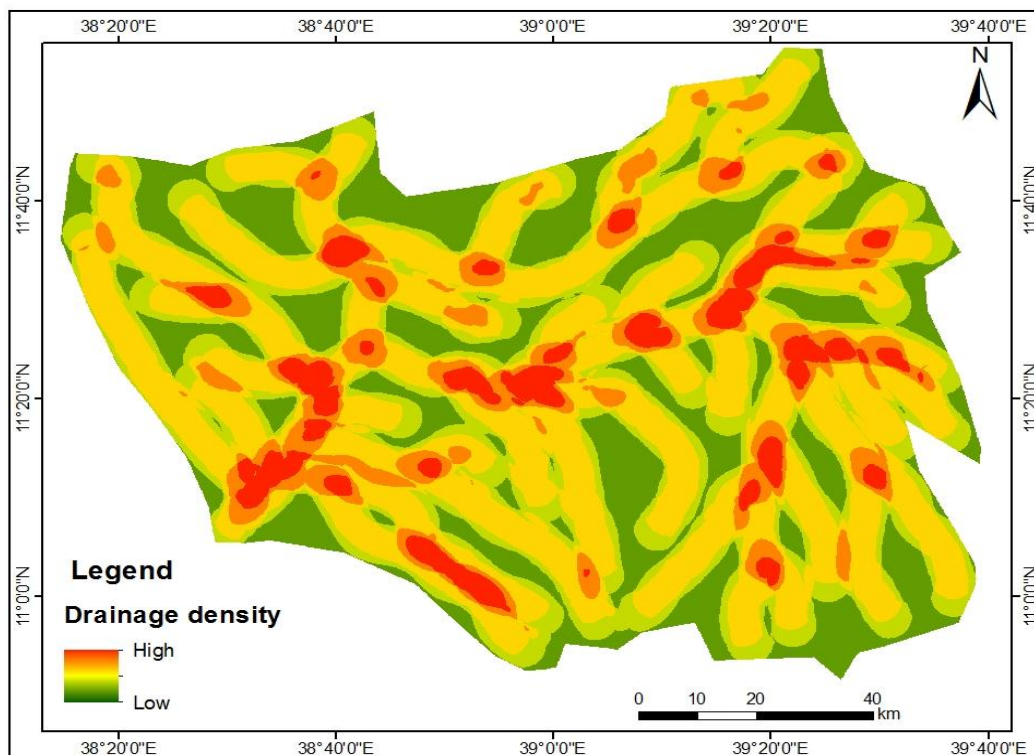


Fig 4.11: Drainage density map of the area

4.4.2 Triggering factors

4.4.2.1 Climatic factor

Triggering mechanisms for the most landslides are related to activities by natural or human activities such as undercutting of slope (stream or river erosion) by human activities.

Primarily triggers are related to the intense rainfall or snowmelt. Slopes are saturated by water, groundwater level rising and filling reservoirs, lakes, streams which could cause erosion at a base of slopes. Sometimes bulk materials located upslope are driven by gravity or triggered by water. The major contributed triggering factors for landslide considered in the present study is discussed as follows;

i) Rainfall

The most common trigger of landslide is sufficient water input during precipitation events. Rainfall is considered the most frequent landslide-triggering factor in many regions of the world (Dai & Lee, 2001). The frequency and magnitude of rainfall events, together with other factors such as lithology, morphology and land cover, influences the type of landslide (Van Ash et al., 1999). Generally, deep-seated landslides are often triggered by moderate intensity rainfall distributed over long periods whereas superficial landslides such as soil slips and debris flows are triggered by short duration, intense precipitation (Dai & Lee, 2001). During intense rainfall events the variations in pore water pressures distributed within the soil are highly variable depending on the hydraulic conductivity, topography, degree of weathering, and fracturing of the soil. The response of the material involved is largely dependent on its permeability. In high-permeability soils the build-up and dissipation of positive pore pressures during intense precipitation events could be very rapid (Johnson and Sitar, 1990). In these cases slope failures are caused by high intensity rainfall and antecedent rainfall has little influence on landslide occurrence (Dai & Lee, 2001). On the contrary, in low-permeability soils slope failures are caused by long duration-moderate intensity rainfall events.

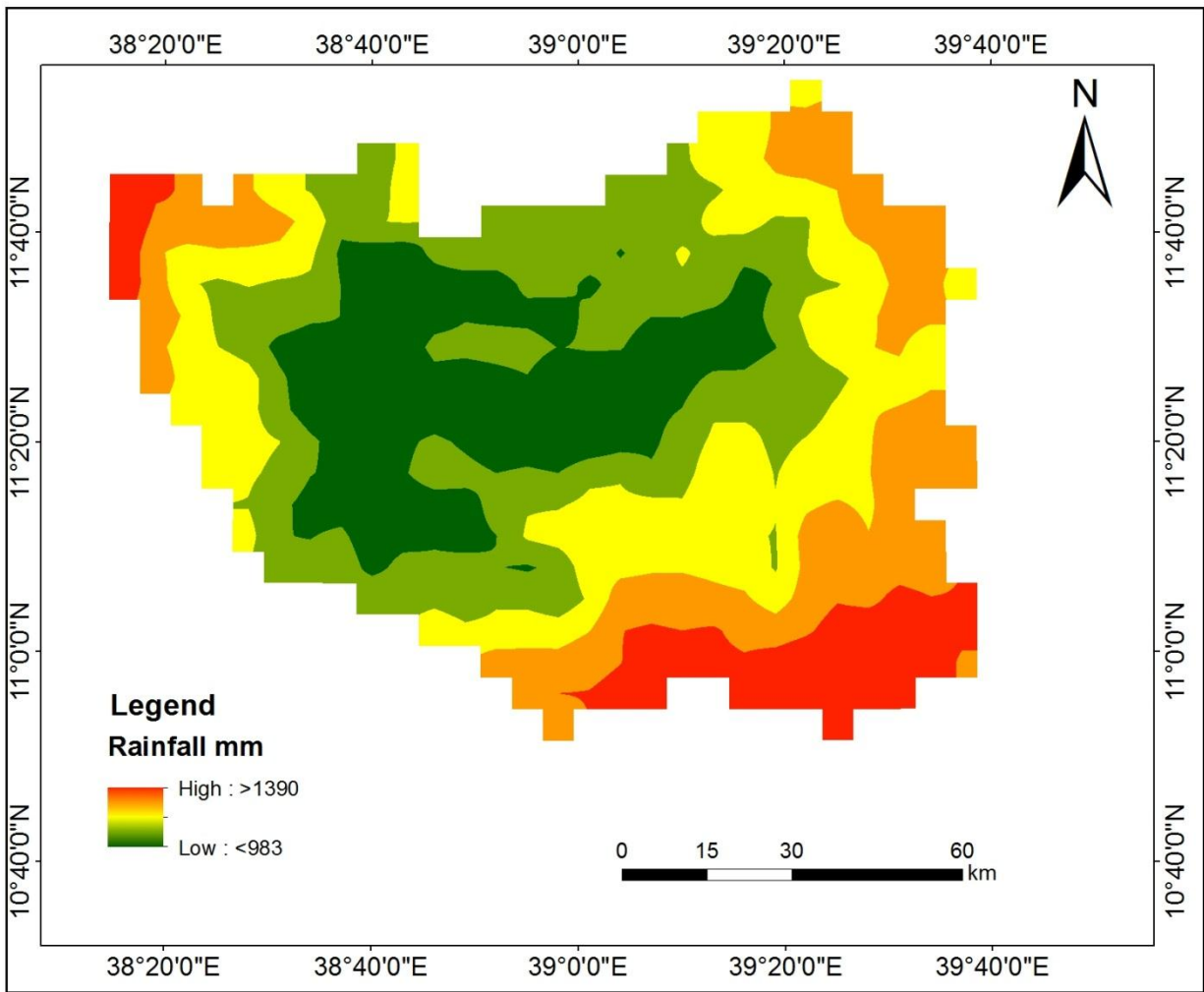


Fig 4.12: Precipitation map of the area

4.4.2.2 Anthropogenic Human/activities

Human activities increase the frequency of landslides and rockslides due to undercutting for roads and railroad excavations (Scharpe, 1938). For example, landslides are easily triggered by removal of lateral support that causes slope failure especially in the development of roads cuts, construction of houses and foot paths. Weathering, land use and cover type are important anthropogenic activities (Singh, 2010).

i) Land use Land cover (Vegetation)

Land use and land cover is one of the main factors in controlling landslide activity (Fikre Girma et al., 2015 and Raghuvanshi et al., 2015). In barren and sparsely vegetated land, the landslide

activity become high because of relatively high weathering, erosion and other activities (Raghuvanshi et al., 2014a; 2014b; Wang and Niu, 2009; Anbalagan, 1992).

The present study area land use land cover map was prepared from Landsat data through supervised classification using ERDAS Imagine. Further, the training pixels were controlled with the help of Google Earth image. Later, land use and land cover classes were prepared in Arc-map. The present study area was classified in to 9 land use land cover class, namely: urban/built up area, cultivated land, sparsely vegetated land, bare land, densely vegetated land, forest and bush/shrubs land (fig 4.13). All factors including land use land cover are summarized in (Table 4.3). Land use land cover has an effect on the strength of slope materials against sliding and control of water content of slope. For instance (Nielsen, et al., 1979), plant roots reinforce the slope and normally are considered as reinforcements. In studies performed by (Komac, 2006), this parameter has been considered as one of the most important factors in preparing landslide susceptibility maps.

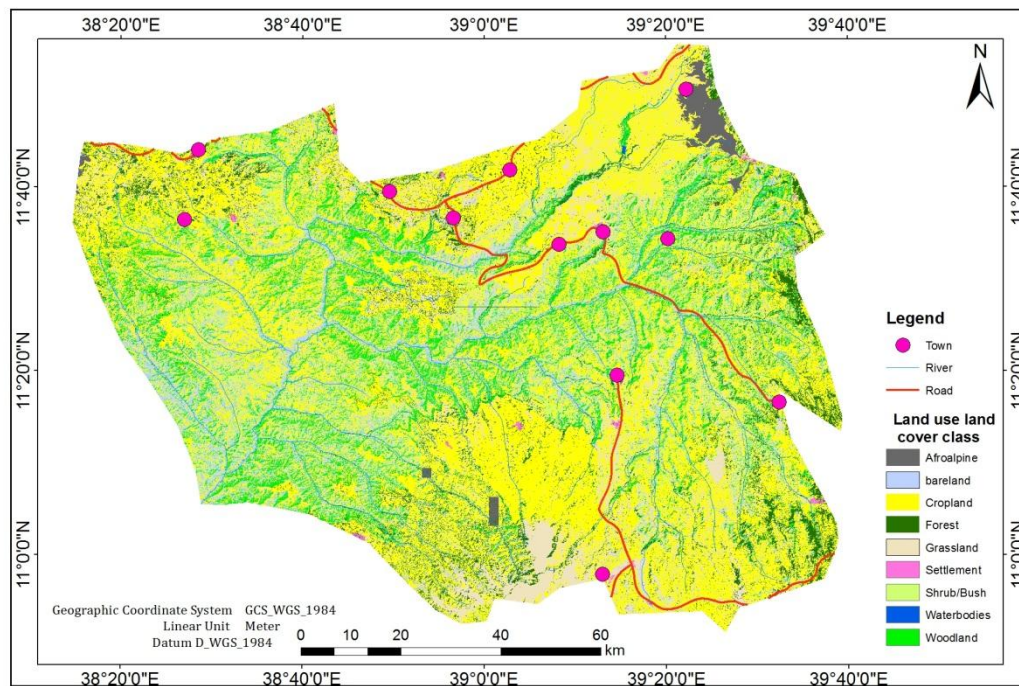


Fig 4.13: LULC map of the area

Table 4.3: Summary of the importance of landslide conditioning factors based on literature review.

No	Factors	Impact	Source
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1	Lithology	Landslides occurrence is under the influence of lithology units because they determine permeability, strength, and susceptibility to failure.	Yalcin et al., 2007. Segoni et al., 2020.
2	Soil Depth	shallow soil is considered to be more unstable and prone to landslide than the deep soil	Sharma et al., 2012
3	Soil texture	Soils with high percentage of clay form very stable aggregates resistant to detachment when we compared to sandy or coarse loams soils.	(Das and Agarwal, 2002).
4	Distance to faults	Since earthquakes have critical roles in cracking of stones that, in turn, cause instability, active faults can be considered as an effective issue in landslides.	Chen et al., 2017.
5	Slope degree	The slope angle has a great impact on landslide events; a larger slope angle is more susceptible to failure.	Ghorbanzadeh et al. 2019.
6	Slope Aspect	The slope aspect, which often controls the amount of water in the hillsides and slopes, influences the slope steadiness.	Pourghasemi et al., 2018.
7	Elevation	The elevation is a critical factor in landslide occurrence due to the huge variability in climate and weather conditions at different elevations that can lead variances in vegetation and soil.	Mahdadi et al., 2018. Conoscenti et al., 2016.
8	Distance to drainage/rivers	It has proven that closer areas to drainage have more soil erosion and as a result higher risk of landslides. Besides, higher wet conditions affect the stability and the underground flow.	Haris et al., 2014.
9	Rainfall	Annual rainfall has introduced as the main triggering factor for landslides occurring. Rainfall amount, varying by topographical characteristics and weather conditions, can trigger landslides.	Bui DT et al., 2013.
10	Land use land cover	The spatial distribution of land cover types affects the propensity of landslide occurrence.	Meneses et al., 2019.

4.5 Defining qualitative ranges/indicators to express landslide hazard or intensity

Quantitative based land slide mapping requires field measurements and absolute value indices. However, in situations where measuring absolute landslide phenomenon, researchers use proxy indicators and label the area using relative terms like high or low. Proxy based landslide mapping is expressed using qualitative indicators such as low moderate and high.

4.5.1 Defining thresholds

Once the factors relationship is established, and the range of each factor is fixed, the value between each classes/range need to be determined. That implies the value of each factor need to be set in the context of the issue, in this case, the landslide hazard. Often, researchers reached to a consensus in determining the thresholds of every factor for a particular issue. For instance, slope in landslide hazard perspective; often it is classified into five landslide susceptibility zone: very low, low, moderate, high, and very high-using the natural break classifier (El Jazouli et al., 2019. and Basu T. and Pal S., 2018).

A natural break classification

Natural break classification is giving classes based on natural groupings inherent in the data. This break are identified that best group similar values and that maximize the differences between classes. The features are divided into classes whose boundaries are set where there are relatively big differences in the data values <https://learn.arcgis.com/>.

4.6 Reclassification and Ranking of factors

In case of AHP (Saaty, 1990) assignment of weight to each feature class of different parameters is considered as prerequisite because calculation of normalized weight is performed from these assigned weights. Besides this, all the parameters do not influence degree of landslide vulnerability in the same direction. For example, greater degree of slope creates greater chances for the occurrence of landslide, but greater vegetation cover reduces the chances of landslide. It is prerequisite to make all the layers unidirectional for the integration process. To solve this purpose a certain weight is assigned for all the feature classes of all layers by following a particular logic. For making data layers unidirectional all the continuous layers are categorized into 5 classes using natural breaks and score 5 is assigned to the class where landslide susceptibility is maximum. But, here some categorical layers (geology, soil) and binary layers

(soil textures) are also present. In those cases treatment is done in other ways. For example, in case of categorical data layers for soil texture maximum rank (5) is assigned to the soil which is more susceptible to landslides.

4.6.1 Reclassification of geologic factor

i) Lithology

Lithology plays an essential role in the slope instability and it is correlated with the properties of the slope forming material. According to [Anbalagan, 1992](#), [Raghuvanshi et al., 2014](#) Rocks which possess high strength are relatively more resistant to erosion. The erodibility of rock is highly influenced by the strength of the rock. Rock which are rich in minerals like (montmorillonite, bentonite), mica, calcite, gypsum etc. are prone to weathering and this leads to landslide. Whereas Lithological units, such as; basalts, shale, sandstones and lime stones have different shear strength characteristics because of the varying conditions under which they were formed. In the present study, a total of ten Lithological units are generated by digitizing the geological sheets of the study area obtained from Ethiopian geological survey (GSE). These are: Ashangie basalts, Wegel Tena rhyolitic ignimbrite, Dessie basalt formation, Tarmaber Megezez Formation, Middle basalt flows, Bedded tuff, Guna tuff, Guna trachyte, Trachyte plug and lacustrine sediments (Table 4.4).

Table 4.4: Reclassification and Ranking of lithologic features from landslide perspective

Lithology	Description	Rank	Class Important	weight
Lacustrine sediments	Silty to sand soil with diatomite.	5	Very high	0.19
Wegel Tena rhyolitic ignimbrite	It is extensively eroded and dissected by the deep gorges forming sharp cuts. Densely welded ignimbrites have a glassy appearance and exhibit a well-developed columnar jointing.			
Guna tuff	Loosely compacted, youngest and softer. It is dominated by pumice and tuffs	4	High	
Bedded tuff	Loosely compacted and friable partly loose deposit is a thin layer			
Ashangie basalts	Exposed as faulted block and along the deep river gorges of NE-SW trending of Beshilo rivers.	3	Medium	
Guna trachyte	Weakly columnar porphyritic sanidine trachyte			

Middle basalt flow	Pyroclastic flow unit alternating with lava flow and exposed in deeply cut valley of Beshilo rivers and its tributaries. Cliff forming basalt and mostly deeply weathering on top of each layer.	2	Low	
Tarmaber megezez formation	Form elevated plains. Characterized by coarse grained, vesicular basalt and columnar jointed aphanatic basalt thick rock	1	Very low	
Dessie basalt formation	Ridge like cliffs along the escarpment and river cuts. Containing aphanatic and porphyritic massive and vesicular basalts.			
Trachyte plug	Rocky and resistant to erosion and form high rising hills. It composed from sanidine and quartz crystals			

The main criterion which was used for ratings lithology is; the response of the rocks to the processes of weathering and erosion. This criterion was to generalize the all over rock mass strength. In principle, hard formations are strong to hold external influence compared to weak formations. The study area mainly covered by the recent volcanic rocks, they are susceptible to weathering and may easily contribute to landslides. However, they have a clear difference in density.

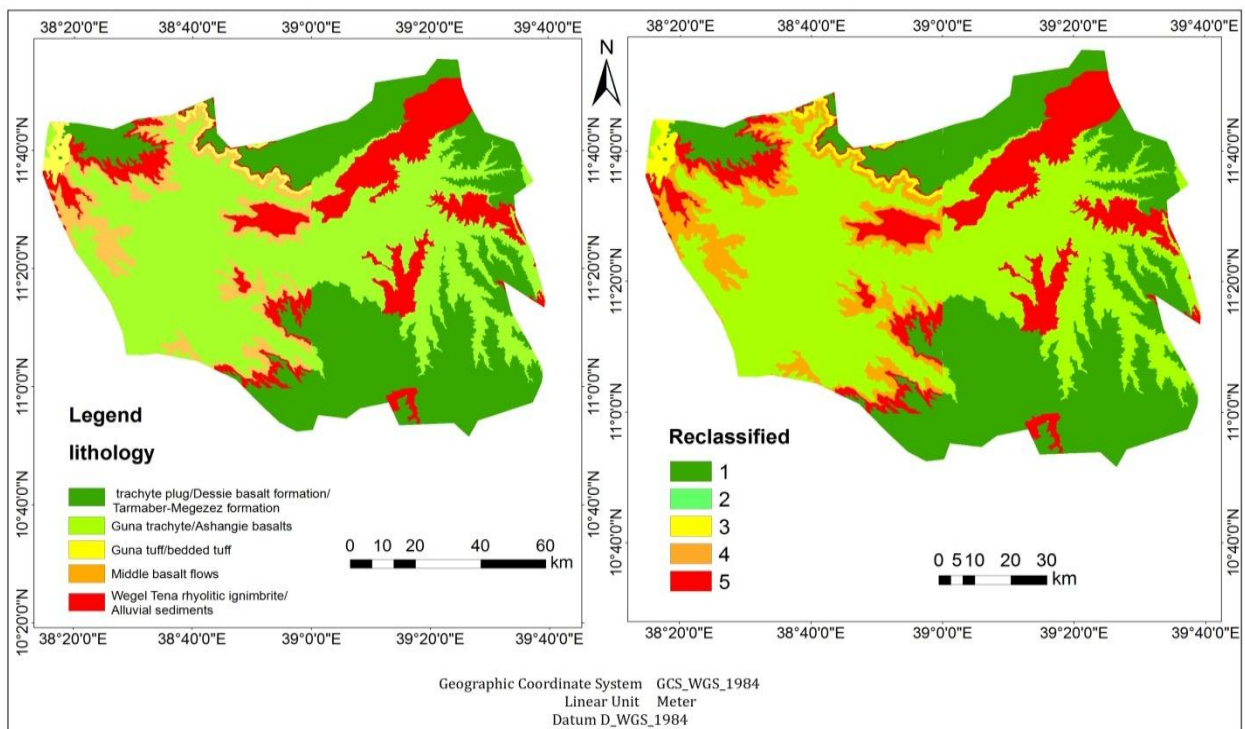


Fig 4.14: Map of regrouped and reclassified based on LSV ranking of lithology

ii) Faults Density

Fault is zone of fractures between two blocks of rock. It permits the blocks to move relative to each other. This movement may occur quickly in the form of creep (<https://www.usgs.gov/faqs/fault>). Historical ruptures hints of a fault are an important dataset to interpret future fault ruptures. Thus historical rupture hints have been used to assess geo-hazard area and susceptibility mapping (Mark et al., 2004). Fault areas are in general, highly vulnerable to landslides because the surrounding rock strength decreases due to tectonic breaks (Chen et al., 2017). In this study, the fault density was reclassified into five categories from line density calculation result (Fig. 15).

Table 4.5: Reclassification and Ranking of fault density

Factor	Weight	Class	Rank	Class importance
Fault density	0.12	0 – 0.067	1	Very low
		0.067 – 0.19	2	Low
		0.19 – 0.34	3	Medium
		0.34 – 0.50	4	High
		0.50 – 0.95	5	Very high

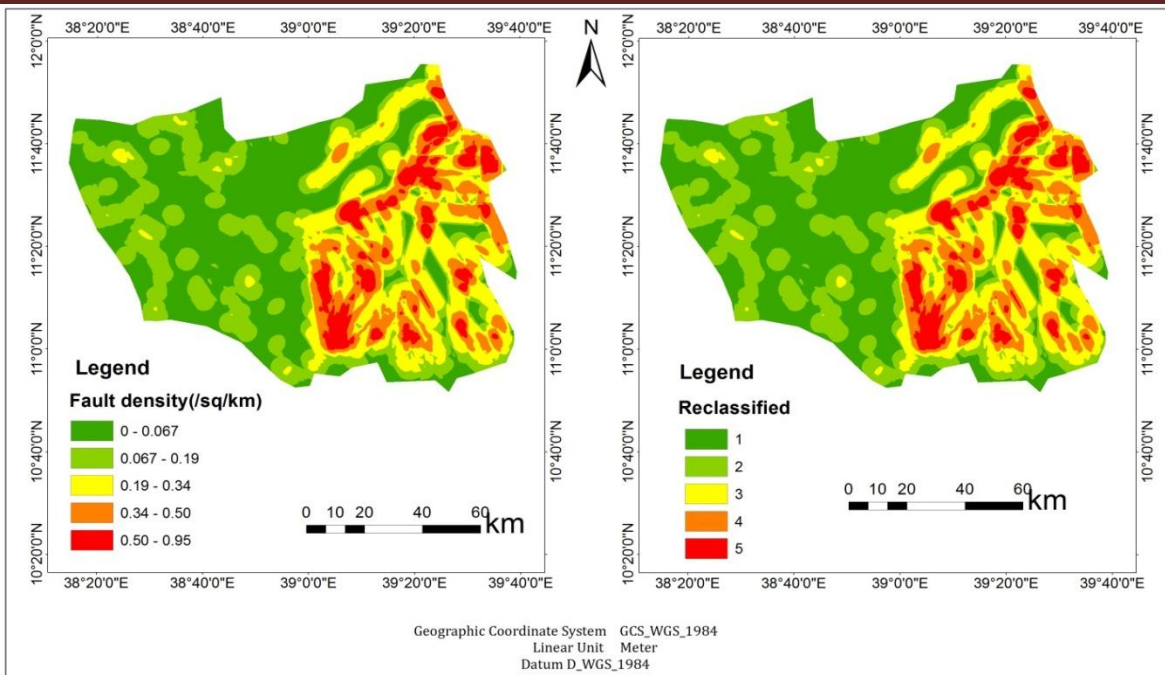


Fig 4.15: Map of reclassified and corresponding rank of fault density

iii) Lineament density

Lineaments are map-able linear features existing on the surfaces of the earth, which designates the area of weakness and structural discontinuities in a rock. Its source possibly will be joints, faults, foliations, and bedding planes also its shape can be linear, curved, and slightly curve. Interpretations related to engineering point of view, such discontinuities are a result of a rupture in rocks or a boundary in rock or soil that indicates a change in the rock mass (Hencher, 1989)

In geo-hazard study knowing the spatial distribution of lineaments and their density is very crucial for the reason that it is directly related to the zone of weak masses in a rock. According to authors like (Saha et al., 2002; Ferdous and Chow, 2004; Roslee et al., 2006; Ramli et al., 2010) indicated that a high density of fractures and joints in a rock mass, which is related to the lineaments can lower the stability of rock by reducing the overall rock mass strength. Therefore in the case of landslide hazard assessment lineament density is very important parameter.

Table 4. 6: Reclassification and Ranking of lineament density

Factor	Weight	Class	Rank	Class importance
Lineament density(km/sq./km)	0.12	0 – 0.225	1	Very low
		0.225 - 0.392	2	Low

	0.392 - 0.569	3	Medium
	0.569 - 0.784	4	High
	0.784 - 1.219	5	Very high

The lineament density was generated by extracted lineament shown in (Fig 4.2). The lineament density was also classified using natural breaks function in ArcGIS and reclassified based on their implication to model susceptibility of landslide hazards (Fig 3.16).

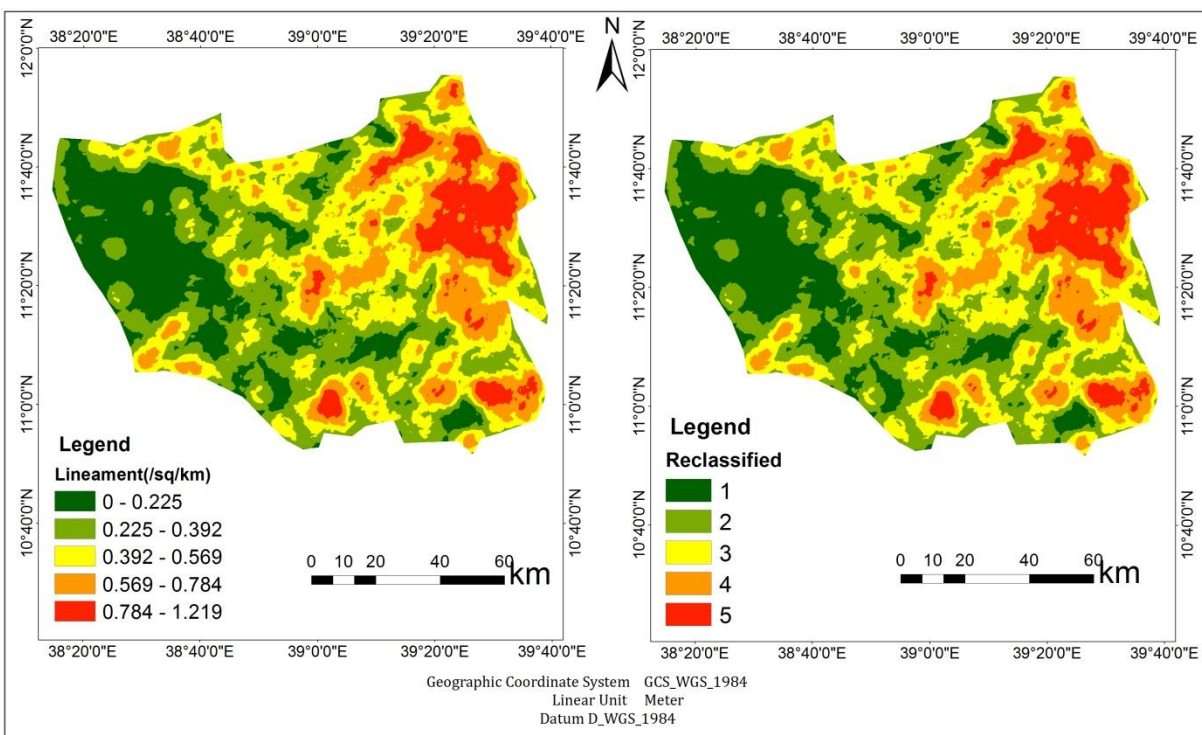


Fig 4.16: Map of reclassified and corresponding rank of lineament density

4.6.2 Geomorphic/Topographic factor

i) Slope angle

Slope is one of the most important topographic parameters influencing the occurrence of landslides hazards. In general, if the slope is steeper it will be more susceptible for instabilities as compared to gentle slope. The gravity pull which is the main driving force for instability is directly proportional to the slope gradient (Raghuvanshi et al., 2014; Bisson et al., 2010).

Generally speaking, as slope increases, the probability of landslide occurrence also increases, having this logic the slope map classified into five categories (Fig 4.17). Using the class their contribution also ranked. For the study area, the slope is derived from 15m DEM using the slope function of the spatial analyst of ArcGIS 10.5. The map for this factor is in the form of a raster having the same pixel size as the DEM.

Table 4.7: Reclassification and Ranking of slope degree

Layer	Weight	Class	Rank	Class importance
Slope degree	0.24	0-5°	1	Very low
		5-12°	2	Low
		12 - 30°	3	Medium
		30 - 45°	4	High
		45 - 83°/>45°	5	Very high

A map of slope classes is generated by grouping the slope angles into five different classes (Fig 4.17): (1) Class I: <5°, (2) Class II: 5-12° (3) Class III: 12-30° (4) Class IV: 30-45° (5) and Class V: >45° (Flagot Mengistu and Raghuvanshi., 2018).

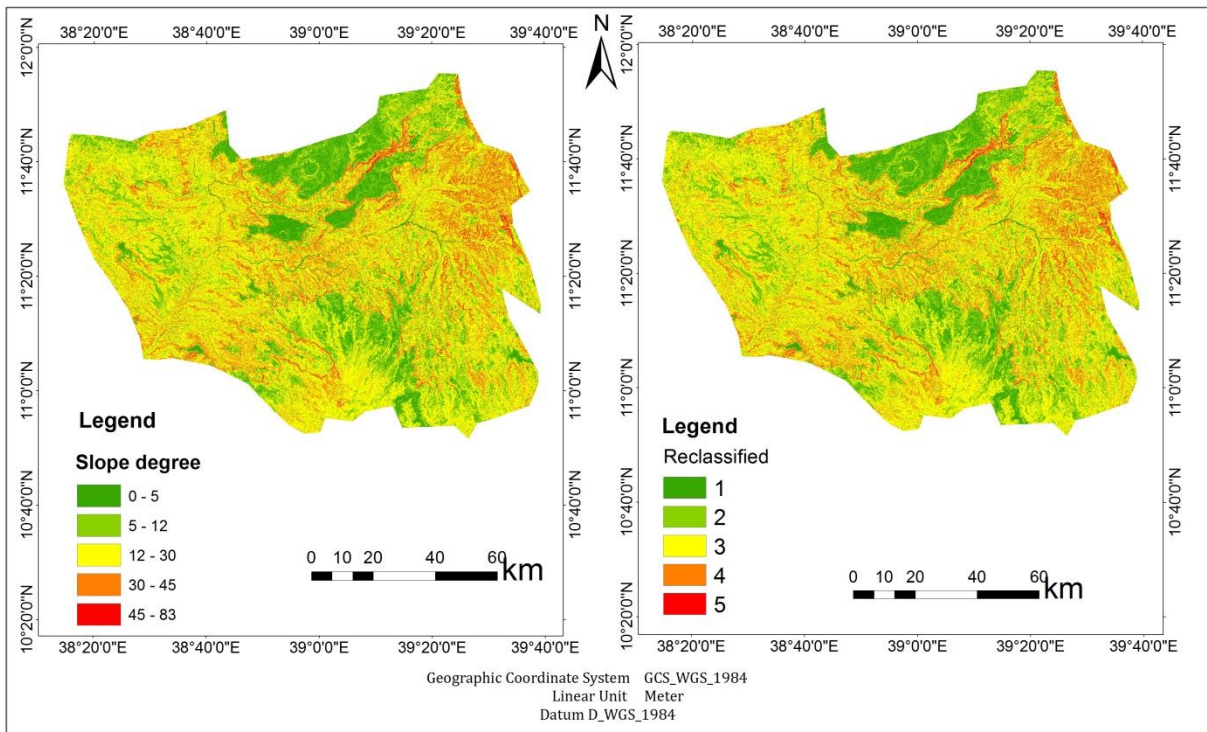


Fig 4.17: Reclassified and corresponding rank of Slope degree map

ii) Elevation

Ayalew *et al.*, 2005 said that Elevation is a significant landslide conditioning factor because it is controlled by several geological and geomorphological processes. The elevation is considered to be an important controlling factor which may possibly affect the slope material by weathering process (Raghuvanshi *et al.*, 2015; Ahmed, 2009). Elevation layer was obtained from the DEM in a resolution of 12.5 m.

Table 4. 8: Reclassification and Ranking of Elevation

Factor	Weight	Class	Rank	Class importance
Elevation	0.04	0 - 1911	1	Very low
		1911 - 2325	2	Low
		2325 - 2742	3	Medium
		2742 - 3177	4	High
		3177 - 4260	5	Very high

As shown in Table, the elevation of the study area ranges from 1911 to 4260m above msl. And it is ranked according to their elevation.

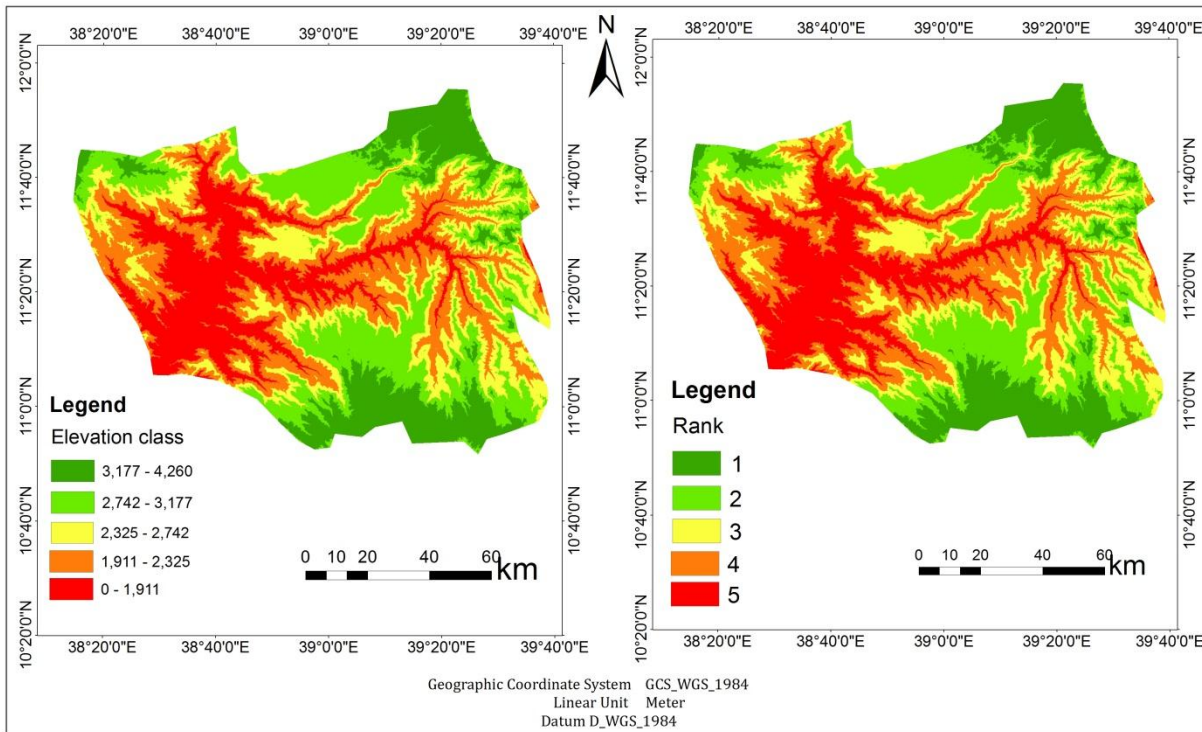


Fig 4.18: Reclassified and corresponding rank of Elevation map

iii) Aspect

The slope aspect, which often controls the amount of water in the hillsides and slopes, influences the slope steadiness (Shahabi et al., 2014; Pourghasemi et al., 2018). It is a real fact that slope aspect affects moisture retention and vegetation cover of a slope. Indirectly, aspect can control the susceptibility of a slope to landslides. It makes also a variation on rainfall distribution over the slopes. Therefore, slope aspect is considered to be an important factor for landslide hazard zonation (Raghvanshi et al., 2015). The aspect map of the study area was generated from the DEM at 12.5m resolution and the aspect was classified according to the angles; Flat (-1–0°), North (0–22.5°), North–east (22.5–67.5°), East (67.5–112.5°), South–east (112.5–157.5°), South (157.5–202.5°), South–west (202.5–247.5°), West (247.5–292.5°), North–west (292.5–337.5°) and North (337.5–360°).

The generated aspect map is reclassified into five classes according to their influence to landslide

occurrence depending on (Asmelash et al., 2019).

Table 4.9: Reclassification and Ranking of aspect

(Asmelash et al., 2019)

Factor	Weight	Class	Rank	Class importance
Aspect	0.04	Flat	5	Very high
		South-east		
		East		
		North	4	High
		North east		
		South		
		South west	3	Medium
		North west	2	Low
		West	1	Very low

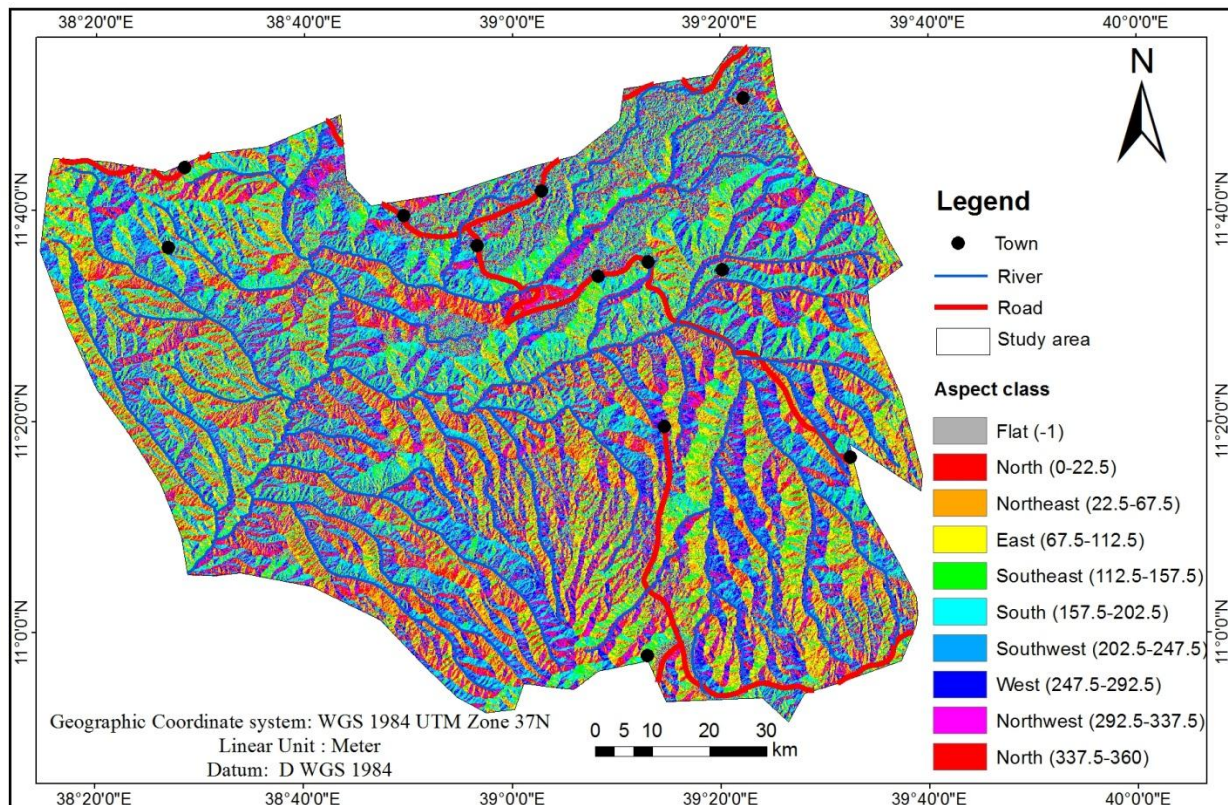


Fig 4.19: Classification of aspect map

iv) Drainage Density

Rivers play a major role in landslide development (El Jazouli et al. 2019). They can lead the failure of banks because of the sub-quotation of slopes, and the modification of the ground caused by gully erosion may also influence landslide initiation (Dai and Lee 2002). The drainage density of the study area ranges from 0–0.4 km/km² (Table 4.10) and was reclassified into five classes depending on its susceptibility to landslide hazard. The "least drainage density areas" (0–0.049 km/km²) were given the least weight (of 1) for landslide susceptibility. The highest weight (of 5) was given to the areas with the “highest drainage density” values (0.25 – 0.40 km/km²). The class important also has given accordingly (Table 4.10). The drainage density was calculated using “Line density” tool in the GIS environment.

Table 4.10: Reclassification and Ranking of drainage density

Factor	Weight	Class	rank	Class importance
Drainage to drainage	0.04	0.25 – 0.40	5	Very high
		0.19 – 0.25	4	High
		0.12 – 0.19	3	Medium
		0.049 - 0.12	2	Low
		0 – 0.049	1	Very low

In the present study, the drainage network was produced from Ethio-GIS under hydrology in ArcGIS 10.5. Five different classes were generated using line density method to determine the degree to which the streams could affect the bank slopes (Fig. 4.20).

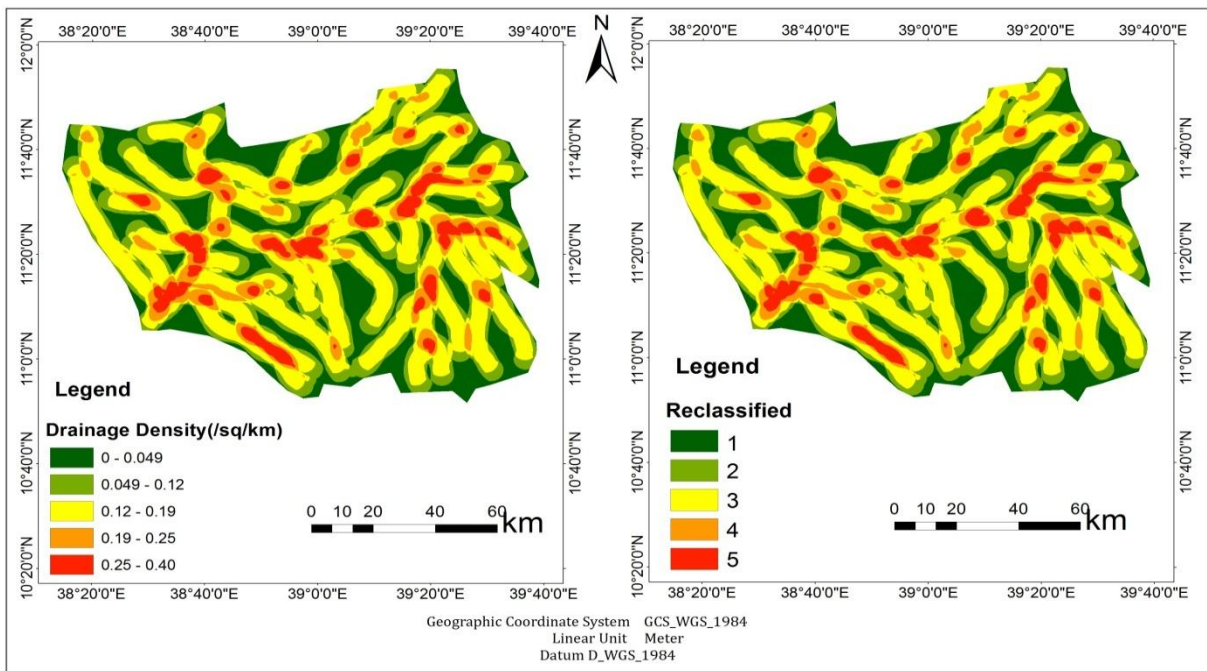


Fig 4.20: Map of reclassified and corresponding rank of drainage density

4.6.3 Edaphic factor/Soil properties

Soil maps are in shape file format with its attributes. The soil has eight different characteristics, namely, depth, inner texture, surface texture, erosion, slope, stoniness, drainage and hydraulic conductivity (Das, 2007). Inclination and orientation of structural surface have the greatest effect on the stability of the slopes (Crozier, 1986). Each of these parameters has been categorized into three to five types by assigning different weights based on stability and landslide susceptibility. For example, soil depth has been classified into five different categories, namely, very deep, deep, shallow deep, moderate deep, and very shallow (Brady and Weil, 2007). Important soil characteristics considered are; soil depth and soil texture.

Table 4.11: Reclassification and Ranking of soil depth and texture

Factor	Weight	Class	Rank	Class importance
Soil depth	0.05	<30(very shallow deep)	5	Very high
		30 – 50(shallow deep)	4	High
		50 – 100(moderate deep)	3	Medium

		100 – 150(deep)	2	Low
		>150/water body(very deep)	1	Very low
Soil texture	0.06	Clay	1	Very low
		Sandy loam	4	High

i) Soil Depth

Soil depth is one of the important factors to assessing the stability of the soil and landslide susceptibility of the land. In fact when soil depth is increase susceptibility to landslide is increase. Despite the fact in this specific area when soil depth increase, the tendency of the soil to absorb moisture is increased, this leads to reduced runoff rate. Hence, shallow soil depth is considered as more unstable and prone to landslide than the deep soil depth. Because, for this specific area deep soil is related to more consolidated and weathering and erosion resistant soil. Depending on this fact, ranking criteria were given for different soil depths found in the study area, as shown in (Table 2).

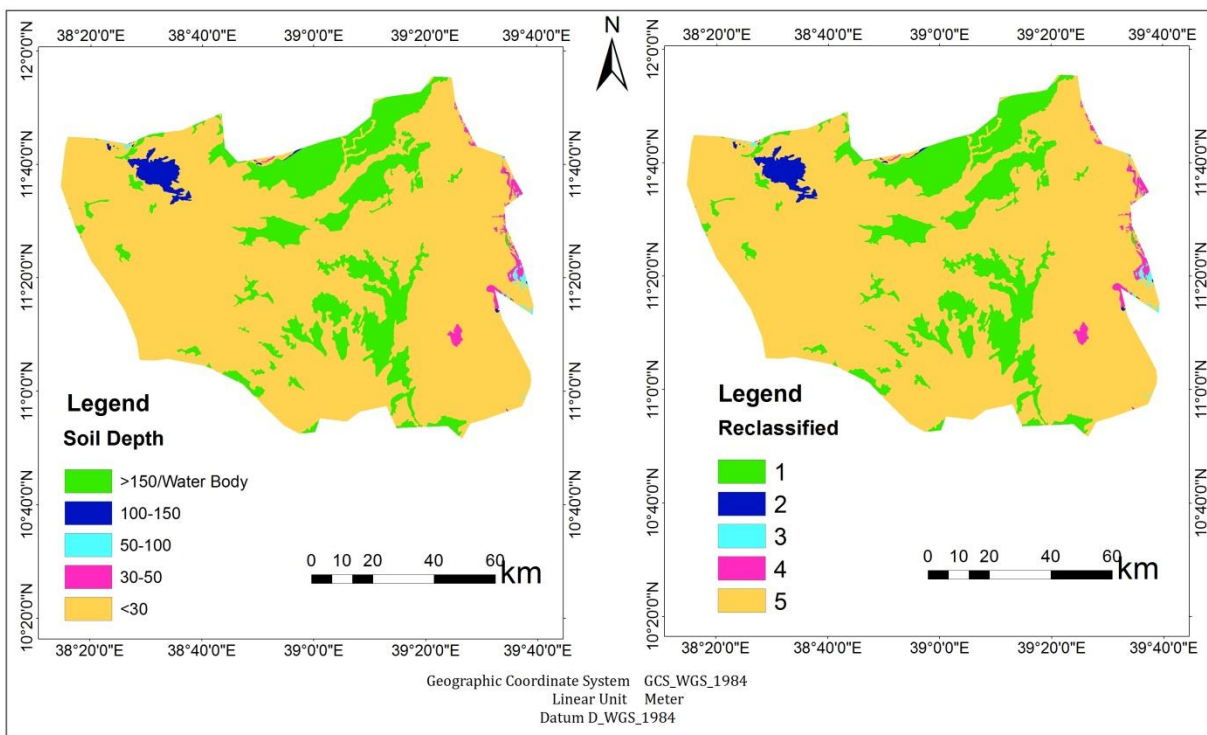


Fig 4.21: Reclassified Soil depth map and corresponding rank

ii) Soil texture

Soil texture is one of characteristics of soil which denotes the relative proportion of sand, silt, and clay content. Soils which contain high proportion of clay form very stable aggregates which resist to detachment. Whereas, light soils like sandy/coarse loams are easy to slide because of low organic matter content, leads to inability to form very stable aggregates (Das and Agarwal, 2002). Hence, soil with more sand, high slope, and intensive rainfall, which constitute most dominant factors of landslide, cause severe damage to the land (Patanakanog, 2001). In this area soils which have clay texture is related to consolidated part, whereas soils which is sandy/coarse loams are more unconsolidated. Based on these characteristics, the soil types based on their textures were assigned different stability ranks, as shown in (Table 4.11).

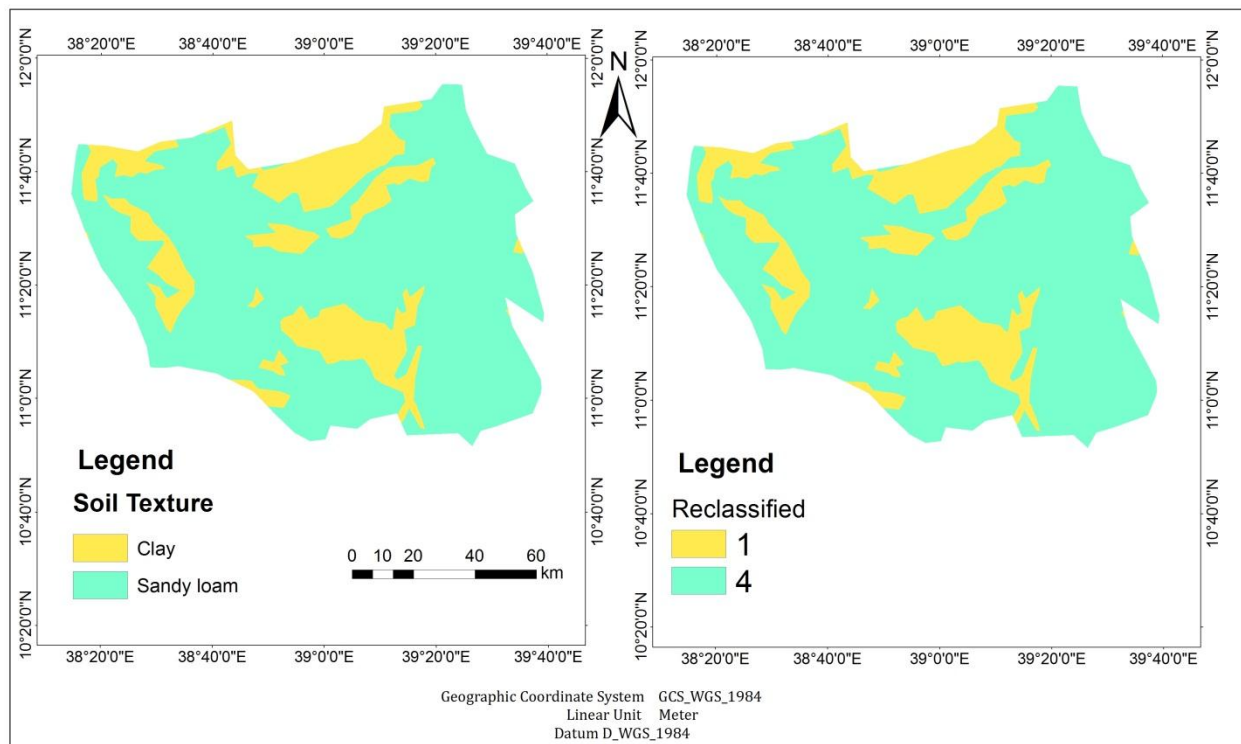


Fig 4.22: Reclassified Soil texture map and corresponding rank

4.6.4 Triggering factor

i) Rainfall

Precipitation in the form of rain is a major factor in the occurrence of landslides (Baum et al., 2008) since it is the dominant source of water in the hydrologic system of landslides (Haneberg

and Anderson, 1995). In this study, the total amount of annual rainfall data was obtained as secondary data from Rainfall (CHIRPS) data set. The total annual rainfall map along the area is shown in (Fig. 23). Rainfall was classified into five (5) categories and ranked by giving weight according to their influence.

Table 4.12: Reclassification and Ranking of rainfall

Factor	Weight	Class	Rank	Class important
Rainfall(mm)	0.04	813 - 983	1	Very low
		983 - 1107	2	Low
		1107 - 1244	3	Medium
		1244 - 1390	4	High
		1390 - 1588	5	Very high

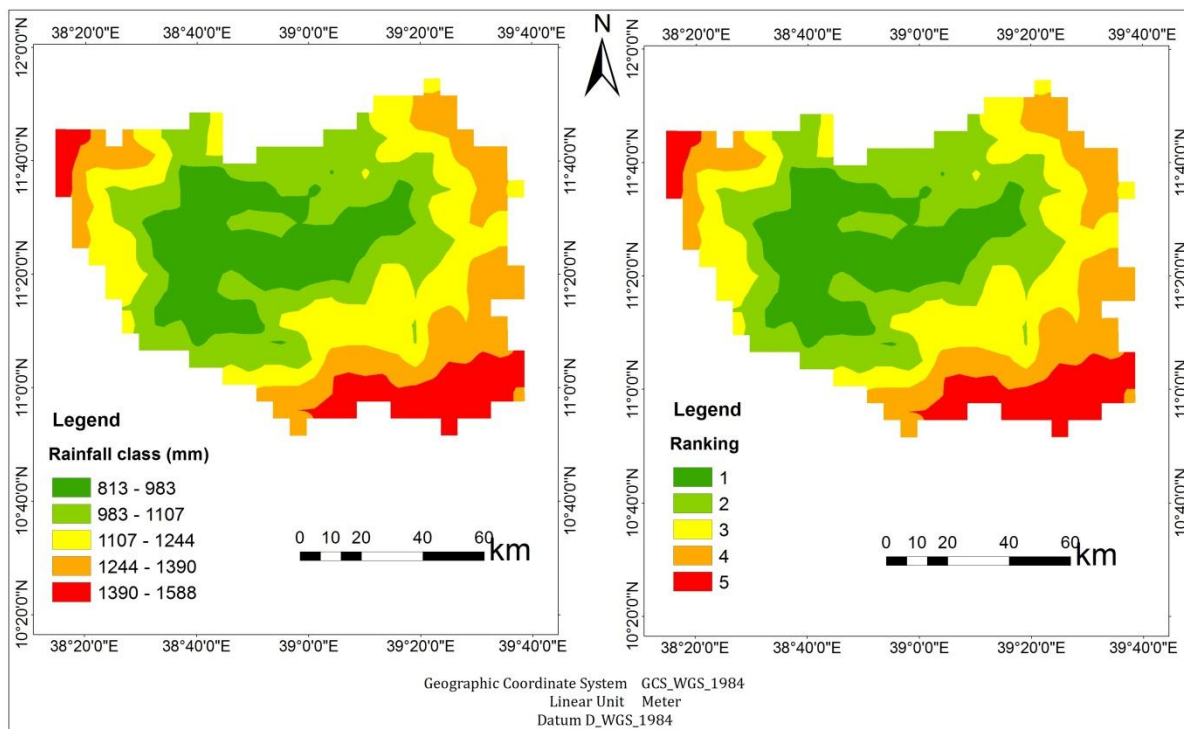


Fig 4.23: Reclassified and corresponding rank Rainfall map

ii) Land use and Land cover

Land use Land cover is influenced by factors relating to population needs, such as converting the

agricultural and forest land to the urban areas, conversion of forest to farmland, and reduction of the involuntary or unethical slope for infrastructure developments. Land use is a major factor in mapping landslide susceptibility. In this study land use was generated using Landsat 8 OLI image, by applying a supervised classification Likelihood with ArcGIS 10.5 and ENVI 5.3 software, and reclassified to five classes depending on their capacity to stabilize the earth. The LULC of the area is listed in (table 4.13).

Table 4. 13: Land-use land-cover categories and their reclassification

Factor	Weight	Rank	Class important	Class	Description
Land use land cover class	0.08	5	Very high	Settlement	Includes all developed areas roads, buildings, housing units, Commercial and resident areas, under construction areas etc.
				Bare land	Mainly refers to open spaces without any function, bare soils, grazing land, open areas in side vegetation and resident areas, it might be covered by grasses.
		3	Medium	Shrub/Bush	Refers to areas covered by loss vegetation of any type, including riverine trees or vegetation and other pockets of green areas.
				Grassland	An area in which the natural vegetation consists of largely of perennial grasses characteristics of sub humid and semiarid climates.
		2	Low	Woodland	Trees and tree canopies generally overlapped and interlink, often forming a more or less continuous canopy which shades the ground to varying degrees.
		1	Very low	Forest	Refers to areas covered by dense vegetation of any type.
				Water body	Lake and river
		Agricultural/Cropland	Includes all areas employed for agricultural activities farmland parcels both with and without crop.		

		4	High	Afroalpine	Trees that found area having 3200 meters above sea level. Afroalpine and subafroalpine environments are highly fragile due to extreme climatic condition and extremely harvested for a numbers of purpose.
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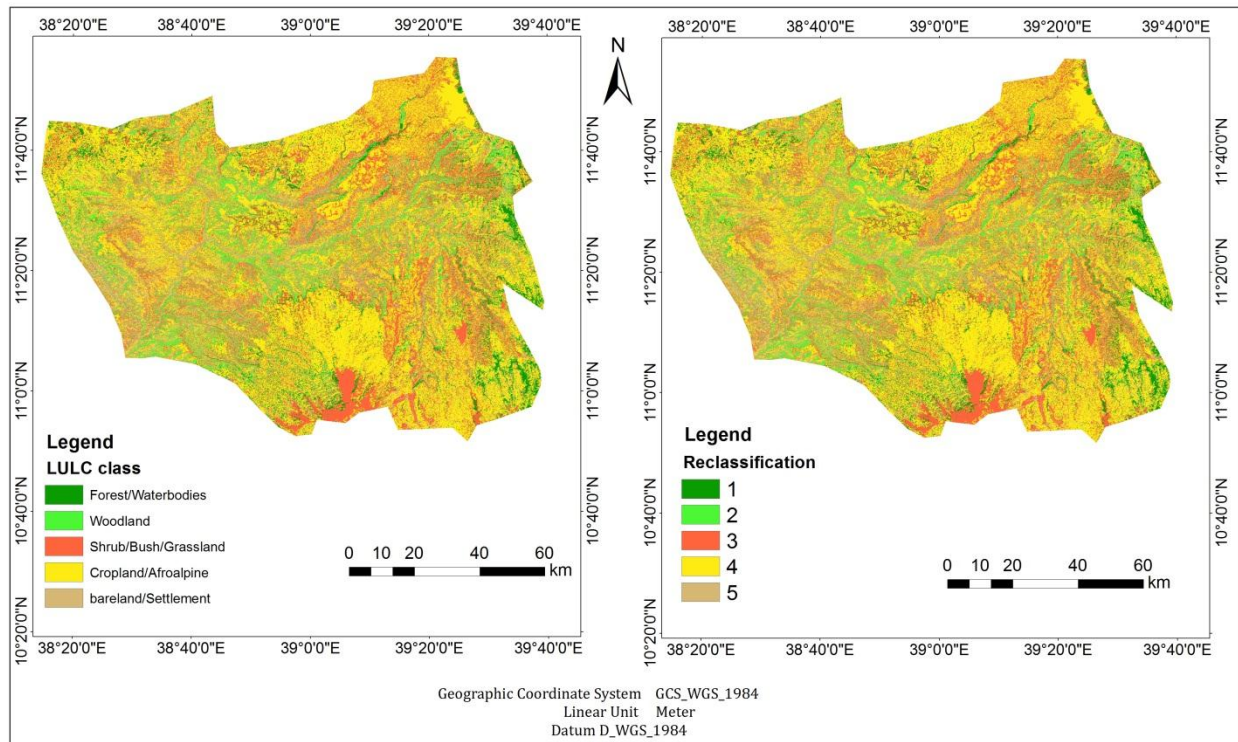


Fig 4.24: Map of regrouped and reclassified based on LSV ranking of LULC

4.7 Criteria settings

Once the possible factors that govern land slide phenomenon are identified, the relationship between each factors need to be established. The relationship between each factor and the landslide phenomenon could be direct or indirect. For example, landslide occurrence has a direct relationship with slope that implies, the higher the slope the high the possibility of the area for sliding. Likewise, before doing the analysis, these relationships between each factor need to be established. Reclassify every factor in relation to land slide phenomenon explanation. You need to base the classification based on known principle. Quantitative land slide mapping requires field measurements and absolute value indices. However, in situations where measuring absolute

values in the matrix are the comparison results of the expert decision makers and the upper right values are the reciprocals of it. In this work, Landslide hazard types were taken to assess its risk using this technique. For landslide hazard susceptibility assessment 11 factors evaluated in the comparison matrix such as LULC, Drainage proximity, fault proximity, lineament density, rainfall, lithology, Slope degree, Slope aspect, Elevation, soil depth and texture (Table 4.16).

Table 4.16: Pairwise comparison of factors

Factor	Slope Degree	Lithology	Rainfall	Distance to fault	Lineament density	Distance-Drainage	LULC	Soil Depth	Soil Texture	Elevation	Aspect
Slope Degree	1										
Lithology	1/3	1									
Rainfall	1/2	2	1								
Fault density	1	3	2	1							
Lineament density	1	3	2	1	1						
Distance density	1	3	2	1	1	1					
LULC	1/4	1/3	1/2	1/4	1/4	1/4	1				
Soil Depth	1/3	1	1/2	1/3	1/3	1/3	3	1			
Soil Texture	1/5	1/3	1/2	1/3	1/3	1/3	3	1	1		
Elevation	1/5	1/3	1/3	1/5	1/5	1/5	1/3	3	3	1	
Aspect	1/6	1/5	1/5	1/5	1/5	1/5	1/2	1/5	1/5	1/3	1

4.7.2.2 Weight and Consistency ratio

The reliability of the pairwise comparison method is tested by a consistency ratio. As it is known that pairwise comparison has subjectivity issue, the reliability of the output need to be checked using a consistency ratio approach. So, the comparison matrix has been developed, consistency or inconsistency of the comparison matrix was checked by using the standard consistency ratio formula (Eq.2). The steps followed to compute the criterion weights (Eigen vector) of a reciprocal matrix involved the following operations:

- (a) Summing of the values in each column for each factor in a matrix;
- (b) Divide each cell value to its column total (the resulting matrix is referred to as the normalized pair wise comparison matrix);
- and (c) Compute the average of the cell value in each row of the normalized matrix, that is, divide the sum of normalized scores for each cell by the number of criteria. These averages give the result of

the relative weights of the compared criteria. The Eigen vector shows relative weights between the factors that we compare. The higher the weight is the more important the criteria.

The weight of each factor and consistency ratio also calculated using IDRISI 17.0 software automatically.

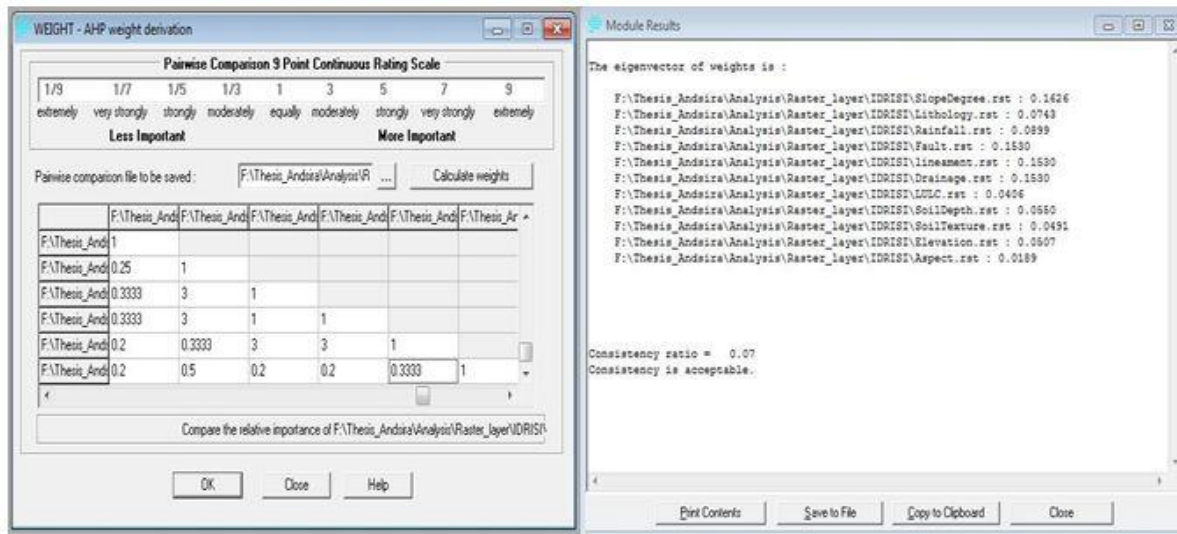


Fig 4.22: Show how the pairwise matrix and weight analysis was done using IDRISI Selva

The software has a module that enables to calculate weights by providing a series of pair-wise comparisons of the relative importance of factors to the suitability of pixels for the activity being evaluated. The procedure by which the weights are produced follows the logic developed by T. Saaty under the Analytical Hierarchy Process (AHP). Weight value of each factor for landslide hazard map is shown in (Table 5.1).

4.8 Methodology adopted for landslide Hazard susceptibility mapping

4.8.1 Analytical Hierarchy Process

AHP has been successfully employed in GIS-based MCDM since the early 1990s (Carver, 1991; Malczewski 1999; 2004; Makropoulos et al., 2003). AHP builds a hierarchy of decision elements (factors) and renders comparisons possible between pairs of factors in form of a matrix. It calculates the required weights associated with criterion map layers with the help of a preference matrix in which all relevant criteria identified are compared against each other on the basis of preference factors from different expert's decision. The results are weights for each factor and also a consistency ratio which quantifies the unambiguity of the pairwise weighting. The weights

can then be aggregated. GIS-based AHP has gained popularity because of its capacity to integrate a large quantity of heterogeneous data, and because obtaining the required weights can be relatively straightforward, even for a large number of criteria. To identify and map hazard-prone areas, eleven data sets have been combined according to their significance. To combining the different factors was done using ArcGIS 10.5 Software. The weighted linear sum (WLS) method (Musigguzi M. and Asiimwe I., 2014) was used to obtain a linear sum of weighted parameters for landslide susceptibility. The classes within each parameter are multiplied with the weight and added using the spatial analysis tool to get susceptibility output maps. Following weighted linear combination (WLC) Model was used to generate landslide susceptible maps (Eq.4).

$$LSI = \sum_{i=1}^n (W_i R_i) \quad (Eq.4)$$

Whereas LSI = Landslide susceptible Index

W_i = Weight value of parameters

R_i = Rating value of class

4.8.2 Model validation method

The landslide susceptibility map was verified with the receiver operating characteristic (ROC) curve statistics, a useful method for representing the quality of deterministic and probabilistic detection and forecast systems. The ROC curve is created by plotting the true positive rate and false positive rate of each possible binary classification of a dataset. The area under the curve (AUC) indicates the performance of the model. Its value ranges from 0 to 1, where 1 indicates a perfect model fit and 0.5 indicates that the model does not perform any better than random chance.

4.9 Landslide risk assessment

Probability of occurrence needs to be qualified by a statement of expected behavior of the failure in terms of its impact characteristics. High levels of susceptibility in developing countries have also been attributed to dependence on external assistance either as disaster relief or in risk management programs (Crozier and Thomas, 2004). It has been argued that these measures can override traditional coping mechanisms, suppress indigenous mitigation practices and reduce the

ability or incentive to take independent measures to mitigate risk.

Risk = hazard × vulnerability/susceptibility × elements at risk (exposure). (Source, Crozier and Thomas, 2004)

Representing hazard, the hazard–risk equation requires identification and valuation of the elements at risk. The elements at risk are difficult to identify and even more difficult to quantify at the current situation. In the broadest sense, they are all those attributes valued by mankind. They range from life, human well-being, through monetary values of property, lifelines, resources and means of production, to ways of life, religious, aesthetic and other values.

At present study risk assessment map can be done by weighted overlay map of exposures with the susceptibility map. For land use land covers and population density the damage potentials for land categories and population density have been evaluated separately. Later by combining the damage potential with the landslide hazard, the risk assessment (RA) map has been prepared for both land categories and population density. This is done through weighted overlay method in ArcGIS environment. Generally risk assessment map can be done based on methodological flow chart of (Fig 4.25).

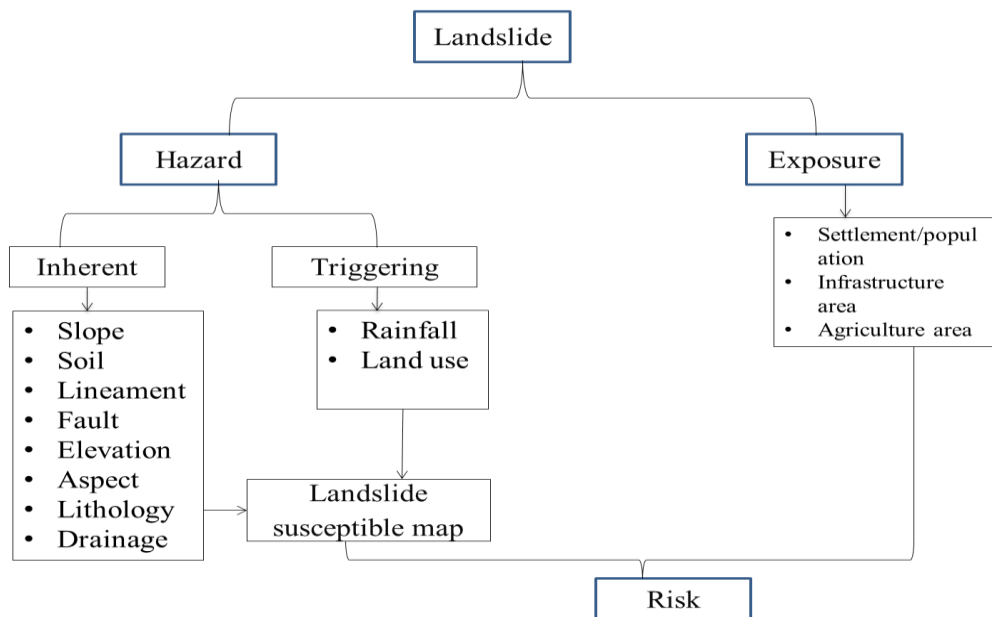


Fig 4.25: Methods of risk assessment mapping

4.9.1 Relationship of hazard probability and damage potential for population density

Relative risk analysis was carried out through the combination of procedures, using the landslide susceptibility map and population distribution as basic elements at risk. Elements at risk considered in this work included population, and the quantifying parameter was the population density, i.e., the population is scaled according to the relative range of population density. Ideally, landslide risk zoning maps are prepared using the hazard zoning maps, as well as the elements at risk. Therefore, the landslide risk analyses were performed within the GIS environment, combining the landslide susceptibility map and map of the exposed element population. The reclassified damage potential for population is shown (Table 4.17).

Table 4. 17 Damage potential for population density

No. of population density	Types of Damage potential
7 – 105	Very low
105 – 196	Low
196 – 640	Moderate
640 – 1773	High
1773 - 4379	Very high

4.9.2 Relationship of hazard probability and damage potential for LULC

When a landslide occurs, the risk to land is unavoidable. This may be barren land, agricultural land or forest. Property likely to be affected by landslides includes transport routes, industrial and business premises, schools and parks. Since properties are located on the land surface likely to be affected, they can be simply shown with different symbols. Hence a damage potential status is proposed for different categories of land (Table 4.19). Therefore, the landslide risk analyses were performed within the GIS environment, combining the landslide susceptibility map and map of the exposed element LULC. The reclassified damage potential for LULC is shown (Table 4.18).

Table 4. 18 Damage potential for LULC

Types of LULC	Types of Damage potential
Bare land	Very low
Shrub/bush/grassland	Low
Woodland	Moderate
Forest/water bodies	High
Settlement /Cropland/Afroalpine	Very high

5 Results and Discussion

5.1. Pairwise comparison and its Consistency of factors

During this study pairwise comparison of factors is given by considering experts, geologists, environmentalists, planners and spatial GIS expert’s decisions. Most of the experts give first rank for slope degree. The higher the weight is the more important the criteria. So, most of the expert’s judgment make slope degree is the determinant factor compared to other factor followed by fault density, lineament density, drainage density, rainfall lithology, soil depth, LULC and soil texture, elevation and slope aspect. From the expert’s judgment and software assisted analysis the weight of factor resulted from pairwise comparison shows out of 100% of contributing factors 16% is given for slope degree followed by fault density, lineament density, drainage density which is 15% for each, rainfall which is 9%, lithology which accounts 8%, soil depth which is 6% then LULC and soil texture which is 5% for each and elevation which accounts 4% and finally aspect which is 2%.

The reliability of the pairwise comparison given by expert’s judgment is tested by a consistency ratio. As it is known that pairwise comparison has subjectivity issue since this is a result of expert’s judgment, the reliability of the output need to be checked using a consistency ratio approach. Consistency ratio calculated using IDRISI 17.0 software automatically results the matrix is consistency which is 0.07. So the judgment of the influencing factor for landslide susceptible area is acceptable.

Table 5.1: Weight and consistency ratio of the pair-wise comparison matrix used for landslide susceptibility mapping

ID	Factors	Weight	Weight %
1	Slope Degree	0.16	16
2	Lithology	0.08	8
3	Rainfall	0.09	9
4	Fault density	0.15	15
5	Lineament density	0.15	15
6	Drainage/river density	0.15	15
7	LULC	0.05	5
8	Soil Depth	0.06	6
9	Soil Texture	0.05	5
10	Elevation	0.04	4

11	Aspect	0.02	2
Consistency ratio= 0.07; Consistency is acceptable.			

5.2 Landslide susceptibility mapping

Landslide susceptibility map is thus a function of the degree of the inherent stability of the slope together with the presence and activity of causative factors capable of reducing the excess strength and ultimately triggering movement. The identification of causative factors is the basis of many methods of susceptibility /stability assessment. In this sense, the factors recognized are preconditioning factors (e.g. slope steepness) and triggering factors (e.g. rainfall).

The final step to produce land slide susceptibility map is combining the reclassified factors based on their weight of influence (Table 5.1). To identify and map hazard-prone areas, eleven data sets have been combined according to their significance. Landslide susceptible map have been modeled using AHP technique. Combining the different factors was done using ArcGIS 10.5 Software. The weighted linear sum (WLS) method (Musigguzi M. and Asimwe I., 2014) was used to obtain a linear sum of weighted parameters for landslide susceptibility. The intra-parameter scores (Table 5.1) developed through literature review, knowledge based and expert opinion were multiplied by the corresponding parameter maps to derive relative susceptibility distribution map. Each parameter was categorized into classes and assigned ranks from having very low influence to very high, 1 (very low), 5 (very high) depending on the classes bearing on landslides. The classes within each parameter are multiplied with the weight and added using the spatial analysis tool to get susceptibility output maps. Following weighted linear sum (WLS) Model was used to generate landslide susceptible maps. Landslide susceptibility Mapping (LSM) (Fig 5.1) was performed using the proposed method.

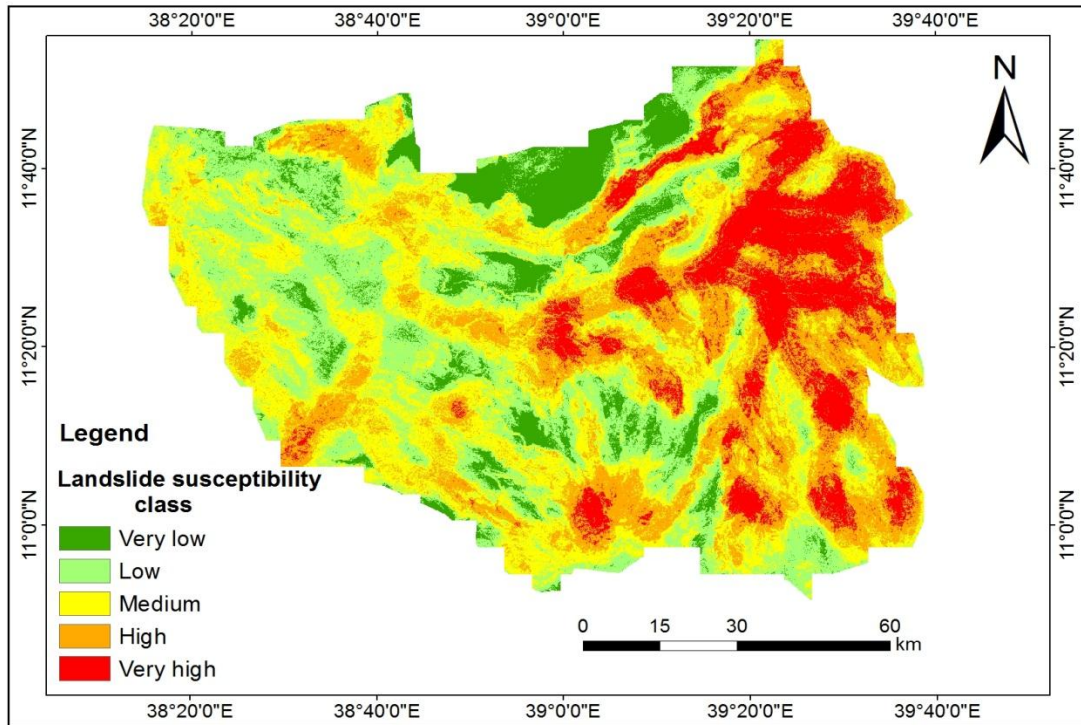


Fig 5.1: Landslide hazard susceptibility map

The result of the susceptibility map shows the spatial distribution of landslide-prone areas is throughout the whole area. However, the level of susceptibility to landslide concentrates towards the north, east and north east part of the study area. More than 50% of high and very high landslide susceptibility areas are found around eastern part of the area. The area coverage for each class is shown in (Table 5.2). The reason of hazard is concentrates towards north east and east part is it is due to the area is characterized in its high density of fault and lineaments.

Table 5.2: Landslide susceptibility statistics of the study area

ID	Susceptibility rank	Area_km ²	Area_%
1	Very low	874.32	9
2	Low	2362.71	24
3	Medium	2955.60	31
4	High	2279.87	23

5	Very high	1215.28	13
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5.3 Model validation of landslide susceptibility map

5.3.1 Landslide inventory map

The inventory of landslides (Fig 5.2) in the study area has collected landslide information from three different data sources. The first source is the Geological Survey of Ethiopia. Forty GPS point data is collected from geological survey which mapped as landslide hazard area as rock fall and debris flow hazard area. The second source of data is literature review (Ismail et al., 2017) and the other is Google earth images. Based on thus data all landslide area is digitized by using GPS location and Google earth images. When I digitized on Google earth, I was used different manifestation of landslide like fault scarp, debris flow and also the displaced area.

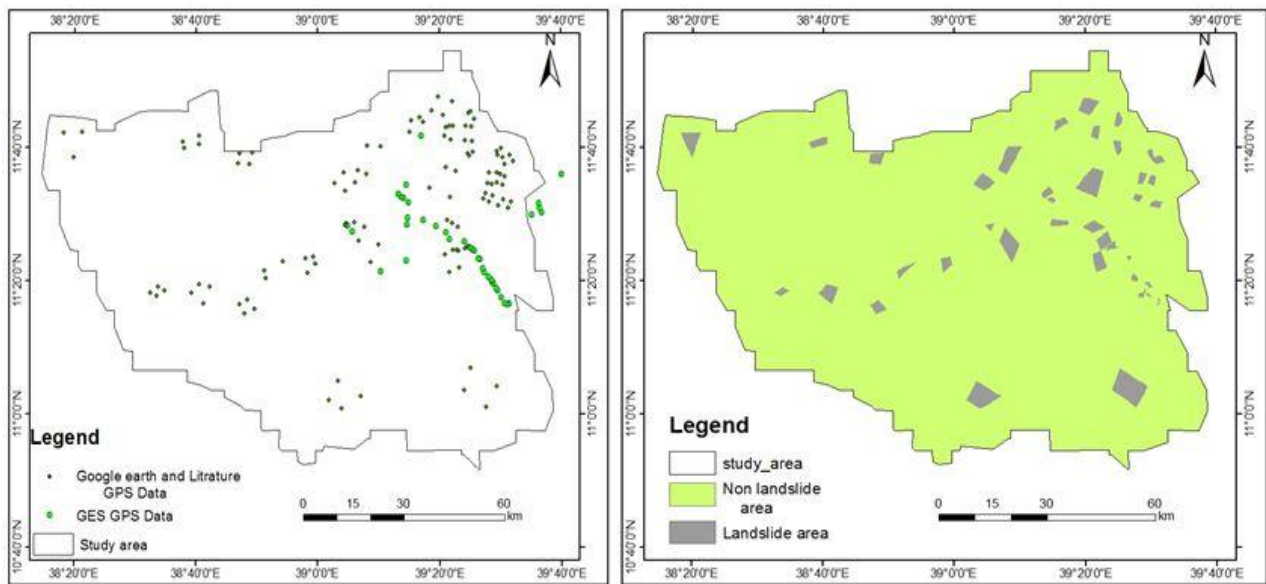


Fig 5.2: Landslide inventory map

5.3.2 Landslide susceptibility mapping model verification

The landslide susceptibility map was verified with the receiver operating characteristic (ROC) curve statistics, to generate ROC curves, landslide inventory map was generated from different data source and analysis of Google earth images by digitizing on GIS environment and rasterized it. Using this data and an index of susceptibility map done in AHP method; a module in IDRISI software generates a result constituting the true positive % and false positive % values for each

threshold that constitute the curve from which the ROC was calculated. The Results are reported in the module results box and saved to a file. Where true Positives are the instances where the model and the reference agree that landslide exists, while misclassifications are presented by False Positives (model claims landslides where they do not exist according to the reference). Finally, the plot of true positive and false positive rate was executed in excels.

The area under the curve (AUC) is the measure that indicates the accuracy of the modeled susceptibility maps. The resulting AUCs indicate the probability that more pixels were correctly labeled than incorrectly labeled. The AUC values obtained from the ROC approach for Landslide susceptibility maps is 0.848 (Fig 5.3). From this result, the performances of the model were acceptable.

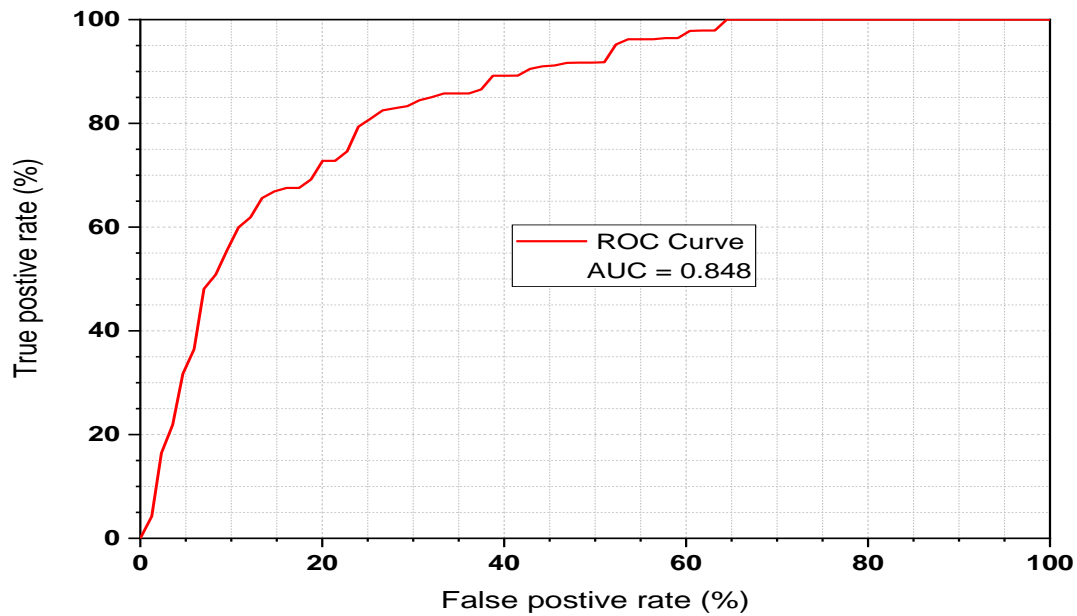


Fig 5.3: Validation results given by Roc curve

5.4 Characterizing landslide hazard in the study area

To characterize the landslide susceptibility in Beshilo watershed, a spatial model has been designed and implemented, which automatically generates landslide susceptibility map AHP approaches. Conditioning factors as geomorphological, geological, climatic, and anthropic factors were considered. The use of an inventory map of landslides that occurred in the past was

also necessary, which was produced by digitizing on GIS environment method for verification analysis. Before the design of the model, weight and ranking of the contribution of each factor, related to the landslide properties, was performed by pairwise comparison depending on expert's opinion. The result of the model consists of a landslide susceptibility index (LSI) calculated through weighted linear combination of the individual contribution of each factor, and the final index allows the susceptibility map to slide in the study area.

In this study, AHP technique was used to prepare the susceptibility maps in the study area and the model was validated using the ROC method. AHP method integrates different hazard contributing factors and finally depicts spots of landslide hazard prone areas.

The susceptibility mapping obtained from AHP model shows that high landslide hazard susceptible classes covers towards the south east, east and north east part of the study area. This could relate to the high lineament and fault density of the place. However, there is an area which falls under low and very low landslide prone including the north and west of the study area.

5.4.1 Spatial variations of landslide hazard level

According to the assessment results, level of susceptibility in the study area considerably vary.

The final GIS generated land slide susceptibility map presented in Figure 5.1. Applying the AHP technique, the Landslide hazard susceptibility map values were computed by using weighted sum analysis in Arc GIS 10.5. These LHS values were then divided into five classes based on the class of weighted sum analysis obtained from the computation. The result indicates that the most susceptible areas are located in east and north Eastern part of Beshilo. The less or no risk areas are located in the north and western parts of the area. According to the available information, the most affected areas include Segora, Ambasel area and around Geshin Mariam. The susceptibility map obtained from AHP techniques are probabilities of hazard occurring in the area.

These results are classified into five levels: very low, low, moderate, high and very high (Fig.5.1) using the natural breaks algorithm, which groups similar values together maximizing the difference between classes. Table 5.2 shows the percentage of landslide susceptibility classes for the whole study area. The landslide hazard susceptibility map prepared for the present study (Fig 5.1) revealed that 9%(874.32km²) of the study area occupies very low, 24% (2362.71km²) low, 31% (2955.60km²) medium, 23% (2279.87km²) High, and the rest 13% (1215.28km²) very

high hazard zones.

5.4.2 The relationship between level of landslide susceptibility and causative factors

At the beginning, in the present study, through review of previous works and Google earth image interpretation, the eleven factors including lithology, LULC, drainage, Faults and lineaments, precipitation, slope, aspect, elevation, soil texture and soil depth were recognized as primary triggering factors for landslide occurrence (Anbalagan, 1992). Factors that directly and indirectly affect slope stability and are responsible for the occurrence of landslides include the above listed factors. Weathering, land use and cover type are important anthropogenic activities. Normally, landslide susceptible map results depend on the combined effect of all these factors.

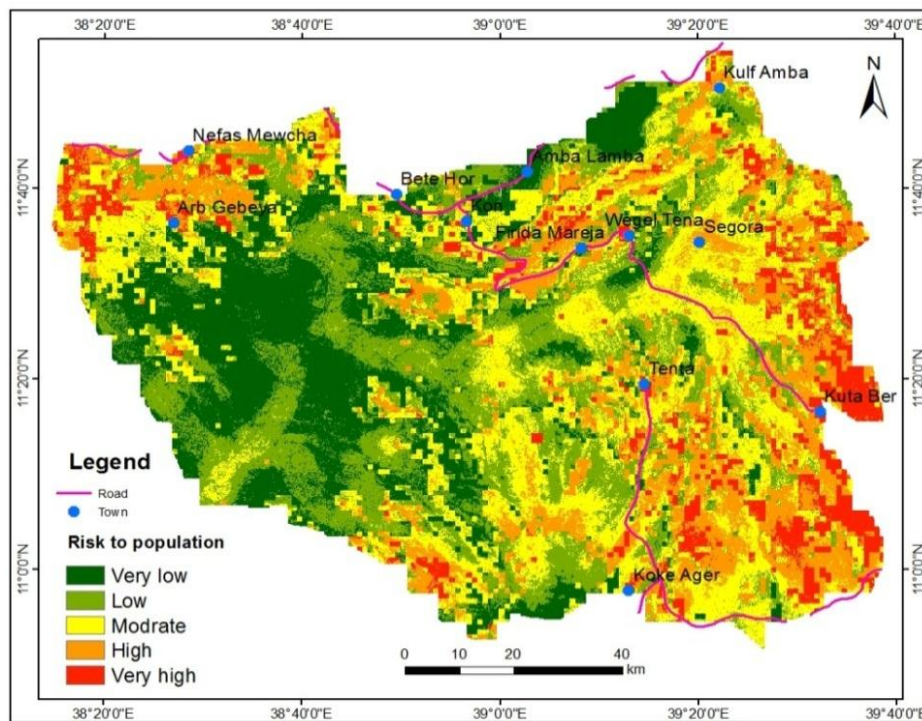
We can understand that high amount and intensity of precipitation, steep slope on hill, high density of drainage and the like doesn't often trigger landslides, whereas landslide will occur a combination of comparative amount of factors is needed. This study shows medium amount of rainfall, rolling to moderately steep slope, loosely compacted loosely deposited and extensively weathered and eroded type of lithology like tuff and rhyolite types of rock with shallow soil depth and sandy loam texture and also high density of geologic structure like fault and lineament leads to land sliding.

5.5 Landslide risk assessment

Many researchs are done on risk assessment of landslide worldwide. Risk due to landslide is mainly depending on the proximity of element at risk from landslide events. Based on the processing method and input data landslide risk assessment can be sub-divided into two as quantitative or qualitative landslide risk assessment. In this study qualitative landslide risk assessment is analyzed. Qualitative landslide risk assessment is done by combinations of qualitative maps generated from expert's opinion, literature review and knowledge based analysis. Analytical hierarchy process approach is done to estimate the landslide susceptible potential zones on the basis of contributing factors. This process is based on assumptions which indicate the relation between landslide susceptibility and contributing factors. These input factors for processed for the landslide susceptibility model with an output as weight map for different contributing factors. Because of lack of measured available data qualitative risk assessment is more applicable for this study. Too little information was available to carry out a sophisticated

landslide risk assessment. In particular, there were not enough data on the probability of landslides of different magnitudes to make a quantitative risk assessment. Hence, relative risk analysis was carried out through the combination of procedures, using the landslide susceptibility map and population distribution and LULC as basic elements at risk. Ideally, landslide risk zoning maps are prepared using the hazard zoning maps, as well as the elements at risk. Elements at risk considered in this work included population, the quantifying parameter was the population density and land use land cover map of the area. In order to understand the susceptibility to human lives, the risk to population was estimated and the high-risk zones were identified by weighting overlay of damage potential reclassified map with susceptibility map (Figure 5.3a). The obtained map was classified into five classes (very low, low, moderate, high, and very high based on the natural break classification technique. According to their capability of is prepared for each element at risk. Then by combining the reclassified map with the susceptibility map we can get the relative risk potential map of land use land cover also (Fig 5.3b).

a) Potential risk to population



b) Potential risk to LULC

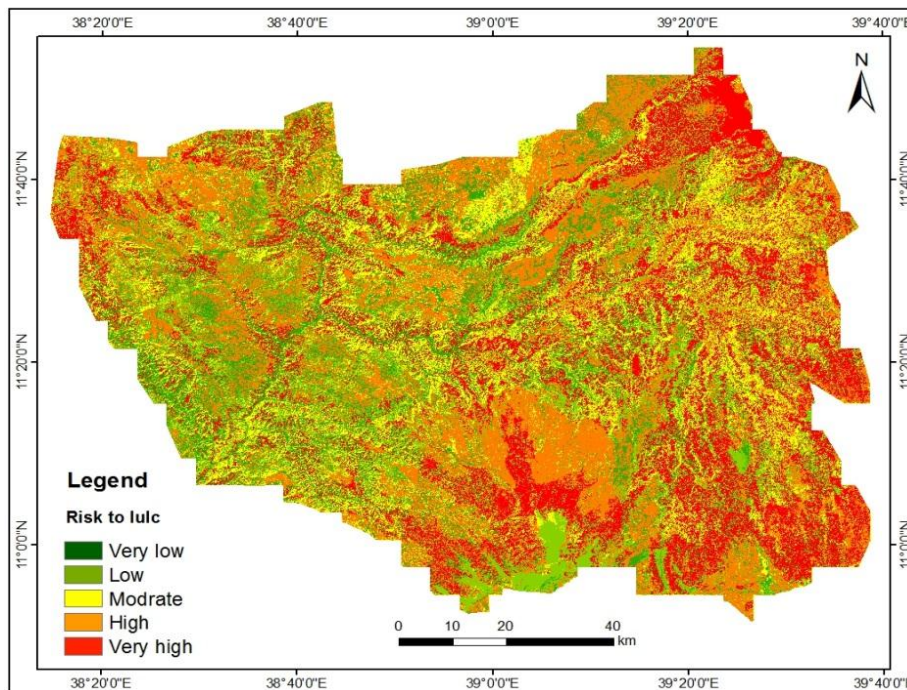


Fig 5.4: Relative risk map

The result shows high population density and some towns like Kutaber, Segora and Tenta are a subset of high to very high hazard susceptibility zone. The main roads also cut across very high to high at some area of hazard susceptible zone. From element at risk considered in this study Land use land cover of the area is found at risk. From Land use land cover natural resources which are forests and agriculture/cropland and also settlement are more risk. Fig 5.4 shows the relative risk map of population and land use and land cover of the area.

5.5.1 Characterizing landslide risk of the study area

To characterize the landslide risk in Beshilo watershed, a spatial model has been designed and implemented, which automatically generates landslide risk map through weighted overlay approaches. At present study risk assessment map can be done by weighted overlay of exposures map with the susceptibility map. This is done for land use land covers and population density the damage potentials for land categories and population density have been evaluated separately. Later by combining the damage potential map with the landslide susceptibility map, the risk assessment (RA) map has been prepared for both land categories and population density.

This is done through weighted overlay method in ArcGIS environment.

5.5.2 Landslide hazard versus landslide risk

In this study landslide hazard maps are still of a qualitative nature and concentrate basically on determining the susceptibility through combinations of a set of environmental factors depending on their response to land sliding, which can be seen as a relative indication of the spatial probability. In this case, probability and losses are expressed in qualitative terms. More work also needs to be done on landslide risk map but it is difficult without knowing actual number of loses of element at risk due to land sliding and generation of damage functions. One of the other main types of data for landslide risk assessment is the elements at risk. Elements at risk refer to the population, buildings, civil engineering works, economic activities, public services, utilities and infrastructure, etc., which are at risk in a given area. In this study emphasis is mostly given to population and land use land cover. To determine the risk map the hazard map is as an input factor. When we see the susceptibility map and the two risk map is the population risk map indicate that the somewhat same to the susceptibility map whereas the land use land cover risk map shows more area is at risk since it is natural resource perspective.

5.6 Impact of risk from development and infrastructure perspective

Geo-hazards like Landslide are one of the crucial environmental problems for the development of infrastructure and urbanization in Ethiopia, (Fubelli *et al.*, 2015; Brown *et al.* 2015). When development is bringing to an area different anthropogenic factor is initiate land sliding. For instance, road construction is one of the anthropogenic factors which can fuel the occurrence of land sliding. On the other hand the hazard susceptibility map produced from this study could enable to assess the susceptibility of existing infrastructural which found at-risk zone. In addition, the spatial location of thus infrastructures with respect to the risk map can be an overlay and known their label of risk to the possible disaster that will pose. The result shows high population density (settlement) and some towns like Kutaber, Segora and Tenta are a subset of high to very high hazard susceptibility zone. The main roads also cut across very high to high at some area of hazard susceptible zone.

5.7 Impact of risk from land resource perspective

From element at risk considered in this study Land use land cover of the area is assessed. From

Land use land cover potential risk map forests which are one of natural resources and the other is agriculture/cropland which is a means of livelihood for the people staying there are located more susceptible zone. It indicates that informing decision-makers about potentially susceptible areas would help them to employing effective technological measures to overcome the potential threat around all element risk like forests, agriculture area to prevent unplanned cultivation in addition to urbanization (settlement) and road construction.

5.8 Potential and gaps of the approach in showing landslide hazard and landslide risk over complex area

This study demonstrates the use of Geographic Information (GIS) and somewhat remote sensing system to assess landslide hazard prone areas. An attempt was made to map landslide hazard susceptibility using AHP method. The production of susceptibility map /hazard zonation mapping/ is the first step in managing a sustainable risk mitigation program in any geo-hazard-prone area. In this research, landslide susceptibility maps for the entire study region were produced. Analytical hierarchy process approach is used to estimate the landslide susceptible potential zones on the basis of contributing factors. GIS-based AHP has gained popularity because of its capacity to integrate a large quantity of heterogeneous data, and because obtaining the required weights can be relatively straightforward, even for a large number of criteria. It has been applied to a variety of decision making problems (Tiwari et al., 1999). Geographic Information Systems are very suitable for indirect landslide susceptibility mapping, in which all possible terrain factors which contribute to land sliding are combined through AHP approaches. The developed susceptibility map can serve as a guideline for local disaster management agencies for development activities. It is necessary to recognize and map landslide-prone areas to achieve efficient and safe operations in the area. Informing decision-makers about potentially susceptible areas would help them to avoid developing unsuitable structures in the area and employing effective technological measures to overcome the potential threat.

The main gap of this research is the weighting and ranking of factors which is highly subjective even if this is expert's opinion and software assisted. And lack of detailed field survey to identify the type, location and time of the occurrence of landslide and lack of record to describe actual loss of element at risk to assess the risk assessment.

6.1 Conclusion

This study demonstrates the use of remote sensing and Geographic Information System (GIS) to assess landslide hazard prone areas. An attempt was made to map landslide hazard susceptibility using AHP method. Satellite data are found to be useful in mapping and qualitatively analyze natural disasters using different available software.

The production of susceptibility maps is the first step in managing a sustainable risk mitigation program in any geo-hazard -prone area. For the entire study, no previous attempts have been made to produce susceptibility maps using GIS and remote sensing approach. In this research, landslide susceptibility maps for the entire study region were done.

As the purpose of geo-hazard susceptibility map, to predict the probability of future landslide hazard occurrence in an area, identify the spatial location of very high landslide hazard prone area were targeted. In the study, available spatial datasets were used as inputs into GIS to predict landslide susceptible areas in Bashilo watershed. For this purpose, eleven landslide hazard contributing factors were generated and evaluated using AHP Technique. These spatial data sets are LULC and geomorphic factor. The Data were combined based on their significance, to map hazard susceptibility. To prepare landslide susceptible map, eleven major landslide causative factors were used; these factors are lithology, LULC, drainage, Faults and lineaments, precipitation, slope, aspect, elevation, soil texture and soil depth. By combining those factors the produced maps shows 9%(874.32km²) of the study area occupies very low, 24% (2362.71km²) low, 31% (2955.60km²) medium, 23% (2279.87km²) High, and the rest 13% (1215.28km²) very high hazard zones. Those tells there is an area which falls under low and very low landslide prone including the north and west of the study area. To validate the produced landslide susceptibility map Roc curve were used. The validation of the model result using ROC curve analysis tells the performance of the susceptibility map was acceptable. The results of the AUC values obtained from the ROC approach validation of the model done using AHP method showed the hazard susceptibility map has greater accuracy, where AUC value is 0.848. To assess the susceptibility of element at risk overlay map of exposure with hazard susceptibility map. And we can say that the most susceptible is densely populated area, agricultural area and forests.

The expectation was that the analysis would be affected by the quality of the data. Furthermore, the subjective nature of the linear combination and pair-wise comparison matrix generation would impose additional errors. Despite these limitations, the results were still reasonable since the validation of the model is acceptable. On the basis of these results, we conclude that pair-wise comparison and linear combination GIS techniques and the available spatial datasets could still be used to predict landslide susceptibility at a regional level in the area.

6.2 Recommendation

There is a need to plan for studying possible hazards that could pose a threat to human lives, settlement, infrastructure and agriculture lands, which found at a hazard prone area. Without any doubt, the study area is among the place in Ethiopia that will have hazard. Understanding the nature of hazards, producing hazard susceptibility maps, assess the level of risks on the existing exposure, change monitoring and others are very crucial and possible measures which should be done. To improve the prediction of landslides risk areas, we recommend use of more recent data. Since expert opinion introduces subjectivity in the results, we recommend replacement of such opinions with researched parameters as more scientific studies are undertaken to determine the actual parameters. Additionally quantify the element at risk numerically helps to know the level of risk in the area and introduced for monitoring the activities developers and disaster management activity governors.

References

- Abolghasem A., Noram I.B., and Ngien, K. (2016). Application of Public Domain Satellite based DEMs in Natural Hazard Modeling. *International Journal of Environmental Science and Development*.7:140-143.
- Ahmed, M. F. and Rogers, J. D., 2012, Landslide mapping and identification of old landslide dams along the Indus River 331 in Pakistan, using GIS techniques. In *Association of Environmental & Engineering Geologists 55th Annual Meeting*: Salt Lake City, UT, **55**, 44p.
- Ahmed, M. F. and Rogers, J. D., 2016, Regional level landslide inventory maps of the Shyok River watershed, northern Pakistan: *Bulletin of Engineering Geology and the Environment*. **75**, pp. 563–574.
- Aleotti, P., Chowdhury.R., (1999). Landslide hazard assessment: summery, review and new perspective. *Bull. Eng. Geol. Environ.* **58**:21–44.
- Anbalagan, R. (1992). Landslide hazard evaluation and zonation mapping in mountainous terrain. *Engineering Geology*, 32(4), 269–277.
- Anbalagan, Rathinam, Kumar, R., Lakshmanan, K., Parida, S., & Neethu, S. (2015). Landslide hazard zonation mapping using frequency ratio and fuzzy logic approach, a case study of Lachung Valley, Sikkim. *Geoenvironmental Disasters*, 2(1).
- Arnous, M. O., (2011). Integrated remote sensing and GIS techniques for landslide hazard zonation: a case study WadiWatier area, South Sinai, Egypt. *Journal of Coastal Conservation*.**15**:477–497.
- Asfawosen Asrat, Eshete Gebretsidik, Tadesse, S., Getaneh, A., Fekede, K., (1996). Land mass movement of November 10, 1994 in Goffa District, Northern Omo Zone, and Southern Ethiopia. **In: Third Ethiopian Geoscience and Mineral Engineering Congress**, Addis Ababa, pp. 18–19.
- Asmelash Abay, Giulio Barbieri and Kifle Woldearegay., (2019). GIS-based Landslide Susceptibility Evaluation Using Analytical Hierarchy Process (AHP) Approach. *Momona Ethiopian Journal of Science*, **11** (1):14–36.
- Ayalew, L. (1999). Causes and mechanisms of slope instability in Dessie town, Ethiopia. *Slope stability engineering*.

Ayalew, L., Yamagishi, H. (2004). Slope failures in the Blue Nile Basin, as seen from landscape evolution perspective. *Geomorphology* **57**: 95-116.

Balezentiene, L., Streimikiene, D., Balezentis, T., (2013). Fuzzy decision support methodology for sustainable energy crop selection. *Renewable Sustainable Energy Review*. **17**:83-93.

Bathrellos, G.D.; Skilodimou, H.D.; Chousianitis, K.; Youssef, A.M.; Pradhan, B. (2017). Suitability estimation for urban development using multi-hazard assessment map. *Science total Environmental*, **575**, 119–134.

Baum, R., Godt, J. W., and Highland, L. (2008). Landslides and Engineering Geology of the Seattle, Washington, Area, Geological Society of America. p. 104.

Bekele Abebe, Dramis, F., Fubelli G., Mohammed Umer, Asfawossen Asrat, (2010). Landslides in the Ethiopian highlands and the Rift margins. *J. Afr. Ear. Sc.* **56**:131–138.

Bisson, M., Sulpizio, R., Zanchetta, G., Demi, F., Santacroce, R. (2010). Rapid terrain-based mapping of some volcanoclastic flow hazard using GIS-based automated methods: a case study from southern Campania, Italy. *Natural Hazards*. **55**, 371–387.

Bonini, M., Corti, G., Innocenti, F., Manetti, P., Mazzarini, F., Abebe, T. and Zoltan P. (2005). Evolution of the Main Ethiopian Rift in the frame of Afar and Kenya rifts propagation, *International Journal of Tectonics*, **24**, TC1007.

Bui, D.T.; Pradhan, B.; Löfman, O.; Revhaug, I., (2012). Regional prediction of landslide hazard using probability analysis of intense rainfall. *National Hazards* **66**, 707–730.

Cevik, E. and Topal, T. (2003). GIS-based landslide susceptibility mapping for a problematic segment of the natural gas pipeline, Hendek (Turkey). *Environmental Geology*. **44**: 949–962.

Clerici, A., Perego, S., Tellini, C. and Vescovi, P. (2002). A procedure for landslide susceptibility zonation by the conditional analysis method. *Geomorphology*. **48**: 349–364.

Chen, W., Chen, W., Panahi, M., Kornejady, A., Wang, J., Xie, X., Cao, S., (2017). Spatial

prediction of landslide Susceptibility using an adaptive neuro-fuzzy inference system combined with frequency ratio, generalized additive model, and support vector machine techniques. *Geomorphology*, **297**, 69–85.

Conoscenti, C.; Rotigliano, E.; Cama, M.; Arias, N.A.C.; Lombardo, L.; Agnesi, V., (2016). Exploring the effect of absence selection on landslide susceptibility models: A case study in Sicily, Italy. *Geomorphology*, **261**, 222–235.

Dai, F.C., Lee, C.F., (2002). Landslide characteristics and slope instability modeling using GIS, Lantau Island, Hong Kong. *Geomorphology*, **42**, 213–228.

Dai, F., & Lee, C. (2001). Frequency–volume relation and prediction of rainfall induced landslides. *Engineering Geology*, **59**(3), 253-266.

Ercanoglu, M. and Gokceoglu, C. (2004). Use of fuzzy relations to produce landslide susceptibility map of a landslide-prone area. *Engineering Geology*. **75**: 229–250.

Erden, T. and Karaman, H., (2012). Analysis of earthquake parameters to generate hazard maps by integrating AHP and GIS. *Nat. Hazards and Earth System Sci.* **12**: 475–483.

Fell R, Corominas J, Bonnard C, Cascini L, Leroi E, Savage WZ. (2008). Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. *Engineering geology*, **102**:85–98.

Gritzner L.M., Marcus W.A., Aspinall R., & Custer S.G., (2001).Assessing landslide potential using GIS, soil wetness modeling and topographic attributes. *Geomorphology*, **37**:149-165.

Ghorbanzadeh, O.; Blaschke, T.; Aryal, J.; Gholaminia, K., (2018). A new GIS-based technique using an adaptive neuro-fuzzy inference system for land subsidence susceptibility mapping. *Journal of Spatial Science*, 1–17.

Handy, R.L. and Spangler, M.G. (2007). *Geotechnical Engineering, Soil and Foundation*. McGraw Hill Companies.

Haneberg, W. C. and Anderson, S. A. (1995). Clay and Shale Slope Instability, Division of Engineering Geology Geological Society of America. p. 90.

Harris, S.M.; Carvalho, L.V., (2014). Atmospheric River Development and Effects on Southern California; American Geophysical Union: Washington, DC, USA.

Hencher, S.R. (1989). The implication of joints and structures for slope stability, In M. & Anderson, Stability. *Geotechnical and Geomorphology*.**8**: 145-186.

<https://www.usgs.gov/faqs/fault> accessed on 20.02.2020.

Ismail, E. H., (2011). Morph-Tectonic Analysis of the Tekeze and the Blue Nile Drainage Systems of Northwestern Ethiopian Plateau, Ethiopia: *M.Sc. Thesis, Missouri University of Science and Technology*, Rolla, MO, 115 p.

Ismail, E.H., Rogers, J.D., Ahmed, M.F., (2017). Regional Landslide Inventory Mapping of Bashilo River Watershed, Ethiopia. *Environmental & Engineering Geoscience*, **13**:2,137–151.

Ismail E.H.;Rogers, J.D.;AHMED,M.F.; ANDABU-BAKAR,M.Z., 2016, Subsurface profile interpretation of landslides, examples from Bashilo River watershed, Ethiopia, *Environmental Earth Sciences*, Vol. 75, 1153 p.

Karim, S., Zhang, Y., Asif, M.R., Ali, S. (2017). Comparative analysis of feature extraction methods in satellite imagery, *Journal of Applied Remote Sensing* **11**(4), 042618.

Kifle Woldearegay, (2013). Review of the occurrences and influencing factors of landslides in the highlands of Ethiopia: With implications for infrastructural development. *Momona Ethiopian Journal of Science*, **5**(1):3–31.

Coçal, A. (2004). A Methodology for Detection and Evaluation of Lineaments from Satellite Imagery. Ms. Thesis, Middle East Technical University, 121 p.

Koike, K., Nagano, S. And Ohmi, M. (1995). Lineament Analysis of Satellite Images Using A Segment Tracing Algorithm (STA). *Computers and Geosciences*. **21**: 1091-1104.

Kanungo, D. P., Arora, M. K., Sarkar, S. and Gupta, R. P. (2009). A comparative Study of conventional, ANN black box, fuzzy and combined neutral and fuzzy weighting procedures for

landslide susceptibility Zonation in Darjeeling Himalayas. *Engineering geology* 85. pp 347-366.

Jensen, J. R. (1996). —Introductory Digital Image Processing, Prentice Hall Series in Geographic Information Science, New Jersey.

Johnson, K. A., & Sitar, N. (1990). Hydrologic Conditions Leading to Debris Flow Initiation. *Canadian Geotechnical Journal*, **27**(6), 789-801.

Ladas I, Fountoulis I and Mariolakos I. (2007). Using GIS and Multicriteria decision analysis in landslide susceptibility mapping—a case study in Messinia prefecture area (SW Peloponnesus, Greece). *Bull Geol Soc Greece* 40(4):1973–1985

Lee, S., Choi, J. and Min, K. (2005). Probabilistic landslide hazard mapping using GIS and remote sensing data at Boun, Korea. *International Journal of Remote Sensing*. **25**: 2037–2052.

Lillesand, T.M., Keifer, R.W. and Chipman J.W., (2004). *Remote Sensing and Image Interpretation*||, 5th Edition.

Lulseged Ayalew and Yamagishi.H. (2004). Slope failure in Blue Nile basin, as seen from landscape evolution perspective. *Geomorphology* **57**: 95–116.

Lulseged Ayalew and Yamagishi, H. (2005). The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda–Yahiko Mountains, Central Japan. *Geomorphology*. **65**: 15–31.

Malik, M.H. (1996). Landslide hazard management and control in Pakistan: A review. *International Centre for Integrated Mountain Development*, pp.77.

Meneses, B.; Pereira, S.; Reis, E., (2019). Effects of different land use and land cover data on the landslide susceptibility zonation of road networks. *National Hazards Earth System Science.*, **19**, 471–487.

Mahdadi, F.; Boumezbeur, A.; Hadji, R.; Kanungo, D.P.; Zahri, F., (2018). GIS-based landslide susceptibility assessment using statistical models. *Arabian Journal Geoscience*. **11**, 476.

Mark, P., Tianqing C., Tim, D., Arthur, F., Chris, W. and David S.(2004). Mapping fault rupture hazard for strike-slip earthquakes. 3rd World Conference on Earthquake Engineering. August 1-6, 2004: Paper No. 1094. Vancouver, B.C., Canada.

Musiguzi M. and Asimwe I., (2014). Application of geospatial tools for landslide hazard assessment. *South African journal of geomatics*. **3**:3.

Nama, E.E. (2004). Lineament detection on Mount Cameroon during the 1999 volcanic eruptions using Landsat ETM. *International Journal of Remote Sensing*. **25**: 501-510.

Neaupane, K.M., and Piantanakulchai. M. (2006). Analytic network process model for landslide hazard zonation. *Engineering Geology* **85**: 281–294.

O’Leary, D. Friedman, J., Pohn, H. (1976). Lineament, linear, lineation: Some proposed new standards for old terms. *Geological Society America Bulletin*. **87**:1463-1469.

Pourghasemi, H.R.; Gayen, A.; Park, S.-J.; Lee, C.W.; Lee, S., (2018). Assessment of landslide-prone areas and their zonation using logistic regression. *Machine-learning algorithms. Sustainability*, **10**, 3697.

Pradhan, B., Lee, S., Buchroithner, M.F. (2010). Remote sensing and GIS-based landslide susceptibility analysis and its cross-validation in three test areas using a frequency ratio model *Photogrammetry Fernerkundung Geoinformation*.

Raghuvanshi, T.K, Jemal Ibrahim, Dereje Ayalew, (2014a). Slope stability susceptibility evaluation parameter (SSEP) rating scheme – an approach for landslide hazard zonation. *Journal of African Earth Science*. **99**: 595–612.

Raghuvanshji, T.K, P.M. Kala and M. Singh (2014b). Landslide disaster management and reduction-An approach through remote sensing and GIS. In: *Landscape Ecology and Water Management*, proceeding of International Geographical Union (IGU) Rohatic Conference.

Raghuvanshi, T.K., Negassa, L., Kala, P.M. (2015). GIS based Grid Overlay Method versus Modeling Approach – A Comparative Study for Landslide Hazard Zonation (LHZ) in Meta Robi

District of West Showa Zone in Ethiopia. Egypt. *J. Remote sensing SpaceSci.***18**: 235-250.

Ramli, M.F., Yusof, N., Yusoff, M.K., Juahir, H., and Shafri, H. (2010). Lineament mapping and its application in landslide hazard assessment: a review. *Bulletin of Engineering Geology and Environment.* **69**: 215–233.

Roslee, R., Tahir, S., Omang, A.K S. (2006). Engineering geology of the Kota Kinabalu area, Sabah, Malaysia. *Geological Society of Malaysia Bulletin.* **52**: 17- 25.

Advance in Geographical and Enviromental Science(M.singh,R.B. Singh and M.I. Hassen:Editor), Sringer Japan. **2**, pp.33–40.

Yalcin, A.; Bulut, F., (2006). Landslide susceptibility mapping using GIS and digital photogrammetric techniques. *National Hazards*, **41**, 201–226.

Saaty, T. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology.* **15**: 234–281.

Saaty, T. and Vargas, G., (2001). Models, Methods, Concepts, and Applications of the Analytic Hierarchy Process, Kluwer Academic Publisher, Boston.

Saaty, T.L. (2005). Theory and Applications of the Analytic Network Process, Pittsburgh, PA: RWS Publications.

Saaty, T. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences.* **1**:83–98.

Safaei, M., Omar H., Huat B.K. and Yousof Z.B.M. (2012). Relation between lithology factor and landslide occurrence based on informative values and frequency ratio (FR) approaches.

Segoni, S, Pappafico, G., Luti, T., Catani, F., (2020). Landslide susceptibility assessment in complex geological settings: Sensitivity to geological information and insights on its parameterization. *Landslides*, 1–11.

Sharma L.P., Debnath M.K. and Patel N., (2012). Assessing landslide vulnerability from soil characteristics. *Arabian journal of Geoscience*. **5**: 789-796.

Singh, A.K., (2010). Landslide management: Concept and philosophy. *Disaster Prevention and Management*, 19,119-134. <http://dx.doi.org/10.1016/j.landusepol.2009.10.013>.

Skilodimou H.D., Bathrellos, G.D., Soukis K. and Rozas D. (2018). Physical and anthropogenic factors related to landslide activity.

Sanderson, G. C., Parlange, J.-Y., & Hogarth, W. L. (1996). Air and water flow, II. Gravitational flow with an arbitrary flux boundary condition. *Journal of Hydrology*, **99**(3), 225-234.

Temesgen, B., Mohammed, M.U & Korme, T. (2001). Natural hazard assessment using GIS and remote sensing methods, with particular reference to the landslides in the Wondogenet area, Ethiopia. *Phys. Chem. Earth*, **26**(9):665-675.

Tenalem Ayenew and Barbieri, G. (2004). Inventory of landslides and susceptibility mapping in the Dessie area, Northern Ethiopia. *Engineering Geology*. **77**:1–15.

Terlien, M. T. J. (1998). The determination of statistical and deterministic hydrological landslide-triggering thresholds. *Environmental Geology*, **35**(2-3), 124-130.

Varnes, D.J., (1978). Slope movements types and processes. **In**: Schuster, R.L., Krizek, R.S. (Eds.), *Landslides: Analysis and Control*. Transportation Research Board, National Academy of Sciences, Special Report 176, 2, Washington, DC, pp. 20–47.

Varnes, D. J. (1984). Landslide hazard zonation: a review of principles and practice. **In**: International Association of Engineering Geology Commission on Landslide and Other Mass Movements on Slopes. *United Nations Educational, Scientific and Cultural Organization* (UNESCO), 60 pp.

Van Asch T.W.J., Van Westen C.J., Soeters R., (2006). Landslide hazard and risk zonation - why is it still so difficult?. *Bulletin of Eng. Geology and the Envir*. **65**:167-184.

Wieczorek, G. F., & Jager, S. (1987). Triggering mechanisms and depositional rates of postglacial slope-movement. *Geomorphology*, 15(1), 17-31.

Woldearegay, K. (2005). Rainfall-triggered landslides in the northern highlands of Ethiopia: Characterization, GIS-based Prediction and Mitigation. Unpublished PhD Thesis. Faculty of Civil Engineering, Graz University of Technology, 176p.

Wolfenden, E., Ebinger, C. and Gezahegn Yirgu. (2005). Evolution of the northern main Ethiopian Rift, *Earth and Planetary Science letters*, 224(1-2):213-228.

Woldearegay, K. (2008). Characteristics of large-scale landslide triggered by heavy rainfall in Tarmaber area, Central Highlands of Ethiopia. *Geophysical Research Abstracts*, 10, 1607-7962.

Workineh Haro, Dejene Hailemariam, Iyasu Getachew, Thomas Kassahun, Shimelis Ashenafi, Getachew Burisa, and Mohamed Edris., (2010). Geology, geochemistry and gravity survey. *Geological survey of Ethiopia*, Unpublished report.

Yalcin, A. (2008). GIS-based landslide susceptibility mapping using analytical hierarchy process and bivariate statistics in Ardesen (Turkey). *Catena*. 72: 1–12.

Yusof N., Ramli M. F., Pirasteh S. and Shafri H. Z. M. (2011): Landslides and lineament mapping. *International Journal of Remote Sensing*, 32:14, 4089-4105.

Zadeh, L., (1965). Fuzzy Sets”, *Information Control* 8,338–353.

Appendix I: GPS points for landslide inventory

No	X (Easting)	Y(Northing)		X(Easting)	Y(Northing)
1	557212.55 m E	1246632.31 m N	1	424024.48 m E	1293878.56 m N
2	556746.62 m E	1246445.26 m N	2	427167.67 m E	1286962.80 m N
3	555972.71 m E	1246475.38 m N	3	429678.21 m E	1293996.29 m N
4	554858.69 m E	1248238.24 m N	4	459623.90 m E	1291200.51 m N
5	553773.35 m E	1250088.70 m N	5	460242.09 m E	1289612.67 m N
6	553309.68 m E	1250840.74 m N	6	464641.65 m E	1292889.43 m N
7	552440.30 m E	1252144.73 m N	7	464643.74 m E	1290702.90 m N
8	552039.08 m E	1252670.93 m N	8	476563.81 m E	1288003.57 m N
9	551851.88 m E	1253041.28 m N	9	480501.27 m E	1288328.62 m N
10	551080.74 m E	1253964.52 m N	10	476262.62 m E	1285336.31 m N
11	549750.39 m E	1255201.95 m N	11	479573.77 m E	1285024.88 m N
12	549251.70 m E	1256409.42 m N	12	449912.90 m E	1249584.62 m N
13	548391.92 m E	1258862.08 m N	13	451793.58 m E	1248643.85 m N
14	548108.57 m E	1259143.13 m N	14	454313.56 m E	1250229.17 m N
15	546842.71 m E	1261173.11 m N	15	452263.49 m E	1251148.07 m N
16	546096.46 m E	1261650.23 m N	16	462164.79 m E	1249445.65 m N
17	545570.86 m E	1262061.15 m N	17	464655.64 m E	1251940.27 m N
18	543837.40 m E	1263690.85 m N	18	465912.90 m E	1246630.17 m N
19	539443.90 m E	1264435.25 m N	19	467818.92 m E	1251158.02 m N
20	538372.28 m E	1266317.07 m N	21	476566.56 m E	1246246.99 m N
21	535450.94 m E	1267962.01 m N	22	478110.03 m E	1243763.56 m N
22	531590.82 m E	1269622.72 m N	23	481094.80 m E	1244978.51 m N
23	526592.96 m E	1268289.56 m N	24	478916.93 m E	1247668.51 m N
24	526928.90 m E	1270233.38 m N	25	484033.56 m E	1255752.35 m N
25	527167.94 m E	1274548.97 m N	26	484478.86 m E	1253590.59 m N
26	525621.97 m E	1275739.22 m N	27	489500.53 m E	1258275.98 m N
27	525067.48 m E	1275994.57 m N	28	496291.27 m E	1259055.88 m N
28	524080.33 m E	1276896.96 m N	29	496903.59 m E	1254974.48 m N
29	526350.99 m E	1279378.93 m N	30	498757.29 m E	1259562.83 m N
30	530851.28 m E	1292892.89 m N	31	499257.96 m E	1257514.56 m N
31	508445.25 m E	1268414.86 m N	32	508378.56 m E	1268302.58 m N
32	508796.65 m E	1268204.72 m N	33	511019.82 m E	1268925.38 m N
33	510256.47 m E	1266526.32 m N	34	514022.72 m E	1267655.02 m N
34	526379.69 m E	1258412.13 m N	35	512288.28 m E	1264034.22 m N
35	518907.64 m E	1255560.28 m N	36	518136.14 m E	1262929.48 m N
36	564044.74 m E	1271067.09 m N	37	515922.63 m E	1258034.04 m N

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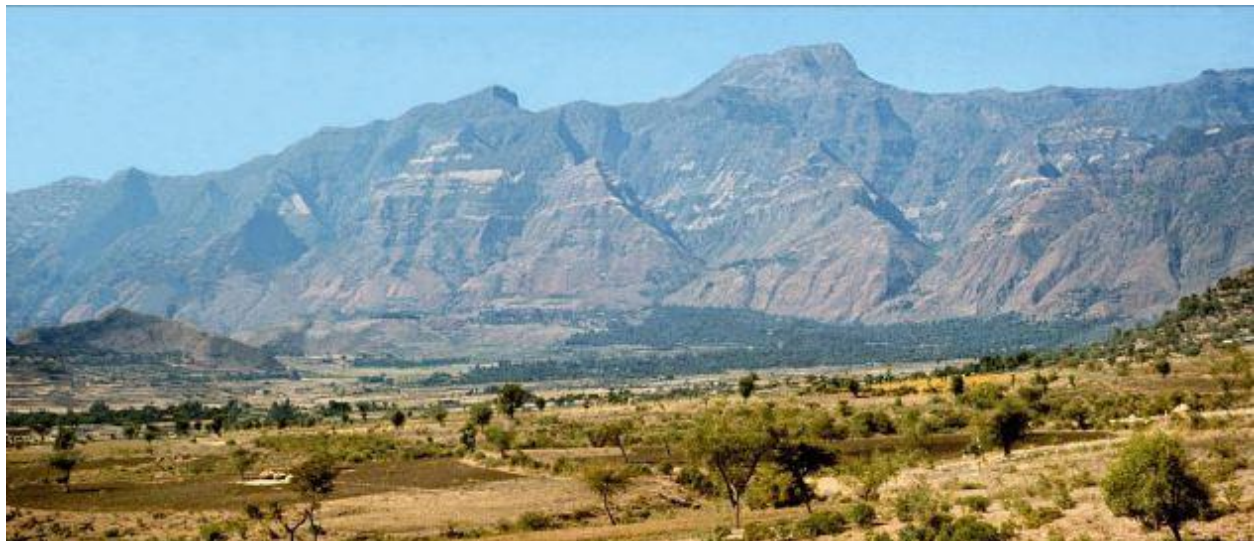
37	566973.78 m E	1271816.54 m N	38	512969.66 m E	1221024.37 m N
38	566361.01 m E	1273044.88 m N	39	506093.30 m E	1225262.61 m N
39	566108.35 m E	1274256.73 m N	40	503439.23 m E	1219904.89 m N
40	572874.15 m E	1282369.16 m N	41	507178.85 m E	1217596.15 m N

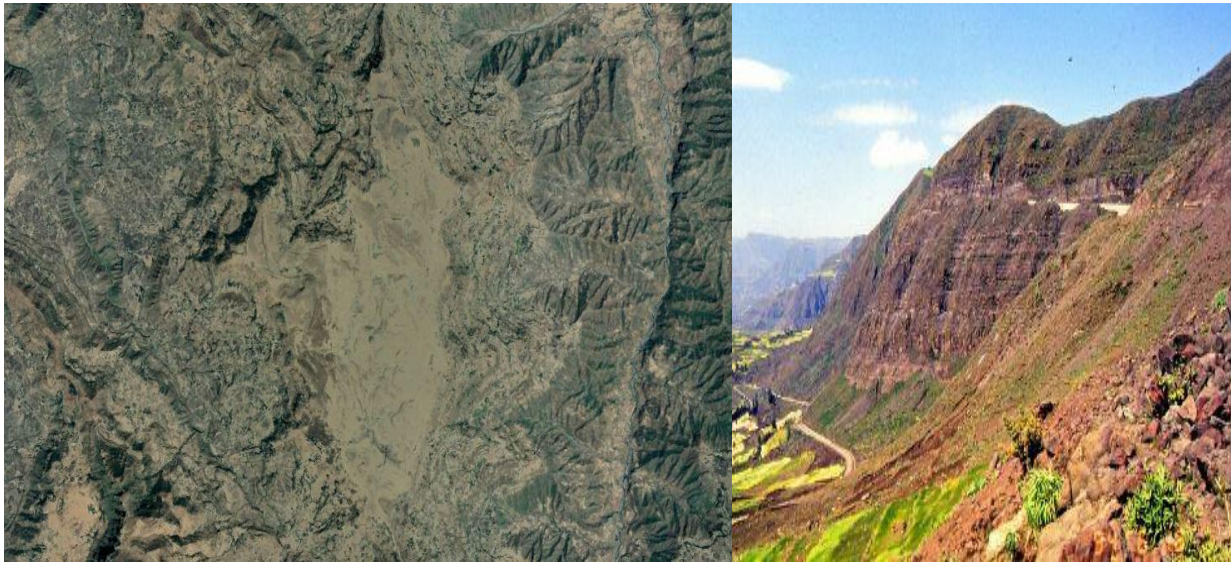
	X(Easting)	Y(Northing)		X(Easting)	Y(Northing)
42	543768.23 m E	1222726.21 m N	75	545341.59 m E	1287534.17 m N
43	545795.21 m E	1228688.18 m N	76	544843.13 m E	1288098.65 m N
44	553610.91 m E	1223638.48 m N	77	555237.42 m E	1287067.98 m N
45	550498.26 m E	1217991.07 m N	78	554839.09 m E	1289579.18 m N
46	507802.95 m E	1282728.90 m N	79	553586.00 m E	1288773.47 m N
47	505137.38 m E	1279749.69 m N	80	553807.19 m E	1287650.85 m N
48	511264.96 m E	1280047.43 m N	81	555984.70 m E	1285059.78 m N
49	508288.71 m E	1277696.46 m N	82	558450.28 m E	1285915.00 m N
50	514489.00 m E	1282439.00 m N	83	557359.23 m E	1287627.17 m N
51	511991.00 m E	1283509.00 m N	84	538283.52 m E	1284194.73 m N
52	514835.00 m E	1290152.00 m N	85	533416.22 m E	1278512.66 m N
53	518780.55 m E	1290072.10 m N	86	541346.79 m E	1283264.17 m N
54	527525.50 m E	1294063.05 m N	87	539543.41 m E	1276022.51 m N
55	528001.22 m E	1297200.27 m N	88	551316.65 m E	1282892.72 m N
56	530522.07 m E	1298155.48 m N	89	553548.16 m E	1282756.33 m N
57	531465.53 m E	1296746.48 m N	90	550865.87 m E	1279786.11 m N
58	534170.89 m E	1299923.70 m N	91	552010.07 m E	1279672.10 m N
59	537477.44 m E	1298652.75 m N	92	554528.44 m E	1282296.42 m N
60	536058.10 m E	1303717.13 m N	93	553644.90 m E	1279953.02 m N
61	540177.93 m E	1302452.02 m N	94	555278.88 m E	1279322.96 m N
62	545008.79 m E	1299347.08 m N	95	555914.16 m E	1281726.58 m N
63	545745.01 m E	1299704.01 m N	96	550286.50 m E	1276970.01 m N
64	546718.19 m E	1297526.96 m N	97	552253.05 m E	1276526.28 m N
65	545859.85 m E	1295518.78 m N	98	551300.01 m E	1274760.65 m N
66	544212.86 m E	1295688.91 m N	99	549490.10 m E	1275644.76 m N
67	540395.24 m E	1295669.40 m N	100	553973.61 m E	1273652.30 m N
68	539370.53 m E	1295795.46 m N	101	555466.00 m E	1275308.42 m N
69	538333.41 m E	1295261.36 m N	102	556883.10 m E	1272959.72 m N
70	537827.85 m E	1292872.26 m N	103	557861.38 m E	1274820.02 m N
71	539828.74 m E	1291906.16 m N	104	538199.32 m E	1260057.34 m N
72	543994.12 m E	1291701.94 m N	105	540490.80 m E	1261307.52 m N

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73	546261.49 m E	1291471.26 m N	106	542239.17 m E	1256588.44 m N
74	546370.82 m E	1288500.60 m N	107	539445.21 m E	1255329.46 m N
108	506067.63 m E	1225194.91 m N	114	544090.50 m E	1261736.73 m N
109	512962.17 m E	1220995.42 m N	115	544966.91 m E	1262495.90 m N
110	507195.53 m E	1217564.82 m N	116	541982.66 m E	1267650.07 m N
111	503388.34 m E	1219889.28 m N	117	540234.47 m E	1268874.27 m N
112	541574.72 m E	1261351.16 m N	118	538672.63 m E	1269712.04 m N
113	542110.90 m E	1261113.65 m N			

Appendix II: Landslide inventory field photo and Google earth image





Appendix III: True positive and false positive values for ROC curve

Result of ROC**
=====

AUC = 0.848

The following section list detailed statistics for each threshold.

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With each threshold, the following 2x2 contingency table is calculated

Simulated by threshold	Reality (reference image)	
	1	0
1	A (number of cells)	B (number of cells)
0	C	D
For the given reference image:	A+C=2762327	B+D=110467337

No. posi. (%)	Exp. Thrhlds (%) B	Act. Thrhlds (%) False posi. (%)	Act. raw cuts	A	True
1	0.0000	0.0000	0.0000	0	
0.0000	0	0.0000			
2	1.3333	1.3333	5.0000	116650	
4.2229	1393080	1.2611			
3	2.6667	2.6667	5.0000	453702	
16.4246	2565757	2.3226			
4	4.0000	4.0000	5.0000	604422	
21.8809	3924766	3.5529			
5	5.3333	5.3333	5.0000	875615	
31.6985	5163302	4.6741			
6	6.6667	6.6667	5.0000	1007470	
36.4718	6541176	5.9214			
7	8.0000	8.0000	5.0000	1328706	
48.1010	7729668	6.9972			
8	9.3333	9.3333	4.0000	1404090	
50.8300	9164014	8.2957			
9	10.6667	10.6667	4.0000	1534878	
55.5647	10542954	9.5440			
10	12.0000	12.0000	4.0000	1656112	
59.9535	11931449	10.8009			
11	13.3333	13.3333	4.0000	1709220	
61.8761	13388070	12.1195			
12	14.6667	14.6667	4.0000	1812172	
65.6031	14794847	13.3930			
13	16.0000	16.0000	4.0000	1847416	
66.8790	16269331	14.7277			
14	17.3333	17.3333	4.0000	1865876	
67.5473	17760601	16.0777			
15	18.6667	18.6667	4.0000	1865876	
67.5473	19270330	17.4444			
16	20.0000	20.0000	4.0000	1910847	
69.1753	20735087	18.7703			
17	21.3333	21.3333	4.0000	2010425	
72.7801	22145238	20.0469			

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18		22.6667	22.6667	4.0000	2010425
72.7801	23654968		21.4135		
19		24.0000	24.0000	3.0000	2060626
74.5975	25114494		22.7348		
20		25.3333	25.3333	3.0000	2192310
79.3646	26492540		23.9822		
21		26.6667	26.6667	3.0000	2234811
80.9032	27959769		25.3104		
22		28.0000	28.0000	3.0000	2278672
82.4910	29425635		26.6374		
23		29.3333	29.3333	3.0000	2290382
82.9149	30923654		27.9935		
24		30.6667	30.6667	3.0000	2301247
83.3083	32422519		29.3503		
25		32.0000	32.0000	3.0000	2332704
84.4471	33900789		30.6885		
26		33.3333	33.3333	3.0000	2349209
85.0446	35394016		32.0403		
27		34.6667	34.6667	3.0000	2369245
85.7699	36883708		33.3888		
28		36.0000	36.0000	3.0000	2369245
85.7699	38393435		34.7555		
29		37.3333	37.3333	3.0000	2369245
85.7699	39903167		36.1221		
30		38.6667	38.6667	3.0000	2390070
86.5238	41392069		37.4700		
31		40.0000	40.0000	3.0000	2463631
89.1868	42828236		38.7700		
32		41.3333	41.3333	3.0000	2463631
89.1868	44337967		40.1367		
33		42.6667	42.6667	2.0000	2464087
89.2033	45847239		41.5030		
34		44.0000	44.0000	2.0000	2499950
90.5016	47321103		42.8372		
35		45.3333	45.3333	2.0000	2513652
90.9976	48817133		44.1915		
36		46.6667	46.6667	2.0000	2518002
91.1551	50322510		45.5542		
37		48.0000	48.0000	2.0000	2531896
91.6581	51818344		46.9083		
38		49.3333	49.3333	2.0000	2533199
91.7053	53326772		48.2738		
39		50.6667	50.6667	2.0000	2533275
91.7080	54836424		49.6404		
40		52.0000	52.0000	2.0000	2535111
91.7745	56344315		51.0054		