Landslide Hazard Evaluation and Zonation in and around Aba-ala town, Northern Ethiopia using Expert Evaluation Techniques.

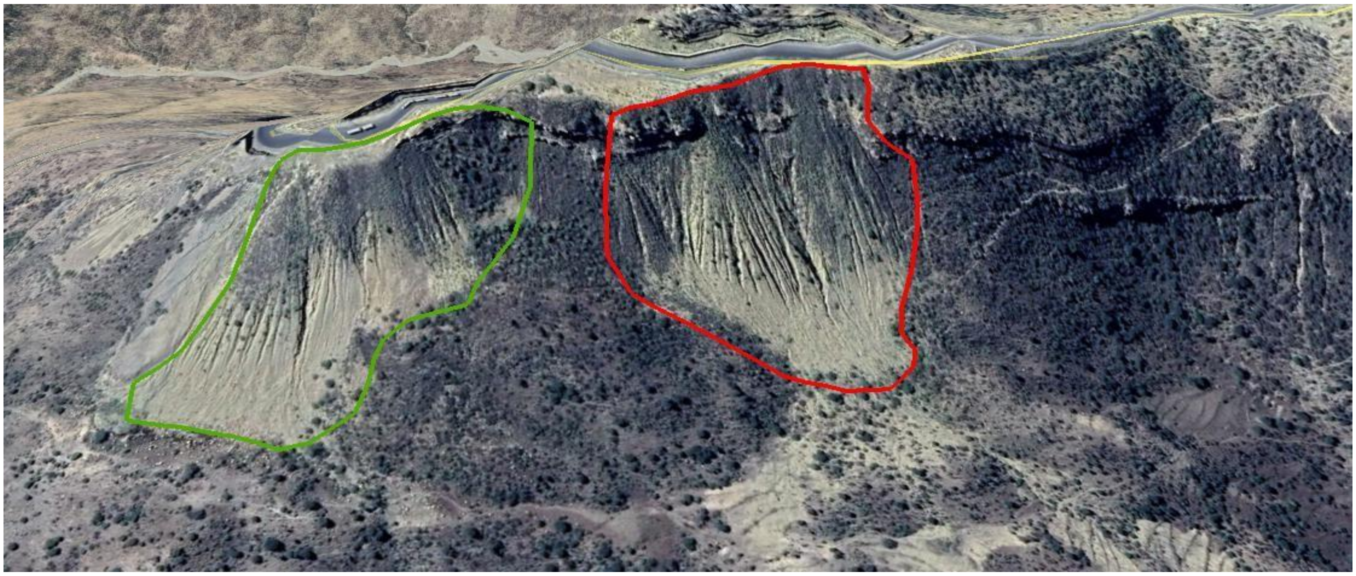
Nora Yanimio

A Thesis Submitted to
School of Earth Science

In partial Fulfillment of the requirements for
the degree of masters in
Engineering Geology

Addis Ababa University
Addis Ababa, Ethiopia

September, 2020



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SIGNITURE PAGE

Addis Ababa University

School of Graduate Studies

This is to certify that the thesis prepared by Nora Yanimio, entitled: Landslide Hazard Evaluation and Zonation in and around Aba-ala Town, Northern Ethiopia Using Expert Evaluation Techniques and submitted in partial fulfillment of the requirement for the Degree of Master of Science (Engineering Geology) compiles with the regulation of the University and meets the accepted standard with respect to originality and quality.

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Examiner Dr. Boyisa Regassa sign ______ date 29/09/2020

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ABSTARCT

In the present research landslide hazard evaluation and zonation was conducted in and around Aba-ala town, northern Ethiopia. The aim of this research is to evaluate landslide hazard and preparing hazard zonation map of the study area using Expert evaluation techniques (SSEP). Slope stability susceptibility evaluation parameter (SSEP) rating scheme is an expert evaluation technique that is based on the past experience of researcher over causative and triggering factors and their relative contribution for slope instability. The intrinsic factors (relative relief, slope morphometry, structural discontinuity, slope materials, groundwater condition, and land use land cover) and triggering factors (rainfall, seismicity, and manmade activity) were considered and data on that parameter collected from the field and secondary sources. Generally the study area classified into 62 facets, the rating provided for each parameter facet wisely, and the evaluated landslide hazard obtained by adding individual parameters for each facet.

Based the value obtained from evaluated landslide hazard (ELH), the study area classified into High, Moderate and Low hazard zones. The landslide hazard zonation map done by SSEP rating schemes indicates 27% (27km^2) falls with high hazard zone, 37% (37km^2) falls into moderate hazard zone and 36 % (36 km^2) falls into low hazard zones.

Based on the inventory data obtained from Google Earth and field observation, 31past landslide events have been recognized. From 31 past landslide events in the area, 17(55%) falls within High hazard zones, 11 (35%) occurred on Moderate hazard zone and 3 (10%) falls into low hazard zones. The verified zonation map shows 90% of existing landslide event occurred in high and moderate hazard zones of prepared LHZ map. Thus the LHZ map validation provides satisfactory results.

Key words: landslide hazard evaluation, hazard zonation, SSEP.

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LIST OF ABBREVIATION

NMA -- National Meteorological Agency

SSEP—Slope Stability Susceptibility Evaluation Parameters

LHZ— landslide Hazard Zonation

GPS—Global Positioning System

GIS – Geographic Information System

ELH—Evaluated landslide hazard

DEM—Digital Elevation Model

UTM—Universal Transverse Mercator

m.a.s.l—Meter above sea level

MPa—Mega Pascal

USGS—United states Geological survey

SRTM ---Shuttle radar Topography mission

1. CHAPTER ONE

1.1. BACKGROUND

The term "landslide" is used to describe a wide variety of processes that result in the detectable downward movement of a slope material (soil, rock, and vegetation) under the influence of gravitational force. The movement of slope materials may be in the form of: falling, toppling, sliding, spreading, or the combination of complex types of landslides (Kanungo et al., 2009). The study of landslides has drawn widen attention mainly due to increasing awareness of its socio-economic impacts on the mountain environment (Aleotti and Chowdhury, 1999).

Slope instability has been identified as one of the most frequent natural disasters and geodynamic process that destroys property, and causes death of life (Singh and Singh, 1992).Relatively individual slope failures are not cost as like earthquake, major floods, or some other natural catastrophic, but their distribution is wide, and May causes more property damage than any geo-hazard throughout the year. Much of the property damage and a considerable proportion of loss of life occurring with earthquake and intense storms are due to landslide (Bommer and Rodriguez, 2001).

Landslide risk is undoubtedly one of the main environmental issues for the growth's, posing a limiting factor for urbanization and infrastructure projects and, generally speaking, for the activities on and at the foot of the slope. The damage caused by landslides in Ethiopia is relevant: from 1993 to 1998 alone, more than 200 houses were demolished, 100km of roads damaged, about 300 peoples were killed, and 500ha of lands destroyed (Ayalew Lulseged, 1999).Generally, slope failure initiates from one or more combination of factors like slope geometry, slope materials, structural discontinuity, weathering, development of weak zones, lithological disturbance and heavy rainfall (Singh and Singh, 1992).

The main purpose of landslide hazard study is to evaluate the degree of hazard and its damage on local community, agricultural lands, and infrastructures (Anbalagan and Singh, 1996).Identifying landslide prone areas is very important to ensure the safety of infrastructures, human life, property damages and to avoid the negative consequence on economy of the country (Anbalagan and Singh, 1996).

Nowadays, landslide hazard becomes a serious concern to local community, planners, and decision makers at different level of government in Ethiopia (Kifle Woldearegay, 2013). Recently, infrastructural projects, urbanization and rural development are expanding on mountainous area of the country so it is foreseeable that the frequency and magnitude of mass wasting and its impacts would be increase unless appropriate action is taken in Ethiopia (Kifle Woldearegay, 2013).

The study area is located in the northern parts of Ethiopia, particularly in North-Western parts of Afar and Southern parts of Tigray. The previous study shows that Landslides hazard is one of common problems on shale hill slopes of northern Ethiopia (e.g. Woldearegay et al., 2005; Assay, 2008, Amare et al., 2011 as cited in Kifle Woldearegay, 2013). The entire study shows that landslide is dominantly controlled by the presence of incompetent and low permeability shale materials. Previously, landside hazard evaluations don’t carried out in the study area. however, the study area have more or less similar geomorphological setting, geological formation and it is also a part of the Mekelle outlier so that the distribution of landslide in the study area also primarily associated with the presence of soft and low permeable materials.

The main aim of the present research is evaluating and preparation of landslide hazard zonation map in and around Aba-ala town using slope stability susceptibility evaluation parameter rating schemes by considering both the inherent and triggering factors responsible for slope failure.

1.2. Problem of statement

The proposed study area is located in the northern Ethiopia, particularly in north-western parts of Afar and southern parts of Tigray. The road running from Aba-ala to Mekelle is one of the major road which join Tigray and Afar regions. Falling materials from mountain causing distress and deformation on road, and the road is frequently exposed to sever damages. In addition to damaging and reducing life span of the road, the falling materials are also blocking and hindering transportation. Recently Aba-ala town is expanding; infrastructures are building at base of mountain. However, the construction activity is being conducted without assessing the stability condition of slope materials. So such, evaluating and zonation of landslide hazard in the area is vital. Therefore, in order to zone the areas into different degree of hazard both internal and external parameters that contributes landslide would be analyzed. Finally, landslide hazard zonation map will be produced.

1.3. Research Question

- What types of landslide is occurred in the area?
- What factors are responsible for landslide?
- Which parts of the study area highly affected by landslide?

1.4. Objectives

1.4.1. General Objective

The general objective of the present research is evaluating and producing landslide hazard zonation map in and around Aba-ala town.

1.4.2. Specific Objectives of the study

- To distinguish the types of a landslide in the study area.
- To assess causative and triggering factors responsible for landslide in the area.
- To produce a landslide hazard zonation (LHZ) map of the study area.
- To validate LHZ map.

1.5. Significance of the research

Landslide is a common geo-hazard almost everywhere in the world. It is relevant to understand the nature and potential of the landslide before and after building infrastructure in mountainous and hilly terrain. So this kind of research helps to identify the problematic area that may cause the death of life, property damage, and disturbance of transportation.

Once the hazardous area is identified and mapped, the outcome of the research used as the backbone to select appropriate and safe area to build engineering related structures for future and to recommend suitable remedial measure to concerned governmental office.

In addition to this, the study helps the researcher to develop skills and scientific knowledge on the subject. The main significance of this study helps to reduce the risk associated with landslide by identifying and providing appropriate corrective measures.

1.6. Limitation of the study

- Since the study area are located at the boundary between two administrative regions (Afar and Tigray), where is inaccessible, it was difficult to collect field data, to take photograph etc. but all effort were made to conduct the research.
- Lack of pre-existing data related the present study is one of limitation that may reduce the quality of the research.

1.7. Outcomes of the study

The main outcome of this research helps the Ethiopian Road Authorities to identify potentially unstable slopes which requires immediate remedial measures, and also helps them to select appropriate remedial measures that should be taken based on the types of slide on the area. Moreover, LHZ map serve as a base map for land use planning, to select safe zone for construction, for researcher, individuals, and organization, who want to conduct similar types of research on the area.

1.8. Thesis outline

Chapter one provides a general introduction to landslide, problem of statement, objective of research, Significance of the research, Limitation of the study, and Outcomes of the study.

Chapter two reviews literatures regarding to landslides, factors influencing landslides, occurrence of landslide, classification of landslide, methods of landslide hazard zonation, types of landslide and their main causative and triggering factors, previous study of landslide in Ethiopia, and adopted methodology prospect and limitation in previous research.

Chapter three discusses the general methodology adopted, and data procurement.

Chapter four Description of study area, discusses the regional geology and geological structures of northern Ethiopia, local geology and geological structure of the study area, rock classification, hydrogeology, geomorphology, land use Land cover, types of landslide in the area, and possible contributing factors and prominent causes of landslide.

Chapter five focus on landslide hazard zonation, evaluating causative and triggering factors, inventory map of the area, producing landslide hazard map of the area and verification of result.

Chapter six conclusions and recommendation would be provided

2. Chapter Two Literature Review

2.1. General

Landslide is one of the major devastating hazards in rugged topographic terrain. The major triggering factors which enhances the process of landslide mainly associated with Seismicity (Bommerand Rodriguez, 2002; Keefer, 2000) and Rainfall (Dai et al., 2002; Dehal et al., 2006). In addition to this, sometimes a landslide also can be triggered by anthropogenic activities such as inappropriate road construction, improper cutting of slope in rugged topography (Gorsevski et al., 2006).

Landslide occurs as result of various geo-environmental processes, which includes geological, meteorological, and manmade activities. Bedrock geology (lithology, geological structure, degree of weathering), Geomorphology (slope gradient, aspect and relative relief), Soil(depth, structure, permeability, and porosity), Land use/cover, Hydro-geologic condition are some of important inherent factors affect stability condition of slope materials, so far landslide can be triggered by many external factors, which is Rainfall, Earthquake, undercutting by river, unplanned construction, Blasting, Drilling and Flash flood (Anbalagan, 1992; Kanungo et al., 2009).

Combination of external, internal and manmade activity made the mountainous terrain vulnerable or susceptible to landslide. A landslide hazard zonation map is produced to enhance the mitigation strategies for landslide hazard. Landslide hazard zonation map gives prior knowledge of landslide hazard susceptible areas based on the factors which causes the events. Assumption of zonation is made based on the future landslide is expected on the area which have the same set of geo-environmental setting as that of the past and present landslide location (Kanungo et al., 2009).

In different parts of the world, the economic decline and causalities as a result of landslide are great and increasing from time to time (Schuster and Fleming, 1986). Landslide is natural events which may turn into hazard and causes loss of lives and damage to natural and manmade structures. From experience of different countries, landslide causes a lot of problems to infrastructure, agricultural lands, and fatally injury up to death throughout the globe (Schuster and Fleming, 1986; Keefer, 2000; Mario and Jibson, 2000; Dai et al., 2002; Kanungo et al., 2006; Pan et al., 2008). In addition to damaging of property and killing of people and animals, landslides have negative influence on the quality of water in rivers, and streams (Schuster and Fleming, 1986).

Observation and identification of unstable slope at the beginning of initial stage of investigation and planning for construction of any engineering related structure, specifically, for construction of road, it is very important to avoid construction of road on those problematic slopes or to take corrective measures that can improve stability of slopes (Gorsevski et al., 2006; Anbalagan and Singh, 1996). Naturally landslide is complex process that caused either by intrinsic or external factors or by combination of both. Intrinsic factors are parameters that causes landslide such as, relative relief, structural discontinuity, land use/cover, groundwater manifestation, slope morpho-metry, and lithology while external factors are also factors which initiates or enhances the process of sliding, such as seismicity, anthropogenic activities, and rainfall (Raghuvanshi et al., 2014; Wang and Niu, 2009; Ayalew et al., 2004; Anbalagan, 1992; Hoek and Bray, 1981).

2.2. Factors influencing landslides

The main causes of slope instability are more or less well known from a lot of case studies of specific failures. Some are inherent in rock or soil. In its composition or structure; some, like inclination of undisturbed slopes, are relatively constant and some are variable, such as groundwater levels, some are transient (seismic vibration) and some are imposed by new events, such as construction activity (Varnes, 1984).

2.2.1. Inherent or basic condition (Intrinsic parameters)

Internal factors are causative parameters which explain favorable and unfavorable condition that influences the stability condition of slope materials or are factors which make the slope vulnerable to movements (Raghuvanshi et al, 2014; Kifle Woldearegay, 2013). This internal parameter includes relative relief, slope morphometry, slope materials, structural discontinuity, land use/cover, and groundwater manifestation (Anbalagan, 1992; Wang and Niu, 2009; Ayalew et al., 2004).

a). Relative relief

The term Slope geometry includes relative relief and slope morphometry **(**Raghuvanshi et al., 2014)**.**Relative relief is elevation difference within a facet (difference between maximum and minimum elevation) or the maximum height between the top ridge and valley floor within individual slope facet (Anbalagan, 1992).When relative relief increase the probability of slope failure will also increase (Bekele Abebe et al., 2010).

b). Slope morphometry

Slope morphometry shows the steepness of slope or defines slope categories on the basis of frequency of occurrence of particular angles of slopes. The distribution of slope categories depends on the geomorphologic history of the area; the angle of slope of each unit is a reflection of a series of localized process and controls, which has been imposed on the facet (Anbalagan, 1992). According to Varnes (1984) the possibility of slope failure has direct relationship with morphometery of slope, when the steepness of slope increases the possibility of landslide on the area will also increase.

c). Slope materials

Slope materials may be composed of rock and soil or both. The mineralogical composition of rock, texture, nature of cementing materials and other properties of slope material affects shear strength, permeability of materials and also enhances the susceptibility of slope materials to chemical as well as physical weathering that may causes slope failures (Varnes,1984).

Moreover, Varnes (1984) states that unconsolidated slope materials are more vulnerable to slope failure compared to consolidate materials as a result of high infiltration rate and lower shear strength and rigidity. Varnes (1984) demonstrate the impact of mineral composition on slope stability regarding to the abundance of clay minerals in the soil or rock. In fine grained sedimentary rock, the relative abundance of clay minerals, clay mineralogy, presence of and chemistry of water are dominant compositional factors which influences slope stability of slope materials. Since the amount of water content increase in clay materials, it loses its strength.

The fundamental requirement for stability of slopes is the shear strength of slope materials must be greater than the shear stress. The most fundamental causes of instability are that for some reason, the shear strength of the soil or rock is less than the shear strength required for equilibrium. This condition can be achieved in two ways, the first way is through a decrease in the shear strength of soil, and another way is through an increase in shear stress required for equilibrium (J. Michael Duncan and Stephen G. Wright, 2005). A lot of process can lead to reduction in shear strength of soil, the following process are particularly important regarding to slope stability: increasing of pore water pressure, cracking, swelling, loading, weathering whereas earthquake and surcharge load within the soil increases the shear stress(J. Michael Duncan and Stephen G. Wright, 2005).

c). Structural discontinuity

A discontinuity represents a plane of weakness within a rock mass across which the rock materials structurally discontinuous. The shear strength of a rock mass and it deformability are influenced very much by the discontinuity pattern, its geometry and how well it is developed. Structure includes primary and secondary discontinuities in the rocks such as bedding, joints, foliation, fault and thrust. The disposition of structural discontinuities in relation to slope inclination and direction has a great influence on the stability of slopes (Anbalagan, 1992). The presence of geological structures affects stability condition of slope (Wyllie and Mah, 2005).

The orientation of discontinuity plane plays an important role in stability condition of rock mass. If the orientations of discontinuity planes are parallel to the slope, the probability of failure becomes high (Anbalagan, 1992). When the dip of discontinuity increase the probability of failure also increase because the angle of friction for discontinuity surface may be reached, until the dip of discontinuity plane does not exceed the inclination of slope, the failure potential remain as high. Relatively the strength of intact rock is high compared to the rock mass with structural discontinuities (Sidle and Ochiai, 2006). While dealing with the stability condition of rock mass, it is vitally important to consider the factors which influence stability of rock mass are: orientation, spacing, continuity, nature of infilling materials, and separation within discontinuity surfaces (Johnson and Degraff, 1991).

d). Groundwater

When the Groundwater enters into slope materials, the slope materials tends to saturated and reduces the shear strength of materials and promotes the movements of rock and soil toward the base of hill under the influence of gravity(Highland and Bobrowsky, 2008). The presence of groundwater reduces the shear strength of materials. Under normal condition these slope materials remain stable, but if fluid pressure rises significantly they can negate the force of friction; in such cases the shear strength of sediments and rock is reduced to zero and it is at this point that the slope materials will fail (https://www.geological-digressions.com/how-groundwater-affects-the-stability-of-slopes).

e). Land use/cover

The presence of vegetation tends to increase the stability condition of slope materials by increasing the strength of soil. According to Cruden and Varnes (1996) degradation of vegetation recognized as one of the most significant factors which facilitates the occurrence of rainfall-triggered landslide in mountainous terrain. Afforestation of slope decreases the probability and susceptibility of slope failures .the root of plants binds the soil particles together, prevents excessive seepage into the slope materials whereas the vegetation is removed the slope will exposed to weathering, erosion and surface runoff that tends to increase slope instability (Tenalem Ayenew, 2004).

Land use land cover is an indirect indication of the stability of slopes. A barren and sparsely vegetated area indicates high erosion and greater instability as compared to protected forest, which are thickly vegetated. Forest cover, in generally, smother the action of climatic agents on the slopes and protects them from the effects of weathering and erosion. A well-spread root system increases the shearing resistance of slope materials (Anbalagan, 1992).

2.2.2. External factors

Varnes (1984) states, the external stress on slope are rarely constant over long period of time, relatively variable, or temporary and imposed by new activities like rainfall, seismic vibration and volcanic activities. Rainfall, seismicity, and manmade activities are some of the most important external parameters which enhance the process of mass movement (Raghuvanshi et al., 2014).

a). Human causes

Manmade activities are: excavation of slope or its toe, loading of slope or its crest, deforestation, mining, artificial vibration, construction of highway and railroads are some of anthropogenic activities that may triggers slope failure. Undercutting of slopes during construction of highway and railway increases the average slope gradients and the extra weight on slope may increase the chance of slope failures (Long, 2008; Kumar, 2009).

The increasing of human activities, such as intensive agriculture, quarrying, road construction, urbanization, etc. is also responsible for slope instability and landslide hazard (Abebe Bekele et al., 2010 as cited Ayalew, 2000; Nyssen et al., 2003). According to Highland and Bobrowsky (2008) anthropogenic activities like disturbing of drainage pattern, destabilizing of the slopes, deforestation, loading the top of slope initiates the sliding process.

b). Earthquake

The destructive impact of earthquakes, in many parts of the world, is greatly enhanced by the triggering of landslides during and after the shaking. Earthquake induced landslide can, in some cases, contribute significantly to death toll (Bommer et al., 2001). The earthquake shocks may be responsible for triggering new landslides and reactivating old landslides. The vibration due to earthquake may induce instability, particularly in loose and unconsolidated materials on steep slopes (Kanungo et al., 2009). Wide spread evidence of seismic triggering of landslides, mostly first generated rapid movements such as rock falls, rock slides, and debris flow, is provided by the historical record of earthquake and related surface effect(Gouin, 1979).

East Africa is one of developing countries which constructing new infrastructures to develop the economy of the region. However, the region is split by the active east African rift valley, which has a history of generating large earthquake (Zygmunt et al., 2014).Interestingly, large amount of infrastructure works already lie or will be in or in close to some of the most seismically active regions of the country such as Afar triangle, the main Ethiopian rift, where well-documented damage causing earthquake are common (Samuel Kassagne et al., 2012).

c). Rainfall

The main triggering factors of slope failures are heavy rainfall. Most of the rain in Ethiopia is concentrated in July and August, during which extremely intensive and long-lasting rainfall events may occur with subsequent high water percolation into the ground, wide spread slope wash and river-bank erosion(Bekele Abebe et al., 2010 as cited in Gamachu, 1977; Ethiopian mapping Authority, 1988).Infiltrating rain water plays vital role in triggering landslides by increasing the total weight of slope materials, causing the water table to rise and increasing the pore water pressure, and can therefore trigger a landslide (Abebe Bekele et al., 2010).

Rainfall is a primary cause of landslides and worse slope stability problems (Lulseged Ayalew, 1999). According to Kifle Woldearegay (2013) the hill and mountainous terrain of Ethiopia highland are affected by rainfall-induced landslides of various types and size, further, the intensity and duration of rainfall plays an important role by triggering landslide like mudflow, debris flow, medium to large-scale rockslides though it depends on topography, geology, geological structures, and permeability of slope materials.

2.3. Occurrence of landslide

A surprising fact too many people is that landslide can occur almost anywhere in the world. The traditional believe that landslides are restricted to extremely steep slopes and inhospitable terrain does not accurately reflects the actual nature of landslide related hazard. The reason for such wide geographic coverage has much to do with many different triggering mechanisms for landslide (Highland and Bobrowsky, 2008).Excessive precipitation, seismicity, and other mechanisms, and more recently, certain dangerous activity of human being on mountainous terrain are some of the key causes that trigger landslides. Similarly, landslide can be occur both on land and underwater; they can be occur in bedrock or soil, cultivated land, barren land, both on extremely dry areas and very humid areas can be affected by slope failures, and most important, presence of steep slopes are not necessary prerequisite for landslide to occur(Highland and Bobrowsky,2008).

2.4. Classification of landslide

Landslide can be classified based on the materials involved and the way the slide materials moved. Based on the materials involved landslide can be classified as rock, debris, earth and based on the kind of movement landslide can be classified as falling, toppling, flowing, etc. Thus landslide can be described by combination of materials and movements, such as rock fall, debris flow, earth flow, and so on (Highland and Bobrowsky, 2008).

Table 2.1 Classification of landslide

Types of Movement			Types of materials		
			Bedrock	Engineering soil	
				Predominantly coarse	Predominantly fine
FALLS			Rock fall	Debris fall	Earth fall
TOPPLES			Rock topple	Debris topple	Earth topple
SLIDES	Rotational	Few unit	Rock slump	Debris slump	Earth slump
	Translational	Many unit	Rock slide	Debris slide	Earth slide
LATERAL SPREAD			Rock spread	Debris spread	Earth spread
FLOWS			Rock flow	Debris flow	Earth flow
COMPLEX Combination of two types of movement					

2.5. Method of landslide hazard zonation

The term zonation widely used for the division of lands into different areas based on the degree of hazards such as low, moderate, and high hazard (Varnes, 1984). Landslide hazard zonation map indicates where the landside event has been occurred, recently occurred and will be occurred in the future and can be used to predict the relative degree of hazard for the given area (Highland and Bobrowsky, 2008).

For the last three decades, landslide zonation mapping has been carried out in different part of world and a lot of zonation mapping techniques developed such as Heuristic, Inventory, probabilistic, deterministic, and statistical methods (Pardeshi et al., 2013).

2.5.1. Statistical methods

For the last few decades the zonation mapping method changed from experience or knowledge based method to quantitative methods or statistical method, in order to overcome and reduce high subjectivity in decision making (Aleotti and Chowdhury, 1999). Statistical method evaluates landslide in the particular area by combining causative factor with the past landslide events in the area to predict the degree of landslide hazard for the future (Carrara et al., 1992).In these quantitative method the causative factors that have led to mass movement in the past are determined (Chalkias et al., 2014).One of the most serious drawbacks of using statistical method for zonation is gathering data at an acceptable cost over large area and the result depends on the quality of input data (Van Western et al., 1997).The statistical method classified as Bi-variate and Multi-variate statistical methods (Kanungo et al., 2009).

a). Bi-variate statistical method

These types of statistical method compare each data of causative factors (relative relief, slope morphometry, structural discontinuity etc.) and existing landslide (Kanungo et al., 2009). Based on the density or contribution of each causative factor to landslide the weight value are provided, and density of landslide are calculated for each parameter class such as, slope class, lithologic unit, land use types (Soeters and Van Western, 1996; Aleotti and Chowdhury, 1999).

According Soeters and Van Western (1996) to determine the relative contribution of each causative factor in inducing landslide, the causative factor map will be prepared and then overlaid on the past landslide distribution map. One of the major drawbacks of this method is the independence between different parameters of causative factors and the probability of landslide (Van Western et al., 1997).

John Mathew et al. (2007), used weight of evidence model for landslide hazard zonation. The model has been further verified using receiver operator characteristic curve which indicates an accuracy of 84.6%.

Mertha et al. (2013) have used the weight of evidence model for landslide hazard and risk assessment. The susceptibility map was made by combing semi-automatically prepared historical inventory and predisposing factor map.

b). Multi-variate statistical method

In this approach the relative contribution of each causative data layers (thematic) to the total susceptibility within a defined area are considered. This approach requires large data and takes a long time. Multi-variate statistical approach for landslide hazard zonation have been widely used for the last few years and it is proved to be more objective approach for assessing landslide hazard in sophisticated or complex geo-environmental setting(Conoscent et al.,2008;Eckhaurt et al.,2009;Ercanglu et al., 2003 as cited in

Pardeshi et al., 2013; Lulseged Ayalew and Yamagishi, 2005).Multi-variate statistical model provides more accurate results even though it requires complex calculation **(**Pardeshi et al., 2013**).**

Lulseged Ayalew and Yamagishi (2005) have compared landslide susceptibility zonation using logistic regression and analytical hierarchy process to evaluate landslide hazard zonation. The output of this study shows that increasing in number of susceptibility classes Analytical hierarchy provides more information compared to Logistic regression model. The map produced by AHP performed better than LR model when compared to the existing landslide.

Lulseged Ayalew et al (2004) conducted research on landslide susceptibility mapping using GIS-based weighted linear combination, the case in Tsugaw area of Agano River, Niigata prefecture, Japan. In this study, six landslide controlling parameters namely, lithology, slope gradient, aspect, elevation, and plan and profile curvature were considered, finally landslide susceptibility map of the area produced.

Asmelash Belay et al. (2019) conducted GIS based research Tramber district, Ethioipia using Analytical Hierarchy process approach. The factors considered are lithology, proximity to fault, land use, proximity to drainage, slope gradient, aspect, and elevation. The result obtained from Analytical Hierarchy process approach validated with the past landslide in the area.

Pourghasemi et al. (2012) have prepared landslide hazard susceptibility map using fuzzy logic and AHP models. The main aim of the study was producing landslide hazard susceptibility map of the area. The past landslide in the area identified using field work and aerial photographs. The result indicates that fozzy logic model provides better result compared to AHP model.

2.5.2. Deterministic Method

Deterministic method is other types of approach which provides numerical or quantitative result for landslide hazard in terms of safety factors. This method mainly applied for small scale and individual slopes (fall, 2006).Deterministic method provides quantitative result which can be used directly in design of engineering structures (Fall et al., 2006).Deterministic method requires Knowledge on geomorphology, geology and clear understanding on potential of slope failure and mainly suitably applied to small areas at the scale of single slope only (Casagli et al., 2004).The main limitation of these methods is requiring of high accuracy of input parameter (Casagli et al., 2004).

2.5.3. Expert methods

The expert techniques are one of direct techniques that depend on skill, experience and knowledge of the researchers (Raghuvanshi et al., 2014; Guzzetti et al., 1999; Sarker et al., 1995; Anbalagan, 1992; Pachuari and Pant, 1992). According to **(**Fall et al., 2006**)** expert evaluation method can be divided into two; landslide inventory and heuristic methods.

a). Distribution (inventory) Approach

According to Cruden (1991) landslide inventory is simplest form of landslide that records landslide events in terms of location and dimension. In this approach, inventory map are produced to portray spatial and temporal patterns of landslide distribution, types of movements, types of slide materials (Pardeshi et al., 2013). The main limitation with landslide inventory mapping approach is time consuming, cumbersome, but map based on this method may be used as a base for landslide hazard zonation (Kanungo et al., 2009).

Galli et al. (2008) have produced landslide inventory maps and compared with different parts of Italy. The result shows that landslide inventory map gives high predictive for landslide susceptibility analysis.

Guzzetti et al. (2003) have compared three landslide event inventories in central and northern Italy. They determines the importance of completeness and resolution of landslide inventory in analysis of landslide. The result showa that number of landslide event rapidly increase with increasing landslide area up to a maximum value and decreased as power law function.

b). Heuristic method

Heuristic method is an expert types of evaluation based on the knowledge and experience of the researcher. In this techniques, individual thematic map layer (causative factor map) are combined together to produce landslide hazard map **(**Dai and Lee, 2002**).**

The heuristic approach based on the prior knowledge of all causes and instability factors of landslide in the area under investigation, is an indirect, mostly qualitative methods, that depends on how well and how much the investigator understand the geomorphologic processes acting upon the terrain **(**Guzzetti et al., 1999**).** Heuristic approaches have been criticized repeatedly by several authors because of their highly subjectivity natures **(**Soeters and Van western, 1996**).**

The major problem associated with this approach is its difficulty to determine the weighting values to the input parameters (Fell et al., 2008). According to Anbalagan

(1992) the numerical rating assigned to input parameters that causes slope failure based on the logical judgment obtained from knowledge and experience of studies of causative factors and relative importance on slope instability. According to Kanungo et al. (2006), the higher values, the greater will be its influence on the occurrence of slope failures. However, Carrara et al. (1992) state that landslide hazard zonation map produced by different researcher on the same place according to expert evaluation method very different. The variation of hazard map indicates high degree of subjectivity in decision making.

Parmar and Purohit (2013) have used landslide hazard evaluation factor rating schemes to prepare landslide susceptibility zonation. The numerical rating provided to each causative factors based on their relative contribution of landslide. The maximum rating to individual factor calculated based on their significance in inducing landslide hazard.

Raghuvanshi et al. (2014) SSEP rating schemes for preparation of landslide hazard zonation map. The method is developed considering inherent and triggering factors that are responsible for slope failure. The maximum rating provided for different categories based on their relative importance in inducing landslide hazard. Slope geometry, slope materials, land use land cover, groundwater condition, structural discontinuity, seismicity, rainfall, and manmade activities are the main input parameters used in this approach.

Anbalagan (1992) conducted research on landslide hazard evaluation and zonation mapping in mountainous terrain using Landslide hazard evaluation factor rating schemes by considering intrinsic factors are responsible for slope stability. Accordingly the methodology adopted in the research has wider application for planners, geologist, and engineers for route selection and other mountains developmental programs.

Ashish et al. (2008) have studied the weighting rating system based on their relative contribution of causative factors as derived from remote sensing data were used to prepare landslide hazard zonation map. From 0-9 rating assigned to each factors. The sum of causative factor multiplied by the corresponding weight to obtain landslide hazard index.

Sarkar and Kanungo (2004) have prepared landslide susceptibility map using GIS and integrated remote sensing approach. To see the effectiveness of the susceptibility map, statistical significance chi-square test was conducted. The susceptibility map also rectified by correlating the existing landslide and the result shows close agreement with past landslide.

Sarker and Anbalagan (2008) conducted research on landslide hazard zonation mapping and comparative analysis of hazard zonation mapping using Landslide hazard evaluation factor rating schemes. The factors chosen that influence landslide occurrence were lithology, slope, relative relief, land use land cover, degree of weathering, and structural data. The result of the research compared with the regional hazard zonation map prepared earlier. The hazard zonation done using LHEF shows detail hazard zones relative to regional hazard zonation mapping.

Anbalagan et al (2015) have been used frequency ratio and fuzzy logic approach for landslide hazard zonation mapping in a case of Luchung valley, Sikkim. The map indicates that steep talus slope, ridges, and spar fall into high hazard zones, settlement area were observed in low –moderate hazard zones, very high hazard zone observed in steep slopes, cliffs and cut slopes excavated for road, and low hazard zone have been observed in agriculture terraces.

Ravindra et al. (2009) have prepared landslide hazard zonation map. The numerical rating for each factors was provided based on their relative significance in causing landslide hazard.

Henok Woldegiorgis et al (2014) have studied landslide hazard zonation using Expert evaluation techniques: a case study of the area between Gohatsion town and Abay River, central Ethiopia. The landslide hazard zonation carried out through the landslide hazard evaluation factor rating schemes (LHEF) that is developed by Anbalagan 1992. Slope morphometry, geology, and land use/cover are the most important parameters which causes slope failure in the area.

Engdawork Mulatu et al (2009), conduct research on landslide hazard zonation around Gilgel Gibe-II hydroelectric project, south western Ethiopia using landslide hazard evaluation factor rating schemes. The major causative factors considered are geology, slope morphometry, relative relief, land use land cover, and groundwater condition.

Birhanu Ermias et al (2017), have prepared landslide hazard zonation map of Alemketema Town, north showa zone, central Ethiopia using GIS based expert evaluation approach. The main causes of landslide in the area are related with; geological, geomorphologic, and hydrological factors and the major triggering factors are rainfall and road construction.

2.5.4. Other Techniques

Bekele Abebe et al (2010) conducted research on landslides in the Ethiopian Highland and Rift margins. Accordingly, the wide distribution of landslide in Ethiopia generally associated with several causative factors which include rugged morphology, high relief energy, and nature of outcrop rocks, while the main triggering factors responsible for landslide are connected with rainfall and lesser extent with seismicity.

Lulseged Ayalew (1999) made the study on the effect of seasonal rainfall on landslide in the highland of Ethiopia. The study indicated those landslides are mostly likely to occur when the ratio between the amount of rainfall and prior to failure and the mean annual rainfall is higher.

Shiferaw Ayele et al (2014) made study on Application of Remote Sensing and GIS for Landslide Disaster Management: A case from Abay Gorge, Gohsion- Dajen section. Nearly all landslides happened during the rainy season, and the frequently occurred landslide has damaged the road, bridges farmlands. Accordingly, the major slope instability of slope related with the presence of huge columnar jointed basalts, uncontrolled surface runoff, presence of soft rock mass such as; marl and shale confined with hard bedrocks, and preferred orientation of discontinuity within the rock mass.

Tenalem Ayenew and Barbieri (2005) made research on inventory of landslide and susceptibility mapping in the Dessie, northern Ethiopia. According these scholar, presence of loose unconsolidated materials overlying highly weathered and degrade basalts in steep topography and prolonged high rainfall made the suitable condition for the occurrence of landslide in the Dessie area. The most important cause of landslide in the area is Hydrological condition (both surface and groundwater) associated with gravity movements favored by geotechnical characteristic of soil and rocks. Many of landslides are triggered by gully erosion connected with heavy rainfall.

Tilahun Hamza and Raghuvanshi (2016) made the study on GIS based Landslide hazard evaluation and zonation: A case from Jeldu District, central Ethiopia. The research shows that landslide in the present area related with the factors like hydrological and hydro geological condition associated with gravity movements favored by geological and geomorphologic conditions that present in the area. The landslide in the area has been trigged by heavy rainfall.

Gemechis Chimidi et al (2017) made study on landslide hazard evaluation and zonation in and around Gimbi town, western Ethiopia-A GIS based statistical approach. The study indicates that the shear strength of slope materials, water force within soil and rock mass, characteristics of discontinuity are the main factors responsible for slope stability condition.

Eleyas Assefa et al (2016) conducted research on Discussion on the analysis, prevention and mitigation measures of slope instability problems: A case of Ethiopian Railways. The study indicates that both shallow and deep seated slope failures have been occur in Ethiopia due to heavy rainfall.

Berhanu Temesgen et al (1999) have studied landslide hazard on the slope of Dabicho ridge. In their research, they used geological, geomorphological, and tectonics in the field, size and slope measurement, topographic map and aerial photo interpretation, and analysis of rainfall data has been considered to know the possible causes of landslide. Based on the finding the main possible causes of landslide in the area produced by heavy rainfall.

2.6. Types of Landslide and their Main Causative and Triggering factors

In the highland of Ethiopia and rift margin landslide activities is one of the common geohazards that occur due to High relief, rugged topography, geology (nature of outcrop rocks), hydrology, rainfall, land use practice, manmade activities and to minor extent related with seismic activity(Kifle Woldearegay, 2013). According to Birhanu Temesegen et al (1999)based on the nature of bedrock lithology and slope morphometry, different types of landslide may occur: (A) on steep slope with hard bedrock which include basalt, ignimbrite, limestone(Antalo limestone) and sandstone(Adigrat sandstone) rock fall, toppling, rock slide are common types of landslide and generally they are triggered by earthquakes, (B) on the steep slopes characterized by deeply weathered volcanic rocks, debris slide, avalanches, debris and mud flow are commonly occurred, and heavy rainfall is the main triggering factors, (C) on the clay materials such as shale marl sedimentary formation (e.g. Agula shale, and Edaga Arbi glacial) , slower landslides which is rotational and translational slides are common types of landslides which is triggered by prolonged rainfall and earthquake. The relationship between landslide and various causative factors show that the Debris/Earth, slide/flow generally common along the, (a) areas which is underlain by Paleozoic glacial sediments, shale, and basalt flow,(b) hill slope which have angle in range of 15-45 °, (c) areas affected by gully erosion,(d) place which have sparse or no vegetation cover (Kifle Woldearegay, 2013).The major types of landslide triggered by rainfall in Ethiopia are Debris/Earth, slide/flow, and rockslide, while Rock fall is one of common types of landslide in Ethiopia highland, but not association is made with rainfall (Kifle Woldearegay, 2013).Most of the rainfall induced landslide have been occurred at the end of rainy seasons mainly in the mid of August to mid of September (Kifle Woldearegay, 2013).

2.7. Overview of landslide in the world

In different parts of the world a lot of research have been conducted using different approach and obtains different solution to mitigate the problems associated with landslide. Some of those researches conducted throughout the world are:

2.8. The adopted Methodology prospect and limitation in previous research

Slope stability susceptibility evaluation parameter is a Heuristic expert method that was developed by considering intrinsic and external factors are responsible for slope instability (Raghuvanshi et al., 2014).Slope Stability Susceptibility Evaluation Parameter rating scheme (SSEP) was used to accomplish the aim of the finding by considering both intrinsic causative and external triggering factors inducing instability of slope. Slope geometry, slope materials, groundwater manifestation, structural discontinuity, land use land cover are some of causative parameters while seismicity, anthropogenic activity and rainfall are triggering factors that consider for instability of slopes. The advantage of using this technique for landslide hazard evaluation and Zonation: it uses detailed facet wise field based data as input, considers both external and internal factors, and relatively it is simple in its application.

Raghuvanshi et al. (2014) applied SSEP approach in Wurgessa area, northern Ethiopia to prepare landslide hazard zonation map. The comparison of landslide hazard zonation map prepared using SSEP and active landslide location indicates that out of 14 landslide activity 6 landslide events occurred in very high hazard zones, and the remaining falls within high hazard zones. This confirms rationality followed in preparation of landslide hazard zonation map.

Zerihun Dawit (2016) applied SSEP approach in Kindo Didaye area, south west Ethiopia to prepare hazard zonation map. Out of 71 landslide activity 2 in moderate hazard zone, 50 falls in high hazard zone while 19 in very high hazard zones. This result indicates that 98% of past landslide event occurred in high and very high hazard zones. This also confirms rationality followed in preparation of landslide hazard zonation map.

Generally, as reviewed from research that has been carried out using SSEP expert techniques the rating provided for seismicity on inducing landslide hazard considered as the same throughout the study area. Since the study area characterized by different topography, and slope materials the effect of seismicity in inducing landslide is different, therefore providing the same rating for the entire area is one of the limitation observed on the research done using SSEP approach. However, this approach is preferred when the data available is insufficient, inaccessible area, and rapid assessment is required.

CHAPTER THERE METHODOLOGY

3. Chapter Three Methodology

3.1. General

Landslide susceptibility assessment becomes an interesting area of research, wherein a lot of approaches are used to delineate hazardous area. Even though different hazard zonation techniques are developed, there is no agreement on which techniques is the most accurate and appropriate to delineated landslide hazard zonation on the particular area (Krusic et al., 2017).

3.2. General Methodology Adopted to the Present Study

Slope stability susceptibility evaluation parameter (SSEP) is a Heuristic expert method that was developed by Raghuvanshi et al. (2014) considering both intrinsic and external factors responsible for slope instability. Slope Stability Susceptibility Evaluation Parameter rating scheme (SSEP) was used to accomplish the aim of the finding by considering both intrinsic causative and external triggering factors inducing instability of slope. Slope geometry, slope materials, groundwater manifestation, structural discontinuity, land use land cover are some of causative parameters while seismicity, anthropogenic activity and rainfall are triggering factors that consider for instability of slopes. The advantage of using this easy and friendly technique for landslide hazard evaluation and zonation is that it uses detailed facet wise field based data as an input to considers both external and internal factors.

For each facet numerical ratings are provided to each causative and triggering factors based on their relative contribution of slope instability (Raghuvanshi et al., 2014). Factors responsible for slope failure has been assigned with numerical rating on the basis of logical judgment the evaluator obtained from his/her experience of studies on both intrinsic and triggering factors and their relative contribution for slope failures (Raghuvanshi et al.,2014). The maximum numerical rating assigned to different intrinsic and external triggering factors is based on their relative contribution in inducing slope instability. In order to achieve the objective of the research, first the area of slope to be covered has to be divided into slope facet. Slope facet is a land unit that is characterized by more or less uniform slope geometry in terms of slope inclination and direction (Anbalagan, 1992). Topographic map with the scale of 1:50000 were used to demarcate the slope facet. The facet boundaries further rectified using stream order, ridge, valleys, and other topographic undulation (Raghuvanshi et al., 2014).

The base map that developed from slope facet map was engaged for various causative factor maps. The intrinsic and external factor data are collected and rating for individual causative parameters are given for each facet. The values rating followed for all causative factors are summed to obtain evaluated landslide hazard. The sum basically (defines the net probability of slope instability conditions).

Evaluate landslide hazard (ELH) =sum of intrinsic factors rating of individual facet and external factors rating of individual facet.

Where intrinsic factors consider are includes (relative relief +slope morphometry+ structural discontinuity + slope materials + groundwater condition + land use/cover) whereas external factors include (rainfall + seismicity + anthropogenic activities)

Table 3.1. Distribution of maximum rating assigned to both intrinsic and external factors **(**after Raghuvanshi et al., 2014**)**

S.no	**Intrinsic parameters**	**Maximum rating**
1	Relative Relief	1
2	Slope Morphometry	2
3	Slope Materials	1
4	Structural Discontinuity	2.5
5	Land use/cover	1.5
6	Groundwater condition	2
	External Factors	
1	Anthropogenic activities	1.5
2	Rainfall	1.5
3	Seismicity	2
	Total Rating	**15**

Finally, ELH would be classified to define the landslide hazard related to the area accordingly to the classification proposed in Raghuvanshi et al. (2014).

Table 3.2 Evaluated landslide hazard (after Raghuvanshi et al., 2014**)**

Landslide hazard zone	landslide hazard class	evaluated landslide hazard
Very low hazard zone	I	<2
Low hazard zone	II	2-4.9
Moderate hazard zone	III	5-7.9
High hazard zone	IV	8-12
Very high hazard zone	V	>12

3.3. Data Procurement

3.3.1. Desk study

a). General

Landslide hazard zonation mapping is one of the ways that used to predict the areas potentially susceptible to landslide hazard. Based on geology of the area, topography, and other factors that led to past landslide incident provides an idea to where and condition that may causes landslide events for the future (Van Western et al., 2006). The main purpose of the desk study is to develop conceptual frameworks about landslide and to have better understanding how the field data is collected and what data should be collected from the field in order to conduct the research.

During desk study a lot activities have been conducted to achieve the aim of this research. Gathering of relevant secondary data and materials were collected from different organization and sources. Some of activities that has been conducted during the desk study are listed as follow:

- Gathering the previous work and review of literature (literature review helps to develop the conceptual frameworks about landslide) related to landslide from Books, journals, articles, reports, published and unpublished academic thesis, and internet resources.
- Meteorological data (such as precipitation of Aba-al town from 1990-2019and temperature from 2003-2019) has been collected from the station found in Aba-ala town (Aba-ala station) to have a better understanding on climatic factors that may trigger landslide on the study area.
- Slope, Drainage and aspect map of the study area prepared from DEM (SRTM) obtained from Ethiopia Geospatial Agency with resolution of 20m x 20m.
- Topographical map with scale of 1:50000 obtained from Ethiopian mapping agency were used to produce a facet map that used as a base map.

- Land use/cover map was produced from satellite image.
- Inventory map was produced from Google earth.

b) Data assessed in desk study

During the desk study the quality of secondary data collected from different sources have be assessed and also meteorological data have been crosscheck by comparing the data obtained from head office of Ethiopian Meteorology Agency, Afar Meteorology Agency, and station found in the study area.

c). Outputs of desk studies and field work design

The main outputs of desk study are:

- Identification of existing landslide on the area using Google Earth.
- The facet map of the area produced from topographic map.
- The Relative relief map of the area was produced.
- Slope morphometry map was produced.
- Land use land cover map and slope was produced.

3.3.2. Field investigation

a). General

The main purpose of field work is to collect data and to have an idea about the geology, geomorphology, and other input parameters to complete the research. During the fieldwork close observation were made to assess different parameters which is important to conduct the research and to verify and to prepare map in the fields.

The field work was conducted in two phase, during the first phase, general site observation, taking photograph of potential susceptible slope materials to landslide and past landslide occurred, while in second phase taking GPS point of landslide occurred area, measurement of geological structures, collection of data on rain induced manifestation on slopes, description on the types of landslide and identifying the possible causes of landslide have been recorded in this phase.

b). Field activities and collected data set

During the field work the relevant and important parameters which are necessary to the research have been collected. Following activities has been done

- Taking GPS point on the area inventoried from the Google Earth which was considered as past landslide events
- Identifying different instability manifestation features on slopes
- Measuring different geological structures found on the study area

- Measuring strength of rock using Schmidt hammer
- Identifying potentially unstable slopes for future.
- Taking the field notes
- Taking photograph for both potentially unstable slope section and past landslide events in the area

c). Output of field investigation

After collection of primary filed data, the pre- field map were modified.

3.3.3. Post-field work

a). Data arrangement and organization

During post-filed work, pre-field and field data were combining together to evaluate landslide hazard and to generate hazard Zonation map of the area using ARCGIS and ERDAS environment. By assigning the rating for each causative and triggering factor the landslide hazard Zonation map were be generated based on the relative contribution of parameter which is responsible for landslide. Generally, the following data arraignment and organization done during post-field work:

- Compiling of thesis
- Generating filed facet map for causative and triggering factors
- The data collected during pre-field work and fieldwork were processed and analyzed
- Preparing a landslide hazard map by dividing the area into different hazardous zones
- Recommending an appropriate remedial and correctives measures
- Based on the result obtained, the conclusion and recommendation would be provided

b). Data analysis

Once the field excretion was completed, all the necessary efforts have been done to combine the data collected from primary and secondary sources of data, it was converted to tangible formats to be processed and analysis. In order to come up with result, SSEP a technique was adopted by providing numerical rating to each intrinsic and external parameter based on the relative contribution of parameters to slope failures. Once the numerical rating provided to each parameter, rating for each intrinsic and external parameters summed up to obtained the evaluated landslide hazard (ELH). Based on the result, the study area classified into different hazard zones.

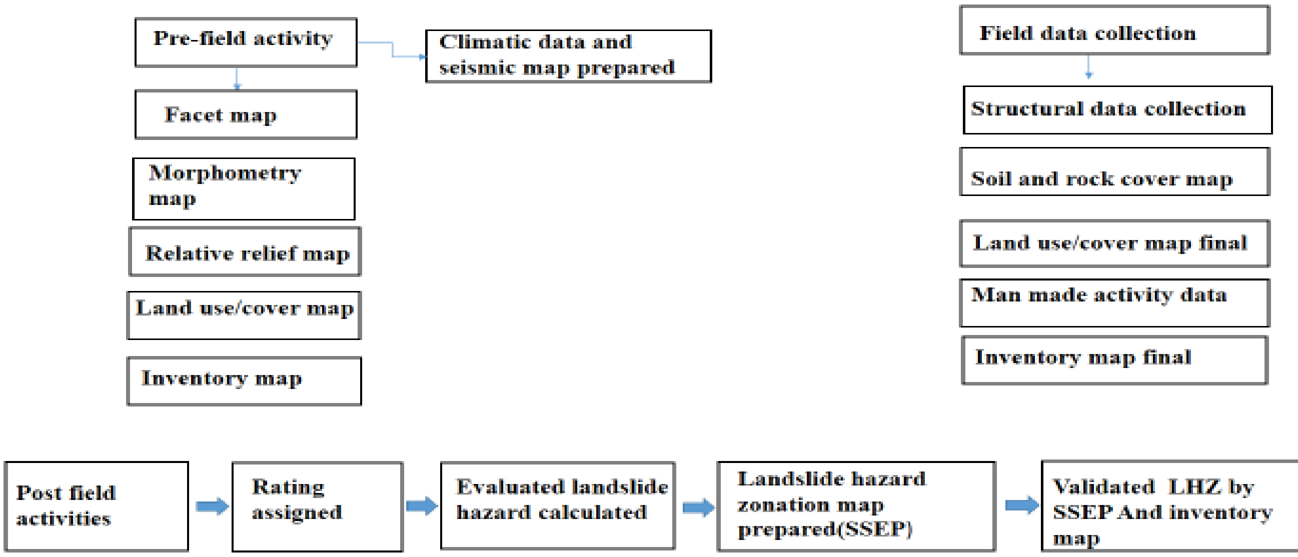


Figure 3.1 Schematic illustration of the methodology followed in the present research

CHAPTER FOUR GENERAL SITE DESCRIPTION AND GEOLOGY

4. Chapter Four General Site Description and Geology

4.1. The Study area

4.1.1. Location and Accessibility of Study Area

The study area is located in the northern parts of Ethiopia, particularly in North-Western parts of Afar and Southern parts of Tigray, specifically; it lies in the North-Western of Samara, Afar Regional State at the distance of 488.1kmand South-Eastern of Mekelle at the distance of 49km. Geographically the study area is bounded by UTM (Zone 37) coordinated 576616-589758m E and 1467432-1477606m N. the area can be accessed by asphalt road which is running from Samara-Mekelle and Aba-ala-Berhale and also by foot trails on rugged topography.

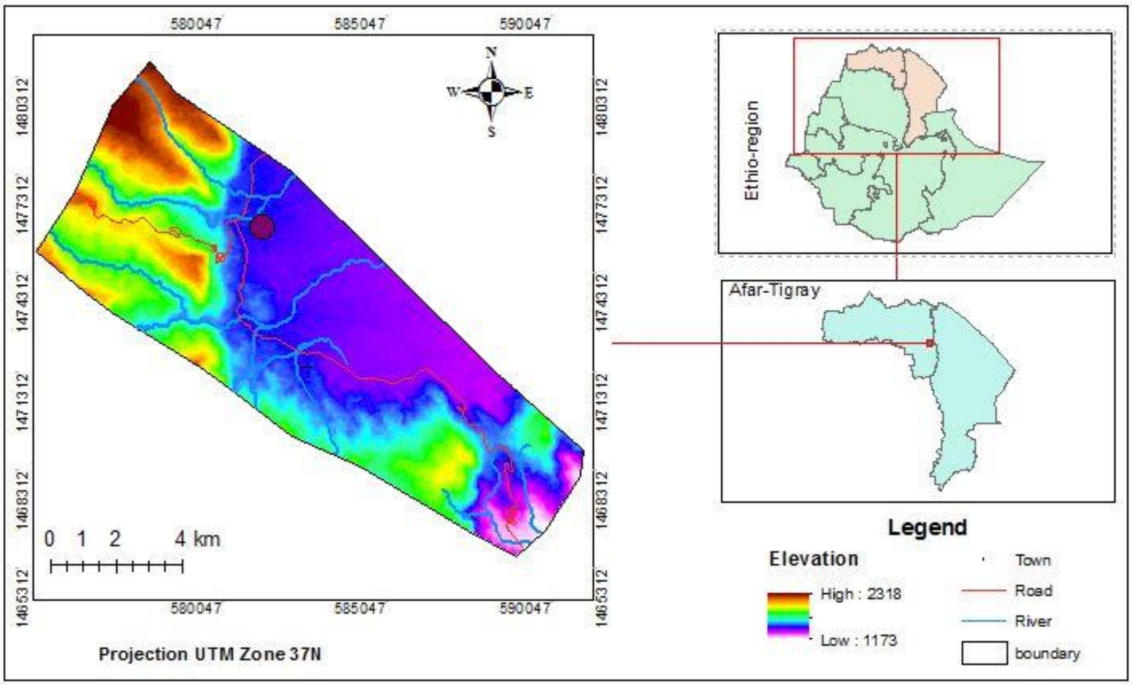


Figure 4.1 Location map of the study area

4.1.2. Topography

a). Elevation

Elevation is one of main causative factors which can controls stability of slope through erosion, weathering and other activities (Ahmed, 2009). The elevation extracted from DEM with resolution of 20m x 20m from SRTM data set in GIS environments. The elevation of the study area ranges from 1173m-2318m.

b). Slope

Angle of slope is one of the main controlling factors which are important to landslide hazard analysis. The probability of slope failure increase as the slope increases its steepness. When the steepness of slope increases, the shear stress will be high so that the frequency of landslide will be high, while the slope angle is low, the frequency of landslide will be less (Lulseged Ayalew and Yamagishi, 2004).

The slope map of the study area extracted from DEM with the resolution of 20m x 20m from SRTM data using GIS environments. Based on data extracted the slope angle of the study area varies from 0°-72 °.According to the classification adopted in Anbalagan 1992 the slope of study area classified into five slope classes' i.e. <15°, 16-25°, 25-36°, 37-45° and >45°.

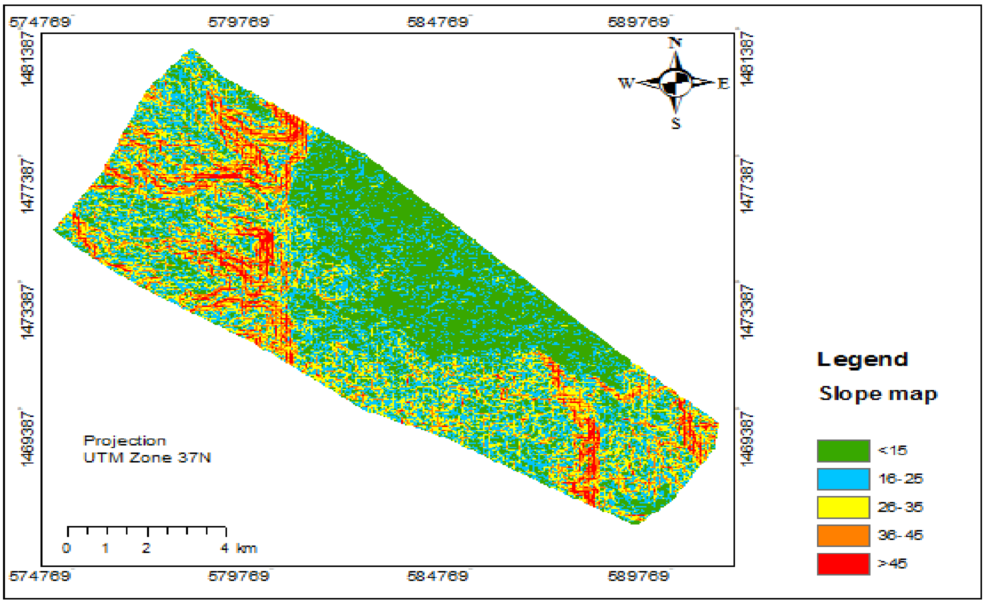


Figure 4.2 slop map of the study area

c). Aspect

Aspect is one of the factors which can influence the distribution and density of landslide by controls the concentration of moisture contents of soil and by influences the distribution of the rainfall over the area (Wieczorek et al., 1997 as cited in Lulseged Ayalew et al., 2003). The aspect map of the study area extracted from DEM with the resolution of 20m x 20m from SRTM data set in GIS environment. The aspect map of the area classified as flat (-1°), North (0-22.5°), Northeast (22.5-67.5°), East (67.5-112.5°), Southeast (112.5-157.5°), South (157.5-202.5°), Southeast (202.5-247.5°), Northwest (202.4-337.5°), and North (337.5-360.5°).

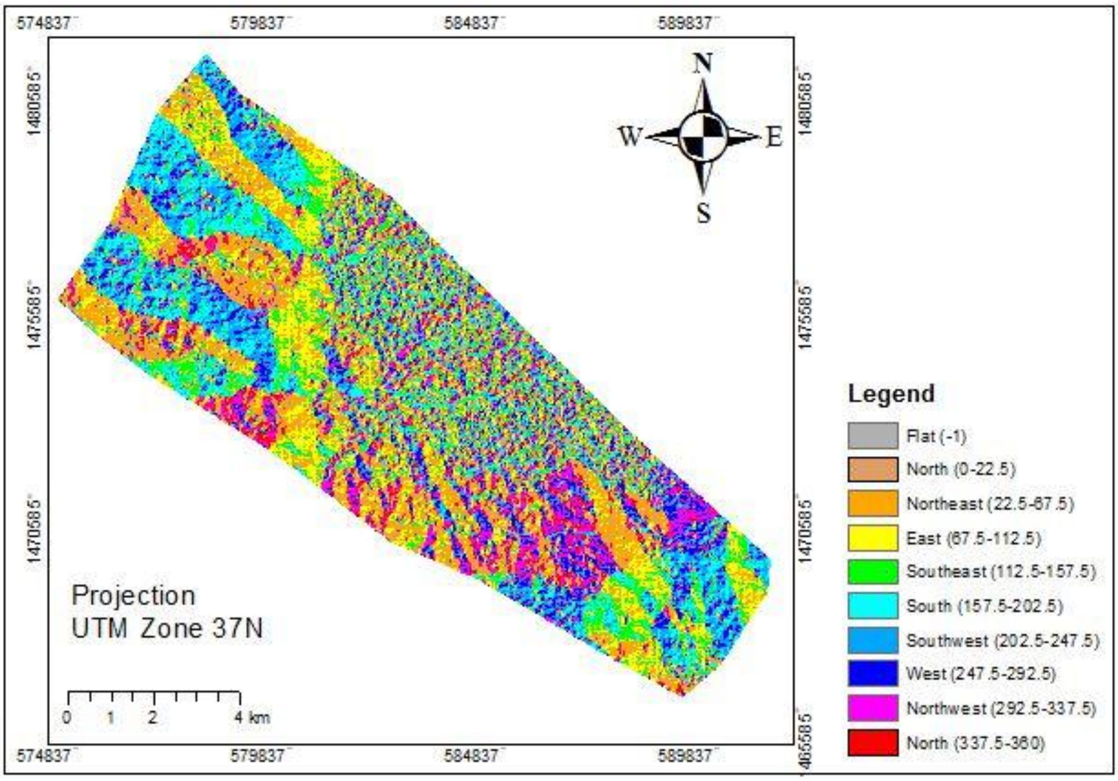


Figure4.3 Aspect map of the study area

4.1.3. Climate

a). Rainfall

The metrological data from 1990-2019 for the last 30 assessed years, the mean annual rainfall of the study area is about 374.8mm, and the highest monthly precipitation recorded was 496.1mm in the month of August, 2018. The study area receives the peak of rainfall in the month of August and July.

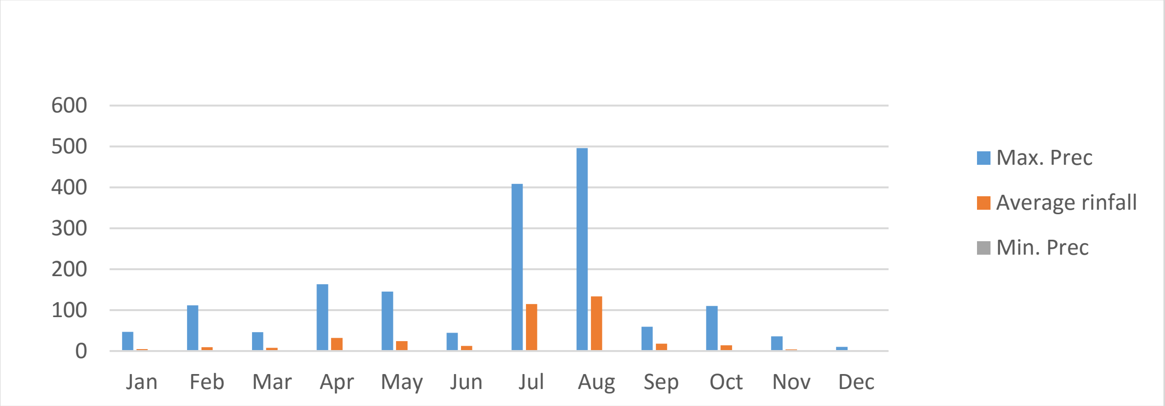


Figure 4.4 Mean Monthly precipitation

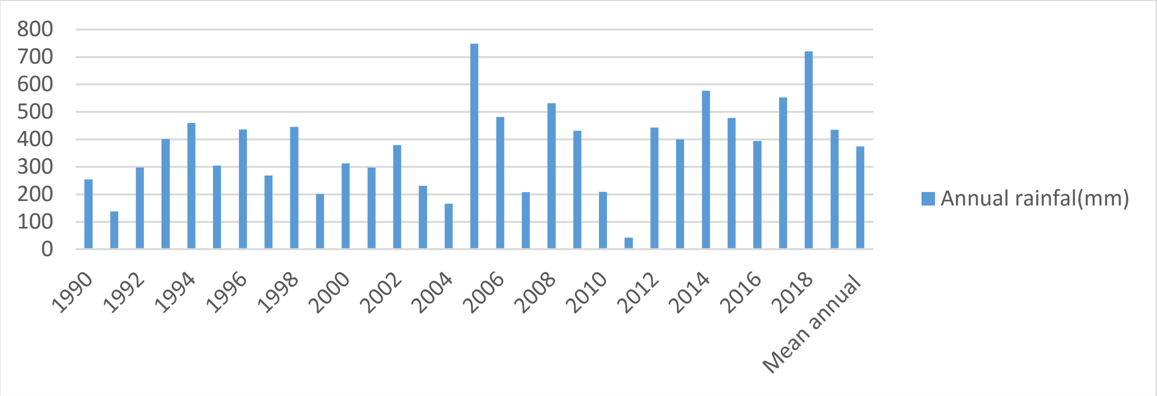


Figure 4.5 Annual Rainfall (1990-2019)

b). Temperature

Daniel Gemechu (1997) traditionally classified the climatic zone into five based on altitude. Accordingly, the climatic zone:

Table 4.1 classification of climatic zone (after Daniel Gemechu, 1997)

Altitude (m.a.s.l)	Description	Local names
3,300 and above	Cool	Kur
2,300 - 3,300	Cool Temperate	Dega
1,500 - 2,300	Temperate	Weina Dega
500 - 1,500	Warm	Kola
Below 500	Hot	Bereha

Based on the above classification, the study area falls within Cool temperate (Dega), Temperate (Weina Dega) and Warm (Kola) climatic zones. The maximum and minimum temperature of the area ranges from 38.5°C to 11.3 °C respectively.

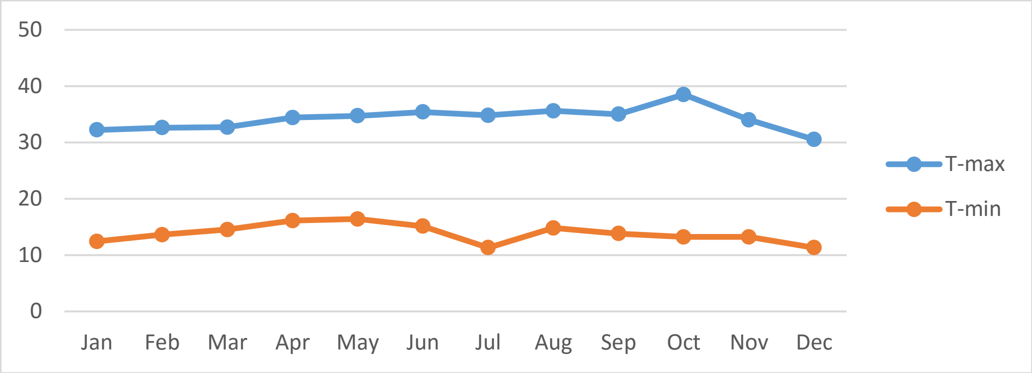


Figure 4.6 Temperature of study area

4.2. Regional Geology

There are different geological formations in the northern parts of Ethiopia. Depending on the geological time scale from the oldest to youngest, geology of northern Ethiopia can be classified as basement rocks, Enticho sandstone and Edaga Arbi Tillite, Adigrat sandstone, Antalo limestone, Agula shale, Amba Aradom formation, and volcanic rocks respectively (Beyth, 1972).

4.2.1. Metamorphic (Basement) Rock

The basement rock of the northern Ethiopia composed from the low grade metamorphic of Tsaliet and Tambien groups (Beyth, 1972).Tsaliet group is the oldest basement rocks in the northern Ethiopia that gets its name after Tsaliet River (EIGS, 1996). The composition of these group ranges from basalt to dacites and rhyolites (EIGS, 1996). The Tsaliet group of basement rock formed mainly of intermediate to acidic tuffs, welded tuffs and agglomerate are bedded well. This group of rock derived from Meta - Volcanic rock (EIGS, 1996). The Tambien group is the youngest basement rock that originated from sedimentary rocks. This group of basement rock composed of slates, phyllite, and so on (Beyth, 1972).

4.2.2. Paleozoic sedimentary rocks

The Paleozoic rock in northern Ethiopia divided into Enticho sandstone and Edaga Arbi tillites **(**Garland, 1872**)**. According to Dow et al. (1971) the Paleozoic sedimentary rock formed as a result of glacial formation. The Enticho sandstone is considered as the oldest sedimentary rocks which composed of coarse grained sandstone, conglomerate, pebbles and the name Enticho sandstone derived after the Enticho town which is located in the way between Aksum to Adigrat main road (Dow et al., 1971).

4.2.3. Mesozoic sedimentary rock

During the Mesozoic era, the transgression of Ocean reaches the northern Ethiopia and forms Mesozoic sedimentary rock. Due to the transgression, the Adigrat sandstone forms near to Adigrat town, followed by sediments mainly composed of limestone and marl intercalation which is mainly known as Antalo limestone **(**Levitte, 1970**)**.After the deposition of Antalo formation, the transgression was followed by regression of Ocean and gives rise to the formation of Agula and Amba Aradom formation (Levitte, 1970**).**Adigrat sandstone is the oldest Mesozoic sedimentary rock in Mekelle outlier and mainly composed of fine grained sandstone and conglomerate (Garland, 1972 as cited in EIGS,1996). Antalo formation gets its name from the town of Antalo Village in southern Tigray and this sequence consists of Antalo limestone and Agula shale. Antalo limestone consists of white and rarely black limestone, and they are fine grained and well bedded formation (Levitte, 1970). Agula shale is second youngest Mesozoic sedimentary in Mekelle outlier which mainly composed of shale with minor intercalation of marl-limestone, mudstone and evaporate layers (Levitte, 1970). The Amba Aradom formation is the youngest of Mesozoic sedimentary rocks in Mekelle outlier and mainly composed of siltstone, sandstone, and argillite (Tesfamichael Gebreyohannes, 2010; Levitte, 1970). The study area mainly found within the Mesozoic sedimentary rock which consists of Antalo limestone and Agula shale.

4.2.4. Regional Geological structures

The geological structures found on basement rock are showing the same strike trending N25°E with small deviation in some localities. The basement rocks found in the eastern and western dips in reversed. In western part, it dips to northwest while in east it dips to southeast (Levitte, 1970). The three main faults exist are: two of them are generally related to main Ethiopian plateau and the other one is associated with the rift of Danakil depression. The faulting systems related to the plateau are normal to each other. The fault associated with the rift of Danakil depression striking at N 65° W. Faulting in the area brings lowermost formation of Antalo formation against uppermost formation (Levitte, 1970).

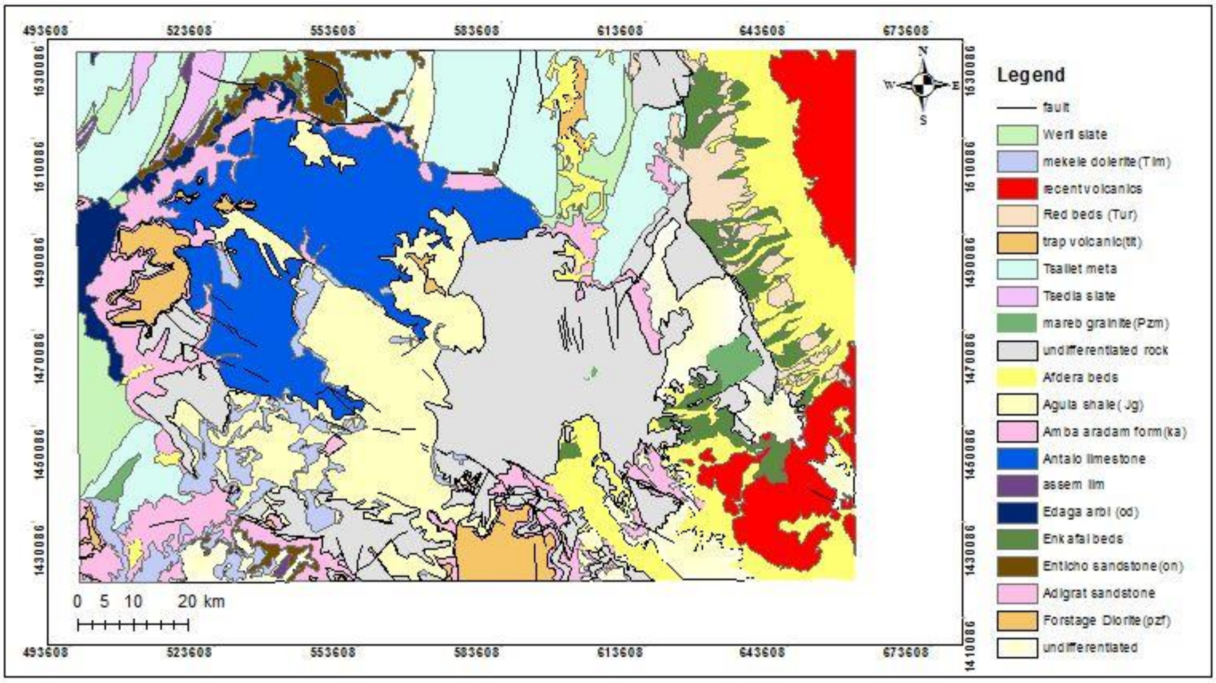


Figure 4.7 Regional Geology map (After Ethiopian geological survey Sheet ND 37-11)

4.2.5. Implication of regional geology to slope instability

According Woldearegay (2005); Woldearegay et al. (2006); Assay (2008), and Amare et al. (2011) as cited in Kifle Woldearegay (2014) Landslides are one of common problems on the shale hill slope of northern Ethiopia. All studies done indicates that landslide occurred on the shale hill slope dominantly controlled by the presence of soft and low permeability shale materials which underline the unconsolidated deposits(Kifle Woldearegay, 2014). The terrain which is underlain Paleozoic sediments in northern Ethiopia reported to have frequent landslide hazard. According to Woldearegay (2005); Woldearegay et al. (2005, 2006) as cited Kifle Woldearegay (2014) shallow debris/earth slide are the most common types of landslide. Landslides in these terrains are mainly controlled by the presence of soft and low permeability Paleozoic sediments (Kifle Woldearegay, 2014).

4.3. Local geology

The geology of the study area is characterized by exposures of the following major lithological units;

4.3.1. Limestone

This rock unit mainly found on the north western and south western and eastern parts of Abala town with small areal coverage along the river cut. The limestone layer is finely crystalline, and black -yellow in color with variable thickness. Most of the joints are vertical to sub vertical. Relative to the other, limestone is slightly affected by weathering.

The limestone rock unit in the study area characterized by fine-grained texture, bedding, and presence of fossil in some places. Based on the above characteristics, the limestone rock unit can be correlated with Antalo limestone of Mesozoic sedimentary rock.

4.3.2. Shale

This rock unit found at south-eastern parts of the town, with forming dome shape and mainly consists of shale and minor amount of mudstone. The layer of shale unit shows Gray, dark gray color with its fissility natures. This rock is highly affected by weathering. In some places it is difficult to identify shale-marl from soil materials due to the influence of weathering. It is characterized by its laminated and fissility nature.

The shale rock unit of study area characterized by it fissility nature, fine grain texture, based on this it can be correlated with Agula shale formation.

4.3.3. Shale-marl-limestone intercalation

This rock unit is found in north-western and south-eastern part of Aba-ala town. This intercalation rock unit covers largest parts of the study area. The Antalo sequence in the study area shows a complex mode of formation, natures, and has a considerable lithological variation from the top to bottom. These intercalation consists of three different rock units such as; Shale, marl, and limestone. This intercalation unit widely observed along gentle slopes, and it shows less resistance to weathering compared to the cliff forming limestone rock unit. The limestone unit shows finely crystalline and black color. The limestone layers stronger than marl and shale. The shale layer shows thinly bedded or laminated layer. This layer shows light-yellowish, greenish, and gray color. The weathering is intensive in shale layer compared to limestone rock unit the study area. The marl layer in the study area mostly shows yellowish color and the thickness of the beds varies from place to place in the study area.

4.3.4. Quaternary sediments

From the visual observation during the field, the quaternary sediment consist alluvial, colluvial, and residual deposit. The alluvial deposit is mainly found in low lying plain of study area and along the stream. Colluvial deposit are also found along the foot of steep slopes or at the bottom of steep slopes. The residual deposit deposited in gentle slopes to moderately steep slopes. The quaternary sediments in the study area are loose and unconsolidated materials containing alluvial, colluvial and residual deposit which comes from the parent rock found in the study area**.**

a). Residual deposit

The residual deposit in the study area ranges from clay to sand with inclusion of angular boulder, mainly yellowish in color. The residual deposit in the area are mainly deposited in low lying/gentle to moderate steep slopes. The residual deposit in the study area results from weathering of parent rock unit found in the study area (mainly from limestone and shale).

Figure 4.8 residual deposit in the area

b). Alluvial deposits

The alluvial deposit ranges in size from clay to sand with minor boulder that is transported to the current location by water. This deposits widely found along flatland and rivers. The alluvial deposit in the study area is deposited by the runoff and stream that drains from the Tigray highlands. These deposits have reddish to gray color.

c). Colluvial deposit

The colluvial deposits are mainly found along the foot of cliff or at the base of steep slope, these deposit observed along the road cut in the western parts of Aba-ala town on the road running from Abala to Mekelle town. The colluvial deposit in the study area mainly composed from gravel, boulder, and sand soil and they are poorly sorted. The colluvial deposit in the area shows variation in size of rock fragments, and consists a block of rock and soil that comes from steep slopes. The fragmented rock materials have the origin of limestone and shale rock unit found in the study area.

Figure 4.9 Colluvial deposit in area

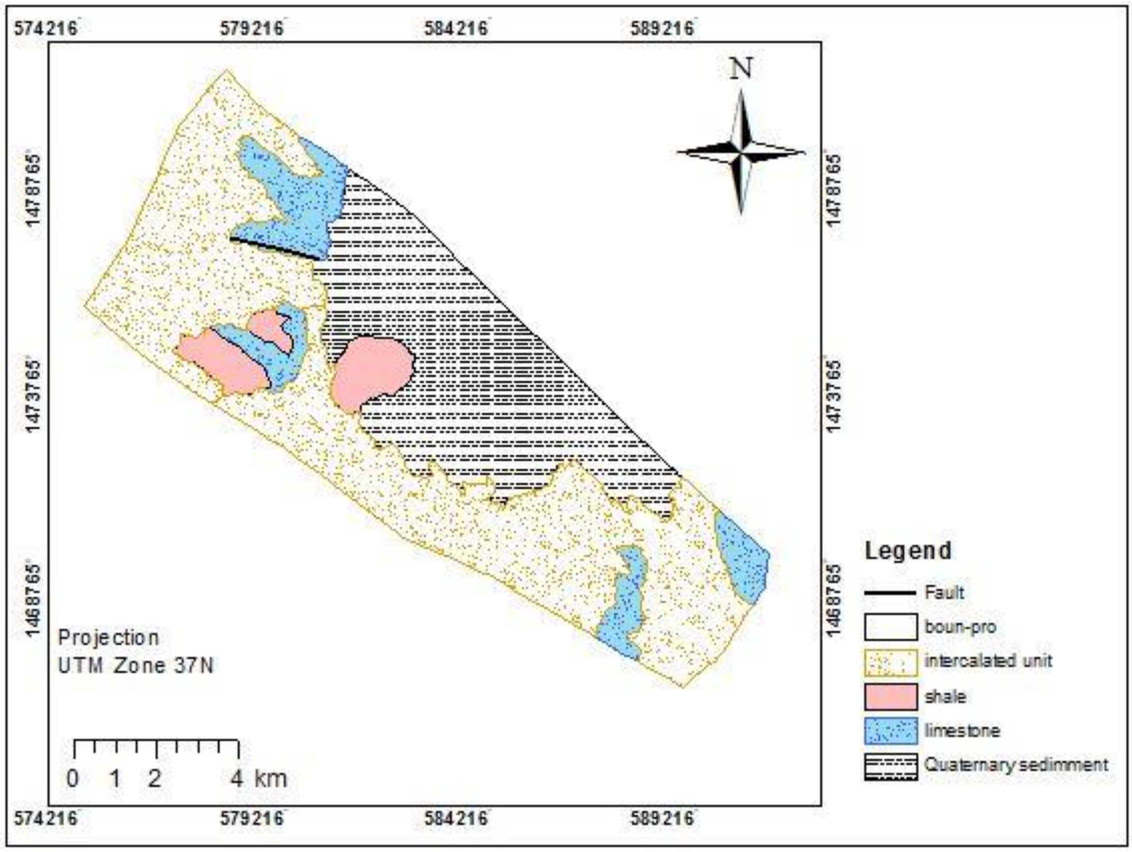


Figure 4.10 Geology map of study area

4.3.5. Local geological Structure

The Fault found in north western parts of Aba-ala town show orientation of NW-SW. Since the area is found in the western escarpment of the Ethiopian Rift Valley, it is obvious to be affected with different regional and local geological structures. Joint is another geological structures found mainly on limestone rock unit in the study area. The nature of joint spacing on limestone rock is not uniform and it shows some variation in some localities. Most of the join in the study area are not filled with secondary materials, most closely spaced and shows the orientation which is similar to fault orientation. Due to the presence of geological structures the strength of rock is highly affected and results disintegration of rocks.

4.4. Seismicity

According to Laike Mariam Asfaw (1986), the seismic risk map produced for a hundred year return period and 0.99 probability shows that the study area falls within 8 M.M scales. Based on the Modified Mercalli scales, the estimated horizontal acceleration for the study area found to be 0.1 – 0.2g, as determined from MM intensity graphs. The seismic intensity over the study area is the same the corresponding ground acceleration will be the average of 0.1 and 0.2 which 0.15 throughout the study area.

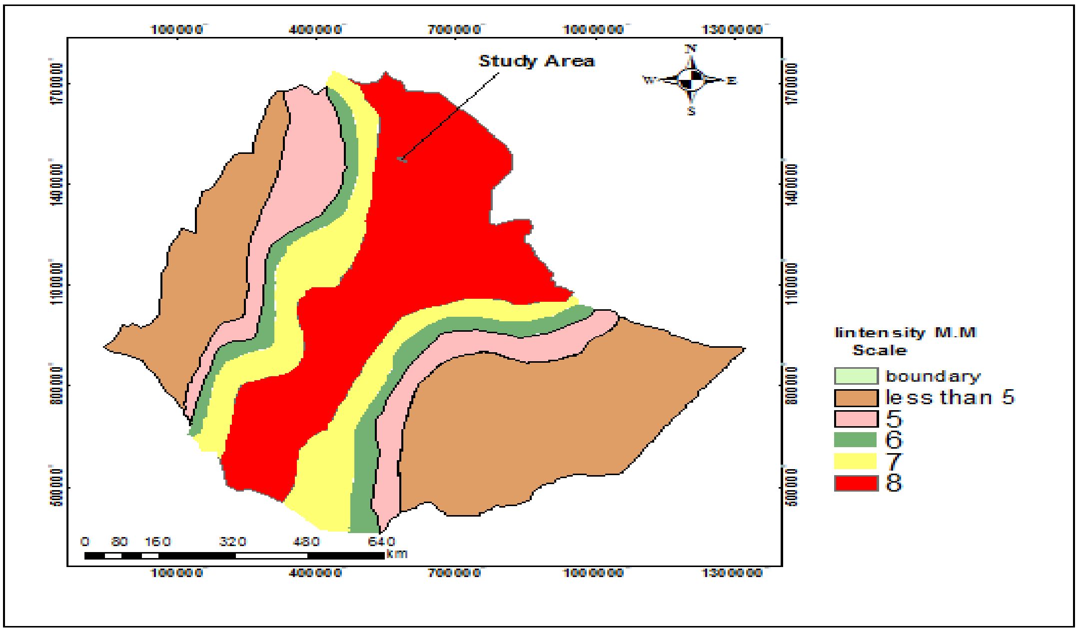


Figure 4.11 Seismic map of study area (After Laike Mariam Asfaw (1986)

4.5. Rock classification

The classification of the rock unit is done based on the value estimated from Schmidt hammer test and visual observation. Based on the value obtained using Schmidt the rock mass in the study area classified into three such as low strength rock, medium strength and high strength rock. The low strength rock mass have strength value mostly less than 25MPa. The intercalation rock unit which is highly affected by weathering mainly found in the study area classified within rock with low mass strength. This rock unit covers large parts of the study area and the degree of weathering activity is high and plays significant role in reducing the strength of the rock unit. The medium strength rock mass is the other types of rock unit found in the study area. The intact rock strength value ranges within 25-50MPa are considered as medium strength rock mass. Limestone is the major rock unit found within this range of intact strength value in the study area and moderately affected by weathering. Rocks with high strength mass characterized by the intact strength value between 50-100MPa. Well bedded limestone is the major rock unit which is characterized by the intact strength value more than the above ranges. Relative to the medium and low strength rock unit, high strength rock unit show high resistance to weathering.

4.6. Drainage

Gumselasa, May Weaba, and Tsahloare the major streams which flow from the highland of Tigray to the study area. They are an ephemeral river which is related to the rainfall on the highland. There are a lot of seasonal and periodic tributary which join theses Major stream in the study area. Most of the stream flow toward the east direction. Relatively the stream is dense at the area of higher slopes and sparse where the slope is relatively flat. The main source of water is rainfall during the rainy season on the highland of Tigray and the study area has a dendritic drainage pattern.

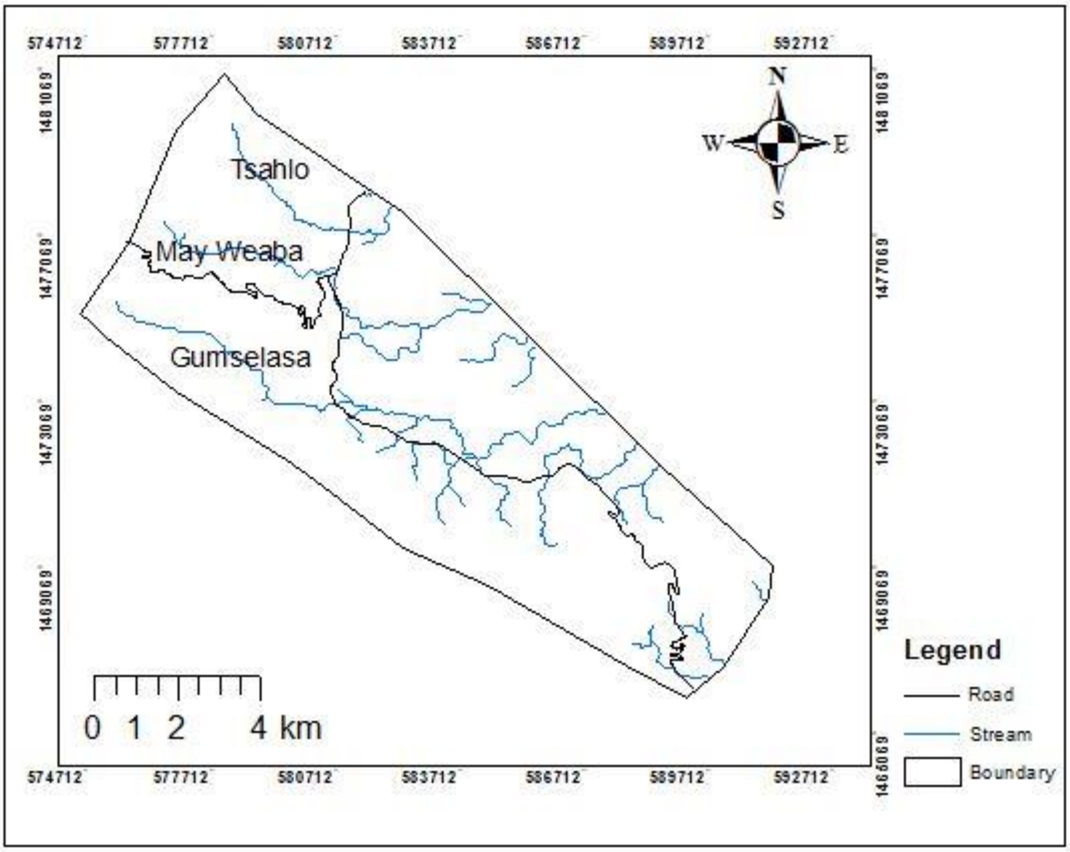


Figure 4.12 Drainage map

4.7. Hydrogeology

Hydrogeology of the area plays a significant role in controlling the incidence of landslide in the particular area (Tenalem Ayenew and Barbieri, 2004; Bekele Abebe et al., 2009). The presence of intensive rainfall is one of the major triggering factors for landslide in highland Ethiopia (Bekele Abebe et al., 2009).Previous research in the highland of Ethiopia on landslide shows that most of landslide related with intensive rainfall occurred mainly in the mid of August and mid of September (Lumb, 1975; Wieczork, 1987; Wilson and Wieczork, 1995 as cited in Kifle Woldearegay, 2013). Most of landslide triggered due to the prolong rain in the highland of Ethiopia are related with the combination of different factors such as shear strength reduction due to saturation in the upper parts of soil, and development of pore water pressure on lower parts of slope. In

Ethiopia both shallow and deep seated landslide has been occurred after prolong and intensive rainfall, and adverse seepage during the period of rainfall are frequent reason for development of pore water pressure and associated decrease in effective stresses within slopes which can enhances the process of slide(J.Michael and Stephen, 2005).

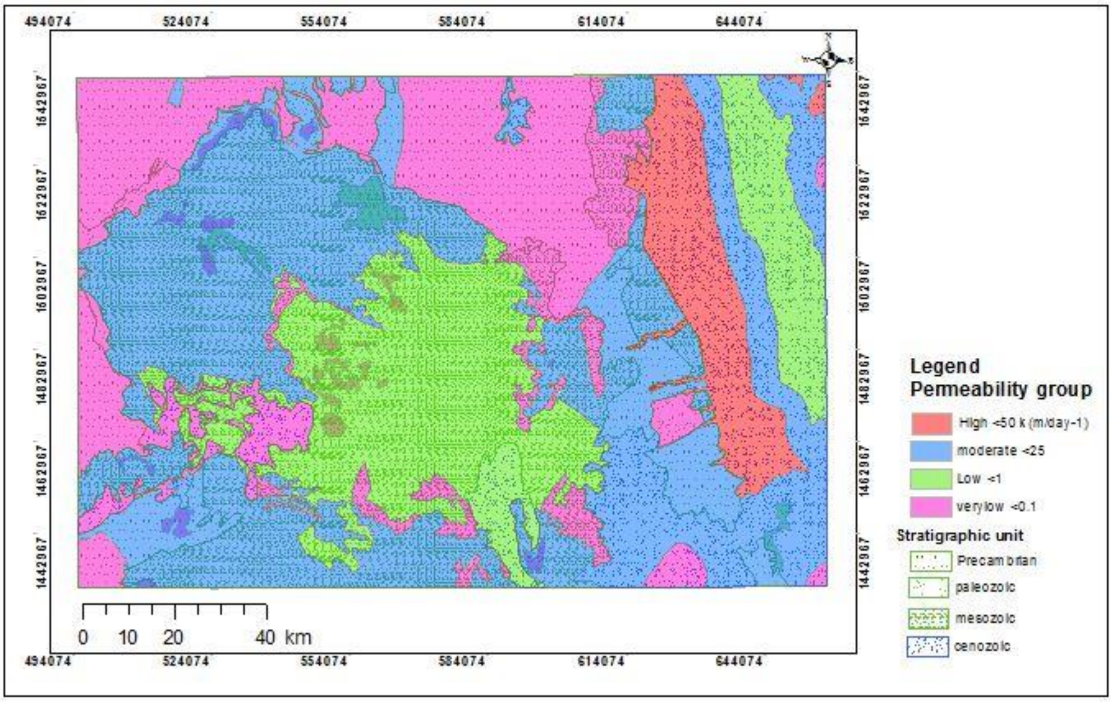


Figure 4.13 Hydrogeology map (After Ethiopian geological survey Sheet ND 37-11)

4.8. Geomorphology

The study area is a part of western Ethiopian highlands and it is characterized by different topographic undulation. Geomorphic process on the area leaves distinct imprints on landforms, and each geomorphic process develops distinguished features on landforms (Bradshaw et al, 1987 as cited in Gebremedhin Berhane et al., 2012).Weathering, erosion, mass movement, faulting and other factors are responsible for the formation of various landforms (Gebremedhin Berhane et al., 2012).The study area is characterized by cliff, gorges, and flat lying topography which forms due to different geomorphic process. Topographic Variation in elevation and rock not only provides variation in landscape but also provides a variety of landslide types in the area. The maximum elevation of the study area around 2318m and minimum elevation about 1173m. Evaluation of geomorphologic process like weathering, erosion, mass movements, and faulting helps to select an appropriate site for urban planning and construction of structures in problematic area.

4.9. Land use Land cover

4.9.1. Vegetation

Vegetation cover affects the stability of slope materials by influencing the hydrology and mechanical properties of soil mass (Greenway, 1987 as cited in Kifle Woldearegay, 2013). Vegetation coverage change could have important influence on slope stability in the area where the forest has been removed (Selby, 1993 as cited in Kifle Woldearegay, 2013)

Most of the vegetation of the study area is found in limestone rock units. In the study area it has been observed that the vegetation cover can be categorized as sparsely and moderately vegetated. Relatively the western parts of the study area with steeper parts are moderately vegetated while the flat-lying areas are sparsely vegetated. The western parts of the study area are using for grazing purpose. Scattered bushes, wild grass are some types of vegetation which widely observed in the area. Maize is the dominant crop production in the area.

4.9.2. Settlement

Abala town is located on the flat and at base of mountains which shows variety of topographic undulation. Recently the settlements are still undertaking at base of mountain and hill slopes. The cliff and flat lying parts of the study area mainly covered by sparsely-moderate vegetated forest and maize respectively.

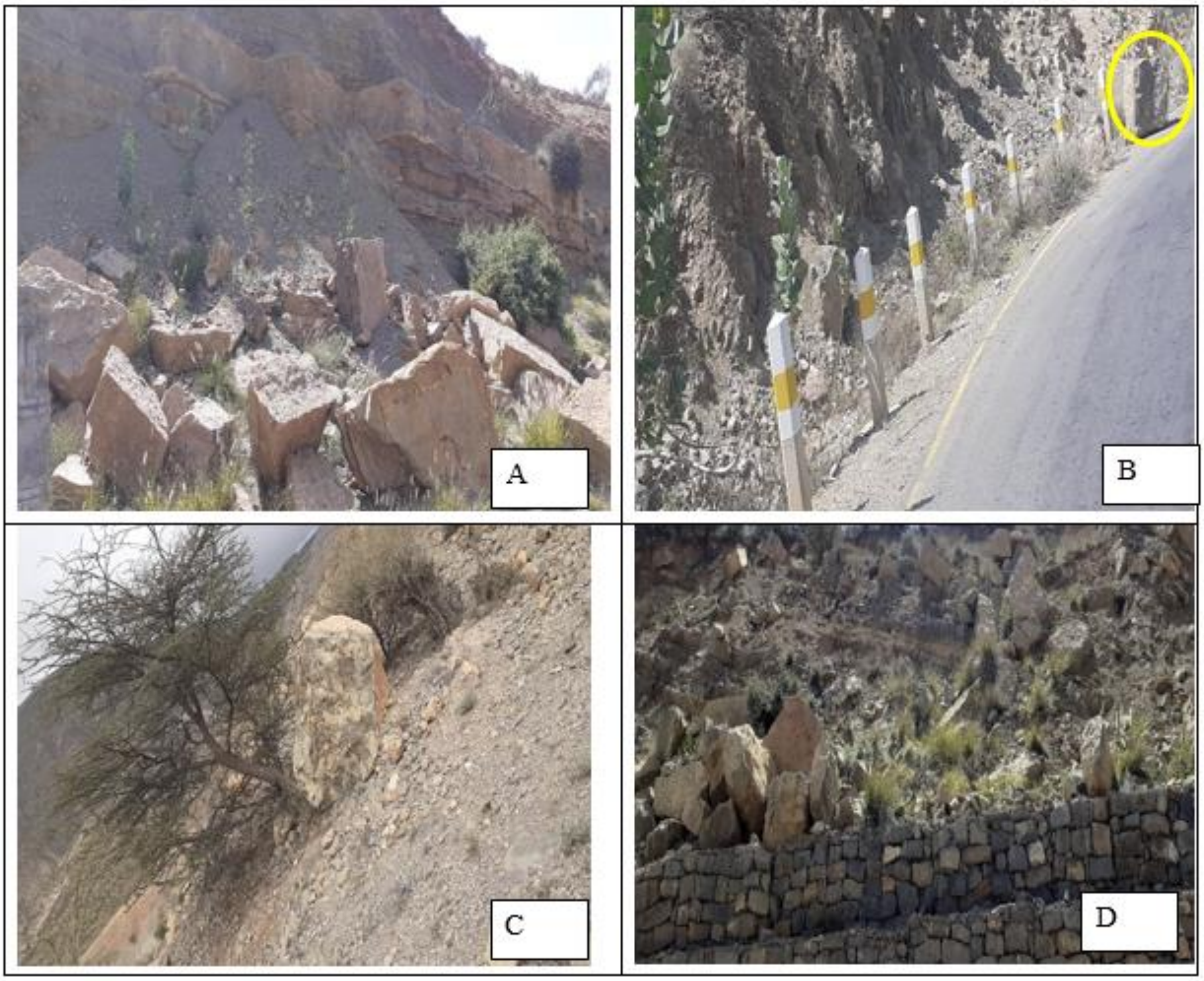
4.10. Landslides in the area

4.10.1. General

During the field observation the landslide affects and destroyed the gabion and road. Generally, the western and south eastern parts of the study area highly affected by landslide particularly along the roads**.** The size of materials moved ranged from soil to a big block of rocks.

4.10.2. Types of landslide in the area

Based on the types of materials displaced and the types of movements, the types of landslide observed in the study area are rock fall, rotational slide, and translational slide. Generally, the translational slide in the area observed on incompetent shale at the top of limestone which has steep angle and various dimension. The translational slide in the area mainly found on the north western parts of the study area which is affected by weathering. Due to the translational slide, the gabion constructed are displaced and collapsed. The major causes of translational slide in the area are associated with lithology which is susceptibility to weathering. The presence of shale within the rock is the main predisposing factors that contributed to the occurrence of translational slide in the area. The intercalation of (shale marl-limestone) of weak (shale, marl and limestone) and unaltered (mainly limestone) rock unit may contribute to slope failure when the other factors provides favorable condition for instability. Under such condition the weak rock unit washed away and serves as a plane of weakness and failure occurred along weak zones. Structural discontinuity is another factor which causes of translation slide. The presence of structural discontinuity affects the strength of rock unit and results disintegration and loosens of the rock unit which causes slope failures. In these types of slide the rupture surface is planer. Rock fall is another types of slide found on the study area. These types of slide mainly observed on steeper portion of slopes and the volume of materials vary from fragmented of rock-block of rocks. The major rock fall in the area resulted from slope material which holds block of rock subjected to saturation (mainly flood coming from highland). Rotational slide types of slide mainly occurred on shale rock unit that is affected by weathering. In this kind of slide the rupture surface is curved concavely upward and it seems fresh slide. The slide material ranges from soil to fragment of rocks and relatively the displaced materials moved few distance compared to the translational slide. This types of slide widely distributed in the study area. The major triggering factors responsible for the occurrence of rotational slide associated after floods coming from the highland of Tigray which causes erosion at the base of slope. Rotational slide in the study area most commonly occurred on moderately steep-gentle slopes.


A
B
C
D

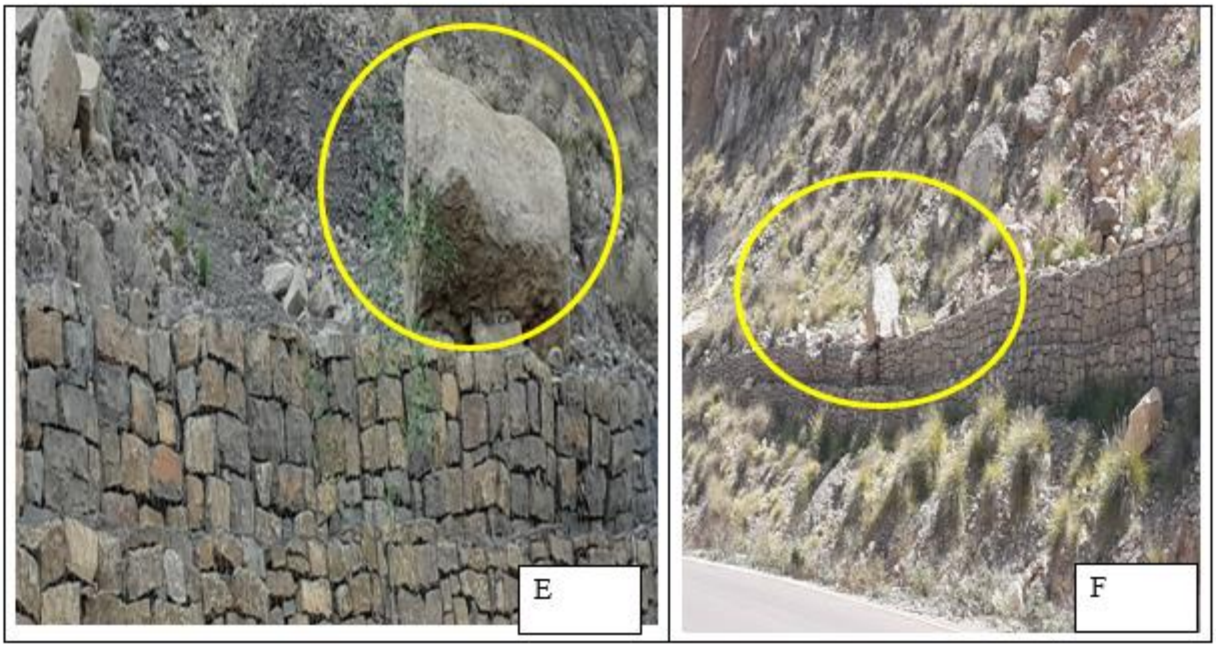


Plate 4.1 block of rock near to the road and on gabion (Rock fall) (A, B, C, D, E and F)

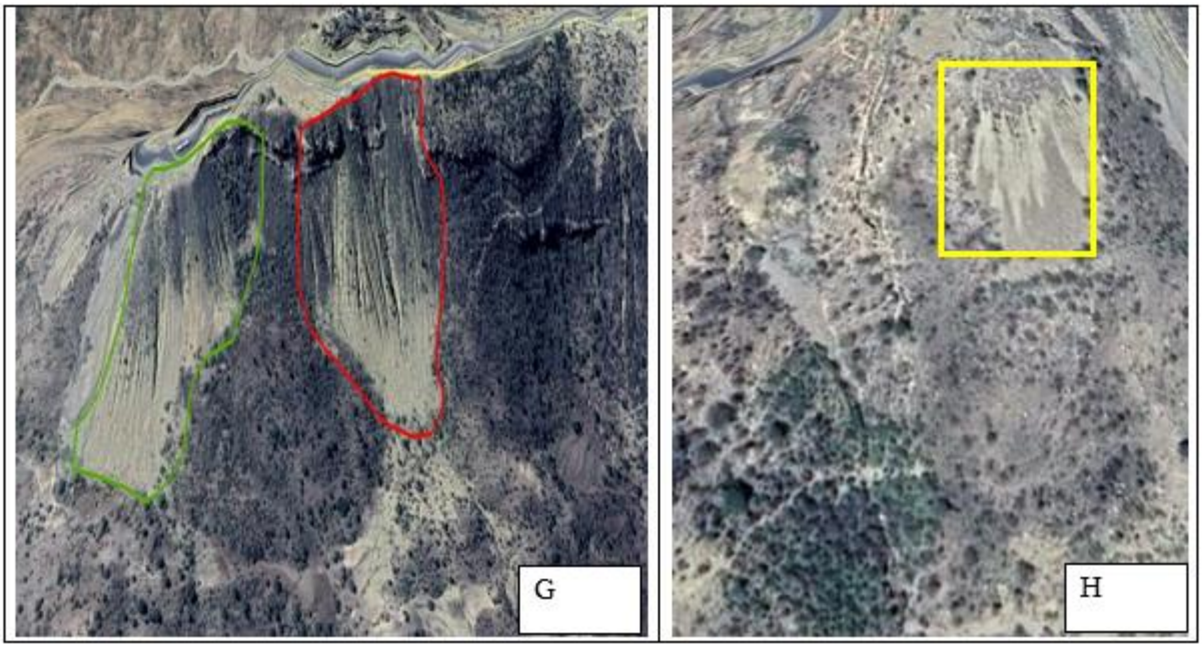
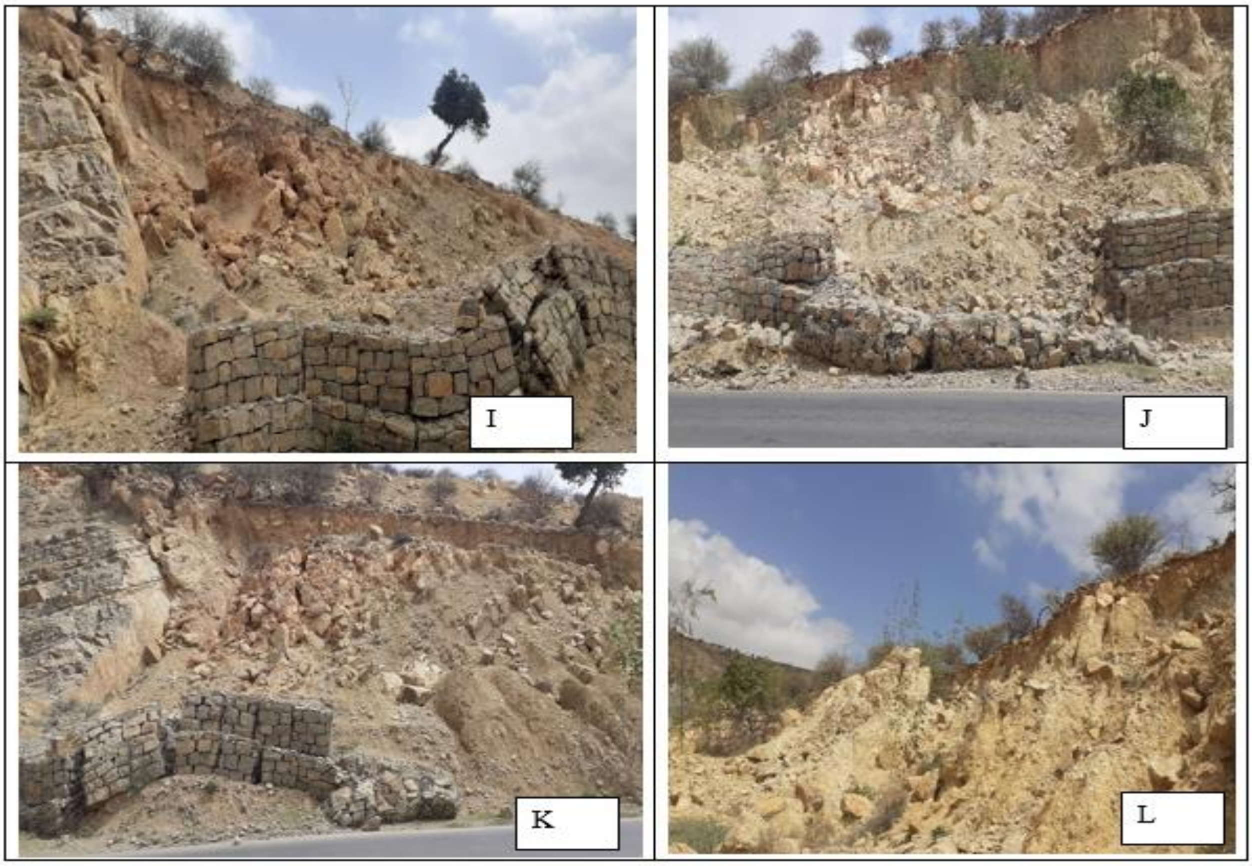


Plate 4.2 showing translation slide in the study area (G and H)


I
J
K
L

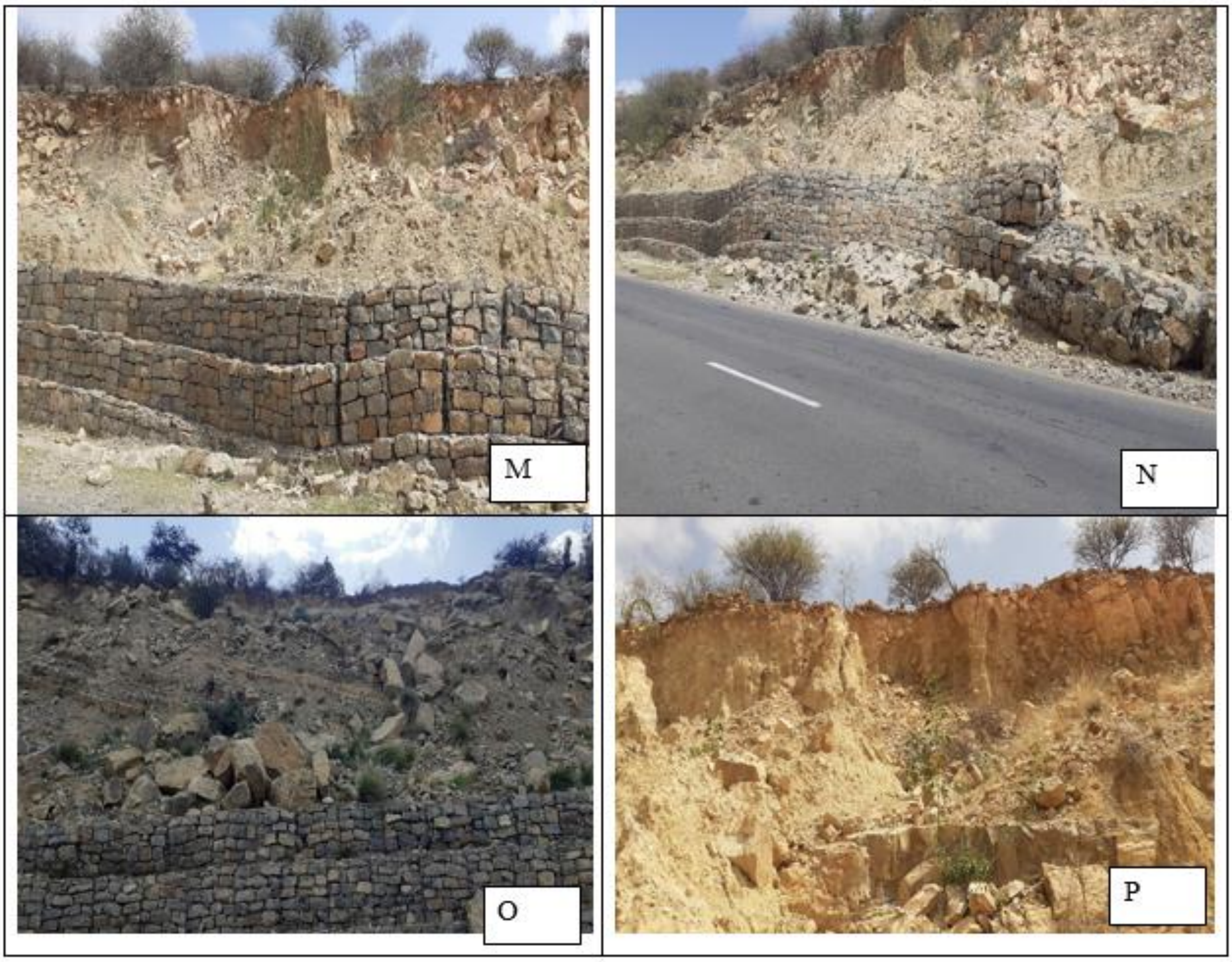


Plate 4.3 showing rotational slides in the study area (I, J, K, L, M, N, O, and P)

4.10.3. Possible contributing factors

According to Varnes (1984) there are a lot of factors to be considered to analyze landslide hazard. As mentioned by Soeters and Western (1996), considering all factors responsible for landslide may not be necessary; because it depends on which parameters are relevant or important for the current study.

The causal factors for landslide in the study area are determined by observation during the field. The possible causes of landslide in the study area generally related to Geology of the area, slope geometry, and structures are some of internal factors which is responsible for landslide in the area while seismicity, anthropogenic actives, and rainfall are the possible contributing factors for slope instability in the area.

4.10.4. Prominent cause of landslide in the study area

a). Lithology

According to Varnes (1984) lithological condition is the primary causes of slope instability. Most of scholar agrees on causative factor for landslide primarily associated with the lithology of the area.

The prominent causes of landslide in the study area primarily associated with the presence of incompetent-competent rock unit in the study area. The presence of incompetent-competent rock layer in the study area affects the stability condition of slope materials. As observed in the field the incompetent layer serve as a weak planes and many slope failure occurred along this weak surface. When the incompetent layer gets saturation it loses its strength and many slope failure occurs.

b). Structure

Geological structures found in the area control the stability condition of slope materials. The direction of intersection of discontinuity and slope, angle of inclination of discontinuity is the primary factors which governs landslide in the study area. The direction of discontinuity, and slopes nearly parallel to each other. Due to the above condition landslide occurred in the study area.

c). Anthropogenic activity

Improperly performed construction of road, carelessness on protective measures to the desired extent, and steep slope cut are some of manmade activities which caused landslide in the study area. Since the study area widely characterized by incompetent-competent layers, the slope cut needs feasible and appropriate corrective measures, but few corrective measures provides for slope. The disturbance of road construction played an important role in inducing instability of slope failures. During the excavation for road construction, the excavations disturbed the slopes and make the slope materials vulnerable to slope failures. Based on observation made during the field in the study area it appears that the risk of landslide on the local community is low but the effect of landslide especially associated with the road system appear to be more critically need concern in the area.

d). Rainfall

The precipitation on the study area is low, and the effects of rainfall can be considered as insignificant. However, the flood coming from highland of Tigray causing gully erosion, stream bank erosion which enhancing landslide in the area. The gully erosion is also caused by grazing practices when the area continuously grazed without a break, it breaks and soften the soil and disturb the structure of soil which in turn reduces cohesion of soil mass which eventually allow the soil particle to becomes vulnerable to the effect of rain and flood. Due to the impact of raindrop on the soil surface, it can break down the soil particles and displaced the soil materials to downward.

Generally, most of landslides observed in the study area were occurred due to the combined effects of internal and external factors considered in present research.

5. Chapter five Landslides hazard zonation

5.1. General

According to Varnes (1984) the term zonation is the division of the land surface into areas and ranking of this area according to the degree or potential of landslide hazard. Landslide hazard zonation can be conducted through the expert approach. In the present studies, landslide hazard zonation was carried out using SSEP. Slope stability susceptibility evaluation parameter (SSEP) is a Heuristic expert method that was developed by Raghuvanshi et al. (2014) considering both intrinsic and external factors are responsible for slope instability. To evaluate landslide hazard, the study area divided into individual facet, the rating provided for both internal and external factors, and then the rating are summed up. The sum of total of all rating would provide Evaluated landslide hazard (ELH).

5.2. Landslide hazard zonation

In slope stability susceptibility evaluation parameter, the first stage is dividing the study area into individual facets (Raghuvanshi et al., 2014; Anbalagn, 1992). Facet map of the area prepared from topographic map based on primary and secondary stream order, the major or minor hill ridges, and other topographic undulation using GIS environment. For this purpose, topographic map with the scale of 1:50,000 were used to demarcate the facet of the area. A total number of 62 facets have been delineated. The facet of study area is believed to have more or less similar of slope direction and inclination. The facet map of the area used as base map for preparation of LHZ.

In slope stability susceptibility evaluation rating schemes the intrinsic parameters considered are slope materials, slope geometry, structural discontinuity, land use/cover, groundwater condition while the external parameters are rainfall, seismicity, and manmade activities (Raghuvanshi et al., 2014).

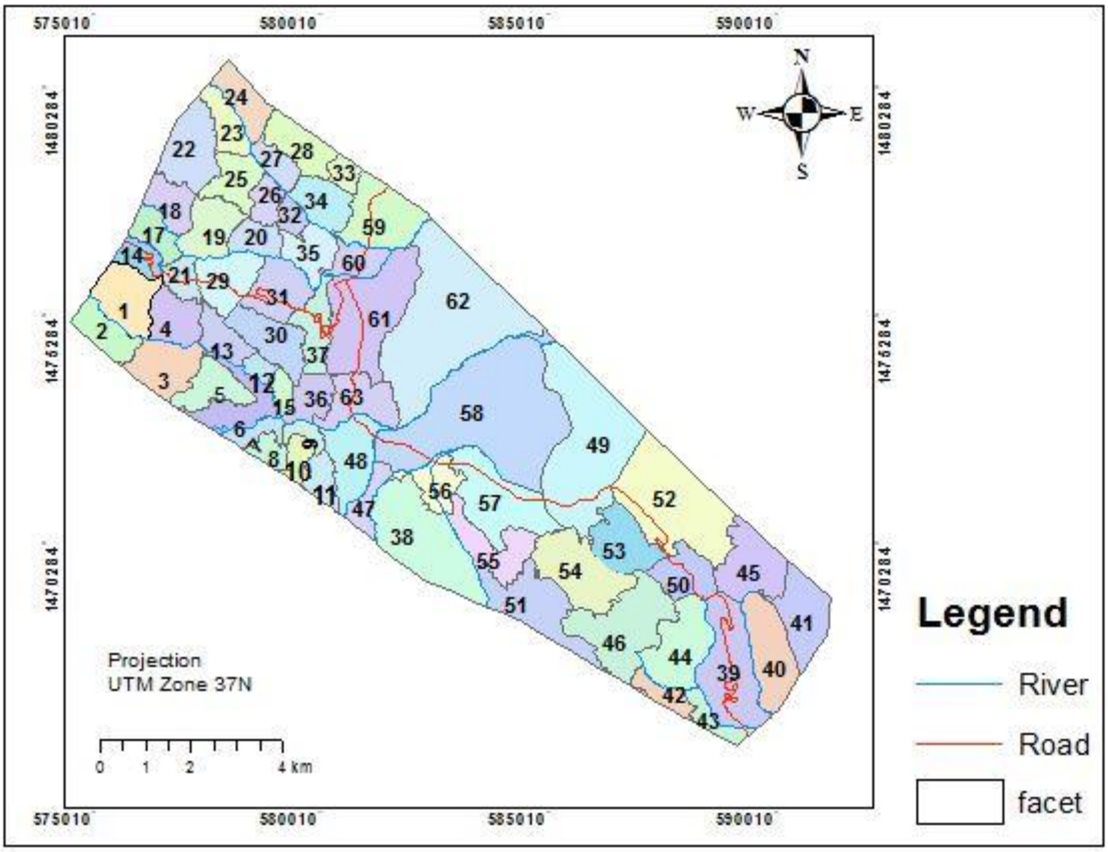


Figure 5.1Base map of study area showing the delineated facets

5.3. Landslide hazard causative parameters

5.3.1. Intrinsic factors (inherent)

Internal parameters are factors which causes the slope materials to move downward and they are the major factors behind the slope failures in the area, in other word inherent factors are causative factors which may be responsible for reducing the strength of slope materials and makes those materials susceptible to slope failures (Raghuvanshi et al, 2014; Kifle Woldearegay, 2013).These internal parameters includes relative relief, slope morphometry, slope materials, structural discontinuity, land use/cover, and groundwater manifestation (Anbalagan, 1992; Wang and Niu, 2009; Ayalew et al., 2004).

a). Slope geometry

The term slope geometry includes relative relief and slope morphometry. Relative relief defines the difference in elevation within facets or the difference in maximum and minimum elevation within a facet while slope morphometry defines steepness of slopes angle of slope. According to Bekele Abebe et al (2010) slope will be more susceptible for slope failure if the relative relief is high.

1). Relative relief

The relative relief map of the study prepared from topographic map with the scale of 1:50,000. For each facet map, the maximum and minimum elevation was determined and the range of two elevations was used to classify the facet into five classes. The relative relief map of the area categorized into very high (>301 m), high (201-300m), medium (101-200m), moderate (51-100 m), and low (<50 m). From the total area of 100 km^2, 10km^2 (10%) of the study area falls within Very high relative reliefs, 10km^2 (10%)falls into high relative relief, about 42km^2 (42%) of the area fall within medium relative relief, 3km^2 (3%) of the area falls into moderate relative relief, and 35km^2 (35%) of the area falls within low relative relief zone.

Table 5.1Relative relief classes with corresponding ratings

Class	Value range(m)	Rating
Very high	>300	1
High	201-300	0.8
Medium	101-200	0.6
Moderate	51-100	0.2
Low	<50	0.1

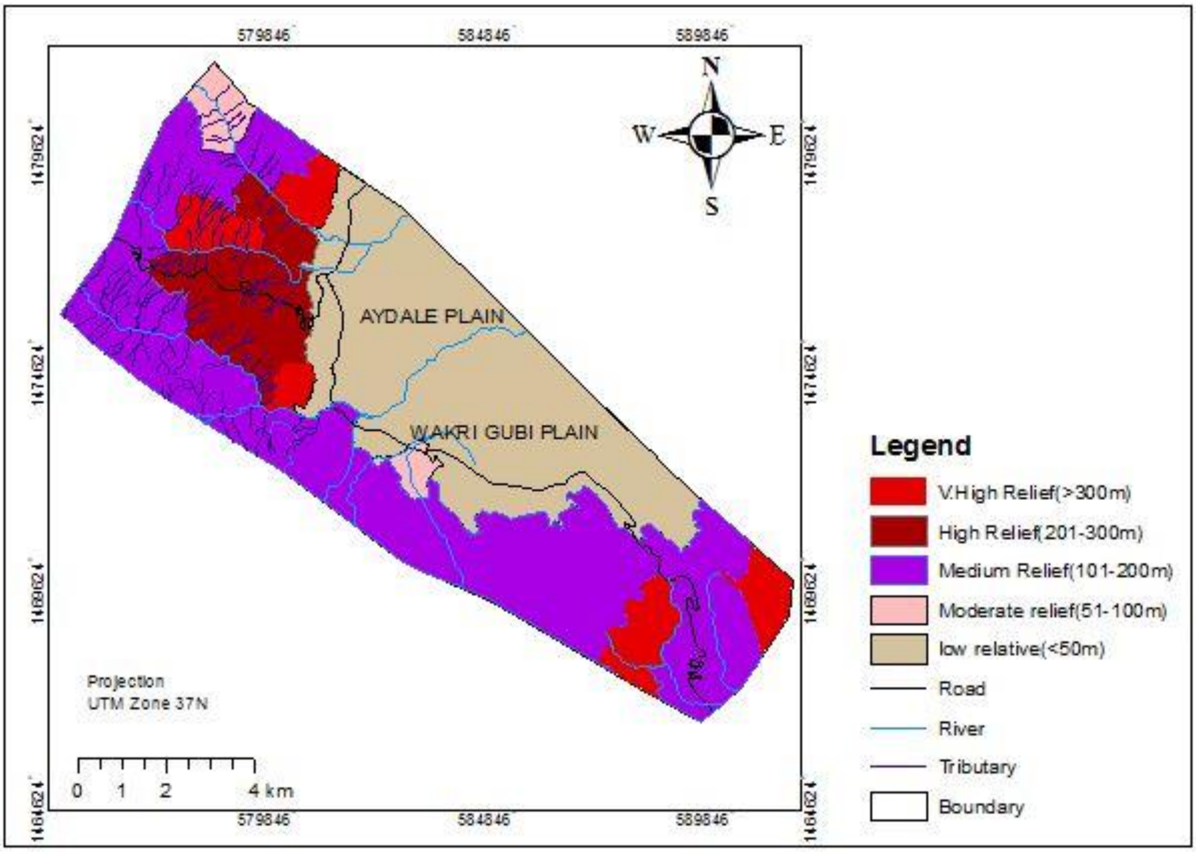


Figure 5.2 Relative relief map of the study area

2). Slope morphometry

According to Anbalagan (1992) slope morphometry defines the steepness or the angle of slopes. Using slope morphometry data it is possible to determine the types and severity associated with landslides hazard.

According to Raghuvanshi et al. (2014) and Anbalagan (1992) slope morphometry can be grouped into 5 classes: very gentle slopes (<15°), gentle slopes (16-25°), moderate steep slopes (26-35°), and steep slopes (36-45 °), and escarpment (>45°). From the total area of 100 km^2about 2km^2 (2%) of the study area falls within escarpment, 4km^2 (4%) falls into steep slopes, 10km^2 (10%) falls within moderate steep slopes, 23km^2 (23%) falls within gentle slopes, and 61km^2 (61%) of the study area falls within very gentle slopes.

Table5.2 Slope morphometry

Slope class	Values range (°)	Rating
Very gentle slopes	<15°	0.3
Gentle slopes	16-25°	0.6
Moderate steep slopes	26-35°	1
Steep slopes	36-45°	1.7
Escarpment	>45°	2

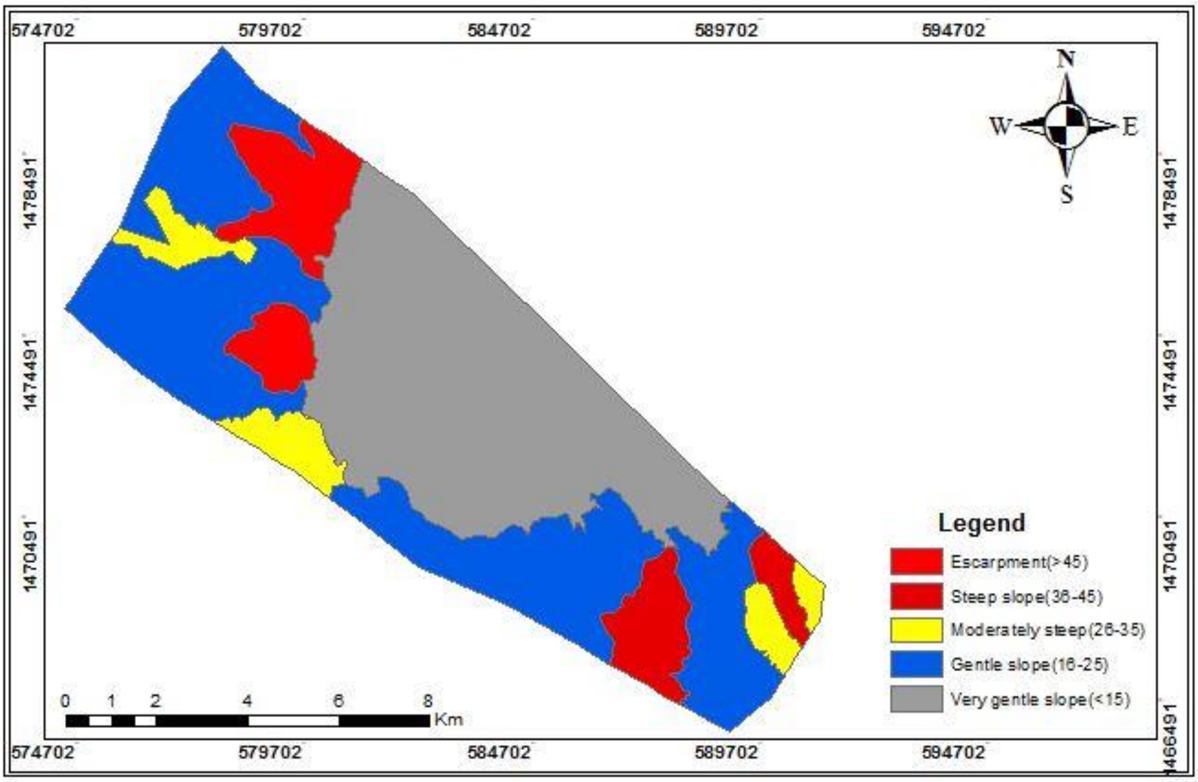


Figure 5.3 Slope Morphometry map of the study area

b). Slope Materials

The slope materials of the study area composed from rock, soil or both rock and soil. The major rocks and soil types in the area includes limestone, shale, and shale marl-limestone intercalation while the types soil are colluvial, residual and alluvial soils. The rock mass in the area comprised from slightly weathered limestone to highly weathered shale. The rating criteria to sub class of rock types based on the intact rock strength and degree of weathering.

The degree of erosion potential of rock is highly affects the strength of the rocks. The classification of rock based on the criteria proposed by Hoek and Brown (1997).These classes are Very weak rock (1-5 MPa), weak rock (5-25MPa), medium strong rock(25-

50MPa), strong rock (50-100MPa), very strong rock (100-250), and extremely strong rock (>250 MPa).

Based the field data obtained using Schmidt hammer, generally the strength of the slope material categorized into weak rock, medium and strong rock (slightly-moderately weathered) and soil mass deposits. Generally, the slope materials of the study area can be classified as highly weathered rocks or disintegrated rock mass (shale, marl and limestone) while blocky disturbed limestone (slightly-moderately weathered)

The degree of weathering that has been considered as; fresh, slightly weathered, moderately weathered, highly weathered, extremely weathered, and rock as soil (Ifran and Dearman, 1978). For the case when the slopes materials covered by soil, the rating criteria are based on genetic class and depth of soil cover. Limestone, shale and Limestone-shale marl intercalation are the dominant lithological unit in the study area. Colluvial, residual, and alluvial soil are the types of soil observed on the study area. The presence of incompetent shale marl makes the slope materials susceptible to weathering. Fault and joints are dominant geological structures which affects the strength of slope materials. Slope material map of the area has been prepared from the observation during the field by using topographic map as base and also from Google earth. From 100km^2 **,** 65 km^2 the study area covered by disintegrated rock mass, 10 km^2 by Blocky disturbed and the rest 25 km^2 covered by soil mass.

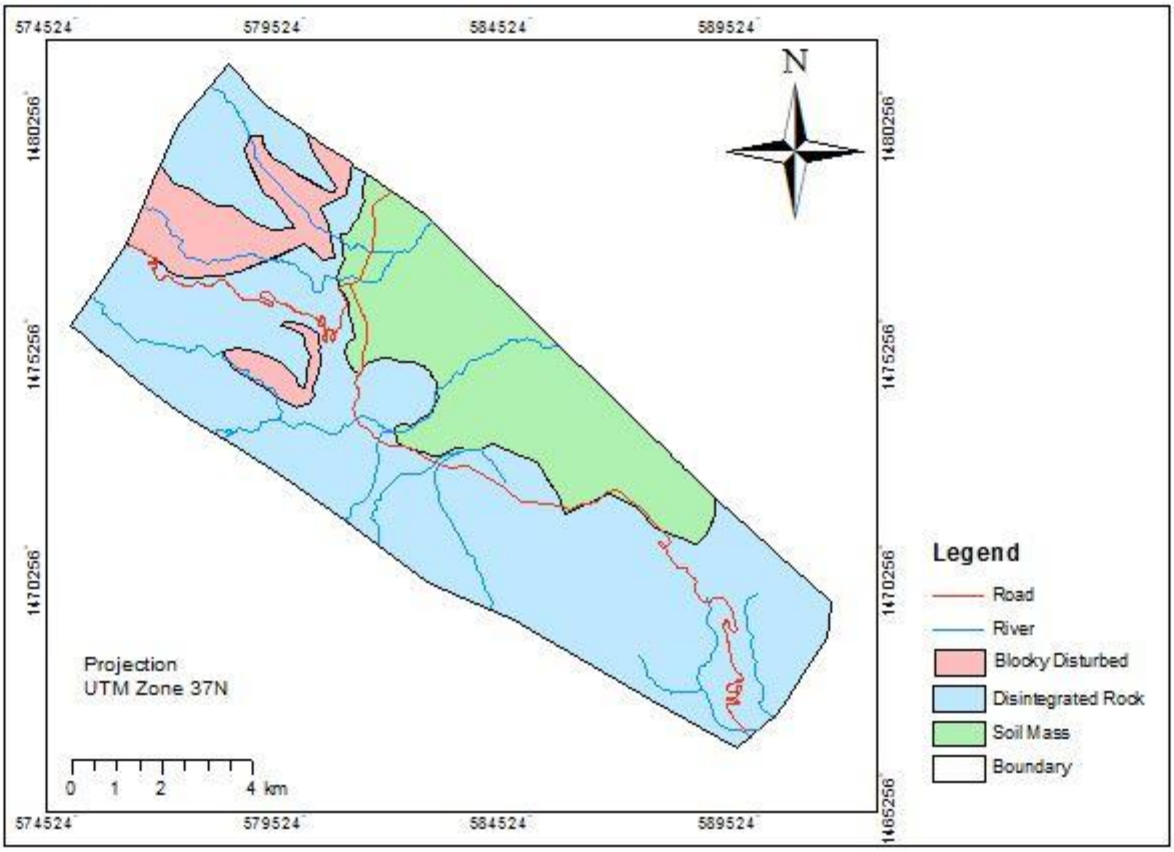


Figure5.4 Slope materials of the study area

c). Structural Discontinuity

A discontinuity represents a plane of weakness within a rock mass across which the rock materials structurally discontinuous. The structural discontinuity refers to primary and secondary structures found within the rock mass. These structures are joint, fault, foliation, lineation, and bedding etc. the presence of discontinuity in rock mass play important role in defining the stability and strength of the rock mass (Hoek and Bray, 1997).The orientation of discontinuity plane plays an important role in stability condition of rock mass, if the Orientation of discontinuity parallel to slope, the probability of slope failure will be high (Anbalagan, 1992). Relatively the strength of intact rock is high compared to the rock mass with structural discontinuities (Sidle and Ochiai, 2006). While dealing with the stability condition of rock mass, it is vitally important to consider the factors which influence stability of rock mass are: orientation, spacing, continuity, nature of infilling materials, and separation within discontinuity surfaces (Price, 2009; Johnson and Degraff, 1991).In the SSEP approach facet wise structural discontinuity or simple measurement are made during the field work. The orientation of discontinuity measured in terms of dip amount and dip direction. During the field work general observation has been made for condition of rock mass and characteristics of discontinuity.

d). Land use land cover

The stability condition of slope affected by land use land cover practice on the hill of slope. Land cover is an indirect indicator of the stability of hill slopes. Barren and sparsely vegetated areas show fast erosion and greater instability relative to thickly vegetated areas (Anbalagn, 1992). A well spread root system increases the shear strength of slope materials because the root of plants binds the soil mass together (Anbalagn, 1992).

The land use land cover of the study area classified as; grazing lands, minor cultivated land, and forest, settlement, and bare lands. Most of the study area particularly on mountainous area is forests and used as grazing lands for local people while the flat part of the area is using as cultivation and many parts of it is bare lands**.** The land use land cover of the study area was prepared from satellite images during the desk study with the help of Google earth to interpreter the images. During the field work previously prepared land use landcover map was modified based on the visual interpretation, then the final land use land cover map of the study area produced in Arc GIS 10.5.From 100 km^2 of the study area, 53km^2(53%) covered by sparsely vegetation, 4km^2(4%) by settlement, 10km^2(10%) covered moderately vegetation, 0.3km^2(0.3%) by crop, and 32.7(32.7%) km^2 by bare land.

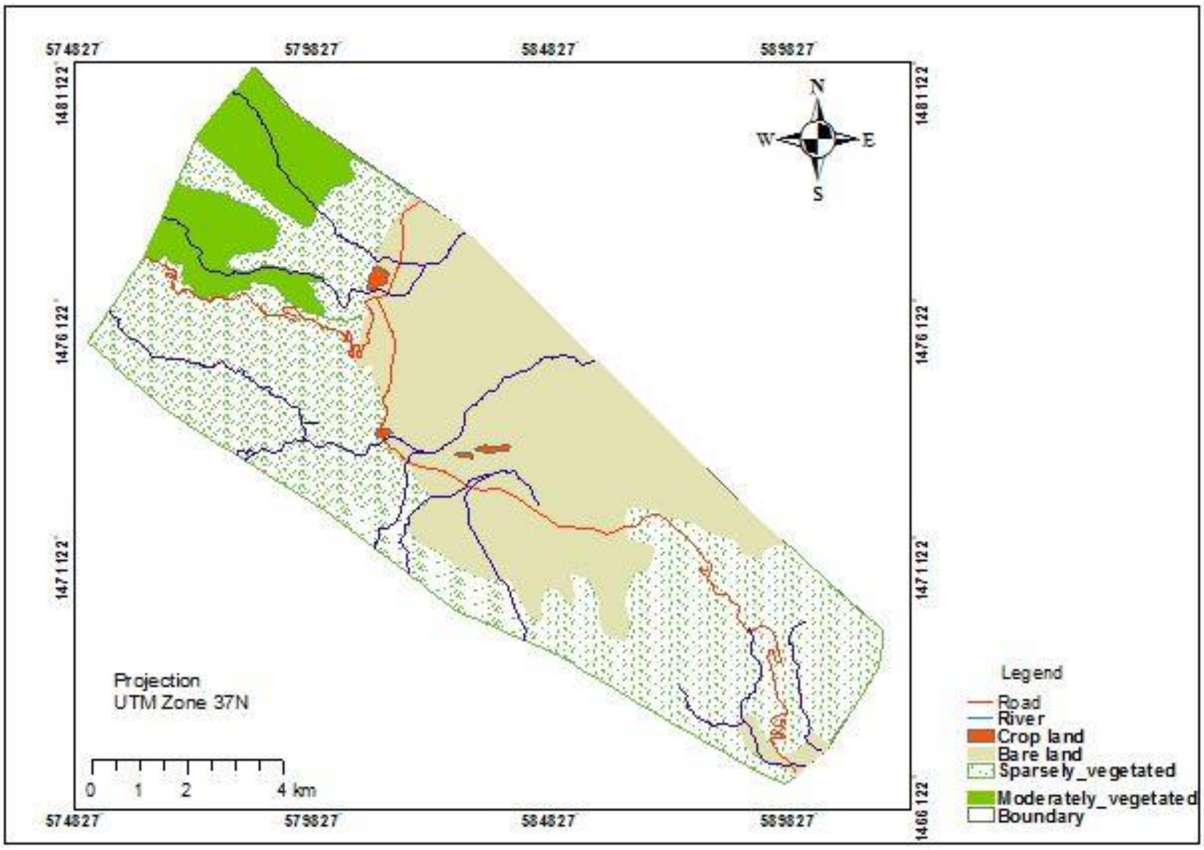


Figure 5.5 Land use Landcover map of the study area

e). Groundwater

According to Hoek and Bray (1981) the presence of groundwater plays an important role on the stability condition of slope materials. Slope stability studies for hazard mapping over large areas makes it difficult to have direct observation of groundwater behavior within slopes. Moreover, information on water table levels and fluctuation is rarely available (Raghuvanshi et al., 2014). The surface indication of water such as damp, wet, dripping and flowing (Anbalagan, 1992).Most of the rivers in the study area are dry in the dry season, and transient water flow may be found in these rivers after rainfall in the rainy season.

5.3.2. External triggering factors

Varnes (1984) states, the external stress on slope are rarely constant over long period of time, relatively variable, or temporary and imposed by new activities like rainfall, seismic vibration and volcanic activities. Rainfall, seismicity, and manmade activities are some of the most important external parameters which initiate the process of mass movement

(Raghuvanshi et al., 2014).For the present study, seismic, rainfall, ad manmade activities were considered as external parameters that triggers landslide.

a) Rainfall

Rainfall is a primary cause of landslides and worse slope stability problems (Lulseged Ayalew, 1999). According to Kifle Woldearegay (2013) the hill and mountainous terrain of Ethiopia highland are affected by rainfall-induced landslides of various types and size.

According to Hoek and Bray (19981) the rainfall recharges the groundwater and saturates the slope materials, in addition to this the groundwater within the structural discontinuity develops water pressure which results reducing of shear strength along the weak planes. In order to incorporate the effect of rainfall in SSEP rating schemes mean annual rainfall has been considered. Further, the rain induced manifestation on slope such as; gully erosion, slope toe erosion and stream bank erosion also considered (Raghuvanshi et al., 2014). In order to assess the impact of rainfall on slope instability factors such as; types of slope materials, discontinuity orientation with respect to slope, slope morphometry has been considered.

The present study area receives the mean annual rainfall of 374.88 mm in the last 30 consecutive years which is considered as low. The study area receives the peak of rainfall in the month of August and July. Gully erosion, stream bank, and slope toe erosion are some of the rain induced manifestation of over the study area.

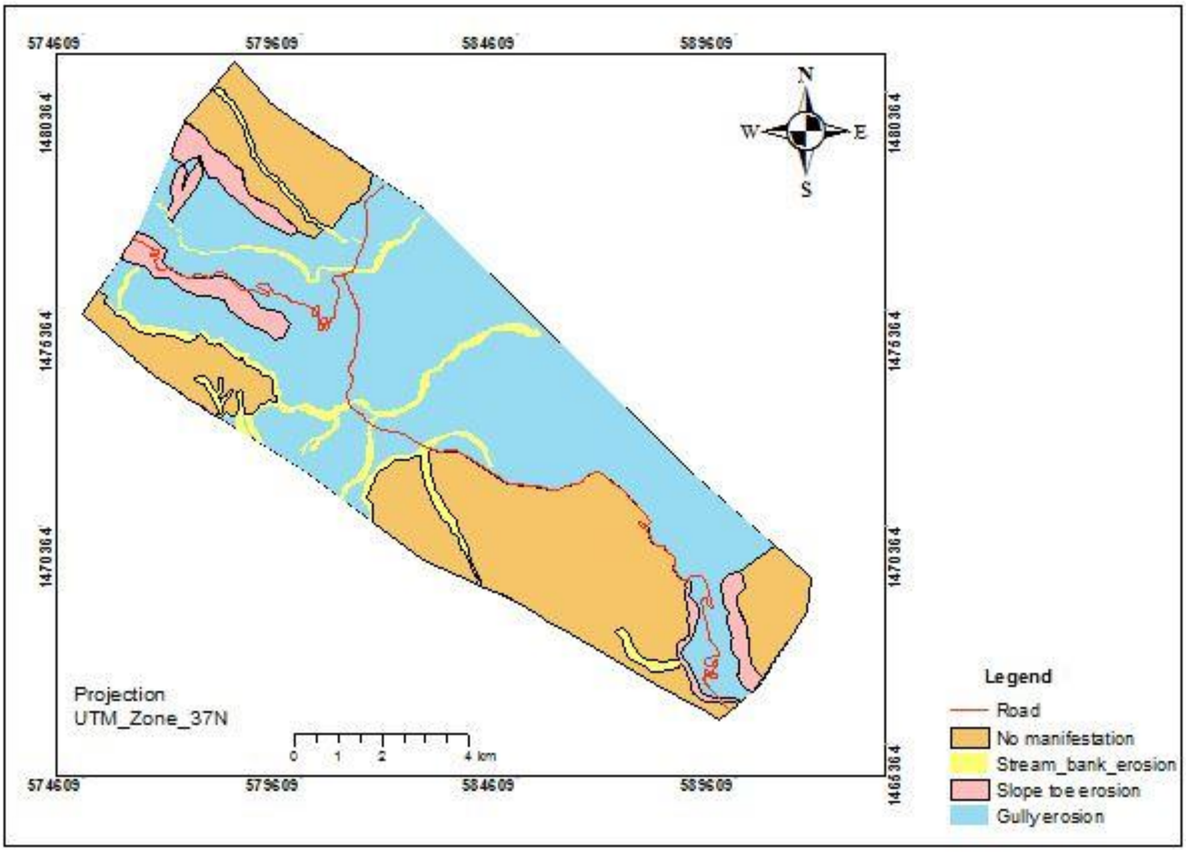


Figure 5.6 Rain induced manifestation

b). Seismicity

Seismicity produces ground acceleration which results slope failure (Keefer, 2000; Paris and Jibson, 2000; Bommer and Rodriguez, 2002). According to Hoek and Bray (1981) the slope materials that remain stable under static load due to the overlaying materials can fail under dynamic load due to earthquake. When slope materials with discontinuity subjected to seismic activity result into widening of structural discontinuity which in turn reduces the strength of slope material and which increase instability of slope materials (Raghuvanshi et al., 2014). The ground acceleration can be related to the intensity of seismic activity. The intensity of earthquake can be determined from the seismic map of the area based on the relationship between intensity of earthquake (Modified Mercalli scale) and ground acceleration (Raghuvanshi et al., 2014).

According to Laike Mariam Asfaw (1986), the seismic risk map produced for a hundred year return period and 0.99 probability shows that the study area falls within 8 M.M scales. Based on The Modified Mercalli scales, the estimated horizontal acceleration for the study area found to be 0.1 – 0.2g, as determined from MM intensity graphs. The seismic intensity over the study area is the same, so the corresponding ground acceleration will be the average of 0.1 and 0.2 which 0.15 throughout the study area.

c). Man Made activity

In addition to natural external triggering parameters, anthropogenic activity on hill slope increases the potential of slope instability (Wang and Niu, 2009). The developmental activities performed on hill slopes like construction of road; agricultural practice and building activities aggravates instability on slopes.

Construction of road and deforestation are some of manmade activity which may trigger landslide on the area.

5.4. Landslide inventory

According to Cruden (1991) landslide inventory is simplest form of landslide information which record landslide events in terms of location and dimension, and it is considered as simplest form of susceptibility map because it shows the position and dimension of landslide on the area. Identification of unusable slopes and preparation of Landslide inventory mapping is used as a base map for landslide hazard zonation mapping (Dai and Lee, 2002). In the present study area landslide inventory data have been obtained from the Google earth interpretation. The inventory data obtained from the Google earth revealed that 31 landslide events have been occurred in the past and most of these landslides are active. Once the landslide events occurred in the area delineated, latter the delineated map was checked and confirmed during the field.

Table 5.3 inventory data of landslide in the area

No	Location of inventory data		Description
	Northing	Easting	
1	1477693 m N	576746 m E	A 50 m by 120m size translational slide observed in incompetent shale on the top of limestone on steep slope with affected by gully erosion. The slide seems fresh.
2	1477525 m N	577053 m E	70 m by 100 m size translational slide observed in incompetent shale on the top of limestone on steep slope with affected by gully erosion. The slide seems fresh.
3	1477350 m N	577080 m E	80 m by 69 m size translational slide observed in incompetent shale on the top of limestone on steep slope. The slide seems fresh.

4	1477549 m N	576693 m E	A 34 m by 110 m size huge block of rock(Rock fall) , rock fragmented and unconsolidated materials (rotational) are failed from steep slope and placed at the base of slope which is near to the road and gabion is collapsed.
5	1477451 m N	576898 m E	A 20 m by 141 m block of rock (Rock fall), rock fragment and unconsolidated materials (rotational) that have origin of shale are failed from steep slopes and collapsed the gabion and filled the drainage line.
6	1477329 m N	576916 m E	22 m By 109 m size translational slide observed in limestone intercalation with highly weathered shale. The retaining wall constructed is washed out or destroyed and the rupture surface looks like planar.
7	1476815 m N	577744 m E	22 m by 100 m size rotational slide in highly weathered shale in moderately steep slope
8	1476524 m N	578831 m E	25 m by 41 m rotational slide in highly weathered shale that is influenced by gully erosion. It seems an old landslide.
9	1476698 m N	578667 m E	22 m by 108 m rotational slide in highly weathered shale that is influenced by gully erosion. It seems fresh landslides.
10	1475997 m N	580483 m E	26 m by100 m size disintegrated material, and highly weathered shale are failed from moderate steep slopes. The gabion is slightly moved toward the road due the load of moved materials. It is fresh landslides
11	1476114 m N	580531 m E	35 m by 120 m size of fragmented rock materials and highly weathered shale slides from steep slopes
12	1475875 m N	580687 m E	26 m by 170 m size of fragmented rock materials and highly weathered shale slides from steep slopes (rotational). The gabion is slightly moved from its original position due to the load of moved materials.
13	1476557 m N	580514 m E	A 46 m By 115 m size highly weathered shale, alluvial, colluvial and residual soil observed at bank of river and the bank of river is highly eroded
14	1476875 m N	577925 m E	27 m by 180 m size rotational slide in highly weathered shale that is affected by gully erosion. The landslide seems fresh
15	1477923 m N	580830 m E	80 m by 190 m highly weathered shale moved from steep slopes (Rotational slide). The slope material is influenced by gully erosion
16	1475705 m N	580765 m E	A 50 m By 79 m size highly disintegrated limestone – shale intercalated materials are failed and completely filled the drainage line
17	1476944 m N	580945 m E	A 36 m by 135 m size disintegrated materials failed along road cut
18	1471028 m N	588110 m E	A 30 m by 103 m size disintegrated material (limestone), and highly weathered shale are failed from road cut and deposited at base of slopes.

19	1470820 m N	588235 m E	54 m by 108 m size fragmented rock materials and soils are slides and deposited at base of slopes.
20	1470679 m N	588322 m E	A 40 m by 196 m size fragmented rock materials, weathered shale and block of rock are slides and deposited at base of slopes (rock fall).
21	1469979 m N	589281 m E	A 35 m by 106 m size highly weathered shale slides and deposited along the road.
22	1469563 m N	589636 m E	A 29 m by 120 m size of huge block materials moved and separated from the upper surface and the rupture surface have spoon shape(concave up ward)
23	1469744 m N	589588 m E	27 m by 101 m size slope materials slide and the gabion constructed as mitigation measure collapsed and moved from its position on the other side(rotational slide)
24	1469456 m N	589547 m E	A 39 m 172 m size large block of materials moved and the slide looks fresh. The slide materials consists of fragmented material, and colluvial materials.
25	1468114 m N	589657 m E	38 m by 170 m highly weathered shale with disintegrated limestone slides and displaced constructed gabion for prevention.
26	1467919 m N	589589 m E	49 m by 94 m size highly weathered shale with disintegrated limestone slides
27	1467952 m N	589688 m E	33 m by 141 m highly weathered shale with disintegrated limestone, and large block of rock displaced. It seems debris flow and rock fall
28	1467785 m N	589612 m E	35 m by 161 m fragment rock displaced and filled the drainage line
29	1467706 m N	589665 m E	33 m by 119 m fragment rock displaced and filled the drainage line (rock fall)
30	1467670 m N	589569 m E	A 52 m by 77 m highly weathered volume of rock are observed on the gabion wall and in some part the gabion wall is destroyed due to displaced materials
31	1468879 m N	589547 m E	A 35 m by 182 m size of huge block of fragmented, and unconsolidated materials displaced from slightly gentle slope. The rupture surface look like concave upward

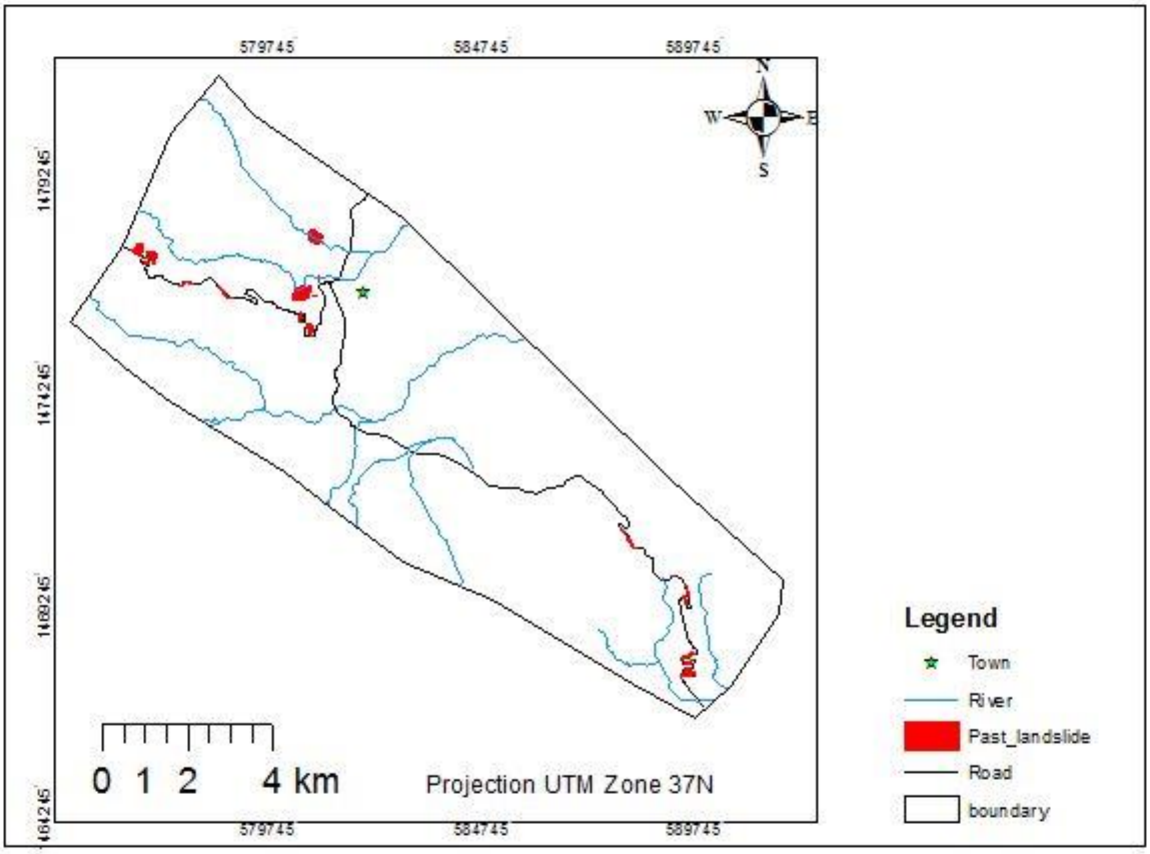


Figure 5.7landslide inventory map

5.5. Landslide hazard evaluation

According to Anbalagan (1992) the net probability of slope instability in a given facet is determined through total estimated hazard or evaluated landslide hazard. In order to evaluate landslide hazard zonation in area individual facet wise rating for both external triggering and intrinsic parameters are summed up. The total sum of all rating provides evaluated landslide hazard (ELH).For the present study data was collected for intrinsic and external factors and the evaluated landslide hazard was computed for each individual facets.

Based on the value obtained from evaluated landslide hazard, the study area classified as Low, Moderate, and High hazard zones. The maximum ELH found is 10.7 which considered as class IV while the minimum value resulted is 2.8 which considered as class II (Appendix 5.3).

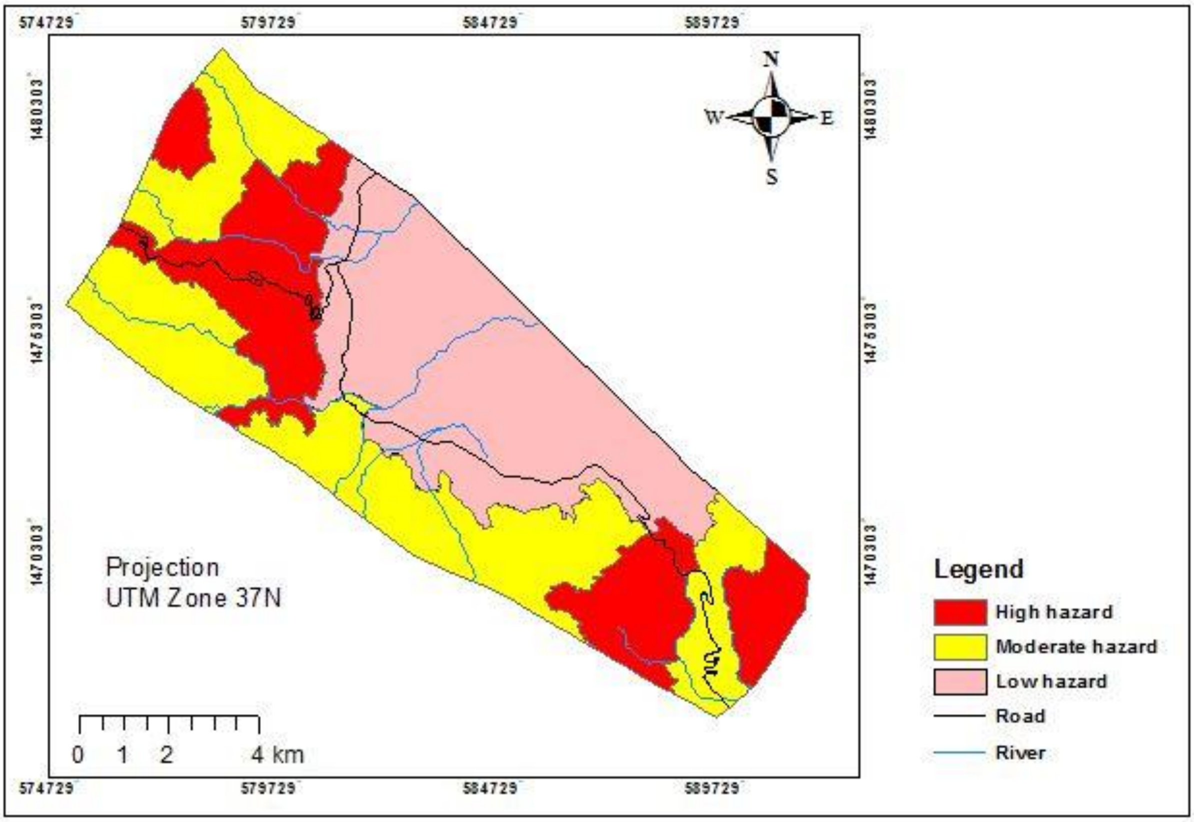


Figure 5.8 landslide hazard zonation maps

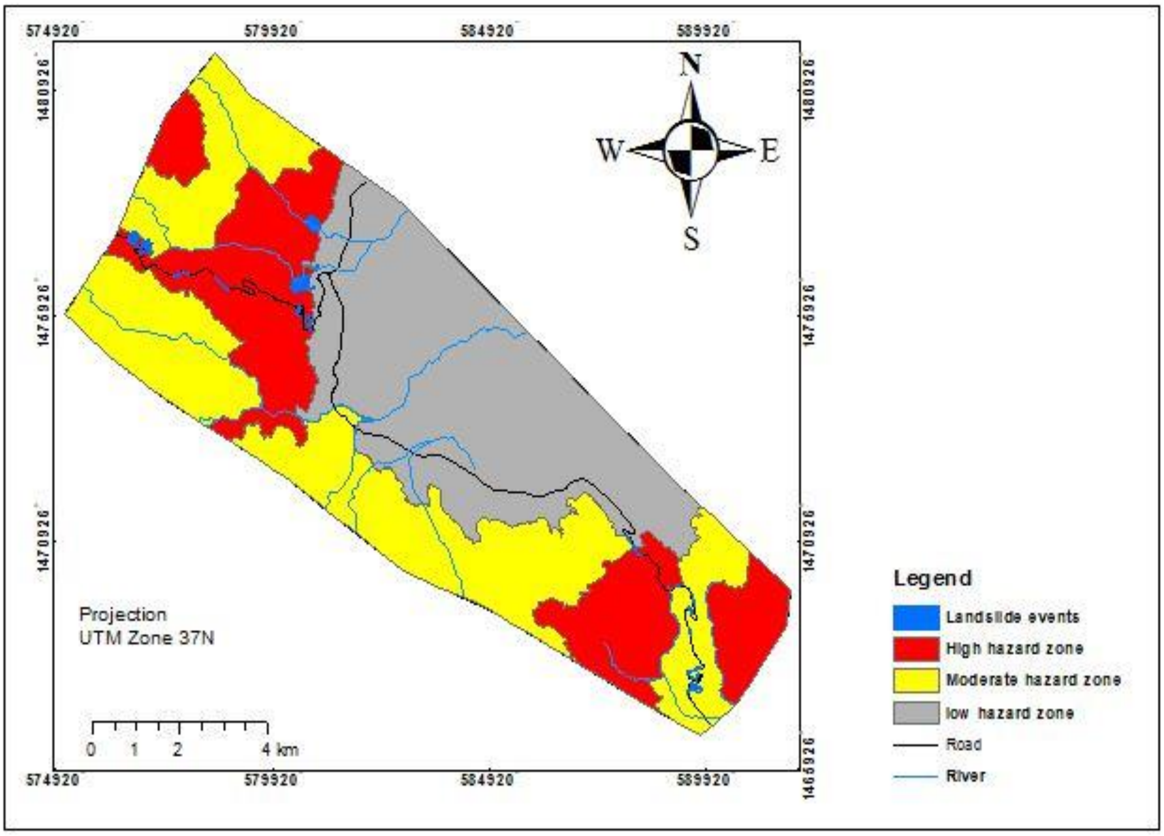


Figure 5.9 landslide Activities overlaid on landslide hazard zonation map

5.6. Discussion

The landslide hazard zonation map of the current study area conducted using slope stability susceptibility evaluation parameter rating schemes. The zonation map prepared based on the result obtained from Evaluated landslide hazard (ELH). Evaluated landslide hazard show the probability of slope failures and the value were calculated facet wise by adding the rating provided for each intrinsic and external factors. Based on the result obtained generally, the study area divided into three hazard classes which is IV, III and II (figure 5.9). The High hazard zone mainly located in the north-western and south-eastern parts of the study area. Out of 62 facets, 24 facets fall within high hazard zones which cover an area of 27km^2 (27%). The high hazard zone in the study area mainly characterized by very high relative relief-medium relative relief. Since the high hazard zones shows the relative relief from very high-medium relative relief which makes the slope prone to failure. The slope morphometry in this hazard zone are found between Escarpment-moderate steep slopes. Since the high hazard zones occurred in the above morphometery the probability of slope failure would be high. The rain induced manifestation observed in high hazard zone is characterized by slope toe erosion, gully erosion, and stream bank erosion. The presence of this rain induced manifestation on slope aggravates the process of landslide. Blocky disturbed and disintegrated rock is the major slope materials observed on high hazard zone and this slope material affected by weathering. These areas mainly used for grazing for local people. The asphalt road from Aba-ala to Mekelle passes through high hazard zones in the north-western parts of the study area, and it is clearly noticed that the major road section failure at various localities observed in high hazard zones. Translation slide is one of landslide events occurred in high hazard zones. The major prominent factors responsible for translational slide generally associated with the presence of incompetent-competent slope materials. Due to the influence of external factors like water coming from highland parts of Tigray, the incompetent shale slope materials displaced and move downward. In addition to incompetent-competent slope materials the presence of discontinuity also affects the strength of slope materials. Due to different prominent factors like presence of weak shale materials, discontinuity, improper construction of road, and less extent to flood and rainfall are the major factors responsible for landslide. Gabion failure, retaining wall failure, rock fall, rotational slide, and translation slide in this hazard zones widely observed. The moderate hazard zones mainly located at north-western, southern, and south-eastern parts of Aba-ala town. These areas are mainly characterized by gully erosion, slope toe erosion, and no manifestation. The moderate hazard zones mainly found within very high-medium relative relief, moderate-steep slopes. The slope materials covering in this hazard zones are mainly disintegrated (mainly) and block disturbed rock mass. From 62 facet, 28 facets fall into moderate hazard zones with the areal coverage of 37km^2 (37%). The road passes through this hazard zone in the south-eastern side of the study area highly affected by landslide. Due to different causative factors like presence of weak shale materials, discontinuity orientation, steep road mass cut, and less extent to flood and rainfall are the major factors responsible for landslide. Retaining wall failure, rock fall, rotational slide, translation slide, and gabion failure has been observed in this hazard zones. The low hazard zone located at the central parts of the study area. This area is mainly characterized by soil mass, low relative relive, gentle slope, and gully erosion. Due to the flood coming from mountainous area it is highly affected by gully erosion. Relatively this parts of the study area is not affected by landslide. Out of 62 facets, 10 facets falls into low hazard zones with areal coverage of 36km^2 (36%).

Generally, the landslide hazard zonation map of the study area indicates 37%, 36% and 27% of slope fall observed in moderate, low and high hazard zone respectively. During the field 31 landslide activities has been recorded. Almost all landslide activity recorded along the road section and this landslide event mainly falls into moderate and high hazard zones. Out of 31 landslide inventory, 17(55%)landslide events occurred in high hazard zones, 11(35%) incident of landslide happened on moderate hazard zone and 3(10%) occurred in low hazard zones. This shows that 90% of existing landside falls within High and Moderate hazard zones. Therefore, the landslide hazard zonation map done using slope stability susceptibility evaluation parameter rating schemes for the present study area validated with the active landslide events in the area.

CHAPTER SIX CONCLUSION AND RECOMMANDATION

6. Chapter Six Conclusion and Recommendation

6.1. Conclusion

The present study area located at North-Western parts of Afar and Southern parts of Tigray. The area particularly located at the base of Western highland of Ethiopian which is around Aba-ala town in afar regional states. Geographically the area is bounded by UTM (Zone 37) coordinated 576616-589758m E and 1467432-1477606m N. The elevation of the study area ranges from 1173m-2318m.The mean annual rainfall of the study area is about 374.8mm, and the study area receives the peak of rainfall in the month of August and July.

The main aim of present study is to evaluate parameters responsible for slope failure in the study area and to produce landslide hazard zonation map using SSEP by considering inherent and external factors. For the present study six inherent (relative relief, slope morphometry, slope materials, structural discontinuity, land use/cover, groundwater condition, and three external (rainfall, seismicity, and manmade activity) triggering factors were considered and data on those factors collected from primary and secondary sources. The study area has been classified into 62 facets and the rating provided for both internal and external factors and then the rating are summed up to obtain evaluated landslide hazard which used to classify the area into different hazard zones. Based on the result obtained from ELH the area classified into low, moderate and high hazard zones. The landslide hazard zonation map of the study indicates 27 % of the study area falls within High hazard zones, 37% of the study area into moderate hazard zones and 36% falls within low hazard zones. The landslide hazard zonation map of the study area was validated by comparing it with the existing landslide or past landslide distribution on the area. The result indicates that 55% landslide events occurred in high hazard zones, 35% of landslide occurred on moderate hazard zone and 10% occurred in low hazard zones. Generally, it may concluded that 90% of past landslide event falls within high and moderate hazard zones.

6.2. Recommendation

Based on the finding of the present research, the following recommendations are given;

- The road section running from Aba-ala to Mekelle in NW and SE parts of the study area passes through high and moderate hazard zones and susceptible to reactivated landslide events, therefore the concerned body of government particularly Ethiopian Road Authority should provide appropriate corrective measures and immediate response should be provided for slope materials blocking and distracting the transportation.
- Due to improper placing of remedial measures, failure materials are causing distress and deformation of the road. Unless the immediate response is provided, the maintenance of road may require huge investment.
- The gabion constructed as corrective measure in study area is simply accumulation of rock and easily displaced by slope materials, therefore it should be replaced by retaining wall and the surface drainage should be provided.
- Before implementing remedial measures for landslide in the study area as suggested, detail study on the types of landslide, causes of landslide and cost effective remedial measures should be implemented based on the result obtained from detail study.

All the effort has been made to conduct the present research with data collected from the field and secondary sources in systematic manner, however, all the efforts made to conduct the study under the constraint of time, resources, and finance. So that it is strongly recommended that detail study must be conducted before implementing any remedial measures recommended in this research.

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Appendix

Appendix 4.1 Rainfall data of Aba-ala station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
1990	1.0	3.0	5.0	0.0	0.0	0.0	100.0	86.0	59.0	0.0	0.0	0.0	254.0
1991	6.0	0.0	2.0	5.0	6.0	6.0	70.0	2.0	35.0	0.0	0.0	6.0	138.0
1992	5.0	2.0	1.0	26.0	5.0	5.0	77.0	110.0	8.0	23.0	36.0	0.0	298.0
1993	3.0	7.0	10.0	95.0	43.0	5.0	119.0	82.0	19.0	18.0	0.0	0.0	401.0
1994	3.0	7.0	0.0	12.0	0.0	31.0	156.0	203.0	48.0	0.0	0.0	0.0	460.0
1995	0.0	2.0	16.0	9.0	3.0	0.0	127.0	136.0	11.0	0.0	0.0	0.0	304.0
1996	5.0	0.0	46.0	0.0	28.0	26.0	118.0	202.0	0.0	0.0	9.0	2.0	436.0
1997	0.0	0.0	9.0	27.0	3.0	15.0	104.0	48.0	0.0	45.0	17.0	0.0	268.0
1998	0.0	0.0	6.0	0.0	47.0	7.0	252.0	116.0	18.0	0.0	0.0	0.0	446.0
1999	0.0	0.0	0.0	0.0	0.0	44.4	27.4	0.0	19.0	110.2	0.0	0.0	201.0
2000	0.0	0.0	0.0	0.0	0.0	30.2	84.9	132.3	33.0	32.3	0.0	0.0	312.7
2001	0.0	0.0	0.0	32.1	0.0	6.5	170.6	88.3	0.0	0.0	0.0	0.0	297.5
2002	0.0	0.0	0.0	5.7	125.8	0.0	27.2	207.3	12.5	0.0	0.0	0.0	378.5
2003	0.0	32.2	18.0	0.0	0.0	14.9	62.1	93.0	3.6	0.0	0.0	7.7	231.5
2004	0.0	0.0	0.0	0.0	1.5	3.1	32.3	90.2	25.2	3.2	0.0	10.1	165.6
2005	1.2	0.0	36.1	40.6	0.0	0.0	408.8	234.1	19.8	0.0	0.0	8.2	748.8
2006	6.8	16.6	0.0	47.0	20.1	0.0	254.8	128.5	1.0	6.8	0.0	0.0	481.6
2007	0.0	1.4	7.8	5.2	57.1	6.9	114.3	6.0	3.4	0.0	0.0	5.7	207.8
2008	0.0	0.0	0.0	163.2	58.5	12.0	145.8	95.0	42.5	0.0	3.1	11.0	531.1
2009	18.5	0.0	31.3	30.3	0.0	61.0	125.1	143.8	17.0	0.0	0.0	4.3	431.3
2010	47.1	2.1	18.8	21.7	0.0	5.3	65.2	48.7	0.0	0.0	0.0	0.0	208.9
2011	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	42.5	0.0	0.0	42.5
2012	0.0	0.0	0.0	13.2	68.2	0.0	138.6	156.3	31.5	23.3	11.0	1.1	443.2
2013	16.8	0.0	1.2	3.2	25.6	4.2	32.1	265.0	23.3	6.0	22.7	0.0	400.1
2014	3.6	0.0	0.0	61.3	145.0	23.0	197.3	136.7	0.0	0.2	9.5	0.0	576.6
2015	9.4	11.1	12.5	20.2	14.5	36.7	160.8	151.1	56.9	4.4	0.0	0.0	477.6
2016	0.0	24.4	0.0	92.0	0.0	0.0	105.3	149.3	23.0	0.0	0.0	0.0	394.0
2017	0.0	112.0	0.4	65.7	82.0	11.4	72.9	207.8	0.0	0.0	0.0	0.0	552.2
2018	0.0	24.4	0.0	92.0	0.0	5.0	0.0	496.1	0.0	103.0	0.0	0.0	720.5
2019	0.0	24.4	0.0	92.0	0.0	0.0	98.7	183.9	18.6	7.8	10.1	0.0	435.5
mean annual													374.8

Appendix 4.2 Schmidt Hammer values of rock mass

Sample NO	Shale	MPa	Limestone	MPa
1	SH1	10	LM1	55
2	SH2	10	LM2	60
3	SH3	10	LM3	65
4	SH4	12	LM4	40
5	SH5	15	LM5	43
6	SH6	15	LM6	35
7	SH7	15	LM7	43
8	SH8	12	LM8	42
9	SH9	12	LM9	25
10	SH10	17	LM10	20
11	SH11	15	LM11	37
12	SH12	11	LM12	38
13	SH13	12	LM13	45
14	SH14	12	LM14	45
15	SH15	15	LM15	45
16	SH16	15	LM16	46
17	SH17	--	LM17	50
18	SH18	--	LM18	65
19	SH19	10	LM19	65

Appendix 5.1 Rating Assigned to Structural Discontinuity Data

Code	Discontinuity type	Maximum Rating
A	Relationship between dip of discontinuity and inclination of slope	0.5
B	Parallelism between discontinuities dip direction and slope inclination	0.5
C	Dip of discontinuities	0.5
D	Soil cover depth	2.5
E	Structural discontinuity and rock mass condition	0.25
F	Separation	0.15
G	Continuity	0.15
H	Infilling	0.15
I	Roughness	0.15
J	Weathering	0.15

Facet ID	A	B	C	D	E	F	G	H	I	J	Total
1	0.5	0.4	0.25	0	0.22	0.12	0.02	0.02	0.03	0.1	1.66
2	0.5	0.4	0.25	0	0.22	0.12	0.02	0.02	0.03	0.1	1.66
3	0.4	0.1	0.5	0	0.22	0.12	0.02	0.02	0.03	0.1	1.51
4	0.15	0.3	0.4	0	0.22	0.12	0.02	0.02	0.03	0.1	1.36
5	0.5	0.3	0.4	0	0.21	0.12	0.02	0.02	0.03	0.1	1.7
6	0.5	0.3	0.25	0	0.21	0.12	0.02	0.02	0.03	0.1	1.55
7	0.5	0.1	0.4	0	0.22	0.12	0.02	0.02	0.03	0.1	1.51
8	0.4	0.2	0.25	0	0.22	0.12	0.02	0.02	0.03	0.1	1.36
9	0.5	0.3	0.4	0	0.22	0.12	0.02	0.02	0.03	0.1	1.71
10	0.15	0.1	0.4	0	0.22	0.12	0.04	0.12	0.1	0.1	1.35
11	0.15	0.2	0.25	0	0.22	0.12	0.04	0.12	0.03	0.1	1.23
12	0.15	0.25	0.25	0	0.15	0.12	0.04	0.12	0.1	0.07	1.25
13	0.15	0.25	0.25	0	0.2	0.12	0.04	0.12	0.1	0.07	1.3
14	0.15	0.25	0.25	0	0.15	0.12	0.02	0.02	0.1	0.1	1.16
15	0.15	0.1	0.4	0	0.18	0.12	0.02	0.02	0.03	0.07	1.09
16	0.15	0.1	0.4	0	0.18	0.12	0.02	0.02	0.03	0.1	1.12
17	0.5	0.1	0.25	0	0.15	0.12	0.02	0.02	0.1	0.07	1.33
18	0.4	0.1	0.4	0	0.2	0.12	0.02	0.02	0.07	0.07	1.4
19	0.5	0.1	0.15	0	0.15	0.12	0.02	0.02	0.03	0.07	1.16
20	0.5	0.1	0.15	0.2	0.12	0.12	0.02	0.02	0.1	0.07	1.4
21	0.5	0.1	0.15	0	0.15	0.12	0.02	0.02	0.1	0.1	1.26
22	0.5	0.4	0.25	0.2	0.22	0.12	0.02	0.02	0.03	0.1	1.86
23	0.5	0.3	0.4	0.2	0.22	0.12	0.04	0.12	0.1	0.1	2.1
24	0.5	0.1	0.4	0.2	0.22	0.12	0.04	0.12	0.1	0.1	1.9
25	0.15	0.3	0.5	0.2	0.22	0.12	0.02	0.12	0.1	0.07	1.8

26	--	--	--	--	--	--	--	--	--		--
27	0.5	0.1	0.25	0.2	0.2	0.12	0.02	0.12	0.03	0.1	1.64
28	0.5	0.1	0.25	0.2	0.21	0.12	0.02	0.12	0.07	0.1	1.69
29	0.4	0.2	0.4	0.2	0.22	0.12	0.04	0.12	0.1	0.07	1.87
30	0.5	0.1	0.15	0.2	0.22	0.12	0.04	0.12	0.1	0.07	1.62
31	0.5	0.1	0.15	02	0.21	0.12	0.04	0.04	0.03	0.1	3.29
32	0.5	0.1	0.15	0.1	0.18	0.12	0.04	0.04	0.03	0.1	1.36
33	0.5	0.1	0.15	0.2	0.15	0.12	0.02	0.02	0.1	0.1	1.46
34	0.5	0.1	0.15	0.2	0.21	0.12	0.04	0.12	0.1	0.07	1.61
35	0.5	0.1	0.15	0	0.2	0.12	0.04	0.12	0.03	0.07	1.33
36	0.1	0.1	0.5	0	0.2	0.12	0.04	0.12	0.1	0.1	1.38
37	0.5	0.1	0.15	0.2	0.2	0.12	0.04	0.12	0.03	0.07	1.53
38	0.1	0.1	0.5	0	0.21	0.12	0.04	0.12	0.1	0.1	1.39
39	0.5	0.1	0.15	0	0.2	0.12	0.04	0.12	0.03	0.1	1.36
40	0.1	0.1	0.5	0	0.21	0.12	0.04	0.12	0.1	0.1	1.39
41	0.5	0.1	0.15	0	0.15	0.12	0.04	0.12	0.03	0.1	1.31
42	0.5	0.1	0.25	0	0.21	0.12	0.04	0.12	0.1	0.1	1.54
43	0.5	0.1	0.15	0	0.21	0.12	0.04	0.12	0.03	0.1	1.37
44	0.5	0.1	0.25	0	0.2	0.12	0.04	0.12	0.1	0.1	1.53
45	0.5	0.1	0.25	0	0.21	0.12	0.02	0.02	0.1	0.1	1.42
46	0.5	0.1	0.25	0	0.21	0.12	0.02	0.02	0.07	0.1	1.39
47	0.5	0.1	0.25	0	0.2	0.12	0.02	0.02	0.1	0.1	1.41
48	0.1	0.1	0.5	0	0.2	0.12	0.04	0.02	0.1	0.1	1.28
49	0	0	0	0	0	0	0	0	0	0	0
50	0.15	0.1	0.4	0	0.15	0.12	0.02	0.02	0.1	0.1	1.21
51	0.15	0.1	0.4	0	0.2	0.12	0.04	0.12	0.1	0.1	1.33
52	0	0	0	0	0	0	0		0	0	0
53	0.1	0.1	0.5	0	0.22	0.12	0.02	0.02	0.03	0.1	1.21
54	0.15	0.3	0.5	0	0.21	0.12	0.02	0.02	0.03	0.1	1.45
55	0.1	0.1	0.4	0	0.21	0.12	0.02	0.02	0.03	0.1	1.1
56	0.1	0.1	0.4	0	0.2	0.12	0.02	0.02	0.1	0.1	1.16
57	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0
62	0	0	0	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0	0	0	0	0

Appendix 5.2 Rating assigned to each Rain induced manifestation

Facet id	Mean annual	Manifestation	Slope materials	Structural discontinuity	Adjustment factors	Total
1	0.2	0.13	0.6	0.12	0.6	0.63
2	0.2	0	0.6	0.12	0.6	0.552
3	0.2	0	0.6	0.12	0.6	0.552
4	0.2	0.12	0.6	0.12	0.6	0.62
5	0.2	0.015	0.6	0.25	0.6	0.64
6	0.2	0.025	0.55	0.25	0.8	0.8
7	0.2	0.12	0.6	0.25	1	1.17
8	0.2	0.105	0.6	0.25	0.8	0.92
9	0.2	0.1075	0.6	0.12	1	1.03
10	0.2	0.105	0.7	0.12	1	1.13
11	0.2	0.1025	0.7	0.12	1	1.122
12	0.2	0.11	0.75	0.25	2	2.62
13	0.2	0.12	0.7	0.25	0.6	0.76
14	0.2	0.245	0.7	0.25	1	1.4
15	0.2	0.11	0.675	0.12	1.8	1.8
16	0.2	0.12	0.75	0.12	1.8	2.14
17	0.2	0.11	0.75	0.25	0.75	0.98
18	0.2	0.15	0.75	0.12	0.75	0.91
19	0.2	0.11	0.75	0.12	0.8	0.94
20	0.2	0.12	0.7	0.25	1.8	2.29
21	0.2	0.18	0.6	0.25	0.8	0.98
22	0.2	0.16	0.6	0.25	0.6	0.73
23	0.2	0.015	0.6	0.25	0.6	0.64
24	0.2	0.03	0.6	0.12	0.6	0.6
25	0.2	0.14	0.7	0.25	0.6	0.8
26						
27	0.2	0.03	0.7	0.12	1	1.05
28	0.2	0	0.6	0.12	0.6	0.6
29	0.2	0.15	0.7	0.25	0.75	0.97
30	0.2	0.16	0.65	0.25	1.75	2.21
31	0.2	0.135	0.65	0.25	0.6	0.74
32	0.2	0.0545	0.675	0.25	2	2.4
33	0.2	0	0.6	0.12	2	1.84
34	0.2	0.0275	0.6	0.12	2	1.9
35	0.2	0.1	0.7	0.25	2	2.5
36	0.2	0.1075	0.7	0.12	1.1	1.24
37	0.2	0.1025	0.6	0.2	1.13	1.24
38	0.2	0.03	0.75	0.12	0.57	0.63
39	0.2	0.13	0.65	0.25	0.6	0.74
40	0.2	0.15	0.65	0.2	0.7	0.84
41	0.2	0.008	0.67	0.2	1.35	1.45
42	0.2	0.03	0.67	0.12	1.7	1.7

43	0.2	0.0075	0.65	0.2	0.6	0.63
44	0.2	0.035	0.65	0.25	1.59	1.8
45	0.2	0.09	0.6	0.2	0.82	0.9
46	0.2	0.0075	0.65	0.12	1.26	1.23
47	0.2	0.115	0.6	0.12	0.48	0.5
48	0.2	0.12	0.6	0	0.52	0.48
49	0.2	0.088	0.7	0.12	0.3	0.33
50	0.2	0.05	0.67	0.25	1.04	1.22
51	0.2	0.006	0.65	0.12	0.6	0.6
52	0.2	0.085	0.7	0	0.3	0.3
53	0.2	0.002	0.7	0.12	0.6	0.6
54	0.2	0	0.8	0.12	0.6	0.7
55	0.2	0.015	0.8	0.12	0.42	0.5
56	0.2	0.073	0.2	0.12	0.3	0.18
57	0.2	0.045	0.2	0	0.3	0.13
58	0.2	0.115	0.2	0	0.3	0.15
59	0.2	0.105	0.2	0	0.44	0.22
60	0.2	0.12	0.2	0	0.44	0.23
61	0.2	0.105	0.2	0	0.415	0.21
62	0.2	0.11	0.2	0	0.3	0.15
63	0.2	0.11	0.2	0	0.3	0.15

Appendix 5.3 rating assigned to each facet for internal and external factors

1. INTERNAL PARAMETER	
A	Relative Relief
B	Slope Morphometry
C	Slope materials
D	Structural Discontinuity
E	Groundwater manifestation
F	Land use landcover
2. EXTERNAL PARAMETER	
G	Seismicity
H	Rainfall
I	Manmade activity

Facet id	Area(m^2)	A	B	C	D	E	F	G	H	I	ELH	HZ
1	1605831	0.6	0.6	0.6	1.66	0.015	1.2	2	0.63	0	7.305	MHZ
2	1041819	0.6	0.6	0.6	1.66	0.015	1.2	2	0.552	0	7.227	MHZ
3	1545704	0.6	0.6	0.6	1.51	0.015	1.2	2	0.552	0	7.077	MHZ
4	1178026	0.6	0.6	0.6	1.36	0.015	1.2	2	0.62	0	6.995	MHZ
5	1149817	0.6	0.6	0.6	1.7	0.015	1.2	2	0.64	0	7.355	MHZ
6	1353967	0.6	0.8	0.55	1.55	0.015	1.2	2	0.8	0	7.515	MHZ
7	516597	0.6	2	0.6	1.51	0.015	1.2	2	0.17	0	9	HHZ
8	461761	0.6	0.8	0.6	1.36	0.015	1.2	2	0.92	0	7.5	MHZ
9	370701	0.6	1	0.6	1.71	0.015	1.2	2	1.03	0	8.155	HHZ
10	502701	0.6	1	0.7	1.35	0.015	1.2	2	1.13	0	7.995	MHZ
11	651344	0.6	1	0.7	1.23	0.015	1.2	2	1.122	0	7.867	MHZ
12	315642	0.8	2	0.75	1.25	0.015	1.2	2	1.62	0	10.635	HHZ
13	860192	0.8	0.6	0.7	1.3	0.015	1.2	2	0.76	0	7.375	MHZ
14	605257	0.6	1	0.7	1.16	0.015	1.2	2	1.4	0.75	8.825	HHZ
15	383093	0.8	1.8	0.675	1.09	0.015	1.2	2	1.8	0	9.38	HHZ
16	621776	0.8	1.8	0.75	1.12	0.015	0.75	2	2.14	0	9.375	HHZ
17	799047	0.6	0.75	0.75	1.33	0.015	0.75	2	0.98	0	7.175	MHZ
18	938967	0.6	0.75	0.75	1.4	0.015	0.75	2	0.91	0	7.175	MHZ
19	1359308	1	0.8	0.75	1.16	0.015	0.75	2	0.94	0	7.415	MHZ
20	759334	1	1.8	0.7	1.4	0.015	1.2	2	2.29	0	10.405	HHZ
21	616742	0.8	0.8	0.6	1.26	0.015	1.2	2	0.98	0.625	8.28	HHZ
22	1822298	0.6	0.6	0.6	1.86	0.015	1.2	2	0.73	0.6	8.205	HHZ
23	891037	0.2	0.6	0.6	2.1	0.015	0.75	2	0.64	0	6.905	MHZ
24	1050935	0.2	0.6	0.6	1.9	0.015	0.75	2	0.6	0	6.665	MHZ
25	1110591	0.6	0.6	0.7	1.8	0.015	0.75	2	0.8	0	7.265	MHZ
26	--	---	---	----	---	---	---	---	---	---	---	---
27	672192	0.6	1	0.7	1.64	0.015	0.75	2	1.105	0	7.81	MHZ
28	1225425	0.6	0.6	0.6	1.69	0.015	0.75	2	0.6	0	6.855	MHZ
29	1448398	0.8	0.75	0.7	1.87	0.015	1.2	2	0.97	0.6	8.905	HHZ

30	1507911	0.8	1.75	0.65	1.62	0.015	1.2	2	2.21	0.5	10.745	HHZ
31	1465074	0.8	0.6	0.65	3.29	0.015	1.2	2	0.74	0	9.295	HHZ
32	419618	0.8	2	0.675	1.36	0.015	1.2	2	2.4	0	10.45	HHZ
33	437511	1	2	0.6	1.46	0.015	1.2	2	1.84	0	10.115	HHZ
34	1166008	1	2	0.6	1.61	0.015	1.2	2	1.9	0	10.325	HHZ
35	1059657	0.8	2	0.7	1.33	0.015	1.2	2	2.5	0	10.545	HHZ
36	871909	1	1.1	0.7	1.38	0.015	1.2	2	1.24	0	8.635	HHZ
37	1123455	0.8	1.13	0.6	1.53	0.015	1.2	2	1.24	0.9	9.415	HHZ
38	3607380	0.6	0.57	0.75	1.39	0.015	1.2	2	0.63	0	7.155	MHZ
39	2923241	0.6	0.6	0.65	1.36	0.015	1.2	2	0.74	0.5	7.665	MHZ
40	2010979	0.6	0.7	0.65	1.39	0.015	1.2	2	0.84	0	7.395	MHZ
41	1730863	1	1.35	0.67	1.31	0.015	1.2	2	1.45	0	9	HHZ
42	581748	1	1.7	0.67	1.54	0.015	1.2	2	1.7	0	10	HHZ
43	625101	0.6	0.6	0.65	1.37	0.015	1.2	2	0.63	0.05	7.115	MHZ
44	2096869	1	1.59	0.65	1.53	0.015	1.2	2	1.8	0	9.785	HHZ
45	1892408	0.6	0.82	0.6	1.42	0.015	1.2	2	0.9	0	7.555	MHZ
46	2950375	0.6	1.26	0.65	1.39	0.015	1.2	2	1.23	0	8.345	HHZ
47	675906	0.6	0.48	0.6	1.41	0.015	1.2	2	0.5	0	6.805	MHZ
48	1700084	0.6	0.52	0.6	1.28	0.015	1.2	2	0.48	0	6.695	MHZ
49	5414273	0.015	0.3	0.7	0	0.015	0.8	2	0.33	0.6	4.76	LHZ
50	1233159	0.6	1.04	0.67	1.21	0.015	1.2	2	1.22	0.75	8.705	HHZ
51	2250887	0.6	0.6	0.65	1.33	0.015	1.2	2	0.6	0	7.00	MHZ
52	4345278	0.015	0.3	0.7	0	0.015	0.6	2	0.3	0.75	4.68	LHZ
53	1583799	0.6	0.6	0.7	1.21	0.015	1.2	2	0.6	0	6.925	MHZ
54	2380415	0.6	0.6	0.8	1.45	0.015	1	2	0.7	0	7.165	MHZ
55	1525522	0.6	0.42	0.8	1.1	0.015	0.8	2	0.5	0	6.235	MHZ
56	964868	0.2	0.3	0.2	1.16	0.015	0.75	2	0.18	0.04	4.845	LHZ
57	2680806	0.015	0.3	0.2	0	0.015	0.5	2	0.13	0.15	3.31	LHZ
58	8069527	0.015	0.3	0.2	0	0.015	0.9	2	0.15	0.15	3.73	LHZ
59	2044749	0.015	0.44	0.2	0	0.015	0.7	2	0.22	0.75	4.34	LHZ
60	806578	0.015	0.44	0.2	0	0.015	0.3	2	0.23	0.75	3.95	LHZ
61	3726764	0.015	0.415	0.2	0	0.015	0.5	2	0.21	0.75	4.105	LHZ
62	7205344	0.015	0.3	0.2	0	0.015	0.2	2	0.15	0	2.88	LHZ
63	1460697	0.015	0.3	0.2	0	0.015	0.3	2	0.15	0.15	3.13	LHZ