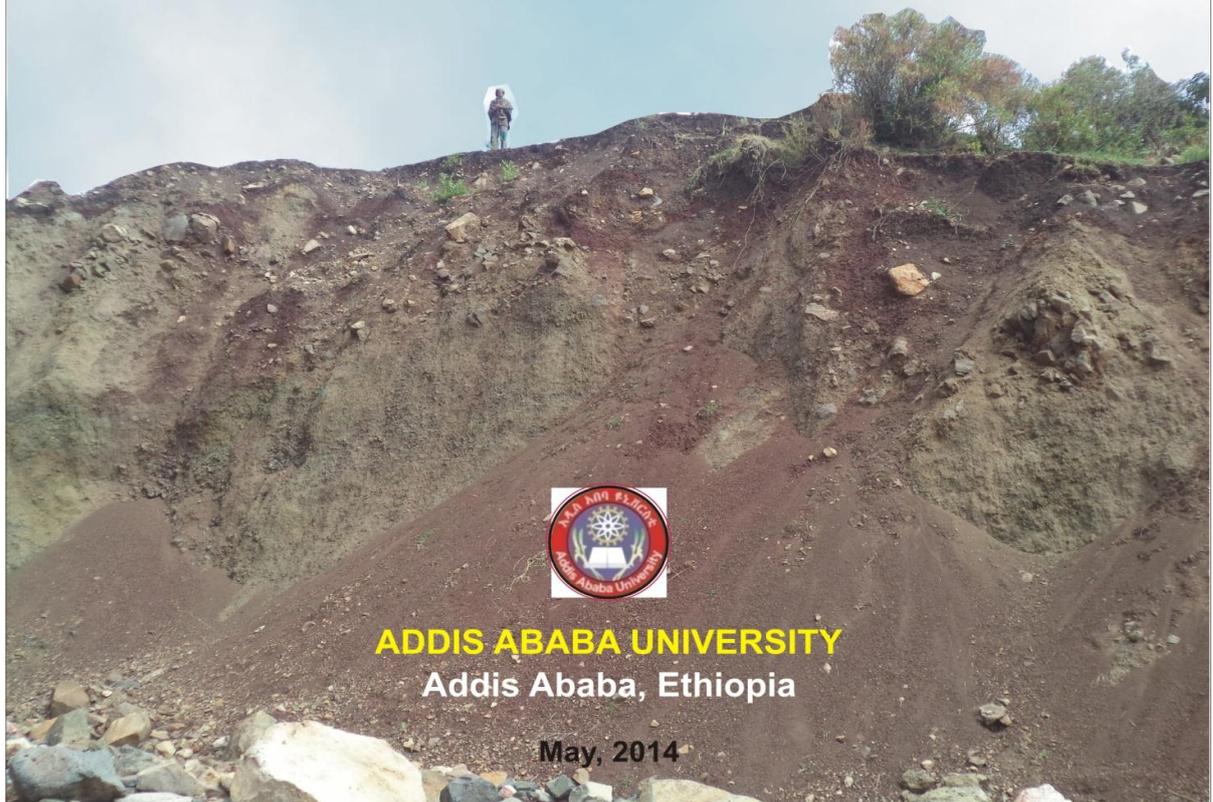


Landslide Hazard Assessment and Zonation By SSEP Rating Scheme - A Case From Debre Sina, Southwestern Margin of Afar Escarpment

Tamene Tadele

A Thesis Submitted to
School of Earth Sciences

Presented in Partial Fullfillment of the requirements for the Degree of
Masters of Science (Environmental Geology)



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**ADDIS ABABA UNIVERSITY
Addis Ababa, Ethiopia**

May, 2014

SIGNATURE PAGE

**Addis Ababa University
School of Graduate Studies**

This is to certify that the thesis prepared by **Tamene Tadele**, entitled: “*Landslide Hazard Assessment and Zonation by SSEP Rating Scheme – A case from Debre Sina, southwestern Margin of Afar Escarpment*” and submitted in partial fulfillment of the requirements for the Degree of Master of Science (Environmental Geology) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

Landslide Hazard Assessment and Zonation by SSEP Rating Scheme – A case from Debre Sina, Southwestern Margin of Afar Escarpment

Tamene Tadele

Addis Ababa University, 2014

The earth's surface is always in a dynamic change. These changes are more pronounced in mountainous terrains as a result of different mass wasting processes. The hilly and mountainous terrains of the highlands of Ethiopia are frequently affected by rainfall-induced landslides of different types and sizes. The study area, Debre Sina, has experienced landslide hazard for a long period of time. The principal objective of the proposed research study was intended to prepare a landslide hazard zonation map of the area, particularly for hazardous zones.

To achieve this objective Slope Stability Susceptibility Evaluation Parameter (SSEP) rating scheme was adopted. Landslide hazard zonation is an integrated approach which considers cumulative effect of several triggering parameters of slope instability. As per the methodology of the present study, nine causative parameters have been dealt with which include relative relief, slope morphometry, slope materials, structures, groundwater, land use land cover, rain fall, seismicity and man-made activities. These all are considered to be responsible for inducing instability in slopes and thus, resulting into landslides.

Because of the fact that the study area is located in Main Ethiopian Rift, it has experienced/experiencing landslide hazards which claimed the life of people and devastated both public as well as private properties. The geology of the area include quaternary sediments, ignimbrite, rhyolite, different kinds of basalts and tuff deposits which are highly weathered and changed in to unconsolidated sediments at some localities. Locally found geological structures like joints, dykes have considerable role in landslide hazard initiation.

As a general methodology, facet map was prepared from topographic map (1:50000) and rating values were assigned to each causative parameter based on its severity in triggering landslides to produce final landslide hazard zonation map. Accordingly, 25 % of the slopes fall in to moderate hazard where as 58 % and 17 % of the study area is found to be high and very high hazard zones, respectively. Validation of LHZ map with past landslide activities suggests rationality of considered governing parameters, the adopted SSEP technique, tools and procedures in developing the landslide hazard map of the study area.

Key words: Landslide Hazard Zonation, Slope Susceptibility, Landslide Hazard Evaluation, Landslide Hazard Mitigation, Debre Sina, Triggering Parameters

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ACRONYMS

AHP	Analytical Hierarchical Process
ANN	Artificial Neural Networks
CAR	Central Afar Rift
CF	Certainty Factor
CMER	Central Main Ethiopian Rift
DEM	Digital Elevation Model
EAR	East African Rift
EIGS	Ethiopian Institute of Geological Survey
ELH	Evaluated Landslide Hazard
FF	Favorability Functions
FM	Favorability modeling
FR	Frequency Ratio
Ha	Hectare
HHZ	High Hazard Zone
IAEG	International Association of Engineering Geology
LHEF	Landslide Hazard Evaluation Factor
LHZ	Low Hazard Zone
LHZ	Landslide Hazard Zonation
LSI	Landslide Susceptibility Index
LSZ	Landslide Susceptibility Zonation
LULC	Land use Land cover
MARF	Mean Annual Rain Fall
MER	Main Ethiopian Rift
MHZ	Moderate Hazard Zone
MMRF	Mean Monthly Rain Fall
NAR	Northern Afar Rift
NMER	Northern Main Ethiopian Rift
OM	Overlay Mapping
PCA	Principal Component Analysis
RF	Rain Fall
SAR	Southern Afar Rift
SMER	Southern Main Ethiopian Rift
SSEP	Slope Stability Susceptibility Evaluation Parameter
TEHD	Total Estimated Hazard
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VHHZ	Very High Hazard Zone
VLHZ	Very Low Hazard Zone

CHAPTER I

INTRODUCTION

1.1 Preamble

The earth's surface is always in a dynamic change. These changes are more pronounced in mountainous terrains as a result of different mass wasting processes. One of these mass wasting processes is landslide. The term landslide doesn't indicate an individual event as the name suggests but it indicates a category of movements. The name itself suggests that it should apply only to features moving across a distinct slide surface. In the past however, landslide has been used as a broad term for all mass movement events (Hansen, 1984).

The term "landslide" basically means a slow to rapid downward movement of instable rock and debris masses under the action of gravity which can be categorized into various types on the basis of failure characteristics (Cruden, 1991; as cited by Mohammad et al., 2012). Types of mass wasting include creep, slides, flow, topple, and falls, each with its own characteristic features, and taking place over timescales from seconds to years. It is one of the most disastrous natural hazards which mostly occur in mountainous terrains. The study of landslides has drawn worldwide attention mainly due to increasing awareness of the socio-economic impacts of landslides (Mohammad et al., 2012).

According to Kifle Woldearegay (2013) the hilly and mountainous terrains of the highlands of Ethiopia are frequently affected by rainfall-induced landslides of different types and sizes. The major types of landslides reported to have been triggered by heavy rainfalls include debris/earth slides, debris/earth flows and medium to large-scale rockslides. The hilly and mountainous terrains of the highlands of Ethiopia which are characterized by variable topographical, geological, hydrological (surface and groundwater) and land-use conditions, are frequently affected by rainfall-triggered slope failures. Even though Earthquakes are one of the triggering factors of landslides, earthquake triggered landslides are little reported in Ethiopia.

Landslides and landslide-generated ground failures are among the common geo-environmental hazards in many of the hilly and mountainous terrains of both the developed and developing world. As defined by (Brunsden 1979; as cited in Kifle Woldearegay, 2013), landslide is the downslope movement of soil and rock under the influence of gravity without the primary assistance of a fluid transporting agent. Landslide poses serious damages to the

life of people; destroys public and private properties and ruins different infrastructures. Slope failures are generally considered as fairly well predictable hazards and economic losses due to such hazards can be reduced significantly (Hansen, 1984).

Gebreslassie Mebrahatu (2011) emphasized that the widespread distribution of landslides in Ethiopia is mainly related to the occurrence of several predisposing factors such as; rugged morphology, high topography, and the nature of the outcropping rocks. The triggering factors are essentially connected with the rainfall regime and, to a minor extent, with seismicity (Abebe Bekele et al., 2009; as cited in Gebreslassie Mebrahatu, 2011).

According to (Asmelash Abay and Barbieri, 2012) Debre Sina is located along the southwestern Afar rift margin, because of which it was frequently affected by landslides in the past few years. It is bounded by different mountains because of which it has experienced rainfall triggered landslides which endangered the life of people and destroyed public and private properties including various infrastructures.

The Debresina area is one of the most landslide prone areas located in the Afar rift margin of Ethiopia. Landslide occurrences and casualties have long history in Debresina area. Information obtained from local people indicated that landslide occurrences and casualties were common since the 1950's at the localities known as Armaniya, Nib Amba, Work Amba, Yizaba, Indode, and Shotel Amba of the Tarmaber Woreda and to some extent at the locality known as Zeb Amba in Dukakit Kebele.

1.2 The Problem Statement

Landslide problem has been causing lots of casualties, economic and social problems to societies especially to those who are living in the mountainous area (Larson, 2008). The present study area has been affected by active geomorphic processes which caused significant impact on people, livestock, settlements, infrastructures and farmlands.

In particular, a large number of landslide events have repeatedly struck the urban area since long time ago, causing the loss of life and property (EIGS, 1995; MWUD, in press; as cited by Gebreslassie Mebrahatu, 2011). Seismicity and rain fall are the two most common external triggering parameters of landslide which are natural but can be managed to some extent by understanding and applying the principle by which they operate. Debre Sina is

located on the lower margin of Afar rift escarpment because of which it is susceptible to earthquake hazards which may likely induce landslides in the area.

Most of the people of the countryside in the study area are living at the toe and sloppy side of mountain leaving the plain land for agricultural purpose. In towns also due to the shortage of suitable lands for building construction increasing number of population at alarming rate, and increased cost of land, peoples are forced to live in mountainous area. This has increased the risk of Landslide by increasing vulnerability, which means the degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude (Varnes, 1984).

1.3 The Study Area

The study area is located in Amhara Regional State at a distance of 200 Km from Addis Ababa, the capital city of Ethiopia. Geographically it is defined by UTM coordinates of 582000-593000 mE; 1080000-1100000 mN (plate 1.1). The study area is located northeast of Addis Ababa city on the main road to Dessie. The prevailing climatic condition of the area is "Dega" with mean annual rainfall of 1736 mm/year and temperature varying between 10°C to 15°C. The boundary of the study area was delineated by using different topographic undulations and major rivers.

1.3.1 Geology

Geologically, Debre Sina area is covered by Alaje formation (basalts, rhyolitic/trachytic ignimbrites, tuffs, and agglomerates), Tarmaber formation (basalts) and Quaternary sediments (alluvial, colluvial-eluvial deposits, fine residual soils).

1.3.2 Physiography and the Drainage Pattern

Physiographically, the study area is located in the Showan highlands, the smallest highlands of the Ethiopian northwestern highlands, which also includes the Tigrean north central massif, South Western highlands of Gojam and Gondar (Leta Alemayehu, 2007). The Showan plateau is bounded by the Ethiopian rift on the eastern and south eastern sides while Abay gorge and Omo gorge border it on the north western and south western sides. The study area generally is characterized by highly variable topographical features which are a reflection of the past geological and erosion process (plate 1.2.). The landscape includes

plateaus, steep hill slopes, and deeply incised valleys and gorges. The elevation of the study area ranges from 1500 m in the Southern sector to 3100 m in the Northern section.

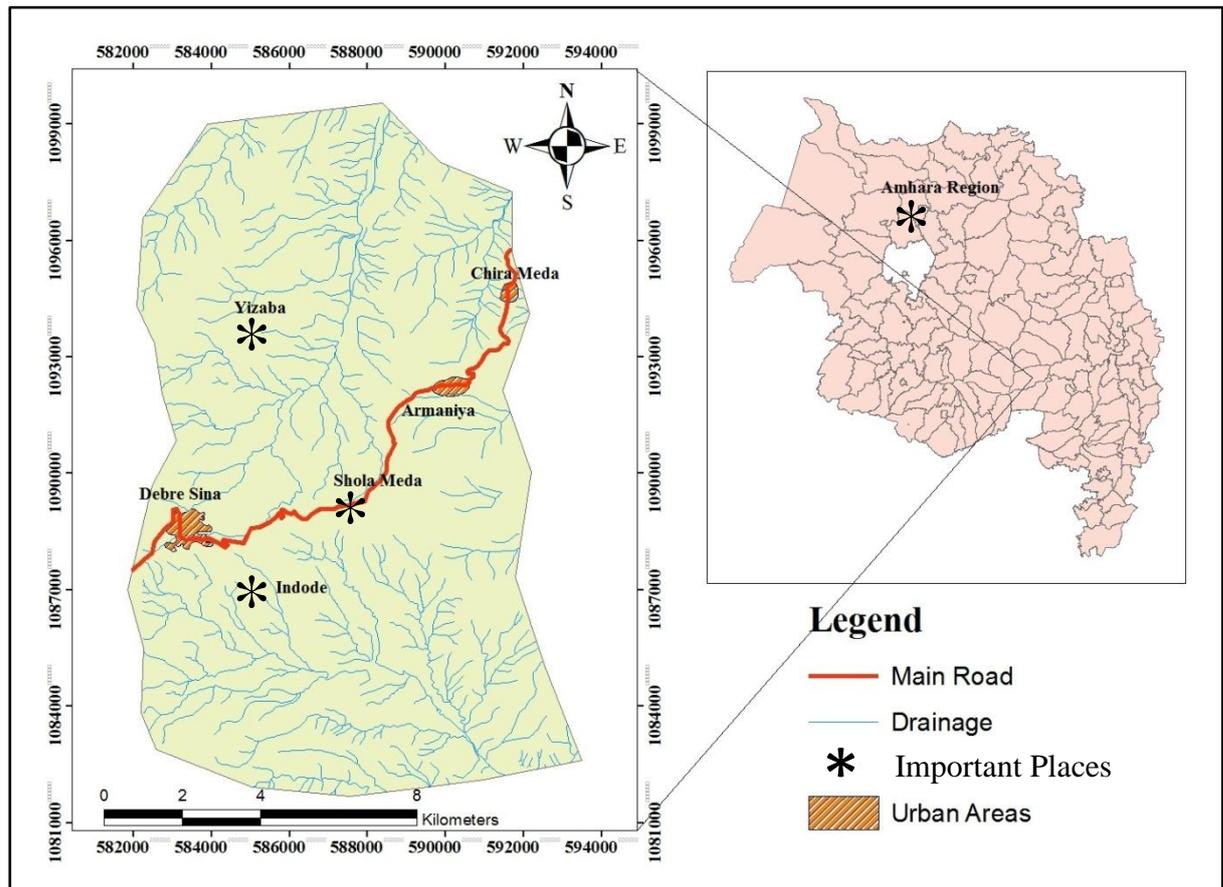


Plate 1.1 Location of the study area

The drainage system of the area includes many small tributaries feeding the main rivers. Most of the rivers were dry during the present field visit. Majority of them, especially small tributaries, arise from high mountains and join the main rivers at the valley floor. The general drainage pattern of the study area is dendritic type (plate 1.1).

1.3.3 Vegetation Cover

Most part of the study area is moderately vegetated with exception of “Wef Washa Forest”, which is thickly vegetated and located at the southernmost tip of the study area. Long trees such as “Tid” dominate most part of the area. Small trees like shrubs and bushes are also common.

Currently due to increased number of people engaged in agricultural activities, cultivated and grazing lands are expanding shrinking vegetated and bare lands. Even if different people grow different kinds of crops in different parts as per their suitability, most commonly grown

crops include; wheat, teff, pea, barley, sorghum, lentil and maize. At some localities where soils are fertile people also grow sugar cane.

1.3.4 Accessibility

Rugged and undulating topography made the area inaccessible except via the main road running to Dessie from Debre Sina through Armania. There is also a gravelly road which runs from Debre Sina to Mezezo but it covers very small portion of the study area. Most of the area has been accessed by foot paths even though it was difficult to travel on it. It is not only the presence of rugged topography that rendered the area inaccessible but also vertical slopes, gorges and some thick forests worsened the situation.

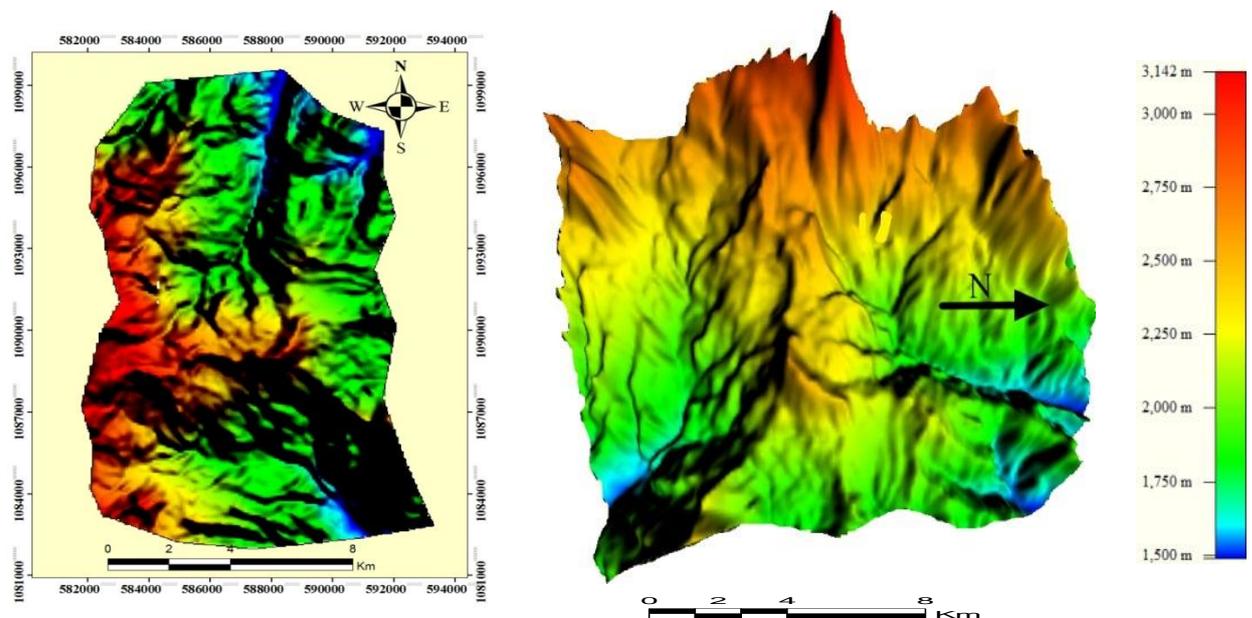


Plate 1.2 DEM showing the general physiography of the study area 2D (left) and 3D (right)

1.4 Significance and Important Outcomes of the Study

The subject of landslide has been considered and studied by many researchers all around the world as it is the issue of almost all countries which have hilly terrains. Landslides cannot be stopped as they occur naturally but the hazards they cause can be minimized by adopting different preventive strategies. To do so understanding the general principles which govern the occurrence of landslides has paramount importance in risk reduction. By hazard zonation based on the degree of risk, it is possible to identify suitable sites for different infrastructures and settlements. Various types of damages are caused by the development of landslide in the area which includes roads, farmlands and other infrastructures.

Most of the landslide hazard zonation methods are based on the basic assumptions that mass movements are caused by the geological, geomorphic, human induced, etc. factors that can be described through physical parameters, and that the knowledge about these conditions enables drawing conclusions on future landslides (LESSLOSS, 2006).

Landslide, like other natural hazards such as, floods, earthquakes and avalanches is often difficult to predict. However, landslide risk can be systematically assessed and managed.

Hazard and risk maps are usually the end product of landslide mapping but they are the basis for decision making. These decisions are usually in the form of technical countermeasures, regulatory management, or combinations of the two. Classic examples of regulatory management are zoning maps which, for instance, exclude some landslide-prone areas from habitation.

Landslide susceptibility maps can be constructed by using the relation between each landslide and causative factors (Anbalagan, 1992).

1.5 Limitations and Scope of the Study

Landslide hazard zonation and assessment by using Slope Susceptibility Evaluation Parameter (SSEP) Rating scheme (Raghuvanshi *et al.*, 2014) needs sufficient time and resources. Collection of secondary data has also delayed due to some inconvenient circumstances that arise from non-willingness of organizations or lack of some relevant data. Some of the lithologies are covered by thick vegetation which made identification and measuring of different parameters difficult. The degree of weathering is so high that some rocks have been changed into fragmented materials including soils. This also added another difficult in identification of different rock units. Another very significant constraint of the study is rugged topography as some of the areas are too high to climb up and may be exposed to active landslide.

Medium scale mapping (1:50,000) was conducted in the present study in order to generate landslide hazard map of the study area. Those areas which are more likely to be affected by landslide hazard were given due attention depending on the degree of hazards posed on the life of people and properties. In order to get the reliable result and achieve the objectives proposed the area of investigation were kept to the minimum.

1.6 Objectives of the Study

1.6.1 Major objective

The principal objective of the proposed research study was intended to prepare a landslide hazard zonation map of the area, particularly for hazardous zones

1.6.2 Specific Objectives

Specifically the study aims at;

- ✿ Analysis of the area based on the degree of hazard
- ✿ Identifying susceptible areas for landslides
- ✿ Understanding the weights of different causative factors
- ✿ Assessment of possible internal and external causative factors and to study the combined effect of these factors in contributing landslides
- ✿ Validation of results based on the existing and anticipated conditions
- ✿ To draw general conclusions based on the landslide hazard zonation of the study area
- ✿ Recommending landslide hazard mitigation strategies which can serve to the local community based on the LHZ

1.7 Methods

1.7.1 Data Collection

(a) Field Observations and Measurements

Observation and collection of various primary data directly from the field is the basic input which advances the quality of the research work. Primary data are important because they give us the direct information about the problem under investigation. Landslide location assessment, spatial data collection of triggering factors of landslide hazards, observation of the type of movements and other data that need direct field observation are some of the primary data which were collected from the field.

(b) Compilation of Existing Data

Data, documents, records, maps and other related materials that are collected from various sources (organizations, individuals) utilized partly or fully as supporting data or information

for the present research study are considered to be secondary data. Primary data alone will not be able to accomplish the research successfully without consideration of the secondary data. Therefore, it is vital to include secondary data in any research. These include:

- ✘ Meteorological data (rain fall, temperature, etc.)
- ✘ Published geological maps and reports
- ✘ Land use/ land cover maps
- ✘ Land hazard maps
- ✘ Groundwater and surface water data
- ✘ Structural discontinuity data
- ✘ Slope geometry
- ✘ Seismicity data
- ✘ Relative relief data
- ✘ Other related data generated in the previous studies

1.7.2 Modeling

Different data collected was analyzed by using the method known as SSEP rating scheme proposed by Raghuvanshi *et al.*, (2014). This method integrates both intrinsic and external factors such as; seismicity and rain fall which are significant in landslide initiation. For SSEP the area of slopes was divided into individual slope facets (a land unit which is characterized by more or less uniform slope geometry in terms of slope inclination and slope direction). Slope facets are demarcated by topographic units which include ridges, primary and secondary streams and other topographic undulations. Plate 1.3 depicts general activities undertaken in the proposed methodology (SSEP).

1.7.3 Data Interpretation and Results

After the filed data have been analyzed, later it was interpreted in the light of laboratory findings so as to come across final results. The results support the hypothesis provided that the relevant and feasible methodology has been followed. Later, the proposed objectives of the present study were met.

1.8 General Outline of the Thesis

This thesis is structured in to six chapters. A brief description of the content of each chapter is presented below:

Chapter I introduces some basic information on landslides and their assessment techniques followed by definition of problem statement and objective of the current study.

Chapter II presents a literature review. It starts with the general overview of landslide hazard problems in Ethiopia. After that, general principles of statistical methods of landslide assessment are summarized.

Chapter III Mainly deals with the geology and structures of the Main Ethiopian Rift in general and the study area (Debre Sina) in particular

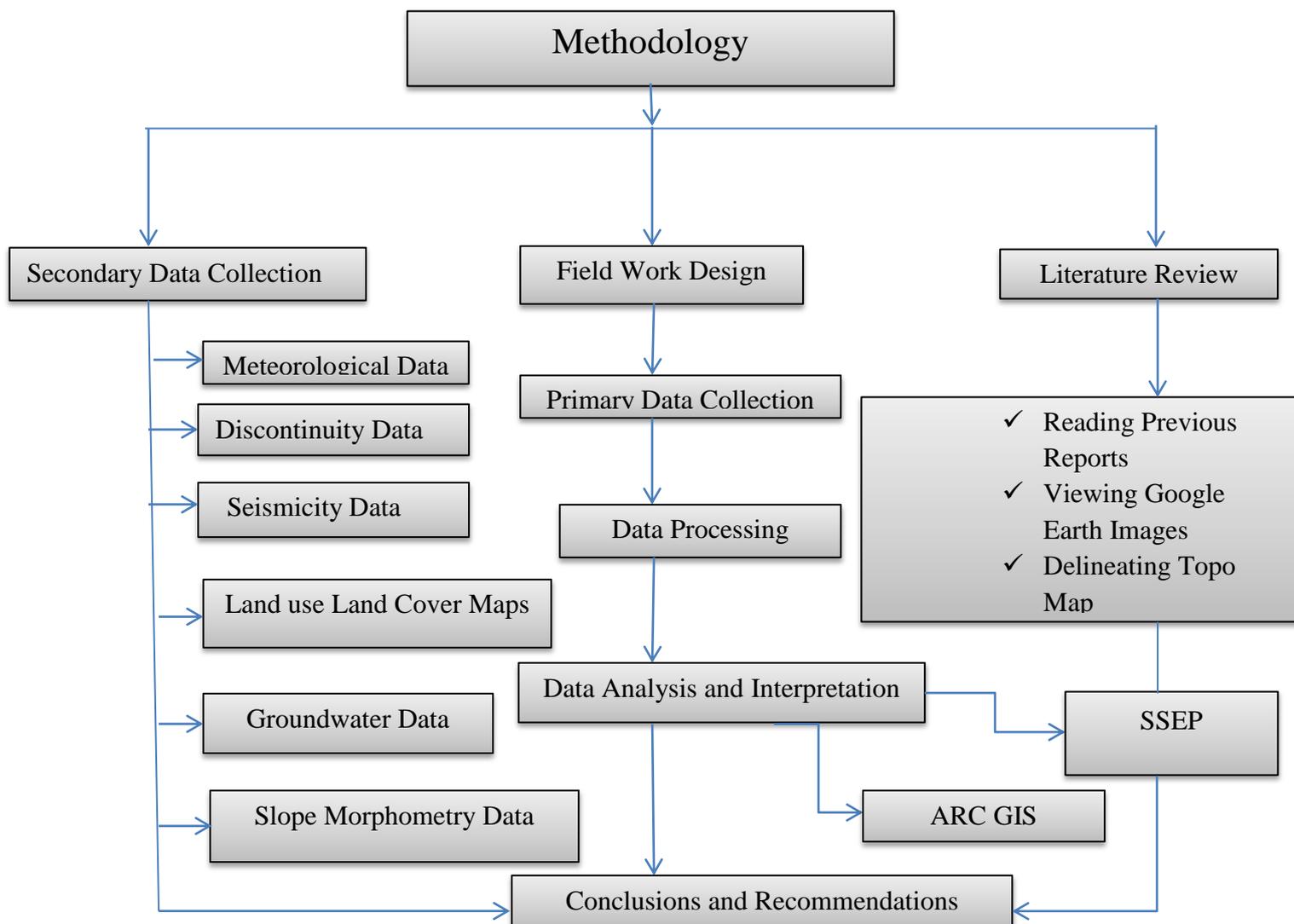


Plate 1.3 Flow diagram of the proposed methodology

Chapter IV attempts to assess impacts of slope movements to present study area.

Chapter V discusses various results obtained by adopting the proposed methodology.

Chapter VI presents conclusions and recommendations. It gives final conclusion on landslide susceptibility in the area with some recommendations for future studies.

CHAPTER II

LITERATURE REVIEW

2.1 General

The term "landslide" is used to describe a wide variety of processes that result in the perceptible downward and outward movement of soil, rock, debris material and vegetation under the direct influence of gravitational influence. The materials may move by: falling, toppling, sliding, spreading, or flowing. Landslide is one of the natural processes that shape the surface of the Earth. It is only when landslides threaten mankind they represent a hazard. Most of the time landslides occur on cut slopes or on embankments along-side roads and highways in mountainous areas. It is one of the major destructive natural hazards in mountainous and rift margins, resulting in loss of human life and property and severe damage to agricultural lands (Saro and Biswajeet, 2006).

The occurrence of slope movements is the consequence of a complex field of forces (plate 2.1). Stress (force per unit area) is the main driving force which is active on a mass of rock or soil on the slope. Movement occurs when the shear stress exceeds the shear strength of the material.

The consequence of these forces in conjunction to the slope morphology and the geotechnical parameters of the material define together the specific type of landslide which might occur.

Although landslides are primarily associated with steep slopes, they also can occur in areas of generally low relief.

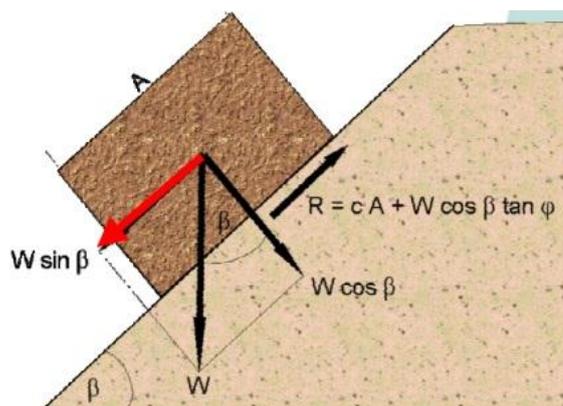


Plate 2.1 Forces acting on the slope

In these areas landslides occur as cut-and-fill failures (high-way and building excavations), river bluff failures, lateral spreading landslides, the collapse of mine-waste piles (especially coal), and a wide variety of slope failures associated with quarries and open-pit mines. Underwater landslides on the floors of lakes or reservoirs, or in offshore marine settings, also usually involve areas of low relief and small slope gradients (USGS, 2004).

Landslides may occur at a very slow rate, particularly in areas that are very dry or those areas that receive sufficient rainfall such that vegetation has stabilized the surface. They may also occur at very high speed, such as in rock slides or landslides, with disastrous consequences, both immediate and delayed, e.g., resulting from the formation of landslide dams (Baeza, *et al.*, 2001).

Landslide hazard is the combination of temporal and spatial probability

$$\text{Hazard} = \text{Temporal Probability} * \text{Spatial Probability}$$

Temporal probability indicates that landslides may occur due to triggering event at a given time whereas spatial probability designates the occurrence of landslides of temporal probability which affect a particular area (Wang and Niu, 2009).

2.2 Causative Factors of Landslides

For Landslides to occur there must be something that distorts natural state of the land in one or other ways. Those parameters that initiate the landslide are called causative factors and they can be either inherent or external. The following are some of the factors which facilitate landslides. Landslides can be triggered by both natural and man-induced changes in the environment. The geologic history of an area, as well as activities associated with human occupation, directly determines, or contributes to the conditions that lead to slope failure. The basic causes of slope instability are fairly well known. They can be inherent, such as; weaknesses in the composition or structure of the rock or soil; variable, such as; heavy rain, snowmelt, and changes in ground-water level; transient, such as; seismic or volcanic activity; or due to new environmental conditions, such as those imposed by construction activity (Varnes and IAEG, 1984).

2.2.1 Geologic Factors

Geology is one of the inherent causative factors considered in slope stability analysis (Clerici *et al.*, 2002). The regolith materials found on the surface are derived from the underlying bed rock or transported from other location. Geologic causative factors are discussed hereunder as subgroups:

(i) Lithology

Lithology is considered as one of the main causes for slope instability. The erodibility or the response of rocks to the processes of weathering and erosion has been the main criteria in awarding the ratings for subcategories of lithology. e.g., rocks like quartzite, limestone and igneous rocks are generally hard, massive and resistant to erosion, forming steep slopes. In comparison, terrigenous sedimentary rocks are vulnerable to erosion and form more easily landslides. Phyllites and schists are characterized by flaky minerals which weather quickly and promote instability. In the case of soil, genesis and age are the main considerations in awarding the ratings. Older alluvium is generally well compacted and has a high shearing resistance. Recent materials such as; slide debris are loose and have low shearing resistance. Lithology indicates the rock type usually of the bed rock underlying the weathered material where failure may occur or of the outcropping rock on the surface. Lithology is among the most important factors commonly considered in slope stability and are used practically in all works dealing with landslide hazard assessment (Clerici *et al.*, 2002 and Saha *et al.*, 2002).

(ii) Unstable bedding sequences

This indicates the stratigraphic sequence of the rock layers. Birhanu Temesgen *et al.* (2001) emphasized that rocks of different properties layered one on top of the other are said to cause instability.

(iii) Bedding slope relations

Bedding slope relations indicate the relationship between the orientation of the bedding and the slope aspect of the terrain. It was given considerable attention by Clerici *et al.* (2002).

(iv) Fault and fracture zone

Saha *et al.* (2002) explained that they gave high rating to specific rock formations which are highly jointed in nature. Varnes (1984; as cited in Yoseph Endalamaw, 2010) concluded that the degree of fracturing and shearing plays an important role in determining slope stability.

2.2.2 Structures

Structure includes primary and secondary discontinuities in the rocks such as; bedding, joints, foliations, faults and thrusts. The disposition of structural discontinuities in relation to slope inclination and direction has a great influence on the stability of slopes. In this connection, the following three types of important relations are considered:

- (i) The extent of parallelism between the directions of the discontinuity, or the line of intersection of two discontinuities and the slope.
- (ii) The steepness of the dip of the discontinuity, or the plunge of the line of intersection of two discontinuities.
- (iii) The difference in the dip of the discontinuity, or the plunge of the line of intersection of the two discontinuities to the inclination of the slope.

The more the discontinuity or the line of intersection of two discontinuities tends to be parallel to the slope, the greater the risk of failure. If the dip of the discontinuity or plunge of the line of intersection of two discontinuities increases, the probability of failure also increases because the angle of friction for the discontinuity surfaces will be reached. Moreover, till the dip of the discontinuity plane or the plunge of the line of intersection of the two discontinuities does not exceed the inclination of the slope, the failure potential remains high (Anbalagan, 2008). In the case of soil, the inferred depth of the soil cover has been used for awarding the ratings.

2.2.3 Land Use and Land Cover (LULC)

It is an indirect indication of the stability of hill slopes. Barren and sparsely vegetated areas show faster erosion and greater instability as compared to reserve or protected forests, which are thickly vegetated and generally less prone to mass wasting processes. Forest cover, in general, smothers 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 material. Agriculture, in general, is practiced on low to very low slopes, though moderately steep slopes are not spared at places. However, the agricultural lands represent areas of repeated water charging for cultivation purposes and as such may be considered stable. Based on criteria of intensity of vegetation cover, the ratings have been awarded. Land use / land cover data is included in many studies involving slope instability (Saha *et al.*, 2002).

The artificial or natural surface cover has influence on its stability. Many authors included the factor land use in their slope instability analysis (Van Westen, 1997a; Clerici *et al.*, 2002; Dai and Lee, 2002; Saha *et al.*, 2002). Forested land has generally higher stability than bare

ground. Land use data can also be used to infer other information. For example; soil depth can be estimated from land use data (Vinh, 2007).

2.2.4 Geomorphic Factors

Geomorphic factors are factors related to the gradient of the slope, slope aspect and others. These data can be derived from digital elevation model (DEM). Geomorphic factors are dependent on slope parameters (Yoseph Endalamaw, 2010).

Gradient: Increasing the gradient of a slope increases the shear stress which leads to failure. Because of this, gradient is among the most important factors commonly considered during slope stability and practically in all works dealing with landslide hazard assessment (Clerici *et al.*, 2002).

Slope Aspect: The aspect of a slope is defined as the horizontal direction to which a slope faces. In other words, it shows the direction of maximum slope of a surface. It can influence landslide initiation (Birhanu Temesgen *et al.*, 2001).

Slope Morphometry: Slope morphometry maps define slope categories on the basis of the frequency of occurrence of particular angles of slope. The distribution of the slope categories is dependent on the geomorphological history of the area; the angle of slope of each unit is a reflection of a series of localized processes and controls, which has been imposed on the facet.

Relative Relief: The relative relief map represents the local relief of maximum height between the ridge top and the valley floor within an individual facet. This shows the major breaks in the slopes of the study area. Three categories of slopes of relative relief have been chosen for hazard evaluation purpose in the present study namely low (<100 m), medium (101-300 m) and high (> 300 m).

2.2.5 Hydrologic factors

Landslides often occur after heavy rainfall for a long time (Long, 2008). This is a triggering factor which is usually considered for dynamic models of landslide hazard. Earth materials respond differently with water. Dry sand is unstable and has a small angle of repose. When little water is added to dry sand, the sand grains get strength because of the surface tension of the capillary water. This force tends to hold the wet sand together as a cohesive mass.

Therefore, the angle of repose increases and can be molded in to almost vertical walls. If we keep adding water to the sand, it will start to flow after some limit. The weight of water increases the shear force pulling the material down. The pore water pressure developed in the soil also reduces its shear strength which leads to failure. Generally, slope materials may retain their stability as long as no changes are made to the slope materials. Because groundwater in hilly terrain is generally channeled along structural discontinuities of rocks, it does not have a uniform flow pattern. The evaluation of observations of the behavior of groundwater on hill slopes is not possible over large areas. Therefore, in order to make a quick appraisal, the nature of surface indications of the behavior of groundwater will provide valuable information on the stability of hill slopes for hazard mapping purposes. Surface indications of water such as damp, wet, dripping and flowing are used for rating purposes (Anbalagan, 2008).

2.2.6 Seismicity

Seismicity is one of the triggering factors of landslides. The vibration released during earth quacks can cause failure of slopes which were previously stable. According to Muthu and Petrou (2007) the possibility of an earthquake triggering a landslide event depends on the shaking of the ground rather than on the actual magnitude of the earthquake. The vibrations released during earthquake can cause resettlement of the soil skeleton which in turn causes expulsion of water. At that moment the water pressure increases and carries part of the soil skeleton. This phenomenon is known as liquefaction.

Also, the horizontal acceleration due to seismic activity may loosen the rock block along the discontinuity surfaces thus it reduces the shear strength along the discontinuities. Besides, dynamic loading increases the driving force and reduces the resisting force thus instability in rock slopes is induced.

2.2.7 Man-made Factors

Human activities triggering landslides are mainly associated with construction and involve changes in slope and in surface-water and ground-water regimes. Changes in slope result from terracing for agriculture, cut-and-fill construction for highways, the construction of buildings and railroads, and mining operations. If these activities and facilities are ill-conceived, or improperly designed or constructed, they can increase slope angle, decrease toe or lateral support, or load the head of an existing or potential landslide.

Changes in irrigation or surface runoff can cause changes in surface drainage and can increase erosion or contribute to loading a slope or raising the ground-water table. The ground-water table can also be raised by lawn watering, waste-water effluent from leach fields or cesspools, leaking water pipes, swimming pools or ponds, and application or conveyance of irrigation water. A high ground-water level results in increased pore-water pressure and decreased shear strength, thus facilitating slope failure. Conversely, the lowering of the groundwater table as a result of rapid drawdown by water supply wells, or the lowering of a lake or reservoir, can also cause slope failure as the buoyancy provided by the water decreases and seepage gradients steepen (Long, 2008).

Some of the human activities that can induce landslide were given by Long (2008) as follows:

- Undercutting during construction of highways and rail-roads increases the average slope gradients, and increases the chance of slope failures.
- Overloading of hill slopes by housing construction is common. This extra weight may increase the chance of slope failure; altering the hydrology may have dramatic effects on hill slope stability.
- Clear cutting of trees promotes soil erosion and weakens the support of soils by tree roots. It also reduces evapotranspiration and raises the water tables.
- Vibrations occurring in earthquake consequence by hydroelectricity lakes, or other artificial causes (machine activities, underground explosions)

2.2.8 Natural Factors

There are a number of natural factors that can cause slope failure. Some of these, such as long-term or cyclic climate changes, are not discernible without instrumentation and/or long-term record keeping. The following are some of the natural processes initiating slope failures (<http://pubs.usgs.gov/fs/2009/3071/pdf/FS09-3071.pdf>).

Climate: Long-term climate changes can have a significant impact on slope stability. An overall decrease in precipitation results in a lowering of the water table, as well as a decrease in the weight of the soil mass, decreased solution of materials, and less intense freeze-thaw activity.

An increase in precipitation or ground saturation will raise the level of the groundwater table, reduce shear strength, increase the weight of the soil mass, and may increase erosion and freeze thaw activity. Periodic high-intensity precipitation and rapid snow melt can significantly increase slope instability temporarily.

Erosion: Erosion by intermittent running water (gullying), streams, rivers, waves or currents, wind, and ice removes toe and lateral slope support of potential landslides.

Weathering: It is the natural process of rock deterioration which produces weak, landslide-prone materials. It is caused by the chemical action of air, water, plants, and bacteria and the physical mechanisms.

Gravity: Gravity works more effectively on steeper slopes, but more gradual slopes may also be vulnerable.

Heavy and Prolonged Rainfall: Water is commonly the primary factor in triggering a landslide. Slides often occur following intense rainfall, when storm water runoff saturates soils on steep slopes or when infiltration causes a rapid rise in groundwater levels. Groundwater may rise as a result of heavy rains or a prolonged wet spell. As water tables rise, some slopes become unstable.

Volcanoes: Strato volcanoes are prone to sudden collapse, especially during wet conditions. (E.g. May 18, 1980, magma moved high into the cone of Mount St. Helens and shoved the volcano's north side outward by at least 150 m and caused huge landslide which completely removed the bulge, the summit, and inner core of Mount St. Helens, and triggered a series of massive explosions.

2.3 Landslide Hazard Problems in Ethiopia

Kifle Woldearegay (2013) emphasized that the hilly and mountainous terrains of the highlands of Ethiopia are frequently affected by rainfall-induced landslides of different types and sizes. The major types of landslides reported to have been triggered by heavy rainfalls including debris/earth slides, debris/earth flows and medium to large-scale rockslides.

Some of the landslide affected areas of the country include; landslide hazards in Dessie town (Tenalem Ayenew, 2002); landslides in the Abay Gorge (EIGS, 1987); the occurrence of landslides in Jimma basin (Zvelebil *et al.*, 2010); landslides records in Goffa, Gilgel Gibe-II,

and Sodo-Shone areas, Southern Ethiopia (Asfawossen Asrat *et al.*, 1996); The Wondogenet area, southern Ethiopia, is reported to have been affected by rainfall-triggered landslides (e.g. Birhanu Temesgen *et al.*, 1999, 2001). According to these authors, landslide took place dominantly on unconsolidated deposits which are underlain by volcanic rocks.

Regarding the present study area, landslides were recorded in Tarmaber area, central highlands of Ethiopia as reported by Kifile Woldearegay (2008) and Schneider *et al.* (2008). As indicated by these authors, the localities “Yizaba Wein” and “Shotel Amba” areas, which are included in the present study area with an estimated total area of 35 Km², were completely affected by a single major deep-seated landslide which took place in September 12, 2006. As a result of this landslide more than 3000 people were displaced; 1250 dwelling houses were demolished; and 4 Churches, 4 Mills, and one elementary school were destroyed. The landslide also devastated about 1500 hectare of agricultural land and caused damage to the natural environment.

Because of its complex geomorphological, hydrological, and geological setting, the hilly terrains of the Ethiopian landmass has been frequently affected by first time as well as reactivated old landslides. Except for some efforts made by the Ethiopian Geological Survey and Ethiopian Roads Authority, so far no comprehensive inventory of landslides and their significance (economic, social and environmental) is made in Ethiopia (Kifle Woldearegay, 2013)

According to previous studies conducted in the present study area, Debre Sina is one of the most landslide prone areas located in the Afar Rift Margin of Ethiopia. In this area a large scale and complex landslide occurred on September 13-14, 2005. This event caused losses of over 900 hectares of arable lands, displacement of more than 4,049 peoples, destruction of more than 1,200 dwelling local houses and over 75% crop harvesting failure specifically in the localities named Yizaba and Shotel Amba (Asmelash Abay and Barbieri, 2012).

Gebresilasie (2007) estimated the cost of the damage attributed by the 2005 landslides to be about 14 million Ethiopian Birr in Yizaba locality only. In fact, if we consider the indirect cost of all the environmental destruction including the downstream arable lands lost by the huge landslide driven debris flow, the cost would have been more than threefold of the mentioned one.

Gebresilassie (2007) also attempted to assess the social impact of the landslide in Debre Sina by interviewing local peoples and mentioned a loss of about 350ha farm and grazing land, 44ha of forest and bush land, more than 26 residential houses and reported lots of houses cracked in various localities of the Debre Sina area from the years 1953 to 2000. In fact, it is very difficult to consider the numbers and figures obtained from the local oral legend, but the idea can generally imply the presence of a frequent and casual landslide in the area since long.

The studies also indicate that even if the present study area has experienced considerable hazard for years neither detailed study at higher scales has been conducted nor appropriate remedial measures have been taken (Asmelash Abay and Barbieri, 2012; Asmelash Abay, 2011; Leta Alemayehu , 2007).

2.4 Previous Works

Certain previous studies that have been conducted in the study area reveal that it is one of the most susceptible sites to landslide hazards.

By using GIS techniques, frequency ration model (FR) and kinematic slope stability method, Asmelash Abay and Barbieri (2012) have identified four landslide hazard classes; namely; very high hazard (0.7%), high hazard (22.7%), moderate (65%) and low hazard (11.6%).

Asmelash Abay (2011) also used GIS-based Overlay Mapping method (OM), Frequency Ratio method (FR) and Analytical Hierarchical Process (AHP) method and has identified four landslide hazard zones which have very high hazard zone (32%), high hazard zone (33%), moderate hazard zone (26%) and low hazard zone (9%). Accordingly, 65% of the study area is susceptible to landslide hazard.

By adopting the methodology known as Logistic Regression and Artificial Neural Networks in GIS (ANN), Leta Alemayehu (2007) has classified the study area in to five landslide susceptibility degree zones; namely; very low, low, medium, high and very high. Most part of the study area falls in medium hazard zone.

In the present study Slope Susceptibility Evaluation Parameter (SSEP) rating scheme proposed by Raghuvanshi *et al.*, (2014) has been used in order to delineate landslide hazard prone areas. This method has been selected over others because it mainly depends on field realistic data and incorporates both intrinsic and external landslide triggering factors.

Elements at Risk

There are several both natural and man-made structures which are damaged by landslide hazards. Not only utilities and properties are destroyed by landslide hazards but also the life of people and animals, as observed during the present field visit from inventory landslide sites. The elements at risk include:

- ✓ Property, which may be subdivided into portions relative to the hazard being considered.
- ✓ People, who either live, work, or may spend some time in the area affected by landslides
- ✓ Services, such as water supply or drainage or electricity supply.
- ✓ Roads and communication facilities.
- ✓ Vehicles on roads, subdivided into categories (cars, trucks, buses).

2.5 Landslide Hazard Zonation (LHZ)

Our planet earth has been experiencing different kinds of natural hazards since its birth. These hazards caused a lot of damages and fatalities to the life of people and private as well as public properties including various infrastructures. Those areas more likely to be affected by natural hazards have been zoned and delineated based on the magnitude of hazard they face so that special treatments are given.

According to Varnes (1984), hazard has been defined as the potential to cause damage or the probability of occurrence of a potentially damaging phenomenon within the specified period of time and in a given area.

Landslide hazard zonation is an important step in landslide investigation and landslide risk management.

Varnes and IAEG (1984) defined the term 'zonation' as *'the process of division of land surface into areas and ranking of these areas according to the degree of actual or potential hazard from landslides or other mass movements'*.

Courtire (2011) explained the concept of landslide hazard as *'division of land into somewhat homogeneous areas or domain and their ranking according to the degrees of actual or potential landslide susceptibility, hazard or risk or applicability of certain landslide related regulations'*.

The natural slope failures in the future will most likely be in geologic, geomorphic, and hydrologic situations that have led to past and present failures. Thus, there is a possibility to estimate the style, frequency of occurrence, extent, and consequence of failure that may occur in future. This can be done by classifying the area into zones of hazard with varied degree of landslide susceptibility. Thus, zonation can be defined as the division of land surface into areas and ranking of these areas according to degrees of actual or potential hazard from landslides or other mass movements on slopes (Saha *et al.*, 2002).

Landslide, like other natural hazards such as, flood, earthquake and avalanche is often difficult to predict. However, landslide risk can be systematically assessed and managed. Hazard and risk maps are usually the end product of landslide mapping but they are the basis for decision making. These decisions are usually in the form of technical countermeasures, regulatory management, or combinations of the two. Classic examples of regulatory management are zonation maps which, for instance, exclude some landslide-prone areas from habitation and various constructions of infrastructures.

Landslide hazard zonation is a critical task in landslide management process. The landslide hazard zonation mapping has great role for town planner to adjust the existing town master plan or to consider the degree of hazard in future town planning. It also helps the road construction authorities for maintenance and to take remedial measures for high and very high hazard slopes if they fall near to the roads. Local residents and concerned government bodies will be highly benefited from this hazard map to take some action with respect to landslide hazard (Anbalagan, 1992).

A landslide hazard zonation map divides the slope surface in to zones of varying degrees of stability based on an estimated significance of causative factors including instability. The Landslide hazard zonation map is a rapid technique of hazard assessment of the land surface (Gupta and Anbalagan, 1995).

A Landslide Hazard Zonation Map serves as a basic tool for perspective project planning like development of township, defense colony, planning of layout of hill cut roads, railway tract or any other civil engineering structures on the landslide prone hilly terrain of a country.

According to Anbalagan (1992) landslide hazard zonation (LHZ) map divides the land surface into zones of varying degrees of stability, based on the estimated significance

of causative factors in inducing instability. If such multi-purpose terrain evaluation maps are used as a basis of preliminary planning of the development schemes, it will help to select geo-environmentally sound sites which may pose minimum hazards of instability. The LHZ maps are prepared based on the basic causative factors of slope instability.

The LHZ maps are useful for the following purposes:

- (a) To identify and delineate unstable hazard-prone areas, so that environmental regeneration programs can be initiated adopting suitable mitigation measures, and
- (b) To help planners to choose favorable locations for citing development schemes, such as, buildings, dam and road constructions. Even if the hazardous areas cannot be avoided altogether, their recognition in the initial stages of planning may help to adopt suitable precautionary measures.

2.6 Landslide Hazard Modeling Approaches

Spatial prediction of landslide is termed as landslide susceptibility, which is a function of landslide and landslide related internal and external factors. The aim is to identify places of landslide occurrence over a region on the basis of a set of internal and external causative factors. This is specifically known as landslide susceptibility zonation (LSZ), which can formally be defined as the division of land surface into near-homogeneous zones and then ranking these according to the degrees of actual or potential hazard due to landslides (Kanungo *et al.*, 2009). Different literatures suggest a variation in LHZ mapping methodologies used by different agencies in different countries. Several methodologies for LHZ mapping have been proposed and are based upon some widely accepted assumptions (Varnes, 1984; Carrara *et al.*, 1991; Hutchinson, 1996), which can be stated as;

- (i) The past and present are the keys to the future. This implies that landslides in future will more likely occur under similar geological, geomorphological, hydrogeologic and climatic conditions, which were and are responsible for the occurrence of past and present landslides. Hence, experiences on existing landslides will be more helpful for landslide susceptibility assessment. However, external causative factors are aggressive and unpredictable with past events due to climatic change and unexpected pressure on land.

- (ii) Landslides with distinct geomorphological features can be identified, classified and mapped both through field surveys and remote sensing image interpretations (Varnes, 1978; Hansen, 1984; Dikau *et al.*, 1996).
- (iii) Landslides are controlled by identifiable inherent and external factors, known as causative factors, which can also be mapped from field surveys and remote sensing image interpretations (Dietrich *et al.*, 1995).

By using GIS and other techniques, different ways of landslide susceptibility modeling approaches have been developed, which have been widely employed throughout the world.

Barredo *et al.*, (2000) divided these methods into inventory, heuristic, statistical, and deterministic approaches. Each of these methods has its own advantages and disadvantages as what is suitable for one methodology may not be suitable for another. Moreover, they all depend on different criteria which define the suitability of proposed methodology for a given site of investigation. They can be either qualitative or quantitative depending on the kind of data collected. They can also be regarded as direct or indirect methods on the basis of the way of data collection.

Qualitative methods are subjective, ascertain susceptibility heuristically, and portray susceptibility levels using descriptive (qualitative) terms. Whereas, quantitative methods produce numerical estimates, i.e. probabilities of the occurrence of landslide phenomena in any susceptibility zone (Guzzetti *et al.*, 2005).

Direct mapping methods are those that identify the spatial distribution of instability directly from existing landslides and/or specific knowledge of areas of potential instability. A direct method consists of direct geomorphological mapping of landslide susceptibility in the field, using aerial photographs (Verstappen, 1983) or from satellite images (Nossin, 1989).

Indirect mapping methods are those that use factors related to landslide to estimate potential landslide hazard. Indirect methods for landslide susceptibility assessment are essentially stepwise. Guzzetti (2005) determined the requirements of indirect methods as:

- (i) the recognition and mapping of landslides over a target region or a subset of it (i.e. the training area), which is obtained by preparing a landslide inventory map;

- (ii) The identification and mapping of the physical factors which are directly or indirectly correlated with slope instability (the instability factors, or independent variables);
- (iii) An estimate of the relative contribution of the instability factors in generating slope failures;
- (iv) The classification of the land surfaces into domains of different levels of susceptibility; and
- (v) The assessment of the model performance

2.6.1 Landslide Inventory Mapping

Landslide inventory maps show locations and characteristics of landslides that have moved in the past but generally do not indicate the mechanism(s) that triggered them. The geologic, topographic and climatic conditions that led to past slope failures often provide clues to the locations and conditions of future slope failures. Therefore, inventory maps provide useful information about the potential for future landslides. It is the most straightforward initial approach to any landslide hazard study and such inventories are the basis for most susceptibility mapping techniques (Dai *et al.*, 2002).

A clear understanding of landslide conditions and a more detailed assessment of the landslide hazard of the area concerned are essential to make a systematic landslide inventory. All failures recorded in historical and technical documents, investigated and identified or by aerial photographic analysis, should be registered. Compiling the locations and conditions of existing landslide zones is the basic requirement before performing any slope stability analysis (Van Westen *et al.*, 2006).

Generally, widely used methods for making a landslide inventory map are field investigations and remote sensing techniques. By fieldwork surveys, evidence of current and former landslides can be determined from slope morphology, sedimentary deposits, or impact features (e.g. deformed trees). As this type of evidence deteriorates or is obliterated progressively with time, care has to be taken in establishing long-term trends in occurrence. A wide range of both relative and absolute methods has been employed for dating of field evidence (Lang *et al.*, 1999; Bull, 1996).

2.6.2 Heuristic Method

McClelland *et al.*, (1997) emphasized the heuristic or expert-driven approach, as a method in which a geomorphological expert decides on the type and degree of hazard for each area,

using either a direct mapping or indirect mapping approach. In a direct mapping approach the degree of hazard is mapped directly in the field, or is determined after the fieldwork on the basis of a detailed geomorphological map

The indirect heuristic approach utilizes data integration techniques, including qualitative parameter combination, in which the analyst assigns weighting values to a series of terrain parameters and to each class within each parameter. The parameter layers are then combined within the GIS to produce hazard values (Pachauri *et al.*, 1998).

It is an indirect and mostly qualitative method that relies heavily on the priori knowledge of landslides and their processes in a region. Therefore, its reliability depends on how well and how much the investigator understands the geomorphological processes acting upon the terrain. Instability factors are classified, ranked and weighted according to their assumed or expected importance in causing mass movements. Based on this information, heuristic, subjective decision rules are established to define possibly unstable areas and to zone landslide susceptibility accordingly (Montgomery *et al.*, 1991).

The advantage of this method is that a landslide inventory is not needed because the weights are assigned based on the field knowledge of an experienced geomorphologist. Each individual polygon outlined on the map can be evaluated separately, based on its unique set of conditions. Moreover, the use of GIS for the weighting assignments and overlays makes this method fast and easy to use provided the needed data are available. However, the disadvantage of this approach is that experts' subjectivity strongly influences the resulting map of landslide susceptibility, although, subjectivity is not necessarily bad, particularly if it is based on the opinion of an expert (Van Westen *et al.*, 1997a).

It is a time consuming method that depends also to a large degree on the expertise of the geomorphologist (Barredoetal, 2000). Nonetheless, subjectivity adds to the uncertainty of the model. To limit this problem, the expected importance of each instability factor can be obtained "objectively" by investigating the relative abundance of landslides (Pachauri *et al.*, 1998; He *et al.*, 2003).

Moreover, expert evaluation techniques are most versatile and widely used but needs improvement. In order to integrate the landslide hazard mapping techniques it is necessary to use techniques which involve statistical methods, mechanical methods and geographical data management tools (Fall *et al.*, 2006). However, application of such expert evaluation

techniques are more practical, simple and provide much more realistic field data well supported by experience of an expert (Raghuvanshi *et al.*, 2014). Perhaps for these reasons, despite the fact that they involved subjectivity, they happen to be popular and widely used over the years.

2.6.3 Statistical Approaches

The statistical approaches have been adopted for LSZ studies to minimize the subjectivity in weight assignment procedure associated with qualitative approaches. The statistical approach compares the spatial distribution of existing landslides in relation to different causative factors (Aleotti and Chowdhury, 1999). GIS tools are quite useful in this analysis.

According to Carrara (1983), these models to determine spatial landslide instability are used to describe the functional relationships between instability factors and the past and present distribution of slope failures. These approaches are indirect and provide quantitative results suitable to the quantitative assessment of landslide hazard. Statistical analyses are popular because they provide a more quantitative analysis of slope instability and have the ability to examine the various effects of each factor on an individual basis.

Statistical Hazard Methods were developed to overcome relatively high level of subjectivity related to expert evaluation (Fall *et al.*, 2006). Statistical hazard methods are good for assessing the spatial probability but there are problems in evaluating either temporal probability or the effects of future environmental changes. They are mostly used in qualitative risk assessment but if combined with landslide inventory maps for different triggering events, might be the best method for quantitative risk assessment over larger areas (Westen *et al.*, 2006). Statistical approaches can broadly be classified into two types; bivariate and multivariate (Chung and Fabbri, 2001).

Bivariate Statistical Methods

The bivariate methods are a modified form of the qualitative map combination with the exception that weights are assigned based upon statistical relationships between past landslides and various factor maps. Indeed, each factor map is combined with the landslide map, and weighting values based on landslide densities are calculated for each parameter class. Alternatively, these statistics can be used to develop decision rules (Van Westen, 1994).

In bivariate approaches, the core of the analysis is to determine the densities of landslide occurrences within each parameter map and its parameter map classes, and to derive data driven weights based on the class distribution and the landslide density (Süzen and Doyuran, 2004). With these weights parameter maps can be combined to obtain a landslide hazard map. In order to apply bivariate analyses, continuous parameter maps have to be converted into discrete (categorical) maps, in order to compute the corresponding weight of each class. However, such conversions remain always unclear in the literature as most of the authors use their expert opinion for dividing into classes (Van Westen, 1993).

Moreover, the result of bivariate analysis methods also depends on the selection of parameters or causative factors for landslide instability. This is also an important subjective element in the method. For a bivariate statistical approach, maps of medium scale are most appropriate, in the range of 1:25000 to 1:50000 (Van Westen *et al.*, 1997a), because the technique is not detailed enough to be applied on a larger scale. In bivariate statistical analysis the dependent variable (in this case the occurrence of mass movements) is compared to each causal factor separately and the importance of each factor is determined independently of the other factors. Specific combinations of factors can also be tested by using a combination map as a new variable. Hence, the technique is based on the assumption that the important factors leading to mass movement can be quantified by calculating the density of mass movements for each variable class, or to combine various parameter maps into a new map, which is then overlaid by the landslide map to give a density per unique combination of input parameters (Soeters and Van Westen, 1996).

The statistical rating of a particular category of a thematic data layer of bivariate statistical method is given by eq. 2.1 (Kanungo *et al.*, 2009):

$$W_i = \ln \left(\frac{Densclas}{Densmap} \right) = \ln \frac{Npix(S_i)/Npix(N_i)}{\sum_{i=1}^n Npix(S_i) / \sum_{i=1}^n Npix(N_i)} \quad \dots\dots eq. 2.1$$

Where, W_i denotes the weight given to the i^{th} category of a particular thematic data layer; $Densclas$ denotes the landslide density within the category; $Densmap$ denotes the landslide density within the thematic data layer; $Npix(S_i)$ denotes the number of pixels, which contain landslides, in a category; $Npix(N_i)$ denotes the total number of pixels in a category and n is the number of categories in a thematic data layer. The thematic data layers are overlaid and

the ratings (InfoVal) are added to prepare a Landslide Susceptibility Index (LSI) map, which is later categorized into five different landslide susceptibility zones to prepare an LSZ map.

Multivariate Statistical Approaches

Multivariate approaches consider relative contribution of each thematic data layer to the total susceptibility within a defined area.

The procedure involves several important steps (Aleotti and Chowdhury, 1999):

- (i) Identification of percentage of landslide affected areas in each pixel and their classification into stable and unstable zones
- (ii) Preparation of an absence/presence matrix of a given category of a given thematic layer,
- (iii) Multivariate statistical analysis (discriminant and regression), and
- (iv) Reclassification of the area based on the results and their classification into susceptibility classes.

These approaches involve analysis of large volume of data and are time consuming. External statistical packages are generally used to support the GIS packages. The statistical analyses most frequently used for LSZ mapping are discriminant analysis and multiple regression analysis (Yin and Yan, 1988; Jade and Sarkar, 1993; Clerici *et al.*, 2002).

According to Baeza and Corominas (2001) a multivariate statistical model forecasts the spatial occurrence of landslides based on a set of Geo-environmental factors considered to be connected to the stability or instability of the slopes in each of the terrain units used to subdivide a territory. The multivariate model is based on an equation whose independent variables are the geo-environmental factors (predictors), with coefficients maximizing the predictive capability of the model, and the independent (predicted) variable is the presence/absence of landslides.

A landslide inventory map is needed to calibrate the model; the model needs to “learn” which geo-environmental factors are associated with stable and unstable slopes.

Süzen and Doyuran, (2004) emphasized that multivariate models currently available are based upon factors predisposing to the instability of the slopes, e.g., the geo-environmental setting, and do not include any variable describing the initiation of landslides (triggering factors, such as intense rainfall, earthquake shaking, etc.). Hence, multivariate models do not

incorporate explicitly the temporal aspect of landslides. This limitation is due to the inability to determine the date of occurrence for a statistically significant number of landslides in the study area. At present, multivariate models do not provide a complete prediction of landslide hazard, incorporating both space and time.

The advantage of multivariate models is that they provide a quantitative, objective and reproducible way, the spatial occurrence of landslides (Cardinali *et al.*, 2000). However, the most serious drawback of the use of statistical methods is the collection of data over large areas and sometimes over large time periods regarding landslide distribution and factors. It could be very problematic to carry out this data gathering at acceptable costs (Van Westen *et al.*, 1997). A further potential source of error, which is common to all statistical methods, is the quality and detail of the landslide frequency or factors data on which the correlations are based. Thus, the results are largely dependent on quality of the data. Recently, multivariate methods have been used for slope instability donation (Carrara, 1983).

The most important techniques used in multivariate methods are multiple linear regression method and logistic regression analysis method. When many factors are available, to reduce the number of variables and to limit their interdependence, principal component analysis (PCA) is an option (Carrara *et al.*, 1995).

Kanungo *et al.* (2009) suggested the following limitations of multivariate statistical approach:

- (i) Discriminant and regression analyses require data derived from a normally distributed population that is frequently violated.
- (ii) A mixture of continuous (i.e., slope, aspect, etc.) and categorical (i.e., lithology, land use land cover, etc.) factors leads to incorrect solution.
- (iii) Some of the factors may bear weak physical relationship with landslide occurrences.

2.6.4 Probabilistic Statistical Methods

Probabilistic method calculates prediction from inventory and period with an assumption that landslide occurrence is determined by landslide-related factors, and that future landslides will occur under the same conditions as past landslides.

These methods use the frequency ratio to evaluate the relationship between landslides and each type of parameter factor. The probabilistic approaches have also been used for LSZ studies to minimize the subjectivity in weight assignment procedure.

Favorability modeling (FM) approach is a good compromise, offering a valid quantitative method, where subjectivity or expert knowledge can be incorporated in the analysis, particularly when data are not sufficient or reliable.

With FM, thematic data can be transformed into continuous data, by considering the degree of relationship between the landslides and the categories of each thematic data layer. Each continuous or non-continuous category can be transformed into a value, called favorability value.

The Certainty Factor (CF) approach is one of the possible proposed Favorability Functions (FF) to handle the problem. The CF, defined as a function of probability, originally proposed by Shortliffe and Buchanan (1975) and modified by Heckerman (1986) is given as eq. 2.2:

$$CF = \begin{cases} \frac{PP_a - PP_s}{PP_a(1 - PP_s)} & \text{if } PP_a > PP_s \\ \frac{PP_a - PP_s}{PP_s(1 - PP_a)} & \text{if } PP_a < PP_s \end{cases}$$

..... eq. 2.2

Where pp_a is the conditional probability of having a number of landslide event occurring in category a and pp_s is the prior probability of having the total number of landslide events occurring in the study area. The range of CF values varies from -1 to 1.

A positive value means an increasing certainty in landslide occurrence, while a negative value corresponds to a decreasing certainty in landslide occurrence. A value close to zero means that the prior probability is very similar to the conditional one. By integrating the CF values of the categories of thematic data layers, LSZ map can be prepared.

2.6.5 Deterministic Methods

Crosta and Agliardi (2004) defined deterministic methods of landslide susceptibility as those approaches which rely upon the understanding of the physical laws controlling slope instability. In general, due to lack of information or poor understanding of the physical laws

controlling landslide initiation and development, only simplified, “conceptual” models are considered.

These models are indirect and provide quantitative results, which may or may not be suited for quantitative landslide hazard assessment depending on the types of output. Review of the literature reveals that process based models are developed mostly to study a particular type of landslide (e.g., shallow soil slips, debris flows, or rock falls), or to investigate the effect of a specific trigger, i.e. an intense rainfall period or an earthquake.

Safety factor analysis is one of the most common models used to determine local stability conditions by the means of the local equilibrium along a potential slip surface. Other models match the infinite slope stability model with rainfall infiltration models (Dietrich *et al.*, 1995).

Table 2.1 portrays the summary of methods of landslide susceptibility mapping in relation to their types and recommended scales of mapping.

2.7 Landslide Hazard Evaluation Factor (LHEF) Rating Scheme

The weight rating system is usually designed in many different ways on the basis of studying the impact of each selected factor, for their importance in inducing the instability.

Anbalagan (1992) has suggested a landslide hazard evaluation factor (LHEF) rating system that incorporates all the causative factors as listed in Table 2. 2. The LHEF rating scheme may be more relevant as it is based on an empirical approach using important inherent causative factors of slope instability such as; lithology, structure, slope morphometry, land use and land cover, relative relief and hydrogeological conditions. In this scheme, the external factors such as; rainfall and seismicity have not been included.

Table 2.1 Methods of landslide susceptibility mapping in relation to types and scales

Types	Techniques	Activities	Characteristics				Scale		
			Direct	Indirect	Qualitative	Quantitative	1:100,000	1:25,000	1:10,000
Heuristic	Geomorphologic analysis	Use field-expert opinion in zonation	X	X	X		X	X	X
	Qualitative map combination	Use expert-based weight values of parameter maps		X	X	X	X	X	
Statistical	Bivariate statistical analysis	Calculate importance of contributing factor combination		X		X		X	
	Multivariate statistical analysis	Calculate prediction formula from data matrix		X		X		X	
	Probabilistic analysis	Calculate prediction from inventory and time period		X		X	X	X	
Deterministic	Safety factor analysis	Apply hydrological and slope stability models		X		X			X
Inventory	Remote sensing and field investigations	Show locations and characteristics of past landslides	X	X	X			X	

(Source: Adopted from Soeters and Van Westen, 1996; VanWesten et al., 1997a)

The maximum weight for individual factor has further been sub-divided into a number of categories to form a detailed LHEF rating scheme. This scheme can then be used for calculating total estimated hazard (TEHD) for individual facets. The total estimated hazard (TEHD) value indicates the net probability of instability of a slope facet. It is calculated slope facet-wise, because adjoining slope facets may have entirely different stability conditions. The TEHD value of an individual slope facet is obtained by summing up the ratings of each causative factor, obtained from the LHEF rating scheme for that slope facet. Thus, TEHD value is equal to the sum of ratings of categories of all causative factors. As depicted in (Table 2.2), TEHD values are then arbitrarily categorized into different landslide hazard zones.

Table 2.2 Maximum LHEF rating for causative factors for macro-zonation

S.No	Causative Factors	Maximum LHEF Rating
1	Lithology	2.0
2	Relationship of structural discontinuities with slope	2.0
3	Slope morphometry	2.0
4	Relative relief	1.0
5	Land use and land cover	2.0
6	Hydrogeological condition	1.0
	Total	10

LHEF rating scheme, which also follows an empirical approach, takes into consideration individual and net effect of all inherent causative factors responsible for slope instability. Inherent factors are used for preparation of Landslide Hazard Zonation (LHZ) mapping on macro-zonation approach. Maximum values of rating for individual parameter is awarded keeping in mind its estimated significance in causing slope failure and also to represent overall field conditions.

Table 2.3 LHZ on the basis of Total Estimated Hazard (TEHD)

S.No	TEHD Value	Hazard Class
1	<3.5	Very Low Hazard (VLH)
2	3.5-5.0	Low Hazard (LH)
3	5.1-6.0	Moderate Hazard (MH)
4	6.1-7.5	High Hazard (HH)
5	>7.5	Very High Hazard (VHH)

Various literatures state that different techniques used for the landslide hazard zonation mapping have their own advantages and disadvantages. The choice of suitable techniques depends on a number of factors. Some of these factors include availability and accessibility of sufficient data, the scale of investigation, nature of the topography of the study area, reliability of the given approach in terms of data analysis, complexity or easy of the proposed methodology in application, etc.

LHEF (Landslide hazard evaluation factor) technique proposed by Anbalagan (1992) was found to be a suitable technique for the landslide hazard zonation as it involves several parameters which are responsible for landslide hazard initiation. It is an empirical technique which consider the relative influence of inherent causative factors like; geology, slope morphometry, relative relief, land use and land cover and groundwater conditions. However, LHEF technique has certain limitations on adoption of inherent causative and external factors. In the present study a modified technique “Slope susceptibility Evaluation

Parameter” (SSEP) developed by Raghuvanshi *et al.* (2014) has been adopted as it overcome the limitations of LHEF.

Limitations and shortcomings of Anbalagan’s LHEF rating system

The LHEF is an empirical technique which utilizes observational past experience of author gained from the study of causative factors and their contribution for instability with conditions anticipated in the study area. The LHEF technique has been utilized successfully over the years by many researchers but as proposed by Raghuvanshi *et al.* (2014) it has following short comings or limitations;

- (a) In LHEF rating scheme the assessment of total estimated hazard (TEHD) is based on major inherent causative factors of slope instability such as; geology, slope morphometry, relative relief, land use and land cover and groundwater conditions. The major short coming of LHEF rating scheme is that it does not account for external factors, both natural and manmade, which are responsible for triggering instability of slopes. The major natural factors which, triggers the instability in slopes are seismicity (Keefer, 2000) and rainfall (Collison *et al.*, 2000) whereas, manmade activity include construction activities on slopes (Wang and Niu, 2009).

These instability triggering external factors are very important and must be considered while evaluating stability condition of slopes. Moreover, LHEF rating scheme provides stability condition for slopes only for the existing conditions prevailed at slopes during the time of investigation. However, the anticipated adverse conditions to which the slopes may be subjected during construction or performance stage represented by seismic loading or heavy rainfall conditions cannot be considered.

- (b) The total LHEF rating assigned for groundwater is 1.0 only whereas for lithology, relationship of structural discontinuities with slope, slope morphometry and LULC maximum LHEF rating has been assigned as 2.0 each. This is a known fact that role of groundwater is significant in landslide process. For that reason only during the rainy seasons, when the groundwater is recharged considerably, landslide activities are increased (Hoek and Bray, 1981). Therefore, the maximum LHEF rating for groundwater is under assigned as the role of groundwater is significant in triggering the landslide activity.

- (c) The total maximum LHEF rating assigned for lithology and relationship of structural discontinuities with slope contributes maximum LHEF rating as 2.0 each. As a fact contribution of relationship of structural discontinuities with slope has to be given more importance than the lithology. As in rock slopes instability is significant when kinematic condition, defined by relationship of structural discontinuities with slope, are satisfied (Gokceoglu *et al.*, 2000) whatever lithology constitutes the slope (Hoek and Bray, 1981). Even in very weak lithology such as; phyllites, shales, claystone etc. slope will only show potential instability when relationship of structural discontinuities with slope is kinematically satisfied. Thus, the maximum LHEF rating for relationship of structural discontinuities with slope is under assigned.
- (d) In LHEF rating system the orientation of structural discontinuities their interrelationships and relationship of structural discontinuities with slope is only considered. The condition of rock mass with respect to structural discontinuities and characteristics of structural discontinuities has not been considered. These characteristics such as; spacing, continuity, surface characteristics, separation of discontinuity surface and thickness and nature of filling material within the discontinuity surfaces are very important in defining stability condition of the rock mass (Price, 2009; Johnson and DeGraff, 1991). Thus, this may be considered as one of the limitations of LHEF rating scheme.
- (e) Besides ignoring external causative factors such as seismicity, rain fall and human-induced constructions, LHEF also does not predict for anticipated adverse conditions during construction and performance stage rather it provides stability condition for the slopes only for the existing conditions prevailed at the slopes during the time of investigation.

2.8 Slope Stability Susceptibility Evaluation Parameter (SSEP) Rating Scheme

This landslide hazard zonation mapping methodology is a modified technique which is developed by Raghuvanshi *et al.* (2014) and is applicable in large areas demanding rapid slope stability assessment. It mainly relies on field data and produces landslide hazard zonation map by combining both intrinsic and external slope instability triggering parameters. It was developed in order to overcome the shortcomings of Anbalagan's (1992) LHEF rating scheme and is found to be suitable to be applied in present study.

The SSEP rating technique involves intrinsic and external triggering parameters responsible for slope instability. The slope stability is mainly governed by intrinsic parameters such as; slope geometry, slope material (lithology or soil type), structural discontinuities, land use and land cover and groundwater (Wang and Niu, 2009).

Besides, external parameters, both natural and manmade, which are responsible for triggering instability of slopes, are also considered. The major natural parameters which, triggers the instability in slopes are mainly seismicity (Keefer, 2000) and rainfall (Collison *et al.*, 2000; Dahal *et al.*, 2006). However, there are other natural factors which may trigger slope instability such as; snow/ avalanche, wind, permafrost conditions, shoreline processes and volcanic activities which are not included in SSEP for landslide hazard purpose. Manmade activities mainly include constructions and cultivation practices on slopes (Wang and Niu, 2009).

SSEP rating scheme, predicts anticipated adverse conditions as well as provides stability condition of slopes during the time of investigation. Its disadvantage is however that it heavily depends on realistic field data which require frequent field visit. Overall advantage of SSEP rating scheme is to improve the quality of final result as most of the input data are directly collected from the field. It is also assumed to be more reliable as compared to GIS-based techniques which mainly rely on secondary data that do not necessarily need frequent field visit as long as the quality of the result is considered. In SSEP rating scheme, the entire study area is divided into individual slope facets in which landslide investigation is conducted separately in each facet because significance of causative parameters in instability initiation vary from facet to facet.

For SSEP empirical technique, numerical rating values are assigned to each of the intrinsic and external triggering parameters on the basis of their contribution towards instability of slope. The parameters responsible for instability of slopes have been assigned with numerical ratings which are based on logical judgments acquired from experience of studies of intrinsic and external triggering factors and their relative impact on instability of slopes.

Slope Facet is defined as a land unit which is characterized by more or less uniform slope geometry in terms of slope inclination and slope direction (Anbalagan, 1992). For this purpose, topographic maps were utilized to demarcate the slope facets. Facet boundaries are delineated by major or minor hill ridges, primary and secondary streams and other

topographical undulations. For the present study Debre Sina topo map of 1:50,000 was utilized to delineate slope facets of the study area.

In SSEP rating scheme, the entire study area is divided into individual slope facets in which landslide investigation is conducted separately. Rating values will be assigned for each intrinsic and external causative factor based on its severity in landslide initiation and the summation of all causative factors will provide Evaluated Landslide Hazard (ELH). Finally landslide hazard zonation (LHZ) map will be prepared based on the facet-wise distribution of ELH values. Table 2.5 portrays different hazard zones with Evaluated Landslide Hazard Values.

Table 2.4 Distribution of maximum SSEP ratings assigned to different intrinsic and external factors

Triggering Parameters		Maximum Rating	
Intrinsic Parameters			
1.	Slope Geometry	Relative Relief	1.0
		Slope Morphometry	2.0
2.	Slope Material		1.0
3.	Structural Discontinuities		2.5
4.	Land use Land cover		1.5
5.	Groundwater		2.0
External Parameters			
1.	Seismicity		2.0
2.	Rain Fall		1.5
3.	Man-made Activities		1.5
Total			15.0

(Source: Raghuvanshi *et al.*, 2014)

ELH= Summation of ratings of intrinsic parameters (relative relief + slope morphometry + slope material + structural discontinuity + land use and land cover + groundwater) + Summation of ratings of external parameters (rainfall + seismicity + man-made activities)

2.8.1 Intrinsic Parameters of SSEP Rating Scheme

Intrinsic parameters are the causative parameters which define the favorable or unfavorable stability conditions within the slope. These intrinsic parameters are slope geometry, slope material, Structural discontinuities, land use and land cover and groundwater (Anbalagan, 1992; Wang and Niu, 2009). Depending upon the given conditions for each of these intrinsic parameters they may have an influence over the stability condition of the slope.

Table 2.5 Evaluated landslide hazard classes (Raghuvanshi *et al.*, 2014)

Landslide Hazard Zone	Landslide Hazard Class	Evaluated Landslide Hazard
Very high hazard zone (VHHZ)	V	>12
High hazard zone (HHZ)	IV	12-8
Moderate hazard zone (MHZ)	III	7.9-5
Low hazard zone (LHZ)	II	4.9-2
Very low hazard zone (VLHZ)	I	< 2

Slope Geometry

Slope geometry includes relative relief and slope morphometry of the slope. The difference in maximum and minimum elevation within a facet defines the relative relief. Relative relief basically represents the height of an individual facet. Relative relief has been categorized into five classes; low (< 50 m), moderate (51-100 m), medium (101-200 m), high (201-300 m) and very high (>301 m). Slope will be more prone for instability if the relative relief is more (Hoek and Bray, 1981), accordingly ratings has been assigned according to SSEP rating table (Annexure A).

The slope morphometry indicates the steepness of the slope. The slope morphometric classes are adopted same as that of Anbalagan's (1992) LHEF rating scheme, accordingly the classes are; escarpment/cliff (> 45°), steep slope (36°-45°), moderately steep slope (26°-35°), gentle slope (16°-25°) and very gentle slope (< 15°). The ratings for each sub class of relative relief and Slope morphometry are given according to SSEP rating table (Annexure A).

Slope Material (Lithology)

According to Kanungo *et al.* (2009), lithology basically involves the composition, texture, degree of weathering, as well as other details that influence the physio-chemical and engineering behaviors such as permeability; shear strength, etc. of the rocks and soils. These characteristics in turn affect the slope stability. Slopes may be composed of rock mass or soils or both. The criteria for assigning ratings to sub classes of rock type are based on intact rock strength and degree of weathering. The errodability of rocks is highly influenced by the strength of the rock. Rocks which possess high strength are relatively more resistant to erosion.

Structural Discontinuities

The inter-relationship between the slope and the discontinuities plays an important role particularly in rock slopes to understand the mechanism of failure. Further, the proximity of a

slope to a tectonically active zone such as; major faults or thrusts or lineaments influences the landslide activity to a great extent (Kanungo *et al.*, 2009).

The disposition of structural discontinuities in relation to slope inclination and direction has a great influence on the stability of slopes. The following three types of relations are considered important (Anbalagan, 1992):

- (i) The extent of parallelism between the directions of the discontinuity, or the line of intersection of two discontinuities and the slope.
- (ii) The steepness of the dip of the discontinuity, or the plunge of the line of intersection of two discontinuities.
- (iii) The difference in the dip of the discontinuity, or the plunge of the line of intersection of the two discontinuities to the inclination of the slope.

Land use and land cover

The land use change, such as; deforestation, exploitation of natural resources, conversion of vegetated slopes into built up area, etc. may result into landslide occurrences. Land use land cover is an indirect indication of the stability of hill slopes (Kanungo *et al.*, 2009). Barren and sparsely vegetated areas show faster erosion and greater instability as compared to reserve or protected forests, which are thickly vegetated and generally less prone to mass wasting processes (Wang and Niu, 2009). Thus, while assigning rating for land use and land cover above mentioned points were considered. Rating values are given in Annexure A as per the standard SSEP table.

Groundwater Conditions

Because groundwater in hilly terrain is generally channeled along structural discontinuities of rocks, it does not have a uniform flow pattern. The evaluation of observations of the behavior of groundwater on hill slopes is not possible over large areas. Therefore, in order to make a quick appraisal, the nature of surface indications of the behavior of groundwater will provide valuable information on the stability of hill slopes for hazard mapping purposes. Surface indications of water such as; damp, wet, dripping and flowing are used for rating purposes (Anbalagan 1992). Thus, while assigning ratings all these points were considered (Annexure A) as per the standard SSEP table.

2.8.2 External Landslide Hazard Triggering Parameters

External parameters are considered in addition to intrinsic parameters in landslide hazard zonation by SSEP rating scheme because they have significant role in slope instability. The most important external parameters which may trigger instability in slopes are rainfall, seismicity and manmade activities.

Rainfall

Rainfall is an important slope instability triggering external parameter. In order to incorporate its effect in SSEP rating scheme mean annual rainfall has been considered as a means to assign ratings (Oberoi, 2004). It is obvious and reasonable to say that the areas where mean annual rainfall is more, slope instability problems are more. As per the standard SSEP table Annexure A depicts rating values awarded for rainfall.

Seismicity

The ground acceleration can be related to the intensity of the seismic activity. Hays (1980) developed a relationship between intensity of earthquake, based on Modified Mercalli intensity scale, and the ground acceleration. This provides indications of g – values; ground motion expressed in terms of gravitational accelerations appropriate to engineering calculations (Johnson and DeGraff, 1991). As per the standard SSEP table ratings are assigned and are presented in Annexure A.

Man-made Constructions

Manmade activities in hilly terrains which affect the slope stability conditions are the developmental activities such as; road or building construction and cultivation practices. All these activities results into increasing moisture in the soil or rock mass and in changing the slope form. Road or building construction involves cutting or blasting of slope material which is often carried out in an unplanned manner (Wang and Niu, 2009). As per the standard SSEP table Annexure A portrays rating values of man-made activities.

2.9 Selection of Methodology for the Present Study

By reviewing different literatures, it is possible to produce landslide hazard zonation map by using different approaches which depend on several circumstances including the availability

of data, nature of the topography, scale of investigation, etc. These techniques include: inventory landslide hazard mapping approach (Dai *et al.*, 2002; Van Westen *et al.*, 2006); heuristic methods (McClelland *et al.*, 1997); Statistical approaches (Aleotti and Chowdhury; 1999) which include bivariate statistical methods (VanWesten, 1994), Multivariate Statistical Approaches (Aleotti and Chowdhury, 1999) and Probabilistic Statistical Methods (Shortliffe and Buchanan, 1975; Heckerman, 1986); Deterministic landslide hazard zonation technique (Crosta and Agliardi, 2004) etc.

In the present study, Slope Stability Susceptibility Evaluation Parameter (SSEP) rating scheme proposed by Raghuvanshi *et al.* (2014) to estimate areas susceptible to landslides was applied. Landslide susceptibility maps have been constructed using the relationship between each landslide and causative factors. Different parts of the study area have been subjected to varying degree of landslide hazards. As a result, landslide hazard zonation mapping has been carried out in order to zone and delineate those areas suffering by high and very high degree of landslide hazard. This approach has been selected over others because it incorporates both intrinsic and external landslide triggering parameters in order to generate the hazard map of the study area. It does not only provide landslide hazard susceptibility at the time of investigation but it also anticipates hazards for adverse condition to which slopes may likely be subjected.

It is also considered to be rapid assessment technique which is intended to cover very large area in a short period of time. Further, SSEP is thought to be more reliable than other techniques which heavily depend on secondary data sources, whereas SSEP relies more on realistic field based primary data. Based on above mentioned reasons, SSEP is found to be more realistic, simple and was preferred over other techniques for the present study.

CHAPTER III

GEOLOGY AND STRUCTURES

3.1 Regional Geology

The basement Precambrian metamorphic rocks, Paleozoic – Mesozoic sediments associated with transgression regression of the sea and Cenozoic volcanic rock which is directly overlying the Precambrian metamorphic and Mesozoic sedimentary rocks, are the main rock units found in Ethiopia (Kazmin, 1973). Among these rock units the geology of the study area and its surrounding can be grouped in to the Cenozoic volcanic rocks.

According to Peccerillo *et al.*, (1997), the Ethiopian volcanics can be related to two main magmatic stages. The first is the Oligocene – Pliocene large fissure eruptions of basalts which build up thick flood lava sequence (known as Ashange and Aiba Basaltic Formations) associated with late ignimbrite sheet (Alaji Rhyolitic Formations).

This magmatic stage was closed by the formation of huge basaltic shield volcanoes (Tarmaber formation). However in the recent studies about the continental flood basalts of north-western part of Ethiopia, the whole formations were considered as a single unit which was flooded in less than 1 my around 30 My ago (Hofman *et al.*, 1997; Pik *et al.*, 1998).

The second stage of volcanic activity is related to Pliocene to Recent in age and is more closely related to the formation of rift valley and Afar. In this group the volcanic rocks are associated with basaltic cinder cone and lava flows that are aligned along extension faults parallel to the rift and intermediate rocks are very scarce.

Recent classification for continental flood basalt of North western part of Ethiopia was followed as Lower Formation, Upper Formation and the Shield Volcano. Both the Lower and Upper Formation of the continental flood basalt was emplaced 30 my ago within short period of time, less than 1My (Hofmann *et al.*, 1997).

The geologic setting of the central Ethiopian high lands is characterized by the voluminous tertiary volcanics capping the Mesozoic sediments which are exposed only in the deep incisions by the major rivers. Examples include; Abay Gorge, Jemma Gorge, and Muger

Gorge. The tertiary rocks are around 30Ma old. Nevertheless the volcanic outpouring took only around 2 million years (Hoffman *et al.*, 1998; Pik *et al.*, 1998, 1999).

The continental flood basalt is the result of impingement of the Afar mantle plume beneath the Ethiopian lithosphere. The longer time of dwelling in some of the temperate like climate along with the quick weathering tendency of the formations which are mostly basic in composition (basalts and few trachyte) quick development of soil and weathering products have led to potentially high slope instability conditions (Pik *et al.*, 1998, 1999).

3.1.1 Ashange Formation

According to Mohr and Zenittin (1988) Ashangie Formation has been defined by three characteristics: - it has experienced a marked dip into the flow sequence of up to 40^o, flow thickness average only about 5m, and individual flows are rarely traceable for more than a few kilometers along strike, the flow is locally cataclysed and faulted. The Ashangie Basalt is the most dominantly observed volcanic rock near to the present study area. It is exposed along Dessie – Mekelle route, north central plateaus and in most parts of the Afar rift marginal grabens. The Ashangie Basalts are characterized by strong weathering, different directional tilting, columnar jointing, intense fracturing and crushing. In many of its exposure it is dominated by inclined columnar jointed Aphanatic Basalts. The unit also contains intercalated layers of agglomerate and volcanoclastic sediments and vesicular basalt (GSE, 2011).

3.1.2 Aiba Basalts

According to Mohr and Zenittin (1988) Aiba Formation is typically composed of entirely of massive flood basaltic flows, with or without intervening agglomerate beds. They are found overlying Ashange Formation. The flow are between 15 to 50 m thick (in extreme cases pouncing to 100 m) and are generally composed of dense, dark, fine grained olivine basalt, commonly columnar. The flow extends sub horizontally for at least tens and possibly a hundred or more kilometers.

3.1.3 Alaje Formation

The other group of upper formation is Alaje Rhyolite. They overlay Aiba Basalts conformably and are characterized by silicic (trachyte /rhyolite) Ignimbrite. The Ignimbrite

succession maintains a similar thickness over kilometers or where preserved, even tens of kilometers lateral extent. Individual flows are up to tens of meters thick. It is the lowest volcanic unit found in the vicinity of the area.

3.1.4 Tarmaber Formation

According to Keffer *et al.*, (2004) the lava flows of shield volcanoes are thinner and less continuous than the underlying flood basalts. This unit is the latest of the flood basalts with tholeiitic composition which forms one of the prominent landmass shield volcanoes. It is more porphyritic containing abundant and often large phenocrysts of plagioclase and olivine. Like the flood volcanic, the shield volcanoes are bimodal and contain sequences of alternating basalts, rhyolite, and trachytic lava flows, tuffs and ignimbrites, particularly near their summits. The change in Formation of the volcanic units between the underlying basic and over lying tholeiitic basalts have been attributed to the tectonic setting and the decrease magma flux rather than pure compositional variation in the magma source.

3.2 Afar Rift and Major Rift Related Structures

Based on geology, structural trends and geographic positions, the Afar depression can be divided into three regions: Northern, East-central and Southern (Hayward & Ebinger, 1996; Samson Tesfaye *et al.*, 2003).

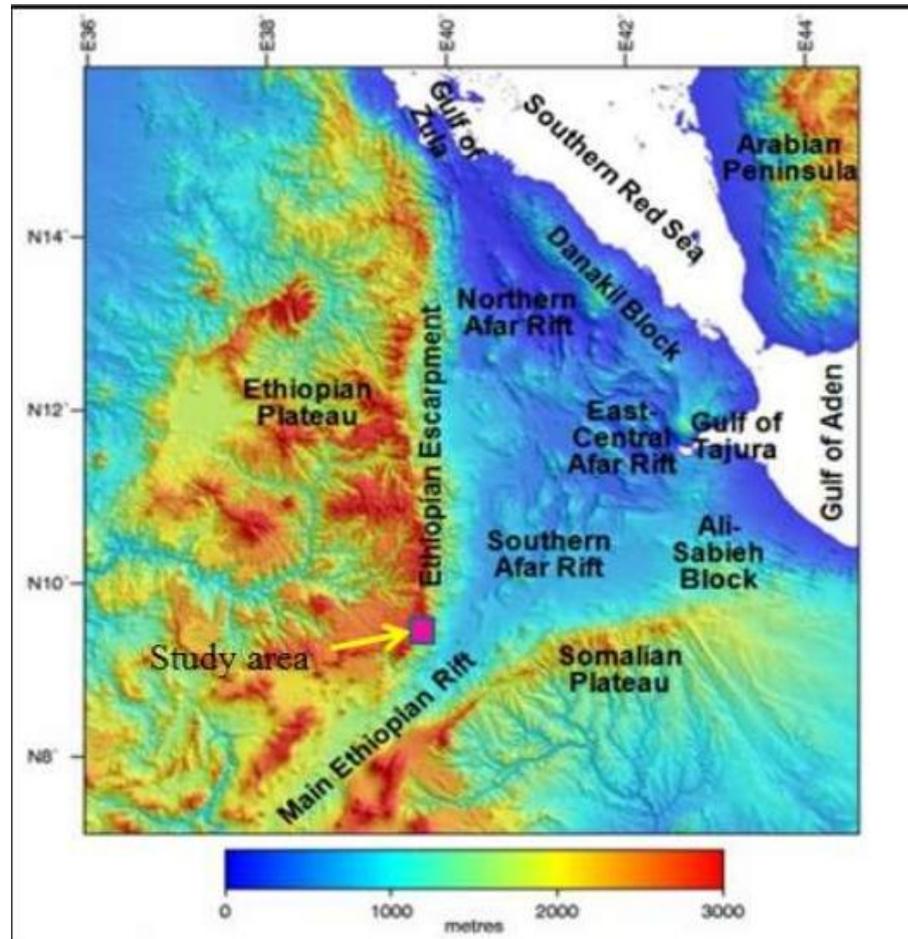
3.2.1 The Northern Afar Rift (NAR)

The northern Afar region (also known as the Danakil Depression) is a low lying area dropping in elevation from around 200 m in the north to 120 m below sea level in its center (Afar consortium, 2012). It is bound to the west by the Ethiopian plateau and to the east by the Danakil block. It is dominated by young axial volcanic ranges that are typically produced by basaltic fissure eruptions and shield volcanoes aligned in Northwest-Southeast belts, parallel to the regional tectonic of the Red Sea (Barbieri and Varet, 1977). The northern Afar depression also hosts Miocene to Holocene evaporites and fluvial sedimentary rocks (Samson Tesfaye, 2003).

3.2.2 The Central Afar Rift (CAR)

The central sector (plate 3.1) dominated by graben and horst structures and bounded to the west and east by axial volcanic ranges is occupied by Pliocene flood basalts and quaternary

sedimentary rocks. The flood basalts, which are inter-bedded with less common and more silicic layers and volcanic centers, are collectively termed the “Afar stratoid series” (Varet and Gasse, 1978).



(Source: <http://www.see.leeds.ac.uk/afar/websitepages/structurepages/structuregeol.ht>)

Plate 3.1 DEM of the Afar area showing geomorphological and structural divisions

Available age data indicate that the stratoid series was emplaced between 4.0 and 1.0 Ma (Barbieri, *et al.*, 1977).

Quaternary extension is distributed across the whole area with many faults in different orientations forming narrow and overlapping northwest-southeast trending grabens that are typical of the region (Hayward & Ebinger, 1996; Samson Tesfaye *et al.*, 2003) and its average crustal thickness is about 25km (Hayward & Ebinger, 1996). One best example is the Dobi Graben which is characterized by the high angle normal faults and sinistral strike-slip faults (Hayward & Ebinger, 1996). This area is an active zone and shallow earthquakes occurrences are common.

The Tendaho Graben is one of the largest active site in the central sector of the Afar depression (Samson Tesfaye, *et al*, 2003).

3.2.3 Southern Afar Rift (SAR)

The SAR bounded by the Somalian Escarpment in the south, the Ali-Sabieh Block in the east, the Tendaho–Gobaad discontinuity in the north and the Main Ethiopian Rift to the west (Fig 3.1). This zone is a transition zone between the central Afar and the Main Ethiopian Rift and it is structurally characterized by:

- (i) North to Northeast trending dominant structures in the West, and East-West trending in the East (Beyene & Abdelsalam, 2005)
- (ii) Northwest-trending transfer fault zones which can be traced to discontinuities in the western Ethiopian escarpment (Hayward & Ebinger, 1996).
- (iii) The kinematically distinct Gulf of Aden normal faulting pattern (trending due to East-Southeast) found in the Southern part (Samson Tesfaye et al, 2003)
- (iv) Escarpment with a length of about 250km and an average crustal thickness of about 26 km
- (iv) Unfaulted Pliocene-Recent (3.3-0Ma) fluvio-lacustrine sediments and basalts between the basins flanks and the escarpment that runs up to a distance of more than 50km (Varet, 1978).

In general, in this zone the three important structures, namely; the NW-SE trending structures (parallel to the general trend of the Red sea); NE - SW trending structures (parallel to the main Ethiopian rift) and the E-W trending (parallel to the Gulf of Aden) are joined. The western bounding rift margins, where the study area is situated, is characterized by this three important regional structures controlling the deep seated landslides along the rift margins, e.g. the Debresina landslide of September 2005.

Three important rift structures, two oceanic (Red Sea and Gulf of Aden) and one continental (East African Rift), come together to form very complex geological features.

3.3 Main Ethiopian Rift and Structures (MER)

The Ethiopian rift system is a part of the EARs, a complex tectonic feature with a system of down faulted, non-continuous but related troughs. The tectonic and volcanic processes of

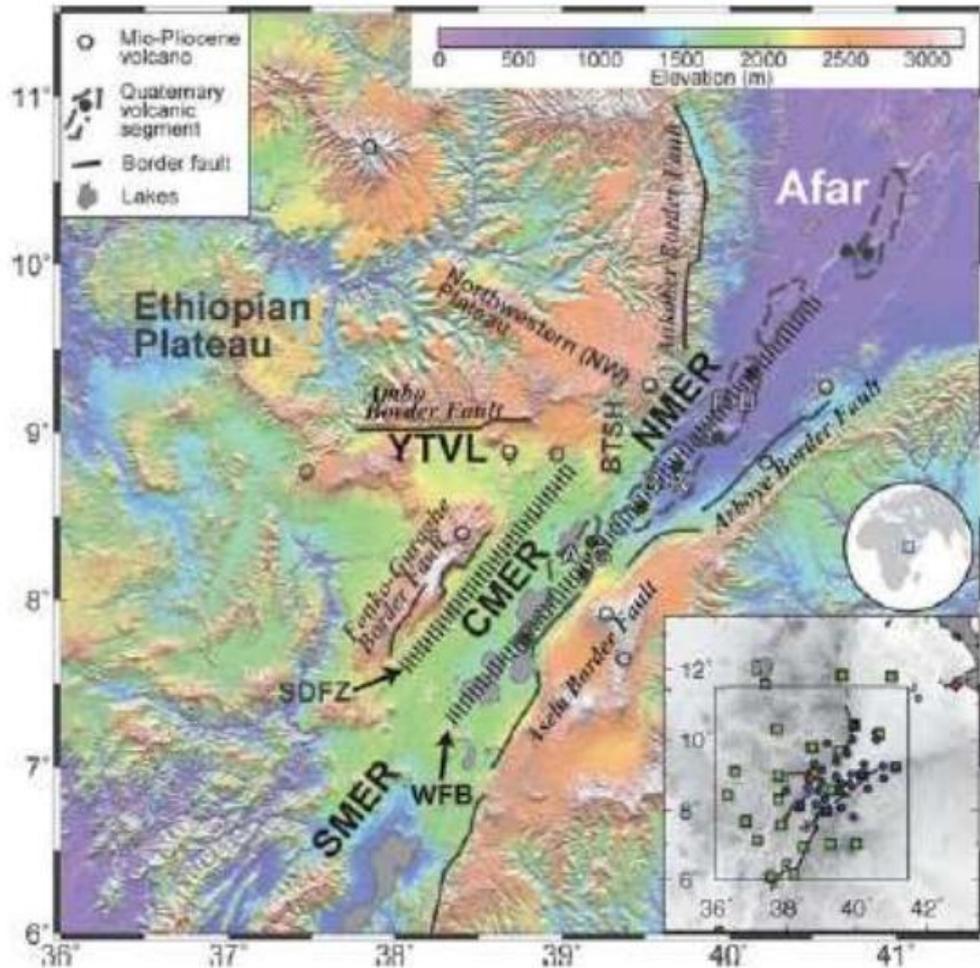
Ethiopian Rift systems are not uniformly continuous; rather they are characterized by distinct periods of increased and decreased activity (Doktorgrades *et al.*, 2009). This rift system is of special interest, as it forms the third arm of the Red Sea, Gulf of Aden rift-rift-rift triple junction where the Arabian, Nubian, and Somalian plates join in Afar, exposing the transitional stage of continental rifting worldwide (Doktorgrades *et al.*, 2009). Continental separation has occurred in the Red Sea and Gulf of Aden, while seafloor spreading has yet to begin in the MER.

The MER lies in a unique transitional zone between the continental rifting of East Africa and the seafloor spreading of Northern Afar and the Red Sea (Rooney *et al.*, 2007), and extends from central Ethiopia to Afar in a NNE-SSW direction, cutting the uplifted Ethiopian plateau into the northwestern and southeastern plateau. Throughout the Late Holocene and Quaternary, the MER has been seismically, tectonically and volcanically active, specially confined within a 10-20 km wide sub-axial zone known as the Wonji fault belt. This belt represents continuous volcano-tectonic activity from the Early Pleistocene to recent times maintaining a NNE-SSW structural orientation along the entire length of the MER (Williams *et al.*, 2004). A series of Quaternary volcanoes, mainly trachytes and pantelleritic rhyolites, occur along the Wonji fault belt, often located at offsets (Williams *et al.*, 2004). Some of these volcanoes collapsed into summit caldera, ejecting widespread pyroclastic deposit covering the rift floor along with fissural basalts and lacustrine sediments. The MER is divided into three sectors based on surface geology and geomorphology (Klemperer, 2008): the northern (NMER), central (CMER), and southern (SMER) sectors (plate3.2).

3.4 Local Geology

3.4.1 Quaternary Sediments

Quaternary sediments are unconsolidated sediments that have been deposited at the base of hill slope or in river bed floor by either rain-wash, sheet-wash, slow continuous downslope creep or variable combination of these processes. These sediments consist of the alluvial deposits and colluvium-eluvium deposits. The alluvial deposits dominantly lie at the eastern part of the catchment where there is relatively flat topography available and also following the river beds and river banks. Those alluvial deposits found at the flat flood plain vary from clayey sand to silty sand with gravels and cobbles while those found at the river bed and banks are dominated by coarser materials like; sands, gravels, and big boulders (plate 3.3).



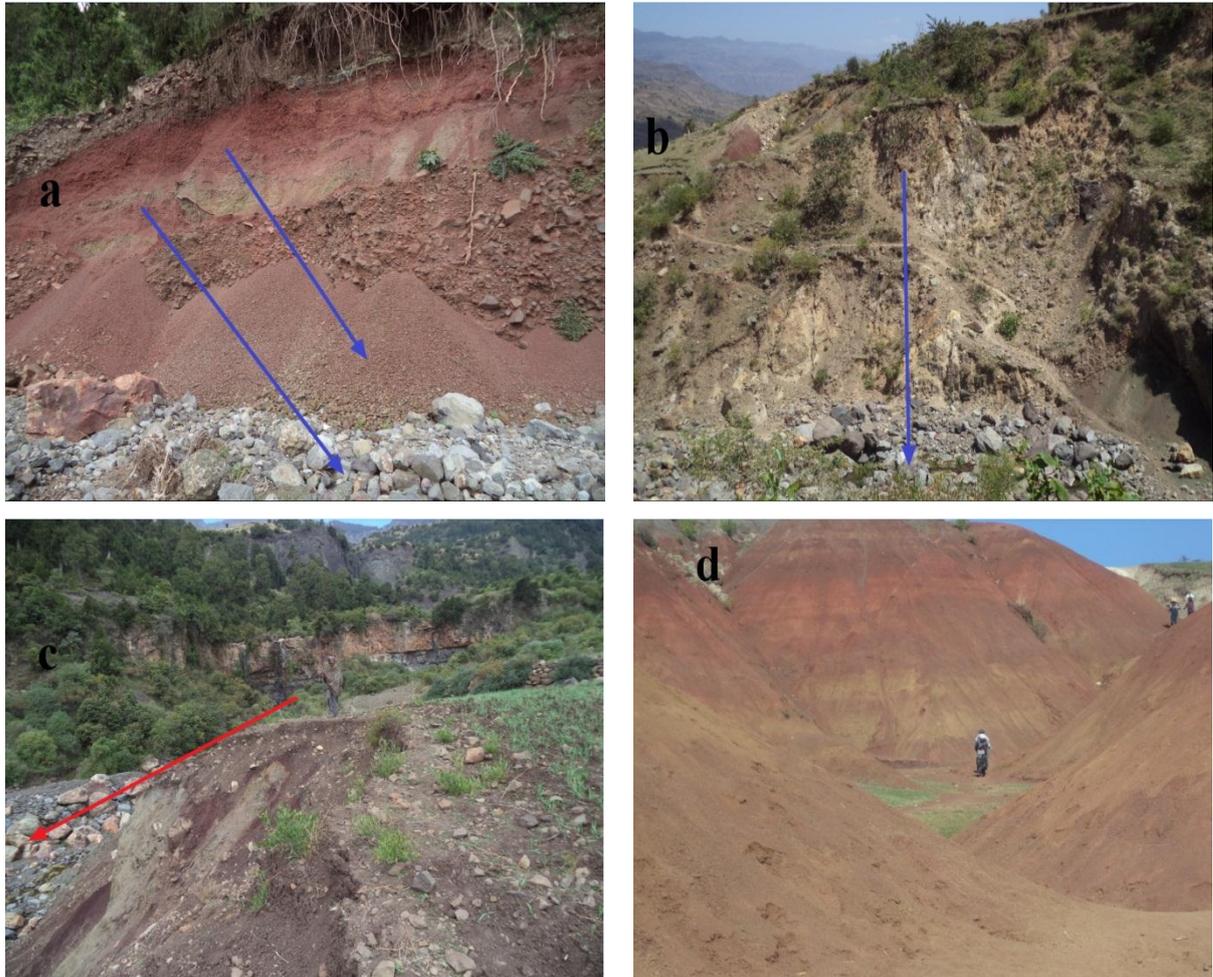
(Source: Kim et al., 2012)

Plate 3.2 Relief map of Main Ethiopian Rift (MER) and surrounding Ethiopian Plateau

This indicates that the streams that initiate their flowing from the sliding land are very rich in debris and are with erosive power damaging farmland and other infrastructures.

While the colluvium-eluvium is found at the foot of the stepped cliffs, ridges and flat hill tops. They are mixed and loose sediments deposited by old landslide, reworked breccia, and sheet floods consisting of fine to boulder sized soils. Most of the time, these are cultivable lands. Some of the seepages and/or springs that drain from the highlands disappear to this thick colluvium and reappear following the lower morphology breaks or the stream banks.

Colluvium can be composed of often a heterogeneous range of sediments ranging from silt to rock fragments of various sizes. They are loose accumulations of different materials broken down from rocks in the vicinity or have been transported and deposited as further movement becomes difficult.



[a] unconsolidated debris material [b] colluvium- dominated materials
[c] mixed colluvium-eluvium materials and [d] residual soil

Plate. 3.3 Different kinds of quaternary sediments

Typically colluvium accumulates gently sloping of fans either the base of or within gullies and hollows within hill slopes. These accumulations of colluvium can be several meters in thickness and often contain buried soils (paleosols), crude bedding, and cut fill sequences. Thick accumulations of colluvium often contain well-preserved and sometimes deeply buried archaeological deposits (Helley and Wesling, 1989).

3.4.2 Ignimbrite

It is highly weathered, fractured and jointed because of which some small blocks tear way and fall forming colluvium deposits. Its fresh color is white while it displays grey to dark weathered color. It is exposed in most parts of the study area such as; Indode, Dukakit, Nib Amba, Zeb Amba, etc. Most of the time ignimbrite is seen intercalated with another volcanic unit called Rhyolite.

An ignimbrite is the deposit of a pyroclastic density current or pyroclastic flow. It is a hot suspension of particles and gases flowing rapidly from a volcano driven by having a greater density than the surrounding atmosphere. They formed as the result of immense explosions of pyroclastic ash, lapilli and blocks flowing down the sides of volcanoes. Ignimbrites are made up of a very poorly sorted mixture of volcanic ash (or tuff when lithified) and pumice lapilli, commonly with scattered lithic fragments. The ash is composed of glass shards and crystal fragments. Ignimbrites may be loose and unconsolidated or lithified (solidified) rock called lapilli-tuff. Proximal to the volcanic source, ignimbrites commonly contain thick accumulations of lithic blocks, and distally, many show meter thick accumulations of rounded cobbles of pumice. Ignimbrites may be white, grey, pink, beige, brown or black depending on their composition and density. Many pale ignimbrites are dacitic or rhyolitic. Darker colored ignimbrites may be densely welded volcanic glass or, less commonly, mafic in composition (Klemperer, 2008).

Ignimbrite is primarily composed of a matrix of volcanic ash (tephra) which is composed of shards and fragments of volcanic glass, pumice fragments, and crystals. The crystal fragments are commonly blown apart by the explosive eruption. Most are phenocrysts that grew in the magma, but some may be exotic crystals such as xenocrysts, derived from other magmas, igneous rocks, or from country rock (<http://en.wikipedia.org/wiki/Ignimbrite> accessed: 25/02/2014).

The mineralogy of an ignimbrite is controlled primarily by the chemistry of the source magma. The typical range of phenocrysts in ignimbrites are biotite, quartz, sanidine or other alkali feldspar, occasionally hornblende, rarely pyroxene and in the case of phonolite tuffs, the feldspathoid minerals such as nepheline and leucite.

Commonly in most felsic ignimbrites the quartz polymorphs cristobalite and tridymite are usually found within the welded tuffs and breccias. In the majority of cases, it appears that these high-temperature polymorphs of quartz occurred post-eruption as part of an autogenic post-eruptive alteration in some metastable form. Thus although tridymite and cristobalite are common minerals in ignimbrites, they may not be primary magmatic minerals.

Most ignimbrites are silicic, with generally over 65% SiO₂. The chemistry of the ignimbrites, like all felsic rocks, and the resultant mineralogy of phenocryst populations within them, is related mostly to the varying contents of sodium, potassium, calcium, the lesser amounts of

iron and magnesium. Some rare ignimbrites are andesitic, and may even be formed from volatile saturated basalt, where the ignimbrite would have the geochemistry of normal basalt.



Plate 3.4 Ignimbrite

Welding is a common form of ignimbrite alteration. There are two types of welding, primary and secondary. If the density current is sufficiently hot the particles will agglutinate and weld at the surface of sedimentation to form a viscous fluid, this is primary welding. If during transport and deposition the temperature is low, then the particles will not agglutinate and weld, although welding may occur later if compaction or other factors reduce the minimum welding temperature to below the temperature of the glassy particles, this is secondary

welding. This secondary welding is most common and suggests that the temperature of most pyroclastic density currents is below the softening point of the particles (Chapin *et al.*, 1979).

Ignimbrite originates from explosive eruptions caused by vigorous exsolution of magmatic gases. The escaping gas accelerates the magma up the conduit, resulting in fragmentation to produce pumice and ash, which dispersed in gas will flow downslope or spread where the dispersal is denser than the atmosphere, as pyroclastic density current, sometimes known as a pyroclastic flow.

Ignimbrites form sheets that can cover as much as thousands of square kilometers. Some examples create thick, valley-filling deposits, while others form a landscape-mantling veneer that locally thickens in valleys and other palaeotopographic depressions.

Many ignimbrites are loose, unconsolidated deposits, but some exhibit welding, giving the ignimbrite the texture of a solid rock mass, hence the terms commonly used to describe these examples: welded tuff and welded ash flow.

Often, but not always, a caldera will form as a result of a large ignimbrite eruption because the magma chamber underneath will drain and thus can no longer support the weight of the rock above. Ignimbrite deposits can be voluminous - examples with up to hundreds or even thousands of cubic kilometers are known from individual eruptions in the geological past.

3.4.3 Rhyolite

Its fresh color is white; weathered color is reddish to brown and is highly weathered and fractured. It has been made so weak that it can be scratched and broken down easily. It is found intercalated with ignimbrite rock unit. Some of the blocks are removed from the top and collected at the foot as colluvium material. It has felsic (silica-rich) composition and aphanitic texture. The mineral assemblage is quartz, alkali feldspar and plagioclase. It also contains some biotite and hornblende as accessory minerals. Rhyolite can be considered as the extrusive equivalent to the plutonic granite rock, and consequently, outcrops of rhyolite may bear a resemblance to granite. They also occur as breccia or in volcanic plugs and dikes. Some rhyolite is highly vesicular pumice. Many eruptions of rhyolite are highly explosive and the deposits may consist of fallout tephra/tuff or of ignimbrites.

3.4.4 Agglomeratic Basalt

It is exposed at a locality near Armania at Debre Sina-Armania road. It is highly weathered, fractured and jointed. Because of intense weathering and fractures, it is broken down into smaller rock fragments.



Plate.3.5 Cliff forming rhyolite

Its fresh color is grayish whereas it also portrays red to brown color following weathering effect. Agglomeratic basalt is characterized by coarse texture and contains more than 75% bombs and some blocks. Agglomerates are typically found near volcanic vents and within volcanic conduits, where they may be associated with pyroclastic or intrusive volcanic breccia. They are typically poorly sorted, may contain a fine ash or tuff matrix and vary from matrix to clast support. They may be monolithologic or heterolithic, and may contain some blocks of various igneous rocks. Agglomerates are coarser and less frequently well-bedded. Agglomerates can be non-welded or welded, such as coarse basaltic 'spatter'. They typically form proximally during Strombolian eruptions, and are common at strongly peralkaline volcanoes.

Crystalline masses of a different kind occur in some numbers in certain agglomerates. They consist of volcanic minerals very much the same as those formed in the lava, but exhibiting certain peculiarities which indicate that they have formed slowly under pressure at

considerable depths. They bear a resemblance to plutonic igneous rocks, but are more correctly to be regarded as agglomerations of crystals formed within the liquid lava as it slowly rose towards the surface, and at a subsequent period cast out by violent steam explosions. Some of the common minerals contained in agglomerate basalt include: olivine, anorthite, hornblende, augite, biotite and leucite (<http://en.wikipedia.org/wiki/Agglomerate> accessed: 13/03/2014).



Plate 3.6 Agglomeratic basalt at Beha

3.4.5 Aphanitic Basalt

It is exposed at a locality known as Beha near Armania and is characterized by high degree of weathering with closely spaced joints. It is characterized by the presence of well-developed columnar joints which makes it susceptible to detachment and falling apart in to blocks and boulders.

It displays dark (or black) and grayish color as fresh and weathered respectively. They possess fine texture which results from rapid cooling in volcanic or hypabyssal (shallow subsurface) environments. The texture of these rocks is not quite the same as that of volcanic glass (e.g. obsidian), with volcanic glass being even finer grained (or more accurately, non-crystalline) than aphanitic rocks, and having a glass-like appearance.

Mineralogically, they consist essentially of very fine-grained minerals, such as plagioclase feldspar, with hornblende or augite, and may contain also biotite, quartz, and orthoclase (<http://en.wikipedia.org/wiki/Aphanite> accessed: 14/02/2014).

3.5 Geological Structures

Because of the fact that the study area is tectonically active, it experiences different geological structures which manifest themselves as fractures, joints, fault, foliation, dykes and other weakness zones which favor instability of slopes. Therefore, it is important to know their orientation in relation to slope angle, direction, and strength along such potential weak planes (Sidle & Ochiai, 2006).

According to Varnes (1984) the degree of fracturing and shearing plays a significant role in determining slope stability.

Binaghi *et al.*, (1998) observed that the drainage lines were located along the direction of principal fault lines and along the direction of jointing. The streams in the study area are aligned in a straight line deviating from the general stream direction following the direction of geological structures.



Plate 3.7 Aphanitic basalt near Armania

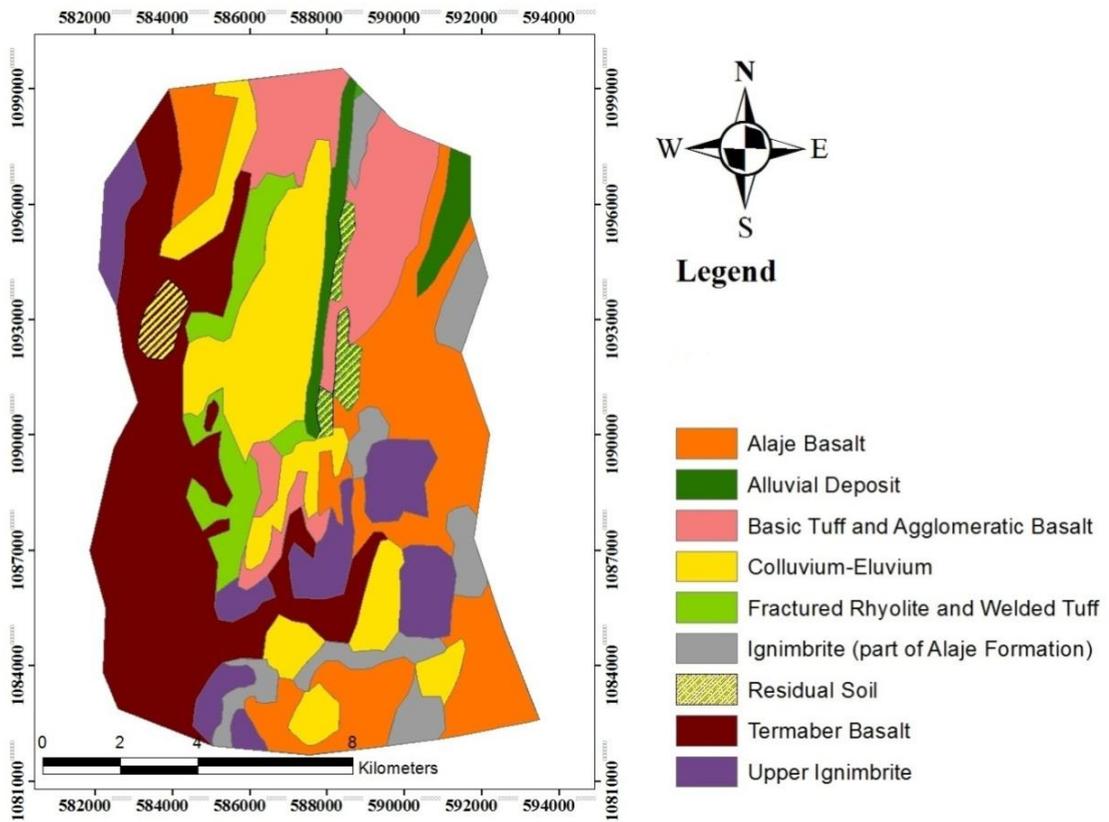
3.5.1 Joints

Joints have been observed in almost all lithologies of the study area. In relative sense ignimbrite, aphanitic basalt, and agglomerate are highly jointed and fractured. The average aperture (opening) and spacing of joints range from 10-30 cm and 50-100 cm, respectively. Most of the joints observed in the study area display rough surface characteristics. Some of the joints are filled with secondary materials like silica and small rock fragments.

3.5.2 Dykes

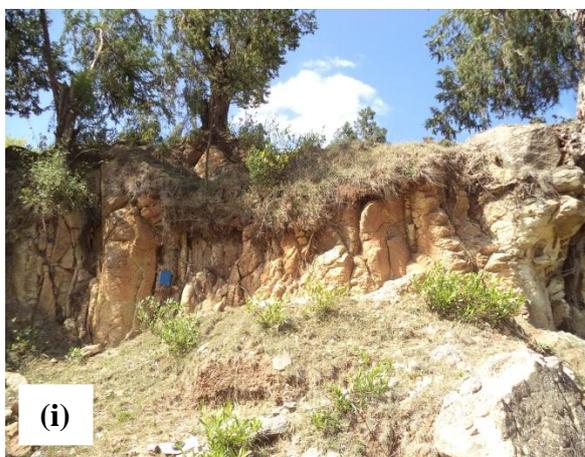
Dykes are one of the most commonly found geological structures in the study area. Most of the dykes observed are aphanitic basalt intruding ignimbrite and quaternary sediments. They

have an average width of 2-3 m. These dykes create favorable condition for the easy passage of water as they are the manifestations of weakness zone.



(Source: adapted from Asmelash Abay and Barbieri, 2012)

Plate 3.8 Geological map of the study area

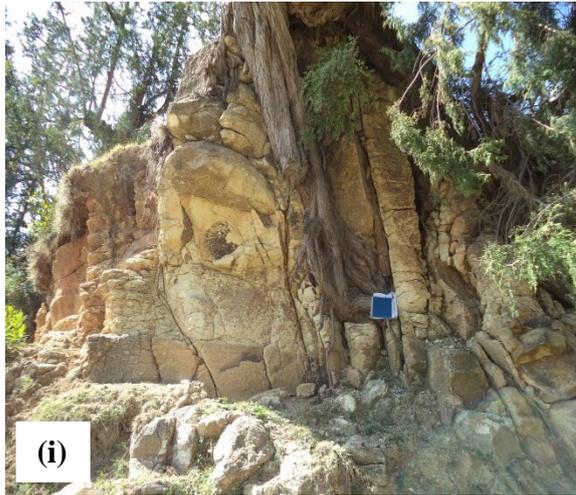


(i) Ignimbrite Unit



(ii) Cliff forming Rhyolite

Plate 3.9 (a) vertical joints observed in the study area



(i)



(ii)

(i) Ignimbrite Unit

(ii) Agglomeratic Basalt

Plate 3.9 (b) vertical joints observed in the study area



(i)



(ii)

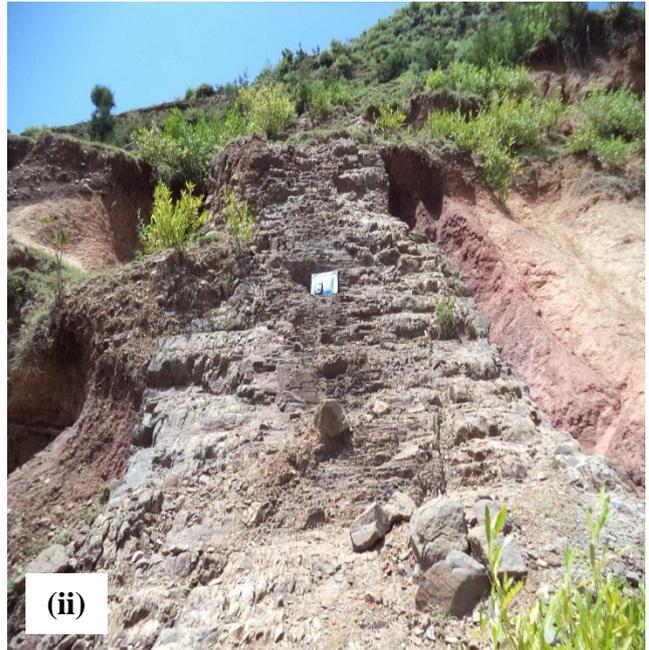
(i) Colluvial-eluvial material

(ii) Quaternary Sediments

Plate 3.10 (a) Dykes in ignimbrite and quaternary sediments



(i) Highly weathered Ignimrite



(ii) Quaternary Sediments

Plate 3.10(b) Dykes in ignimbrite and quaternary sediments

CHAPTER IV

LANDSLIDE INVENTORIES AND RELATED IMPACTS

4.1 Landslide Inventories

Previous research conducted by Asmelash Abay and Barbieri (2012) indicate that in the present study area more than 160 landslides were identified, out of these 90 are debris/earth slide, 39 are rock slide, 18 are earth slide, 12 are complex/composite slide and 1 is debris flow. However, considering the landslide areal coverage, 58.2% is covered by complex/composite slide; 19.3% by debris/earth slide; 13.3% by debris flow; 7.2% by rock slide and 2% by earth slide. Complex and composite types, debris and earth slides, rock slide, debris flow and some rock falls are common types of landslides in the area. For example, the massive landslide of September 2005 is a complex and composite types consisting of various types of movements in sequence and in different parts of the displaced mass and with mixed rocks, earth and debris materials. These slope failures were related to geological, topographical, and climatic conditions. Thus, they can often facilitate the prediction of locations and conditions of future landslides. For this reason, it is important to determine the location and area of the landslide accurately when preparing the landslide susceptibility maps.

Interview made to local people living around the study area, and Woreda administrators reveal that there were several landslides in localities such as; Yizaba, Shotel Amba, Nib Amba, Shola Meda, Indode, Armania, Dukakit, etc. (Table.4.1).

4.2 Impacts of Landslides in the Present Study Area

Landslides have caused great disasters in the study area including the destruction of houses, agricultural lands, trees and displacement of local people as observed in the field and evidenced by interviewed people. Some of the trees which are considered to be strong enough to stand erect otherwise were destroyed by landslide hazards (plate 4.1 h).

In the study area significant amount of cultivable lands are being destroyed frequently and the number of landless farmers is increasing from time to time. For this reason several farmers are moving into sloppy areas which are potentially endangered by landslide hazards or are migrating to nearby towns. Besides, the local villages and towns in the study area are

expanding into landslide-prone areas without any prior landslide hazard assessment and risk analysis. Moreover, landslides are posing serious challenges to infrastructure. The Addis Ababa-Desse-Mekelle main asphalted road crossing the study area has been damaged many times due to the first time failures and/or reactivated old landslides in the areas between Debresina-Armanya towns. Even during the fieldwork of this research, a new crack has been observed at the places between Sar-Amba and Armaniya just for a length of 500m. On the 14th of August 2010, two houses were partially damaged by the landslide which is found at about 150 m downstream of this cracked road indicating that it is still active. Similarly, some cracks were observed in the foundation of two of the high tension electric poles that pass near the Armaniya area.

Table 4.1 Historical landslide prone localities of the study area

S.N	Locality name	Time of occurrence	Damage
1	Yizaba, Gishrit locality	1995	1575m ² wood land was affected
2	Yizaba, Aynemariam locality	1995,1998 & 1999	Some residential units cracked and 3ha of bush land damaged
3	Shotel-Amba	1953 & 1998	Residential units, farmland and grazing areas were affected by both periods
4	Weibila	1995 & 1997	18 residential units and 30 hectare of farm land and grazing land was affected by the 1995 landslides
5	Sina/Aregai	October, 1971	35-40 hectare of forest land was destroyed
6	Armania	1953, 1979 & 1997	The asphalt road has been affected in all the three landslide events. Still active and a tensional cracks are observed at the roadside
7	Nib-Amba	1953, 1997 & 2000	>100ha of farm land, grazing area destroyed
8	Sholla-Meda	July, 2000	20ha of farm land, grazing area and settlement
9	Lay Indode	September, 2000	It destroyed 8 residential unit & 30ha of farm land and grazing land. It is still active and has been reactivated event rainy season
10	Tach Indode	1999 & September, 2000	It destroyed an estimated of 40ha of grazing land and farm land. It is still active and has been reactivated event rainy season.
11	Yizaba, Shotel Amba, Armania,Ainemariam	September 2005	Over 900ha arable lands destroyed, more than 4049 peoples displaced, more than 1200 dwelling local houses destructed & over 75% crop harvesting failure specifically in the localities named Izaba and Shotel Amba

(Source: Gebresilassie, 2007)

In Indode area at a particular locality of Nebre Gore, landslide destroyed agricultural land of about three hectares. The owner of the land Ato Alemu Assefa stated that it happened during the rainy season in 20-25th of July, 2010. Since then, he added, his land has been continuously diminishing and also some of the blocks falling down from hill slopes also covered the cultivable land as well as endangered the life of people (Plate. 4.1 e).

As outlined above, landslide and related problems and risks are still continuing with an increasing trend to damage life and properties, and devastate infrastructure and the environment at various localities of the rift margin and highland of Ethiopia including the study area.

4.3 Landslide Hazard Mitigation Strategies in the Study Area

In the study area no mitigation method has been applied except small gabions and retaining walls constructed at the section of Debre Sina-Armania road. The use of gabions can be considered for slope protection. They not only provide protection to slopes against sliding but also they are useful to prevent erosion of river banks.

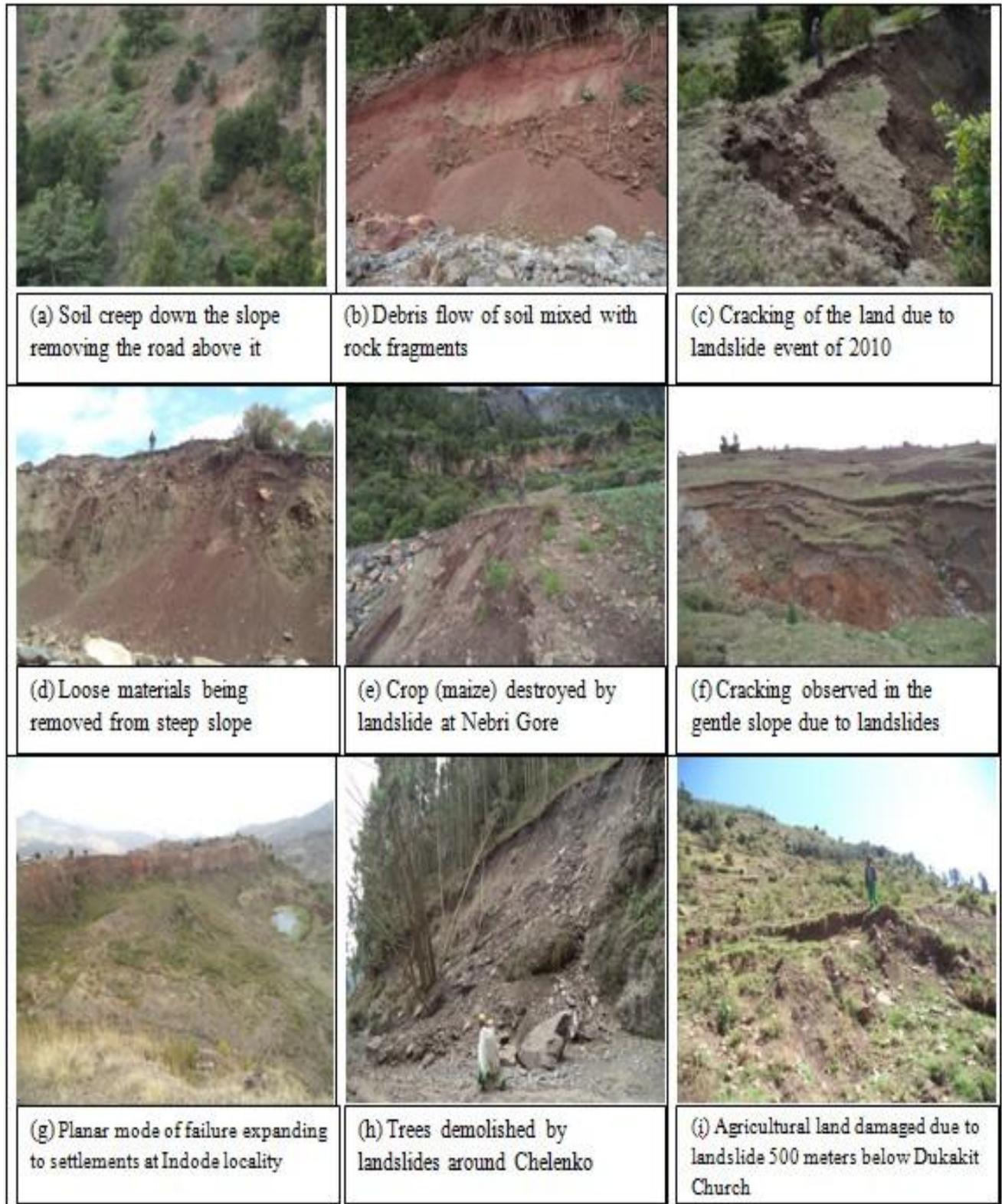


Plate 4.1 Some of the landslides and related damages in the study area

For all types of retaining walls, adequate drainage through the structure is essential because very high ground-water pressure can build up behind any retaining wall, leading to its failure.

Drainage can be provided simply with a coarse backfill and foundation material. Gabions and retaining walls are two different engineering structures used for slope stabilization but in the present study area they have been built side by side (Plate 4.2). Vegetation cover could have been the better option as it stabilizes the slope as well as ensures long term green appearance of the area. However, because of the lack of awareness, people of the locality are facing serious damages of landslide hazards without adopting any preventive mechanism.



Gabions (left) and the retaining walls (right)

Plate 4.2 Preventive mechanisms of landslides in the study area:

CHAPTER V

RESULTS AND DISCUSSIONS

5.0 Preamble

In the present study, Slope Stability Susceptibility Evaluation Parameter (SSEP) rating scheme proposed by Raghuvanshi *et al.* (2014) to estimate areas susceptible to landslides was applied. Landslide susceptibility maps have been constructed using the relationship between each landslide and causative factors. Different parts of the study area have been subjected to varying degree of landslide hazards. As a result, landslide hazard zonation mapping has been carried out in order to zone and delineate those areas suffering by high and very high degree of landslide hazard.

The present chapter presents the results on various evaluated intrinsic and causative factors, landslide hazard zonation (LHZ) and validation of LHZ map. Systematic discussion on results is also made.

5.1 Preparation of Facet Map

For convenience and ease assessment of landslide hazard, the study area has been divided into different slope facets which were delineated by major or minor hill ridges, primary and secondary streams, and other topographic undulations.

According to Anbalagan (1992), slope facets are characterized by more or less uniform slope inclination and slope direction. These slope facets were prepared from topographic map of scale 1:50,000 and verified in the field. Slope facet was used as base map to award rating values for landslide hazard triggering parameters.

Facet is a polygonal area of mountainous terrain which has more or less similar characters of slope, showing consistent slope direction and inclination. The slope facets are generally delimited by ridges breaks in slope, streams, spurs, gullies and rivers etc.

The facet maps form the basis for the preparation of thematic maps in general and SSEP mapping in particular and individual facet is the smallest mappable unit. In all 60 facets have been delineated in the study area on the basis of visual interpretation of topographic maps (Plate 5.1).

The facets of the study area are believed to have more or less similar characters of slope, showing consistent slope direction and inclination (plate 5.2). The facet map forms the basis for the preparation of thematic maps in general and LHZ mapping in particular.

5.2 Landslide Hazard Triggering Parameters

For landslide hazard zonation numerical ratings have been assigned to each of the intrinsic and external triggering parameters on the basis of their contribution towards instability of slope, based on standard SSEP rating table.

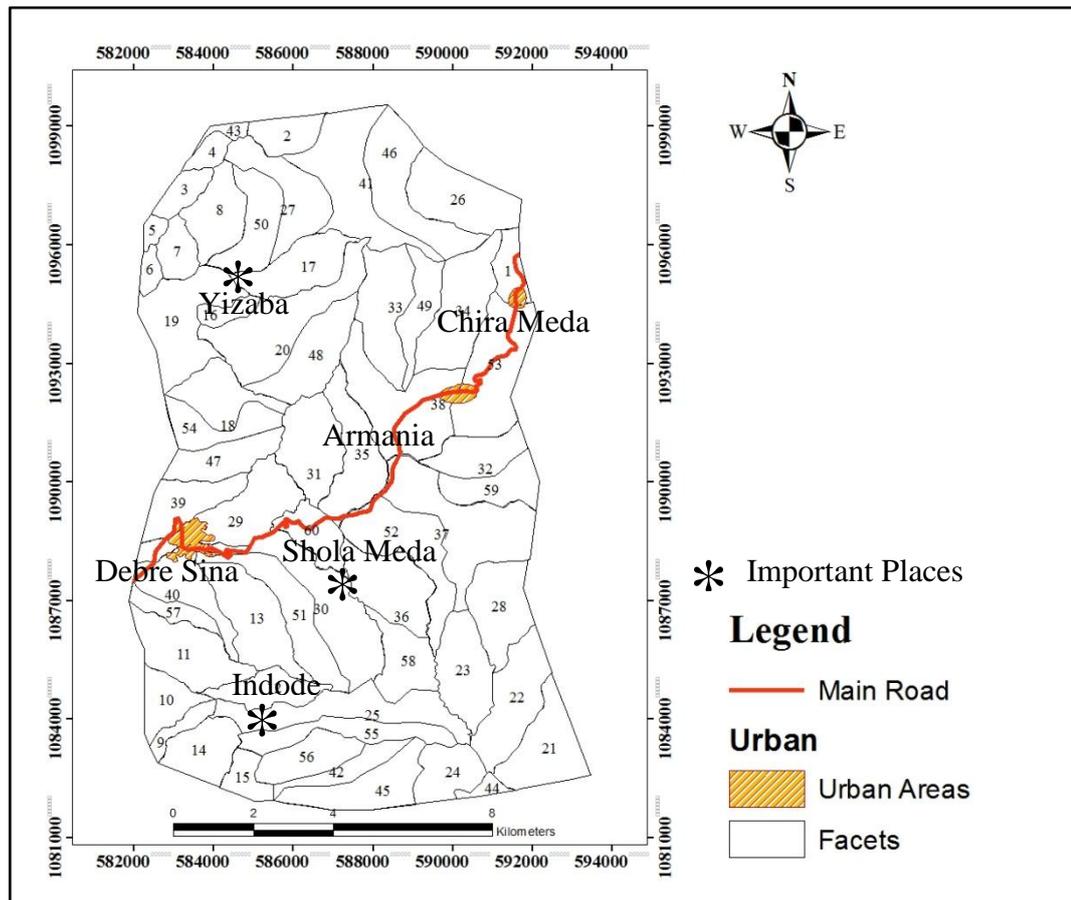


Plate 5.1 slope facet map of the study area

The parameters responsible for instability of slopes have been assigned with numerical ratings which are based on logical judgments acquired from experience of studies of intrinsic and external triggering factors and their relative impact on instability of slopes. The distribution of maximum ratings assigned to different intrinsic and external triggering factors is based on their relative order of importance in contributing instability to the slope. Plate 5.3 portrays the general methodology adopted in Slope Stability Evaluation Parameter rating scheme.

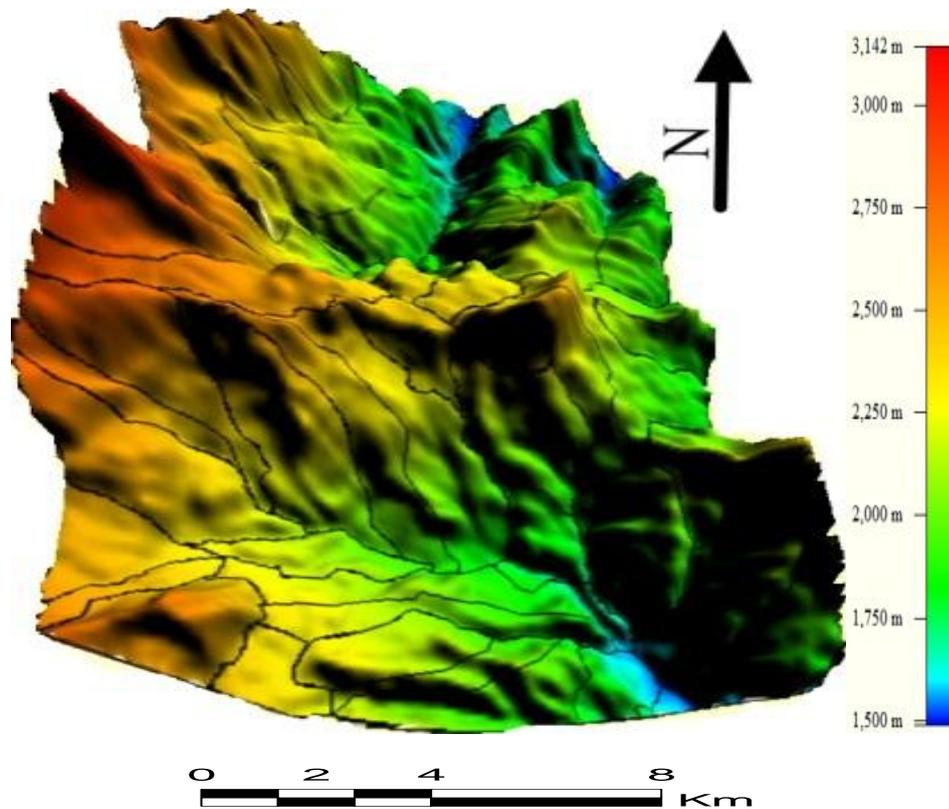


Plate 5.2 Three dimensional views of the slope facets of the study area

5.2.1 Intrinsic Parameters

Intrinsic parameters are considered in hazard mapping because they play a great role in the stability conditions of the slope. These intrinsic parameters are relative relief, slope morphometry, slope material, structural discontinuities, land use and land cover and groundwater (Anbalagan, 1992; Wang and Niu, 2009).

Depending upon the given conditions for each of these intrinsic parameters they may have an influence over the stability condition of the slope.

5.2.1.1 Relative Relief

Relative relief is one of the important causative factors which may cause slope instability. It affects the instability condition by increasing the gravitational energy which pulls the slope material down the slope. The relative relief map represents the local relief of maximum height between the ridge top and the valley floor within an individual facet (Anbalagan, 1992). Relative relief map of the study area has been prepared by taking the elevation difference between hill top and valley bottom within individual slope facet which was later

processed by ArcGIS-10 software. More the value of relative relief higher will be its role in slope instability.

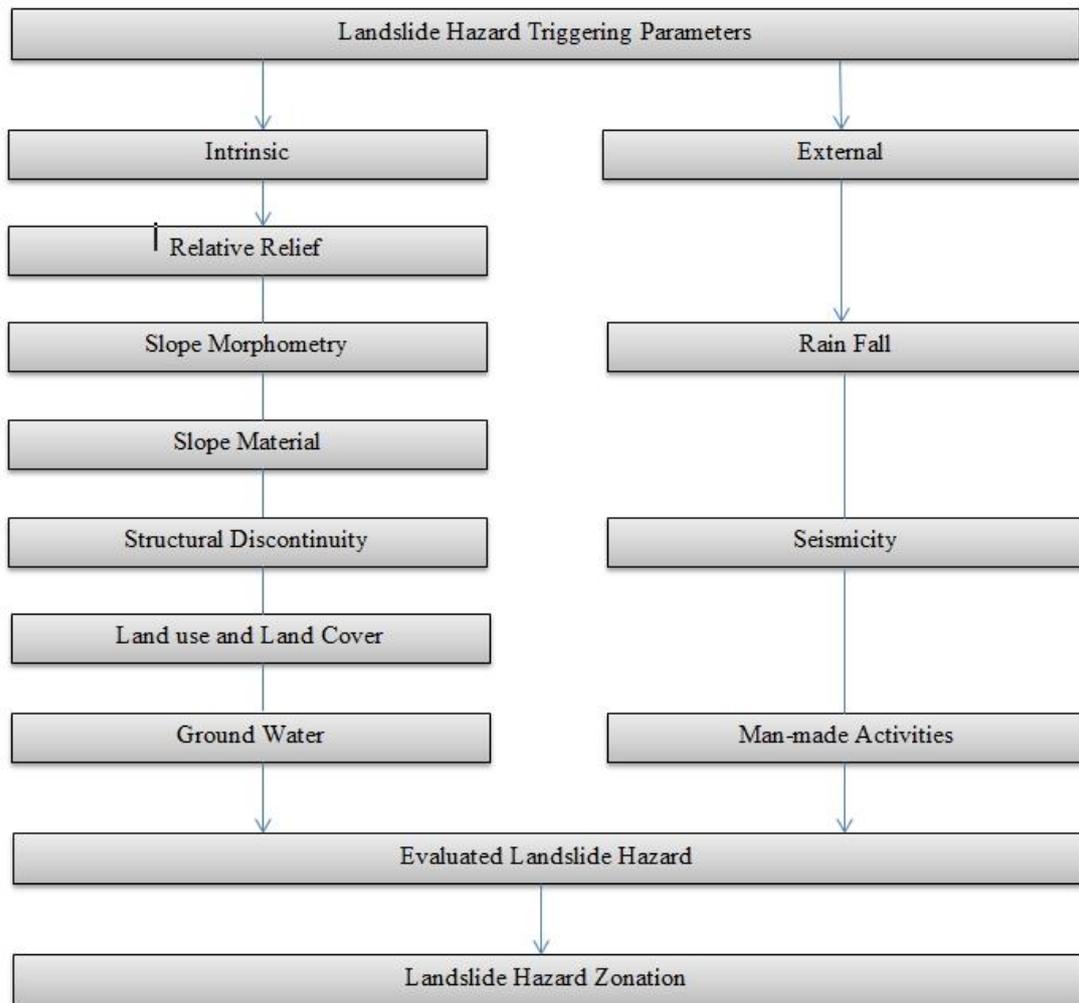


Plate 5.3 General methodology of SSEP

In the study area 57% of the facets fall in very high relative relief whereas 22% fall in high relief. The remaining facets (21%) fall in medium and moderate relative relief (plate 5.4). This implies that more than half of the study area possesses very high relative relief which renders it susceptible to landslide.

5.2.1.2 Slope Morphometry

Slope morphometry defines the inclination of the slope. More steeper the slope is, more it will be prone for instability. Slope morphometry map of the study area has been prepared by calculating the slope angles from topographic map. The ratio of height difference between two points in a given facet to horizontal distance gives decimal value of the slope. By taking

the inverse tangent of this value slopes in degrees have been manipulated. These values were checked against the slope estimations values proposed by Anbalagan (1992) as follows:

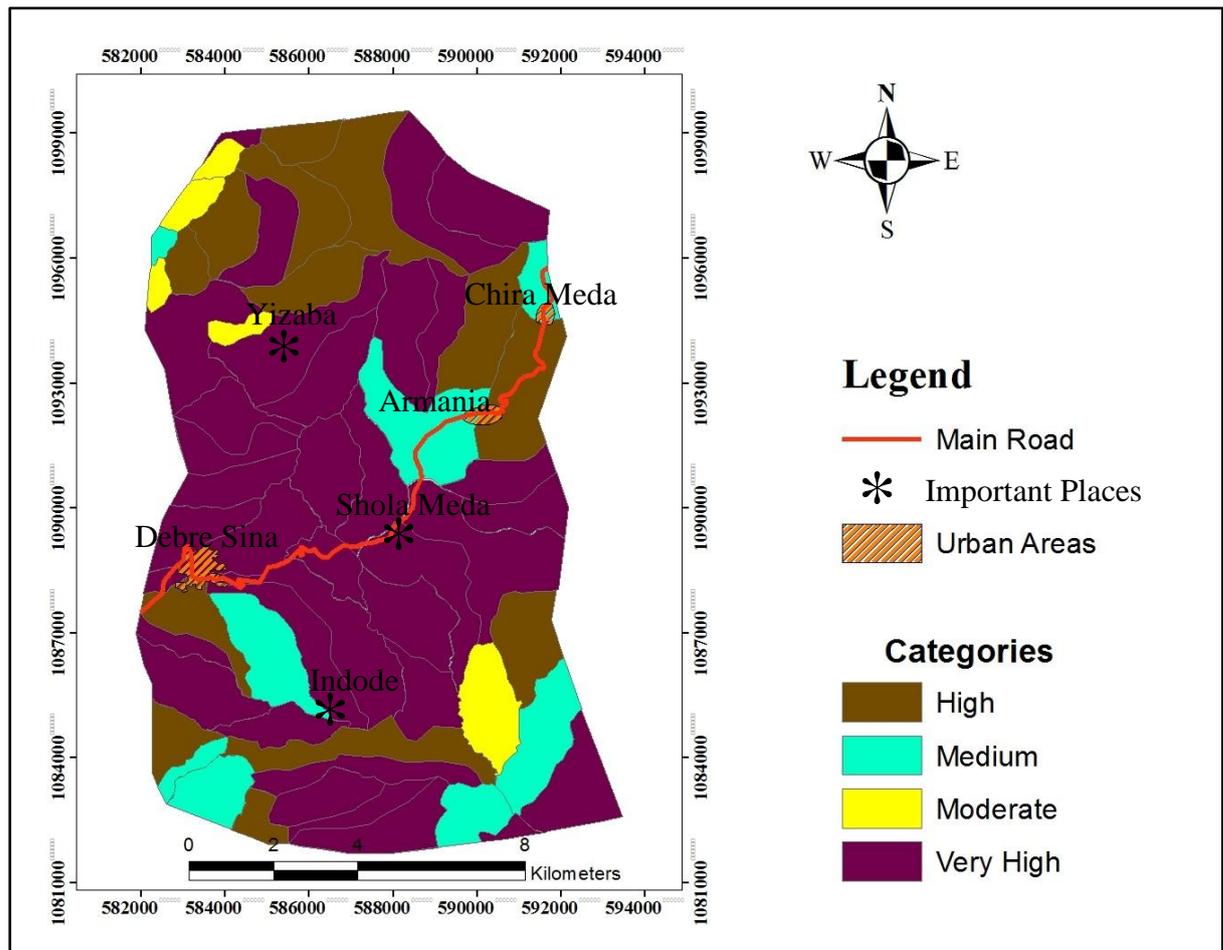


Plate 5.4 Relative relief map

These slopes fall in to different slope classes of Anbalagan (1992) as escarpment/cliff ($> 45^\circ$), steep slope ($36^\circ-45^\circ$), moderately steep slope ($26^\circ-35^\circ$), gentle slope ($16^\circ-25^\circ$) and very gentle slope ($< 15^\circ$). Later, slope morphometry map of the study area has been prepared by using ArcGIS-10 software. Accordingly, 42% of the facets experience moderately steep slope ($26^\circ-35^\circ$) while 33% fall under gentle slopes. The remaining facets possess steep slopes, escarpment and very gentle slope which account for about 10%, 8% and 7%, respectively (plate 5.5). Generally most of the facets have moderately steep slope ($26^\circ-35^\circ$).

5.2.1.3 Slope Material

Distinguishing the kind of slope materials in terms of engineering properties (physical properties) has a paramount role in landslide hazard zonation. According to Hoek (1997)

slopes may be composed of rock mass or soils or both. The criteria for assigning ratings to sub-classes of rock type are based on intact rock strength and degree of weathering. The errodability of rocks is highly influenced by the strength of the rock. Rocks which possess high strength are relatively more resistant to erosion.

Tab. 5.1 Estimation of slope angle by counting contours over 10 mm length

Estimation of Slope angle (Anbalagan, 1992)	
Number of contour lines over one cm length (1 : 50,000)	Slope angle
>25	>45°
19-25	36°-45°
13-18	26°-35°
8-12	16°-25°
<7	<15°

The rock sub classes in SSEP rating system are adopted from classification of rocks based on field estimates of strength by observation which is proposed by (Hoek, 1997). Thus, slope material is classified as very weak rock (1-5 MPa), weak rock (5-25 MPa), medium strong rock (25-50 MPa), strong rock (50-100 MPa), very strong rock (100-250 MPa) and extremely strong rock (>250 MPa).

Although rocks are strong by nature, they are highly affected and weakened by weathering. If the degree of weathering increases, rocks will become more and weaker losing their natural strength. Fresh rocks display higher strength as compared to weathered rocks of the same composition. Irfan and Dearman (1978) emphasized that the degree of weathering may affect the relative strength of the rocks therefore it has to be considered while assigning ratings to the rock type. The degree of weathering in SSEP rating system has been considered as; fresh, slightly weathered, moderately weathered, highly weathered, and extremely weathered. Extremely weathered rocks will be gradually changed into soil. For the case when slopes are covered by soils the rating criteria in SSEP rating system is based on the genetic class and depth of the soil cover. The residual soils are more consolidated and possess better shearing strength than the alluvial or recent deposited soils (Anbalagan, 1992).

Thus, the various soil types considered and their relative ratings are presented in Annexure A. Depth of soil cover is also considered while assigning ratings to various soil types.

Slope material map of the study area has been prepared from field observation using 1:50,000 scale topographic map as base map (plate 5.6).

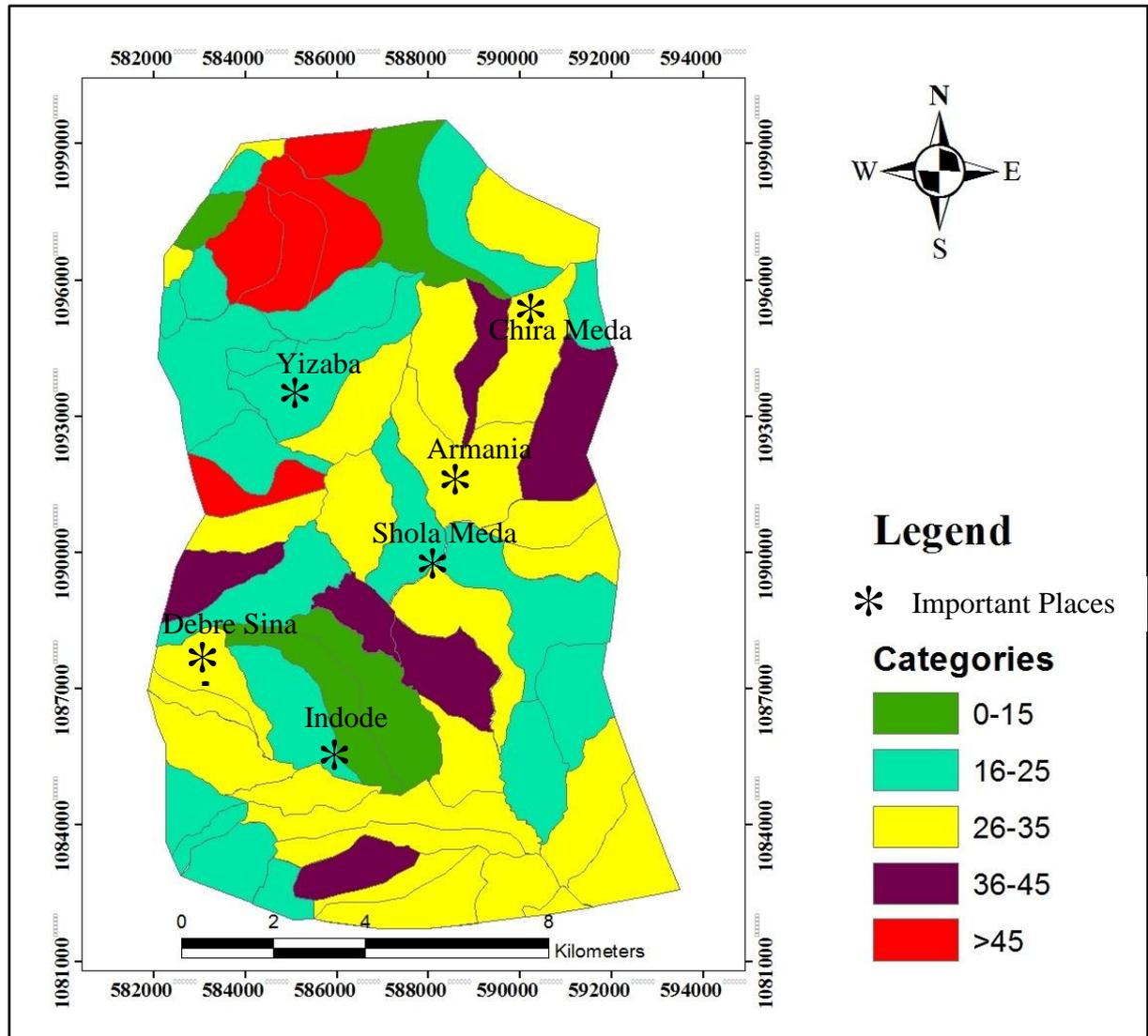


Plate 5.5 Slope morphometry map

Slope material of the study area is characterized by highly weathered and disintegrated rock mass that made it difficult to distinguish some rocks from soil during field visit. Ignimbrite, Alaje Basalt and fractured rhyolite are some of the lithologies on which intense weathering was observed. Generally, 38% of the study area is covered by medium strength rocks while colluvium materials cover about 27% of it. Highly weathered materials and weak rocks each comprise 22% and 13%, respectively.

5.2.1.4 Structural Discontinuities

Geological structures have great contribution in slope instability. As a result, they are considered as one of the intrinsic triggering parameters of landslide hazard. Because of the fact that discontinuities have great role in slope instability initiation, a maximum rating value

of 2.5 has been assigned in SSEP rating scheme. Data pertaining to discontinuity parameters such as; spacing, aperture, filling, surface roughness, continuity was collected and ratings were awarded accordingly.

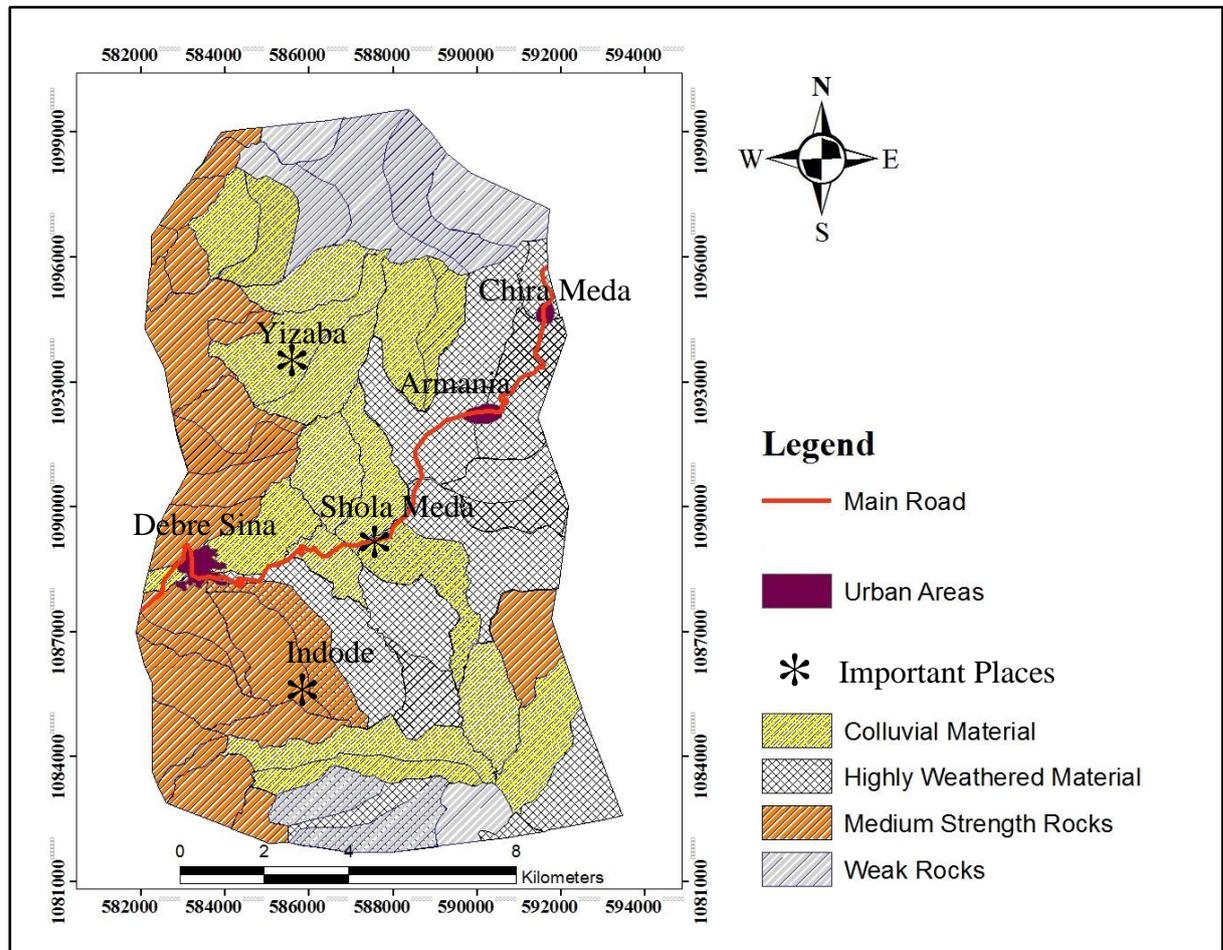


Plate 5.6 Slope material map of the study area

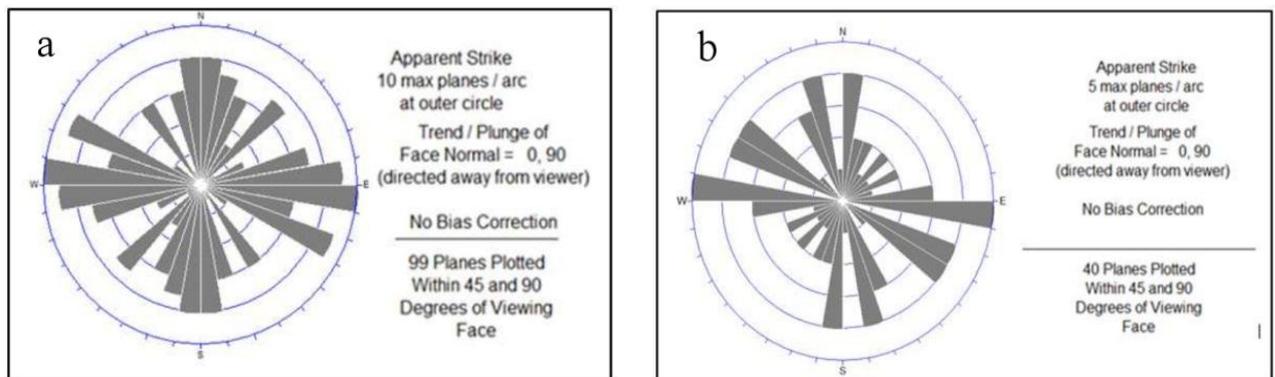
Degree of fracturing and shearing, attitude of bedding or jointing in relation to slope, and nearness to thrust zones are the important criteria in determining the slope stability. The faults, fractures and joints not only tend to destabilize the area through deterioration of the strength of the rocks, but also accelerate the weathering process. The probability of landslides is higher close to the faults (Murck *et al.*, 1996).

Two to four sets of systematic joints are recognized in the rock masses of the Alaje and Tarmaber Formations besides to the non-directional fractures. The systematic sets of joints are mostly dipping vertical to sub vertical. The dominant trends of the joint sets are N-S dominantly dipping toward East but some towards West; E-W dipping to both either North or

South wards; NE-SW dominantly dipping towards SE and NW-SE dominantly dipping towards NE. Plate. 5.7 depicts rose diagram of structural discontinuities.

5.2.1.5 Land Use Land Cover

Land use and land cover pattern is one of the important parameters governing slope stability. Vegetation has major role to resist slope movements, particularly for failures with shallow rupture surfaces. A well spreaded network of root system increases the shearing resistance of the slope material due to natural anchoring of slope materials, particularly for soil slopes. Moreover, a thick vegetation or grass cover reduces the action of weathering and erosion, hence adds to stability of the slopes. On the other hand, barren or sparsely vegetated slopes are usually exposed to weathering and erosion action, thus rendering it vulnerable to failure (Wang and Niu, 2009).



(a) Alaje basalts and

(b) Tarmaber basalts

Plate 5.7 Rose diagram of strike trends of discontinuities

Agricultural activity is generally practiced on very gentle and gentle slopes. For higher slope angle, usually it is carried out when the slopes are made flat by making terraces. These slopes, apart from receiving natural precipitation, also get recharged by additional water for agriculture purpose. Because of the fact that even after many years of such practice they remain stable, it is quite logical to consider them as safe from landslide point of view. Similarly, a populated land on a very gentle slope ($<15^\circ$) under normal circumstances is least expected to suffer from slope instability.

Slope instability is also induced because of anthropogenic activities, i.e. urbanization, particularly on higher slope angles ($>30^\circ$). It not only removes vegetation cover but also adds to the natural weight of the slope as surcharge due to the weight of civil structures. In a hill

slope with higher slope angle, buildings are usually located by constructing local cut slopes and flat terraces. With this concept urbanization is broadly classified into three categories (Zubair et al., 2012). A sparsely urbanization slope is where construction terraces are located far apart (more than 15 m of horizontal spacing) providing a considerable distance between two terraces along the slope. A moderately urbanized slope is characterized by comparatively closer location of construction terraces but leaving an optimal horizontal spacing of 5-15 m between individual terraces. In a heavily urbanized slope construction terraces are located very close to each other (≤ 5 m horizontal spacing) in such a way that successive terraces almost touch each other at places. With increasing urbanization, water due to domestic usage may be released on the slope surface wherever the drainage measure is inadequate. This water may get added up to the subsurface water and may develop pore water pressure, leading to slope instability. Similarly barren land, affected by anthropogenic activities is also most vulnerable to landslides. All these factors are taken suitable account while awarding the ratings in SSEP rating system (Annexure A, plate 5.8). The maximum rating for this parameter is 1.5.

Bushes and shrubs alone cover 29 % of the study area whereas bare land comprises 23 %. On the other hand heterogeneous agricultural areas, arable land and forest encompass 20 %, 17 % and 11 % of the study area, respectively.

5.2.1.6 Groundwater Conditions of the Study Area

Groundwater of an area plays vital role in determining the susceptibility of rock/ soil to failure. Hydrological properties of an area include presence of streams, rivers, underground water conditions, saturation state of rock/soil, and drainage pattern of the area. Dislocated water bodies due to presence of discontinuities and shallow water-table conditions in hilly terrains along with heavy rainfall make the slopes prone to instability. According to Murck *et al.* (1996) during the prolonged monsoon phases, increased pore-water pressure creates favorable conditions for deep-seated landslides.

(Anbalagan (1992) emphasized that because groundwater in hilly terrain is generally channeled along structural discontinuities of rocks, it does not have a uniform flow pattern. This is what has really been observed in the study area during field visit. The evaluation of observations of the behavior of groundwater on hill slopes is difficult over large areas. Therefore, in order to make a quick appraisal, the nature of surface indications of the

behavior of groundwater will provide valuable information on the stability of hill slopes for hazard mapping purposes. Surface indications of water such as damp, wet, dripping and flowing are used for rating purposes in SSEP rating system. The observations taken after the monsoon provide probably the worst groundwater conditions possible.

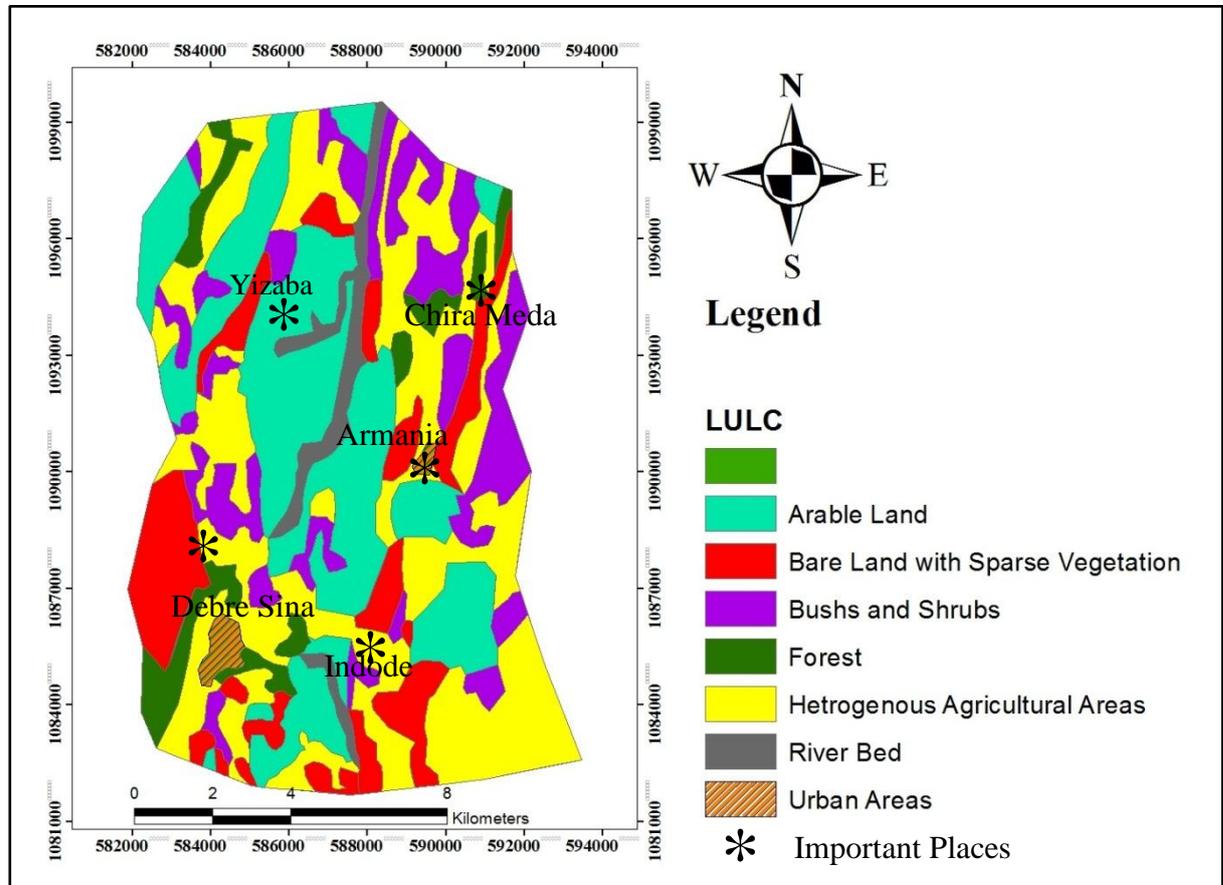


Plate 5.8 Land use land cover map of the study area

In the present study area, groundwater is not uniformly distributed over all facets. Therefore, groundwater investigation has been conducted facet wise. Some facets have small flowing streams whereas others display wet to dry conditions. As plate 5.9 depicts, surface terraces of groundwater of the study area portray dry slopes (28 %), wet (22%), flowing (18 %), damp (18 %) and dripping (14 %), respectively.

6.2.2 External Landslide Hazard Triggering Parameters

6.2.2.1 Rain Fall

To assess and see the effect of rainfall to the landslide occurrences of the area, rain fall data for 35 years (1981-2013) was collected from National Meteorology Agency of Ethiopia. It

indicates that the maximum, minimum and average annual rainfall in the study area is 3592.7 mm, 683.6 mm and 1,735.591 mm, respectively (Plate 5.10). The maximum annual rainfall was recorded in the year 1997, while the minimum in the year 2012.

The monthly maximum rainfall is always in the months of July and August for all the recorded data. The daily maximum RF of the year 2005 was recorded on August 8, but the landslide occurred on September 13-14, 2005. Hence, the RF shows weak correlation to that landslide occurrence as compared with the annual, monthly and daily rainfalls (plate 5.11)

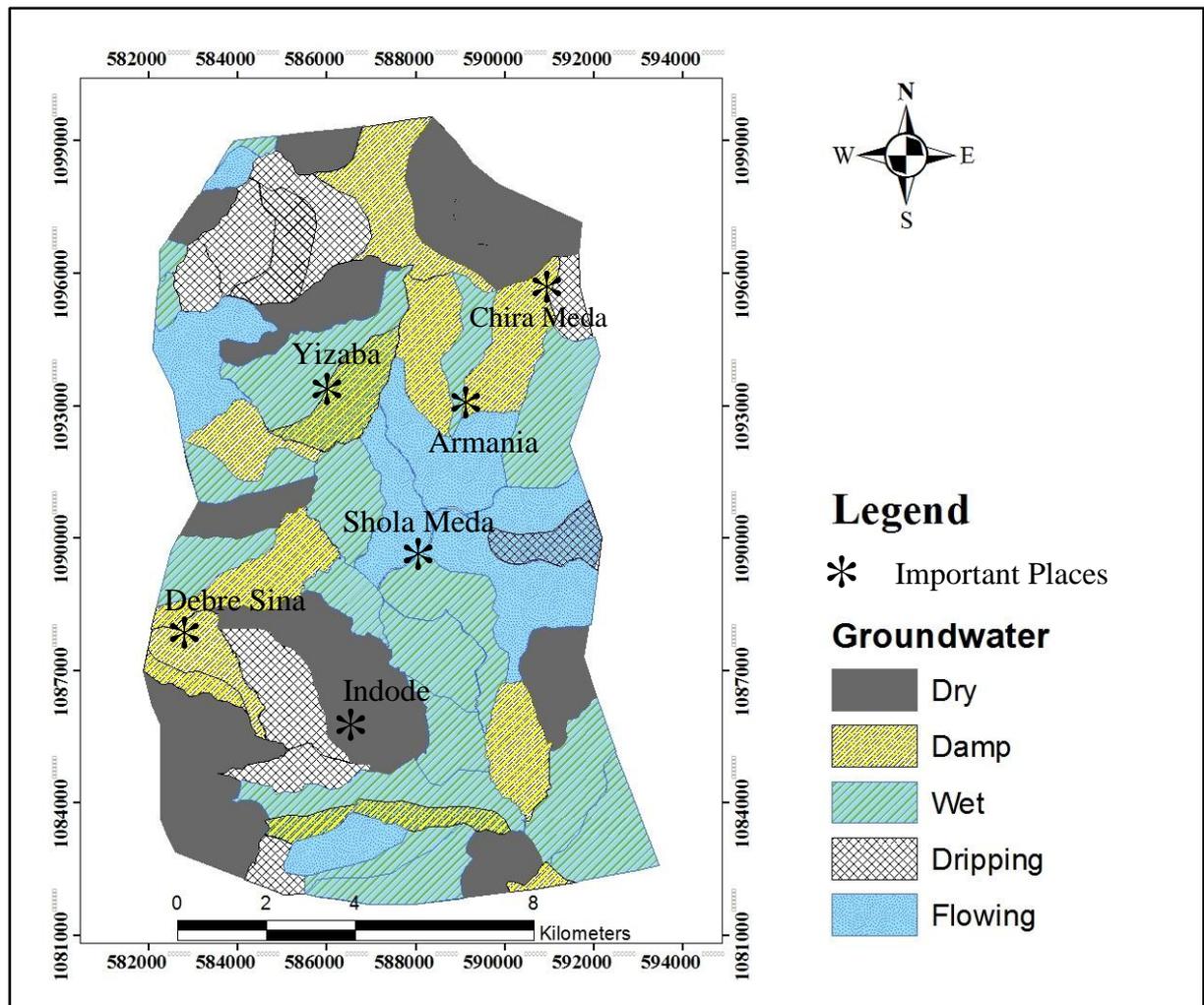


Plate 5.9 Surface traces of groundwater

Localized landslide occurrences are common in every rainfall period in the rift margin including the study area, especially along stream banks and road cuts. The study area is one of the areas receiving a high rainfall in the country having a bimodal rainfall nature which possesses alternating dry and rainy seasons. It receives exceptionally peak precipitation in the months of July and August. These two months alone contribute 43% of annual precipitation.

On the other hand months such as; March, April, May and September experience moderate amount of monthly precipitation. Low amount of mean monthly precipitation is recorded in the months of October and November whereas December, January and February are generally regarded as dry months as they receive very low amount of monthly precipitation (Plate. 5.12).

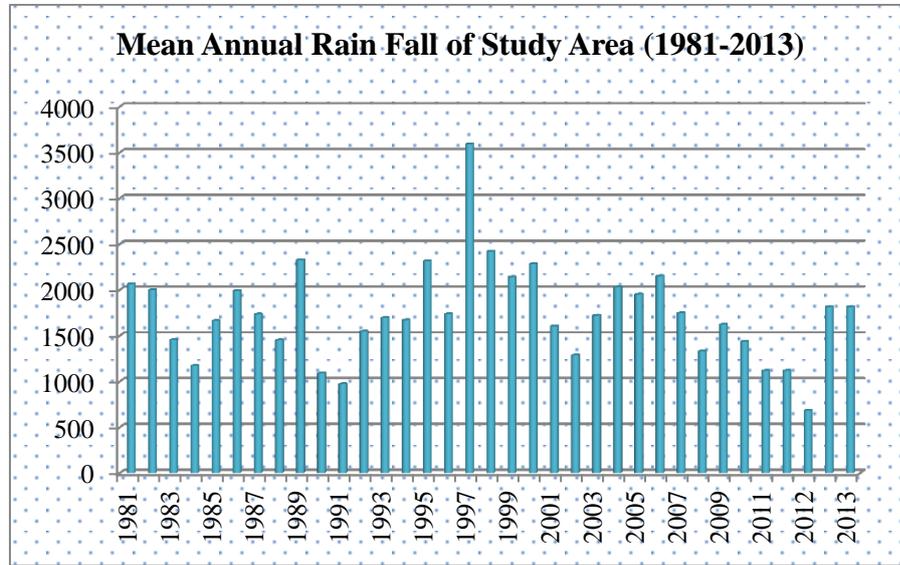


Plate 5.10 Mean annual rainfall of the study area (1981-2013)

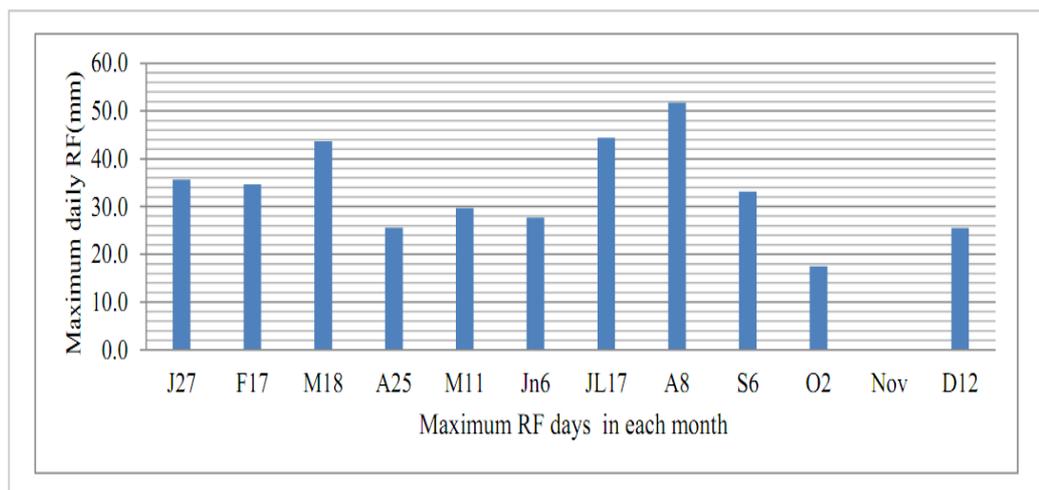


Plate 5.11 Daily maximum RF (mm) for 2005

As the cases in every corner of the world, rainfall is one of the potential triggering factors for the slope failure in the study area.

Most of the landslides recorded in the study area occurred when the annual rain fall exceeds the long term average rainfall. However, there were lower occurrences of major landslides

between the years of 1983 to 1994 where the amounts of annual rainfalls were lower than the long term average except for 1986 and 1989.

Cumulative monthly RF of the years having maximum annual rainfalls monthly distribution of rainfalls of the three consecutive years of 2004, 2005 and 2006 and the daily maximum of 2005 (plate 5.11) were also compared and analyzed to see the triggering effect of rainfall to landslides, with emphasis to the event of September 2005.

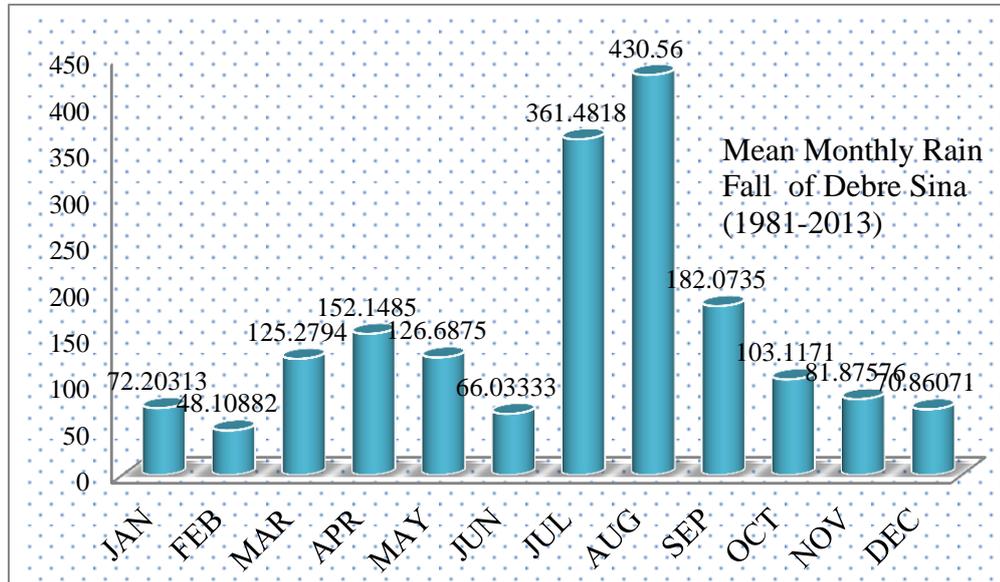


Plate 5.12 Mean monthly rain fall of the study area (1981-2013)

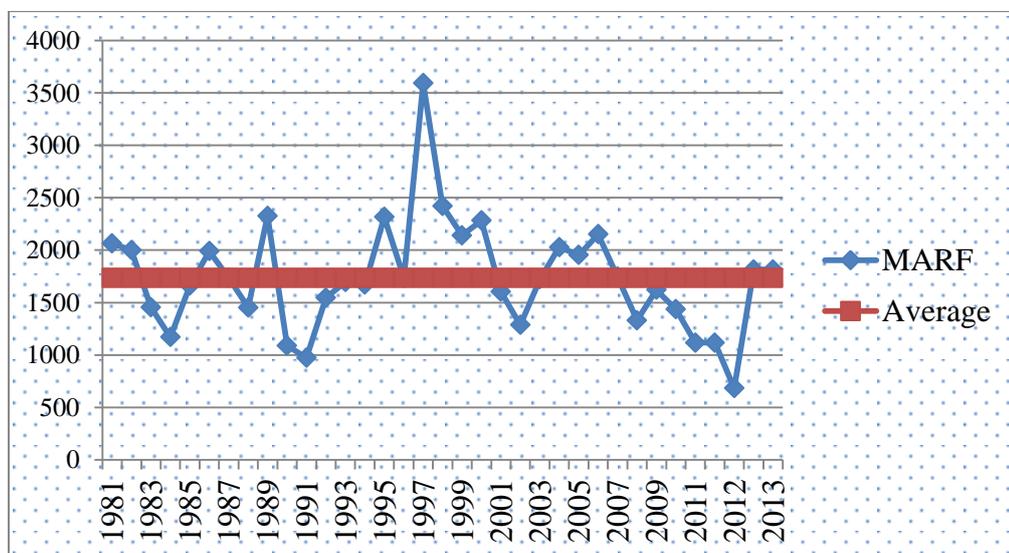


Plate 5.13 Deviation of mean annual rainfall from average value

The cumulative values are plotted and compared in plate 5.14. The evaluation of these rainfall values depicts that the possibility of large scale landslide could have been existed in the earlier years (e.g. in 1997) than in 2005 if rainfall only was the triggering factor. Therefore, the significant triggering factor of the September 2005 landslide event was most probably the earthquake in addition to the rainfall.

Mean annual rainfall of the study area is calculated to be 1,736 mm which is regarded as very high because it exceeds 1500 mm. According to Slope Stability Susceptibility Evaluation Parameter (SSEP) Rating Scheme (Annexure A), a rating of 0.75 is awarded to all slope facets of the study area.

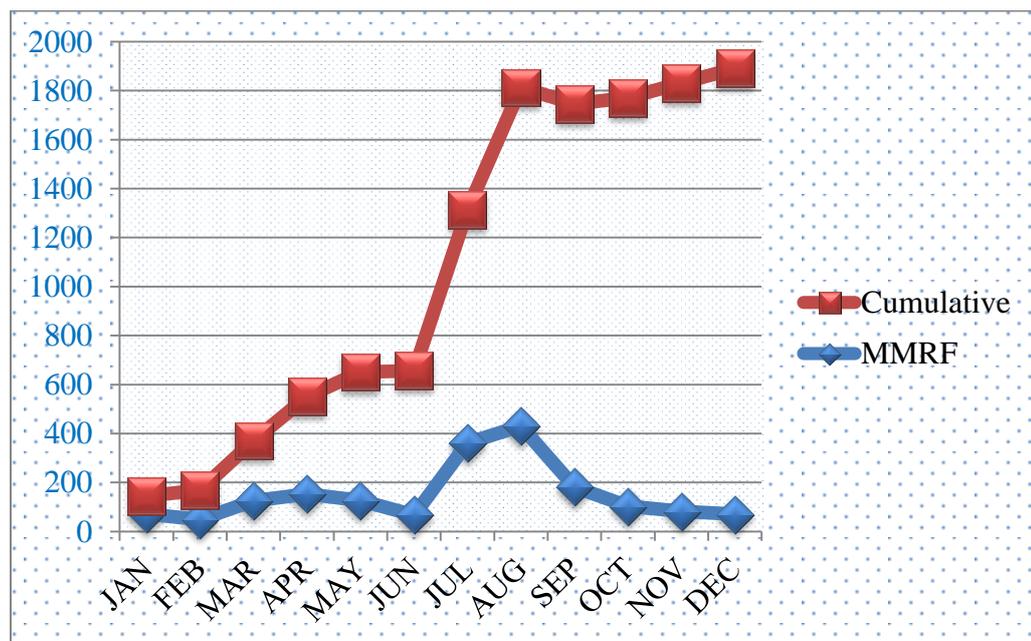


Plate 5.14 Cumulative mean monthly rainfall

5.2.2.2 Seismicity

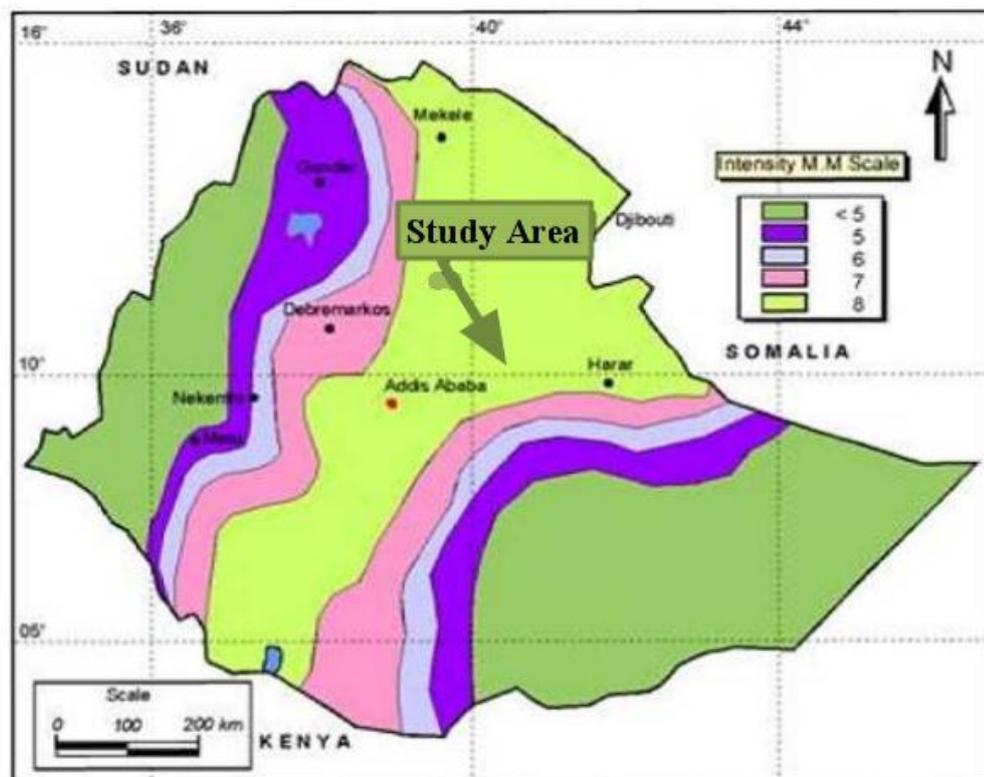
The earthquake shocks may be responsible for triggering new landslides and reactivating old landslides. The vibrations due to earthquake may induce instability, particularly in loose and unconsolidated material on steep slopes. The Afar rift margin, where the study area is situated, is known for its earthquake occurrences. Most of the earthquake ranges from small to medium level (Atalay Ayele, 2007).

Although not registered, the occurrences of landslide in association with Afar earthquake in the area are common as evidenced by local dwellers. For example, as obtained from local

information, there was a landslide occurrence around the Nibamba Gebriel and Sina Aregawi contemporaneous with the 1961 Kara-Kore earthquake.

According to Asmelash Abay and Barbieri (2012) there was an earthquake occurrence on September 9, 16, 17 and 19/ 2005 around the locality known as Ankober which is 60-80 km south of the study area as registered in the Addis Ababa Geo-observatory. Thus, the most probable triggering factor for some of the initial cracks of the September 2005 large landslide occurrence could be the earthquake associated to the dike episode at Dabbahu and Manda-Hararo or to that of the Ankober (at the rift margin).

In order to analyze the seismicity, in the study area seismic map of Ethiopia was utilized (Laike Mariam Asfaw, 1986). According to this map (plate 5.15) the present study area falls in Seismic zone which has an intensity of 8, this zone has a ground acceleration of 0.1- 0.5g. Thus, the rating for ground acceleration of 0.1-0.5g, as per the standard SSEP table (Annexure A) is estimated to be 1.5. Accordingly, this rating value has been distributed to all 60 slope facets in order to generate landslide hazard zonation map of the study area.



(Source: Laike Mariam Asfaw, 1986)

Plate 5.15 Seismic risk map of Ethiopia

5.2.2.3 Man-made Activities

Human being disturbs the natural equilibrium of slopes in various ways besides natural forces. Continuous interaction of humans to slopes generally plays an important role in triggering landslides. Slopes will always remain stable provided that neither man-made activities nor natural factors influence them. The worst condition is when humans and nature pose combined effects in slope instability. As evidenced in the field most of the landslides are associated with steep cut slopes made for various purposes such as; road construction, building construction, quarry developments and agricultural activities. The main man-made activities which prevailed in the present study area are mainly construction activities and cultivation practices. The developmental activities has resulted into steep slope cuttings which has made many slopes to overhang and thus, more prone for landslide activities. The cultivation practices over the slopes have also an impact on slope instability. Unplanned irrigation practices over the slopes makes slope mass recharge and which may result into reduction of shear strength of the soil mass, besides pore water pressures may also develop within the soil mass. Thus, ultimately leading the soil mass to fail provided other causative factors also favor the sliding (Raghuvanshi *et al.*, 2014).

The human activities observed in the study area include densely cultivated land (15 %), moderate steep rock mass cut (32%), moderate steep soil mass cut (10 %), and moderately cultivated land (13 %). No human-induced activities were observed in the remaining 30 % of the study area during field visit (plate 5.16).

5.3 Calculation of Evaluated Landslide Hazard (ELH)

The evaluated landslide hazard indicates the net probability of instability and has been calculated facet-wise. The ELH of an individual facet was obtained by adding the ratings of the individual causative factors obtained from the SSEP rating scheme.

ELH = Summation of ratings of intrinsic parameters (*relative relief + slope morphometry + Slope material + structural discontinuity + land use and land cover + groundwater*) + Summation of ratings of external parameters (*rainfall + seismicity + man-made activities*)

On the basis of evaluated landslide hazard (ELH), three categories of landslide hazard zones have been identified for the present study area (plate 5.17) viz., moderate hazard (MH), high hazard (HH) and very high hazard (VHH). These zones are distributed in accordance with the

geology and geomorphology of the area. Areal coverage of moderate hazard is 25 % whereas those of high hazard and very high hazard are 58 % and 17 %, respectively. These figures indicate that 75 % of the study area is very susceptible to landslide hazard (Plate 5.18).

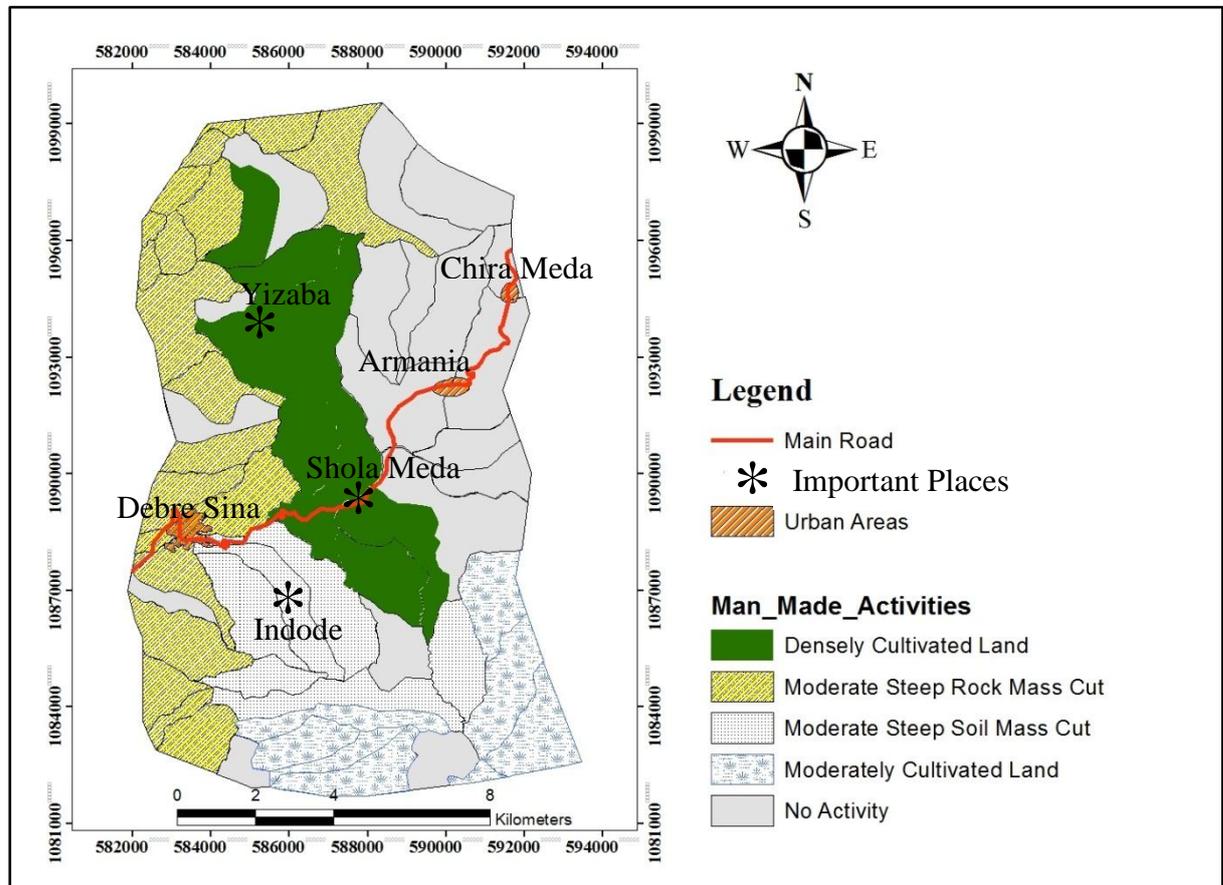


Plate 5.16 various human induced activities in the study area

5.3.1 Moderate Hazard Zone

Moderate hazard zone represents relatively safe areas for construction and various infrastructural activities. It covers 25 % of the study area and out of 60 slope facets 15 fall in moderate hazard zone. Moderate hazard zones are mostly distributed in Northern, Central and Southern parts of the study area. Chira Meda area falls in this zone. Even if this zone is not totally suitable, it should not be avoided because it has less probability of landslide occurrence as compared to others.

5.3.2 High Hazard Zone

The maximum area of the study area is covered by high hazard zone which accounts about 58 % of the study area. This zone represents high susceptibility to landslide hazard as compared

to moderate hazard zone. Some of the inventoried landslides are known to occur in this zone. High hazard zone is mostly distributed in Northern, Eastern and Southern parts of the study area. Out of 60 slope facets 35 are categorized under this zone. Part of the town Debre Sina and Armania also fall in High hazard zone.

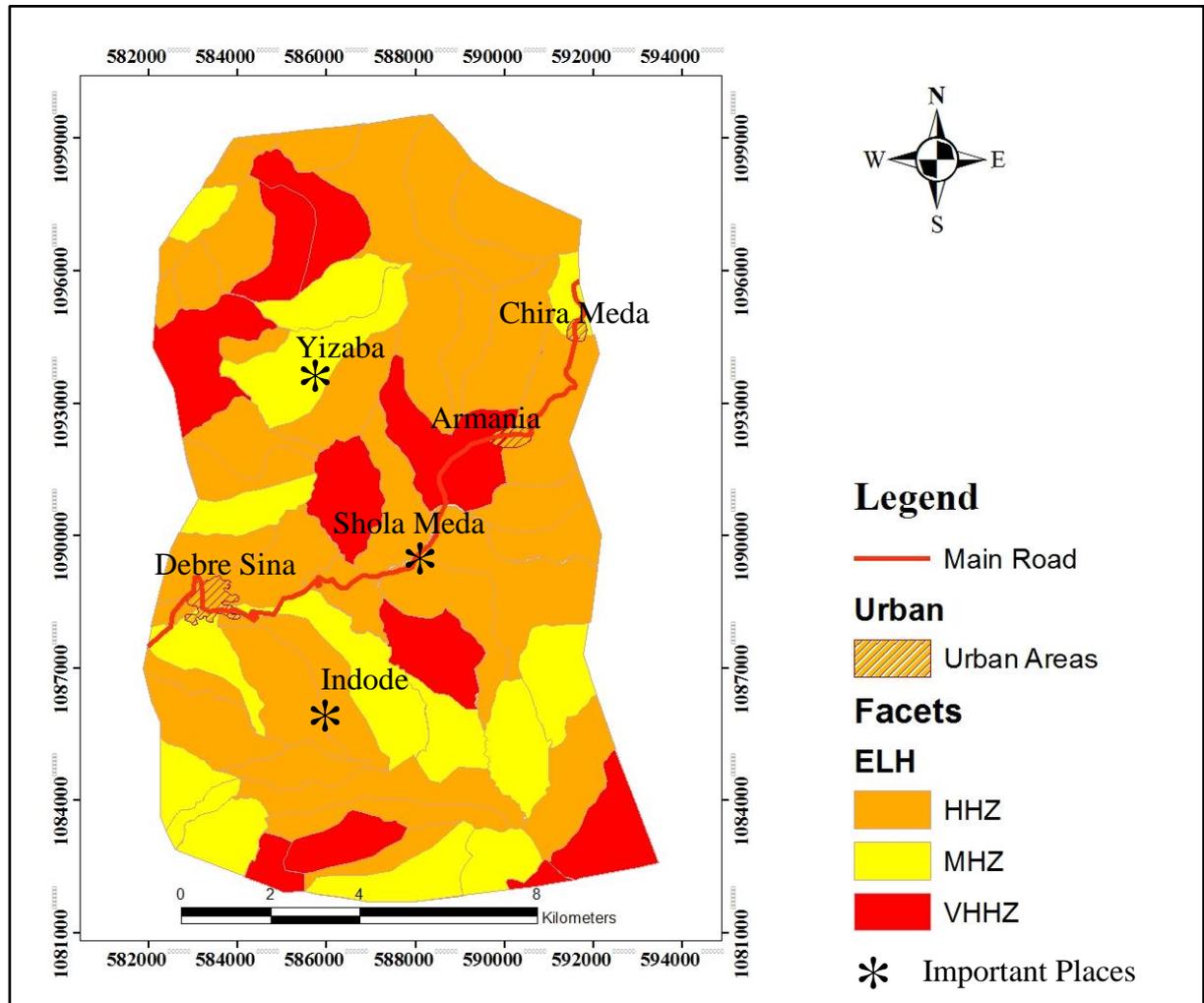


Plate 5.17 Evaluated landslide hazard of the study area

Those slopes falling in this zone should be partially avoided or detailed study on larger scale (1:1000) should be done to evaluate the status of stability of these slopes. Suitable control measures should also be identified before taking up constructions in order to minimize related geo-environmental hazards.

5.3.3 Very High Hazard Zone

This zone represents totally unsuitable areas for constructions and settlement as well as agricultural activities. It covers the least area coverage and accounts 17 % of the study area.

Because of very high susceptibility of landslide occurrence in very high hazard zone, it is not advisable and should be totally avoided. 10 facets of the study area have been identified to be very susceptible to landslide hazard. Very high hazard zones are located in North-Western, Central and South-Eastern part of the study area. Part of town Armania also falls in this zone.

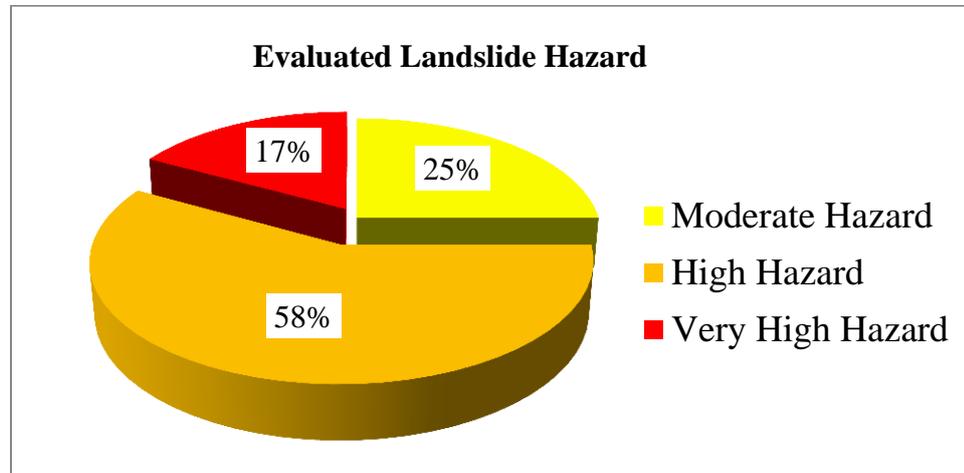


Plate 5.18 Areal coverage of Evaluated Landslide Hazard (ELH)

5.4 Validation of LHZ Map

The results obtained in present study should correlate with the past landslide events recorded in the study area. Thus, the final Landslide Hazard Zonation map has been checked against the inventoried landslides of the study area for its validity. Landslide inventory map of the study area has been prepared by integrating field observation and GPS data collection with some ideas obtained by interviewing local people living around the study area.

Most of the inventory landslides are concentrated in high and very high hazard zones as depicted in the inventory map of the study area (plate 5.19). Out of 36 landslide inventories prepared during the field visit, 22 (61 %) of them fall in high hazard zone while the remaining 14 (39 %) fall in very high hazard zone.

The methodology followed during the present study relates intrinsic and external landslide triggering parameters to landslide occurrences. It has produced the results that match to past landslides. Thus, Slope Stability Evaluation Parameter (SSEP) rating scheme is found to be suitable methodology in landslide hazard zonation as it validated with the past landslide hazard events.

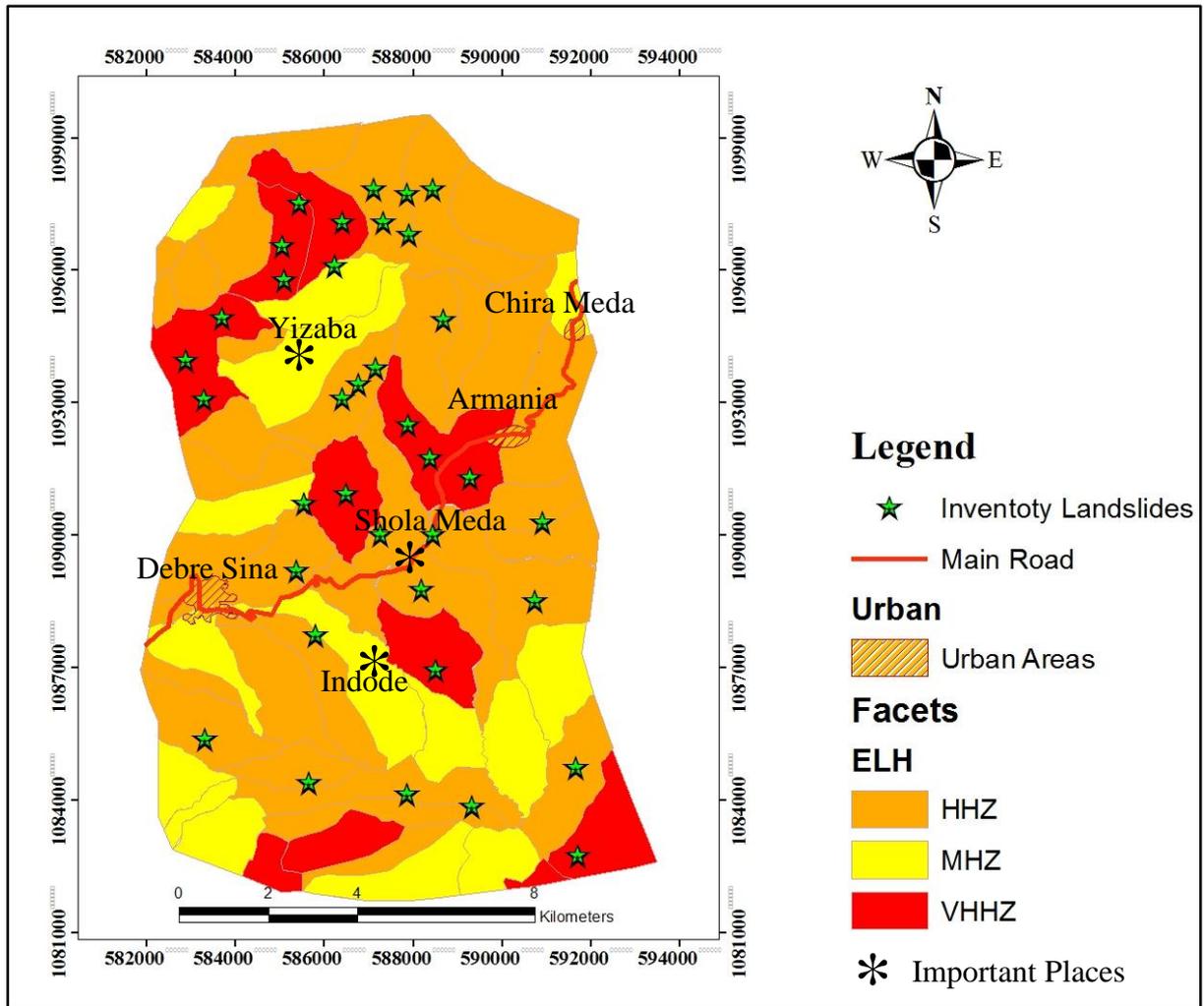


Plate 5.19 A map showing the correlation of SSEP result to past landslide records

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

The present study area has been affected by landslide hazard which devastated both public as well as private properties including infrastructures. It also threatened the life of people and animals living around the study area. Landslide hazard and fatalities have been reported in the study area for a long period of time.

Different triggering parameters were responsible for the initiation 2005 landslide recorded in the present study area. Based on the possible factors responsible for landslides and availability of data on these factors, nine causative factors in total were considered during the present study, these includes both intrinsic and external parameters. It is the combination and integration of various causative parameters that make the landslide hazard zonation result more reliable as they all have individual role and contribute for slope instability.

Several landslide hazard assessment approaches are available depending on the kind of data input, study area size, data availability, kind of topography, etc. Each of these approaches has its own advantages and disadvantages. Statistical methods are considered to be more trustable as they are intended to minimize the subjectivity of qualitative approaches. However, these techniques require data on parameters which needs to be generated through remote sensing and GIS techniques and requires statistical software to analyze it. Much of such remotely sensed data is not readily available. If available, it requires special skill to manipulate it with sophisticated analysis procedures. Regarding the present study, SSEP has been adopted which is the modified approach of LHEF (Raghuvanshi *et al.*, 2014). It is found to be more effective method in mapping landslides in large areas in a short period of time provided that sufficient field data has been collected as it heavily depends on realistic field data.

Concerning slope susceptibility in the present study area, areas covered with bare land, shrub and urban classes are more vulnerable to landslides, as compared to vegetation cover and forest classes which disfavor landslides. North, Northeast and West facing slopes are favorable to landslides, whereas South, Southwest and West orientation disfavor slope failure. Moreover, slopes inclined at greater than 25° angle have strong susceptibility to landslides. Distance to streams also has strong relations with landslide occurrence because

areas close to streams prove to be highly prone to slope instability suggesting that slope undercutting by stream is an important process.

In accordance to geological setting and structures, the present study area is a part of Main Ethiopian Rift which has been frequently affected by natural hazard such as seismicity, volcanism, slope failures, etc. The local geology of the area includes ignimbrite, different kinds of basalts and cliff forming rhyolites which are highly weathered and as a result favor slope instability. Major and minor geological structures like faults and joints are also responsible for landslide hazard occurrences.

On the basis of the evaluated landslide hazard (ELH), three categories of landslide hazard zones have been identified for the present study: moderate hazard (MH), high hazard (HH) and very high hazard (VHH). These zones are distributed in accordance with the geology and geomorphology of the area. Areal coverage of moderate hazard is 25 % whereas those of high hazard and very high hazard are 58 % and 17 %, respectively. These figures indicate that 75 % of the study area is vulnerable to landslide hazard.

Further, an attempt was made to validate the Landslide Hazard Zonation map of the study area. Result showed that 61 % of past landslide or related instability problems fall in high hazard (HH) and the remaining 39 % fall in very high hazard (VHH). Thus, the validation confirms the rationality of considered governing parameters, the adopted SSEP technique, tools and procedures in developing the landslide hazard map of the study area.

In reference to the current study in general and the selected landslide susceptibility zonation map in particular, the following recommendations are suggested for future study:

- ❖ A considerable portion of the study area is susceptible to landslides. Areas with slope class $30^{\circ} - 45^{\circ}$ and more are very susceptible to landslides. Hence, local administrators should be made aware of the area regarding the possibility of landslide occurrence. The landslide susceptibility map may help administrators as well as planners for decision making and proper management.
- ❖ In the present study, the causes of slope instability are wide and multi-directional, therefore integrated approach of remedial measures may be more appropriate to mitigate the possible landslide hazards in the area.

- ❖ No remedial measure has been taken in the present study area except some retaining walls and gabions constructed at some section of the main road regardless of the occurrence of landslides. Therefore, the area should be protected by adopting different preventive mechanisms such as; covering the slopes with vegetation, using devices like drain pipes and piles, and other techniques which are intended to minimize long term losses arising from landslide hazards and associated risks.
- ❖ Large scale mapping and very recent aerial photographs ought to be used to obtain the inventories of all observed landslides in the study area.
- ❖ Detailed field based data should be collected to produce susceptibility maps. Likewise, landslide risk map should be produced in order to demarcate the risk area from less susceptible area. Consequently, policy makers may use it to prevent the damage.
- ❖ Landslide hazard zonation map has been prepared in order to delineate (demarcate) vulnerable areas from safer sites. Therefore, Very high hazard and high hazard zones, as delineated during the present study, are probably susceptible landslide prone areas. For slopes falling in HH and VHH classes, it is advisable to avoid constructions. If unavoidable, detailed study on 1:1,000-2,000 scales ought to be done to evaluate the status of stability of these slopes.
- ❖ Hill slopes falling in MH class are safer for construction practice but the problem is that they may contain local pockets of instability which should be suitably accounted during constructions.
- ❖ Suitable control/remedial measures should be identified and adopted before taking up constructions in order to minimize geo-environmental hazards and economic loss.

All care was taken to conduct the present study with authentic data and appropriate methodology. However, the study was conducted under constraints of time, finance and resources. This might have affected the results to certain degree of inaccuracy. Therefore, it is strongly recommended that more detailed studies would be required before making any decisions for implementing these results for planning and development.

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ANNEXURES

Annexure A: Rating values assigned to intrinsic and external parameters

(i) Intrinsic Parameters

1. Slope Geometry

(i) Relative Relief			(ii) Slope Morphometry		
Class	Value Range	Ratings	Class	Value Range	Rating
Very High	>300m	1.0	Escarpment/cliff	>45°	2.0
High	201-300m	0.8	Steep slope	36°-45°	1.7
Medium	101-200m	0.6	Moderately steep slope	26°-35°	1.0
Moderate	51-100m	0.2	Gentle slope	16°-25°	0.6
Low	<50m	0.1	Very gentle slope	< 15°	0.3

Estimation of Slope angle (Anbalagan, 1992)

Number of contour lines over one cm length (1 : 50,000)	Slope angle
>25	>45°
19-25	36°-45°
13-18	26°-35°
8-12	16°-25°
< 7	<15°

2. Slope Material

(a) Rock Type

	Class *	Description*	Ratings
Grade I	Very weak rock	Strength: 1-5 MPa ; Field Estimate of Strength: Crumbles under firm blows with point of a geological hammer, can be peeled by a pocket knife. Examples: Highly weathered or altered rock.	1.0
	Weak rock	Strength: 5-25 MPa ; Field Estimate of Strength: Can be peeled with a pocket knife with difficulty, shallow indentation made by firm blow with point of a geological hammer. Examples: Chalk, rocksalt, potash.	0.8
Grade II	Medium strong rock	Strength: 25-50 MPa; Field Estimate of Strength: Cannot be scraped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer. Examples: Claystone, coal, concrete, schist, shale, siltstone.	0.5
	Strong rock	Strength: 50-100 MPa ; Field Estimate of Strength: Specimen requires more than one blow of geological hammer to fracture. Examples: Limestone, marble, phyllite, sandstone, schist, shale.	0.4
Grade III	Very strong rock	Strength: 100-250 MPa ; Field Estimate of Strength: Specimen requires many blows of a geological hammer to fracture it. Examples: Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone, marble, rhyolite, tuff.	0.3
	Extremely strong rock	Strength: >250 MPa; Field Estimate of Strength: Specimen can only be chipped with a geological hammer. Examples: Fresh basalt, chert, diabase, gneiss, granite, quartzite	0.1

Adjustment Factor for Weathering grade for rock mass

Weathering Grade**	Description**	Adjustment Factor
Fresh	No visible sign of rock material weathering; perhaps slight discoloration on major discontinuity surfaces	1
Slightly weathered	Discoloration indicates weathering of the rock material and discontinuity surfaces	1.2
Moderately weathered	Less than 35% of the rock material is decomposed and/or disintegrated to a soil. Fresh or discoloured rock is present either as a continuous framework as core stone	1.5

Highly weathered	More than 35% of the rock material is decomposed and/or disintegrated to a soil. Fresh or discoloured rock is present either as a continuous framework as core stone	1.65
Extremely weathered	All the rock material is decomposed and/or disintegrated to a soil. The original mass structure is still largely intact	1.8
Residual soil	All the rock material is converted to soils, the mass structure and material fabrics are destroyed	2.0
Note: The adjustment factor for weathering of rock has to be multiplied to the respective rating of fresh rock type of Grade II and Grade III rocks.		
* Rock mass classification and description adopted from Hoek 1997		
** Weathering class and description adopted from Irfan and Dearman, 1978		

(b) Soil Type

Class	Description	Ratings
Collapsible Soil	Loose mix of granular material comprising mainly sand and silt. Mainly cohesionless material which may undergo suffusion.	1.0
Alluvial Deposits	Well graded material comprising mix of cobble/ pebbles, sand and silt in a matrix of clay.	0.8
Residual Expansive Soils	Mainly comprising clay. Exhibits swelling when saturated and typical shrinkage cracks when dry.	0.6
Poorly Graded Colluvial Material	Poorly graded rounded to sub-rounded rock fragments/ cobble/pebbles mixed in a matrix of fine grained sand or silt.	0.5
Fluvio-glacial Deposits	Well graded angular rock fragments mixed in a matrix of clayey material. Partial interlocking of angular rock fragments.	0.4
Well Graded Colluvial Material	Well graded angular to sub-angular rock fragments mixed in a matrix of clayey material. Partial or well interlocking of angular rock fragments.	0.3
Residual Soils	Well compacted residual deposits of soil mainly comprising silt and clay.	0.2

3. Structural Discontinuities

(i) Parallelism between discontinuities dip direction and Slope			(ii) Relationship between dip of discontinuity and inclination of slope			
$(\alpha_j - \alpha_s)$ or $(\alpha_i - \alpha_s)$	Rating	Planer Mode of Failure $(\alpha_j - \alpha_s)$ Wedge Mode of Failure $(\alpha_i - \alpha_s)$ α_j - Discontinuity dip direction α_i - Direction of line of intersection of two wedge forming discontinuities α_s - Direction of Slope inclination	$(\beta_j - \beta_s)$ or $(\beta_i - \beta_s)$	Rating	Planer Mode of Failure $(\beta_j - \beta_s)$ Wedge Mode of Failure $(\beta_i - \beta_s)$ β_j - Dip of Discontinuity plane β_i - Plunge of line of intersection of two wedge forming discontinuities β_s - Direction of Slope inclination	
0°	0.5		< (-10°)	0.5		
1°-5°	0.4		0°-(-10°)	0.4		
6°-10°	0.3		0°	0.2		
11°-15°	0.25		10°-0°	0.15		
16°-20°	0.2		> 10°	0.1		
>20°	0.1		(iii) Dip of discontinuity or plunge of line of Intersection of wedge forming planes			
(iv) Soil cover depth			(β_i) or (β_s)	Rating		
Depth	Rating		> 45°	0.5		
> 20 m	2.5		45° – 35°	0.4		
20 – 15 m	1.8		34° – 30°	0.25		
14 – 10 m	1.4		29° – 20°	0.15		
9 – 5 m	1.0		< 20°	0.1		
< 5m	0.5					
(v) Structural discontinuities and Rock mass condition ****						
Condition					Rating	
Disintegrated – poorly interlocked, heavily broken rock mass with a mixture of angular and rounded rock pieces.					0.25	
Blocky/ Disturbed – folded and/or faulted with angular blocks formed by many intersecting discontinuity sets.					0.2	
Very Blocky – interlocked, partially disturbed rock mass with multifaceted angular blocks formed by four or more discontinuity sets.					0.1	
Blocky – very well interlocked undisturbed rock mass consisting of cubical blocks formed by three orthogonal discontinuity sets.					0.05	

(vi) Characteristics of structural discontinuity							
Continuity	Rating	Seperation	Rating	Roughness	Rating	Infilling	Rating
< 1m	0.02	None	0.02	Very rough	0.02	None	0.02
1 – 2m	0.04	< 0.1 mm	0.05	Rough	0.03	Hard filling < 5mm	0.04
3 – 9 m	0.07	0.1–0.9 mm	0.07	Slightly rough	0.07	Hard filling > 5mm	0.07
10 – 20 m	0.10	1 – 5 mm	0.12	Smooth	0.10	Soft filling < 5mm	0.12
> 20 m	0.15	> 5mm	0.15	Slickensided	0.15	Soft filling > 5mm	0.15
Weathering	Rating	**** Hoek & Bray 1997					
Unweathered	0.02						
Slightly weathered	0.05						
Moderately weathered	0.07						
Highly weathered	0.10						
Decomposed	0.15						

4. Landuse and Landcover

Class/ Description	Rating
Barren land – No vegetation, land not used for any activity	1.5
Sparsely vegetated – Very thin scattered vegetation in the form of wild grass, bushes, scrub and random small trees.	1.2
Moderately vegetated area - Moderately covered vegetation land in the form of wild grass, bushes, scrub and trees.	0.75
Thickly vegetated forest area – Dense forest area with very thick vegetation cover.	0.4
Cultivated land with populated area	0.4

5. Groundwater

Surface traces of groundwater	Ratings
Flowing – presence of spring on slope face	2.0
Dripping – dripping of water through structural discontinuities.	1.5
Wet – water marks on rock surface, some droplets along structural discontinuities, algal growth in shadow areas.	1.0
Damp – Moist conditions on rock face surface, moss and algal growth in shadow areas.	0.6
Dry – rock face surface is dry, no water traces along structural discontinuity surfaces	0.0

ii) External Parameters

1. Seismicity		2. Rainfall		
Ground acceleration*	Rating	(a) Mean annual rainfall (mm)		
1.0 – 0.5g	2.0	Class	Mean annual rainfall (mm)	Rating
0.5 – 0.1g	1.5	Very High	> 1500	0.75
0.1 – 0.05g	1.0	High	1101 – 1500	0.6
0.05 – 0.01g	0.8	Moderate	701 – 1100	0.3
0.01 – 0.005g	0.4	Low	300 – 700	0.2
< 0.005g	0.4	Very low	< 300	0.1

* For ground acceleration estimation refer Fig. 6 and seismic intensity map of the area

(b) Rain induced manifestation on slope

Surface Traces	Rating
Slope Toe erosion – Toe of the slope is eroded by stream flow, Surface material overhangs and prone for failure.	0.25
Stream bank erosion – Stream water has undercut the banks and made the sides of the slope hang.	0.15
Gully erosion over the slope face	0.1
No Rain induced manifestation on slope	0.0

(c) Slope Material

Description	Rating
Soil mass – Rainfall will saturate soil mass and pore water pressures will develop.	0.25
Disintegrated – heavily broken rock mass. Much of the rain water will seep into the rock mass and will recharge groundwater considerably.	0.2

<u>Blocky/ Disturbed</u> – folded and/or faulted with angular blocks formed by many intersecting discontinuity sets.	0.15
<u>Very Blocky</u> – Partially disturbed rock mass having four or more discontinuity sets.	0.1
<u>Blocky</u> – Undisturbed rock mass consisting of cubical blocks formed by three orthogonal discontinuity sets.	0.05

(d) Discontinuity orientation with respect to slope

Description		Rating
Soil Mass		0.25
More than one discontinuity dipping into the hill or the bedding joint/discontinuity dipping into the hill.		0.25
At least one discontinuity dipping into the hill. Which may or may not be a bedding joint.		0.12
None of the discontinuities dips into the hill.		0
Rainfall adjustment factor for slope morphometry #		
Class	Value Range	Adjustment factor
Escarpment/cliff	>45°	0.1
Steep slope	35°-45°	0.25
Moderately steep slope	25°-35°	0.5
Gentle slope	15°-25°	0.75
Very gentle slope	< 15°	1.0
# Rainfall adjustment factor for slope morphometry has to be multiplied with Rainfall rating after summing up (a, b, c and d).		

3. Manmade Activities

(a) Developmental Activities		Adjustment factor for developmental activities ##	
Description	Rating	Description	Adjustment factor
Steep soil mass cut (slope > 45°). Slope overhangs.	1.25	Slope toe supported by retaining structure.	0.15
Moderate steep soil mass cut (slope 35° - 45°).	1.0	Proper drainage system provided.	0.1
Soil mass cut into gentle slope (slope < 35°).	0.75	Slope face dressing into terrace design.	0.1
Steep rock mass cut (slope > 45°). Slope overhangs.	1.0	Excavated material not dumped over the down slope.	0.1
Moderate steep rock mass cut (slope 35° - 45°).	0.75	## Adjustment factor for developmental activities has to be subtracted from the rating of development activity.	
Rock mass cut into gentle slope (slope < 35°).	0.5		
(b) Cultivation Activities		Adjustment Factor for Irrigation***	
Description	Rating	Irrigation practice	Rating
Sparsely cultivated land with small populated area	0.1	Rain fed irrigation	0.75
Moderately cultivated land with medium populated area	0.15	Unplanned irrigation	0.5
Dense cultivated land with large populated area	0.25	Channelized Planned	1.0
		*** Multiply adjustment factor for irrigation with ratings of cultivated land	

Annexure B: Rain fall data

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	*MARF
1981	0	37.4	415.2	265.7	34.2	2	545.2	564.8	136.5	60.8	0	3.4	2065.2
1982	58.8	96.2	176.8	160.6	193.3	0	187.8	436.7	174.2	197.5	245.9	71.5	1999.3
1983	68.3	51.6	72.9	184.3	344.4	18.2	270.9	376.2	21.1	34.7	0	11.2	1453.8
1984	14.2	54.7	4.2	34.1	351.4	82.6	159.1	97	278.5	0	0	95.4	1171.2
1985	34.4	0	25.1	119.6	144.8	3.2	425.5	701.5	167.7	41	0	0	1662.8
1986	0	101.2	280.9	281.2	110.7	225.5	383.2	271.9	168.3	63.3	0	104.1	1990.3
1987	0	29.5	274.3	154.7	437.6	0	27.7	429.7	144.1	85.6	0	151	1734.2
1988	188.1	149.8	13.2	138.8	38.2	39.7	230.7	281.7	208.5	163.9	0		1452.6
1989	41.1	101.5	295.4	401.1	13.4	75.5	281.3	384.2	218.2	186.7	0	327.4	2325.8
1990	88	124.2	66.6	140.8	10.4	3.4		287.8	274.9	94.6	0	0	1090.7
1991	10.4	78	192.4				168.2	252.9	159	0	30.9	80.3	972.1
1992	121.4	133.4	50.8	133.4	45.5	15.3	113.5	562	202.5	114.4	9.4	44.9	1546.5
1993	189.6	40.8	1.2	351.3	397.8		210.7	144.2	121.8	119.3	87.4	31.4	1695.5
1994	0	22.8	100.2	64.1	102.7	85.1	485.4	375	165.7	37.9	204.9	27.1	1670.9
1995	0	13.6	119	349.4	120.8	212.2	675	468.5	213.8	0	130.6	12.2	2315.1
1996	96.2	0	229.7	125			675.3	411.6	83.2	4.6	110.3		1735.9
1997	76.3	0	183.3	132.5	41.5	200	268	727.2	187.4	717.8	999.9	58.8	3592.7
1998	235.4	50.8	76.1	175.9	95.7	33.1	621	593.7	454.6	84.9	0	0	2421.2
1999	60.3	0	127.1	49.3	24.7	139.2	508.3	723.7	226.4	271.7	10.2		2140.9
2000	0	0	29	104	132.7	33.3	453.7	599.3	412.5	198.4	118	201.4	2282.3
2001		73.2	319.3	20.8	26.8	33.7	472.3	437.2	116.8	36.8	11.8	54.5	1603.2
2002	106.5	0	100.2	131.2	4	64.9	121.8	404.9	166.6	0	0	185.9	1286
2003		74.5	127.3	256.7	43.7	128.1	369.2	346.4	227.2	9.4	39.4	99.5	1721.4
2004	178.3	107.3	79.4	235.8	12.3	96.2	390.8	417	187.2	173.3	89.5	60.9	2028
2005	101.6	10.6	196.3	183.2	202.1	83.4	441.6	427.1	185.1	24.2	97.7	0	1952.9
2006	114.6	43.6	154.8	136	59	49.6	485.8	506.4	235.9	109.1	0.6	256.2	2151.6
2007	46.5	61.7	82.2	96.5	81.4		512.6	610.2	155.5	48.7	50.9	0	1746.2
2008	59	0	0.5	125.7	146.2	110.8	432.1	352.7		103.5			1330.5
2009	108.6	23	66	87.4	52.3	47.3	395.6	395.6	36.2	160.8	143.6	105.3	1621.7
2010	8.9	71.3	169.1	32.6	292.4	13.1	353.4	343.6	110.1	18.3	21.1	1.7	1435.6
2011	50.3	0	63.4	39.1	178.2	56.9	129.2	391.1	139	1.6	68.8		1117.6
2011	50.3	0	63.4	39.1	178.2	56.9	129.2	391.1	139	1.6	68.8		1117.6
2012								449.9	176.4	57.3			683.6
2013	101.7	42.5	52.1	135.5	68.8	35.9	502.4	453.4	148.3	193.7	81.1	0	1815.4
2013	101.7	42.5	52.1	135.5	68.8	35.9	502.4	453.4	148.3	193.7	81.1	0	1815.4
Average	72.2	48.1	125.3	152.1	126.7	66.0	361.5	430.6	182.1	103.1	81.9	70.9	1735.6

*MARF=Mean Annual Rain Fall

Annexure C: Rating values assigned to different slope facets

Facets	Relative Relief	Slope Morphometry	Structures	Groundwater	LULC	Slope Material	Man-made Activities	Seismicity	Rain Fall
1	0.6	0.6	1.66	0.6	0.4	0.5	1	1.5	0.75
2	0.8	2	1.86	0	0.4	0.8	1.25	1.5	0.75
3	0.2	0.3	2.31	0	0.75	0.8	1	1.5	0.75
4	0.2	0.6	2.49	2	0.4	0.3	1	1.5	0.75
5	0.6	1	1.82	1	1.5	0.4	0.75	1.5	0.75
6	0.2	0.6	2.5	1	1.5	1	0.75	1.5	0.75
7	0.8	0.6	2.38	1.5	1.2	0.5	0.1	1.5	0.75
8	0.8	2	1.84	1.5	1.5	0.4	0.1	1.5	0.75
9	0.6	0.6	1.58	0	0.4	0.4	0.1	1.5	0.75
10	0.8	0.6	1.88	0	0.75	0.5	0.15	1.5	0.75
11	1	1	2.49	0	1.5	0.4	1.25	1.5	0.75
12	1	1	2.23	1.5	1.5	0.1	1	1.5	0.75
13	0.6	0.6	2	1.5	0.4	0.4	1	1.5	0.75
14	0.6	0.6	1.86	0	0.75	0.8	1	1.5	0.75
15	0.8	1.7	2.5	1.5	1.5	1	1	1.5	0.75
16	0.2	0.6	2.43	2	1.5	1	1.25	1.5	0.75
17	0.8	0.6	1.86	0	0.4	0.3	1	1.5	0.75
18	1	0.6	2.24	0.6	1.2	0.3	0.5	1.5	0.75
19	1	1.7	2.32	2	1.5	1	1	1.5	0.75
20	1	0.6	1.81	0	0.4	1	0.1	1.5	0.75
21	1	1.7	2.5	2	1.5	1	1.25	1.5	0.75
22	0.6	1	1.6	1	0.4	1	0.75	1.5	0.75
23	0.2	0.6	2.11	0.6	1.2	0.8	0.15	1.5	0.75
24	0.6	1	2.13	0	0.4	0.8	0.1	1.5	0.75
25	0.8	1	2.38	1	0.4	0.25	0.75	1.5	0.75
26	1	1	2.5	0	0.4	0.5	0.75	1.5	0.75
27	0.8	2	1.71	2	1.5	1	1	1.5	0.75
28	0.8	0.6	1.94	0	0.4	0.5	0.1	1.5	0.75
29	1	0.6	2.39	0.6	0.75	1	1	1.5	0.75
30	1	0.3	1.78	0	1.5	1	0.1	1.5	0.75
31	1	2	2.32	1	1.5	1	1.25	1.5	0.75
32	1	1	2.16	2	0.4	1	1.25	1.5	0.75
33	1	1	1.6	0.6	0.75	0.5	1	1.5	0.75
34	0.8	1	2.45	0.6	1.2	0.8	0.75	1.5	0.75
35	1	0.6	1.62	2	0.4	0.1	1.25	1.5	0.75
36	1	1.7	2.46	2	1.5	0.4	1	1.5	0.75
37	1	0.6	2.17	2	1.5	0.8	0.75	1.5	0.75
38	0.6	1	2.5	2	1.5	1	1.25	1.5	0.75
39	1	1.7	1.69	1	0.4	0.8	0.1	1.5	0.75
40	0.8	1	2.22	0	0.4	0.8	0.1	1.5	0.75
41	0.8	0.3	2.48	0.6	0.75	0.8	0.75	1.5	0.75
42	1	1	2.03	1	0.4	1	0.15	1.5	0.75
43	1	1	1.94	1	1.5	0.5	1	1.5	0.75
44	1	1.7	2.48	1.5	1.5	1	1.25	1.5	0.75
45	1	1	1.55	0.6	0.4	0.8	0.1	1.5	0.75
46	1	0.6	1.7	0	1.2	0.5	1	1.5	0.75
47	1	1	1.64	0	0.75	1	0.1	1.5	0.75
48	1	1	1.83	0.6	1.2	0.5	0.75	1.5	0.75
49	1	1.7	2	1	1.2	1	0.1	1.5	0.75
50	1	2	2.48	1.5	0.75	0.8	1.25	1.5	0.75
51	1	0.3	2.24	0	0.75	1	1	1.5	0.75
52	1	1	2.5	1	1.2	1	1	1.5	0.75
53	0.8	1.7	1.98	1	1.5	0.5	0.75	1.5	0.75
54	1	2	2.33	1	1.5	0.5	0.75	1.5	0.75
55	1	1	1.84	0.6	1.2	0.8	1	1.5	0.75
56	1	1.7	2.4	2	1.5	1	1	1.5	0.75
57	1	1	2.39	0.6	1.5	0.4	1.25	1.5	0.75
58	1	1	1.98	0	1.2	0.4	0.1	1.5	0.75
59	1	1	2.08	1.5	0.75	1	1	1.5	0.75
60	1	1.7	2.08	1	1.2	0.4	1	1.5	0.75

Annexure D: Rating values awarded to structures

Facets	I	II	III	IV	V	VI	VII	VIII	IX	X
1	0.1	0.15	0.5	0.5	0.05	0.02	0.12	0.04	0.03	0.15
2	0.5	0.1	0.25	0.5	0.1	0.02	0.15	0.1	0.04	0.1
3	0.4	0.4	0.25	1	0.05	0.02	0.02	0.12	0.03	0.02
4	0.3	0.2	0.15	1.4	0.05	0.07	0.15	0.1	0.02	0.05
5	0.25	0.2	0.1	0.5	0.25	0.07	0.12	0.03	0.15	0.15
6	0.1	0.1	0.5	1.4	0.1	0.15	0.02	0.02	0.04	0.07
7	0.4	0.15	0.25	1	0.2	0.02	0.12	0.07	0.15	0.02
8	0.3	0.2	0.15	1	0.05	0.02	0.05	0.03	0.02	0.02
9	0.2	0.15	0.1	0.5	0.2	0.12	0.05	0.07	0.12	0.07
10	0.1	0.2	0.15	1	0.1	0.07	0.05	0.1	0.04	0.07
11	0.5	0.15	0.4	1	0.05	0.15	0.02	0.02	0.15	0.05
12	0.25	0.2	0.25	1	0.2	0.04	0.03	0.04	0.12	0.1
13	0.3	0.15	0.1	1	0.1	0.1	0.03	0.15	0.02	0.05
14	0.1	0.1	0.4	0.5	0.25	0.04	0.1	0.12	0.15	0.1
15	0.4	0.5	0.15	0.5	0.2	0.07	0.15	0.04	0.04	0.07
16	0.5	0.2	0.5	1	0.1	0.04	0.02	0.03	0.02	0.02
17	0.1	0.15	0.15	1	0.25	0.1	0.02	0.03	0.04	0.02
18	0.2	0.5	0.1	1	0.2	0.04	0.05	0.03	0.07	0.05
19	0.3	0.1	0.25	1.4	0.05	0.07	0.05	0.03	0.02	0.05
20	0.4	0.4	0.1	0.5	0.1	0.1	0.02	0.02	0.12	0.05
21	0.25	0.15	0.15	0.5	0.05	0.02	0.05	0.03	0.02	0.1
22	0.2	0.4	0.1	0.5	0.2	0.04	0.02	0.07	0.02	0.05
23	0.5	0.2	0.25	0.5	0.25	0.1	0.07	0.15	0.04	0.05
24	0.4	0.5	0.15	0.5	0.25	0.02	0.15	0.1	0.04	0.02
25	0.1	0.5	0.15	1	0.1	0.04	0.12	0.15	0.15	0.07
26	0.25	0.2	0.25	1.4	0.23	0.02	0.04	0.02	0.04	0.05
27	0.4	0.2	0.15	0.5	0.21	0.04	0.06	0.05	0.04	0.06
28	0.3	0.15	0.4	0.5	0.11	0.1	0.06	0.1	0.12	0.1
29	0.3	0.4	0.1	1	0.05	0.15	0.12	0.1	0.15	0.02
30	0.1	0.15	0.1	1	0.05	0.02	0.15	0.15	0.04	0.02
31	0.31	0.21	0.24	1	0.21	0.1	0.06	0.02	0.02	0.15
32	0.32	0.15	0.2	1	0.12	0.04	0.12	0.07	0.04	0.1
33	0.11	0.15	0.25	0.6	0.05	0.06	0.15	0.07	0.03	0.13
34	0.51	0.4	0.15	0.6	0.25	0.07	0.16	0.14	0.12	0.05
35	0.26	0.11	0.11	0.5	0.2	0.11	0.02	0.15	0.01	0.15
36	0.45	0.3	0.41	0.9	0.21	0.02	0.05	0.03	0.04	0.05
37	0.28	0.5	0.23	0.8	0.05	0.03	0.06	0.1	0.06	0.06
38	0.17	0.14	0.16	0.8	0.11	0.15	0.07	0.07	0.15	0.15
39	0.21	0.11	0.1	0.6	0.24	0.12	0.05	0.03	0.13	0.1
40	0.5	0.23	0.15	0.7	0.23	0.02	0.07	0.15	0.12	0.05
41	0.42	0.45	0.41	0.9	0.05	0.02	0.15	0.04	0.02	0.02
42	0.35	0.43	0.15	0.6	0.04	0.06	0.15	0.03	0.07	0.15
43	0.28	0.22	0.4	0.4	0.2	0.1	0.05	0.1	0.12	0.07
44	0.31	0.15	0.16	0.8	0.1	0.07	0.07	0.15	0.04	0.06
45	0.1	0.11	0.1	0.5	0.24	0.15	0.02	0.03	0.15	0.15
46	0.43	0.41	0.26	0.12	0.23	0.02	0.01	0.03	0.06	0.13
47	0.38	0.29	0.13	0.21	0.19	0.1	0.11	0.15	0.03	0.05
48	0.25	0.15	0.41	0.4	0.11	0.03	0.12	0.1	0.15	0.11
49	0.33	0.11	0.15	1	0.05	0.04	0.05	0.1	0.02	0.15
50	0.22	0.41	0.18	1	0.21	0.15	0.02	0.13	0.12	0.04
51	0.44	0.42	0.21	0.8	0.11	0.02	0.15	0.03	0.02	0.04
52	0.23	0.15	0.43	1.2	0.21	0.07	0.12	0.05	0.03	0.01
53	0.31	0.23	0.15	0.5	0.22	0.11	0.13	0.15	0.03	0.15
54	0.42	0.41	0.11	0.8	0.25	0.14	0.07	0.1	0.02	0.01
55	0.1	0.48	0.13	0.6	0.13	0.05	0.05	0.03	0.12	0.15
56	0.47	0.41	0.44	0.8	0.05	0.01	0.05	0.11	0.03	0.03
57	0.36	0.39	0.34	0.6	0.12	0.15	0.12	0.12	0.04	0.15
58	0.23	0.14	0.47	0.5	0.2	0.04	0.11	0.15	0.03	0.11
59	0.13	0.26	0.16	1	0.24	0.07	0.13	0.03	0.02	0.04
60	0.22	0.11	0.24	1	0.23	0.06	0.12	0.02	0.03	0.05
Where										
I= Parallellism between discontinuities dip direction and slope						II=Relationship between dip of discontinuity and inclination of slope				
III=Dip of discontinuity or plunge of line of wedge forming planes						IV= Soil cover depth				
V=Structural discontinuities and Rock mass condition						VI=Continuity				
VII=Separation						VIII=Roughness				
IX=Infilling						X=Weathering				

