Addis Ababa University

School of Graduate Studies,

College of Natural Sciences

LANDSLIDE HAZARD EVALUATION AND ZONATION IN THE AREA KINDO DIDAYE WOREDA, SOUTH WEST ETHIOPIA

"A Thesis submitted to

The School of Graduate Studies of Addis Ababa University in partial fulfillment of the requirements for the

Degree of Master of Sciences in

Engineering Geology ''

By

Zerihun Dawit

May 2016

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This is to certify that the thesis prepared by **Zerihun Dawit**, entitled: *Landslide Hazard Evaluation and Zonation in the area Kindo Didaye, South West Ethiopia:* submitted in partial fulfillment of the requirements for the Degree of Master of Science (Engineering Geology) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the Examining Committee:

Examiner: ________________ Signature _______________ Date ________________

Examiner: __________________ Signature _______________ Date ________________

Advisor: Dr.Trufat H/Mariam Signature ___________ Date ________________

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Chair of School or Graduate Program Coordinator

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Zerihun Dawit

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Abstract

Landslide Hazard Evaluation and Zonation
in the area Kindo Didaye, South West, Ethiopia.

Zerihun Dawit

Addis Ababa University, 2016

In the present study landslide hazard evaluation and zonation (LHZ) was carried out in the area Kindo Didaye Woreda in South western Ethiopia, about 450 km South West of Addis Ababa, the capital city of Ethiopia. The main objective of the present study was to evaluate landslide hazard zonation by using integrated Slope stability Susceptibility Evaluation Parameter (SSEP) expert technique and a raster based Information Value statistical approach.

In the case of Landslide Hazard Zonation carried out by Slope stability Susceptibility Evaluation Parameter (SSEP) the landslide hazard zonation of the study area was carried out through facet wise Evaluated landslide hazard which indicates the net probability of instability. Relative relief, slope morphometry, slope material, structural discontinuity, landuse/landcover, groundwater surface manifestations are intrinsic causative parameters that were considered in this method. The external causative parameters include: rain induced manifestations, seismicity and manmade developmental activities. The area has been classified into 102 facets. The data for above mentioned have been collected and the rating values were given based on SSEP rating scheme for each causative parameters. The Evaluated landslide hazard (ELH) for an individual facet was obtained by adding the ratings of individual parameter obtained from the SSEP rating scheme. Later, landslide hazard zonation has been classified into three classes.

For integrated SSEP and a raster based Information Value method the methodology followed was based on the analysis of seven causative parameters and past landslides in the study area. For the present study seven causative parameters namely; relative relief, slope morphometry, slope material, landuse/landcover, groundwater surface manifestations, rain induced manifestations and manmade developmental activities were considered. Later, Information value was calculated based on relative influences of causative factors on past landslides. The landslide inventory mapping for this study has been prepared using through field investigation and google earth image interpretation. The distribution of landslide over each of each of factor maps have been obtained and analyzed. Weights for each of the classes within these factor maps have been obtained using the information value method. Final landslide susceptibility value for each pixel within the study area has been obtained using by summing up the weight derived for that pixel in all of the factor maps. The resultant landslide susceptibility index map has been classified in to three landslide hazard zonation classes.

The landslide hazard zonation map of the study area through SSEP method shows that moderate hazard zone covers 21 % (18 km^2), high hazard Zone covers 63% (54 km^2) and very high hazard zone covers 16% (13 km^2) of the total study area. In case of the landslide hazard map of the study area through integrated SSEP and raster based statistical information value 24%(20km^2) area fall in the moderately hazard zone whereas 41%(35km^2) and 35%(30km^2) and of the area fall high and very high hazard zone , respectively. In the case of landslide hazard zonation map through SSEP method, out of 71 landslides inventory data 2 falls (3%) in moderate hazard zone, 50 falls (71%) in high hazard zone and 19 falls (27%) on very high hazard zone. Whereas, landslide hazard zonation map of the study area through SSEP and raster based Information Value method, out of 71 landslide inventory data 4 (6%) falls in moderate hazard zone, 14 (20%) falls in high hazard zone and 53 (74%) falls on very high hazard zone. The verified landslide hazard zonation maps indicates that 94 % of inventory data fall on high and very high hazard zones in both the approaches. The validation of LHZ map thus, reasonably showed that the adopted methodology produced satisfactory results and the delineated hazard zones may practically be applied for the regional planning and development of infrastructures in the area.

Key words: landslide, landslide hazard zonation, Information Value Model, SSEP, validation

Chapter One Introduction

1.1 Background

The term natural hazard is described by Varnes (1984) as the occurrence of a natural condition or phenomenon, which threatens or acts hazardously in a defined space and time. Landslide is considered as one the most significant natural hazard throughout the world (Crozier and Glade, 2005).

Varnes (1984); Cruden (1991) and Highland and Bobrowsky (2008) defined landslides as downslope movement of soil, rock, and organic materials which consists of rock topples, rock falls, earth or debris flows that involve shear displacement along one or several slip surfaces, which are either visible or may be reasonably inferred under effects of gravity.

Whether occurring naturally or triggered by human activity, landslides are among the common geoenvironmental hazards in many of the hilly and mountainous terrains of both developed and developing world. It is responsible for hundreds of billions in property damage per year, damages transportation networks, buildings and structures, public works projects, causes deaths and injuries for thousands each year. It often cause long-term economic disruption, population displacement, and negative effects on the natural environment which is becoming severe with the increasing population and poor economics of developing area (Wachal and Hudak, 2000; Dai et al., 2002; Arnous, 2011 and Kifle Woldearegay, 2013).

The aim of landslide study is to evaluate the nature of hazard and the damages to the human life, land, roads, buildings and other properties (Anbalagan and Singh, 1996, Arnous, 2011). Determining landslide prone areas is important to ensure the safety of human life and avoid negative impacts on the regional and national economy. Landslide hazard map provide valuable information for government agencies, planners, decision makers, and local landowners to make emergency plans to reduce the negative effects on infrastructure, superstructure, and human life (Ercanoglu and Gokceoglu 2003, Anbalagan and Singh, 1996).

The previous studies show that landslide is common in northern, southern and western highlands and partly rift escarpment of Ethiopia due to various natural and man-made influencing factors (Berhanu Temesgen et al., 1999; Lulseged Ayalew and Yamagishi, 2004; Lulseged Ayalew et al., 2004; Tenalem Ayenew and Barbieri, 2005; Engedawork Mulatu et al., 2009; Bekele et al, 2010; Kifle Woldearegay, 2013; Raghuvanshi et al., 2014; Matebie Meten et al, 2015; Fikire Girma et al., 2015).

1.2 Description of the Study Area

1.2.1 Location and Accessibility

The present study area is located in South Western Ethiopia, South Nations Nationalities Peoples Regional State (SNNPRS), Wolaita Zone in Kindo Didaye Woreda (Fig 1.1). It is about 450 km South West of the capital city, Addis Ababa and covers a total surface area of 85 Km^2. Geographically it is bounded between 738000m N - 750000 m N latitude and 312000 m E- 330000 m E longitude at UTM Zone 37N.

The study area can be acessed from Addis Ababa through Butajira-Hossana-Woliata Sodo-by asphalted road while from Woliata Sodo- through Bele Woreda-Kindo Didaye by gravel road.

1.2.2 Climate

Daniel Gemechu (1977) traditionally catagorized climatic zones into five elevation classes. The elevation <800m catagorized into Desert climatic zone (Bereha), from 800 m-1500 m Tropical (Kola), from 1500-2300 m Subtropical (Weynadega), from 2300-3300 m Temprate (Dega), > 3300 m Alpine (Kur). The elevation of the study area ranges from 859 to 2826 m . Accordingly, cliamte zone of the study area is classified into tropical (800-1500 m), subtropical (1500-2300 m) and temperate (2300-3330 m)(Fig.1.2).

From 1986 to 2014 , the recorded mean annual rainfall of the study area is about 1378 mm. The highest monthly average precipitation recorded was 400.3 mm in the month of May, 1993. The area is characterized by unimodal rainfall pattern. From October to February the area receives low rainfall whereas from May to September it recieves high rainfall (Fig. 1.3 and Fig. 1.4).

The monthy average temperature of the study area from 1986-2014 is 22.6 °C . The monthly maximum temperature of study the area is 30.3 °C in the month of March, 1988 whereas minimum monthly temperature which was recorded in the month of September, 1986 is 12.1 °C.

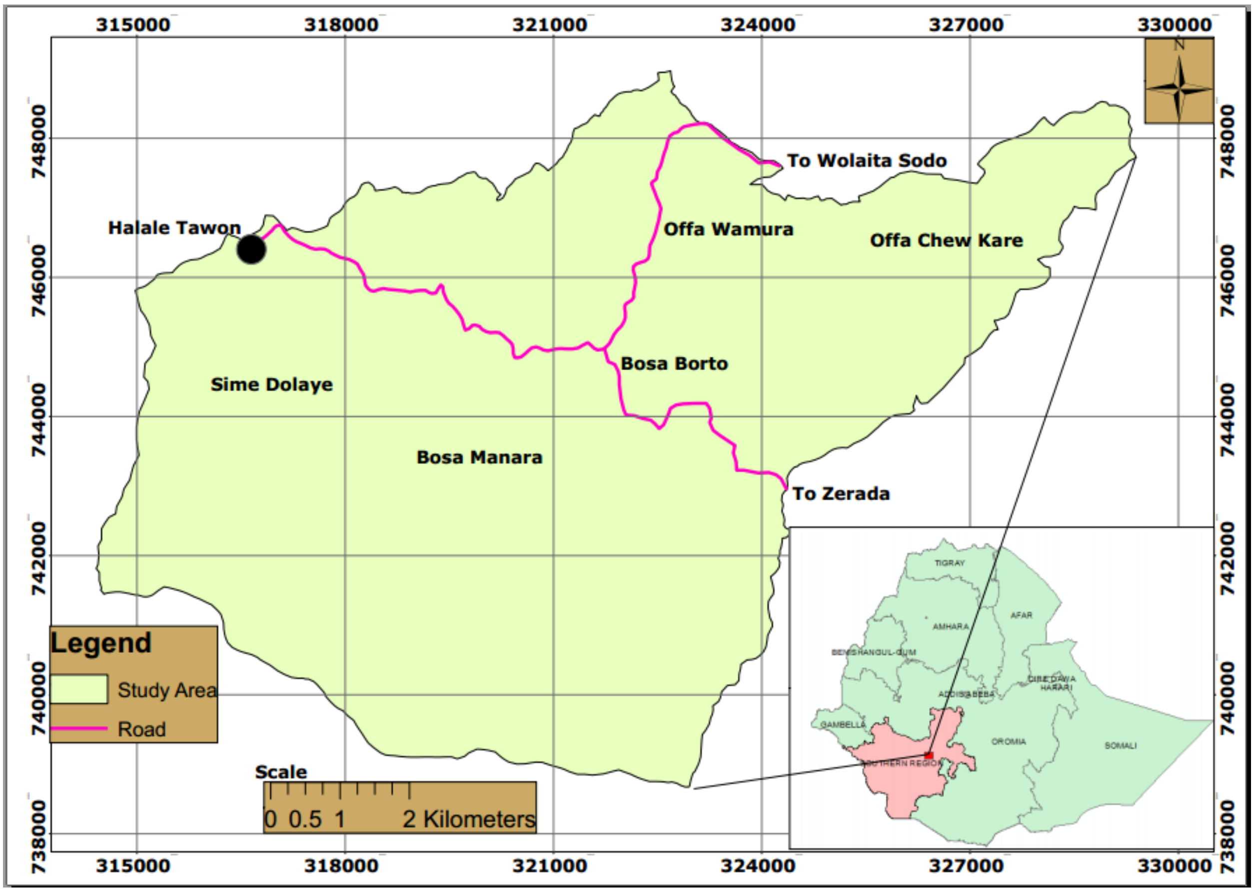

Fig.1.1. Location map of the study area.

1.2.3 Physiography and Drainage Pattern

The study area is located in southwest Ethiopian plateau with the range of elevation from 859 m to 2826 m. The study area extends from the highland in north part to deeply eroded southern part of Deme River valley. Generally, the elevation declines from northeast to south-west. The study area is bordered in West side by Didaye Ridge, North side by Watame and Gaza Ridge, East side by Koyisha Mountain and towards South by Deme River. The physiography of the study area is a result of volcanism and erosion. The area is modified by erosion, resulting in highly dissected topography with steep gullies after volcanism which has formed ridges in the area (Plate 1.1).

The study area is located within Omo river basin. Deme River is a major River which flows from southeast direction and finally joins Omo River. Mayle, Becha, Kila and Zala Kare are a tributary river which flow from NE-SW and finally joins the Deme River. Mayle, Becha and Kila rivers are parallel to each other. Many small tributaries from different direction are flowing into these rivers. Although there are some important tributaries from different directions the general direction of flow is southwards, towards Deme River. The drainage pattern of the present study area is parallel and dendritic (Fig. 1.5).

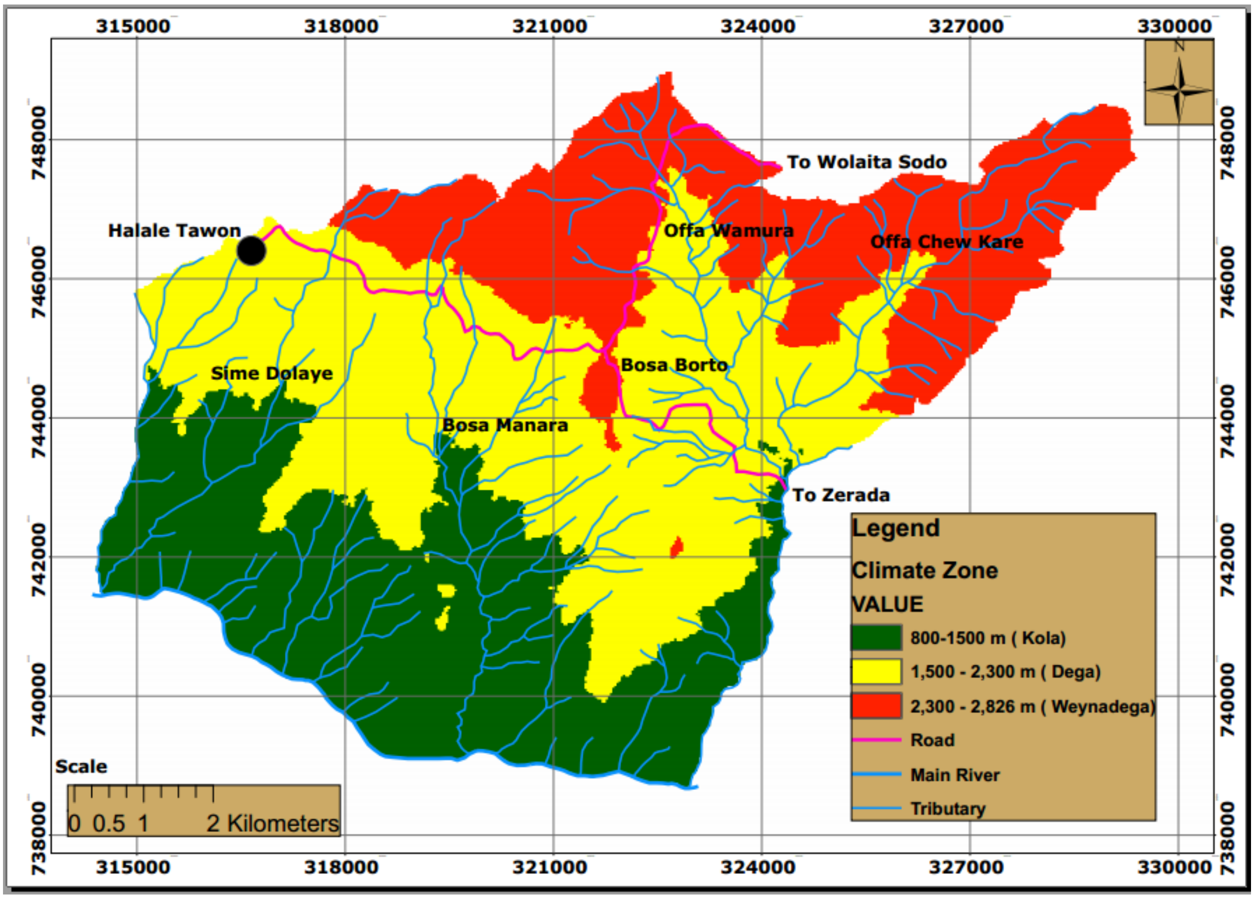

Fig.1.2. Climatic zone map of the study area.

1.2.4 Vegetation

Scattered bushes, wild grass and some trees are the types of vegetation which cover most parts of the ridges in the study area. The gorges and river sides are relatively densely vegetated, the steeper parts are sparsely vegetated and foot of the mountain is cultivated by different kinds of crops and vegetables. The dominant crop production in the area is sorghum, maize, teff, enset, mango, banana, casaba and vegetables (Plate 1.2).

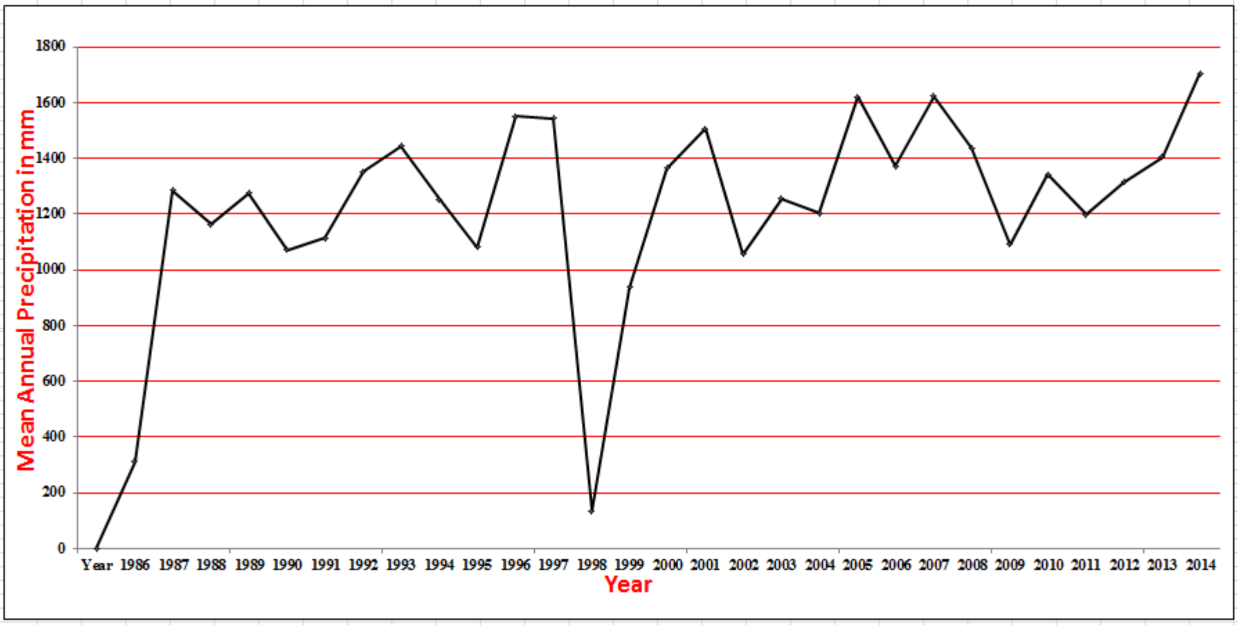

Fig. 1.3. The mean annual precipitation of study area (1986-2014).

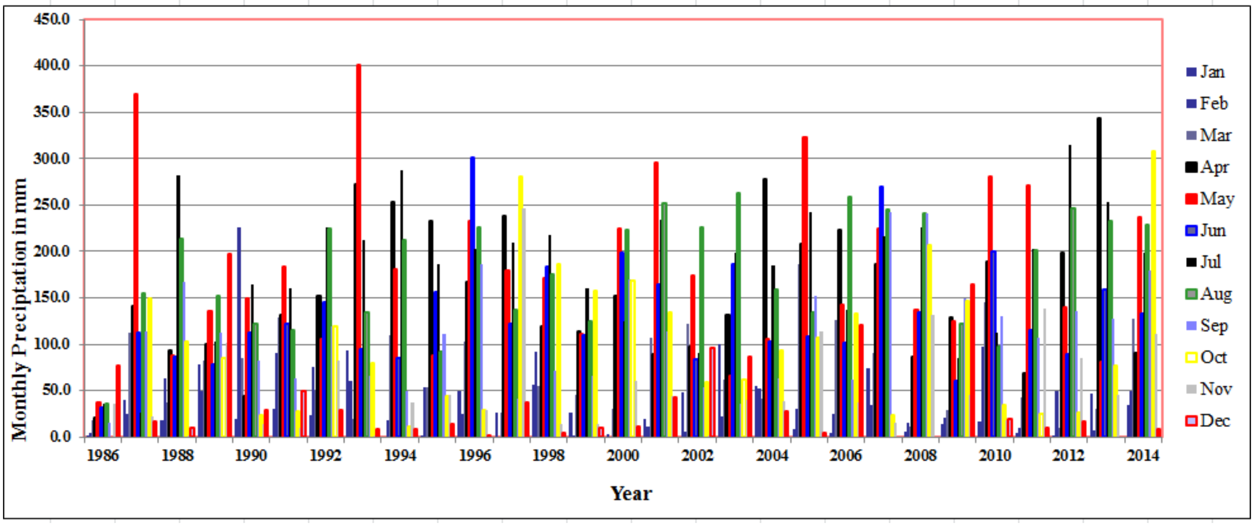

Figure 1.4. The monthly precipitation of the study area(1986-2014).

1.2.5 Seismicity

Seismic Risk Map produced by Laike Mariam (1986) shows that the likely peak ground acceleration (PGA) with a hundred year return period and 0.99 probabilities the study area falls within 6 M.M scale (Fig.1.6). Based on the Modified Mercalli intensity scale the estimated horizontal earthquake acceleration comes out to be 0.06 g, as determined from the MM intensity graph (Johnson and Graff, 1988).

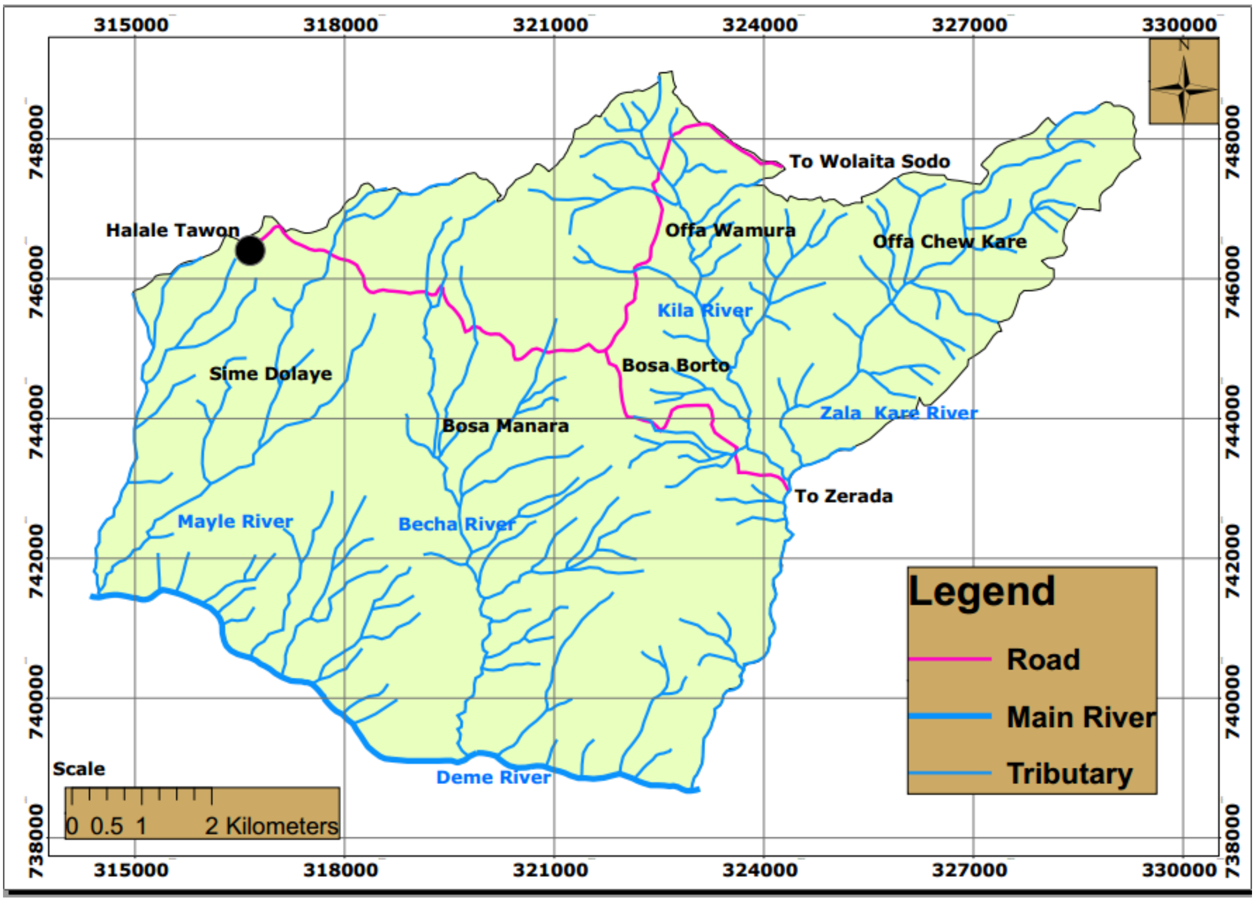

Fig.1.5 Drainage map of the study area.

(A). Ridge at North East of Halae Tawon. (B). The rige and valley at Bosa Manara Kebele. (C). The dissected valley along the the Deme and Mayle River. (E). Gully cut formed due to erosion at Offa Wamura Kebele. (F). Halale Tawon at rugged topography.

Plate 1.1 Physiography of the study area.

***(A) Mongo and casaba. (B). Casaba. (C) Banana. (D). Enset*.**

Plate 1.2 Vegetation coverage of the study area.

1.3 Problem of the Statement

The studies by Berhanu Temesgen et al. (1999); Lulseged Ayalew and Yamagishi (2004) Tenalem Ayenew and Barbieri (2005); Engedawork Mulatu et al. (2009); Bekele Abebe et al., (2010), Kifle Woldearegay (2013); Raghuvanshi et al. (2014) and Fikire Girma et al. (2015) verified that landslide is common in northern, southern and western highlands and partly rift escarpment of Ethiopia due to various natural and man-made factors.

According to Lulseged Ayalew (1999) the Ethiopian Highland is a highly populated region, in which more than 60% of the country's population is settled. Due to settlement of population in such areas it made landslide generated hazards a serious concerns to public, planners and decision-makers at various levels of the government in Ethiopia (Bekele Abebe et al., 2010; Kifle Woldearegay, 2013).

As shown in table 1.1, landslide has been causing serious problem on human life, animals, crops and property in Kindo Didaye area. Among these August 31, 2010 landslide hazard has killed 8 people and destruction of house and property (Plate 1.3). In May 9, 2016 landslide has caused death of 39 people and displacement of 192 people in Kindo Diadye area. The report from local people and office of Woreda agriculture and natural resources indicates that from 2005 to 2016 alone, landslide have resulted death of 51 people and damaged agricultural lands, houses and infrastructures in Kindo Didaye area.

In order to minimize the damage due to landslide hazard it is needed that the areas which have a potential for such landslide should be identified and mapped (Varnes, 1984). Due to this evaluation of the factors influencing landslide hazard initiation and occurrence, and mapping landslide hazard zonation is important to recognize the spatial probability of landslide for safer strategic planning of future developmental activities and to minimize the upcoming impact. This was initiated me for studying the landslide process, analyze threatening landslide hazard and predict the future landslides for reducing ongoing and future damage from landslides in the area.

Currently, landslide hazard zonation mapping had not been done yet in Kindo Woreda even though the area is often suffering by landslide. Thereby, this study focused on generating landslide hazard zonation for this area so as to improve the current spatial plan and to guide local government in managing present and future land utilization. Landslide hazard zonation is essential before planning and executing any developmental activities in mountainous terrain (Raghuvanshi et al., 2014; Matebie Meten et al., 2015; Anbalagan, 1992).

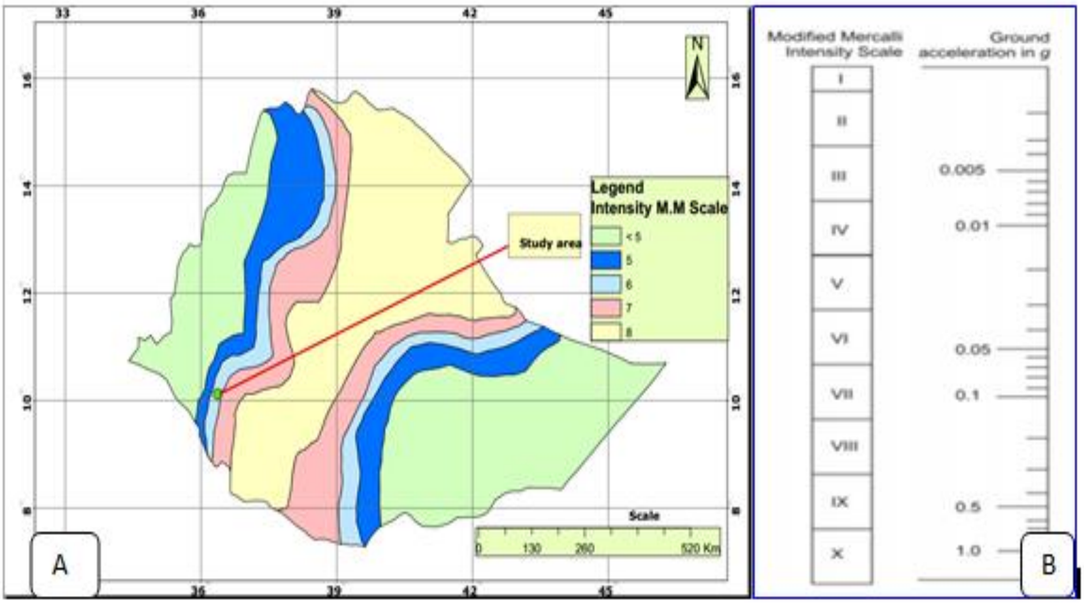

Fig.1.6 (A) Seismic risk map of Ethiopia 100 year returns period, 0.99 probabilities (Source: Laike Mariam, 1986). B). Relationship between intensity of earthquake, based on Modified Mercalli intensity scale, and the ground acceleration (Source: Johnson and Graff, 1988**).**

1.4 Objectives of the Study

1.4.1 General Objective of the Study

The main objective of this study is to evaluate landslide causative factors and prepare landslide hazard zonation map of the Kindo Didaye area by using integrated Slope stability Susceptibility Evaluation Parameter (SSEP) and a raster based Information Value method.

1.4.2 Specific Objectives of the Study

Specific objectives of the research are:

- To understand the relationship between various causative factors.
- To carry out inventory mapping.
- To understand mechanism and responsible triggering factors.
- To build landslide potential hazard zone.
- To check the accuracy of landslide hazard map.
- To determine areas of future very high, high and moderate potential landslide hazard zone.

Table 1.1 Landslide hazard damage on life and property in different Kebeles of Kindo Didaye Woreda.

Woreda /Kebele name	**Year of occurrence**	**Death**		**Damage on property**
		Human life	**Animals**	
Kindo Didaye /Offa Chew Kare Kebele	August, 2010.	8 people from two families.	3cow and 3 goat	Total destruction of Ato Bosa Osa and Ato Zerma Shaga houses and property.
Kindo Didaye, Offa Chew Kare Kebele	July , 2005	2 people	6 cow and 8 sheep	It caused damage of Ato Chulto Mana house property and enset. The farmer changed his settlement to other place.
Kindo Didaye, Offa Chew Kare	2012	2 people	5 cow and 4 sheep	It caused damage on Ato Enko Maja house property and enset. The farmer changed his settlement to other place.
Offa Wamura, Patata and Gocho Kebele	May 9, 2016	39 People		192 people displaced their home.

1.5 Significance of the Study

The landslide hazard map of the study area can be used to recognize the spatial likelihoods of landslide for safer strategic planning of future developmental activities. This may help to select appropriate sites for agriculture, construction and other development activities, and to minimize the upcoming impact in landslide prone areas by providing important information for concerned bodies and local government in managing present and future land utilization. Identification of landslides and production of landslide zonation map is important to planners, local administrations, and decision makers in disaster planning for reducing the losses of life and property (Anbalagan and Singh, 1996; Ercanoglu and Gokceoglu, 2003; Bekele et al., 2010).

Location of study area in South West Plateau and Omo Gibe basin tells that the area have rugged topography and high relative relief (Bekele Abebe et al., 2010; Kifle Woldearegay, 2013). This shows that the rugged topography and high relative relief can be one of causes of landslide occurrence in the area. 70% of the area a fall in Dega to Woyna Dega climatic zone and it receives 1378 mm annual mean annual rainfall. According to Raghuvanshi et al., the area receives high annual rainfall. The previous reported landslides (Table 1.1) in the area shows that most of landslide occurred at the rainy season from May to September month and in Dega to Woyna Climatic Zone indicates that landslides have strong relationship climatic condition. According to Bekele Abebe et al., (2010) high summer rainfall is one of influencing factor for occurrence of landslide in Ethiopia. This reveals that the rainfall is causes for landslide in the area. According to Lulseged Ayalew (1999) the study area is located in South West Ethiopian highland which is a highly populated region. In addition, it is located in Wolaita Zone the most densely populated area in Ethiopia. This shows that the human life and property are exposed to landslide hazard.

1.6 **Future Studies and Extension of the Research Work**

According to Fana Broad Casting Corporate 99.9 and local government report in May 9, 2016 landslides in Kindo Didaye has killed 39 people references. This tells how much the area is hazardous to life and property. The landslide in the area is life threatening so that this study must have a continuation in the future in either assessment of vulnerability and risk to landslide hazard or other large scale study since to reduce the effects of landslide hazard on life and resources.

1.7 Thesis Outline

The present study is organized into six chapters.

Chapter one gives a general introduction to landslide, description of the study area, introducing the study problem of statement, the objectives of the study, its significance of result, and future extension of the study..

Chapter two reviews wide and detail literatures with regards to landslide, its causative factors, classification of landslides, failure mechanism, effects of landslides, landslide hazard zonation approaches and previous studies on landslide in Ethiopia.

Chapter three discusses the methods and materials followed: pre-field, field, post-field investigations followed.

Chapter four focus on regional and local geology of the study area.

Chapter five is devoted to discussion and result which focuses on relationship landslide hazard zonation, evaluating the most influential parameter, inventory mapping, landslide hazard mapping and verification of the result.

Chapter six is about conclusion and recommendation of the study

In the next chapter, literature reviews with regards to landslide, its causative factors, and classification of landslide, failure mechanism, and effects of landslide, landslide hazard zonation approaches and previous studies on landslide in is Ethiopia is discussed.

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Chapter Two Literature Review

2.1 General

Varnes (1984), Wachal and Haduk (2000), Highland and Bobrowsky (2008) used the word landslide to describe any downslope movement of rock and regolith near the earth's surface under influence of gravity with little or no true sliding. It is triggered by rainfall, earthquake, volcanic and manmade activity (Keefer, 2000; Dai et al., 2002; Highland and Bobrowsky, 2008). Anbalagan (1992) and Raghuvanshi et al. (2014) categorized landslide causative factors into intrinsic or inherent and external or dynamic factors. By understanding these causative factors and nature of past landslide of terrain it is possible to divide the terrain into homogenous area domains and their ranking according to actual or potential landslide susceptibility (Varnes, 1984; Wachal and Haduk, 2000). Landslide hazard zonation map plays important role by providing valuable information to planners, developers, and engineers who advise or implement land use strategies (Ercanoglu and Gokceoglu, 2003). Due to damage on transportation networks, buildings and structures, public works projects, and personal property and human and animal life (Dai et al, 2002; Kifle Woldearegay, 2013) study of landslide has come to be worldwide attention (Varnes, 1984).

2.2 Factors Influencing Landslides

2.2.1 Intrinsic Factors

Intrinsic parameters are the inherent or static causative parameters which define the favorable or unfavorable stability conditions within the slope (Anbalagan, 1992; Raghuvanshi et al., 2014) and include slope geometry, slope material, structural discontinuities, land use and land cover and groundwater into causative parameters (Raghuvanshi et al., 2014).

2.2.1.1 Slope Geometry

This intrinsic parameter includes the relative relief and slope morphometry of the slope (Raghuvanshi et al., 2014). Slope morphometry express the steepness of the slope and it causes slope instability within the slope (Hoek and Bray, 1981). According to Hoek and

Bray (1981) the slope will be prone to instability when the slope morphometry is steep. Varnes (1984) explained that the chance of occurrence of landslide increases with an increase in slope steepness though landslide occurs in all slope. The relative relief tells the difference between maximum and minimum elevation of individual facet. As the relative relief is higher the slope is prone to instability (Bekele Abebe et al., 2010, Raghuvanshi et al., 2014).

2.2.1.2 Slope Material

Slope material can be soil, rock or both soil and rock (Varnes, 1984). The composition, fabric, texture and other properties of slope material influence shear strength, permeability and susceptibility to chemical and physical weathering of slope material. The grain size, shape, sorting, the amount and type of cement also determine the strength and stability of slope material. The unconsolidated slope materials are more susceptible to instability than consolidated one because they have less cohesion and friction, have higher infiltration rates than consolidated slope materials (Varnes, 1984).

Slope material and slope morphometry determine the type of landslide with in the slope. In areas where the slope morphometry is steep and the slope material is covered by hard bed rock like basalt, welded ignimbrite, limestone and sandstone landslide like rock falls, topplings and rockslides/avalanches are common (Varnes, 1978; Berhanu Temesgen et al, 1999). As Varnes (1978) and Berhanu Temesgen et al. (1999) clarified when the slope material deeply weathered volcanic rocks like pyroclastic rocks, rapid landslides mostly involving the eluvial-colluvial cover (debris slides and avalanches, debris flows, earth flows and mudflows) happen. In the banks of deeply incised rivers and gullies the rapid collapse phenomena like topples and slumps frequently occur (Varnes, 1978). When the slope material is like alluvial and coluvial deposits at the foot of the steep slopes, and thick weathered layers on volcanic bed-rock the rotational slides, sometimes passing to earthflows or mud-flows are often produced. Rapid translational slide is probable in slope where hard competent layer overlain by soft clayey bed that dipping downslope. In thick alluvial and coluvial deposits slow translational slides may happen (Varnes, 1978; Cruden and Varnes, 1996).

2.2.1.3 Structural Discontinuities

According to Bell (2007) a discontinuity represents a plane of weakness within a rock mass across which the rock material is structurally discontinuous. Both primary and secondary discontinuities such as bedding, joints, foliation, cleavage, schistosity, folds and faults are potentially weak planes in a slope that intense influence up on the stability of the slope especially if their inclination facilitates downhill movement of the slope in which they occur (Blyth and de Freitas, 2005). As Blyth and de Freitas (2005) described the strength of joints and other geological surfaces is usually less than that of the intact rock they bound; often they are the weakest component of slope geology. It is therefore vital to know their orientation, spacing, continuity, roughness, separation, and nature of filling material in relation to slope angle, direction, and strength along such potential weak planes. Fault zones increase landslide potential by creating steep slopes and sheared and weak zones (Wachal and Haduk, 2000). The rock mass may fail along one or more discontinuity plane (Raghuvanshi et al., 2014).

2.2.1.4 Land Use and Land Cover

Land use/landcover affects slope stability. Vegetation tends to increase the stability of slope by increasing shear strength, and the action of climatic agents on natural mass. By intercepting and protecting the mass from action of sunshine, wind and rain it reduces soil erosion. Vegetation cover also prevents the excesses seepage of water into the slope though it depends on soil depth, slope and type of vegetation. The roots of plants also increase the shear strength the slope by binding the soil mass. Regions with dense vegetation are found to be less prone to slope instability than sparse vegetation, agriculture and urbanization. The areas that are barren and sparse vegetation cover are more prone to erosion and weathering because the type of ground cover affects the stability (Varnes, 1987; Berhanu Temesgen et al., 1999; Turrini and Visintainer, 1998; Wachal and Haduk, 2000; Bekele Abebe et al., 2010; Raghuvanshi et al., 2014; Kifle Woldearegay, 2013).

2.2.1.5 Groundwater

Saturation of groundwater in slope reduces the shear strength of the material and also creates pore water pressure which plays important role in slope stability condition

(Waltham, 2009; Highland and Bobrowsky, 2008). Waltham (2009) explained that groundwater with in jointed rock mass, and in soil mass reduces the shear strength of slope material by developing of joint water and pore water pressure.

2.2.2 External Factors

According to Varnes (1984), Dai and Lee (2001) and Raghuvanshi et al. (2014) the external causative factors are relatively variable or dynamic, temporary and imposed by new events which include rainfall, volcanic activity, seismic vibration and manmade activities.

2.2.2.1 Rainfall

Rainfall is a primary cause of landslides and worse slope stability problems (Berhanu Temesgen et al., 1999; Lulseged Ayalew et al., 2004; Collision et al., 2000; Dai and Lee, 2001; Dahal et al., 2006). According to Varnes (1984), Espizua and Bengochea (2002) and Kifle Woldearegay (2013) the rainfall intensity and duration play an important role by triggering landslide like debris flows, mudflows, and medium to large-scale rockslides though it depends on climatic conditions, topography, the geological structure of slopes, and permeability of material. It plays vital role by decreasing the shear strength of material by saturating the slope material. It also cause the sliding of rock along discontinuities plane by lubricating discontinuities surface and developing pore water pressure in rock slope (Highland and Bobrowsky, 2008). The rainwater can cause the slope instability by increasing the weight on slope especially in areas where the slope material is soil mass (Hoek and Bray, 1981).

2.2.2.2 Seismicity

Earthquakes are a major cause of landslide in many parts of the world and have caused tens of thousands of deaths and billions of dollars in economic losses. Earthquake shaking is one of the agents that can cause landslide due to ground shaking, liquefaction of susceptible sediments, or shaking-caused dilation of soil materials (Keefer et al., 1984, 2000; Highland and Peter, 2008). As stated by Highland and Bobrowsky (2008) due to ground shaking and shaking caused the rapid infiltration water strong seismic ground motion is triggering mechanism of large landslides. Ground shaking decreases the shear resistance of slope material and also generates the high excess pore water pressure which adds slope instability condition (Highland and Bobrowsky, 2008).

2.2.2.3 Volcanic activity

Volcanic activity can cause most devastating type of slope failures. Volcanic lava can melt snow which forms a flood rock, soil and water which escapes from steep slopes the volcano can devastate anything in its path (Highland and Bobrowsky, 2008). Volcanic activity causes the most devastating types of landslide due to volcanic lava which may melt snow rapidly and form a flood of rock, soil, ash, and water that go rapidly on the steep slopes of volcanoes (Highland and Bobrowsky, 2008).

2.2.2..4 Man-made factors

Highland and Bobrowsky (2008), Bekele Abebe et al. (2010), Kifle Woldearegay (2103) explained that the demand for new land for settlement, infrastructure and agriculture are primary means by which humans can contribute to slope instability condition. Human activities like changing or disturbing drainage pattern, destabilizing the slopes, removing vegetation, overstepping of slopes by undercutting the bottom slope, loading the top of slope and irrigation may result directly or indirectly initiate the slope instability condition Highland and Bobrowsky, 2008).

2.3 Occurrence, Classification, Causes, Failure Mechanisms and Effects of Landslides

2.3.1 Occurrence of Landslides

As Highland and Bobrowsky (2008) explained landslides can occur anywhere in the world. It occur both land and under water, they can occur in bedrock or soils, cultivated land, barren slopes and natural forests, extremely dry areas or wet areas, gentle slope or steep slope.

2.3.2 Classification of Landslides, failure mechanism and effects of landslides

Landslide includes almost all varieties of mass movements on slopes, including such as rockfall, topples, debris flow that involve a little slide or no true sliding under influence of gravity (Varnes, 1984; Highland and Bobrowsky, 2008). It can be categorized based on type of movement and kind of material involved into falls, topples, slides, spreads, flows and complex movements (Varnes, 1984; Wachal and Haduk, 2000; Highland and Bobrowsky, 2008). The speed of movement, volume of displacement, distance of travel, possible effects and appropriate mitigative measurements are depends on the type of landslide (Wachal and Haduk, 2000; Highland and Bobrowsky, 2008).

2.3.2.1 Fall

Falls are most often characterized as abrupt free fall of bedrock or soil. A fall starts with the detachment of soil or rock from a steep slope along a surface on which little or no shear displacement takes place. The material then descends mainly through the air by falling, bouncing, or rolling (Highland and Bobrowsky, 2008) (Fig.2.1). The triggering mechanism of fall are undercutting of slopes by streams and rivers or differential weathering, excavation during road building and earthquake shaking. It is common in on steep slopes, or vertical slopes also in coastal area, along rocky bank of river and streams, road cuts, and jointed, fractured and weathered bedrock (Wachal and Haduk, 2000). The material in fall can vary from individual rocks or masses of soil o massive blocks. The rate of movement depends on steepness of slope and usually ranges from very rapid to extremely rapid. It can damage on life and property particularly beneath the fall line of large blocks (Wachal and Haduk, 2000; Highland and Bobrowsky, 2008)

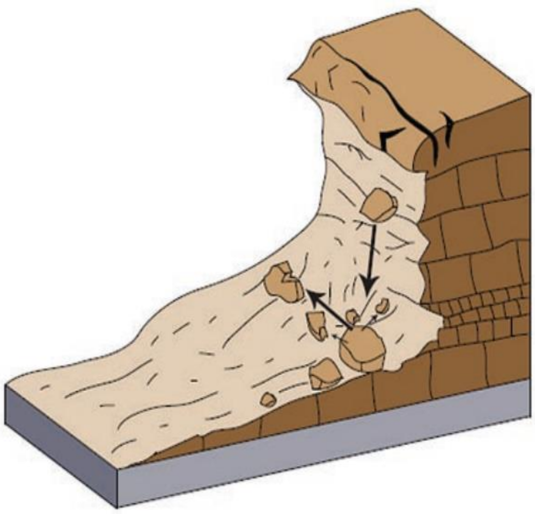

Fig. 2.1.Schematic of rockfall (Source: Highland and Bobrowsky, 2008).

2.3.2.2 Topples

Topples is the forward rotation out of the slope of mass of soil or rock about a point or axis below the centre of gravity of the displaced mass (Fig.2.2). The triggering mechanism of topples are gravity, water or ice occurring in cracks within the mass, vibration, undercutting, differential weathering, excavation or stream erosion. It occurs in columnar jointed volcanic terrain, as well as along streams and river courses where the banks are steep. It can consist of rock, coarse and fine materials. The rate of movement ranges from extremely slow to extremely rapid. It can be extremely destructive especially when failure is sudden or velocity is rapid (Highland and Bobrowsky, 2008).

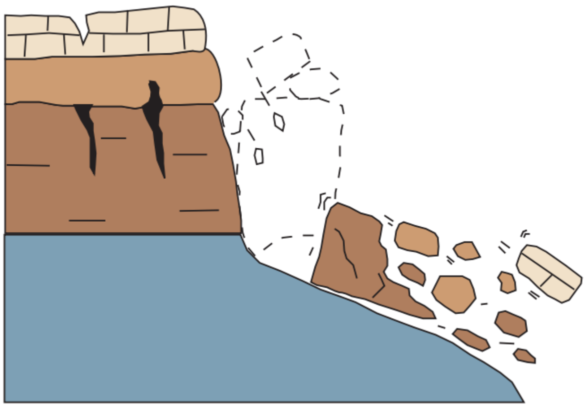

Fig.2.2.Schematic of topple (Source: Highland and Bobrowsky, 2008)

2.3.2.3 Slides

A slide is a down slope movement of soil or rock mass occurring predominantly on the surface of rupture or on relatively thin zones of intense shear strain (Wachal and Haduk ,2000; Highland and Bobrowsky, 2008). It is categorized into rotation slide and translational slide.

In rotational slide surface of rupture is curved or spoon-shaped and it is triggered by intense rainfall or snowmelt (Fig. 2.3 (A)). They are common in loose unconsolidated soils and their rate of movement ranges from extremely slow to moderately fast. It can extremely damage structures but not life if the movement is slow (Highland and Bobrowsky, 2008).

In translational slide the surface of rupture is planar surface and it is triggered by intense rainfall, snow melt, and human induced disturbances (Fig. 2.3 (B)). Translational slides commonly fail along geologic discontinuities such as faults, joints, bedding surfaces or the contact between rock and soil (Highland and Bobrowsky, 2008). The material ranges from loose, unconsolidated soil to extensive slab of rock or both. The movement may initially slow but many are moderate to extremely rapid. Highland and Bobrowsky (2008) added that slow moving landslides can occur on relatively gentle slopes and can cause significant property damage, but are far less likely to result in serious injuries than rapidly moving landslides.

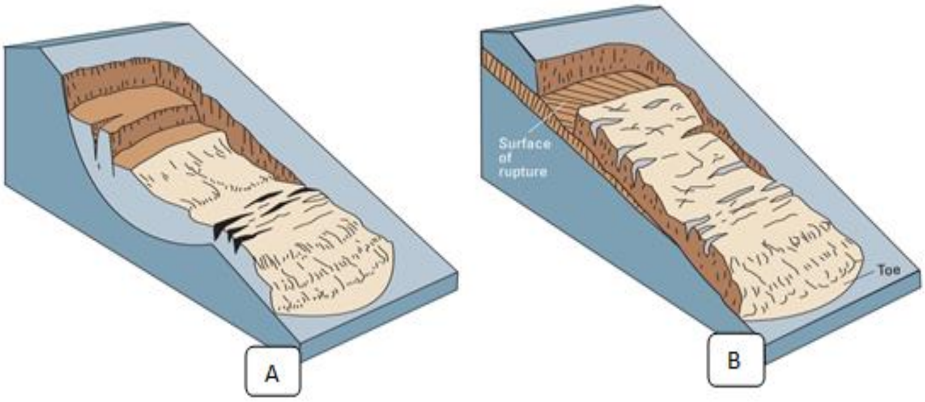

Fig.2.3. ***Schematic of Slides. A). Rotational slide. B). Translational slide (Source: Highland and Bobrowsky, 2008).***

2.3.2.4 Spread

Spread is defined as an extension of a cohesive soil or rock mass combined with a general subsidence of the fractured mass of cohesive material into softer underlying material (Fig. 2.4). The dominant mode of movement is lateral accommodated by shear or tensile fractures. They often occur on gentle slopes. They are more common in fine grained soils, such as clay, especially if the soil has been remodeled or disturbed by construction, grading or similar activities. Lateral spreads typically damage pipelines, utilities, bridges, and other structures having shallow foundations (Highland and Bobrowsky, 2008).

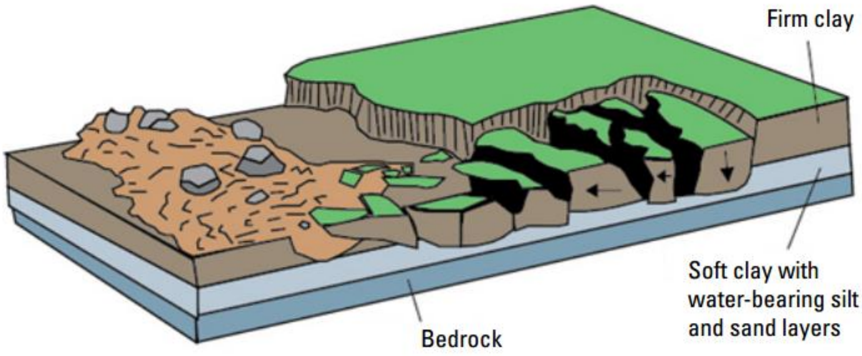

Fig.2.4. Schematic of a spread (Source: Highland and Bobrowsky, 2008).

2.3.2.5 Flow

Wachal and Haduk (2000) described flows as rapid but viscous movement of soil, bedrock, or debris. The component velocities in the displacing mass of a flow resemble those in a viscous liquid. Often, there is a gradation of change from slides to flows, depending on the water content, mobility, and evolution of the movement (Highland and Bobrowsky, 2008). Flows can be classified into debris flow or earth flows.

Debris flows is a form of rapid mass movement in which loose soil, rock and sometimes organic matter combine with water to form slurry that flows downslope (Fig. 2.5). It occurs around in steep gullies and canyons and, nearly saturated, and consists of a large proportion of silt and sand-sized material. They are commonly caused by intense surface water flow, due to heavy precipitation or rapid snowmelt, which erodes and mobilizes loose soil or rock on steep slopes. They can move objects as large as houses in their downslope flow or can fill structures with a rapid accumulation of sediment and organic matter (Highland and Bobrowsky, 2008).

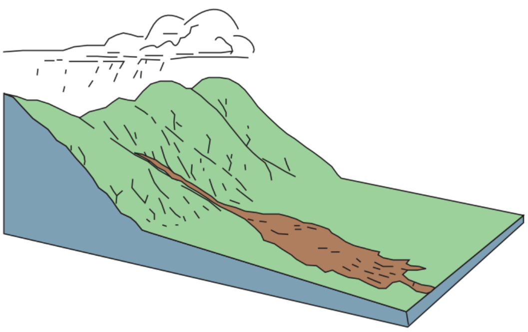

Fig.2.5 Schematic of a debris flow (Source: Highland and Bobrowsky, 2008).

Earthflows can occur on gentle to moderate slopes, generally in fine-grained soil, commonly clay or silt, but also in very weathered, clay-bearing bedrock. It is triggered by prolonged or intense rainfall or snowmelt, sudden lowering of adjacent water surfaces causing rapid drawdown of the ground-water table, stream erosion at the bottom of a slope, excavation and construction activities, excessive loading on a slope, earthquakes, or human-induced vibration. It possibly results in human fatalities, destruction of buildings and linear infrastructure, and damming of rivers with resultant flooding upstream and water siltation problems downstream (Highland and Bobrowsky, 2008).

2.3.2.6 Complex movements

Complex movement is a combination of falls, topples slides, spreads and flows (Highland and Bobrowsky, 2008).

2.4 Landslide Hazard Zonation Approaches

The aim of landslide study is to evaluate the nature of hazard and the damages to the human life, land, roads, buildings and other properties (Anbalagan and Singh, 1996). Various researchers used different methods in determining landslide hazard zone or potentially unstable areas. According to Leroi (1997) various methodologies for determining potentially unstable areas or landslide hazard assessment may be divided into expert evaluation, statistical methods, and mechanical approach.

2.4.1 2.4.2 Expert Evaluation

Expert evaluation is the most widely used approach for landslide hazard evaluation. It is classified into heuristic methods and landslide inventory mapping. Landslide inventory mapping is the simple method in which the landslide events are recorded for their location and dimension. They are considered as an elementary form of susceptibility map because they highlight the position and dimension of recorded landslides (Dai and Lee, 2001; Dai et al., 2002; Tenalem Ayenew and Barbieri, 2005; Fall et al., 2006). Landslide data are obtained through field survey mapping, historical records, satellite images and aerial photo interpretation. Landslide distribution and density maps provide basis for other landslide susceptibility methods. According to Dai and Lee (2001) landslide inventory mapping is bases for landslide hazard zonation.

In the heuristic methods, the opinion is used to estimate and or classify the landslide hazards based on intrinsic and external triggering variables (Dai and Lee, 2001; Dai et al., 2002; Anbalagan, 1992; Raghuvanshi et al., 2014). It is most widely used and versatile though it is subjective because the landslide hazard maps produced by different researchers according to expert evaluation can be very different (Leroi, 1997).

2.4.3 Statistical Approach

Statistical methods involve the statistical determination of the combinations of variables that have caused past instability processes. Quantitative or semi quantitative estimates are then performed for areas not affected by landslides, but where the same conditions exist. The statistical methods for landslide hazard zonation can be grouped into two: bivariate statistical analysis and multivariate statistical analysis (Dai and Lee, 2001). This method relatively reduces the subjectivity nature of expert evaluation. If the study area is large and the data collected for long time periods using of the statistical method in landslide hazard assessment consume time and cost. The other limitation of statistical method is the result largely depends on quality and detail landslide frequency and factor data on which the correlations are based (van Westen et al., 1997).

2.4.3.1 Bivariate statistical analysis

The bivariate statistical analysis for landslide hazard zonation compares each data layer of causative factor to the existing landslide distribution (Kanungo et al. 2009). Weights to the landslide causative factors are assigned based on landslide density. Frequency Analysis approach, Information Value Model (IVM), Weights of Evidence Model, Weighted overlay model etc. are important bivariate statistical methods used in landslide hazard zonation mapping.

Information Value Model (IVM) is a bivariate statistical method for spatial prediction of landslides based on relationships between landslide occurrence and related parameters (Sarkar et al. 2006). The information values are determined for each subclass of landslide related parameter on the basis of presence of landslide in a given mapping unitThe Weights of Evidence model uses different combinations of landslide causative factors in order to describe their interrelation with landslide distribution (Blahut et al. 2010). Frequency ratio is based on observed relationships between landslide distribution and each causative factor related to landslides. This method can be used to establish spatial correlation between landslide location and landslide explanatory factors (Lee, 2005). Frequency ratio for each sub-class of individual causative factor is calculated based on their relationship with landslide occurrence. Landslide Susceptibility Index (LSI) is computed by summing of frequency ratio values of each factor. Weighted overlay is based on the relationship of landslide causative factors with the landslide frequency (Sarkar et al., 1995).

2.3.4.2 Multivariate statistical analysis

Multivariate statistical analysis for landslide hazard zonation considers relative contribution of each thematic data layer to the total landslide susceptibility (Kanungo et al. 2009). These methods calculate percentage of landslide area for each pixel and landslide absence presence data layer is produced followed by the application of multivariate statistical method for reclassification of hazard for the given area. Logistic regression model, Discriminant analysis, multiple regression models, conditional analysis, Artificial Neural Networks (ANN) are commonly used methods for landslide hazard zonation mapping.

2.4.4 Mechanical Approach

Mechanical approaches allow the evaluation and analysis of the stability of the slopes by a safety factor state using deterministic methods (Atkinson and Massari, 1998). The advantage of using mechanical method in landslide susceptibility or hazard assessment the result is physically sound. In mechanical method due to the high spatial variability of the geotechnical parameters and the laborious methods involved in acquiring input data, an acceptable approximation of the values is practically only attainable at the level of site investigation, which implies a serious limitation of these models in large area stability hazard zoning at a reasonable cost /benefit ratio (van Westen et al., 1997).

2.5 Overview of Landslide in Ethiopia

Landslide activity is very common mostly in the Highlands of Ethiopia and rift margin due to the influencing factors like high relief and the rugged topography, geological (the nature of the out-cropping rocks), hydrological (surface and groundwater), heavy summer rainfall, land-use conditions, manmade activity and to a minor extent, with seismicity large variety of landslides occur. The most important landslide types are soil slips or mud flows, rock slides, topplings and falls in hilly and mountainous terrains of the highlands of north, south and western regions of Ethiopia and parts of rift valley escarpments. Human lives, infrastructures, agricultural lands and the natural environment have been affecting by different types and sizes of landslides (Berhanu Temesgen et al., 1999; Lulseged Ayalew, 1999; Tenalem Ayenew and Barbieri, 2005; Lulseged Ayalew and Yamagishi, 2004; Engedawork Mulatu et al., 2009; Bekele Abebe et al, 2010; Kifle Woldearegay, 2013; Raghuvanshi et al., 2014; Fikre Girma et al, 2015; Matebie Meten et al., 2015, Tilahun Hamza and Raghuvanshi, 2016). Several studies have been conducted following various qualitative, analytical and empirical approaches to assess the causes and factors that trigger landslides in different parts of the highlands of the country. Some of studies described in the following paragraphs.

Berhanu Temesgen et al., (1999) conducted the research on the nature and distribution of landslide in the Dabicho Ridge around Wondo Genet area using geological and geomorphological field investigations. They concluded that heavy rainfall, geotectonics, geomorphology, climate and landuse/landcover are the triggering factor for the translational sliding and mud flow in the area.

Tenalem Ayenew and Barbieri, (2005) made a comprehensive study of landslide processes in the city of Dessie and its environs in northern Ethiopia. According to this study hydrological conditions (both surface and ground-water), geotechnical characteristics of soils and rocks and gully erosion associated with heavy rainfall are major causes for the debris slides, earth and soil slumps, rock and debris falls and toppling and complex landslides in Dessie area.

Engdawork Mulatu et al. (2009) were carried landslide hazard zonation along the newly constructed road from Fofa town to Gilgel Gibe-II powerhouse in South western Ethiopia by using the landslide hazard evaluation factor rating scheme (LHEF) empirical approach proposed by Anbalagan (1992). The results indicate that 54% of the slopes in fall in High Hazard, 34% in the Moderate Hazard and 12% in the Low Hazard zone the area.

Bekele Abebe et al., (2010) studied landslides in the Ethiopian highlands and the rift margins. Findings show that the high relief and rugged topography, the occurrence of clayey horizons within the sedimentary sequences, the dense network of tectonic fractures and faults, the thick eluvial mantles on volcanic out-crops, and the thick colluvial–alluvial deposits at the foot of steep slopes are the predisposing factors for a large variety of mass movements. Heavy summer rainfall is the main triggering factor of most landslides, some of which undergo a step-like evolution with long-lasting quiescence intervals. In last decade landslide have been occurred area such as the northern Omo River basin, the lower Wabe-Shebele River valley, the Wendo Genet slope, the Blue Nile Gorge, the town of Dessie, the Wudmen area in Weldiya, the Gilgel Gibe River, the Uba Dema village in Sawla, and parts of Tigray(Fig. 2.7).

Kifle Woldearegay (2013) made the study on review of the occurrences and influencing factors of landslides in the highlands of Ethiopia: With implications for infrastructural development. Findings of this study show rainfall is major triggering factor for debris/earth slides, debris/earth flows and, medium to large-scale rockslides are rainfall induced landslides of different types and sizes.

Raghuvanshi et al., (2014) made study on landslide hazard zonation using Slope stability susceptibility evaluation parameter (SSEP) expert approach in the area around Wurgessa Kebelle of North Wollo Zonal Administration, Amhara National Regional State in northern Ethiopia. The results obtained indicates that 8.33% of the area fall under Moderately hazard and 83.33% fall within High hazard whereas 8.34% of the area fall under Very high hazard.

Fikire Girma et al., (2015) made study on landslide hazard zonation in Ada Berga district, central Ethiopia using GIS based statistical approach. The considered landslide causative factors in this study are lithology, soil deposit, slope, aspect, elevation, curvature and landuse/landcover and groundwater. The result revealed that 24% fall under no hazard, 32% in low hazard, 17% as moderate hazard, 25 % high hazard and the rest 2% as very high hazard.

Tilahun Hamza and Raghuvanshi et al., (2106) made study on landslide hazard evaluation and zonation (LHZ) in Jeldu District in Central Ethiopia. The considered governing factors in this study are: aspect, slope and elevation, lithology, soil and land use/land cover. The results revealed that 12% of the study area falls under no hazard, 27% as low hazard, 32% as moderate hazard, 21% as high hazard and the rest 8% as very high hazard.

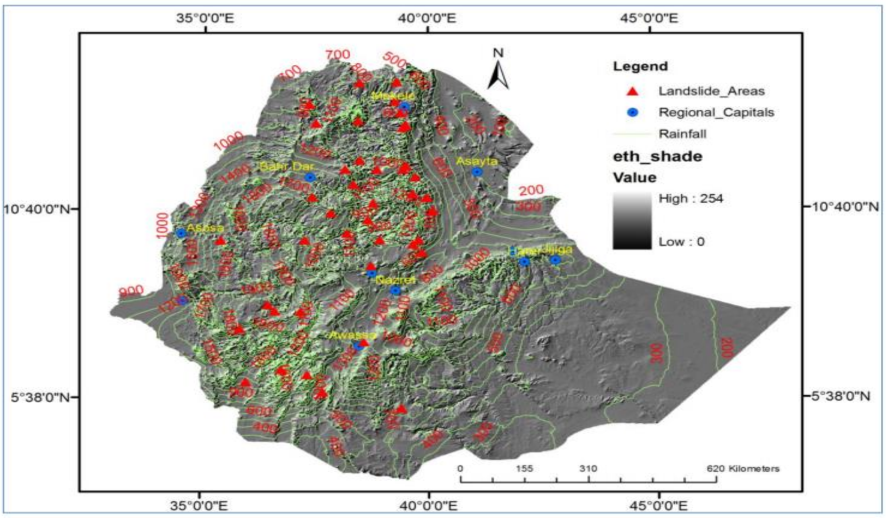

Fig.2.6. Locations of landslide affected areas in the highlands of Ethiopia (Kifle Woldearegay, 2014)

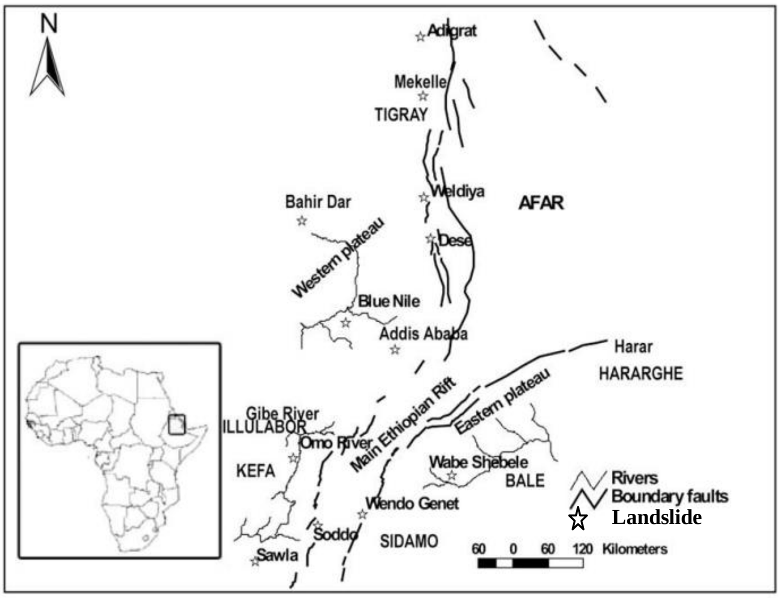

Fig.2.7. Locations of landslide affected areas in Ethiopia (Bekele Abebe et al, 2010).

In next chapter the methods and material followed in the present study are discussed.

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Chapter Three Methodology

3.1 General

Landslide hazard zonation involves prediction of areas where a potentially damaging landslide may occur without any reference to the time, or the intensity of associated damage. It expresses the spatial correlation between predisposing terrain factors and the distribution of past landslide (van Westen et al., 2006). Various researchers used different methods in determining landslide hazard zone or potentially unstable areas. According to Leroi (1997) various methodologies for determining potentially unstable areas or landslide hazard assessment may be divided into expert evaluation, statistical methods, and mechanical approach.

3.2 Methodology adopted for Landslide Hazard Zonation Mapping in the present study

In the present study integrated Slope stability Susceptibility Evaluation Parameter (SSEP) Rating approach and a raster based Information Value approach was used.

Slope stability Susceptibility Evaluation Parameter (SSEP) is an expert evaluation approach which was developed by Raghuvanshi et al. (2014) by considering both intrinsic and external landslide causative parameters. Slope geometry (relative relief and slope morphometry), slope material, structural discontinuity, landuse/landcover, and groundwater are intrinsic causative parameters whereas rainfall, seismicity and manmade activity are the external causative parameters that are considered in this method. They have assigned the rating values for each causative parameter on the basis of logical judgments acquired from experience of studies of intrinsic and external triggering factors and their relative impact on instability of slopes (Table 3.1).

In this approach, the landslide hazard zonation of study area can be carried out in the following order: First, the area is classified into facets (a land unit with more or less uniform slope geometry in terms of slope inclination and slope direction). Secondly, the data on intrinsic and external causative parameters is collected and rating for each causative parameter is assigned for each facet. Thirdly, the ratings values of all causative parameters for individual facet have to be summed up to obtain Evaluated landslide hazard (ELH) which indicates the net probability of instability. Finally, the area classified into different hazard zone based on the obtained (ELH) value (Table 3.2).

$$ELH = Sum\ of\ Ratings\ of\ intrinsic\ parameters\ (\text{relative relief} + \text{slope morphometry} + \text{slope material} + \text{structural discontinuity} + \text{Landuse and landcover} + \text{Groundwater}) + Sum\ of\ Ratings\ of\ External\ parameters\ (\text{Rainfall} + \text{Seismicity} + \text{Manmade activities})$$

Table 3.1 Distribution of maximum SSEP ratings assigned to different intrinsic and external triggering factors (Raghuvanshi et al., 2014).

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**

Raghuvanshi et al. (2014) proved the rationality of considered governing parameters, the adopted (SSEP) technique, tools and procedures in developing the landslide hazard zonation mapping. The advantage of using this technique for landslide hazard evaluation and zonation is it use detailed facet wise field based data as input, and relatively it is simple in its application. However its drawback is subjectivity of the result in landslide hazard evaluation and zonation (Leroi, 1997).

Table 3.2 Evaluated landslide hazard Classes

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

Bivariate statistical analysis involves the determination of the abundance of landslides within each factor class. According to Yin and Yan (1988), Jade and Sarkar (1993), van Westen (1997), Lin and Tung (2003) Information Value Model (IVM) is a bivariate statistical method for spatial prediction of landslides based on relationships between landslide occurrence and related parameters. The information values are determined for each subclass of landslide related parameter on the basis of presence of landslide in a given mapping unit. To evaluate the influence of each factor class on landslide susceptibility, the distribution of the landslide pixels derived from the training dataset for each factor classes was calculated. In case of integrated Slope stability Susceptibility Evaluation Parameter (SSEP) and a raster based Information Value method seven causative parameters namely; relative relief, slope morphometry, slope material, landuse/landcover, groundwater surface manifestations, rain induced manifestations and manmade developmental activities were selected and their thematic maps were prepared. The landslide inventory map for this study has been prepared from data collected during field investigation and from google earth image. The causative parameters and inventory map transformed have been transformed into raster. Each causative factor map has been combined with landslide map in order to get weight of each class.

According to Yin and Yan (1988) weight mathematically obtained by:

$$W_j = \ln \frac{\text{Density of landslide within a class of a factor}}{\text{Density of landslide within the study area}}$$

$$= \ln \frac{\text{Conditional probability}}{\text{Prior probability}}$$

$$\text{Conditional probability} = \frac{Nspixj}{Ncpixj}$$

Where

Wj = Weight of a factor class

Nspixj = Number of pixel of landslide within class j

Ncpixj = Number of pixel of class j;

ƸNspixj = Number of pixel of landside within the whole study area.

ƸNcpixj= Number of pixel in of the whole area.

The use of natural logarithm yields negative weights where densities of landslide in lower average and positive when density is higher. To avoid negative weighting values, the weighted values are rescaled by adding the absolute value of the minimum weighted value in each factor (the largest negative value) to the weights of all the other factor classes in each factor (Che et al., 2012).

The distribution of landslide over each of each of factor maps have been obtained and analyzed. Weights for each of the classes within these factor maps have been obtained using the information value method. The rescaled weights (Information value) are assigned to each factor class to obtain weighted factor maps. These factor maps are then summed up using the raster calculator to obtain a landslide susceptibility index value for each pixel. The landslide hazard zonation map reclassified classified into three classes.

Prepared landslide hazard zonation map of the study area in both approach were verified by using landslide inventory data.

For integrated Slope stability Susceptibility Evaluation Parameter (SSEP) and a raster based Information Value method seven causative parameters namely: relative relief, slope morphometry, slope material, landuse/landcover, groundwater surface manifestations, rain induced manifestations and manmade developmental activities were selected and their thematic maps were prepared. According to Ayalew et al. (2005), factors selected for landslide susceptibility assessment in a GIS-based study, must be operational, represented over the entire area, non-uniform, non-redundant and measurable so that seismicity and structural discontinuity not included in this study. The landslide inventory map for this study has been prepared from data collected during field investigation and from google earth image interpretation. The inventory map combined with each of seven causative factors to determine the relationship causative class and landslide.

Also, prepared landslide hazard zonation map of the study area in both approach were verified by using landslide inventory data. Finally, the effectiveness of landslide hazard zonation map prepared by SSEP was determined by checking it with inventory data and landslide map prepared by integrated SSEP and raster based statistical information calculated value. Schematic illustration of the methodology followed in the present study shown in figure 3.

Generally, the stage followed in the present study was classified into pre-field investigation, field investigations, and post-field investigation.

3.2.1 Pre-field Investigation

In this stage of investigation secondary data and required materials were gathered from different organization. The topographic maps at 1:50,000 scale, climate data (rainfall and temperature) and field equipment include GPS, compass, geological hammer and measuring tape were taken from Ethiopian Map Agency, Ethiopian Metrological Agency and Addis Ababa University, School of Earth Sciences respectively. Pre-field causative factor maps of the study area were prepared in pre-field stage of investigation.

3.2.2 Field Investigation

The facet wise observation and measurement of field data of slope material, landuse and landcover, groundwater surface manifestations, structural discontinuity, rain induced manifestations, manmade activities and landslide inventory were collected using facet map, topographic map, GPS, geological hammer, compass and measuring tape. Also pre-field data and maps were verified and modified.

3.4 Post field Investigation

Activities preformed in post field investigation stage include:

- ✓ The data collected in pre-field and field investigation were organized, interpreted and presented.
- ✓ The ratings of intrinsic and external causative factor for individual facet were summed to get ELH value and also based on ELH, landslide hazard zonation of the area were prepared.
- ✓ The thematic maps of causative factors and inventory map were prepared using secondary and primary data in Arc GIS, and these maps have transformed into raster.
- ✓ The causative factors and inventory map was combined to get the relationship between causative factor class and landslide in the study area.
- ✓ The information value maps of causative factor maps were prepared and summed to get landslide hazard zonation map of the area.
- ✓ The landslide hazard zonation maps were verified using inventory data.
- ✓ At last, final landslide hazard zonation map was prepared.

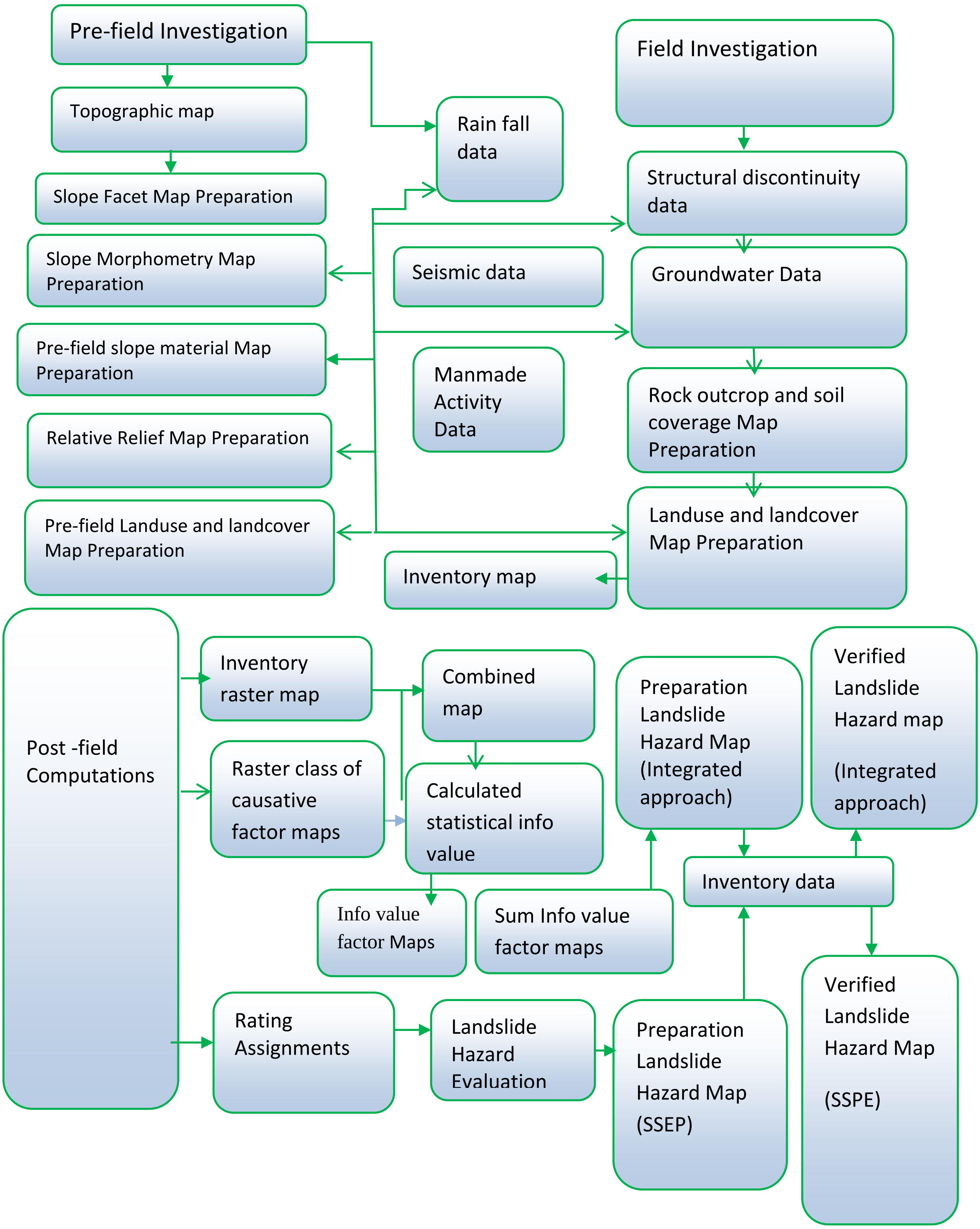

Figure 3.1. Schematic illustration of the methodology followed in the present study.

In next chapter the regional and local geology of the study area was described. It focuses on regional geological setting and geology of the study area.

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Chapter Four Geology

4.1 Geology

4.1.1 Regional Geology

4.1.1.1 Introduction

The study area is located in Omo-Gibe River basin in South Western Ethiopia. The geology of the basin contains Precambrian crystalline basement, Tertiary volcanic rocks and Quaternary alluvial sediments and volcanic flows (Davidson, 1983). Approximately, 90% of the basin area is underlain by Cenozoic rocks, no Paleozoic and Mesozoic sedimentary successions found elsewhere in Ethiopia occur in the area (Davidson, 1983). Other than basal red sandstone, which is mostly found in between Precambrian and Cenozoic rocks, Tertiary volcanic rocks are rest directly on the Precambrian crystalline basement (Davidson, et al., 1973; 1976; 1983). The southwestern Ethiopia Cenozoic rocks sub divide into Pre-rift, and post-rift succession. The basin is bordered on the northeast by the Main Ethiopian Rift, on the southeast by the Chew Bahir rift systems and on the south by the Lake Turkana rift which extends northwards from Kenya into Ethiopia (Davidson, 1983).

The geology of the study area is dominated pre-rift and post rift deposits. The pre-rift deposits include: Early Flood Basalts (Pv), Salic, Basaltic, and Intermediate Flows and Pyroclastic Rocks (pv1) and Salic, Basaltic, and Intermediate Flows and Pyroclastic Rocks (pv2) whereas post rift include Holocene Sediment Deposits (Davidson, 1983).

4.1.1.2 Precambrian crystalline basement rocks

The crystalline basement, mainly outcrop in the southern half of the Omo-Gibe River basin, comprised of high grade metamorphic rocks consisting of upper amphibolite facies, ortho and para-gneisses, migmatites and granulites. These include a complex of northwest trending, strongly deformed, recrystallized and migmatized gneisses, such as hornblende, biotite- hornblende, biotite, quartzo-feldspatic, garnet–augite, hypertine, garnet–sillimenite and calcsilicate gneisses and marble (Davidson, 1983).

4.1.1.3 Pre - Rift Succession

The pre-rift stratigraphy of (Davidson et al., 1973, 1976, 1983) consists the following major units in Omo gibe basin: Basal Red Sandstone, Early Flood Basalts (pv), Salic, Basaltic, and Intermediate Flows and Pyroclastic Rocks (pv1), Salic, Basaltic, and Intermediate Flows and Pyroclastic Rocks (pv2), Makonnen basalt, Assillie Group, Surma basalt, alkali, trachyte and phonolite, hypabyssal intrusive rocks.

4.1.1.3.1 Early Flood Basalts (Pv)

The early flood basalts are products of fissure eruptions, and are characterized by thin, extensive flows, locally columnar and with jointing parallel to flow layering. The basalts overlie the red basal sandstone, where the sandstone is missing, directly rest on the Precambrian basement. The main occurrences of this unit is in three separate areas in the basin, namely in the south-western, south-eastern and along the north-eastern parts of the Omo River valley. The flood basalts are mostly soft weathering, consequently giving rise to a subdued topography in their areas of occurrence. They are either aphyric or porphyritic, containing olivine or plagioclase phenocrysts or both. Pyroxene-phyric basalts are less common. Amygdales containing zeolites, calcite and chalcedony are present in places (Davidson et al., 1973, 1976, 1983).

4.1.1.3.2 Salic, Basaltic, and Intermediate Flows and Pyroclastic Rocks (pv1)

In the south-western segment of Omo-gibe basin, a map unit containing intercalated basaltic, intermediate, and salic volcanic rocks has been mapped (Davidson et al., 1976). In this area, the early flood basalts are separated from the overlying thick salic lavas and pyroclastic rocks with minor intercalated basalt flows of the Tertiary volcanic sequence by a zone of mixed rocks containing intercalated resistant salic rocks and less resistant basaltic and intermediate flows. The intermediate rocks in this unit are massive, medium grey and plagioclase-phyric, with a notably lower groundmass color index than basalt, and are probably andesitic in composition (Davidson et al., 1976)

4.1.1.3.3 Salic, Basaltic, and Intermediate Flows and Pyroclastic Rocks (pv2)

Salic volcanic rocks occupy a dominant portion of the Tertiary volcanic succession within the basin. A thick succession of salic volcanic flows, pyroclastic rocks and subordinate intercalated basalt flows dominate the upper portion of the pre-rift volcanic succession. A significant part of the Omo-Gibe basin stretching from far north to the south is occupied by trachyte and rhyolite flows and pyroclastic rocks such as tuff, ignimbrite, and breccia with subordinate basalt flows, forming north and north-east trending zones. Basalt flows are present in parts of these predominantly salic sequences, just as salic flows occur within the flood basalts (Davidson et al., 1973, 1976, 1983).

4.1.1.4 Post - Rift Succession

Post rift succession (Davidson et al., 1973, 1976, 1983) includes: nazerth group, omo group, harr basalt, ileret sediments, kibish formation, lacustrine and deltic deposits, late volcano and associated flows and Holocene sediment deposits units. The following major unit may possible exist in the study area or in the surrounding.

4.1.1.4.1 Holocene Sediment Deposits

An extensive area of Quaternary sedimentation occurs at the northwestern end of the basin along the upper reaches of the Omo River. Some relatively narrow grabens in the western part of the surveyed area are covered by recent unconsolidated alluvial sediments. The extensive area between Jimma and Sokoru is also covered by both recent alluvial sediments on which reddish brown soil, up to 10 m thick, has developed on the bed rock on both sides of the sediment deposits. The alluvial deposits occur along the Gilgel-Gibe River course and are mainly represented by sand, silt and clay. The soils are mainly reddish-brown and rarely are they black cotton soils (Davidson et al., 1976).

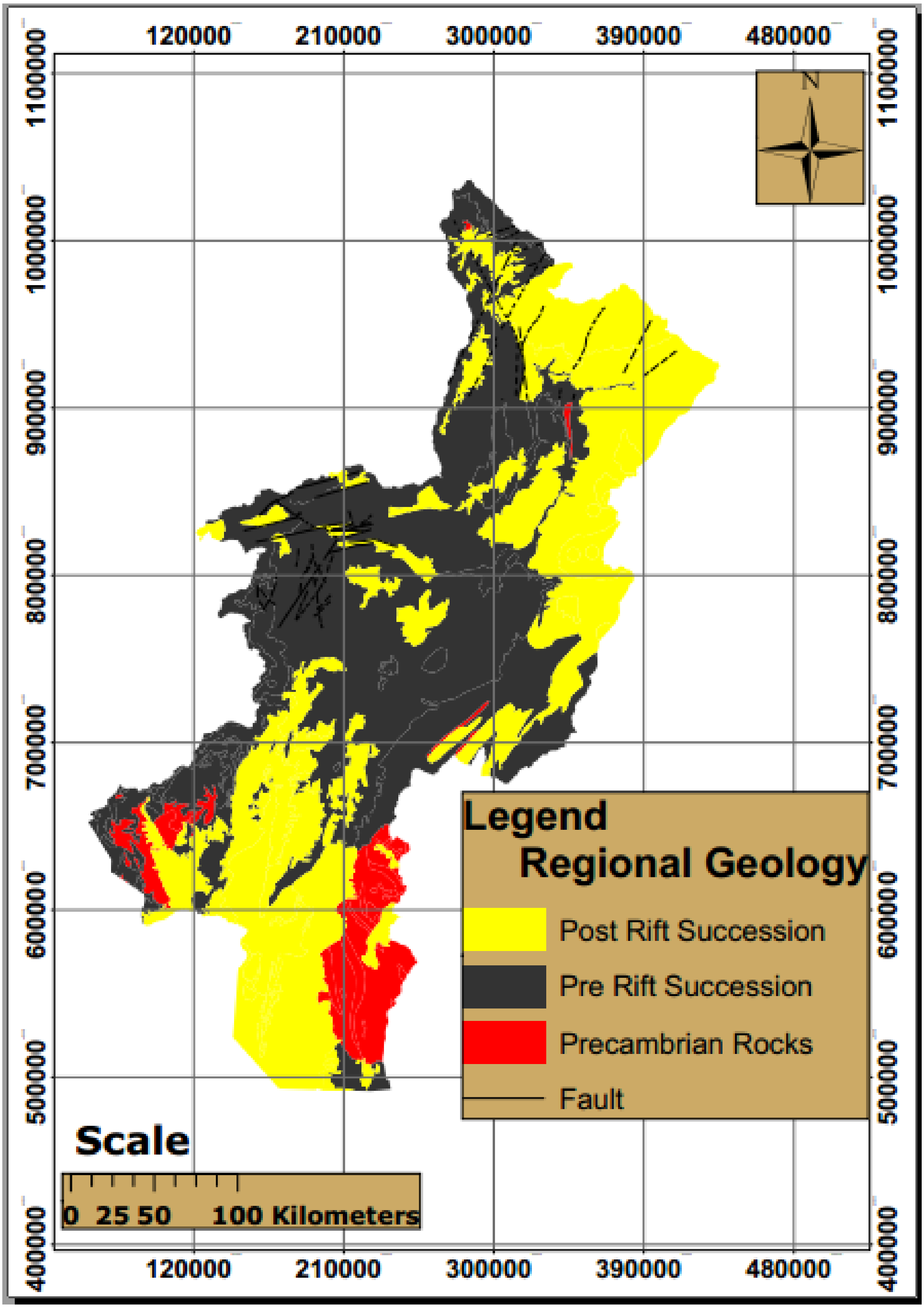


Fig.4.1 Regional Geological Map (Davidson, 1983).

4.1.2 Local Geology

The geology of the study area was mapped by field investigation. The geologic units present in the study area are: basalt: trachyte, tuff and unconsolidated alluvial–colluvial deposits, and residual soils. Dykes of basaltic lava flows are also observed in the study area. The geology of the area is well exposed along river, road, and natural hillside in the study area.

4.1.2.1 Unconsolidated Deposits

These units are result of weathering and the result of rivers, gravity and residual deposits from different parent rocks. The unconsolidated deposits in the study area include alluvial and colluvial deposits and also residual soils.

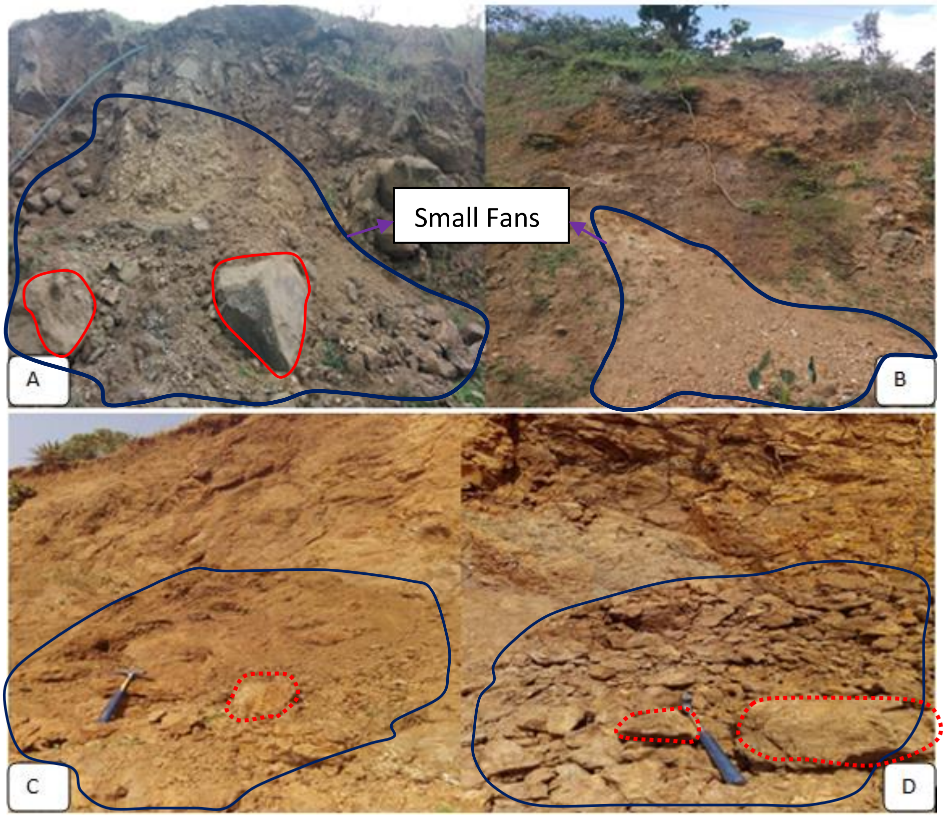
4.1.2.1.1 Alluvial Deposits

These deposits are located in low-lying areas close to the river courses and deeply cut gullies. They contain cobbles and gravels within a matrix of silty clay soils. These deposits are observed along Mayle, Becha and Kila River in the study area (Plate 4.1).

Plate 4.1. Alluvial deposits along Mayle River (A) and Becha River (B).

4.1.2.1.2 Coluvial Deposits

Colluvial deposits form small fans at the feet of hills and steep slope areas along the road and river. The talus deposits in the area comprises of blocks of basalt associated with weathered friable loose tuff, and also soil that fell from the steep cliffs (Plate 4.2).



A). Talus deposits of highly weathered basalt at Bosa Borto Kebele.

B). Talus deposits of soil mass at Offa Wamura Kebele.

C). Talus deposits of tuff at back Halale town.

D). Talus deposits of highly weathered basalt in Sime Dolaye Kebele.

Plate 4.2. Colluvial deposits.

4.1.2.1.3 Residual Soil

The residual soil deposit in the study area varies in color from black-reddish-yellowish. It is loose mix of granular material comprising sand and silt. It ranges in thickness from 5-10 m. Tension cracks are observed in most part of the study area in this unit. It is underlain by aphanatic basalt and unwelded tuff unit and thickness (Plate 4.3).

A). Reddish brown residual soils which are mainly at Sime Dolaye Kebele.

B). Reddish residual soils at Bosa Manara Kebele.

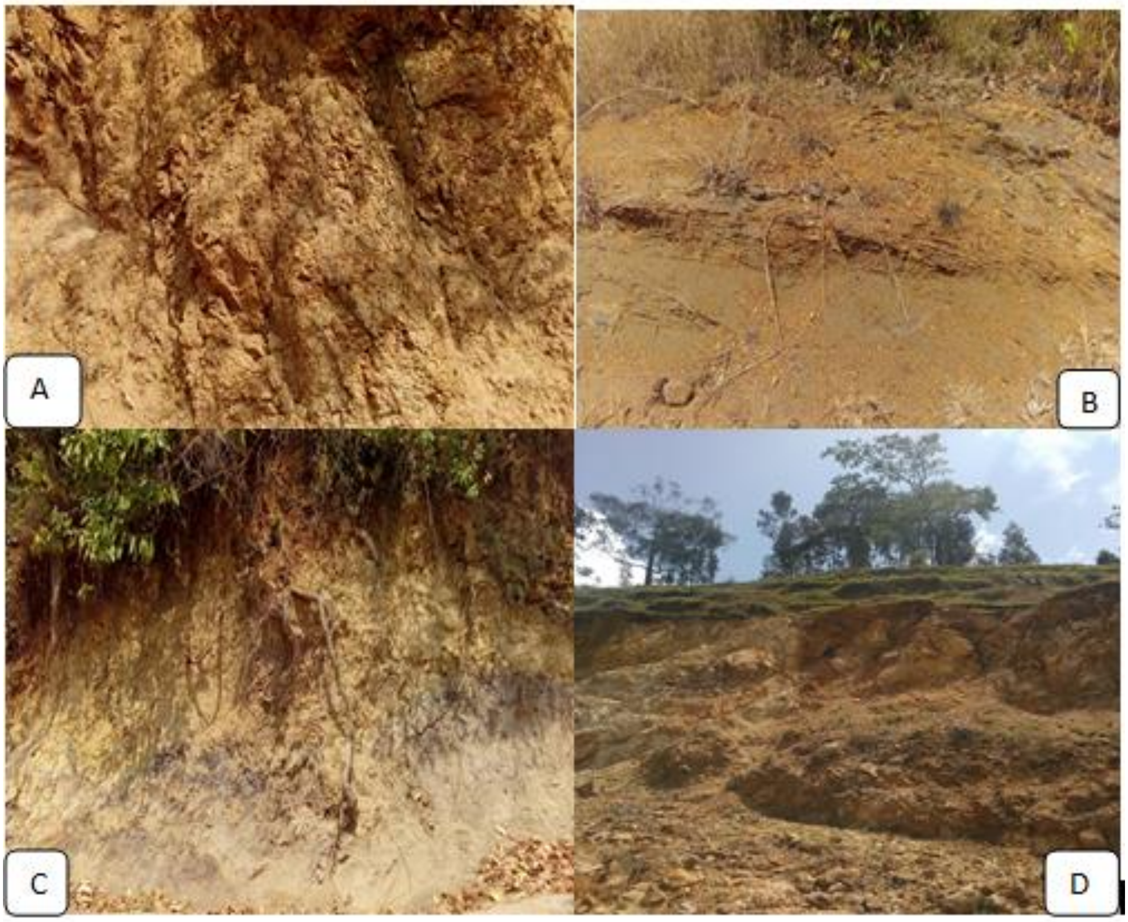
c). Gully erosion in residual soil at Offa Wamura.

D). Gully erosion in residual soil in Bosa Borto Keble.

Plate 4.3. Residual soil deposits.

4.1.2.2 Unwelded Tuff

This lithologic unit consists of volcanic pyroclastic materials and thin layers of volcanic ash. They are exposed well along river and road and most parts of the region. It is characterized as yellow to light gray in color, very weak and, friable by hand and with a single blow of geological hammer it powdered into soils. It is underlain by soil cover (Plate 4.4).



A). Very weak highly weathered yellow color unwelded tuff in Offa Chew Kare Kebele.

B). Yellow unwelded tuff in Bosa Manara Kebele.

C). Unwelded tuff at Bosa Borto Kebele.

D). Unwelded tuff in Offa Wamura Kebele.

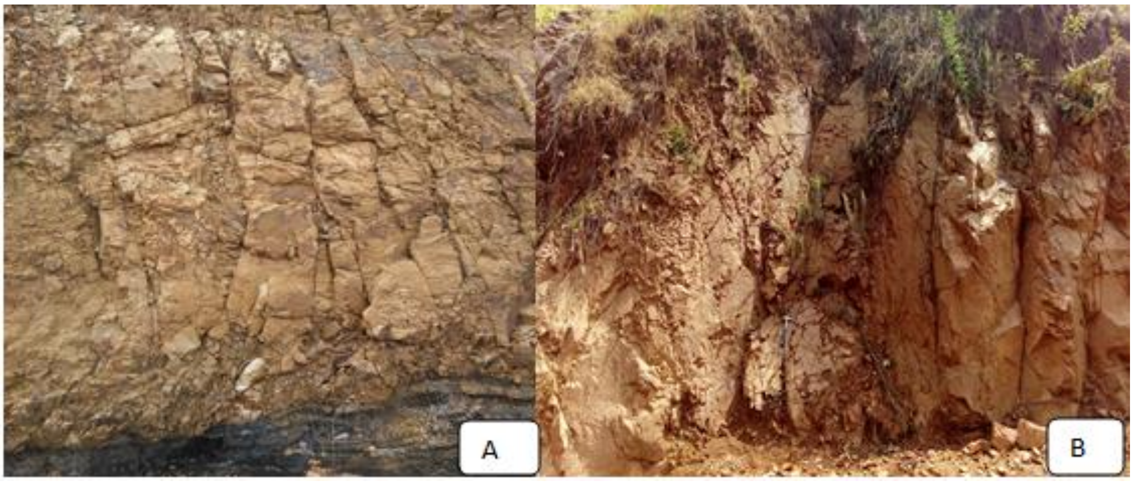
Plate 4.4. Unwelded tuff.

4.1.2.3 Trachyte

This lithologic unit is well exposed along road. The surface this unit shows light color and aphanatic texture. It is characterized by cooling joints, weathered and altered by fractures. (Plate 4.5)

4.1.2.4 Basalt

The exposed basalt with aphanatic texture is observed in study area. This rock unit in the study area is highly weathered, altered and at places intruded by aphanatic basaltic dikes. It is affected by exfoliation weathering (Plate 4.6).



***A). Trachyte at along the road to Zerada. B). Trachyte in Sime Dolaye Kebele*.**

Plate 4.5. Trachyte.

***A). Exfoliation weathering is observed in dark gray aphanatic basalt. B). Jointed aphanatic basalt*.**

Plate 4.6. Basalt.

4.2 Geological Structures

Joints are the geological structures which are observed in the study area. They are characterized by orientation, separation, continuity, roughness, infilling material and weathering. The characteristics of measured joints from different location are shown in (Appendix 4.1).

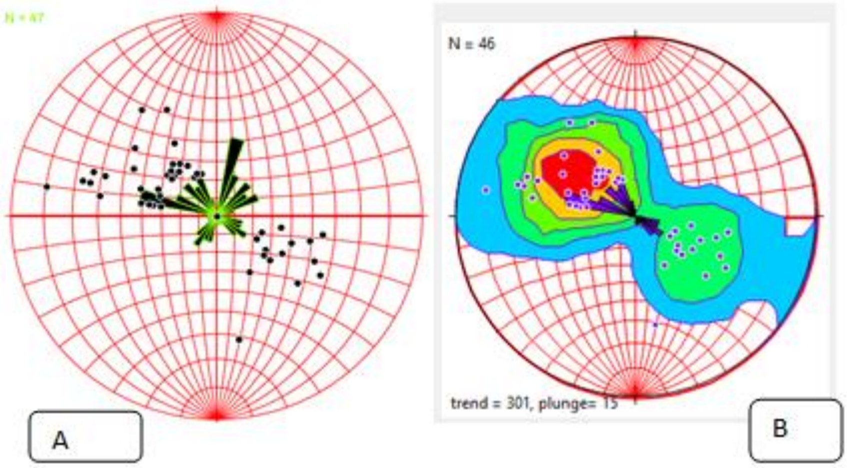


Figure 4. 2. A) Rose diagram. B). Contour plot of measured joints in the study area.

The rose diagram shows that the strike direction of joints is NW-SE and NE-SW. The poles of joints are concentrated in fourth and second quadrants. The average dip amount of joints ranges from 30^0 to 80^0. Most of the joints have measured continuity greater than 1 meter whereas the least measured continuity of joints is 0.2. The separation of joints ranges from 1mm to 1 cm and their surface are smooth to very rough. The surfaces of joints are either filled by soft material or no filling with moderately to high degree of weathered.

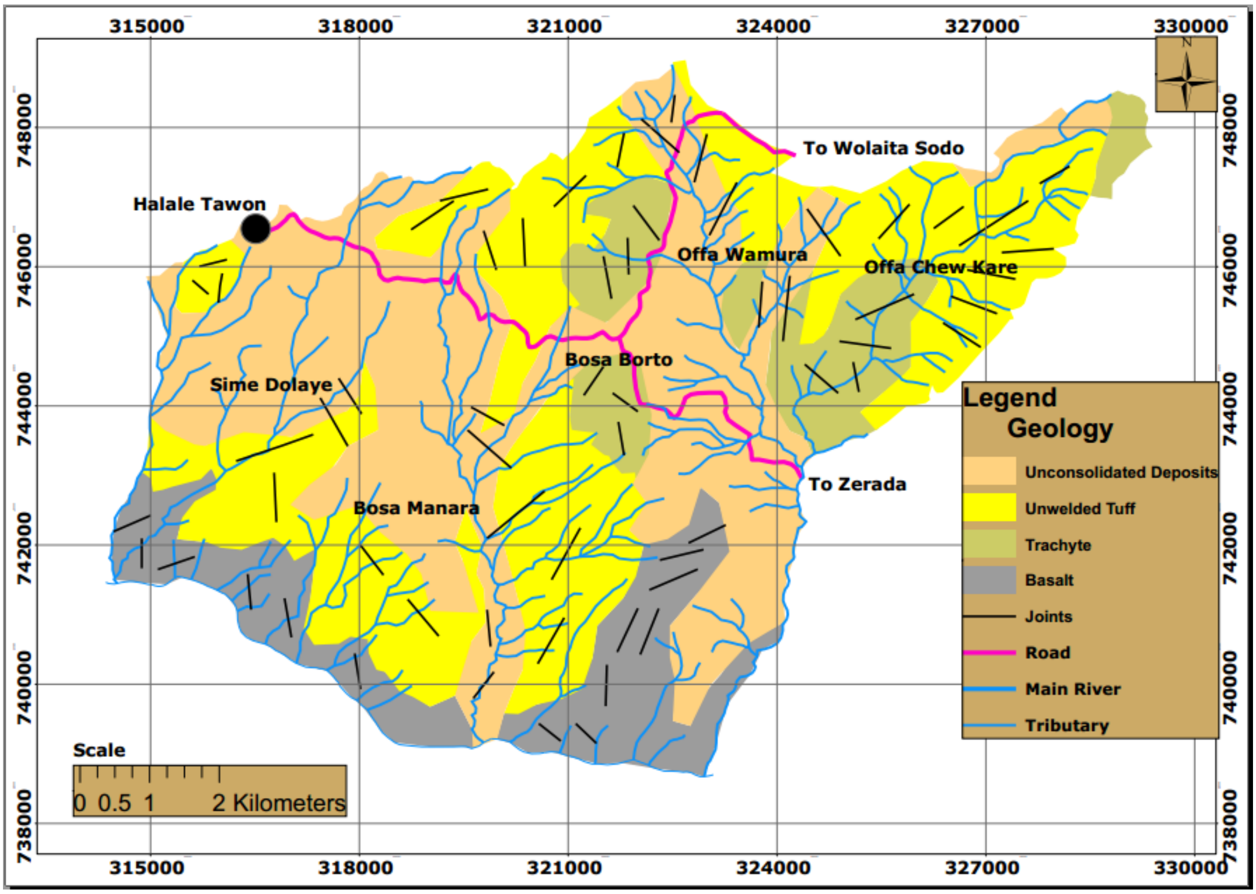


Figure 4.3 Geological Map the study area.

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Chapter Five Landslide Hazard Zonation

5.1 General

According to Varnes (1984) landslide hazard zonation is the process of dividing the land surface into areas and ranking of these areas according to the degree of actual or potential hazard from landslides. It is an important step in landslide investigation and landslide risk management. Landslide hazard zonation can be carried out though several approaches. Leroi (1997) classified landslide hazard study methods into expert evaluation, statistical and mechanical approach.

Slope stability Susceptibility Evaluation Parameter (SSEP) is the expert method which developed by Raghuvanshi et al. (2014) used to evaluate landslide hazard zonation of an area individual facet wise ratings for causative intrinsic parameters and external triggering parameter ratings are summed up. The sum total of all ratings for causative intrinsic parameters and external triggering parameter will give Evaluated landslide hazard (ELH).

According to Yin and Yan (1988), Jade and Sarkar (1993), van Westen (1997), Lin and Tung (2003) Information Value (IVM) is a bivariate statistical method for spatial prediction of landslides based on relationships between landslide occurrence and related parameters. The information values are determined for each subclass of landslide related parameter on the basis of presence of landslide in a given mapping unit. According to Kanungo et al. (2009) Information Value Model has proved useful method in determining the degree of influence of individual causative factor responsible for landslide occurrence.

In present study, landslide hazard zonation was carried out in two ways namely: Landslide Hazard zonation using Slope stability Susceptibility Evaluation Parameter (SSEP) expert method; Landslide hazard evaluation using integrated Slope stability Susceptibility Evaluation Parameter and raster based information value method. Value based statistical method, raster map of relative relief, slope morphometry, slope material, landuse/landcover, groundwater surface manifestation, rainfall induced manifestation, manmade developmental activities and landslide inventory map were used.

5.2 Landslide Hazard Zonation

In slope stability susceptibility evaluation parameter (SSEP) empirical landslide hazard zonation method, initial stage is classifying the study area into individual facets (Anbalagan, 1992; Raghuvanshi et al, 2014). Facet map of the study area was prepared by delineating major or minor hill ridges, primary and secondary streams and other topographical undulations on the basis of visual interpretation of topographic map and Arc GIS software. A total number of 102 facets have been delinated in the study area (Fig. 5.1).

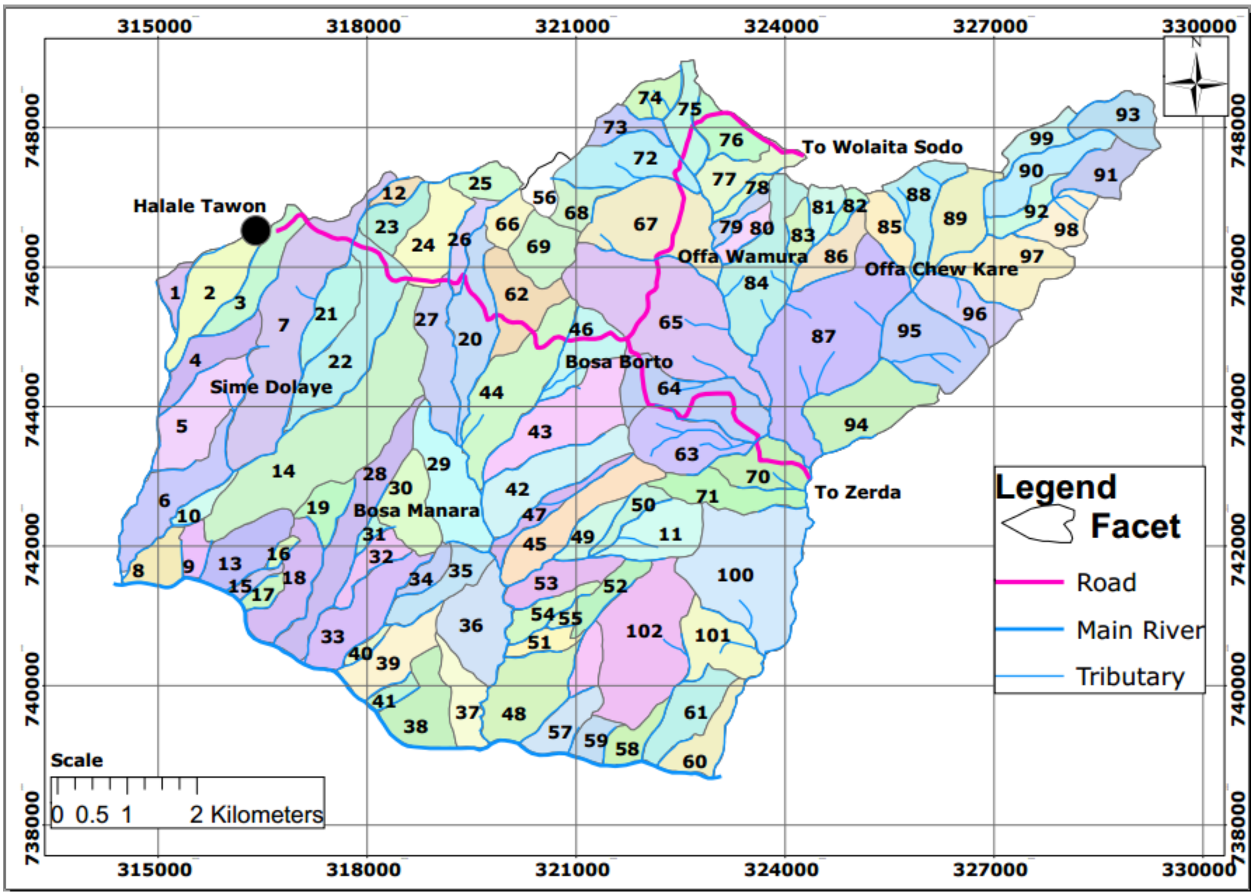


Fig.5.1 Facet map of the study area. The bounded polygon in map indicates individual facets and the number that written inside the bounded polygon represent facet number.

5.2.1 Landslide Hazard Triggering Parameters

5.2.1.1 Intrinsic Parameters

Intrinsic parameters are the inherent or static causative parameters which define the favorable or unfavorable stability conditions within the slope (Anbalagan, 1992; Raghuvanshi et al., 2014). Relative relief, slope morphometry, slope material, structural discontinuities, land use and land cover and groundwater surface manifestations are intrinsic causative parameters which were considered landslide hazard zonation using Slope stability Susceptibility Evaluation Parameter (SSEP) expert method. In case of landslide hazard evaluation using integrated Slope stability Susceptibility Evaluation Parameter and raster based information value method except structural discontinuity other causative parameters were considered since factors selected for landslide hazard zonation in a GIS-based study, must be operational, represented over the entire area, non-uniform, non-redundant and measurable (Lulseged Ayalew et al., 2005).

After combining each causative factor map with landslide inventory, statistical information value for each class of causative parameters were calculated. In table 5.1-5.7 below: Ncpix indicates number of pixel in each class of causative parameter. Nspix indicates number landslide pixel in each class of causative parameter. Cond_Prob indicates conditional probability. It tells probability of occurrence for landslide in each class of causative parameter or how much probable of each class of causative factor for landslide. Conditional probability of each class of causative parameter was calculated dividing number of landslide pixel in each class of causative parameter by number of pixel in each class of causative parameter. Prior_Prob indicates prior probability. It tells the total area probability for landslide. Prior probability was calculated dividing the total number of landslide pixel within study area by total number of landslide pixel within study area. Info value indicates information value. It tells the influence of each class of causative parameter on the entire area or the comparison of the landslide density per each factor class of causative parameter to the landslide density in the entire study area. It is calculated using logarithm (Cond_Prob. /Prior_Prob) (Yin and Yan , 1988). The total pixel number of the area is 94323 whereas the 71 total landslides pixel of is 1207.

5.2.1.1.1 Relative Relief

Relative relief is the difference between maximum and minimum elevation within a facet. According to Hoek and Bray (1981) and Bekele Abebe et al. (2010) slope will be more susceptible for instability if the relative relief is high and it is affecting factor for a large variety of mass movements.

From total area of 85 km^2, 78 km^2 (92 %) falls into very high relative relief (>300 m), 1.7 km^2 (2 %) falls into to high relative relief (201-300 m), 3.8 km^2 (3.8 %) falls into medium relative relief (101-200 m), and 1.9 km^2 (2.2 %) falls into moderate relative relief (50-100 m) (Fig. 5.2).

Table 5.1 Information Value for Relative Relief

No.	Relative relief class	Ncpix	Nspix	CP	PP	CP/PP	IV
1	Very High	86938	1132	0.013	0.0128	1	0
2	High	1732	75	0.043	0.0128	3.36	1.2
3	Medium	1669	0	0	0.0128	0	0
4	Moderate	3984	0	0	0.0128	0	0

As shown in above table 5.1, 94% and 6 % of the landslides occurred in very high and high class of relative relief, respectively. No landslides occurred in medium and moderate class of relative relief. The conditional probability of occurrence for landslide in very high and high class of relative relief is 0.013 and 0.0430.079, respectively. The conditional probability of occurrence for landslide in medium and moderate class is zero. From information value high relief has 1.2 value.

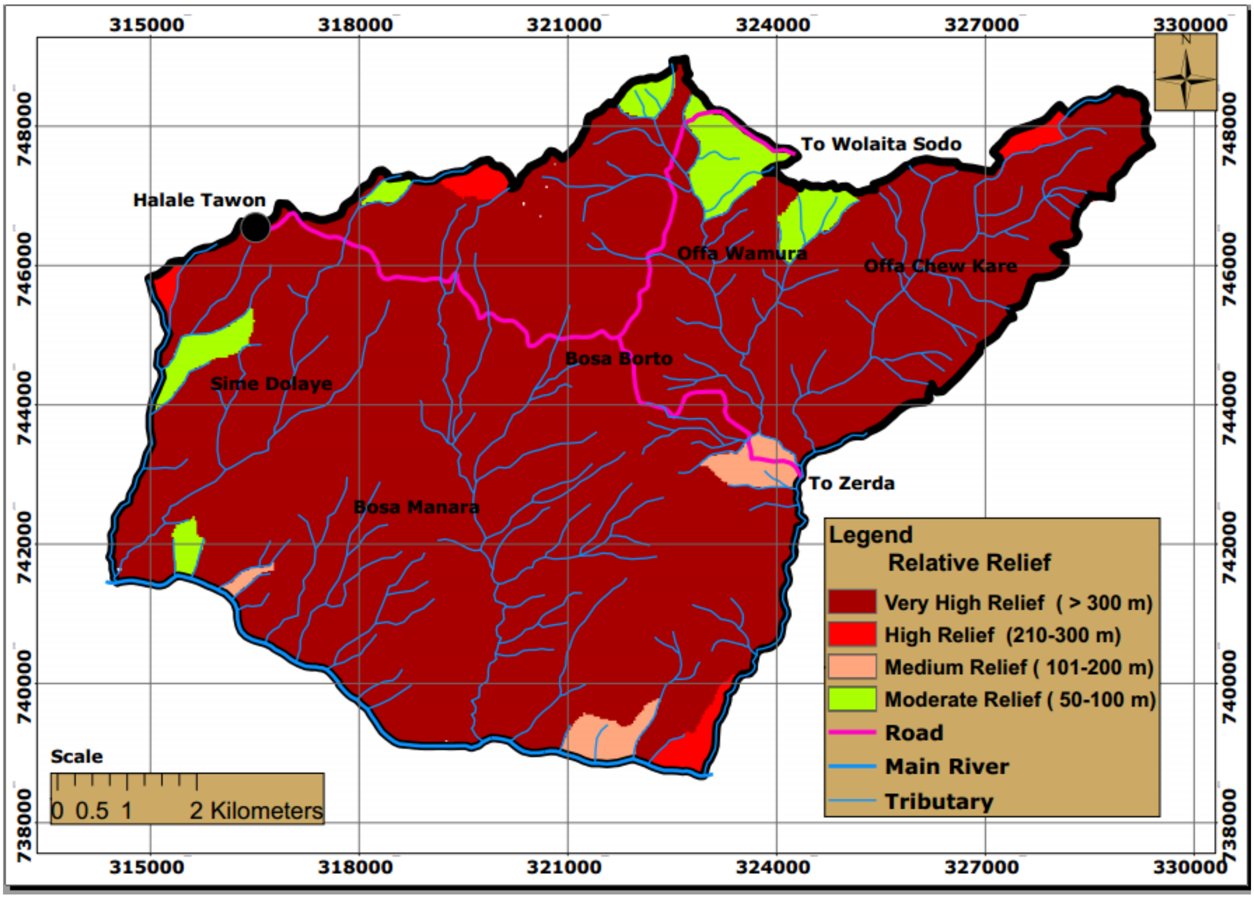


Fig. 5.2 Relative relief map of the study area.

5.2.1.1.2 Slope morphometry

Anbalagan (1992) defined slope morphometry as the steepness of slope. Slope morphology brings to bear major controls on landslide types and severity of associated dangers to life and property. It is categorized into five class: escarpment/cliff (>45°), steep slope (36°–45°), moderately steep slope (26°–35°), gentle slope (16°–25°) and very gentle slope (< 15°) (Raghuvanshi et al. , 2014).

In the study area about 9%, 20 %, 13 %, 42% and 16 % of the slopes fall under the category of escarpment (>45^0), steep (35°-45°), moderately steep (25°-35°) , gentle (16-25^0), rand very gentle slope class , respectively (Fig 5.3).

Table 5.2 Information Value for slope morphometry.

No	Slope morphometry class	Ncpix	Nspix	CP	PP	CP/PP	IV
1	Escarpment/Cliff	8526	221	0.026	0.0128	2	1.2
2	Steep	19371	143	0.0074	0.0128	0.6	0
3	Moderately steep	11559	288	0.025	0.0128	1.95	1.18
4	Gentle	39232	396	0.01	0.0128	0.78	0.1
5	Very gentle	15635	159	0.01	0.0128	0.78	0.1

As shown in above table 5.2, 13%, 32%, 24%, 12%, and 19% of the landslides occurred in very gentle, gentle, moderately steep, seep and escarpment/cliff class of slope morphometry respectively. The conditional probability of occurrence for landslide in very gentle, gentle, moderately steep, seep and escarpment/cliff is 0.01, 0.01, 0.025, 0.0074 and 0.026, respectively. From information value, very gentle, gentle, moderately steep and escarpment/cliff class of slope morphometry is 0.1, 0.1, 1.18, and 2 value, respectively.

5.2.1.1.3 Slope Material

The rock mass comprised highly weathered tuff, highly weathered and fractured basalt and trachyte, and moderately weathered and fractured basalt and trachyte. While the soil mass of the slopes comprised residual, alluvial and colluvial deposits. Generally, the area is classified into soil mass (residual, alluvial and colluvial unconsolidated deposits) (Plate 5.1), disintegrated rock mass (highly weathered tuff, highly weathered and fractured basalt and trachyte) (Plate 5.2) and blocky disturbed rock mass (moderately weathered and fractured basalt and trachyte) (Plate 5.3). Slope material map (Fig.5.4) indicates that 59 % of the total area covered by soil mass, 31 % covered by disintegrated rock mass whereas 10% is covered by blocky disturbed rock mass.

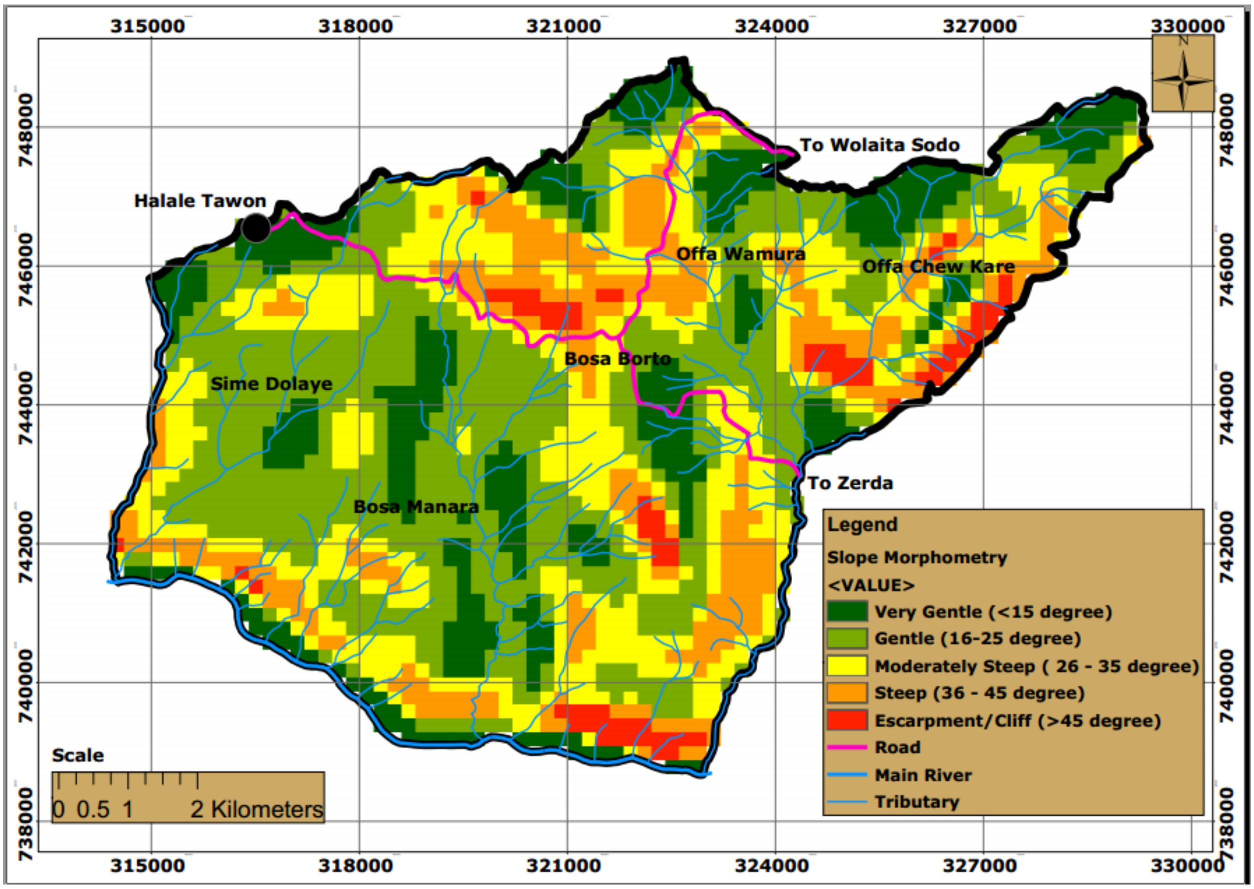
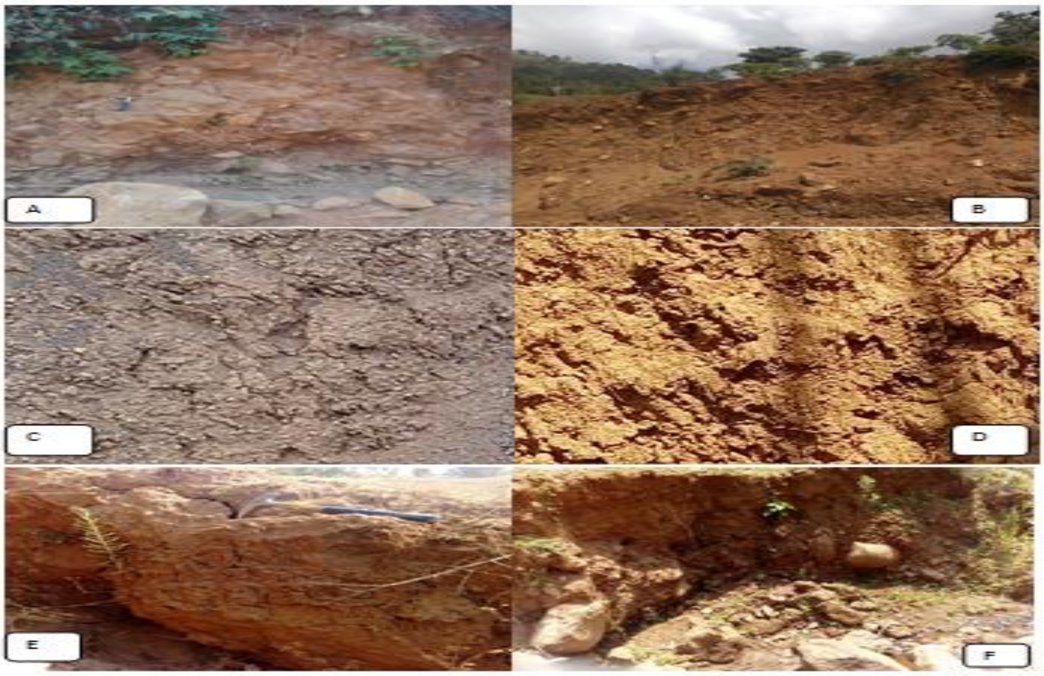


Fig.5.3 Slope morphometry map of the study area.

Table 5.3 I Information Value for slope material.

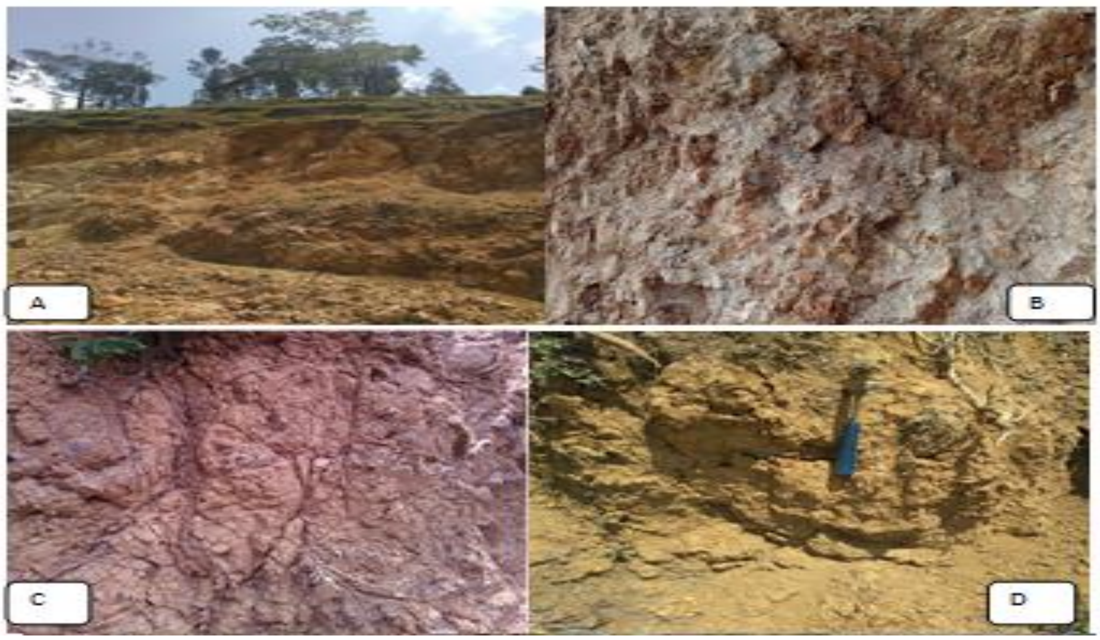
No.	Slope material class	Ncpix	Nspix	CP	PP	CP/PP	IV
1	Soil mass	55537	687	0.0124	0.0128	0.97	0.064
2	Disintegrated rock mass	29171	343	0.0117	0.0128	0.91	0
3	Blocky disturbed rock mass	9615	177	0.0184	0.0128	1.44	0.5

As shown in above table 5.3, 57%, 28 % and 15% of the landslides occurred in soil mass, disintegrated rock mass and blocky disturbed rock mass of slope material class, respectively. The conditional probability of occurrence for landslide in soil mass, disintegrated rock mass and blocky disturbed rock mass is 0.0124, 0.0117 and 0.0184, respectively. From information value, soil mass and blocky disturbed rock mass of slope material class is 0.064 and 0.5 value, respectively.



(A and F) Alluvial deposits. (B,C, D and E) residual soil.

Plate 5.1 Soil slope material in the study area



(A and D). Yellow, very weak unwelded tuff. (B) Light gray, weak and highly weathered tuff. (C) Reddish, weak and highly weathered basalt with exfoliation weathering.

Plate 5.2 Disintegrated rock mass slope material in study area

(A and D) Light gray blocky disturbed Basalt . (B and C). Blocky disturbed trachyte.

Plate 5.3 Blocky disturbed rock mass slope material.

5.2.1.1.4 Structural Discontinuities

Data relating to structural discontinuities orientation has been collected facet wise from the exposed rock mass and its relation to slope inclinations was determined. The rock mass condition with respect to structural discontinuities was also observed. Besides, data on characteristics of structural discontinuities with respect to spacing, continuity, and surface characteristics, separation of discontinuity surface and thickness and nature of filling material within the discontinuity surfaces has also been collected.

5.2.1.1.4 Landuse and Landcover

Land use and land cover is also a key factor responsible for landslide occurrences (Kifle Woldearegay, 2013). The landuse-landcover of the study area is characterized as agricultural land, bare land, sparsely vegetated land, moderately vegetated land and forest. A major portion of the slopes in the study area is covered by agricultural land (46%), whereas, areas covered by sparsely vegetation, moderately vegetation, bare land and forest are 8%, 7%, 21 % and 17% , respectively (Fig.5.5).

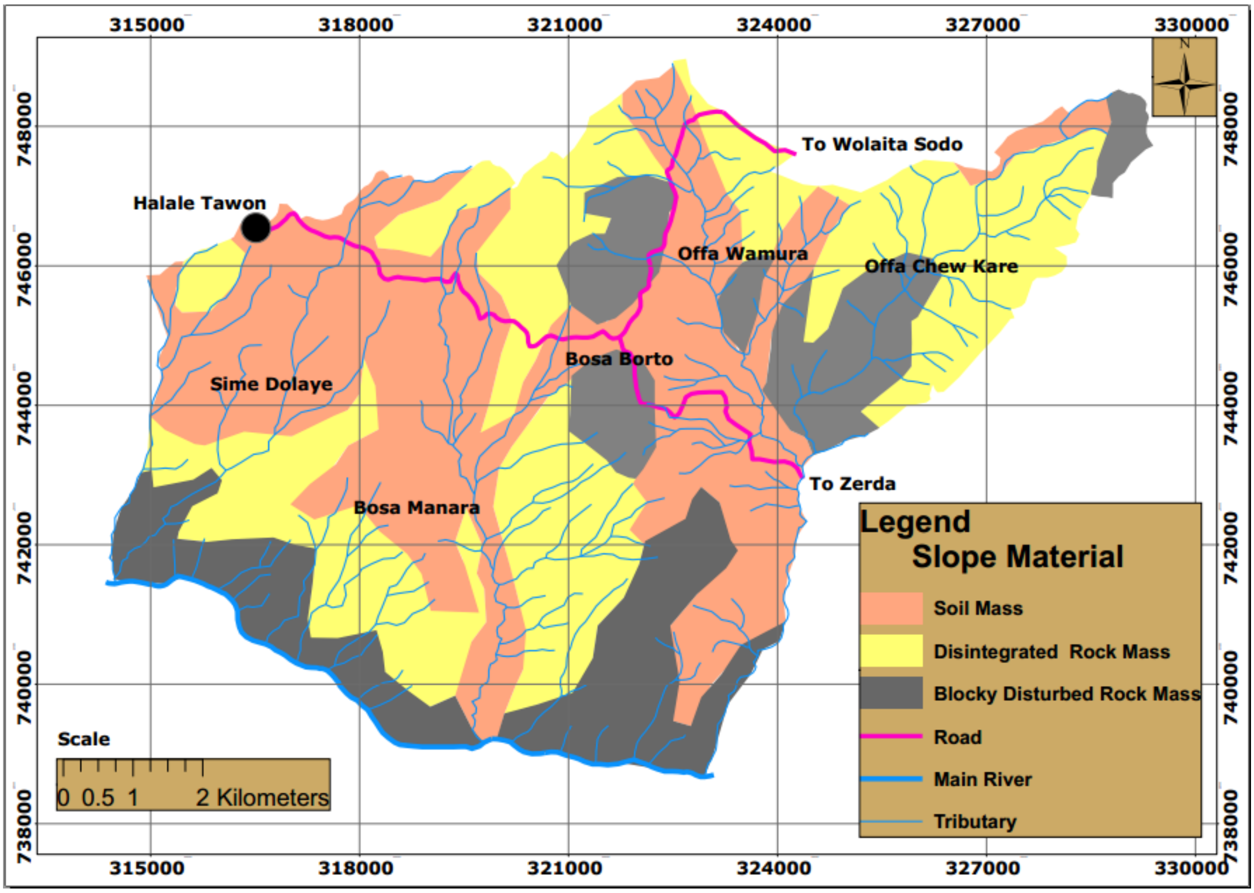


Fig.5.4 Slope material map of the study area.

Table 5.4 Information Value for landuse/landcover.

No.	Landuse/ landcover Class	Ncpix	Nspix	CP	PP	CP/PP	IV
1	Agriculture	43085	706	0.0164	0.0128	1.28	2.45
2	Bare Land	7769	279	0.036	0.0128	2.8	3.2
3	Sparsely Vegetated	6512	84	0.0123	0.0128	0.96	2.16
4	Moderately Vegetated	19595	112	0.0057	0.0128	0.44	1.38
5	Forest	17362	26	0.0015	0.0128	0.11	0

As shown in above table 5.4, 58%, 24%, 7%, 9% and 2% of the landslides occurred in agricultural land, bare land, sparsely vegetated land, moderately vegetated and forest class of landuse/ landcover, respectively. The conditional probability of occurrence for landslide in agricultural land, bare land, sparsely vegetated land, moderately vegetated and forest is 0.0164, 0.036, 0.0123, 0.0057 and 0.0015 0.002, respectively. From information value, agricultural land, bare land, sparsely vegetated land and moderately vegetated is 2.45, 3.2, 2.16 and 1.38 values, respectively.

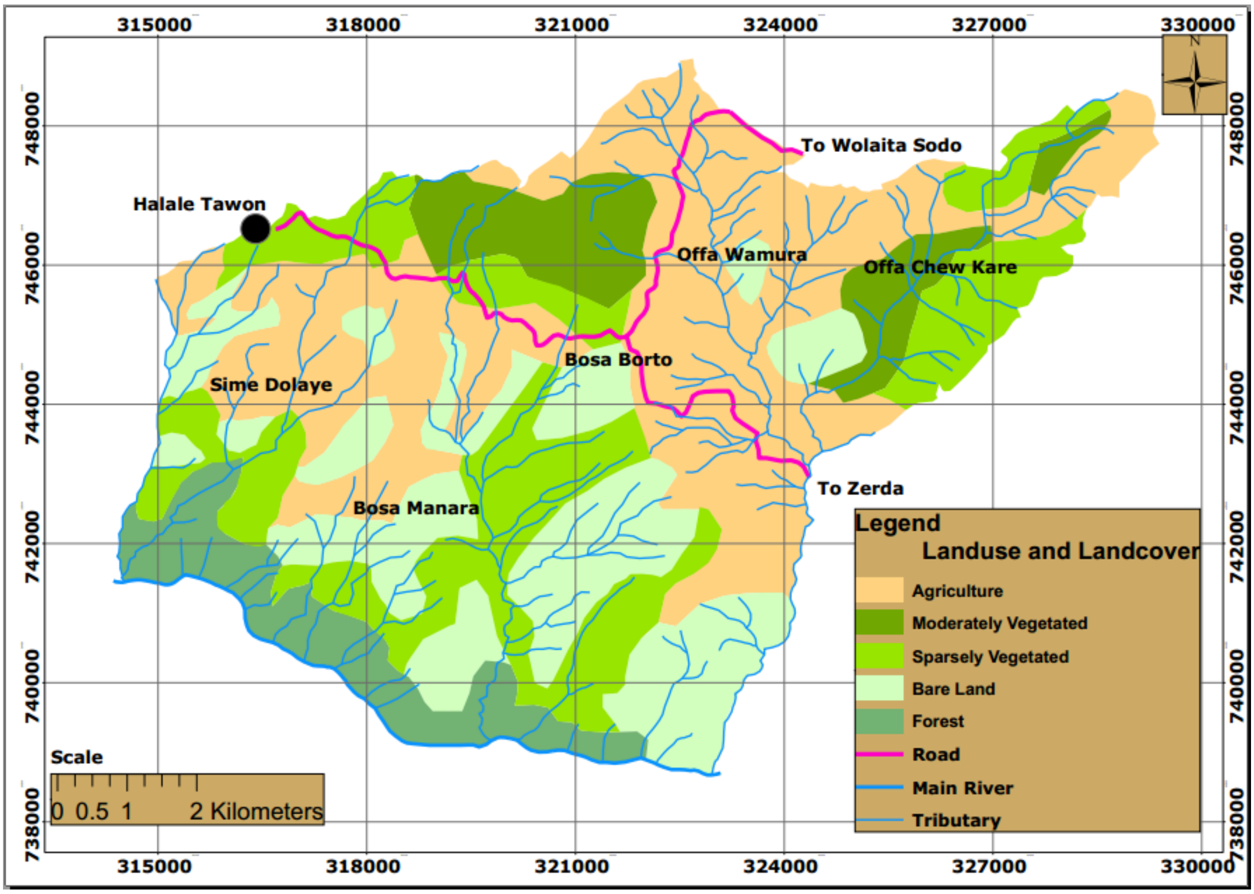


Fig.5.5 Landuse and Landcover map of the study area.

5.2.1.1.5 Groundwater

Surface indications such as; damp, wet, dripping and flowing were observed on each facet in order to consider the groundwater condition in the study area. Field observations were also made to note the water marks and algal growth (Plate 5.4). Seventy six spring's data were collected during field investigation. As observed during field, most of spring waters are found from highly weathered fractured basalt unit and alluvial deposits. From total area 42%, 16%, 7% and 35% covered by flowing, dripping, wet and dry groundwater surface manifestation classes respectively (Fig. 5.6).

(A) Wet. (B) Algal growth. (C). Spring water in alluvial deposit. (D and E) Dripping. (F). Spring water.

Plate 5.4 Groundwater surface traces.

Table 5.5 Information Value for groundwater surface manifestations.

No.	Groundwater Surface Manifestations Class	Ncpix	Nspix	CP	PP	CP/PP	IV
1	Flowing	40116	336	0.0084	0.0128	0.66	1.5
2	Dripping	14737	734	0.05	0.0128	3.9	3.36
3	Wet	7488	77	0.01	0.0128	0.78	1.65
4	Dry	31982	59	0.00185	0.0128	0.15	0

As shown in above table 5.5, 28%, 61%, 6% and 5% of the landslides occurred in flowing, dripping, wet and dry class of groundwater surface manifestations, respectively. The conditional probability of occurrence for landslide in flowing, dripping, wet and dry is 0.0084, 0.05, 0.01 and 0.00185, respectively. From information value, flowing, dripping and wet is 1.5, 3.36 and 1.65values, respectively.

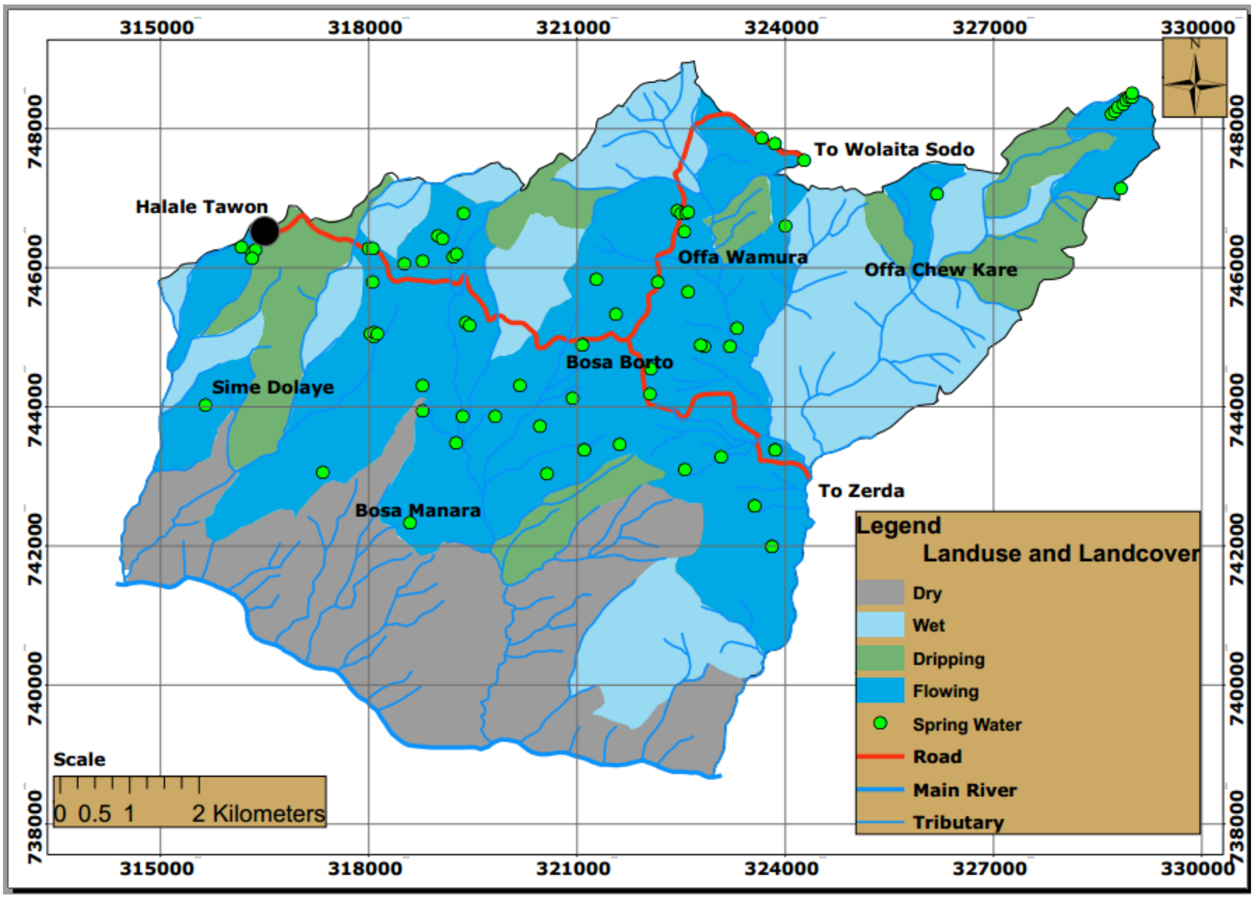


Fig.5.6 Groundwater surface traces map of the study area.

5.2.1.2 External Causative Parameters

According to Varnes (1984), Dai and Lee (2001) and Raghuvanshi et al. (2014) the external causative factors are relatively variable or dynamic , temporary and imposed by new events which include rainfall, volcanic activity, seismic vibration and manmade activities. In this study, rainfall, seismicity and manmade developmental activities were considered as external causative parameters in landslide hazard zonation of study area by using Slope stability Susceptibility Evaluation Parameter expert method whereas in Landslide hazard evaluation of the study area by using integrated Slope stability Susceptibility Evaluation Parameter and raster based information value method except seismicity the others were considered.

5.2.1.2.1 Seismicity

Seismic Risk Map produced by Laike Mariam shows that the likely peak ground acceleration (PGA) with a hundred year return period and 0.99 probabilities the study area falls within 6 M.M scale (Fig. 1.7). Based on the Modified Mercalli intensity scale the estimated horizontal earthquake acceleration comes out to be 0.06 g, as determined from the MM intensity graph (Johnson and DE Graff, 1991).The seismic intensity over the study area is the same therefore the corresponding ground acceleration will be 0.06 g throughout the study area. Accordingly, the seismicity rating value of the study area is 0.8 (Fig.1.7).

5.2.1.2.2 Rainfall

The present study area on an average receives mean annual rainfall of 1378 mm which is considered as very high. Rainfall has a significant influence over the slope stability condition (Bekele Abebe et al., 2010; Kifle Woldearegay, 2014). Rainfall in the study area is high, with mean annual precipitation 1378 mm in the last 28 years. Most of the rain in study area is concentrated in the months as May to September. Moreover, the rain induced manifestation on slope such as; gully erosion, toe erosion, stream bank erosion etc. has also been considered (Plate 5.5) (Fig.5.7). Slope toe erosion, stream bank erosion and gully erosion of rain induced manifestations cover 9%, 12% and 79% within study area, respectively.

Table 5.6 Information Value for rain induced manifestation.

No.	Rainfall Manifestations Class	Ncpix	Nspix	CP	PP	CP/PP	IV
1	Slope toe erosion	8825	158	0.018	0.0128	1.4	4.24
2	Stream bank erosion	11250	1027	0.0913	0.0128	7.13	5.87
3	Gully erosion on slope face	74248	19	0.00026	0.0128	0.02	0

As shown in above table 5.6, 13%, 85% and 3% of the landslides occurred in slope toe erosion, stream bank erosion and gully erosion on slope face class of rainfall induced manifestation respectively. The conditional probability of occurrence for landslide slope toe erosion, stream bank erosion and gully erosion is 0.018, 0.0913, and 0.00026, respectively. From information value, slope toe erosion and stream bank erosion on slope face is 4.24 and 5.87 values, respectively.

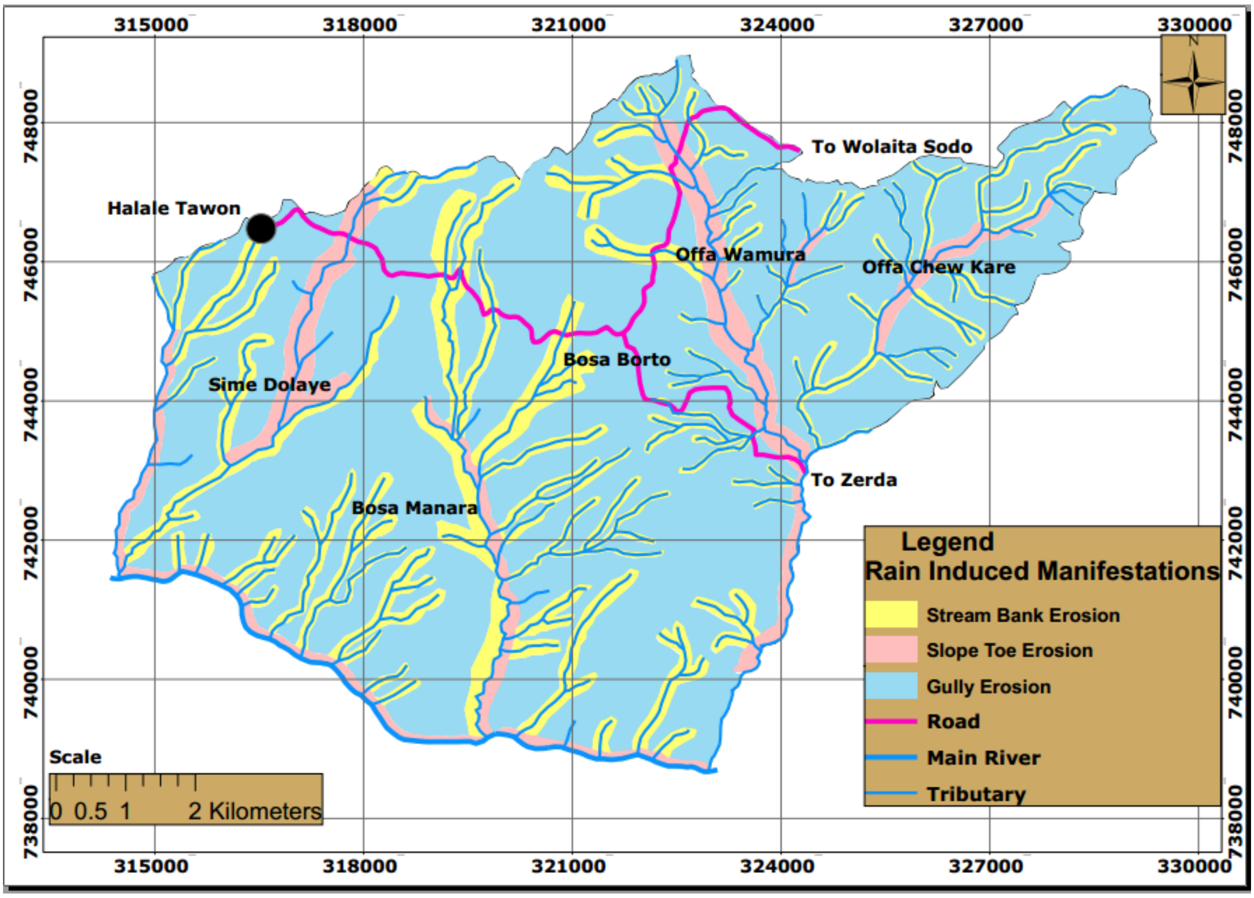
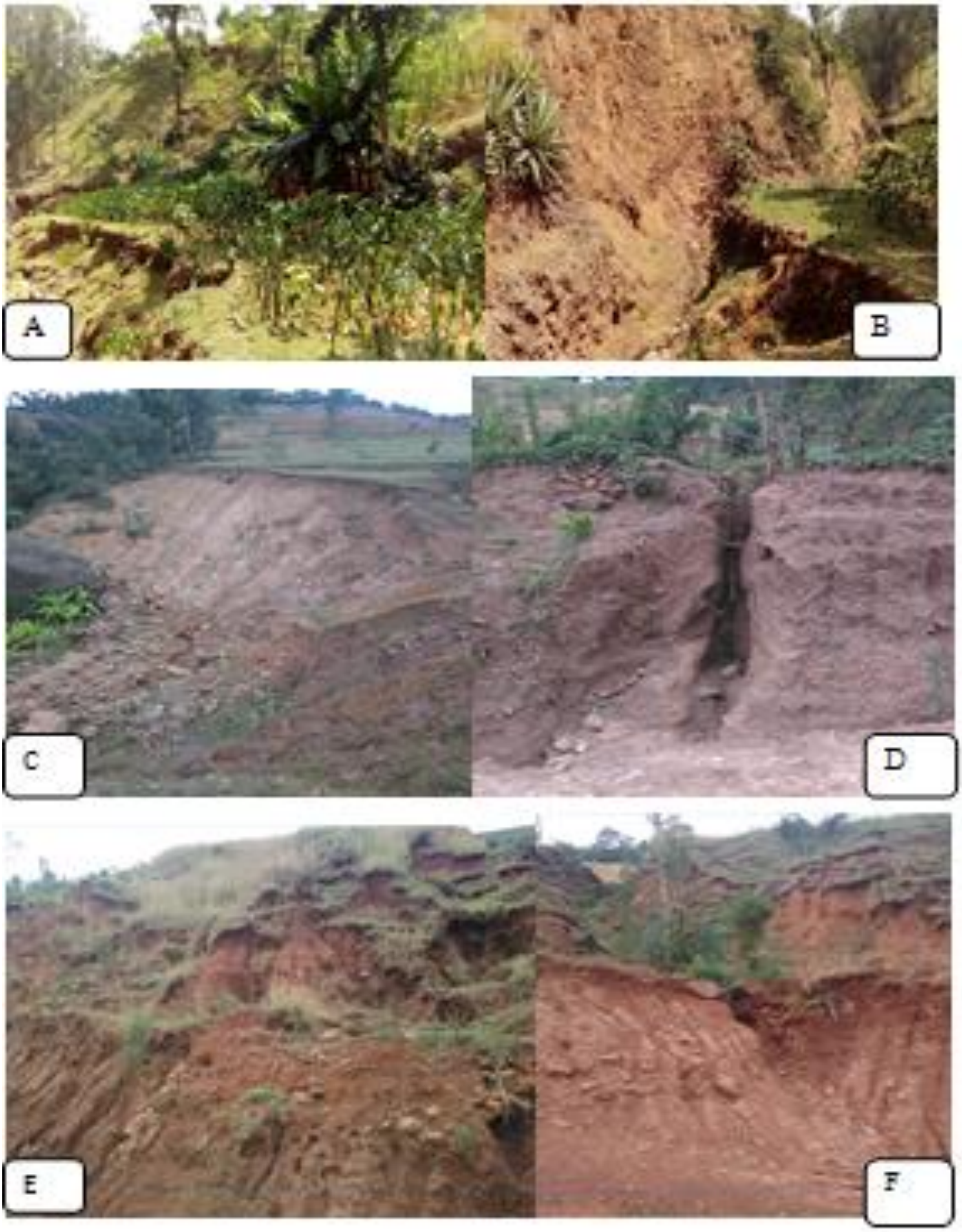


Fig. 5.7 Rain induced manifestations map of the study area.

5.2.1.2.3 Manmade Developmental Activities

The man-made main activity which affect the slope stability in the study area are cultivation activity, steep rock mass cut for road construction and quarry for gravel road construction (Fig.5.8). 0.4% of the study area is used as quarry site whereas 0.6% is steep cut rock mass. Besides, 42% of the area is covered by dense cultivation, 28% by moderate cultivation 21% by sparse cultivation, 6% by steep rock mass cut for construction activities, 3% by dumped excavated material and quarry.



Stream bank erosion (A and B). Gully erosion (D, E and F). Slope toe erosion(C).

Plate 5.5 Rain induced manifestations on slope face.

Table 5.7 Information Value for man-made developmental activities.

No	Man-made developmental class	Ncpix	Nspix	CP	PP	CP/PP	IV
1	Quarry	348	203	0.58	0.0128	45.31	7.3
2	Steep rock mass cut	528	671	1.28	0.0128	100	8.1
3	Dumped excavated material	9427	199	0.02	0.0128	1.56	3.95
4	Densely cultivated	45929	34	0.00074	0.0128	0.058	0.65
5	Moderately cultivated	6490	72	0.01	0.0128	0.78	3.25
6	Sparsely cultivated	10790	20	0.0019	0.0128	0.15	1.6
7	No activity	20811	8	0.00038	0.0128	0.03	0

As shown in above table 5.7, 17 %, 55%, 16%, 3%, 6%, and 2 % and 1% of the landslides occurred in quarry, steep rock mass cut, dumped excavated material, densely moderately, and sparsely cultivated class of man-made developmental activities, respectively. The probability of occurrence for landslide quarry, steep rock mass cut, dumped excavated material, moderately cultivated, and sparsely cultivated is 0.58, 1.28, 0.02, 0.00074, 0.01, and 0.0019 , respectively. From information value, quarry, steep rock mass cut, dumped excavated material, densely, moderately and sparsely cultivated 7.3, 8.1, 3.95, 0.65, 3.25, and 1.6 values, respectively.

5.3 Influencing Parameters

Influence of each parameter was rated to define the most influential parameter in the landslide process of study area. As shown in below table 5.8 and fig 5.9 the Relative relief: 1.2, Slope Morphometry: 2.58, Slope Material: 0.567, Landuse and Landcover: 9.19, Groundwater Surface Manifestations: 6.51, Rainfall Induced Manifestations: 10.11 and Manmade Developmental Activities: 24.85. The information values; manmade developmental activities, rainfall induced manifestations; landuse/landcover and groundwater are most influential causative parameters in study area with values 24.85, 10.11, 9.19, and 6.51, respectively. It reveals that the deforestation, cultivation and modifying the slopes by manmade activities in addition with high rain fall and groundwater are most influential causative parameter for the occurrence landslides in study area.

Steep slope cut(A,C, D and F).
Cultivation on slope face (B).
Qaurry (E).

Plate 5.6 Manmade made developmeental activities on slope face.

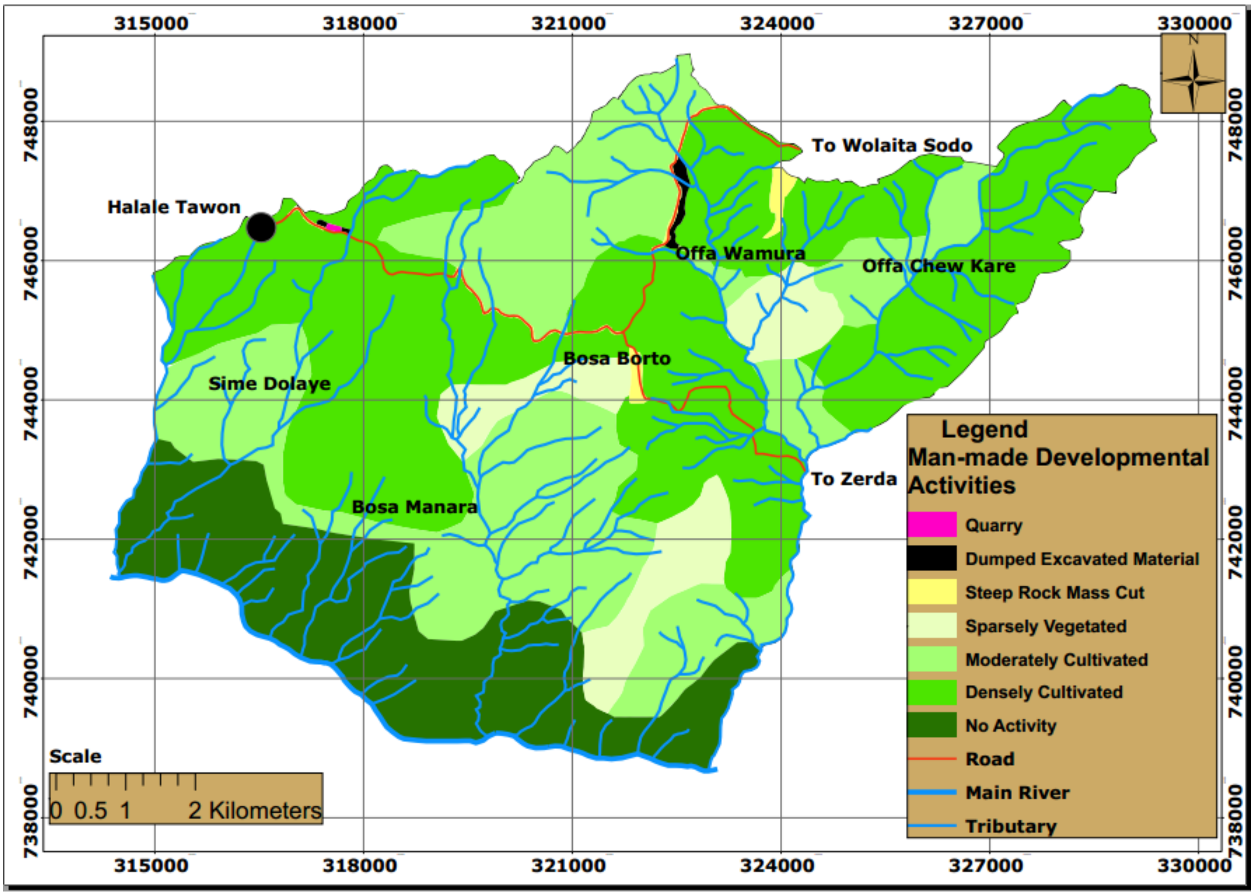


Fig.5.8. Man-made developmental activities map of the study area.

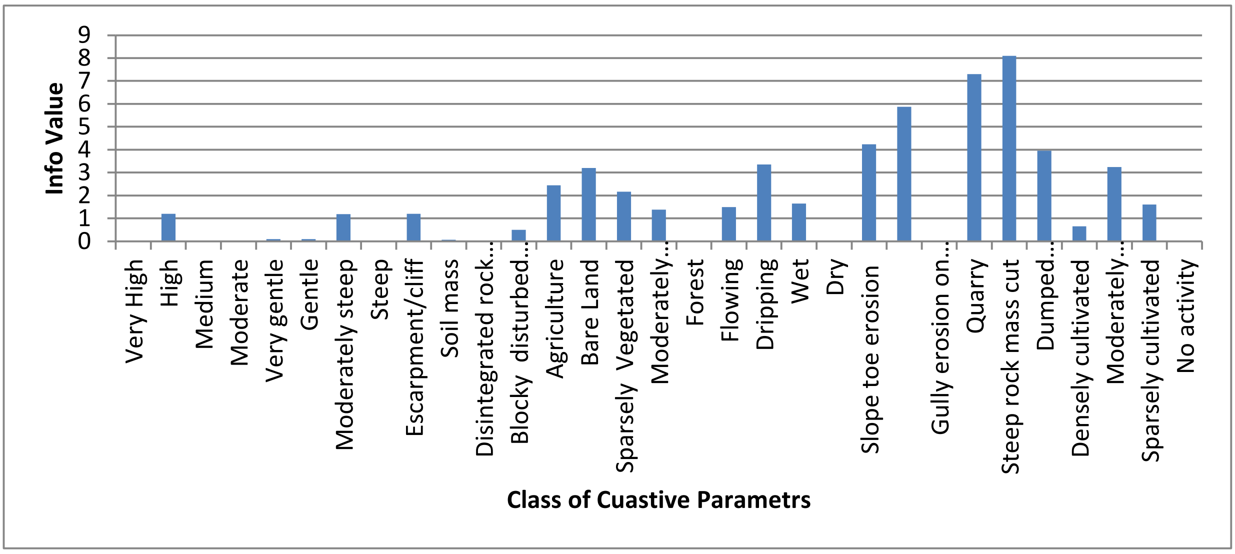


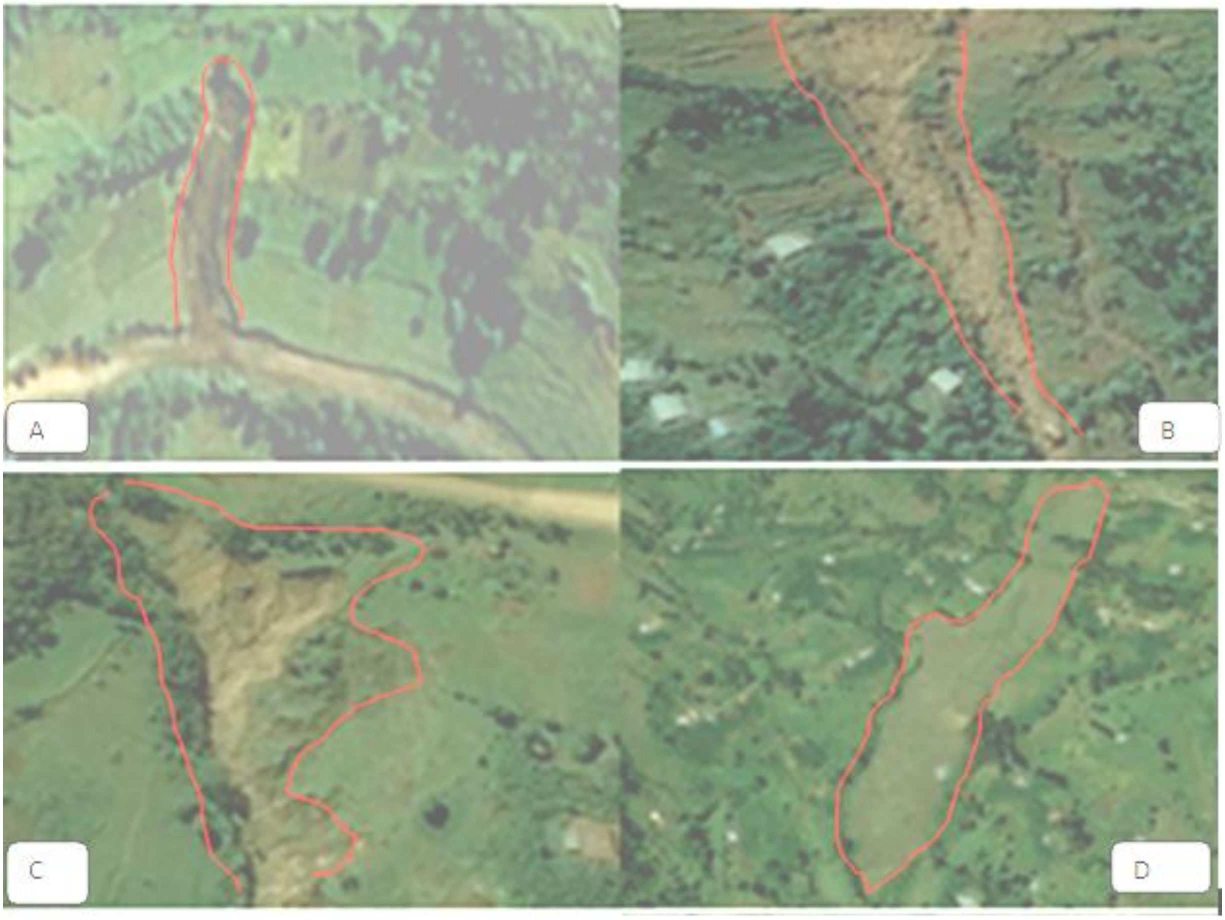
Fig.5.9. Influencing parameters.

Table 5.8 Information Values for all the classes in each causative factor maps.

Factor Map	Classes	Description	Class pixel	% Map area	Landslide pixel	% Landslide	Weight
Relative Relief	1	Very High	86938	92	1132	94	0
	2	High	1732	2	75	6	1.2
	3	Medium	1669	3.8	0	0	0
	4	Moderate	3984	2.2	0	0	0
Slope Morphometry	1	Very gentle	15635	16	159	19	0.1
	2	Gentle	39232	42	396	12	0.1
	3	Moderately steep	11559	13	288	24	1.18
	4	Steep	19371	20	143	32	0
	5	Escarpment/cliff	8526	9	221	13	1.2
Soil Mass	1	Soil mass	55537	59	687	57	0.064
	2	Disintegrated rock mass	29171	31	343	28	0
	3	Blocky disturbed rock mass	9615	10	177	15	0.5
Landuse and Landcover	1	Agriculture	43085	46	706	58	2.45
	2	Bare Land	7769	8	279	24	3.2
	3	Sparsely Vegetated	6512	7	84	7	2.16
	4	Moderately Vegetated	19595	21	112	9	1.38
	5	Forest	17362	17	26	2	0
Groundwater Surface Manifestations	1	Flowing	40116	42	336	28	1.5
	2	Dripping	14737	16	734	61	3.36
	3	Wet	7488	7	77	6	1.65
	4	Dry	31982	35	59	5	0
Rain Induced Manifestations	1	Slope toe erosion	8825	9	158	13	4.24
	2	Stream bank erosion	11250	12	1027	85	5.87
	3	Gully erosion on slope face	74248	79	19	3	0
Manmade Developmental Activities	1	Quarry	348	0.4	203	17	7.3
	2	Steep rock mass cut	528	0.6	671	55	8.1
	3	Dumped excavated material	9427	10	199	16	3.95
	4	Densely cultivated	45929	48	34	3	0.65
	5	Moderately cultivated	6490	7	72	6	3.25
	6	Sparsely cultivated	10790	12	20	2	1.6
	7	No activity	20811	22	8	1	0

5.4 Landslide Inventory Mapping

According to Dai and Lee (2002) landslide inventory mapping is bases for landslide hazard zonation. Seventy one landslides have been identified through interpretation of Google Earth Image (Fig 5.10 - 5.11) and direct field survey (Plate 5.7 - 5.9), and then digitized directly into inventory map using GIS (Fig.5.11) (Table 5.9).



(A) Debris flow in Offa Chew Kare Kebele.

(B) Debris slide along Zala Kare River.

(C) Rotational slide along Kila River.

(D) Debris flow in Offa Wamura.

Figure 5.10 Identified landslides in the study area.

(A) Debris slide in Offa Chew Kare Kebele.

(B) (B, C and D) A rotational slide.

Figure 5.11 Identified landslides in the study area.

Table.5.9. Inventory data of Past Landslide activities in the study area.

No	Location		Description
	Northing	Easting	
1	322887	748102	A 60 m by120 m size rotational slide observed in highly weathered unwelded tuff that overlain by basalt in moderately steep slope.
2	322308	748105	A 30 m by 142 m size rotational slide in residual soil mass in moderately steep slope along the road.
3	328247	748018	A 35 m by 180 m size rotational slide in residual soil mas in gentle steep slope.
4	323137	747668	A 80 m by 110 m size debris slide in highly weathered unwelded tuff unit overlain by basalt unit.
5	322721	747575	A 30 m by 120 m size earth slide in residual soil mass in steep slope.
6	321098	747449	A 85 m by 200 m size debris flow in residual soil overlain by unwelded tuff.
7	322590	747360	A 35 m by 180 m size earth fall in soil mass along the steep cut road.
8	328404	747254	A 80 m by 130 m size rotational slide along the road in highly weathered and jointed basalt in moderately steep slope.
9	322426	747182	A 75 m by 90 m size rock fall/rock slide in blocky disturbed rock mass.
10	322848	747157	A 90 m by 125 m size rotational slide in highly weathered tuff overlain by basalt along the road in moderately steep slope.
11	324441	747103	A 60 m by 115 m size rotational slide highly weathered tuff overlain by basalt along the road in moderately steep slope.
12	322459	747028	A 82 m by 100 m size rock slide in in blocky disturbed rock mass in steep slope.
13	323621	747051	A 70 m by 165 m size rock fall in blocky disturbed rock mass in steep slope.
14	328399	746981	A 35 m by 65m rotational slide in disintegrated rock mass.
15	317988	746897	A 65 m by100 m rotational slide by disintegrated rock mass.
16	323646	746839	A 60 m by 90 m size rotational slide in disintegrated rock mass.
17	324311	746885	A 60 m by 120 m size rotational slide in disintegrated rock mass.
18	318019	746733	A 35 m by 70 m size rotational slide in soil mass.
19	328252	746710	A 45 m by 80 m size debris slide in disintegrated rock mass
20	317709	746665	A 50 m by 120 m size rotational slide in soil mass.
21	323621	746651	A 60 m by 70 m size debris slide in disintegrated rock mass.
22	323738	746552	A 75 m by 95 m size rotational slide in disintegrated rock mass.
23	324586	746495	A 40 m by 80 m earth slide in soil mass.
24	317489	746493	A 40 m by 110 m size rotational slide in soil mass.
25	322329	746464	A 105 m by130 m size topples in blocky disturbed rock mass.
26	317676	746395	A 35 m by 158 m rotational slide in soil mass.
27	326201	746290	A 100 m by 230 m size debris slide in disintegrated rock mass.
28	324356	746214	A 50 m by 60 m size debris slide in disintegrated rock mass.

29	317856	746227	A 35 m by 170 m size rotational slide in soil mass
30	318088	746231	A 45 m by 185 m size rotational slide in soil mass
31	322208	746192	A 90 m by 105 m size topples in blocky disturbed rock mass.
32	317657	746092	A 35 m by 90 m size rotational slide in soil mass
33	322125	746079	A 50 m by 90 m rockfall blocky disturbed rock mass.
34	318638	745927	A 90 m by 195 m size debris slide in disintegrated rock mass
35	319470	745918	A 110 m by 240 m size debris fall in disintegrated rock mass
36	326058	745645	A 50 m by 85 m size rotational slide in disintegrated rock mass
37	317399	745537	A 60 by 120 m size rotational slide in soil mass.
38	326241	745492	A 55 m by 140 m size rotational slide in disintegrated rock mass
39	317316	745426	A 30 m by 115 m size rotational slide in soil mass.
40	319222	745412	A 35 m by 161 m size rotational slide in soil mass
41	319807	745356	A 40 m by 216 m size rotational slide in soil mass.
42	320214	745272	A 106 m by 129 m by debris slide in disintegrated rock mass.
43	326699	745203	A 30 m by 90 m size debris fall in disintegrated rock mass
44	322053	745226	A 35m by 220 m size rotational slide in soil mass.
45	326849	745153	A 60 m by 110 m size debris slide in disintegrated rock mass
46	320355	745140	A 100 m by 120 m size rotational slide in disintegrated rock mass
47	318895	745113	A 30 m by 175 m size shallow rotational slide in soil mass.
48	321317	745113	A 100 m by 115 m size debris slide in the disintegrated rock mass.
49	321683	745100	A 100 m by 160 m size rotational slide in disintegrated rock mass.
50	320877	744897	A 60 by 80 m size debris slide in disintegrated rock mass.
51	320601	744862	A 40 m by 190 m size rotational slide in soil mass.
52	326074	744873	A 80 m by 120 m size rotational slide in disintegrated rock mass.
53	326492	744837	A 50 m by 230 m size debris flow slide in disintegrated rock mass.
54	318664	744781	A 38 m 175 m size rotational slide in soil mass.
55	324291	744614	A 100 m by 172 m size debris slide in in disintegrated rock mass.
56	325979	744569	A 90 m by 210 m size debris slide in disintegrated rock mass.
57	326546	744582	A 100 m by 120 m size debris slide in blocky disturbed rock mass.
58	320599	744521	A 35 by 120 m size rotational slide in soil mass
59	326131	744451	A 100 m by 192 m size debris fall in disintegrated rock mass.
60	321937	744366	A 51m by 375 size earth slide in soil mass.
61	322296	744147	A 36 m by 215 size rotational slide in soil mass.
62	318377	743964	A 45 m by 155 m size rotational slide in soil mass.
63	322177	343889	A 40 m by 110 m size rotational slide in soil mass.
64	318982	743910	A 35 m by 210 m size rotational slide in soil mass.
65	321512	743828	A 95 m by 165 m size rotational slide in disintegrated rock mass.
66	722414	743773	A 50 m by 200 m size rotational in soil mass.

67	318345	743729	A 30 m by 195 m size rotational slide in soil mass.
68	321355	743677	A 65 m by 110 m size rotational slide in disintegrated rock mass
69	318252	743444	A 30 by 200 m size rotational slide in soil mass
70	318150	743578	A 40 m by 125 m size rotational slide in soil mas.
71	319048	743026	A 35 m by 130 m size rotational slide in residual soil mass.

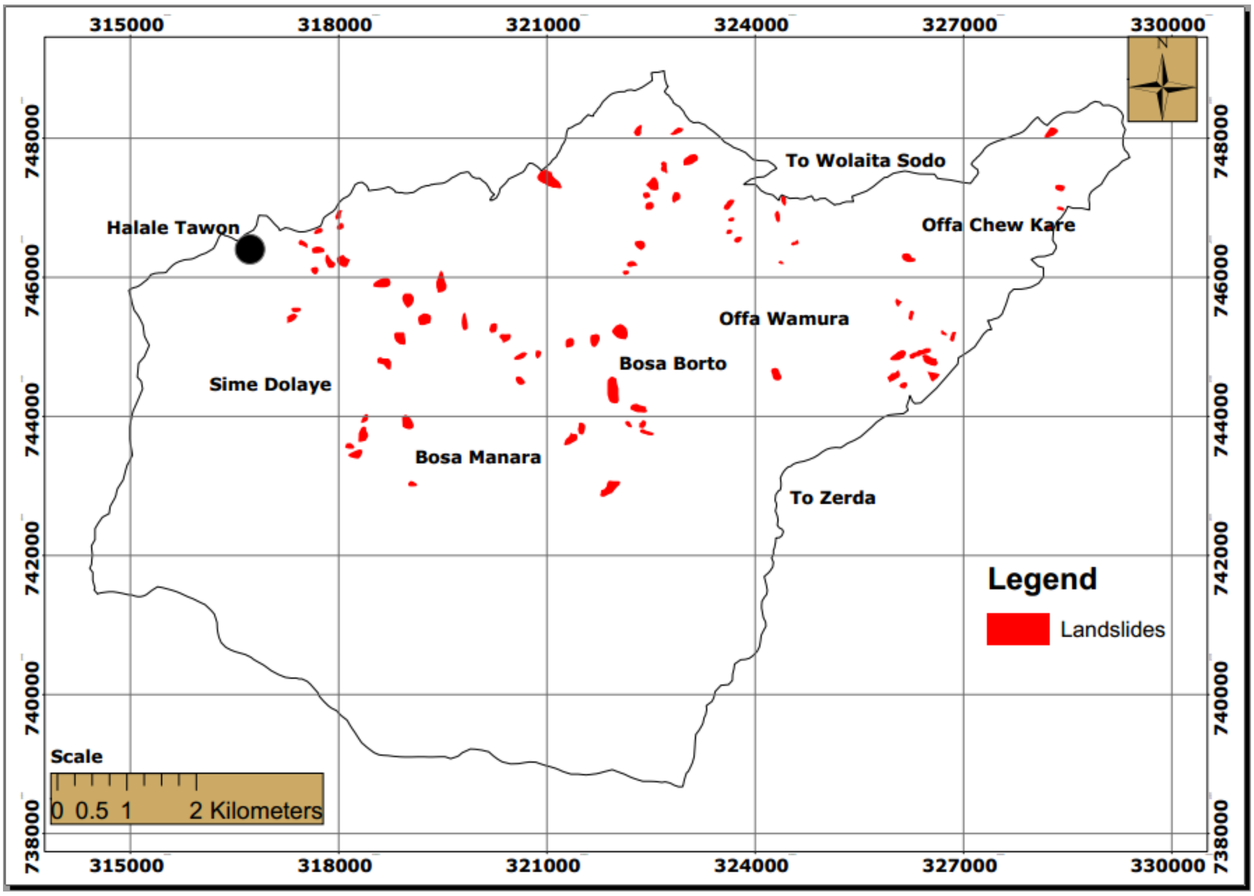
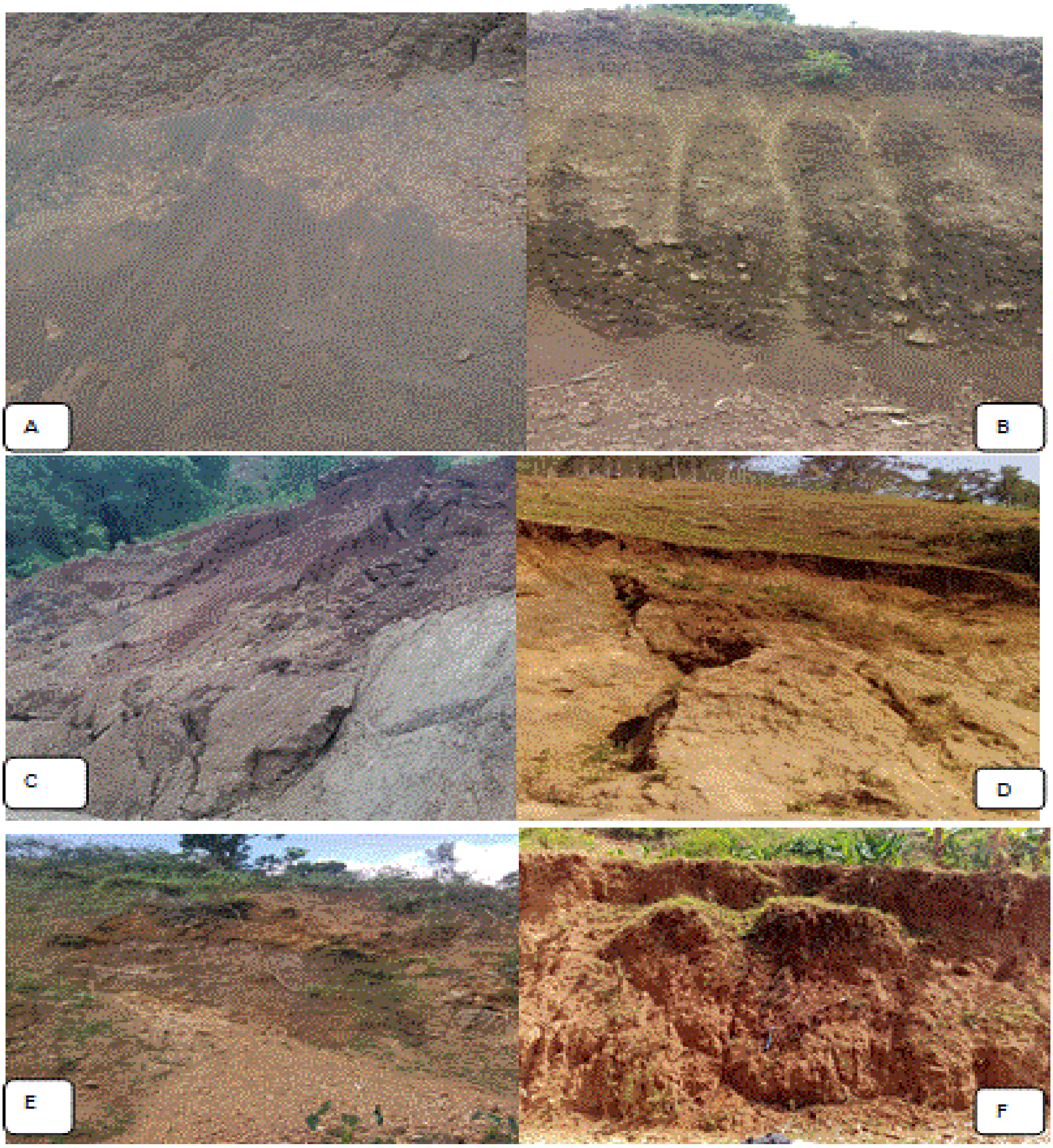


Fig.5.10. Inventory Map



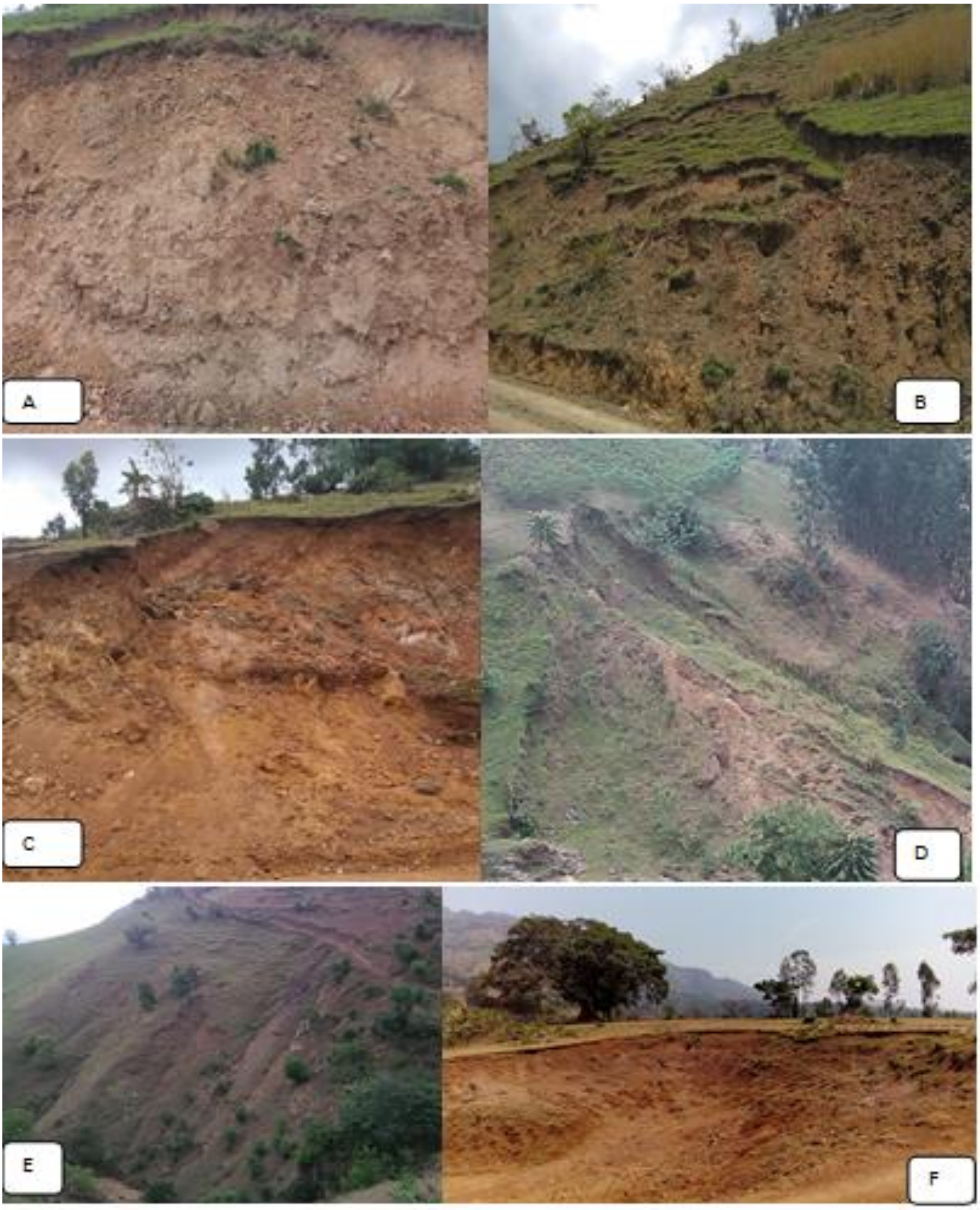
(A and B) Earth slides in soil mass at the Bosa Borto Kebele along the road to Zereda.

(C and D) Rotational slides in residual soils at back Halale Town.

(E) Debris slides at the Offa Wamura Kebele in disintegrated rock mass and also fallen materials that accumulated at foot are visible on the accumulation area.

(F) Rotational slides at Sime Dolaye Kebele around Kele Hiwot church in soil mass.

Plate 5.7 Landslide in the study area.

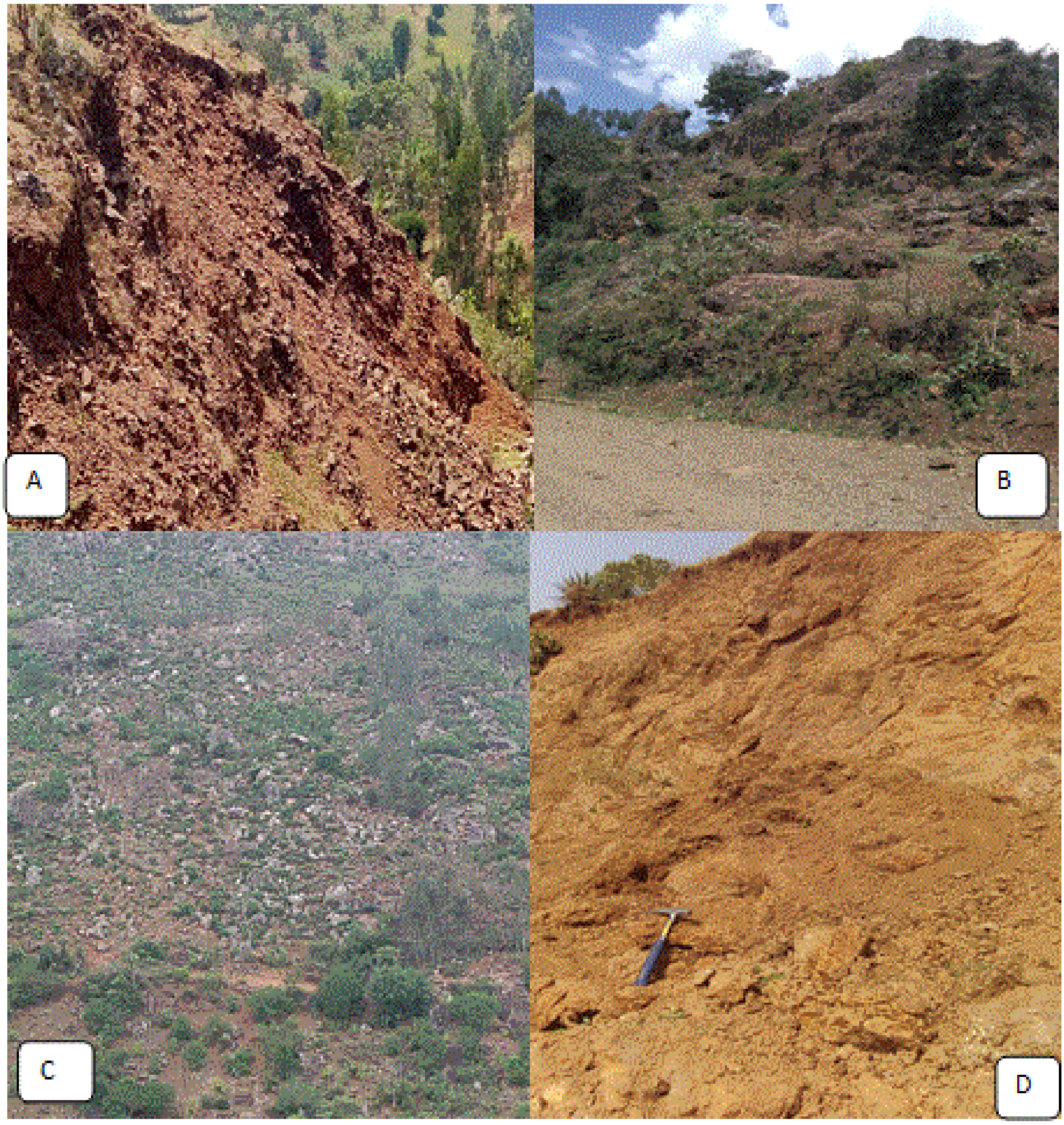


(A, B and C) A rotational slide Offa at Wamura and Bosa Borto Kebele in unwelded tuff.

(D and E) A rotational slide at Offa Wamura Kebele along the Kila River.

(E) A rotational slide at Sime Dolaye Kebele in residual soil mass.

Plate 5.8. Landslide in the study area.



(A) A debris slide/ rock slide in disintegrated rock mass at Sime Dolaye Kebele.

(B) A rockfall/topple in blocky rock mass at Bosa Borto Kebele along the left side of road to Offa Wamura Kebele.

(C) A rock slide at boundary between Zereda and Offa Chew Kare Kebele.

(D) Rotational slide in Halale Town in unwelded tuff and also fallen materials that accumulated at foot are visible on the accumulation area.

Plate 5.9. Landslide in the study area.

5.5 Landslide Hazard Mapping

Landslide hazard mapping involves predicting where a potentially damaging landslide may occur without any reference to the time, or the intensity of associated damage (van Westen et al., 2006). Generally, landslide hazard zonation is out are based on the assumption that future landslides will occur in similar areas and under the same conditions as past and present failures (Cararra et al., 2003; Guzzetti et al., 2005). Inventory based mapping, heuristic approach, probabilistic assessment, deterministic approach, statistical analysis and multi criteria decision making approach method that used for landslide hazard mapping. According to Leroi (1997) various methodologies for landslide hazard mapping may be divided into expert evaluation, statistical methods, and mechanical approach.

The SSEP rating technique involves intrinsic and 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), rainfall (Dai and Lee, 2001) and manmade activities (Wang and Niu, 2009). For SSEP empirical technique numerical ratings are assigned to each of the intrinsic triggering parameters on the basis of their contribution towards instability of slope. The parameters responsible for instability of slopes has been assigned with numerical ratings which is 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 SSEP ratings assigned to different intrinsic and external triggering factors is based on their relative order of importance in contributing instability to the slope (Table 3.1). For the purpose of landslide hazard mapping (LHZ) the area of slopes to be covered has to be divided into individual slope facets. In order to evaluate landslide hazard zonation of an area individual facet wise ratings for causative intrinsic parameters and external triggering parameter ratings are summed up. The sum total of all ratings for causative intrinsic parameters and external triggering parameter will give Evaluated landslide hazard (ELH) . The ELH has been categorized into five classes and is presented in Table 3.2

For the purpose of landslide hazard mapping (LHZ) the area of slopes in the study area has been divided into individual facets. For this purpose topographical map on 1:50,000 scales were utilized to demarcate the facets. Facet boundaries were delineated by major or minor hill ridges, primary and secondary streams and other topographical undulations. A total of 102 slope facets were delineated (Fig. 5.1).

Slope geometry includes relative relief and slope morphometry of the slope. About 92% of the study area falls into very high (>301 m), 1.7% in to high (201 – 300m), 3.8 % falls into medium (101-200 m) and 2.2 %) falls into moderate (50-100 m) relative relief category (Fig.5.2). Thus, depending upon the relative relief class ratings has been assigned to respective slope facets.

Slope morphometry defines the steepness of the slopes. About 9%, 20 %, 13 %, 42% and 16 % of the slopes fall under the category of escarpment (>45^0), steep (35°-45°), moderately steep (25°-35°) , gentle (16-25^0), and very gentle slope class , respectively (Fig 5.3). Thus, accordingly SSEP ratings were assigned to each of the slope facets for slope morphometry.

Due to the nature of the geological setting of the area, slope material of the study area is characterized by highly weathered and disintegrated rock mass. The rock mass comprised highly weathered tuff, highly weathered and fractured basalt and trachyte, and moderately weathered and fractured basalt and trachyte. While the soil mass of the slopes comprised residual, alluvial and colluvial deposits. Generally, the area is classified into soil mass (residual, alluvial and colluvial unconsolidated deposits), disintegrated rock mass (highly weathered tuff, highly weathered and fractured basalt and trachyte) and blocky disturbed rock mass (moderately weathered and fractured basalt and trachyte). About 59 % of the total area covered by soil mass, 31 % covered by disintegrated rock mass whereas 10% is covered by blocky disturbed rock mass (Fig.5.4). Thus, accordingly SSEP ratings were assigned to each of the slope facets for slope material.

Data pertaining to structural discontinuities orientation has been collected facet wise from the exposed rock mass and its relation to slope inclinations was determined. The rock mass condition with respect to structural discontinuities was also observed. Besides, data on characteristics of structural discontinuities with respect to spacing, continuity, and surface characteristics, separation of discontinuity surface and thickness and nature of filling material within the discontinuity surfaces has also been collected. Accordingly ratings were assigned for structural discontinuities.

The landuse-landcover of the study area is characterized as agricultural land, bare land, sparsely vegetated land, moderately vegetated land and forest. A major portion of the slopes in the study area is covered by agricultural land (46%), whereas, areas covered by sparsely vegetation, moderately vegetation, bare land and forest are 8%, 7%, 21 % and 17% , respectively (Fig.5.5). Thus, accordingly SSEP ratings were assigned to each of the slope facets for landuse-landcover.

In order to assess the groundwater condition in the study area surface indications such as; damp, wet, dripping and flowing were observed on each facet. Observations were also made to note the water marks, algal growth etc.; accordingly ratings were assigned. From total area 42%, 16%, 7% and 35% covered by flowing, dripping, wet and dry groundwater surface manifestation classes, respectively. The facet wise groundwater condition in the study area is shown in Fig. 5.6. Thus, accordingly SSEP ratings were assigned to each of the slope facets for groundwater.

Seismic Risk Map produced by Laike Mariam shows that the likely peak ground acceleration (PGA) with a hundred year return period and 0.99 probabilities the study area falls within 6 M.M scale (Fig. 1.7). Based on the Modified Mercalli intensity scale the estimated horizontal earthquake acceleration comes out to be 0.06 g, as determined from the MM intensity graph (Johnson and DE Graff, 1991).The seismic intensity over the study area is the same therefore the corresponding ground acceleration will be 0.06 g throughout the study area. Accordingly, the seismicity rating value of the study area is 0.8 (Fig.1.6).

Rainfall has a significant impact over the slope stability condition. The present study area on an average receives mean annual rainfall of 1378 mm which is considered as high. Thus, the rating assigned for this mean annual rainfall is 0.6. Moreover, the rain induced manifestation on slope such as; gully erosion, toe erosion, stream bank erosion etc. has also been considered Slope toe erosion, stream bank erosion and gully erosion of rain induced manifestations cover 9%, 12% and 79% within study area, respectively (Fig.5.7).

Thus, accordingly SSEP ratings were assigned to each of the slope facets for rainfall induced manifestations.

The man-made main activity which affect the slope stability in the study area are cultivation activity, steep rock mass cut for road construction and quarry for gravel road construction (Fig.5.8). 0.4% of the study area is used as quarry site whereas 0.6% is steep cut rock mass. Besides, 42% of the area is covered by dense cultivation, 28% by moderate cultivation 21% by sparse cultivation, 6% by steep rock mass cut for construction activities, 3% by dumped excavated material and quarry. Thus, accordingly SSEP ratings were assigned to each of the slope facets for manmade activities.

The Landslide Hazard Zonation of the study area was carried out through Evaluated landslide hazard (ELH) which indicates the net probability of instability and was determined facet wise. The ELH for an individual facet was obtained by adding the ratings of individual intrinsic factors and external triggering parameter obtained from the SSEP rating scheme.

After collecting primary data for the rating values facet wise and evaluating them, the study areas have only three classes of hazard zones. The landslide hazard zonation map of the study area (Fig.5.11) carried out by Slope stability Susceptibility Evaluation Parameter expert method, shows that Moderate Hazard Zone covers 21 % (18 km^2), High Hazard Zone covers 63% (54 km^2) and Very High Hazard Zone covers 16% (13 km^2) of the total study area.

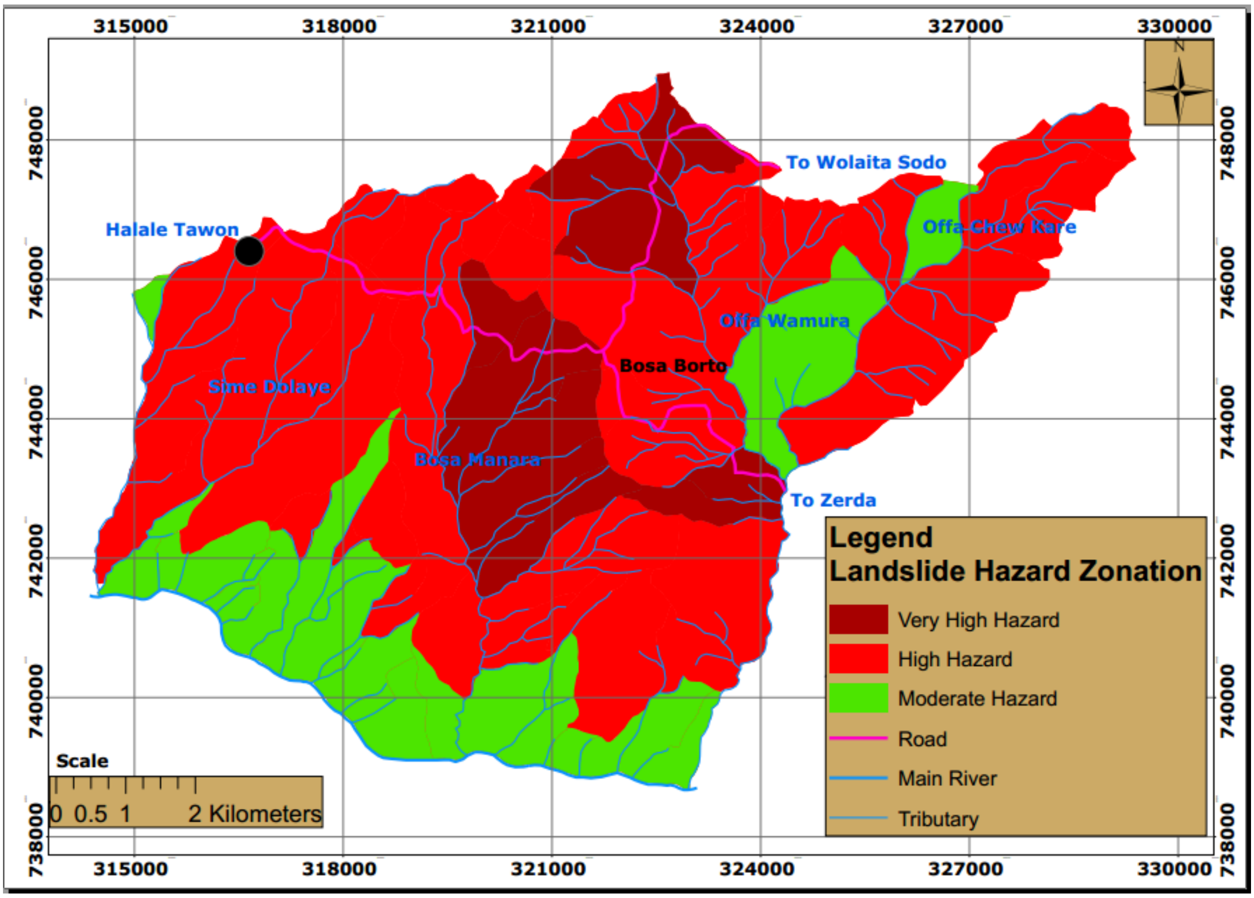


Figure 5.11. Landslide Hazard Zonation map prepared by Slope stability Susceptibility Evaluation Parameter (SSEP) expert method.

According to Yin and Yan (1988), Jade and Sarkar (1993), van Westen (1997), Lin and Tung (2003) Information Value (IVM) is a bivariate statistical method for spatial prediction of landslides based on relationships between landslide occurrence and related parameters. The information values are determined for each subclass of landslide related parameter on the basis of presence of landslide in a given mapping unit. According to Kanungo et al. (2009) Information Value Model has proved useful method in determining the degree of influence of individual causative factor responsible for landslide occurrence.

In integrated SSEP and a raster based Information Value method seven causative parameters namely: relative relief, slope morphometry, slope material, landuse/landcover, groundwater surface manifestations, rain induced manifestations and manmade developmental activities were selected and their thematic maps were prepared. According to Ayalew et al. (2005), factors selected for landslide susceptibility assessment in a GIS-based study, must be operational, represented over the entire area, non-uniform, non-redundant and measurable so that seismicity and structural discontinuity not included in this study. The landslide inventory map for this study has been prepared from data collected during field investigation and from google earth image interpretation. The inventory map combined with each of seven causative factors to determine the relationship causative class and landslide (Fig.5.13).

The use of natural logarithm yields negative weights where densities of landslide in lower average and positive when density is higher. To avoid negative weighting values, the weighted values are rescaled by adding the absolute value of the minimum weighted value in each factor (the largest negative value) to the weights of all the other factor classes in each factor (Che et al., 2012).

The distribution of landslide over each of each of factor maps have been obtained and analyzed. Weights for each of the classes within these factor maps have been obtained using the information value method. The rescaled weights (Information value) are assigned to each factor class to obtain weighted factor maps. These factor maps are then summed up using the raster calculator to obtain a landslide susceptibility index value for each pixel. The landslide hazard zonation map reclassified classified into three classes.

94% and 6 % of the landslides occurred in very high and high class of relative relief, respectively. No landslides occurred in medium and moderate class of relative relief. The conditional probability of occurrence for landslide in very high and high class of relative relief is 0.013 and 0.0430.079, respectively. The conditional probability of occurrence for landslide in medium and moderate class is zero. From information value high relief has 1.2 values (Table 5.1).

13%, 32%, 24%, 12%, and 19% of the landslides occurred in very gentle, gentle, moderately steep, seep and escarpment/cliff class of slope morphometry respectively. The conditional probability of occurrence for landslide in very gentle, gentle, moderately steep, seep and escarpment/cliff is 0.01, 0.01, 0.025, 0.0074 and 0.026, respectively. From information value, very gentle, gentle, moderately steep and escarpment/cliff class of slope morphometry is 0.1, 0.1, 1.18, and 2 value, respectively (Table 5.2).

57%, 28 % and 15% of the landslides occurred in soil mass, disintegrated rock mass and blocky disturbed rock mass of slope material class, respectively. The conditional probability of occurrence for landslide in soil mass, disintegrated rock mass and blocky disturbed rock mass is 0.0124, 0.0117 and 0.0184, respectively. From information value, soil mass and blocky disturbed rock mass of slope material class is 0.064 and 0.5 value, respectively (Table 5.3).

58%, 24%, 7%, 9% and 2% of the landslides occurred in agricultural land, bare land, sparsely vegetated land, moderately vegetated and forest class of landuse/ landcover, respectively. The conditional probability of occurrence for landslide in agricultural land, bare land, sparsely vegetated land, moderately vegetated and forest is 0.0164, 0.036, 0.0123, 0.0057 and 0.0015 0.002, respectively. From information value, agricultural land, bare land, sparsely vegetated land and moderately vegetated is 2.45, 3.2, 2.16 and 1.38 values, respectively (Table 5.4).

28%, 61%, 6% and 5% of the landslides occurred in flowing, dripping, wet and dry class of groundwater surface manifestations, respectively. The conditional probability of occurrence for landslide in flowing, dripping, wet and dry is 0.0084, 0.05, 0.01 and 0.00185, respectively. From information value, flowing, dripping and wet is 1.5, 3.36 and 1.65values, respectively (Table 5.5).

13%, 85% and 3% of the landslides occurred in slope toe erosion, stream bank erosion and gully erosion on slope face class of rainfall induced manifestation respectively. The conditional probability of occurrence for landslide slope toe erosion, stream bank erosion and gully erosion is 0.018, 0.0913, and 0.00026, respectively. From information value, slope toe erosion and stream bank erosion on slope face is 4.24 and 5.87 values, respectively (Table 5.6).

17 %, 55%, 16%, 3%, 6%, and 2 % and 1% of the landslides occurred in quarry, steep rock mass cut, dumped excavated material, densely moderately, and sparsely cultivated class of man-made developmental activities, respectively. The probability of occurrence for landslide quarry, steep rock mass cut, dumped excavated material, moderately cultivated, and sparsely cultivated is 0.58, 1.28, 0.02, 0.00074, 0.01, and 0.0019 , respectively. From information value, quarry, steep rock mass cut, dumped excavated material, densely, moderately and sparsely cultivated 7.3, 8.1, 3.95, 0.65, 3.25, and 1.6 values, respectively (Table 5.7).

In case of the landslide hazard map of the study area (Fig. 5.12) which is carried out by using (SSEP) expert and raster based Information Value approach , 24%(20km^2) area fall in the moderately hazard zone whereas 41%(35km^2) and 35%(30km^2) and of the area fall high and very high hazard zone , respectively.

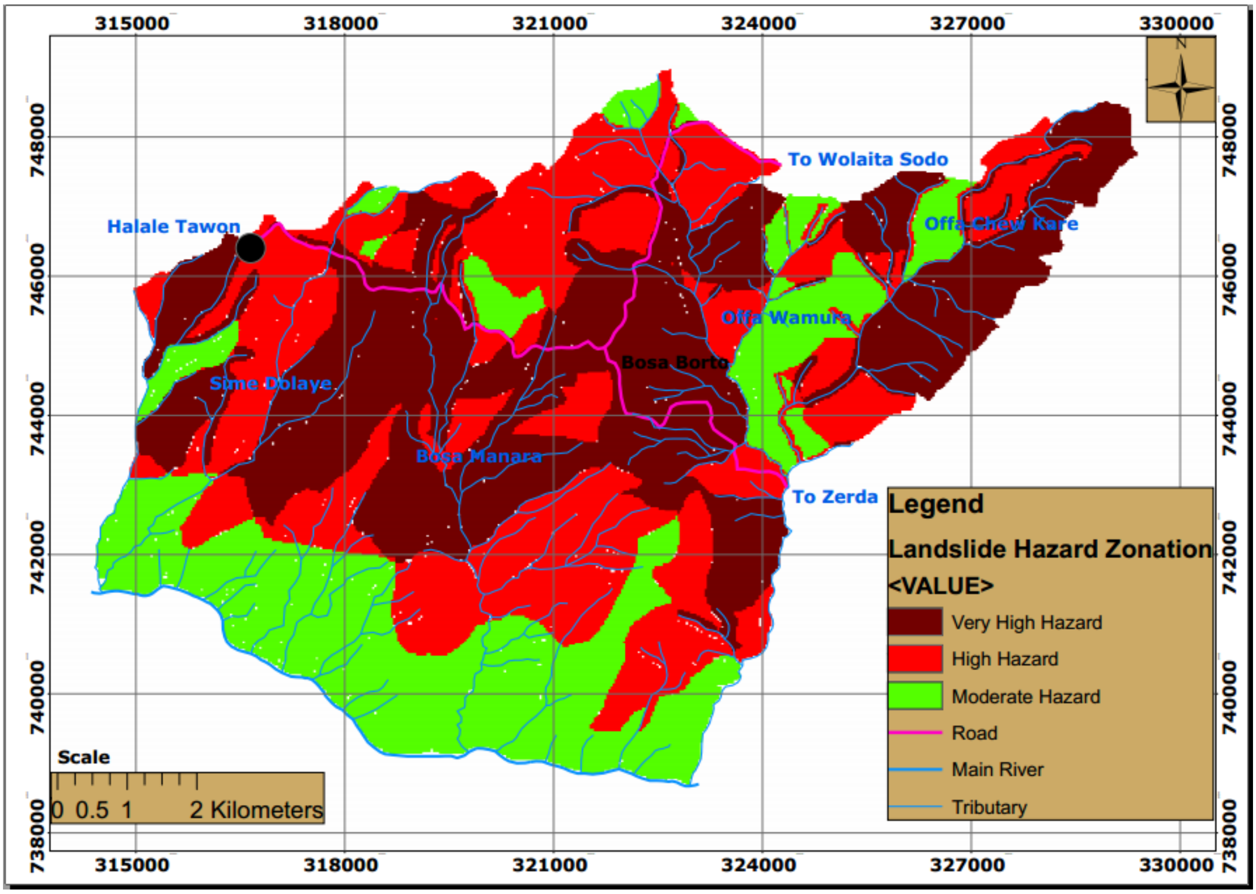


Fig 5.12 Landslide Hazard Zonation map prepared by Slope stability Susceptibility Evaluation Parameter (SSEP) expert and raster based information value approach.

5.6 Verification of Landslide Hazard

Verification of the prepared landslide hazard zonation map of the study area was performed by comparing it with existing landslide inventory data.

In the case of landslide hazard zonation map prepared by SSEP method, out of 71 landslides inventory data 2 falls (3%) in moderate hazard zone, 50 falls (71%) in high hazard zone and 19 falls (27%) on very high hazard zone (Fig. 5.13). This shows that

98% of existing landslide location is high and very high hazard zone and it agrees with the present landslide hazard zonation map.

Whereas, landslide hazard zonation map of the study area prepared by integrated Slope stability Susceptibility Evaluation Parameter (SSEP) and raster based Information Value method, out of 71 landslide inventory data 4 (6%) falls in moderate hazard zone, 14 (20%) falls in high hazard zone and 53 (74%) falls on very high hazard zone (Fig. 5.14). This shows that 94% of existing landslide location is high and very high hazard zone and it agrees with the present landslide hazard zonation map.

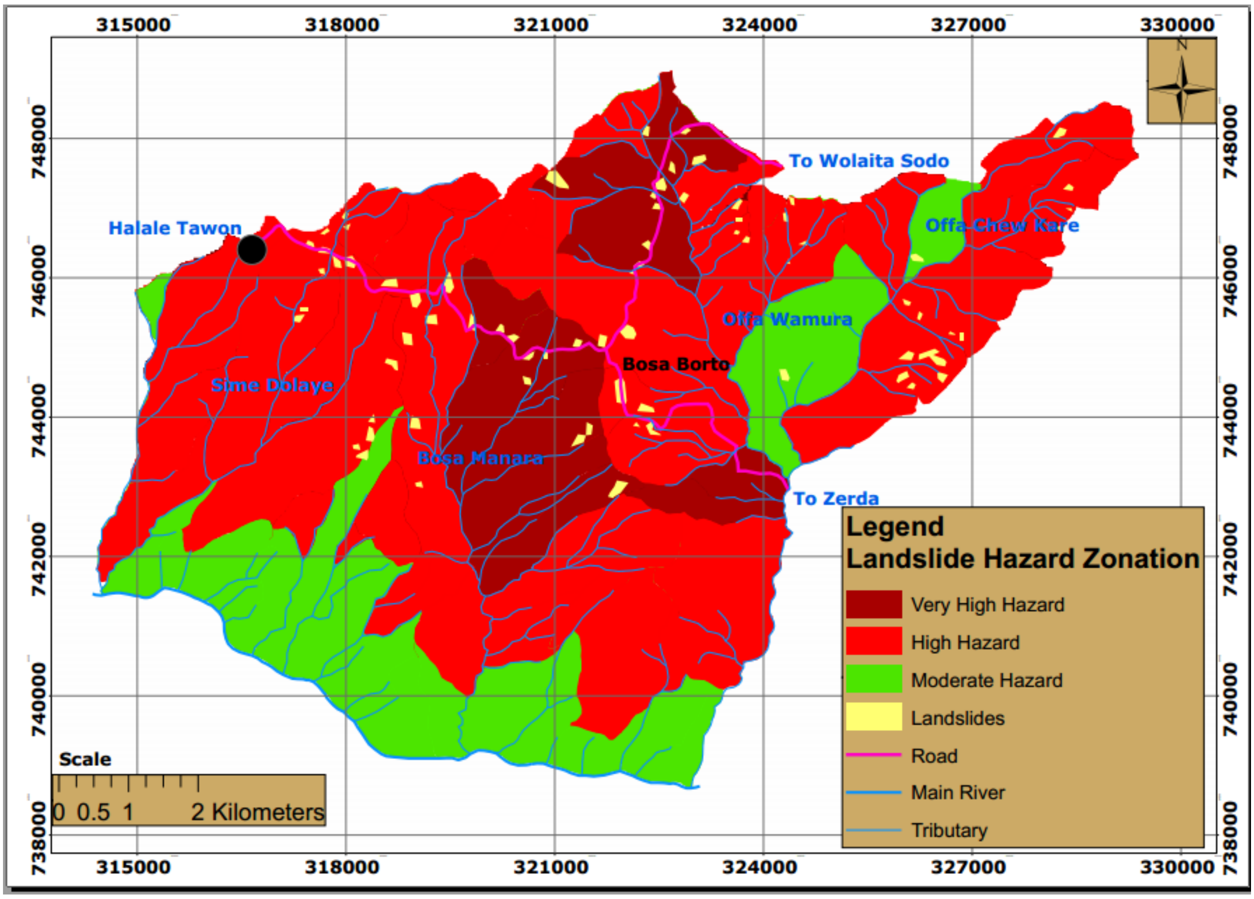


Fig 5.13. Past landslide activities overlain on landslide hazard zonation map prepared by Slope stability Susceptibility Evaluation Parameter (SSEP) method.

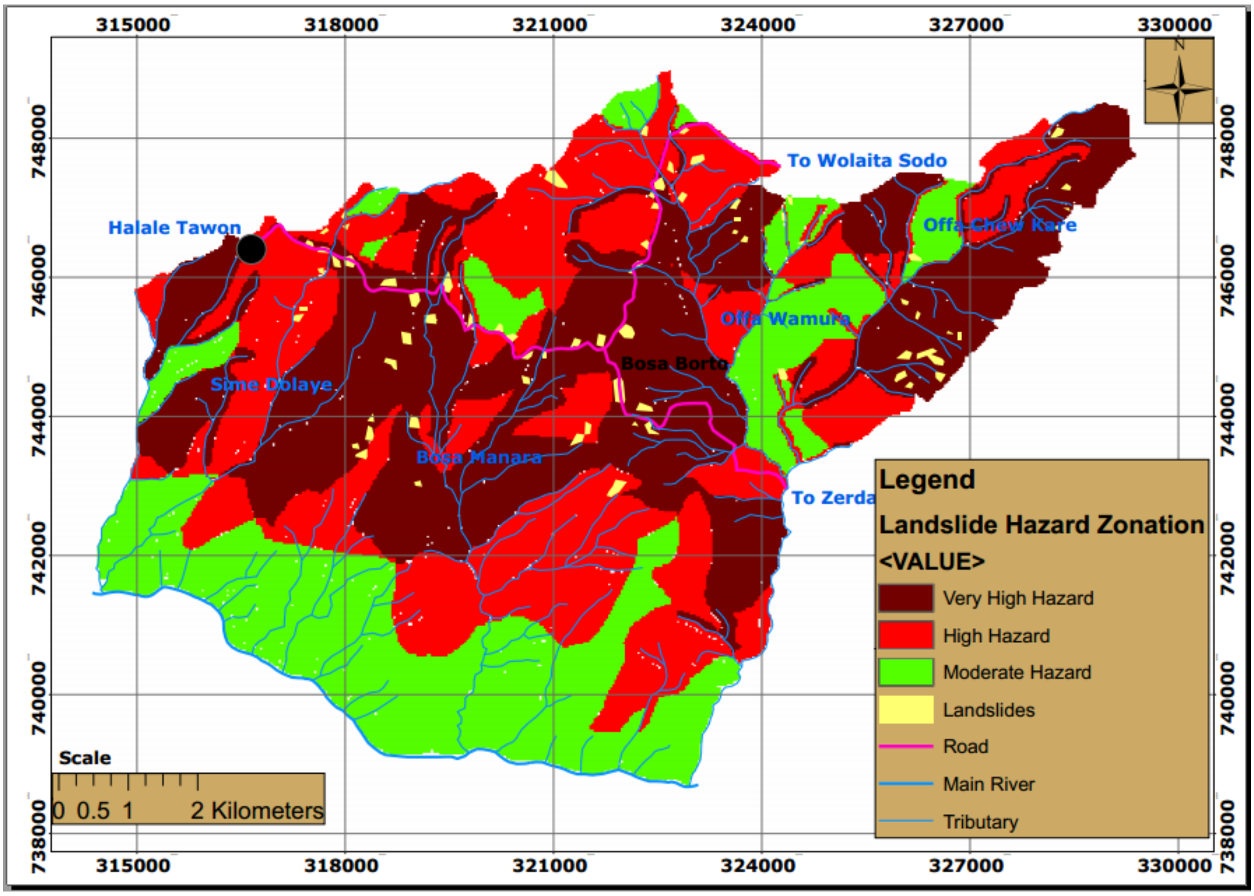


Fig.5.14. Past landslide activities overlain on landslide hazard zonation map prepared by integrated SSPE and GIS based Information Value method.

The landslide hazard map prepared for the present study area by SSEP empirical technique (Fig. 5.11), has revealed that 21 % (18 km^2), and of the study area falls under moderate hazard, 63% (54 km^2) as high hazard, and the rest 16% (13 km^2) as very high hazard. In case of the landslide hazard map of the study area (Fig. 5.12) which is carried out by using SSEP expert and raster based Information Value approach , 24%(20km^2) area fall in the moderately hazard zone whereas 41%(35km^2) and 35%(30km^2) and of the area fall high and very high hazard zone , respectively. The result shows 94% of the area fall in high and very high hazard zone. Further, perusal of Fig. 5.13 clearly indicates that very high hazard (VHH) zones are mainly concentrated in the central and northeastern regions of the study area. Similarly, high hazard (HH) zones are mainly distributed in western, northern and southwestern regions in the study area. The moderate hazard (MH) zones mainly concentrated in eastern and southern regions of the study area. The evaluation of most important causative parameter using Information value shows that manmade developmental activities, rainfall induced manifestations, landuse/landcover and groundwater are most influential causative parameters in study area. It reveals that the deforestation, cultivation and modifying the slopes by manmade activities in addition with high rain fall and groundwater are most influential causative parameter for the occurrence landslides in study area. The verified landslide hazard zonation map of the study area prepared using both SSEP technique and also integrated approach (Fig 5.14 and Fig.15) shows that 98% and 94% of existing landslide location is high and very high hazard zone, respectively. This shows at least 94% of the area fall in high and very high hazard zone in both methods. Next, the conclusion of present study and also recommendation was described.

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Chapter Six Conclusion and Recommendation

6.1 Conclusion

The present study area is located in South West Ethiopian Plateau within Omo River basin with total surface area of 85 square kilometer. It is characterized by rugged topography with maximum elevation of 2826 m. 70% of the area a fall in Dega to Woyna Dega climatic zone and it receives 1378 mm annual mean annual rainfall. The economic activities of population in the study area is based the mixed farming. Regionally, the geology of the area comprises Precambrian crystalline basement, Tertiary volcanic rocks and Quaternary alluvial sediments and volcanic flows. The geology of the study composed of unconsolidated alluvial, colluvial and residual deposits; unwelded tuff, trachyte and basalt.

The main objective of the present study is to evaluate and prepare Landslide Hazard Zonation Map in the area Kindo Didaye woreda, South West. In this study, landslide hazard zonation of the study area was carried out in two methods namely: Slope stability susceptibility Evaluation; Integrated Slope stability Susceptibility Evaluation Parameter (SSEP) and a rater based Information Value approach. The study was carried out in pre-field, field and post filed stage of investigation.

In the case of Landslide Hazard Zonation by Slope stability Susceptibility Evaluation Parameter (SSEP) the landslide hazard zonation of the study area was carried out through facet wise Evaluated landslide hazard which indicates the net probability of instability. Slope Geometry (relative relief and slope morphometry), slope material, structural discontinuity, landuse/landcover, groundwater surface manifestations are intrinsic causative parameters that considered in this method. The external causative parameters include: rain induced manifestations, seismicity and manmade developmental activities were also considered in this method. The area has been classified into 102 facets. The data for nine causative parameters namely; relative relief, slope morphometry, slope material, structural discontinuity, landuse/landcover, groundwater surface manifestations, rain induced manifestations, seismicity and manmade developmental activities have been collected and the rating values were given based on Slope stability Susceptibility Evaluation Parameter (SSEP) rating scheme for each causative parameters. The Evaluated landslide hazard for an individual facet was obtained by adding the ratings of individual intrinsic factors and external triggering parameter obtained from the SSEP rating scheme. Final landslide hazard zonation has been classified into three classes.

For SSEP and a raster based Information Value method the methodology followed was based on the analysis of seven causative parameters and past landslides in the study area. For the present study seven causative parameters namely; relative relief, slope morphometry, slope material, landuse/landcover, groundwater surface manifestations, rain induced manifestations and manmade developmental activities were considered. Later, Information value was calculated based on relative influences of causative factors on past landslides. The landslide inventory mapping for this study has been prepared using though field investigation and google earth. The distribution of landslide over each of each of factor maps have been obtained and analyzed. Weights for each of the classes within these factor maps have been obtained using the information value method. Final landslide susceptibility value for each pixel within the study area has been obtained using by summing up the weight derived for that pixel in all of the factor maps. The resultant landslide susceptibility index map has been classified in three landslide hazard zonation classes.

Influence of each parameter was rated to define the most influential parameter in the landslide process of study area. As shown in below table 5.8 and fig 5.9 the Relative relief: 1.2, Slope Morphometry: 2.58, Slope Material: 0.567, Landuse and Landcover: 9.19, Groundwater Surface Manifestations: 6.51, Rainfall Induced Manifestations: 10.11 and Manmade Developmental Activities: 24.85. The information values; manmade developmental activities, rainfall induced manifestations; landuse/landcover and groundwater are most influential causative parameters in study area with values 24.85, 10.11, 9.19, and 6.51, respectively. It reveals that the deforestation, cultivation and modifying the slopes by manmade activities in addition with high rain fall and groundwater are most influential causative parameter for the occurrence landslides in study area.

The landslide hazard map prepared for the present study area by SSEP empirical technique (Fig. 5.12), has revealed that 21 % (18 km^2), and of the study area falls under moderate hazard, 63% (54 km^2) as high hazard, and the rest 16% (13 km^2) as very high hazard.

Whereas the landslide hazard map of the study area (Fig. 5.13) which is carried out by using SSEP expert and raster based Information Value approach , 24%(20km^2) area fall in the moderately hazard zone whereas 41%(35km^2) and 35%(30km^2) and of the area fall high and very high hazard zone , respectively.

The resulted Landslide Hazard Zonation Map of study area in both methods was validated by comparing it with the actual past landslide inventory data of the area. The comparison shows that Landslide Hazard Zonation Map through SSEP method, out of 71 landslides inventory data 2 falls (3%) in moderate hazard zone, 50 falls (71%) in high hazard zone and 19 falls (27%) on very high hazard zone. This shows that 98% of existing landslide location is high and very high hazard zone and it agrees with the present landslide hazard zonation map.

Whereas, Landslide Hazard Zonation Map of the study area through SSEP and raster based Information Value method, out of 71 landslides inventory data 4 (6%) falls in moderate hazard zone, 14 (20%) falls in high hazard zone and 53 (74%) falls on very high hazard zone. This shows that 94% of existing landslide location is high and very high hazard zone and it agrees with the present landslide hazard zonation map. . This shows that 94% of existing landslide location is high and very high hazard zone and it agrees with the present landslide hazard zonation map.

The result shows that about 94% of landslide inventory data fall in high and very high hazard zone in both Maps. This indicates at least more than 94% result found through empirical Slope stability Susceptibility Evaluation Parameter (SSEP) method match with the result obtained by using integrated Slope stability Susceptibility Evaluation Parameter (SSEP) method and a raster-based Statistical Information Value approach.

6.2 Recommendation

In the last ten year landslide caused the death of 51 people, damage on cultivated land, infrastructure and human settlement at the Kindo Didaye Woreda. This shows that humans, animals, property and infrastructure are exposed to landslide in the study area.

As the population growth increases, the demand for new land for settlement, infrastructure and agriculture and also landslide risk will increase unless adequate mitigation measures. In addition to the present study the assessment of vulnerability to landslide hazard in the area is needed to reduce the effects of landslide hazard on life and resources. The effects of landslides on people and property can be reduced by total avoidance of landslide hazards areas or by restricting, prohibiting or imposing conditions on hazard activity. The landuse and manmade developmental activities are the most influential causative parameter of landslide in the study area. Local governments can reduce landslide effects through landuse landcover policies and regulations. Individuals can reduce their exposure to hazards by educating themselves on past hazard history of site and by making inquiries to planning of local governments. In additional, possible mitigation measurements recommended by Bekele Abebe et al., (2010) like gully recovering and control, planting of trees and avoiding construction on unstable slopes and intensive cultivation at the foot of steep rocky slope or escarpments to reduce landslide damage on human and animal life, property and agricultural land can be performed.

The both SSEP expert method, and Integrated SSEP and raster based Information Value Model was used to prepare landslide hazard zonation in the study area. The verification of two maps shows that 98% and 94% fall in both high hazard and very high hazard zones, respectively. The result shows that about 94% of landslide inventory data fall in high and very high hazard zone in both Maps. Using integrated SSEP and a raster based Information Value Model is more effective method because it relatively reduces the subjectivity SSEP empirical technique.

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References

Anbalagan, R., (1992). Landslide hazard evaluation and zonation mapping in mountainous terrain. *Eng. Geol.* **32:**269–277.

Anbalagan, R. and Singh, B. (1996). Landslide hazard and risk assessment mapping of mountainous terrains- a case study from Kumaun Himalaya, India. *Eng. Geol.* **43**:237-246.

Arnous, M. O. (2011).Integrated remote sensing and GIS techniques for landslide hazard zonation: a case study Wadi Watier area, South Sinai, Egypt. *Journal of Coastal Conservation*. **15**:477-497.

Atkinson, P.M., and Massari, R. (1998). Generalized linear modeling of landslide susceptibility in the central Apennines, Italy. *Computers & Geosciences.* **24**:373-385.

Bekele Abebe, Dramis, F., Fubelli, G., Mohammed Umer, Asfawossen Asrat (2010). Landslides in the Ethiopian highlands and the Rift margins. *Journal of African Earth Sciences*. **56**:131-138.

Bell, F.G.1999. Landslides associated with the colluvial soils overlying the Natal Gropu in the greater Durban region, South Africa. *Environmental Geology***.** **39**:1029-1038.

Bell, F.G. (2007). Engineering Geology, 7th ed., Elsevier Butterworth-Heinemann Linacre House, London, 61-76.

Berhanu Temesgen, Mohammed Umer, Asfawossen Asrat, Ogbaghebriel Berakhi, Abayneh Ayele, Dramis Francesco and Metasebia Demissie. (1999). Landslide Hazard on the Slopes of Dabicho Ridge, Wondo Genet area: The case of June 18, 1996 event. *SINET.* **22**: 127-140.

Blyth, F.J.H and de Freitas, M.H. (2005). Geology for Engineers, 7th ed., Elsevier Butterworth-Heinemann Linacre House, London, 227-239.

Carrara, A., Crosta, G., Frattini, P., 2003. Geomorphological and historical data in assessing landslide hazards. *Earth Surface Processes and Landforms*. **28**: 1125–1142.

Che,V.B., Kervyn, M., Suh ,C.E., Fontijn , K., Ernst G.G.J., del Marmol , M..A., Trefois, P., and Jacobs P. (2012). Landslide susceptibility assessment in Limbe (SW Cameroon): Afield calibrated seed cell and information value method. *Elsavier*. **92**: 83-96.

Collison, A., Wade, S., Griffiths, J., and Dehn, M., 2000. Modelling the impact of predicted climate change on landslide frequency and magnitude in SE England. *Eng. Geol.* **55**:205-218.

Crozier, M.J. 1986. Landslides: Causes, Consequences, and Environment. Croom Helm, London. 252 pp.

Crozier, M.J., and Glade, T., 2005. Landslide Hazard and risk: Issues, concepts, and approach. In: Glade, T., Anderson, M., and Crozier, M. (eds): Landslide hazard and risk. Wiley, Chichester, 1-40 pp.

Cruden DM. 1991. A simple definition of a landslide. *Bulletin of the International Association for Engineering Geology* **43**:27-29.

Cruden, D.M., and Varnes, D.J. (1996). *Landslide types and processes*. In: Turner, A.K., and Schuster, R.L. (eds), Landslides investigation and mitigation, special report 247. Transportation Research Board, National. Academy Press, Washington D.C, 36–75PP.

Dai, F. C. and Lee, C. F., 2001. Terrain-based mapping of landslide susceptibility using a geographical information system: a case study. *Canadian Geotechnical Journal* **38:**911 – 923.

Dai, F.C., Lee, C.F., and Ngai, Y.Y. (2002). Landslide risk assessment and management: an overview. *Eng. Geol*. **64** :65– 87.

Daniel Gemechu. (1977). *Aspect of climate and water balance in Ethiopia*. Addis Ababa University press, Addis Ababa, 79pp.

Davidson , A.,Alemu Shiferaw, Eyob G.Luel, Davies, J.C., Moore,J.M,Abera Degefu, Alemayehu W.Rafael and Muluneh Geleta (1973). Preliminary Report on the Geology and Geochemistry of parts of Sidamo, Gamu Gofa and Kefa Provinces. Omo River Report No.1.Imperial Ethiopian Government, Ministry of Mines.

Davidson , A.,Alemu Shiferaw, Davies, J.C., Moore,J.M, Mengesha Tefera, Abera Degefu, Alemayehu Rafael , Muluneh Geleta and Nigist Hintsa (1976). Preliminary Report on the Geology and Geochemistry of parts of Sidamo, Gamu Gofa and Illulabor Provinces, Ethiopia. Omo River Report No.2. Ethiopian Government, Ministry of Mines. and Power.

Davidson, A., (1983). (Compiler). The Omo River Project, Reconnaissance Geology and Geochemistry of parts of Illulabor, Kefa , Gamu Gofa and Sidamo. Bulletin No.2, Ministry of Mines and Energy, Ethiopian Institute of Geological Survey.

Engedawork Mulatu, Tarun Kumar Raghuvanshi and Bekele Abebe (2009) Landslide Hazard Zonation around Gigel Gibe II Hydroelectric Project, Southwestern Ethiopia. *SINET: Ethiop. J. Sci*. **32**:9–20.

Ercanoglu, M., C. Gokceoglu, (2003). Landslide Susceptibility Zoning of North Yenice (NW Turkey) by Multivariate Statistical Technique. *Natural Hazards*. **1**-23.

Espizua, L.E and Bengochea, J. D. (2002). Landslide Hazard and Risk Zonation Mapping in the Río Grande Basin, Central Andes of Mendoza, Argentina. *Mountain Research and Development.* **22**:177-185.

Fall, M., Azzam, R. and Noubactep, C. (2006). A multi-method approach to study the stability of natural slopes and landslide susceptibility mapping. *Eng.Geol*.**82**:241-263.

Fikre Girma, Raghuvanshi, T.K., Tenalem Ayanew, and Trufat Hailemariam (2015). Landslide hazard zonation in Ada Berga district, Central Ethiopia – A GIS based statistical Approach. *Journal of Geomatics*. **9**:1-14.

Guzzetti, F., Reichenbach, P., Cardinali, M., Galli, M., Ardizzone, F., 2005. Landslide hazard assessment in the Staffora basin, Northern Italian Apennines. *Geomorphology*. **72**: 272–299.

Highland, L.M. and Bobrowsky, P. (2008). *The Landslide Handbook- A Guide to Understanding Landslides*. U.S. Geological Survey, Reston, Virginia, 147 pp.

Hoek , E. and Bray, J.W. (1981). *Rock Slope Engineering (revised third ed*.). Ins. of Mining and Metallurgy, London, 358Pp.

Jade, S. and Sarkar, S., (1993). Statistical Models for Slope Instability Classification. *Engineering Geology*. **36:** 91-98.

Johnson R., De Graff J. (1988). *Principles of Engineering Geology*. John Wiley and Sons, New York,26-35pp.

Kanungo, D. P., Arora, M. K., Sarkar, S., and Gupta, R. P., 2009. Landslide Susceptibility Zonation (LSZ) Mapping – a review. *Journal of south Asia disaster studies*. **2**:1-81.

Keefer, D. K., 2000. Statistical analysis of an earthquake-induced landslide distribution —the 1989 Loma Prieta, California event. *Eng. Geol*. **58**:231–249.

Kifle Woldearegay. (2013). Review of the occurrences and influencing factors of landslides in the highlands of Ethiopia: With implications for infrastructural development. Mekelle University, Mekelle, Ethiopia. *Journal Name* Volume. **5**:3-31.

Laike Mariam Asfaw, (1986). Catalogue of Ethiopian Earthquakes, Earthquake parameters, Strain release and Seismic risk, Geophysical Observatory, Faculty of Science, Addis Ababa University.

Leroi, E. (1997). Landslide risk mapping: problems, limitation and developments. In: Cruden, Fell (Ed.), Landslide Risk Assessment. Balkema, Rotterdam, 239–250 pp.

Lin, M.L. and Tung, C. C., (2003). A GIS based Potential Analysis of the Landslides induced by the Chi- Chi Earthquake. *Engineering Geology***.71**: 63-77.

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

Lulseged Ayalew, Yamagishi, H. and Ugawa, N. (2004). Landslide susceptibility mapping using GIS-based weighted linear combination, the case in Tsugawa area of Agano River, Niigata Prefecture, Japan. *Landslides.* 1:**73**–81.

Luelseged Ayalew., and Yamagishi, H. (2005). The application of GIS-based logistic regression forlandslide susceptibility mapping in the Kakuda-Yahiko mountains, Central Japan. *Geomorphology*. **65**:15-31.

Lulseged Ayalew. (1999). The effect of seasonal rainfall on landslides in the highlands of Ethiopia. *Bull. Eng. Geol. Environ*. **58**: 9-19.

Matebie Meten, PrakashBhandary, N. and Yatabe, R. (2015). Effect of Landslide Factor Combinations on the Prediction Accuracy of Landslide Susceptibility Maps in the Blue Nile Gorge of Central Ethiopia. *Geoenvironmental Disasters*. **2**:1-17.

Raghuvanshi T.K., Jema Ibrahim, and Dereje Ayalew. (2014). Slope Stability Susceptibility evaluation parameter (SSEP) rating scheme: An approach for landslide hazard zonation. *Journal of African Earth Sciences*. **99**:595-612.

Tenalem Ayenew and Barbieri, G., 2005. Inventory of landslides and susceptibility mapping in the Dessie area, Northern Ethiopia. *Eng. Geol.***77**: 1-15.

Turrini, C. T and Visintainer, P., 1998 Proposal of a method to define areas of landslide hazard and application to an area of the Dolomites, Italy. Eng. Geol. **50**: 255–265.

Van Westen, C.J., Rengers, N., Terlien, M.T.J., Soeters, R., 1997. Prediction of the occurrence of slope instability phenomena through GIS-based hazard zonation. *Geologische Rundschau*. **86**: 404-414.

Van Westen, C.J., Van Asch, T.W.J., Soeters, R., 2006. Landslide hazard and risk zonation - why is it still so difficult. *Bull. Eng. Geol. Environ*.**65**: 167–184.

Varnes, D.J. (1978). *Slope movements, types and processes*. In: Schuster, R.L., Krizek, R.J. (eds.), Landslide analysis and control, National Academy Sciences, Washington DC, 11-33pp.

Varnes, D.J. (1984). *International Association of Engineering Geology Commission on Landslides and Other Mass Movements on Slopes: Landslide hazard zonation*: a review of principles and practice, UNESCO, Paris, 63 pp.

Varnes, D.J. (1996). Landslide Types and Processes. *In: Turner, A.K., and R.L. Schuster (eds), Landslides: Investigation and Mitigation, Transportation Research Board*

Special Report 247, National Research Council, Washington, D.C. National Academy Press.

Westen Van, C.J., Rengers, N., Terlien, M.T.J. (1997). Prediction Of The Occurrence of Slope Instability Phenomena Through GIS-based Hazard Zonation. *Geologische Rundschau*. **86**: 4004– 4414.

Yin, K.L., and Yan, T.Z. (1988). Statistical Prediction Models for Slope Instability of Metamorphosed Rocks. ***In:*** *Proceedings of the 5th International Symposium on Landslides*, pp. 1269– 1272. Lausanne, Switzerland.

Wachal, D.J. and Hudak, P.F. (2000). Mapping landslide susceptibility in Travis County, Texas, USA. *GeoJournal*. **51**:245-253

Waltham, T. (2009). *Foundations of engineering geology*. CRC Press. 3rd ed. Madison Avenue, New York, 72-74 pp.

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Appendix 1.1 Rainfall data of Wolaita Sodo Station

Name	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Rai
Wolaita	1986	0.7	4.0	18.7	21.2	37.1	31.8	36.1	35.3	15.2	0.0	35.3	76.6	312.0
Wolaita	1987	40.1	25.1	112.8	141.1	370.0	112.8	25.9	154.4	114.1	149.9	21.9	16.9	1285.0
Wolaita	1988	17.9	62.7	37.4	93.8	87.3	87.1	282.6	213.0	166.9	102.3	2.3	10.1	1163.3
Wolaita	1989	78.8	50.2	82.6	100.8	135.3	77.9	102.8	152.4	112.4	85.2	100.9	196.6	1275.9
Wolaita	1990	19.6	226.2	85.5	44.1	149.3	112.1	163.9	121.9	82.8	24.0	13.5	29.3	1072.2
Wolaita	1991	30.8	90.3	129.2	131.0	183.5	121.7	160.1	115.8	62.6	28.2	10.0	49.5	1112.7
Wolaita	1992	23.7	74.9	51.2	152.0	106.1	145.0	225.8	224.2	118.9	119.0	82.3	29.4	1352.5
Wolaita	1993	93.1	60.9	19.7	272.9	400.3	94.7	211.8	134.6	66.1	79.0	2.1	8.3	1443.5
Wolaita	1994	0.0	18.5	110.2	252.7	180.1	85.5	287.4	212.0	49.7	11.6	37.7	8.2	1253.6
Wolaita	1995	0.8	54.3	53.8	232.5	88.3	156.7	186.6	92.1	111.5	43.7	45.3	14.6	1080.2
Wolaita	1996	49.8	25.1	102.3	166.6	232.7	301.0	203.0	226.2	185.9	28.8	29.4	0.5	1551.3
Wolaita	1997	26.8	0.0	26.2	238.2	179.4	122.2	210.1	136.6	40.7	280.0	246.2	37.3	1543.7
Wolaita	1998	56.1	92.1	54.6	119.1	171.0	182.9	217.1	175.3	71.1	186.7	13.8	4.1	1343.9
Wolaita	1999	25.7	0.6	45.6	113.6	111.3	110.1	159.7	125.0	66.5	157.0	13.7	9.4	938.2
Wolaita	2000	2.5	0.0	31.0	151.7	224.8	197.9	124.2	223.4	169.5	168.0	59.8	11.3	1364.1
Wolaita	2001	19.1	11.6	107.4	89.8	295.4	163.7	233.5	252.2	113.2	134.0	43.8	42.3	1506.0
Wolaita	2002	47.8	5.5	121.9	97.7	173.3	83.9	90.5	225.2	54.2	58.6	2.0	96.4	1057.0
Wolaita	2003	99.5	22.5	62.0	131.3	66.6	186.7	198.1	262.6	36.2	62.4	40.3	86.0	1254.2
Wolaita	2004	55.4	52.5	41.0	277.8	106.0	103.3	185.2	159.3	63.6	93.0	39.2	27.7	1204.0
Wolaita	2005	8.2	30.7	186.9	208.4	323.2	108.4	241.7	134.5	151.5	107.2	113.5	5.0	1619.2
Wolaita	2006	4.4	25.0	125.5	222.7	142.6	101.7	136.7	258.6	62.1	133.4	37.6	120.9	1371.2
Wolaita	2007	74.1	35.1	91.2	186.4	225.0	269.0	215.8	244.6	242.2	23.2	15.0	0.0	1621.6
Wolaita	2008	6.1	15.1	10.9	86.7	136.5	134.6	225.4	241.5	241.2	206.8	131.6	0.0	1436.4
Wolaita	2009	13.5	21.3	29.2	128.9	125.0	60.6	85.4	122.3	148.9	146.3	45.5	164.0	1090.9
Wolaita	2010	16.2	97.1	144.7	189.4	280.8	199.3	112.9	97.4	130.7	34.2	18.7	19.8	1341.2
Wolaita	2011	4.5	9.5	43.2	68.4	270.8	115.4	202.8	201.9	106.6	25.2	138.4	10.5	1197.2
Wolaita	2012	1.2	48.9	10.1	199.2	139.3	89.0	314.3	246.7	135.8	26.8	85.7	17.2	1314.2
Wolaita	2013	47.4	7.5	30.7	342.8	80.8	159.1	252.8	232.9	127.4	77.5	44.8	0.0	1403.6
Wolaita	2014	33.9	50.0	127.3	90.1	237.1	132.9	198.8	229.0	179.2	307.7	111.2	8.7	1705.9

Appendix 4: 1 measured characteristics of joints from different location in the study area.

Type of discontinuity	Characteristics of discontinuities						
	Orientation		Continuity	Separation	roughness	Infilling	weathering
	Strike	Dip/ Dip dxn					
Joint	20NW	42SW	>1m	3mm	Smooth	soft filling	highly weathered
Joint	40NE	35 SE	>1m	5mm	Smooth	Soft filling	Highly Weathered
Joint	45NE	32 SE	>1m	6mm	Soft	Soft filling	Highly weathered
Joint	55NW	35SE	>1m	4mm	Slightly smooth	No filling	Highly weathered
Joint	35NE	32SW	>1m	1cm	Smooth	Soft filling	Moderately weathered
Joint	60 NE	25SE	>1m	6mm	Rough	No filling	highly weathered
Joint	50NE	32SE	>1m	8mm	Smooth	Soft filing	Moderately weathered
Joint	55NE	65SE	>1m	4mm	Slightly smooth	Soft filing	Highly weathered
joint	10NW	55SW	>1m	1cm	Rough	No filling	Moderately weathered
Joint	80NE	63SW	20cm	6mm	Rough	No filling	Moderately weathered
Joint	60NE	45SE	>1m	1cm	V. rough	No filling	Moderately weathered
Joint	30 NW	40 SW	>1m	1cm	V. rough	No filling	Moderately weathered
Joint	40NW	33 SW	80cm	2mm	Soft	Soft filling	Highly weathered
Joint	20 NE	65SE	>1m	10mm	V. rough	Soft filling	Highly weathered
Joint	50NE	37SE	60cm	5mm	Soft	Soft filling	Highly weathered
Joint	25NW	55SW	>1m	1cm	Smooth	Soft filling	Highly weathered
Joint	70NE	25SE	80cm	10mm	Smooth	Soft filling	Highly weathered
Joint	10NE	35 SE	65 cm	5mm	Smooth	Soft filling	Highly weathered
Joint	30 NW	25 SW	80cm	6mm	Smooth	Soft filling	Highly weathered
Joint	10NE	60SE	>1m	1cm	Rough	No filling	Moderately weathered
Dyke	30 NE	50SE	>1m	1cm	Rough	No filling	Highly weathered
Joint	20NW	26 SW	65 cm	5mm	Smooth	Soft filling	Highly weathered
Joint	10 NE	31 SE	70 cm	6mm	Smooth	Soft filing	Highly weathered
Joint	20 NE	43 SE	70cm	1cm	Smooth	Soft filling	Highly weathered
Joint	40 NE	55 SE	>1m	3cm	Rough	No filling	Moderately weathered
Joint	60NE	32SE	>1m	1cm	Rough	No filling	Moderately weathered

Joint	10NW	35SW	>1m	1cm	Rough	No filling	Slightly weathered
Dyke	15 NE	68 SE	>1m	1cm	Rough	No filing	Moderately weathered
Joint	60NW	35SW	>1m	1cm	Rough	No filling	Moderately weathered
Joint	30 NW	60SW	>1m	1cm	V. rough	No filling	Moderately weathered
Joint	15NE	65 SE	>1m	8 mm	Rough	Soft filling	Moderately weathered
Joint	10 NE	80 SE	>1m	6mm	Smooth	Soft filling	Highly weathered
Joint	70 NE	25 SE	>1m	1cm	Smooth	Soft filling	Highly weathered
Joint	20 NE	60 SE	>1m	1cm	Rough	No filling	Moderately weathered
Joint	20 NW	65SW	>1m	1cm	Rough	No filling	Moderately weathered
Joint	40 NW	54 SW	>1m	2cm	V. rough	No filling	Moderately weathered
Joint	60 NE	54SE	80cm	5mm	Smooth	Soft filling	Highly weathered
Joint	45NW	35 SW	65cm	6mm	Smooth	Soft filling	Highly weathered
Joint	40NW	37 SW	>1m	1cm	Rough	No filling	Moderately weathered
Joint	15NW	50SW	>1m	1cm	rough	No filling	Highly weathered
Joint	10NE	60 SE	1m	6mm	Smooth	Soft filling	Highly weathered
Joint	65 NE	60SE	1m	7cm	Rough	No filling	Moderately weathered
joint	10NW	37SE	>1m	8cm	Rough	No filling	Highly weathered
Joint	40NE	32 SE	50cm	6mm	Smooth	Soft filling	Highly weathered
Joint	20NE	33SE	>1m	5mm	Smooth	Soft filling	Highly weathered
Joint	65NE	26 SE	90cm	7mm	Smooth	Soft filling	Highly weathered
Dyke	10NW	41SW	>1m	1cm	Smooth	Soft filling	Highly weathered
Joint	25 NE	35E	70cm	6mm	Smooth	Soft filling	Highly weathered

Appendix 5.1 Rating assigned to Individual facets for Intrinsic and external parameters.

SSEP Ratings Assigned to different Intrinsic and External Triggering Factors											
Facet No.	Intrinsic Parameters						External Parameters			ELH	H Z
	Relative Relief	Slope Morphometry	Slope Material	Structural Discontinuity	Landuse/ Landcover	Groundwater	Seismicity	Rainfall	Man-made Activities		
1	0.6	0.3	0.6	1.67	0.4	1	0.8	1.25	1	7.62	MH
2	1	0.6	0.88	1.66	0.4	2	0.8	0.975	1	9.315	HH
3	1	0.6	0.88	1.72	0.4	1.5	0.8	0.94	1.5	9.34	HH
4	0.8	0.6	0.6	1.86	0.4	1	0.8	0.94	1	8	HH
5	1	1	1	1.54	0.4	2	0.8	0.625	1	9.365	HH
6	1	1	0.6	1.71	1.5	0	0.8	0.6	0.85	8.06	HH
7	1	0.6	0.6	1.79	0.4	1.5	0.8	0.975	1.5	9.165	HH
8	0.2	1	0.67	1.83	0.4	0	0.8	0.625	0.75	6.275	MH
9	0.8	1	0.67	1.88	0.4	0	0.8	0.625	0.75	6.925	MH
10	0.6	0.6	0.8	1.64	0.4	0	0.8	1.012	0.75	6.6025	MH
11	1	1.7	0.67	1.78	0.4	0	0.8	1.012	0.75	8.1125	HH
12	0.8	0.6	0.88	1.91	0.75	1	0.8	0.937	0.75	8.4275	HH
13	1	1	1	1.83	0.4	0	0.8	0.625	0.75	7.405	MH
14	1	1	0.8	1.99	1.2	2	0.8	0.937	1.25	10.977	HH
15	1	1.7	0.8	1.93	0.4	0	0.8	0.312	0.75	7.6925	MH
16	1	1	1	1.59	0.4	0	0.8	0.937	0.75	7.4775	MH
17	1	1.7	0.8	1.91	0.4	0	0.8	0.625	0.75	7.985	MH
18	1	1	0.72	1.9	0.4	0	0.8	0.625	0.75	7.195	M H
19	0.8	0.6	0.8	1.93	1.2	0	0.8	1.012	0.75	7.8925	MH
20	1	1	0.88	1.94	0.4	2	0.8	0.65	1.5	10.17	HH
21	1	1	0.5	1.84	0.4	1	0.8	0.975	1	8.515	HH
22	1	0.6	0.5	1.91	0.4	2	0.8	1.012	1	9.2225	HH
23	1	1	0.88	1.99	0.75	1	0.8	0.937	0.75	9.1075	HH
24	1	1	0.68	1.94	0.4	2	0.8	0.575	1	9.395	HH
25	0.6	1.7	0.68	1.94	0.75	1	0.8	0.575	0.75	8.795	HH
26	1	1	0.68	1.86	0.75	2	0.8	0.625	0.65	9.365	HH
27	1	0.6	0.8	1.99	0.4	2	0.8	1.3	1	9.89	HH
28	1	1	0.8	1.99	0.4	0	0.8	0.975	1	7.965	MH
29	1	0.6	0.8	1.84	0.4	2	0.8	0.975	1	9.415	HH

30	0.6	0.6	0.8	1.87	0.4	2	0.8	1.25	1	9.32	H H
31	0.2	1	0.68	1.49	0.4	0	0.8	1.35	1	6.92	MH
32	1	1	0.68	1.73	0.4	0	0.8	0.975	1	7.585	MH
33	1	1	0.68	1.83	0.4	0	0.8	0.975	0.65	7.335	MH
34	0.8	1	0.68	1.71	0.4	0	0.8	0.625	0.65	6.665	M H
35	1	1	0.68	1.76	1.2	0	0.8	0.625	0.65	7.715	MH
36	1	0.6	0.68	1.79	1.5	0	0.8	1.25	0.65	8.27	HH
37	1	1.7	0.68	1.85	1.5	0	0.8	1.25	0.6	9.38	HH
38	1	1.7	0.68	1.81	1.5	0	0.8	0.937	0.6	9.0275	HH
39	1	1	0.68	1.88	0.4	0	0.8	0.625	0.6	6.985	MH
40	0.6	1	0.68	1.89	1.5	0	0.8	0.625	0.6	7.695	MH
41	1	1.7	0.8	1.91	0.4	0	0.8	0.625	0.6	7.835	MH
42	1	1	0.88	2.19	1.2	2	0.8	1.5	1.5	12.07	V HH
43	1	1	0.88	2.22	1.2	2	0.8	1.5	1.5	12.1	V HH
44	1	0.6	0.88	2.29	1.5	2	0.8	1.5	1.5	12.07	V HH
45	1	1	0.88	2.01	1.5	2	0.8	1.5	1.5	12.19	V HH
46	1	1.7	0.88	1.86	1.25	2	0.8	1.5	1.5	12.49	V HH
47	1	1	0.82	2.19	1.5	2	0.8	1.5	1.5	12.31	V HH
48	1	1	0.82	1.83	0.4	0	0.8	0.625	0.6	7.075	MH
49	1	1	0.82	1.89	1.2	0	0.8	0.975	0.6	8.285	HH
50	1	1.7	0.67	1.87	0.4	0	0.8	6.5	0.6	7.5825	MH
51	0.8	1	0.67	1.84	1.2	0	0.8	0.975	0.6	7.885	MH
52	0.8	1	0.82	1.79	1.2	0	0.8	0.937	0.6	7.9475	MH
53	1	1	0.82	1.66	1.2	0	0.8	0.975	0.6	8.055	HH
54	1	1	0.8	1.79	1.2	0	0.8	0.975	0.6	8.165	HH
55	0.6	1	0.68	1.84	1.2	0	0.8	0.862	0.6	7.5825	MH
56	0.6	0.6	1	1.89	0.4	1.5	0.8	0.862	0.65	8.3025	H H
57	1	1.7	0.8	1.84	0.4	0	0.8	0.125	0.6	7.265	M H
58	0.6	1.7	0.8	1.88	0.4	0	0.8	0.135	0.6	6.915	MH
59	0.6	1.7	0.8	1.74	0.4	0	0.8	0.135	0.6	6.775	MH
60	0.6	1.7	0.6	1.77	1.5	0	0.8	0.125	0.6	7.695	MH
61	1	1.7	0.72	1.62	1.5	0	0.8	0.125	0.6	8.065	HH
62	1	2	0.68	1.91	0.4	1	0.8	0.287	1.5	9.5775	HH
63	1	0.6	0.6	1.74	0.4	2	0.8	0.9	0.9	8.94	HH
64	1	1	0.6	1.69	0.4	2	0.8	0.937	0.9	9.3275	HH

65	1	1.7	0.88	1.89	0.4	2	0.8	0.65	1.25	10.57	HH
66	1	1.7	0.72	1.94	0.75	1.5	0.8	0.3	0.65	9.36	HH
67	1	1.7	0.88	1.84	0.4	2	0.8	0.65	1.5	10.77	HH
68	1	1	0.88	1.89	0.4	1.5	0.8	0.9	0.65	9.02	HH
69	1	1.7	0.72	1.94	0.4	1	0.8	0.287	0.65	8.4975	HH
70	1	1	0.67	2.29	1.5	2	0.8	1.25	1.5	12.01	V HH
71	1	1.7	0.72	2.29	1.5	2	0.8	1.25	1.5	12.76	V HH
72	1	1	0.67	2.04	0.4	1	0.8	0.65	1.5	9.06	HH
73	1	0.6	1	2.29	1.5	2	0.8	1.5	1.5	12.19	V HH
74	0.8	1	1	2.39	1.5	2	0.8	1.5	1.5	12.49	VH H
75	1	1	1	2.29	1.5	1.5	0.8	1.5	1.5	12.09	VHH
76	1	1	1	2.29	1.5	2	0.8	1.5	1.25	12.34	VH H
77	0.8	0.3	1	1.99	0.4	2	0.8	1.012	1	9.3025	HH
78	0.8	0.6	1	1.99	0.4	1.5	0.8	1.012	1	9.1025	HH
79	1	0.6	1	1.99	0.4	1.5	0.8	1.012	1	9.3025	HH
80	1	0.6	1	1.99	0.4	1.5	0.8	0.675	1	8.965	H H
81	0.8	1	0.87	2.14	1.5	2	0.8	1.5	1.5	12.11	VHH
82	0.8	1	1	1.79	0.4	1	0.8	0.625	1	8.415	H H
83	0.8	1	0.87	2.17	1.5	2	0.8	1.5	1.5	12.14	VHH
84	1	1	0.6	1.84	0.4	2	0.8	1.012	0.75	9.4025	HH
85	1	1	1	1.86	0.4	1.5	0.8	0.937	1	9.4975	HH
86	1	1	0.67	1.83	1.2	1	0.8	0.625	1	9.125	H H
87	1	1	0.87	1.5	0.4	1	0.8	0.65	0.75	7.97	MH
88	1	1	1	1.99	0.4	2	0.8	0.675	0.75	9.615	HH
89	1	1.7	1	2.19	1.5	1.5	0.8	1.5	1.25	7.7	MH
90	1	1	1	1.93	0.4	1.5	0.8	0.675	1	9.305	HH
91	1	1	1	1.91	0.4	2	0.8	0.675	1	9.785	H H
92	1	1	0.82	1.93	0.4	1	0.8	0.675	1	8.625	HH
93	1	1	1	1.74	0.4	2	0.8	1.012	1	9.9525	HH
94	1	1.7	0.67	1.74	0.75	1	0.8	0.312	1	8.9725	HH
95	1	2	0.67	1.74	0.75	1	0.8	0.312	1	9.2725	H H
96	1	2	0.82	1.74	0.4	1	0.8	0.312	1	9.0725	HH
97	1	1.7	0.82	1.89	0.4	1.5	0.8	0.325	1	9.435	HH
98	1	1.7	0.82	1.89	0.4	1.5	0.8	0.325	1	9.435	HH

99	1	1	1	1.93	0.4	1.5	0.8	1.012	1	9.6425	HH
100	1	1.7	0.72	1.71	0.4	2	0.8	0.625	1.25	10.205	HH
101	1	1.7	0.72	1.74	1.5	1	0.8	0.625	0.6	9.685	HH
102	1	1	0.72	1.69	1.5	1	0.8	0.575	0.6	8.885	HH

Appendix 5.2 Rating assigned to structural discontinuity

Facet	I	II	III	IV	V	Continuity	Separation	Roughness	Infilling	Weathering	Total
1	0.1	0.1	0.15	0.5	0.25	0.02	0.15	0.1	0.15	0.15	1.67
2	0.2	0.15	0.1	0.5	0.25	0.02	0.12	0.07	0.15	0.1	1.66
3	0.25	0.2	0.15	0.5	0.25	0.02	0.15	0.03	0.07	0.1	1.72
4	0.2	0.15	0.25	0.5	0.25	0.02	0.12	0.1	0.12	0.15	1.86
5	0.25	0.15	0.15	0.5	0.2	0.02	0.15	0.03	0.02	0.07	1.54
6	0.25	0.15	0.15	0.5	0.25	0.02	0.15	0.1	0.07	0.07	1.71
7	0.25	0.15	0.15	0.5	0.25	0.02	0.15	0.1	0.15	0.07	1.79
8	0.3	0.2	0.25	0.5	0.2	0.02	0.15	0.07	0.07	0.07	1.83
9	0.3	0.2	0.25	0.5	0.2	0.02	0.15	0.1	0.07	0.07	1.86
10	0.1	0.1	0.15	0.5	0.25	0.02	0.12	0.1	0.15	0.15	1.64
11	0.3	0.2	0.15	0.5	0.2	0.02	0.15	0.07	0.12	0.07	1.78
12	0.25	0.15	0.25	0.5	0.25	0.04	0.12	0.1	0.15	0.1	1.91
13	0.3	0.15	0.25	0.5	0.2	0.02	0.15	0.1	0.07	0.07	1.81
14	0.1	0.1	0.1	1	0.25	0.02	0.05	0.1	0.12	0.15	1.99
15	0.3	0.2	0.25	0.5	0.2	0.02	0.15	0.1	0.12	0.07	1.91
16	0.1	0.1	0.15	0.5	0.2	0.02	0.12	0.1	0.15	0.15	1.59
17	0.3	0.2	0.25	0.5	0.2	0.02	0.15	0.1	0.12	0.05	1.89
18	0.3	0.2	0.25	0.5	0.2	0.02	0.12	0.1	0.12	0.07	1.88
19	0.1	0.1	0.1	1	0.25	0.02	0.07	0.1	0.12	0.07	1.93
20	0.3	0.2	0.2	0.5	0.25	0.02	0.15	0.1	0.12	0.1	1.94
21	0.25	0.15	0.2	0.5	0.25	0.02	0.15	0.1	0.15	0.07	1.84
22	0.3	0.2	0.2	0.5	0.25	0.02	0.15	0.07	0.12	0.1	1.91
23	0.25	0.15	0.25	0.5	0.25	0.15	0.12	0.1	0.12	0.1	1.99
24	0.25	0.15	0.25	0.5	0.2	0.15	0.12	0.1	0.12	0.07	1.91
25	0.25	0.15	0.2	0.5	0.25	0.15	0.15	0.1	0.12	0.07	1.94
26	0.25	0.15	0.25	0.5	0.2	0.15	0.12	0.1	0.07	0.07	1.86

27	0.3	0.2	0.25	0.5	0.25	0.02	0.15	0.1	0.12	0.1	1.99
28	0.1	0.1	0.1	1	0.25	0.02	0.05	0.1	0.12	0.15	1.99
29	0.25	0.15	0.15	0.5	0.25	0.02	0.12	0.1	0.15	0.15	1.84
30	0.25	0.15	0.15	0.5	0.25	0.02	0.15	0.1	0.15	0.15	1.87
31	0.1	0.1	0.1	0.5	0.25	0.02	0.05	0.1	0.12	0.15	1.49
32	0.25	0.15	0.15	0.5	0.25	0.02	0.15	0.07	0.12	0.07	1.73
33	0.3	0.15	0.25	0.5	0.2	0.02	0.15	0.1	0.07	0.07	1.81
34	0.25	0.15	0.15	0.5	0.25	0.02	0.15	0.1	0.07	0.07	1.71
35	0.25	0.15	0.15	0.5	0.25	0.02	0.15	0.07	0.12	0.1	1.76
36	0.25	0.15	0.15	0.5	0.25	0.02	0.07	0.1	0.15	0.15	1.79
37	0.3	0.2	0.25	0.5	0.2	0.02	0.12	0.07	0.12	0.07	1.85
38	0.3	0.15	0.25	0.5	0.2	0.02	0.15	0.1	0.07	0.07	1.81
39	0.3	0.2	0.25	0.5	0.2	0.02	0.12	0.1	0.12	0.07	1.88
40	0.3	0.2	0.25	0.5	0.2	0.02	0.15	0.1	0.12	0.05	1.89
41	0.3	0.2	0.25	0.5	0.2	0.02	0.15	0.1	0.12	0.07	1.91
42	0.5	0.2	0.25	0.5	0.25	0.02	0.15	0.1	0.12	0.1	2.19
43	0.5	0.3	0.15	0.5	0.25	0.02	0.15	0.1	0.15	0.1	2.22
44	0.5	0.4	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	2.29
45	0.5	0.15	0.15	0.5	0.25	0.02	0.12	0.1	0.12	0.1	2.01
46	0.3	0.2	0.15	0.5	0.25	0.02	0.12	0.1	0.12	0.1	1.86
47	0.5	0.3	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	2.19
48	0.3	0.15	0.25	0.5	0.2	0.02	0.12	0.1	0.12	0.07	1.83
49	0.3	0.2	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	1.89
50	0.3	0.15	0.15	0.5	0.25	0.02	0.15	0.1	0.15	0.1	1.87
51	0.25	0.2	0.15	0.5	0.25	0.02	0.12	0.1	0.15	0.1	1.84
52	0.25	0.15	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	1.79
53	0.3	0.1	0.15	0.5	0.25	0.02	0.07	0.1	0.07	0.1	1.66
54	0.25	0.15	0.15	0.5	0.25	0.02	0.12	0.1	0.15	0.1	1.79
55	0.3	0.15	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	1.84
56	0.25	0.1	0.25	0.5	0.2	0.15	0.12	0.1	0.12	0.1	1.89
57	0.25	0.2	0.25	0.5	0.2	0.02	0.15	0.1	0.12	0.05	1.84
58	0.3	0.2	0.25	0.5	0.2	0.02	0.12	0.1	0.12	0.07	1.88
59	0.25	0.2	0.25	0.5	0.2	0.02	0.15	0.03	0.07	0.07	1.74
60	0.25	0.15	0.25	0.5	0.2	0.02	0.15	0.03	0.15	0.07	1.77
61	0.25	0.15	0.2	0.5	0.2	0.02	0.15	0.03	0.07	0.05	1.62

62	0.25	0.15	0.25	0.5	0.2	0.15	0.12	0.1	0.12	0.07	1.91
63	0.25	0.2	0.25	0.5	0.2	0.02	0.15	0.03	0.07	0.07	1.74
64	0.25	0.15	0.25	0.5	0.2	0.02	0.15	0.03	0.07	0.07	1.69
65	0.3	0.2	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	1.89
66	0.25	0.15	0.25	0.5	0.2	0.15	0.12	0.1	0.12	0.1	1.94
67	0.3	0.15	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	1.84
68	0.3	0.2	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	1.89
69	0.25	0.15	0.25	0.5	0.2	0.15	0.12	0.1	0.12	0.1	1.94
70	0.4	0.15	0.25	0.5	0.2	0.02	0.15	0.03	0.07	0.07	1.84
71	0.25	0.4	0.25	0.5	0.2	0.02	0.15	0.03	0.07	0.07	1.94
72	0.25	0.4	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	2.04
73	0.5	0.4	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	2.29
74	0.5	0.4	0.25	0.5	0.25	0.02	0.15	0.1	0.12	0.1	2.39
75	0.5	0.4	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	2.29
76	0.5	0.4	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	2.29
77	0.1	0.1	0.1	1	0.25	0.02	0.05	0.1	0.12	0.15	1.99
78	0.1	0.1	0.1	1	0.25	0.02	0.05	0.1	0.12	0.15	1.99
79	0.1	0.1	0.1	1	0.25	0.02	0.05	0.1	0.12	0.15	1.99
80	0.1	0.1	0.1	1	0.25	0.02	0.05	0.1	0.12	0.15	1.99
81	0.4	0.25	0.25	0.5	0.25	0.02	0.15	0.1	0.15	0.07	2.14
82	0.25	0.15	0.15	0.5	0.25	0.02	0.15	0.1	0.15	0.07	1.79
83	0.4	0.15	0.2	0.5	0.25	0.15	0.15	0.1	0.12	0.15	2.17
84	0.25	0.15	0.15	0.5	0.25	0.02	0.12	0.1	0.15	0.15	1.84
85	0.3	0.2	0.25	0.5	0.2	0.02	0.15	0.1	0.07	0.07	1.86
86	0.3	0.15	0.25	0.5	0.2	0.02	0.12	0.1	0.12	0.07	1.83
87	0.25	0.15	0.25	0.5	0.2	0.02	0.15	0.03	0.07	0.07	1.69
88	0.1	0.1	0.1	1	0.25	0.02	0.05	0.1	0.12	0.15	1.99
89	0.3	0.1	0.1	1	0.25	0.02	0.05	0.1	0.12	0.15	2.19
90	0.1	0.1	0.1	1	0.25	0.02	0.07	0.1	0.12	0.07	1.93
91	0.3	0.2	0.2	0.5	0.25	0.02	0.15	0.07	0.12	0.1	1.91
92	0.1	0.1	0.1	1	0.25	0.02	0.07	0.1	0.12	0.07	1.93
93	0.1	0.1	0.1	1	0.25	0.02	0.05	0.1	0.12	0.15	1.99
94	0.25	0.2	0.25	0.5	0.2	0.02	0.15	0.03	0.07	0.07	1.74
95	0.25	0.2	0.25	0.5	0.2	0.02	0.15	0.03	0.07	0.07	1.74
96	0.25	0.2	0.25	0.5	0.2	0.02	0.15	0.03	0.07	0.07	1.74

97	0.3	0.2	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	1.89
98	0.3	0.2	0.15	0.5	0.25	0.02	0.15	0.1	0.12	0.1	1.89
99	0.1	0.1	0.1	1	0.25	0.02	0.07	0.1	0.12	0.07	1.93
100	0.25	0.15	0.15	0.5	0.25	0.02	0.15	0.1	0.07	0.07	1.71
101	0.25	0.2	0.25	0.5	0.2	0.02	0.15	0.03	0.07	0.07	1.74
102	0.25	0.15	0.25	0.5	0.2	0.02	0.15	0.03	0.07	0.07	1.69

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