

**Landslide Hazard Zonation and Evaluation in and around Funyan Biro town (Gursum District), Hararghe Oromia, Eastern Ethiopia: using statistical approach**

**Ahmed Abdikerim**

**A Thesis submitted to School of Earth Sciences**



**Presented in Partial fulfillment of the requirements for the Degree of Master of Science  
(Engineering Geology )**



**ADDIS ABABA UNIVERSITY**

**ADDIS ABABA, ETHIOPIA**

**August, 2020**

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This is to certify that the thesis prepared by Ahmed Abdikerim, entitled: *Landslide hazard zonation and evaluation in and around Funyan biro (Gursum district), Hararghe Oromia, Eastern Ethiopia: using statistical approach* and submitted in partial fulfillment of the requirement 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. Tarun Kumar Raghuvanshi: Signature  Date 29-09-2020

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**Chair of School or Graduate Program Coordinator**

## ABSTRACT

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### **Landslide Hazard Zonation and Evaluation In and Around Funyan Biro town (Gursum District), Hararghe Oromia, Eastern Ethiopia: Using Statistical Approach**

**Ahmed Abdikerim**

Addis Ababa University, 2020

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The present study area is located in the eastern Hararghe zone of the Oromia region, Gursum District, Eastern Ethiopia, 581km from Addis Ababa. The area is prone for landslide activities and roads in the area, agricultural lands and human and animal lives are at risk to this devastating natural hazard. The main objective of this study is to evaluate landslides and to produce landslide hazard zonation map for the study area. In order to prepare landslide hazard zonation map, statistical approach was followed. Landslide inventory map was developed through field work, and with help of remote sensing data. A total of 35 past landslides in the present study area were identified and recorded through field work and with the help of GPS. Six causative factors were used namely; slope, elevation, aspect, slope materials, land use and land cover, and groundwater conditions were considered for landslide hazard zonation and evaluation. Information value method was used for the present study. Then, landslide hazard zonation map of the study area was classified into five hazard classes namely; very low, low, moderate, high and very high hazard landslide classes. The result of landslide hazard zonation (LHZ) map of the study area revealed that 33% (40Km<sup>2</sup>) of the study area falls under very low hazard, 29% (35 Km<sup>2</sup>) as low hazard, 23% (28Km<sup>2</sup>) as moderate hazard, 10% (11 Km<sup>2</sup>) as high hazard, and the rest 5% (6 Km<sup>2</sup>) as very high hazard area. The result of overlay analysis of past landslide and LHZ map showed that 62.8% (22) of past landslides occurred within very high hazard (VHH) zone whereas 34.2% of the past landslide fall under high hazard (HH) zone of landslide hazard zonation map of the present study area. Further, only 3% (1) of the past landslide fall within moderate hazard zone. Thus, the results clearly shows that 97% of the past landslide fall within high hazard (HH) and very high hazard zones (VHH).

**Key words**      **Landslide hazard zonation map, statistical approach, information value**

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## List of Acronyms

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### List of Acronyms

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FAO	Food and Agricultural Organization
GSE	Geological Survey of Ethiopia
GPS	Global Positioning System
LHZ	Landslide Hazard Zonation
NMSA	National Mission of Sustainable Agriculture
OWWBSE	Oromia Water Work Design and Supervision Enterprise
NLHMS	National Landslide Hazards Mitigation Strategy
UNFOA	United Nation Food and Agricultural Organization
WofE	Weight of Evidence
SSEP	Slope Stability Susceptibility Evaluation Parameter
GIS	Geographic Information system
LHEF	Landslide hazard evaluation factor
FOS	Factor of Safety
IV	Information Values
IVM	Information Value Model
LULC	Land Use Land Cover
LSI	Landslide Susceptibility Index
DEM	Digital Elevation Model
ERDAS	Earth Resource Data Analysis System

## Chapter – 1

## INTRODUCTION

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### 1.1 Background

Landslides are the downward movement of slope materials such as; rocks, debris or soils due to gravitational pull. The term landslide includes variety of movements' viz. flowing, sliding, toppling or falling and combination of two or more types, which results in a complex type of slope failure (Varnes, 1984). Landslide causes substantial human, economic and farm land losses throughout the world. Only from 1995 up to 2005 over 12,730 casualties have been reported due to landslide worldwide (World Bank, 2010). From 1900 to 2011 a total of 54,020 people have been killed, about 6.8 Billion US dollars have been lost by landslides, excluding subsidence and avalanches ([www.em-dat.net](http://www.em-dat.net)).

Ethiopia is a country with great geographic diversity with mountains, high plateaus, deep gorges, river valleys, and lowland plains (Aregay Waktola, 1999). Broadly, the Ethiopian landmass is divided into highlands and lowlands. According to FAO (1986 as cited in Kifle Wolderearagay, 2013) the Ethiopian highlands cover about 44% of the Ethiopian landmass. These highlands represent the most densely populated area; with over 60% of the population living in these areas (Kifle Wolderearagay, 2013). Ethiopia has been frequently affected by landslide hazards, especially in the toe of mountainous area and escarpment of rift valley (Kifle Woledearegay, 2013). The mountainous areas of Ethiopia are susceptible to landslides hazard, especially near the escarpment of the rift valley. Intensive and prolonged rainfall causes landslides, erosion and slope failures, mainly during rainy season (Lulseged Ayalew, 1999; Lulseged Ayalew and Yamagishi, 2004; Tenalem Ayenew and Barbieri, 2004; Kifle Woldaregay, 2013; Raghuvanshi et al., 2014; Henok Woldegiorgis et al., 2014; Fikre Girma et al., 2015; Raghuvanshi et al. 2015; Tilahun Hamza and Raghuvanshi, 2016; Gemechis Chimidi et al., 2017). Landslides are amongst the most natural hazards in the rugged mountainous terrain of Ethiopia (Rai et al., 2014). According to Anbalagan (1992, as cited in Raghuvanshi et al., 2014) the developmental activities in mountainous terrains, particularly road constructions, cover large area of slopes and therefore,

require some rapid slope stability analysis techniques. Landslide hazard zonation techniques may be employed for rapid assessment of slope stability condition over a large area.

Although landslide occurs virtually every year in Ethiopia, general awareness and recognition of landslide hazards remain relatively low (Kifle Wolederegay, 2013).

According to Varnes (1984) landslide hazard zonation is defined as the mapping of areas with an equal probability of occurrence of landslides within a specified period of time. Landslide hazard zonation consists of two different aspects: (a) the assessment of the susceptibility of the terrain for a slope failure, in which the susceptibility of the terrain for a hazardous process expresses the livelihood that such a phenomenon, occurs under the given terrain conditions or parameters. (b) The determination of the probability that a triggering event occurs. Further, prediction of hazard in areas presently free of landslides is based on the assumptions that hazardous phenomena that have occurred in the past can provide useful information for the prediction of occurrences in the future (Varnes, 1984; Carrara et al., 1991; Aleotti and Chowdhury, 1999; Dai et al.2002; Lan et al. 2004; Fikre Girma et al., 2015; Raghuvanshi et al., 2015; Tilahun Hamza and Raghuvanshi, 2016; Gemechis Chimidi et al., 2017). Therefore, mapping these phenomena and the factors thought to be of influence is very important in hazard zonation (Anbalagan, 1992).

The main components that increases the number of landslides in Ethiopia is the rapid change in land use and land cover, unplanned rural road constructions and unplanned urban settlement as well as rainfall (Raghuvanshi et al., 2014; Wang and Niu, 2009; Lulseged Ayalew et al., 2004; Anbalagan, 1992; Hoek and Bray, 1981). In addition, there are also factors such as; complex geological setup and geomorphic factors which have contributed significantly to the landslides in the highlands of Ethiopia (Kropáček Jan, 2015). Landslide is one of the main problems which damages and destroys agricultural land, roads, houses, and loss of human life throughout the world (Fikre Girma et al., 2015; Raghuvanshi et al., 2014; Tilahun Hamza and Raghuvanshi, 2016; Pan et al., 2008; Kanungo et al., 2006; Crosier and Glade, 2005; Dai et al., 2002; Parise and Jibson, 2000; Varnes, 1996). The study area is one of the landslide prone areas located in southeastern plateau of Ethiopia. The area is covered by agricultural land, forest, and pasture. Various types of damages are caused by the landslides in the area which includes damage to roads, Loss of Farmlands, and damage to other developmental infrastructures. Compared to other natural hazards, landslide can create significant damage, especially in the hilly areas of the study

area. Thus, it is very essential to identify landslide hazard zones, in order to mitigate the effect of landslide (Youssef et al., 2016). The main objective of this study is to perform landslide hazard zonation map of the study area. Therefore, In order to produce the landslide hazard zonation map of the present study area bivariate statistical approach (Information value method) was adopted.

## **1.2 Statement of problem**

The present study area is located in the eastern part of Oromia region in Ethiopian highlands which is rugged mountainous terrain. The area is prone for landslide activities and roads in the area, agricultural lands and human and animal lives are at risk to this devastating natural hazard.

In mountainous terrain developmental activities especially, road construction covers large area of slope therefore it needs detailed slope stability assessment (Raghuvanshi et al., 2014). A road from Bambas town to Kombolcha town which passes through the present study area is under construction, besides other developmental activities in the area are also progressing. Most of the rural people in the study area have settled near to the toe of the cliffs and the sloppy areas, as flat areas are generally used for the agricultural purpose. Moreover, awareness about devastations from the landslides is very less among the local communities. Due to increasing population rate and shortage of suitable lands for building constructions in the towns, people have no other choice better than living in mountainous areas. Although the study area is very rugged and affected by landslides, a considerable emphasis was not given by the local community and the administration. As such, there is no study about landslide hazard zonation and evaluation in the present study area. Therefore, landslide hazard zonation mapping of the study area is very essential to show the prone areas to landslide activities in order to inform the government and public about the probability of landslides. Thus, this study will help to plan safer developmental activities and proper and safe land use planning which can decrease the impact of landslide in the study area.



(a) Large block of rock slide towards vicinity houses in Gelmais Kebele (b). Agricultural land effected by landslide in Muhyadin kebele (c) Soil slide along road cut in Dayfras Area

**Plate 1.1** Landslides in the study area

### **1.3 Previous studies**

The highlands of Ethiopia have experienced a lot of landslide activities. In the western, northern, and southern highlands of the country the damage due to landslide has been increasing due to various natural and man-made factors. Different studies have been carried out using several qualitative, analytical and empirical techniques to evaluate and assess the factors and causes that trigger landslides in different parts of the highlands of the country (Filagot Mengistu et al., 2019; Gemechis Chimidi et al., 2017; Tilahun Hamza and Raghuvanshi, 2016; Raghuvanshi et al., 2014; Shifraw Ayele et al., 2014; Kifle Woldearegay, 2013; Engdawork Mulatu et al., 2010; Engdawork Mulatu et al., 2009; Tenalem Ayenew and Barbieri, 2004; Lulseged Ayalew and Yamagishi, 2004; Lulseged Ayalew, 1999 etc.). The present study area is located in the southeastern plateau of the country. However, for present study area no published or unpublished studies on landslides are available, except studies made by Geological Survey of Ethiopia (GSE) which is about engineering geology and geo-hazard as a part of Harar sheet area. Therefore, the present study is the first study about landslide hazard zonation and evaluation in Funyan Biro town and its surrounding areas.

### **1.4 Research questions**

Through the present research following questions were intended to be answered;

- What are the triggering and causative factors that are responsible for landslides in the study area?
- What are the locations where the landslides are distributed in the study area?
- What are the areas which are highly affected by the landslides in the present study area?
- What types of failure mechanism are responsible for the landslide in the area?
- What are the possible remedial and mitigation measures to be recommended?

## **1.5 Objectives**

In order to answer the research questions for the present study following objectives were formulated;

### **1.5.1 General objective**

The main objective of this study is to evaluate landslides and to produce landslide hazard zonation map for the study area.

### **1.5.2 Specific objectives**

The specific objectives of this study are listed below;

- To evaluate the main triggering and causative factors responsible for landslide in the area.
- To prepare the landslide inventory map of the study area.
- To identify type of landslides in the study area.
- To produce landslide hazard zonation map.
- To recommend the appropriate mitigations and remedial measures

## **1.6 Significance of the study**

Currently, different developmental activities are in progress in Oromia region. For socio-economic development, landslide and landslide related-generated ground failures need to be given due attention in order to minimize economic and human losses and to create safe geo-environment. Therefore, the main objective of the present study is to produce landslide hazard zonation map of the study area. The landslide hazard zonation map helps to the future developmental activities such as; agriculture, selection of best sites for road construction, building house in the appropriate site and also any other developmental activities. It can also be helpful to decrease or minimize the upcoming impacts in landslide susceptible areas by considering landslide hazard during planning of future activities for the local government and concerned bodies.

## 1.7 General methodology

In order to meet out the objectives of the present study effectively, the following systematic methodology has been followed;

- Review of relevant literature such as; books, technical journal articles, academic thesis and other related secondary material about landslides.
- Desk study –Collection of secondary data of the study area such as; topographic maps, geological maps, hydro-geological maps, engineering geological map, satellite imageries, Digital elevation model of the study area. Preparation of base map (facet map) and other thematic maps from secondary sources.
- Field investigation - Field data or primary data of the study area were collected such as; landslide inventory; GPS points of past landslides, spring locations etc. Verification and updating of thematic maps based on field observations.
- Post field activities – The data collected from the field was thoroughly processed, analyzed and interpreted to meet out the objective of the study.

Generally, several methods have been employed by several authors to assess the landslide hazard and to map hazard zones in different parts of Ethiopia. These techniques or methods can be categorized into three: statistical approach, expert evaluation and deterministic method (Ler,oi 1997; Guzzetti et al. 1999; Casagli et al. 2004; Fall et al. 2006; Kanungo et al. 2006; Raghuvanshi et al., 2014; Raghuvanshi et al., 2015; Fikre Girma et al., 2015; Tilahun Hamza and Raghuvanshi, 2016; Gemechis Chimidi et al., 2017).

According to Fall et al (2006) **expert evaluation method** is further classified into two; landslide inventory mapping and Heuristic method. Landslide inventory mapping is the simple method and a method in which the landslide events are recorded for their location and dimension. The heuristic method includes opinion in classifying the landslide hazard which is based on quasi-static variables only. Furthermore, the **statistical methods** are indirect and landslide hazard assessment is made based on the rules evolved statistically with the relative contribution of instability factors on the past landslides. It is used to evaluate spatial landslide instability based

on the relationship in between the past landslide activities and the instability causative factors (Fikre Girma et al., 2015; Raghuvanshi et al., 2014; Carrara et al., 1992). This method includes bivariate and multivariate methods. The **Deterministic method** provides hazard in absolute values in the form of factors of safety. These methods provide the quantitative results for landslide hazard can be directly in the engineering design (Fikre Girma et al., 2015; Raghuvanshi et al., 2014). In these methods various forces responsible for instability and the forces responsible for stability are evaluated in quantitative terms. These methods need geotechnical data and can be applied at a large scale only (Barredo et al., 2000).

For the present study bivariate statistical method was adopted which is a part of statistical method.

## **1.8 Scope and Limitations**

The present study has been conducted with all possible efforts acquiring the required field data, secondary data, analysis and technical interpretation. However, the study has faced certain limitations. The occurrences and effects of landslides in the study area have a long-time history; however no systematic landslide event data is being maintained by the concerned local authorities. There is also scarcity of written documents and reports on landslides in the study area except some of the geo-hazard reports compiled by Ethiopian Geological Survey. Besides, the study area is very rugged therefore some of the areas were inaccessible during the field work. Moreover, the pandemic covid-19 crisis during the final stage of this research work has also affected the progress of the present research. Ethiopia is one the countries which Corona virus has confirmed. There were also insufficient resources; closure of libraries, closure of labs and limited access to internet has also affected the present study.

## **1.9 Thesis structure**

The present research study is presented in seven chapters;

**Chapter one:** this chapter presents about introduction of landslide, statement of problem, the objectives of the study, methodology, significance of the study and scope and limitations.

**Chapter two:** –An overview of the study area: description of the study area, regional and local geology of the study area, climate condition of the study area

**Chapter three:** gives literature review about landslide, classification of landslide, failure mechanism, discussion of approaches or methods for landslide hazard zonation, the causative factors of landslide.

**Chapter four:** this chapter describes the method or approach that was followed for this study which is bivariate statistical method (information value model). It discusses the methodology and materials used for this study.

**Chapter five:** Data Collection, Processing and Analysis: LHZ descriptions, landslide inventory of the study area, triggering and causative factors of landslide, failure mechanisms of landslide in the study area

**Chapter six:** Results, Discussion and Interpretation: it is about result and discussion landslide inventory mapping, landslide hazard zonation and result verification

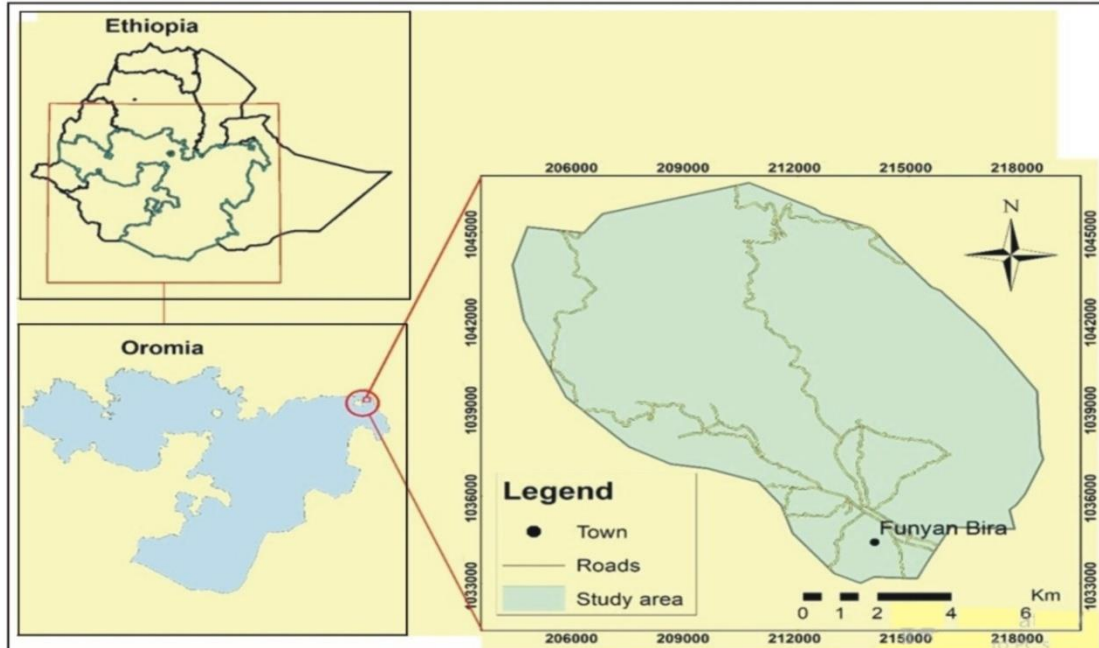
**Chapter seven:** conclusion and recommendation

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## **Chapter – 2 AN OVERVIEW TO THE STUDY AREA**

### **2.1 Location and Accessibility**

The present study area is located in the eastern Hararghe zone of the Oromia region, Gursum District, Eastern Ethiopia, 581km from Addis Ababa. The study area covers Funyan biro town and its surroundings. The area is commonly known by its recent name, Gursum District. Gursum is bordered on south by Babile, on north by Jarso, on the east by Somali region, and on the west by Harari region. The study area is accessed by the main road which connects Addis Ababa to Harar-Bombas to Funyan biro. From Addis Ababa to Bombas, the road is asphalt road, whereas from Bombas to Funyan biro, the road is gravel road. Geographically, the study area lies in between 9° 07' - 9° 32' North latitudes and 42° 17' - 42° 38'E longitudes (Fig.2.1). Most of the area is rugged with the elevation variation from 1500 to 2938m above the sea level. The annual rain fall in the area is 650 to 750mm with mean annual minimum and maximum temperature of 18 and 25°C, respectively. The total coverage of the study area is 120 km<sup>2</sup>.



**Fig 2. 1 Location map of the study area**

## **2.2 Physiography**

The study area is located in the southeastern plateau of Ethiopia. The area is characterized by very rugged topography (Plate 2.1) with elevations that ranges from 1500m to 2950m, respectively. However, most of the study area has very high elevation. The area is modified by erosion, resulting in to highly dissected topography with steep hills and deep gullies. The study area has high ridges such as; Belensa, Kundudo and Humo ridges. There are many streams and tributaries which originate from ridges and drains in to the main rivers of the study area. The two main rivers found in the study area are; Goda River and Lafto river. The general trend of drainage in the study area is from the northern mountains to the southern lowland plain area of the Wabe Shabelle basin and is characterized by parallel drainage system in the western parts and dendritic system in its eastern parts (Fig.2.2).



**Plate 2.1 Rugged topography of the study area**

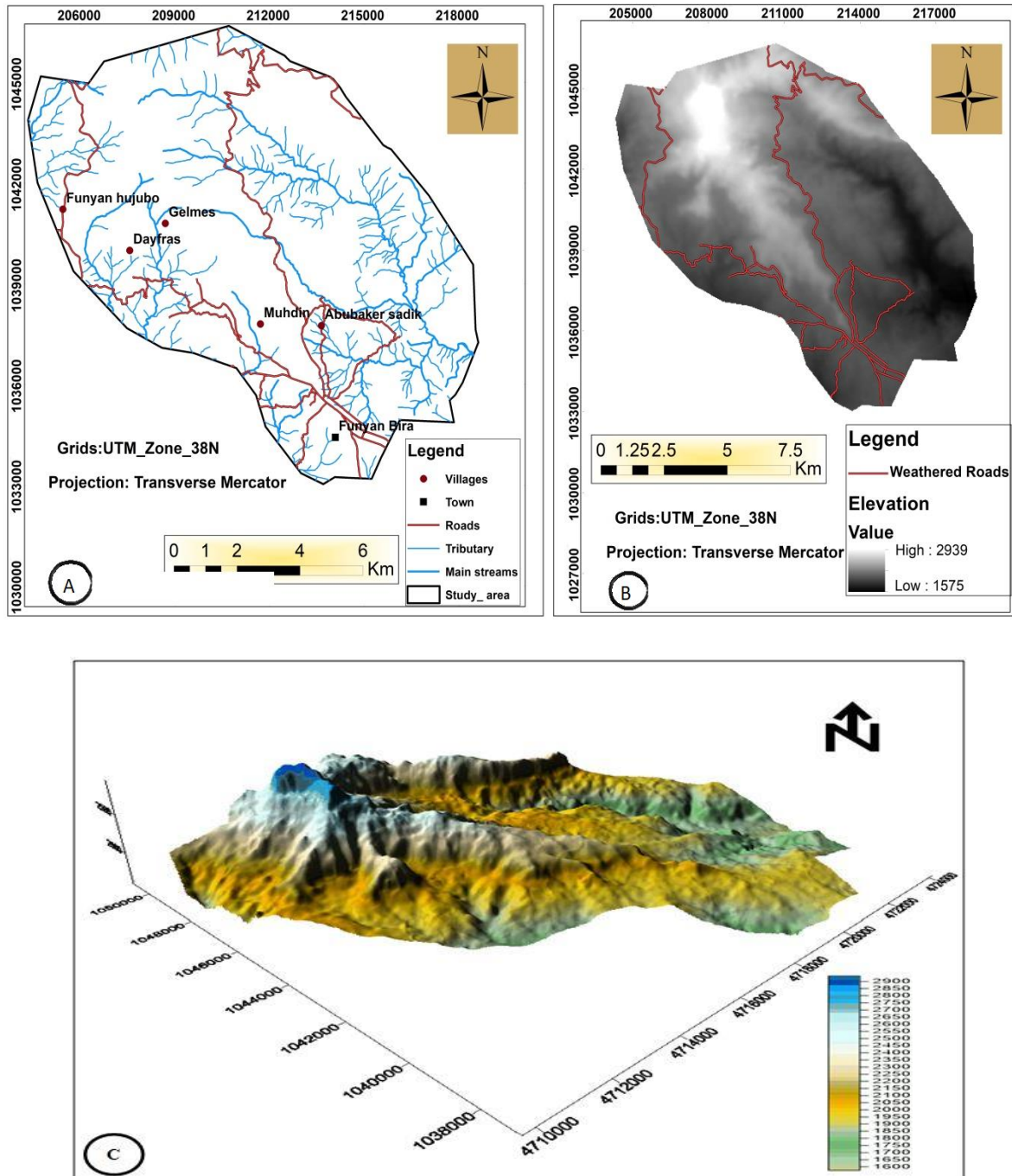


Fig 2. 2 A) Drainage map of the study area, B) Elevation of study area, c) Physiography of the study area

## **2.3 Climate**

The climatic conditions of Ethiopia are mostly controlled by Altitude variation. [Daniel Gemuchu \(1977\)](#) has classified climatic zones into five elevation classes. The elevation greater than 3300m Alpine (Kur), from 2300 to 3300m temperate (Dega), from 1500 to 2300m subtropical (Weinadega), from 800 to 1500m tropical (Kola) and less than 800m desert climate zone (Berha). The elevation of the present study area ranges from 1500 to 2950m. Therefore, based on this classification, the climate zone of the study area is categorized into temperate (2300-3300m) and subtropical zone (1500-2300m).

### **2.3.1 Rainfall**

The seasonal classification and precipitation regimes of Ethiopia are classified into four zones ([NMSA, 1999](#)). (i) Zone A: it is characterized by three distinct zones, and bimodal precipitation pattern with small peaks in April and the main rainy season during mid-June to Mid-September with peaks in July. This region mainly covers the central and central eastern part of the country, (ii) Zone B: this zone is characterized by a single precipitation peak. Two distinct seasons, one being wet and the other dry, are encountered in this region. This zone can be split into southwestern with the wet season (February/march to October/November), western with wet season (April/May to October/ November), and Northwestern with the wet zone (June to September). This region covers the western part of the country, (iii) Zone C: this region has two distinct precipitation peaks with a dry season in between. The first wet season is from March to May and the second is from September to November. This region mostly covers the southern to southeastern parts of the country and (IV) Zone D: the red sea region in the extreme northeastern part of the country receives diffused precipitation with no distinct, however precipitation occurs mainly during the winter. Thus, according to [NMSA \(1999\)](#) zones, the present study area is characterized under zone A. The maximum and minimum rainfall in the study area was found to be 930.1mm and 264.7mm, respectively (Table 2.1). The mean annual rainfall as recorded was 682.58mm from the year 2000 to 2017 (Fig. 2.3). For the assessed 17 years the maximum monthly rainfall was 303.5mm which was recorded in the month of August. The study area receives maximum rainfall from April to September and from October to minimum rainfall

based on the data received from Ethiopian Metrological station. In the months of April and August, the rainfall reaches at its peak.

**Table 2.1** Monthly rainfalls (mm) as recorded at Gursum (Funyan biro) Meteorological station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual rainfall (mm)
2000	0.0	0.0	1.7	107.6	112.4	31.6	66.6	303.5	160.0	58.5	32.9	31.3	906.1
2001	0.0	0.0	97.5	60.0	139	82.5	45.5	185.3	16.2	38.3	0.0	0.0	664.3
2002	9.2	1.5	49.8	108.7	61.1	66.1	96.8	88.7	75.0	62.4	0.0	29.1	648.4
2003	24.3	0.0	58.4	162.8	36.4	92.9	66.4	138.0	112.7	0.0	0.0	19.9	711.8
2004	-	0.0	28.8	285.0	0.0	42.3	89.1	76.7	89.3	86.8	36.9	0.0	734.9
2005	5.9	23.7	38.0	142.8	148.5	23.7	61.4	84.7	51.9	16.5	6.3	0.0	603.4
2006	6.5	23.4	92.5	244.6	98.3	27.9	102.6	156.8	-	76.5	5.6	59.2	893.9
2007	0.0	3.4	20.3	118.8	193.5	75.7	158.5	56.3	104.1	53.5	9.7	0.0	793.8
2008	0.0	0.0	7.7	32.3	298.6	30.3	126.7	81.5	130.8	47.9	61.2	0.0	817.0
2009	8.5	0.0	21.2	104.1	111.3	30.9	97.1	129.1	62.3	47.8	0.0	0.0	612.3
2010	0.0	195.4	6.5	234.4	84.0	59.0	84.5	140.4	104.1	14.8	7.0	0.0	930.1
2011	0.0	0.0	5.2	48.7	124.1	94.4	60.8	83.4	-	3.0	0.0	-	419.6
2012	0.0	0.0	12.8	124.9	35.0	70.1	107.8	98.9	109.8	0.0	0.0	0.0	559.3
2013	6.0	0.0	191.8	135.8	45.3	3.2	89.0	86.0	161.0	-	-	0.0	718.1
2014	-	0.0	120.4	64.0	32.1	7.6	95.7	230.1	237.0	5.0	0.0	0.0	791.9
2015	0.0	0.0	58.5	42.1	132.0	87.1	56.3	167.1	26.1	23.8	16.5	-	609.5
2016	4.9	21.4	6.1	165.2	122.9	61.9	80.2	143.3	-	0.0	-	1.5	607.4
2017	0.0	-	103.1	42.3	67.4	50.6	-	-	-	1.3	-	-	264.7
Mean annual rainfall													682.58

### 2.3.2 Temperature

The hottest month in the study area is March with mean maximum temperature of 25.5<sup>0</sup>C and the mean minimum temperature of 13.5<sup>0</sup> C is in the month of September with mean monthly temperature of 10.12<sup>0</sup> C and maximum temperature of 23.5<sup>0</sup> C ([Annex 1.1](#); [Annex 1.2](#)).

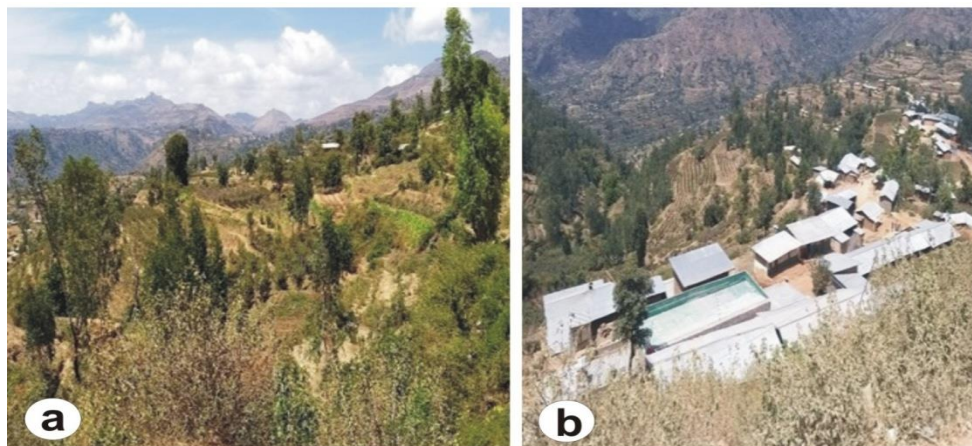
### 2.4 Land use and land cover

Land cover is the observed biophysical cover on earth’s surface. These include native vegetation, soils, exposed rocks and water bodies as well as anthropogenic elements such as plantation, crops and also built up areas ([Workineh Haro, 2010](#)).

The land cover of the study area mainly includes dense shrub land, grass land, artificially planted area and cultivated land. Along the river's elephant grasses, shrub reveries trees are common (Plate 2.3). The gentle and low slope area of the study area which is covered by alluvial soil and limestone is moderately and highly cultivated. Most of the local people intensively cultivate sorghum, coffee, and maize as well as chat, barley along the suitable areas of the plateaus and gentler slopes, and in valley plains.

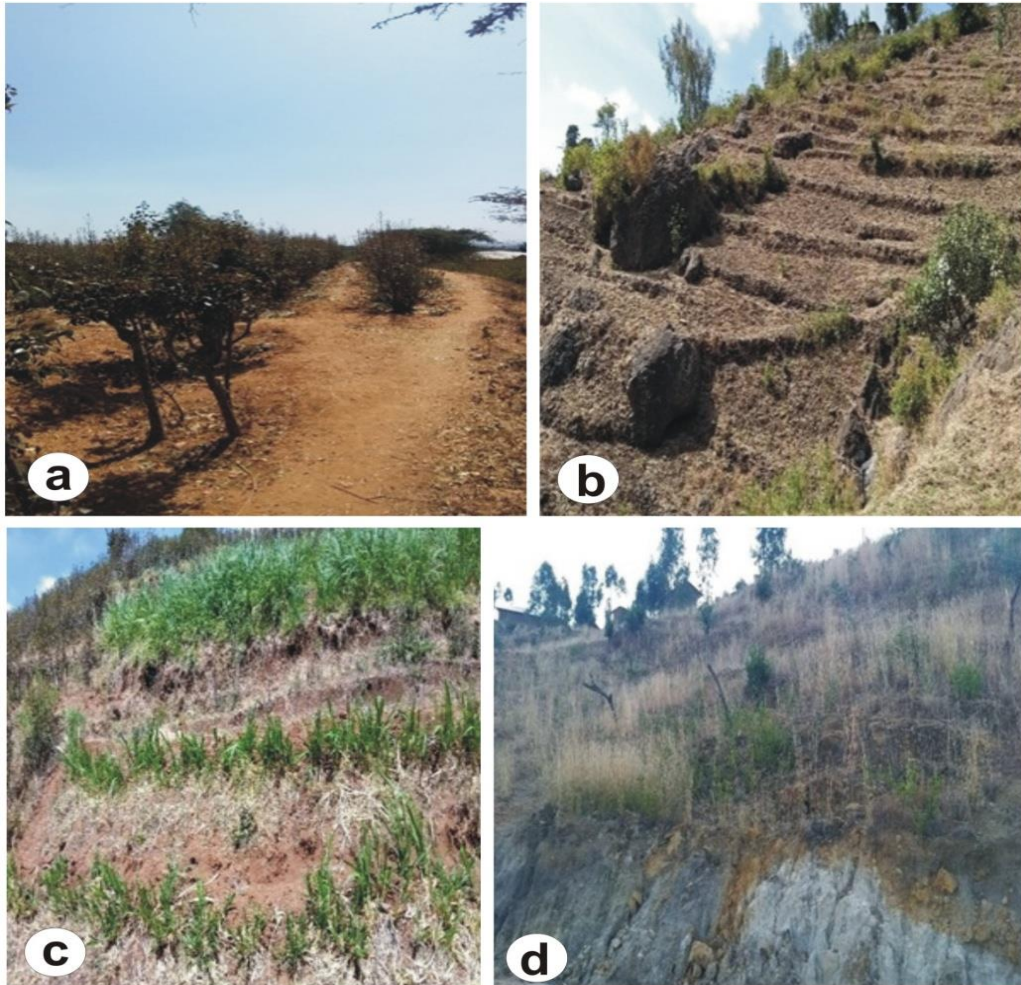
### **2.5 Soil and vegetation cover**

The study area consists of different type of soils. The plain areas and rivers of the study area have silty to sandy, alluvial soils. The volcanic and gently slope areas have brown to black soils. On the other hand, the vegetation cover of the study area varies from place to place with variations of altitude and population density (Plate 2.2). The high elevation areas are partly covered by green forests whereas the low elevation areas are covered by short grass, acacia trees and planted trees like banana, behrasaf. The riverine forests are found along the banks of the rivers.



(a) Planted area around FunyanHujuboWerada and (b) Sloppy built-up area near FunyanHujuboWerada

**Plate2. 2** Vegetation covers in the study area



(a) Chat in Abubeker area, (b) Cultivated Lands in FunyanHujub town, (c) elephant grass and (d) grass land

**Plate2. 3 Land use and land cover in the study area**

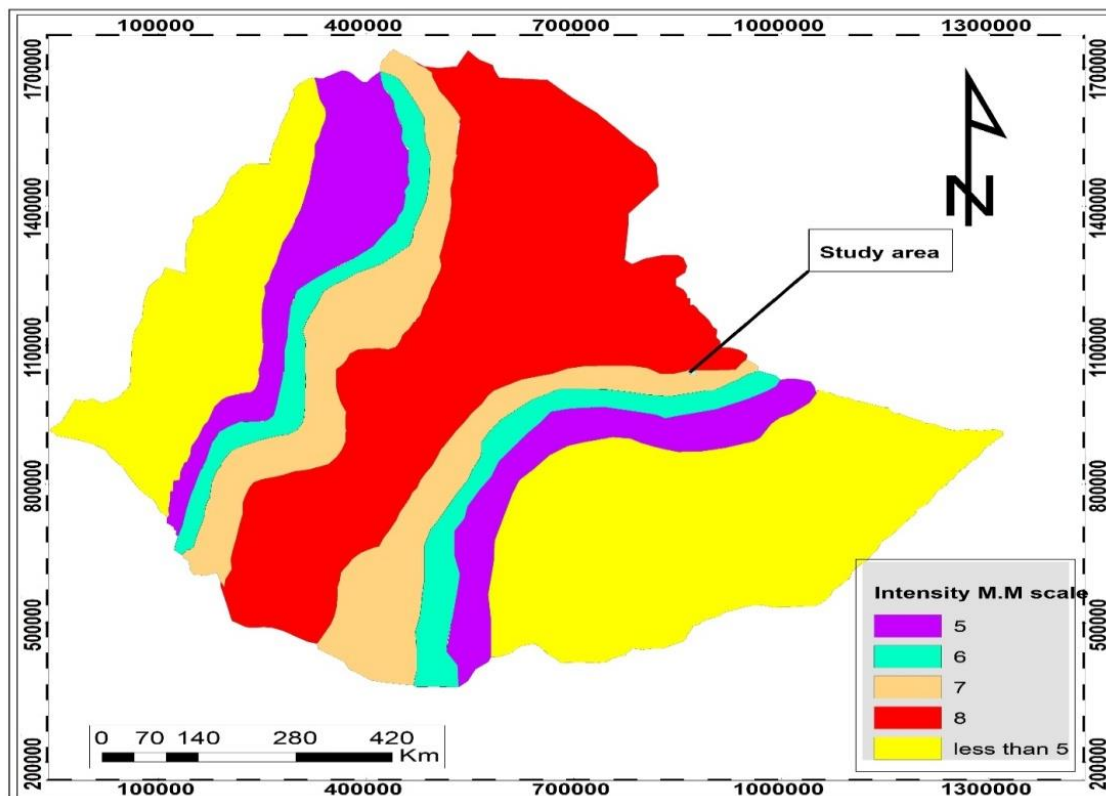
## **2.6 Seismicity of the study area**

Earth quake is one of the principal triggering factors of landslides that cause great hazard of life and property loss (Raghuvanshi et al., 2019; Raghuvanshi et al., 2014; Birhanu Ermias et al., 2017; Bommer and Rodri'guez, 2002; Keefer, 2000). The possibility of an earthquake in triggering a landslide event depends on the shaking of the ground rather than on the actual magnitude of the earthquake (Muthu and Petrou, 2007).

The vibrations released during the quake can cause resettlement of the soil skeleton which in turn causes expulsion of water. Rock falls and slides of rock fragments that form on steep slopes are common earthquake induced landslides although other types of landslide is also possible,

including highly disaggregated and fast-moving falls, more coherent and slower-moving slumps blocks slides, and earth slides, and lateral spreads and flows that involve partly to completely liquefied material (Keefer, 2002). All types of landslide can be triggered by seismic activity. However, liquefaction type landslide is unique for seismic activity (Keefer, 2002; Raghuvanshi et al., 2019; Raghuvanshi et al., 2014; Birhanu Ermias et al., 2017; Bommer and Rodri'guez., 2002).

The seismic zones of Ethiopia have been delineated by Gouin (1979) and later updated by Laike Mariam Asefaw (1986). The seismic risk map produced by Liake Mariam for a hundred-year return period and 0.99 probability shows that the study area falls almost within 8 M.M scale (Fig.2.5).



(Source: After Laike Mariam Asefaw, 1986)

Fig 2. 4 Seismic risk map of Ethiopia 100-year return period, 0.99 probabilities

## **2.7 Geological setting**

### **2.7.1 Regional Geology**

The geology of eastern Ethiopia, particular in the Harar area generally consists of Precambrian metamorphic rocks and intrusive, Paleozoic sediments, the Triassic to lower Jurassic Adigrat sandstone, middle to upper Jurassic carbonate sequences (Hamanlei, Urandab and Gabredarre formations), and Cretaceous continental sandstone called the Amb aradom formation and an unconformably overlying Tertiary in an ascending order (Davidson, 1983).

#### **2.7.1.1 Precambrian rocks (Lower complex)**

These basement rocks comprise high grade gneisses and magmatites can be referred as lower complex with approximately ages of 600 million years (Berhe Seifu, 1978). They expose in areas where the younger cover rocks have been eroded away; namely Harla, Adada, Harer, Beke halo and Bishan bane (Berhe Seifu, 1978). They include biotite gneiss, quartzo-feldspathic gneiss and biotite amphibole gneiss (Gilamichael Kidanemariam et al., 2011).

#### **2.7.1.2 Paleozoic-early Jurassic sediments**

Adigrat Sandstone is exposed in the uplifted central north and north east corner of the basin, and within the deeply cut river valleys of Galete, Jerjertu, Ramis, Gobeles rivers and their tributaries, In the northern Ogaden Basin. It is unconformably overlies the Precambrian metamorphic basement. The contact with overlying Middle-Late Jurassic carbonate is sharp and marked by erosional unconformity. Its thickness was measured between 10 and 120m, but in Bedesa area the maximum thickness of the unit is estimated to be more than 200m (Kibre Tadesse and YirgaTura, 2008).

#### **2.7.1.3 Middle -Late Jurassic sediments**

##### **2.7.1.3.1 Hamanlei formation:**

The Hamanlie formation presents the first marine sediments formed by the first flooding of the sea in the area. Typically, these formations have upper limestone and lower limestone (Tadesse

Alemu, 2008). The upper limestone represents the stratigraphic upper most of the carbonate sequence of the area. They form flat-topped, ridges, and are characterized by karastic topography with well-developed sinkholes and caverns (Andarge Mekonen and Jiri Sima, 2010).

#### **2.7.1.3.2 Urandab formation**

The Urandab formation forms plains, local hills, ridges, and river and stream beds, in the northern Ogaden basin (Kibre Tadesse and Yirga Tura, 2008). It attains an exposed thickness of 257m at Shanan-Mechara section which thickens towards the SW. It is generally horizontally bedded, but at some places along Shanna-Mechara roads the beds are inclined and gently folded by monoclinial flexure fold dipping to the northwest (OWWBSE, 2008). This formation is characterized brown, gray and greenish gypsum-bearing shale intercalated with grey argillaceous limestone in the middle and shale in the lower part (Migliorini, 1956).

#### **2.7.1.3.3 Gabredarre formation**

Gabredarre formation is characterized by karst topography with the development of sink holes and cavernous. It is composed of massive to thickly bedded and fossiliferous limestone, oolitic limestone, sandy and silty limestone, which attains a maximum thickness of 247m at shanna-mechara section. In the northern Ogaden, the Gabredarre formation stands prominently on the underlying Urandab formation forming a small, but continuous cliff forming escarp (KibreTadesse and YirgeTura, 2008).

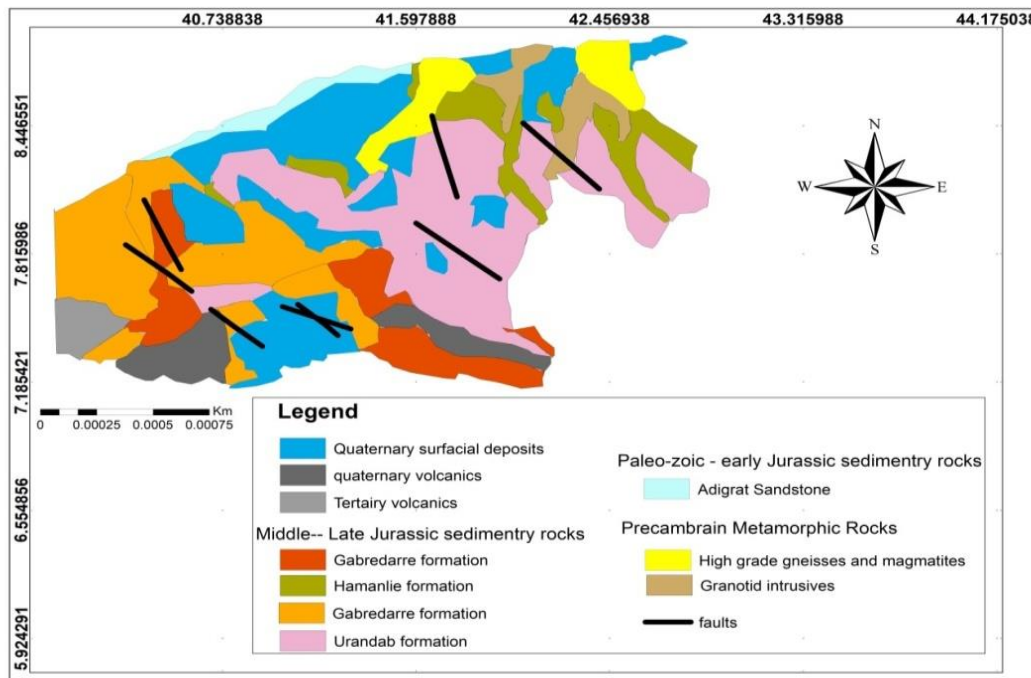
#### **2.7.1.4 Cretaceous sediments**

##### **2.7.1.4.1 Amba Aradom Formation:**

These rock units are comprised dominantly of sandstone with thin bed of limestone (Andarge Mekonen, 2010). These outcrops may be traced continuously down the west flank of the basin, at least to the Web River near Ginir, where inter-bedded limestones and marls grade through yellow calcareous sandstone and thin dolomite bands into white and red sandstone. This rock unit also occurs under the isolated outcrops of the Trap Series basalts along the Wabi-Shabelle River (Kibre Tadesse and YirgaTura, 2008).

### 2.7.1.4.2 Tertiary and quaternary basalts (T-Qv)

The volcanic rocks can be found in all parts of mapped area either as scattered domes, tilted blocks, and ridges at the plateau, fresh lava flows and cones when they outcrop on the Afar plain. The Basalt Flow/Trap series form continuous ridge masses and isolated hills unconformably overlying Mesozoic succession in the north and central parts of Harar area. The rock is greyish black, aplanatic and columnar jointed and also attains a thickness of 30 to 300m (Andarge Mekonen, 2010).



**Fig 2.5** Geological map of Northern Ogaden Basin (source: Tadesse Alemu, 2008)

### 2.7.2 Tectonic setup

The study area is part of the southeastern escarpment of the main Ethiopian rift valley. Many metamorphic rocks show foliations of meridional to submeridional trends. The foliations within high-grade rocks are represented by gneissosity banding and those in low grade rocks by schistosity layers. In some places, Precambrian rocks were exposed by due to the Main East African rifts. The Precambrian rocks Northeastern parts of Harar map are affected by series of

parallel faults having NW trend and steep dips. Some of the faults in the western Ahubarre strike in the NE direction and show sub-vertical dips (Tadesse Yihune, 2005).

The Mesozoic sea was formed as a result of down warping of the Horn of Africa. The lower sandstone, the lower limestone, upper sandstone and the limestone-sandstone interbeds are generally horizontal to sub-horizontal (Workineh Haro, 2010).

Older Cenozoic structures recorded in the area are the faults producing lava flow on the ridges extending from Karamara to Goro areas which are known as be the Marda fault belts (Kazmin, 1972; Merla et al., 1979; Senbeto et al., 1981; Mengesha et al., 1996).

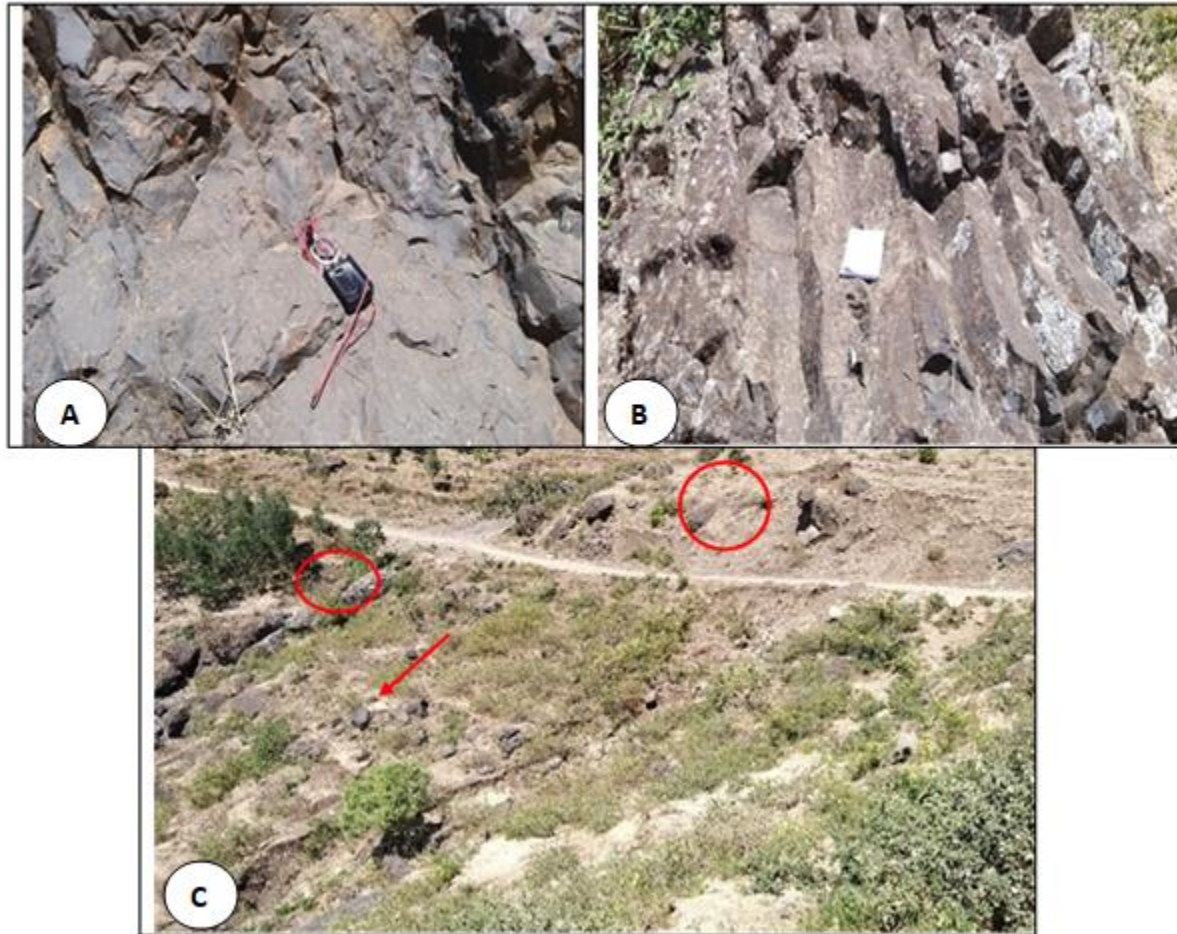
### **2.7.3 Local geology**

#### **2.7.3.0 Introduction**

The study area is dominated by Mesozoic sedimentary, quaternary alluvial and colluvial sediments and Precambrian rocks. The sedimentary rocks that are found in the study area are limestone and sandstone where Precambrian rocks are granite gneiss. Some parts of the study area especially at the Peak of Kundodo Mountain are covered by basalt. The quaternary sediments consist of alluvial and colluvial deposits. This local geology of the study is discussed below

#### **2.7.3.1 Basalt**

The upper basalt unit is exposed in Ridge of Kundodo Mountain which is found in north western part of the study area. It outcrops as blocks and boulders forming an elongated NW-SE trending ridge. Rarely, it occurs as a dyke within the limestone unit; however it is also exposed on low-lying terrains as a block over the basement rocks and sedimentary rocks. This rock unit is characterized grayish black, aphanitic and columnar jointed (Plate 2.4).

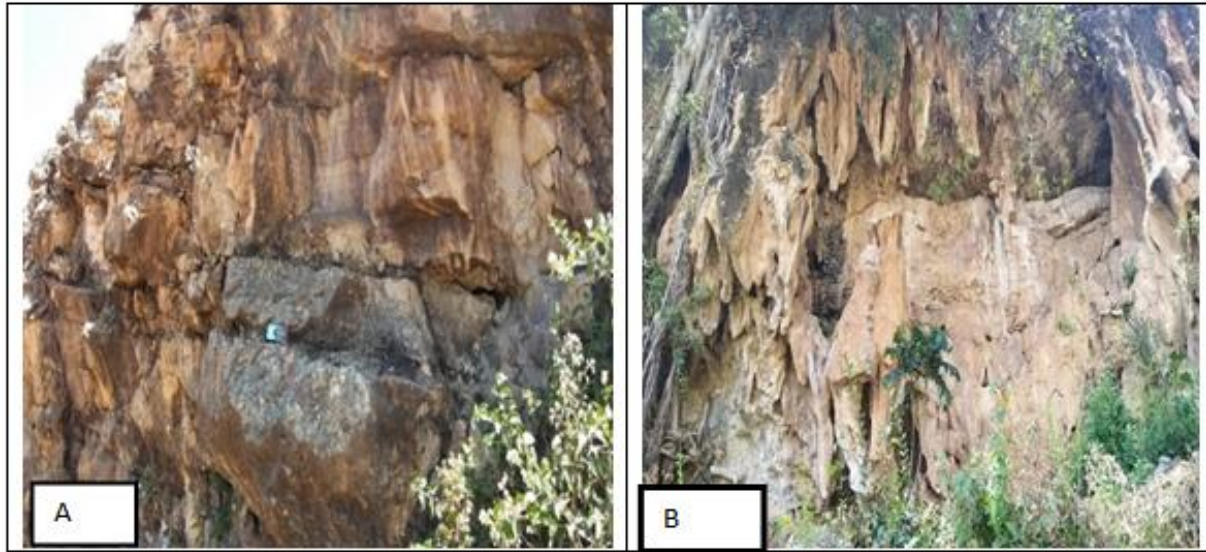


(a) Aphanitic Basalt in kundodo mountain, (b) Basalt with columnar joints  
(c) Boulder of basalt fallen from at the top kundodo mountain

**Plate2. 4 Basalt rock units in the study area**

### **2.7.3.2 Limestone**

This rock unit is mostly found in northern, north western and north eastern of the study area. It forms ridge and at places of flat topped and often show karstic (sink holes) topography. They also show very thick bedded and highly cliffs, but the thickness varies from place to place and it is comprised of various limestones such as micritic limestones with minor marls. Micritic limestone in the study area forms the major part of the upper limestone. This is creamy, light gray to light brownish gray. The marl limestone is inter-bedded with anhydrite. This rock unit is highly weathered at top and fresh at the bottom. Stalagmite and stalactite structures are formed at the cliffs of the exposure areas (Plate 2.4)



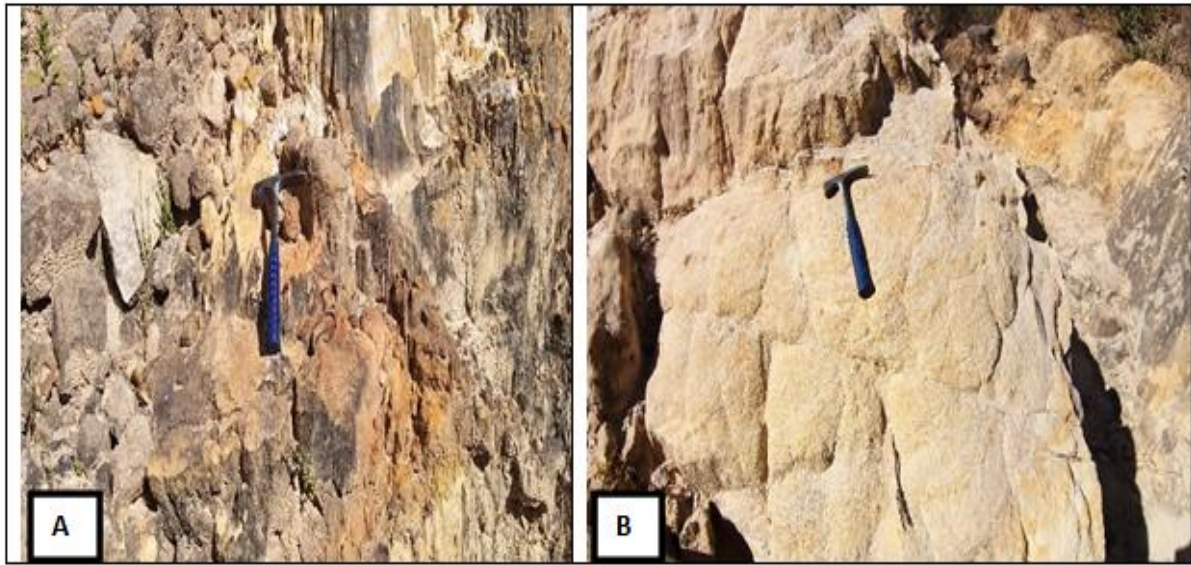
(a) limestone unit in Muheyadin kebele and (b) stalagmite and stalactite Around Gelmes areas

**Plate2. 5 Limestone Rock unit of the study area**

### **2.7.3.3 Adigrat Sandstone**

Adigrat sandstone is the oldest sedimentary rock unit in the study area and has limited outcrop distribution lying unconformably on the high-grade Precambrian basement rock. Exposures of this rock unit are found at the bottom of limestone outcrops such as road cut and deep valleys.

It is composed of conglomeratic sandstone, coarse to medium grained sandstone and mudstone beds, with rarely development of fine sandstone. Whereas coarser sediments are characterized by thick beds, fine sediments show thin bedding and lamination. Red color dominants in the sediments with light grey beds to a lesser extent. This rock unit is also found with violet, grayish white, yellow and reddish colors (Plate 2.6 A and B). Cross bedding is a common structure developed in this sandstone.

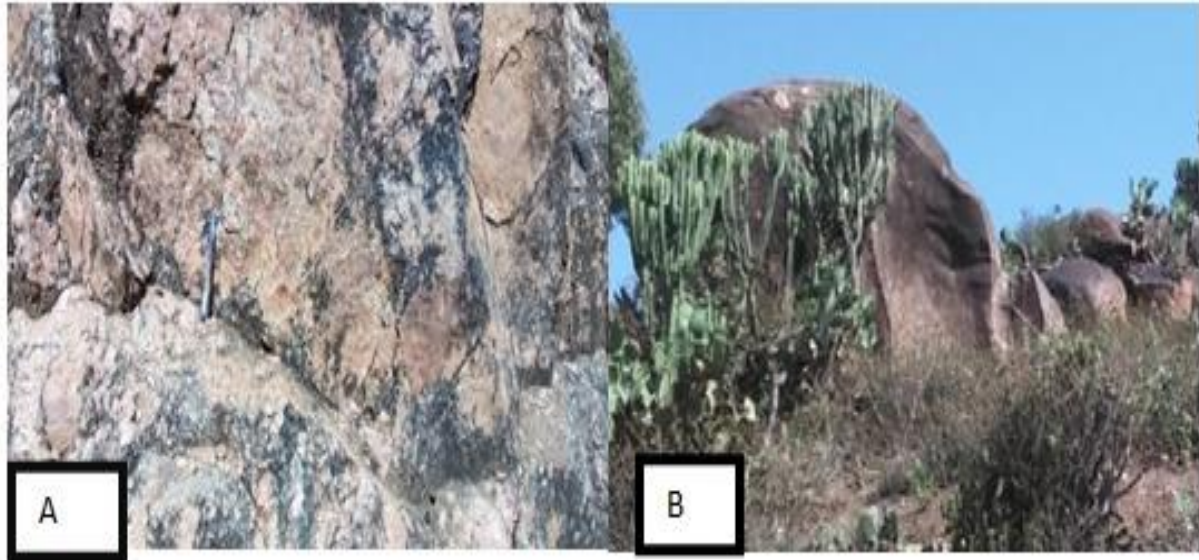


(A) Reddish sandstone and (B) Whitish sandstone

Plate2. 6 Sandstone in the study area

#### **2.7.3.4 Granite**

This rock unit is south western part of the study area. The granites in many areas form sub circular body forming localized small hills but also form ridges and well exposed along hill side, roads cut exposures (Plate 2.7 A). It is characterized by variegated color such as pink, white, and black. It is dominantly pink color which is K-feldspar and with some dark color (Biotite mica) minerals (Plate 2.7 B). It is also characterized by medium to coarse grained, massive and slightly weathered. There are granite boulders at the gentle slope areas of the study area.



**A) Granite rock unit**

**B) Granite boulders**

**Plate2. 7 Granite rock units in the study area**

#### **2.7.3.5 Granite gneiss**

This unit is mainly exposed mainly in western part of the study area. They form rock blocks of big boulders, with rugged terrain of erosion resistant hills. It also occurs in valleys and plains. This unit is mylonitized at places but mainly show light grey color. The gneissic layering is defined by banding of quartz and feldspar rich layers and biotite rich layers (Plate 2.8).



**Plate 2. 8 Granite gneisses**

### 2.7.3.6 Quaternary deposits

Alluvial and colluvial deposits that are found in the study area are deposited in low-lying areas. However, in the sloppy parts of the mountains of the study area colluvial materials are deposited. The alluvial deposits of the present study area are mainly composed of course grained materials with very low amount of fine soils. These indication of that the streams initiate their flowing from slide land are very rich in debris and are erosive power damaging farmland and other infrastructures. The thicknesses of the alluvial deposits in the study area which are exposure in river bank vary from 1m to 5m). It is mostly found the drainage lines, banks and valleys where relatively flat topography is available. They include talus and rock debris at the toe of the valley walls and silt soil over the flood plains. The quaternary deposits of the study area are illustrated in (Plate 2.9)



Alluvial soil in the study area (A) colluvial deposits in Kundodo area (B) Talus (C)

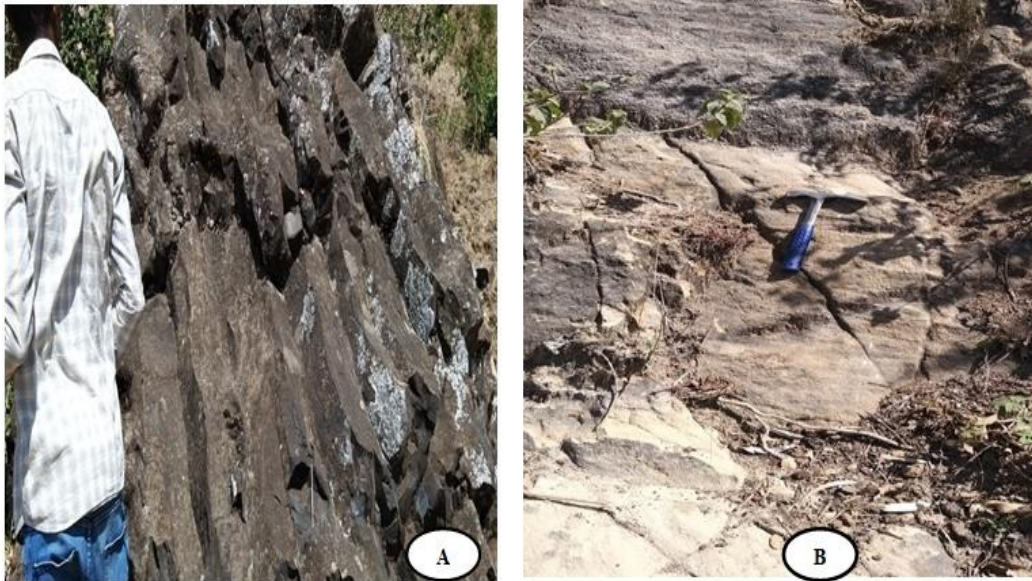
Plate2. 9 Quaternary deposits of the present study area

## **2.7.4 Geological structures in the study area**

The local structures mainly present in exposed rocks in the study area are joints, beddings, and faults.

### **2.7.4.1 Joints and faults**

Since the study area is located near the southeast escarpment of Ethiopia different geological structures were observed such as faults and joints. Most of the major in the study area are parallel to the major escarpment. However, some of the faults in the study area are having strike of east to west and northeast to southwest. Different types of joints such as columnar joints are also observed in the study area. The average dip of joints in the study area ranges from  $5^{\circ}$  to  $80^{\circ}$ . Moreover, the joints observed in the study area have separation or spacing of 1mm to 2cm.



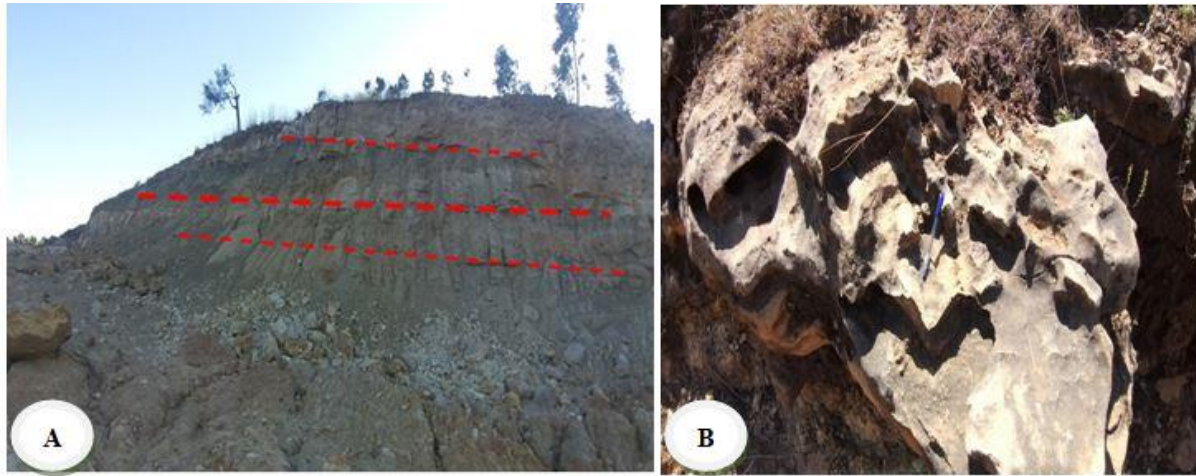
**a) Columnar joints**

**b. joints in sandstone rock units**

**Plate2. 10 Joints in the study area**

### 2.7.4.2 Bedding

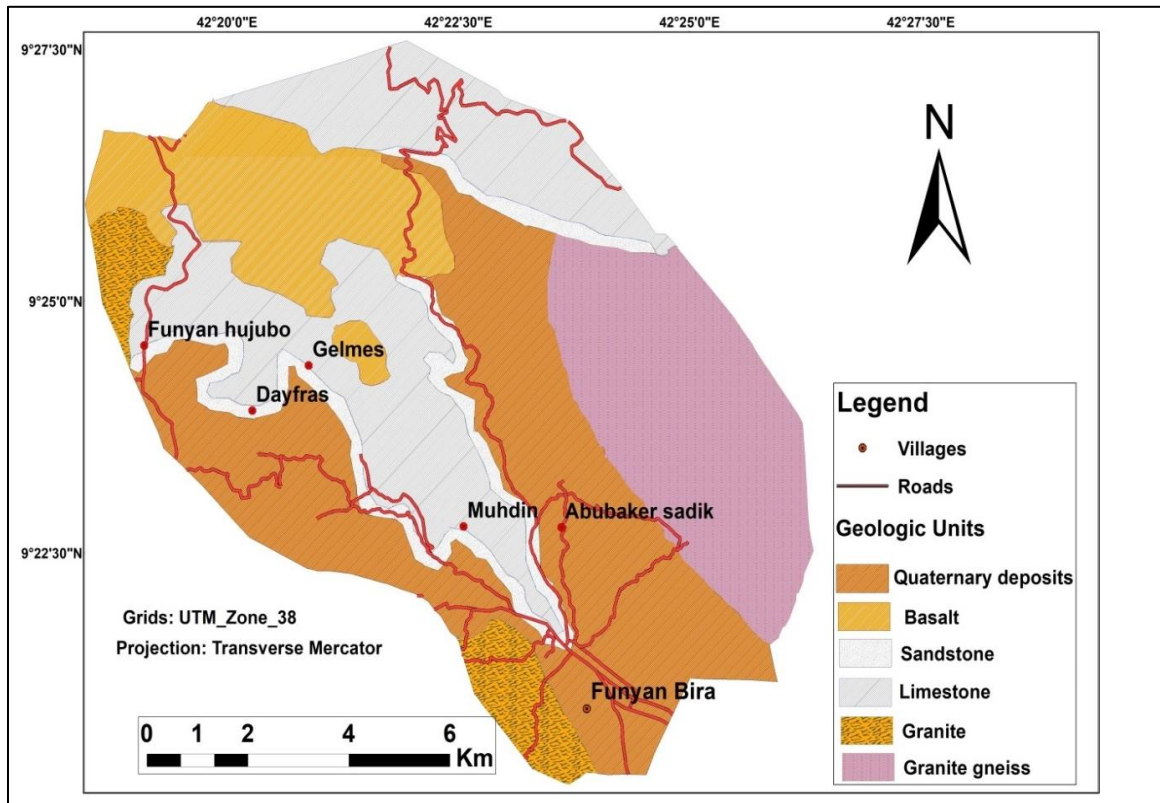
The limestone-sandstone of the study area interbeds is generally horizontal and sub-horizontal. Bed thickness varies from fine lamination to thickly bed in the present study area. Cross bedding is restricted to the bottom of lower sandstone bed. The thickness of limestone horizontal bedding in the study area varies from 1 to 15m. locally limestone beds are observed to be tilted about  $(152/05^0)$  major structure such as  $(68/80^0)$   $(327/81^0)$  oriented two set joint systems and some place it is karsted.



A) Bedding of limestone with sandstone

B) limestone with karstified structures

Plate2. 11 Bedding of the study area



**Fig. 2.7** Local geology of the study area

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## **Chapter - 3**

## **LITERATURE REVIEW**

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### **3.0 Introduction**

Landslides fit in to a much broader group of slope processes referred to as mass movement. The definition of mass movement includes all those processes that involve the outward or downward movement of slope-forming materials under the influence of gravity. Some mass movement processes, such as soil creep, are almost imperceptibly slow and diffuse while others, such as landslides, are capable of moving at high velocity, discrete, and have clearly identifiable boundaries, often in the form of shear surfaces (Crozier, 1989).

According to Moosavi and Niazi (2016) the landslide is known as a natural hazard occurrence that plays a critical role in the evaluation of landscapes and represents serious vulnerability in many areas of the world. Landslides also cause thousands of losses and fatalities, and hundreds of billions of dollars in damage, and environmental troubles every year (Aleotti and Chowdhury, 1999; Gutierrez et al., 2015).

Landslides occur due to a combination of trigger mechanisms and susceptibility factors such as; complex geology, fragile and steep slopes, rugged topography, variable climatic and microclimatic conditions, rainfall, earthquake and vegetation degradation (Gerrard and Gardner, 2002; Wobus et al., 2003; Hasegawa et al., 2009). Further, landslides can be grouped in three types based on the state of phenomena; these types are active, passive and reactivated. Active landslide is a landslide that is moving at present either for the first time or reactivated while passive landslide is that of which occurred in the past such as prehistoric landslide but bears a potentiality to be reactivated. Reactivated landslide is a landslide that is active after being inactive (Fell et al., 2008).

In the literature, confusion exists between the term landslide “susceptibility” and landslide “hazard”. Mostly, the terms are used as synonymous although the two words expressing different concepts. Landslide susceptibility is the likelihood of a landslide occurring in an area on the basis of local terrain condition (Leulalem Shano et al., 2020; Brabb, 1984). The landslide is known as a natural hazard phenomenon that plays a critical role in the evaluation of landscapes

and represents serious vulnerability in many areas of the world (Moosavi and Niazi, 2016). It is the degree to which a land can be affected by slope movements, i.e. an approximate of where landslides are to be expected to occur. Susceptibility does not consider the temporal probability of failure (when or how frequently landslides occur), nor the magnitude of the expected landslide such as how large or destructive the failure will be (NLHMS, 2004). In mathematical language, landslide susceptibility is the probability of spatial occurrence of the slope failures, given a set of geo-environmental conditions. This is called landslide analysis (Vandine et al., 2004). Landslide hazard is the probability that a landslide of a given magnitude will occur in a given period and in a given area. Besides, predicting where a slope collapse will take place, landslide hazard forecasts when or how repeatedly it will happen and how large it will be (Guzzetti et al., 2005).

Ethiopia is characterized a country with great geographic diversity with mountains, high plateaus, deep gorges, river valleys, and lowland plains (Aregay Waktola, 1999). Broadly, the Ethiopian landmass is divided into highlands and lowlands. According to UNFOA (1986 as cited in Kifle Wolderearagay, 2013) the Ethiopian highlands cover about 44% of the Ethiopian landmass. These highlands represent the most densely populated area; with over 60% of the population living in these areas (Kifle Wolderearagay, 2013). Ethiopia has been often affected by landslide hazards, especially in the toe of mountainous area and escarpment of rift valley (Kifle Woledearegay, 2013). The mountainous areas of Ethiopia are prone to landslide hazard, especially near the escarpment of the rift valley. Intensive and extended rainfall causes landslides, erosion and slope failures, mainly during the rainy season. Landslides are amongst the most natural hazards in the rugged mountainous terrain of Ethiopia (Rai et al., 2014).

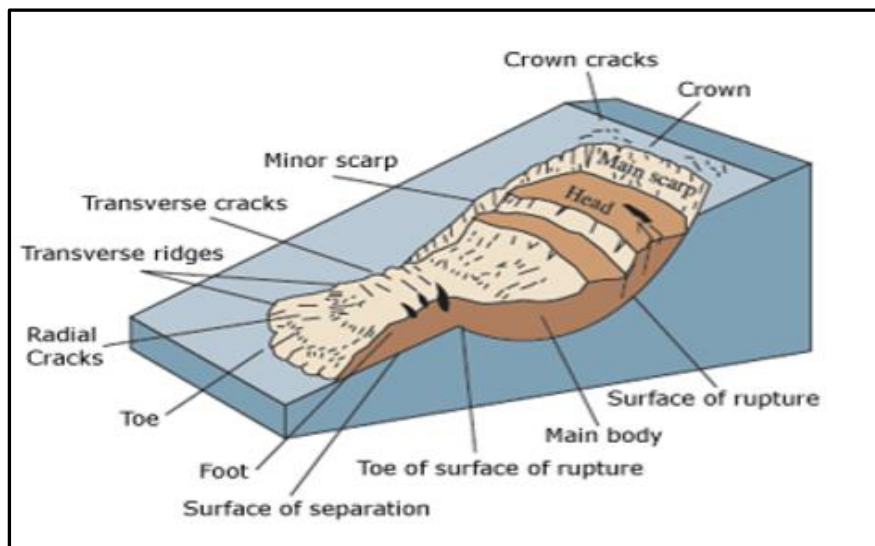
According to Anbalagan (1992 as cited in Raghavanshi et al., 2014) the developmental activities in mountainous terrains, particularly road constructions, cover large area of slopes and therefore, it require some rapid slope stability analysis techniques. Landslide hazard zonation techniques may be employed for rapid assessment of slope stability condition over a large area. In Ethiopia, the magnitude of landslide occurrence and its resulting damages have been increasing in recent times (Fikre Girma et al., 2015; Lulseged Ayalew, 1999). However, different researchers tried to evaluate or assess the situation of landslide occurrences and consequences in different parts of the country, mainly in the highland plateaus, as about 60% of the Ethiopian populations live in

the highlands with an altitude of more than 1750m, where landslide activities are more expected (Lulseged Ayalew, 1999).

A number of methods and techniques have been proposed for landslide hazard zonation mapping (Leulalem Shano et al., 2020; Raghuvanshi et al., 2014; Gemechis Chimidi et al., 2017). The choice of type and scale of the map depends on the requirements of the end user and the purpose of the investigation. Landslide hazard mapping may be qualitative or quantitative (Leulalem Shano et al., 2020; Guzzetti et al., 1999). Qualitative methods are subjective, and they depict the hazard levels in descriptive terms, whereas, the quantitative methods generate numerical evaluation of the occurrence of landslide phenomena (Leulalem Shano et al., 2020; Bhandari, 1987).

### **3.1 Classification and types of landslides**

The term landslide describes a wide variety of processes that result in the downward and outward movement of slope-forming material such as rocks, soils, artificial fills and combination of these. The materials may move by falling, sliding, toppling spreading or flowing (Varnes, 1996). According to Cruden and Varnes (1996) mass movement types include fall, topple, slide, spread and flow (Table 3.1). Falls and topples are sudden movement of mass movement of earth materials mainly caused by gravity. Falls show rapid or abrupt movement of mass of rocks and soils from steep slopes or cliffs. They occur due to free fall and rolling which are highly influenced by gravity, mechanical weathering and inertial water. Falls occur along discontinuities such as; fractures, faults joints and bedding planes. Topple is the forward rotation out of the slope of a mass of soil or rock about a point below the center of the gravity of the displaced mass. Topple is driven by gravity and ice or water present in the mass. Slide is the mass movement from a discrete zone weakness that separates the slide material from stable underlying material. Two main types of slides are rotational (Fig. 3.1) and translational.



**Fig.3. 1** Parts of a Rotational landslide (source: USGS, <http://landslides.usgs.gov>)

Spread is the slow movement of cohesive mass of rock or soil combined with subsidence of fractured mass of cohesive material into softer underlying material. Flow is a continuous movement of soil or rock materials in which surface of shear are short lived.

**Table3. 1** Types of landslide, abbreviated version of Varnes' classification of slope movements

(Source: Varnes, 1978)

Types of movement		Types of materials		
		Bedrock	Soil	
			Coarse	Fine
Falls		Rock fall	Debris fall	Earth fall
Topples		Rock topple	Debris topple	Earth topple
Slides	Rotational	Rock slump	Debris slump	Earth slump
	Translational	Rock block slide	Debris block slide	Earth block slide
Lateral spreads		Rock spread	Debris spread	Earth spread
Flows		Rock flow (deep creep)	Debris flow (soil creep)	Earth flow (soil creep)
Complex of slope materials (e.g., combination of two or more types)				

Landslides can also be classified based on the velocity of its movement. According to Cruden and Varnes, (1996) those movements which have a velocity of  $>5\text{m/s}$  are considered as extremely rapid, and those  $<16\text{mm/year}$  are considered as extremely slow.

According to Varnes (1978) landslides are classified based on their principal behavior shown during sliding: type of movement, type of material. Accordingly landslide types are divided into six main groups: (i) Topples, (ii) Slides, (iii) Flows, (iv) Falls, (v) Lateral spreads and (vi) Complex movements or combinations of two or more type landslide

All these types of landslides are discussed in the following paragraphs;

### **3.1.1 Topples**

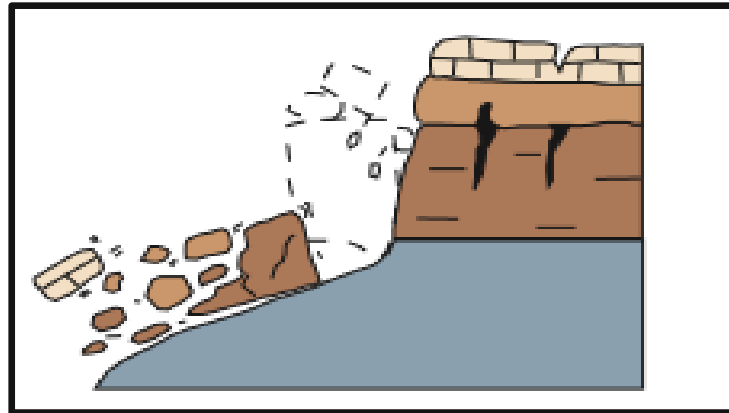
Topples are the forward rotation out of the slope of mass of slope materials about a point or axis below the center of gravity of the displaced mass. This type of failure occurs as a result of overturning of the blocks rather than sliding (Fig.3.2) (Varnes, 1975).

The main triggering mechanism of topples are gravity, water or ice occurring in cracks within the mass, vibration, undercutting, excavation, stream erosion or differential weathering. It happens 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 range from extremely slow to extremely rapid. It can be extremely critical especially when failure is rapid or velocity is rapid (Highland and Peter, 2008).

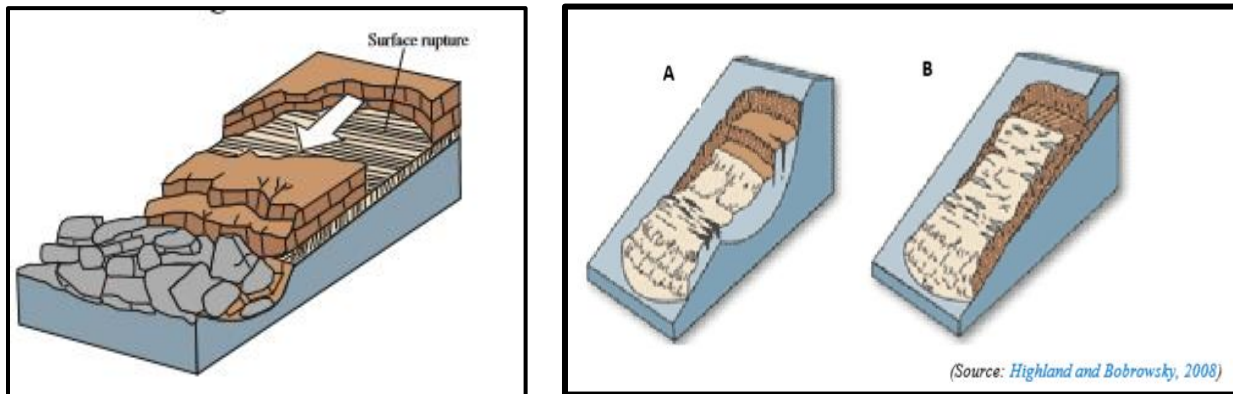
### **3.1.2 Slides**

A slide is a downward slope movement of slope materials occurring predominantly on the surface of rupture or on relatively thin zones of intense shear strain in slides the materials move as coherent blocks or masses along the failure plane. According USGS (2004) Rotational and translational slides are the two major types of slides (Fig. 3.3). Rotational slides are in which the surface rupture is curved concavely upward and the slide movement is roughly rotational about the axis that is parallel to the ground surface and transverse across the slide. Translational slide is

the landslide mass which moves along a roughly planar surface with little rotation or backwards tilting (Highland and Peter, 2008).



**Fig.3. 2 Toppling**

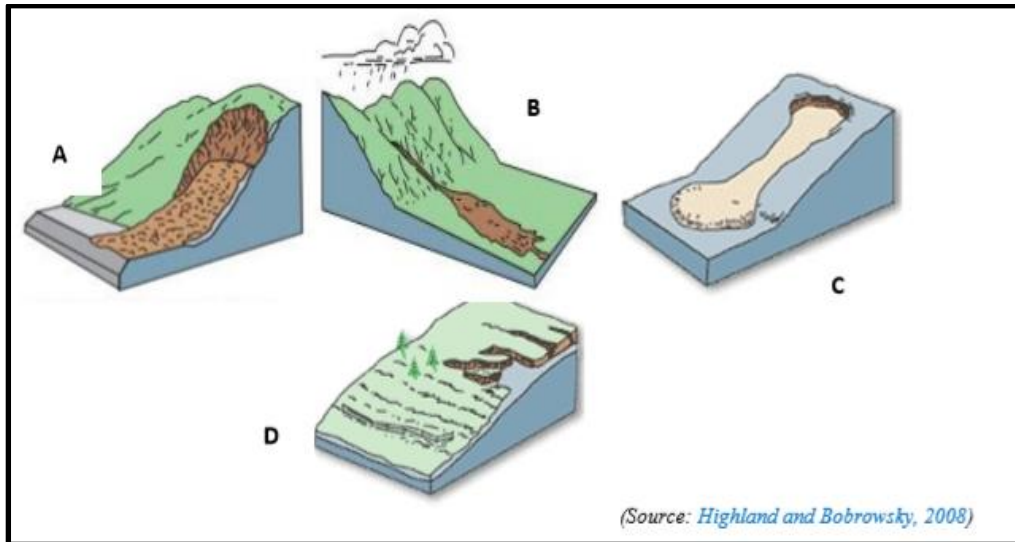


**Fig.3. 3 Rotational slide (A), Transitional slide (B)**

### **3.1.3 Flows**

Flows have five basic categories that differ from one another in fundamental ways such as; debris flow, debris avalanche, mudflow, creeps and earth flow (Fig. 3.4). Debris flow is described as rapid downhill movement of loose earth material usually with water. Debris avalanche is similar to debris flow but has a more rapid flow. In an earth flow, the earth material is finer and is washed away leaving a depression bowl at the head. Mudflows are made up of silt, sand and clay materials saturated with water and flowing very rapidly. Creep is a slower in nature and can be evident when electric poles and road bend slightly. They are commonly caused

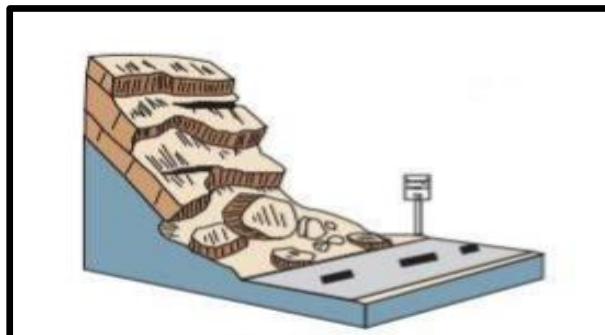
by intense surface water flow, due to heavy precipitation or rapid snowmelt, which erodes and mobilizes loose soil or rock on the steep slopes. They can also move objects as large as houses in their down slope flow or can fill structures with rapid accumulation of sediment and organic matter (Highland and Bobrowsky, 2008).



**Fig 3.4** Debris Avalanche (A), Debris flow (B), Earth flow(C) and Creep (D)

### 3.1.4 Rock fall

Rock falls are abrupt movements of masses of large rocks or boulders which are detached from their parent rock. They usually fall along steep slopes or cliffs. Separation occurs along discontinuities such as; fractures, joints, and bedding planes and movements occur by free-fall, bouncing, and rolling (Fig. 3.5).

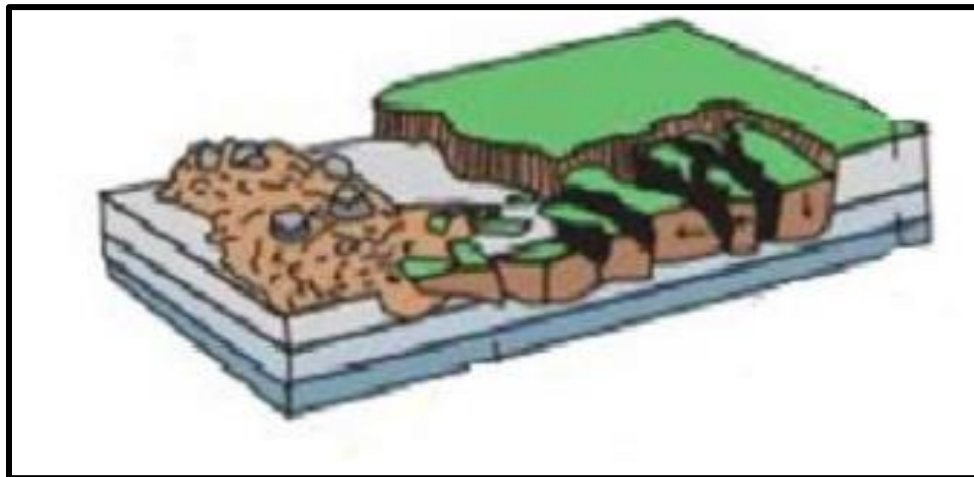


**Fig 3.5** Rock fall

Falls are usually influenced by gravity, mechanical weathering, and presence of interstitial water. It is common in steep slopes, or vertical slopes also in coastal area, along rocky bank of river and streams, roads cuts, and jointed, fractured and weathered bedrock (Wachal and Haduk, 2000).

### **3.1.5 Lateral spread**

Lateral spreads are distinctive because they occur on very gentle slopes or flat terrain. The dominant mode of movement is lateral extension accompanied by shear or tensile fractures (Fig. 3.6). The failure is caused by liquefaction, the process whereby saturated, loose, cohesion less sediments (usually sands and silts) are transformed from a solid into a liquefied state. Failure is usually triggered by rapid ground motion, such as that experienced during earthquake, but can also be artificially induced. When coherent material, either bedrock or soil, rests on materials that liquefy, the upper units may undergo fracturing, extension and then subside, translate, rotate, disintegrate, or liquefy and flow off. Lateral spreading in fine-grained materials on shallow slopes is usually progressive. Lateral spreads typically damage pipelines, utilities, bridges, and structures having shallow foundations (Highland and Bobrowsky, 2008).



(Source: Highland and Bobrowsky, 2008)

**Fig 3. 6 Lateral Spread**

## **3.2 Landslide processes**

Landslide processes are related with slope movements which include a continuous series of events from cause to effect. Different types of landslides have different occurrence mechanisms. Landslide processes broadly include increasing shear stresses, contributing low strength, and reducing material strength (Varnes, 1978).

## **3.3 Factors affecting landslides**

Landslide is affected by many geo-environmental factors such as; geomorphological factors, geological factors, hydrological factors, land use and land cover, besides triggering factors (earthquakes, rainfall, human activities). Degree of effect of these factors depends on the characteristics of each area, meteorological condition, and anthropogenic activities (Gerrard 1994, Gerrard and Gardner 2002).

Landslide occurs due to combined effects of landslide inducing and causal factors (Leulalem Shano et al., 2020; Raghuvanshi et al., 2014; Gerrard 1994, Gerrard and Gardner 2002, Hasegawa et al. 2009, Ghimire 2011). These landslide activating factors such as; rainfall, earthquake and seismic events are called trigger factors (Raghuvanshi et al., 2014). The susceptibility factors include intrinsic material properties of earth and physical topography such as; steep slopes, rugged topography, sparse vegetation cover, fragile geological formations and structurally fragmented rock materials (Wieczorek, 1996).

### **3.3.1 Geomorphological factors**

Geomorphological factors such as; slope, aspect, elevation, and curvatures are considered as conditioning factors to landslide occurrences (Leulalem Shano et al., 2020; Van Westen et al., 2003; Zhou et al., 2002).

#### **3.3.1.1 Elevation**

Elevation is a height of terrain surfaces that affects to landslide occurrences (Varnes, 1984). The weathering process of rocks on high elevation is slower than those on low elevation; therefore, weathered rocks on higher elevation might have higher shear resistance than those in low

elevation (Sidle and Ochiai, 2006; Varnes, 1978). The relationship between elevation and landslide occurrences have been proven in many landslide studies (Gemechis Chimidi et al., 2017; Fikre Girma et al., 2015; Ayalew and Yamagishi 2005; Dai and Lee 2002).

### **3.3.1.2 Slope**

Slope is one of the most influencing factors to landslide occurrence. As slope angle increases, shear resistance in unconsolidated materials (soils and rocks) generally decreases (Gemechis Chimidi et al., 2017; Fikre Girma et al., 2015; Lee and Min, 2001). In general, gentle slopes usually have a low frequency of landslide occurrences than steep slopes. However, some types of landslides such as rapid landslides, debris flow can also occur in very low and gentle slope angles (Highland, 2004). In many regions, landslides are more susceptible in the slope angles ranging from 15 - 45<sup>0</sup> (Anbalagan, 1992; Saha et al., 2005). Landslide analysis show that the interrelation between slope angle and slope stability is not simple as the steepest slope may not always fail (Varnes, 1984). In fact, many steep slopes of competent rock are more stable than comparatively gentle slopes of weak material (Varnes, 1984). Therefore, the spatial distribution of slope is required to be investigated for evaluation of the effect of the increased slope angles (Van Westen et al., 2006).

### **3.3.1.3 Aspect**

Aspect is the direction in which slope faces, also related to landslide occurrences due to impaction of solar radiation and rainfall causing change of topographic moisture which can change the properties of slope forming materials, affect the weathering process, and vegetation development (Varnes, 1978; Sidle and Ochiai, 2006). For landslide analysis, aspect is usually classified into several classes such as; flat, north, northeast, east, southeast, south, southwest, west, and northwest (Kavzoglu et al., 2014; Tien Bui et al., 2012).

### **3.3.1.4 Curvature**

Curvatures are morphologic factors reflecting terrain surface shapes which affect the water flow on earth surface, thus they are considered as conditioning factors to landslide occurrences (Fikre

Girma et al., 2015; Lee et al., 2004). It is often divided into three categories such as; convex, flat, and concaves (Lee et al., 2004). Landslide analysis show that landslide occurs more frequently in convex area than concave area (Lee, 2006). The other types of curvatures such as; plan curvature and profile curvature are also taken into account for landslide analysis in many studies (Ayalew and Yamagishi, 2005). Plan curvature represents the bending of terrain surface in slope perpendicular direction. It affects to landslide occurrences because it affects the water flow on earth surface which controls the moisture of the terrain. Profile curvature indicates slope changed rate for each terrain unit. It affects to landslide occurrences because it also affects the water flow on earth surface which also controls the moisture of the terrain (Ayalew and Yamagishi, 2005).

### **3.3.2 Geological factors**

Geological factors include properties and characteristics of different types of slope forming materials that are strongly related to landslide occurrences (Semenza and Ghirotti, 2000). The potential effects of these factors to landslide occurrences are different from place to place. For the landslide studies different geological factors such as; lithology, soil and geological structure have been considered (Lee and Min 2001; Van Den Eeckhaut et al., 2006). Some of the geological factors are discussed below:

#### **3.3.2.1 Soil**

Soil types influence the landslide occurrences due to different geotechnical properties such as; shear strength parameters. Moreover, the mechanical movement of soils is closely related to chemical, mineralogical and engineering properties of soil materials (Varnes, 1978). According to Terzaghi et al. (1996) soil types are usually classified on the basis of the analysis of their mechanical and chemical properties and the components and distribution of the soil solids.

#### **3.3.2.2 Lithology and Lineaments**

This factor describes the physical characteristics of a rock unit, and is one of the most effective factors in the occurrence of landslides, as lithological and structural changes alter the strength and permeability of the rocks and soil (Sadr et al., 2014). Lineaments are defined as fractures, faults, geomorphologic ridges and other tectonic and topographic structures that cause the

discontinuity of the rocks and soil masses affecting stability of slope (Ayalew and Yamagishi., 2005). To evaluate the impact of lineaments to landslide occurrences, distance to lineaments (faults) and density of lineaments are frequently taken into consideration (Ayalew and Yamagishi., 2005; Fikre Girma et al., 2015; Fall et al., 2006; Dai and Lee., 2001; Dai et al., 2002).

### **3.3.3 External factors (triggering factors)**

External factors such as rainfall, earthquakes, and anthropogenic activities are considered as important affecting factors for landslide occurrences (Raghuvanshi et al., 2014).

#### **3.3.3.1 Rainfall**

The most common triggering factor of landslide is sufficient water contribution during rainfall events. The movements of debris material during debris flow events is related either to the onset of sediment transport due to water runoff or to slope failures caused by an increase in pore-water pressures. Shallow debris flows are often triggered by intense rainstorms of the short duration whereas deep-seated landslides are triggered by precursor rainfall (High cumulative rainfall) over days or weeks often combined with intense rainfall over a much shorter period (Chowdhury, 2010). Intensity of rainfall has a direct relation with the slope instability problems. Due to this reason most of the landslides occur only during rainy season (Raghuvanshi, 2019; Ayalew et al., 2004; Collision et al., 2000; Dai and Lee, 2001; Dahal et al., 2006).

#### **3.3.3.2 Seismicity**

Earthquake is one of the principal triggering factors of landslide that cause large hazard to both of life and properties loss. Rock falls and slides of rock fragments that form on steep slopes are common earthquake induced landslides. Earthquakes reduce stability by imparting both a shearing stress and a reduction in resistance to slope materials. Earthquake wave propagation has three principal effects (Crozier, 1986; Alexander, 1993). These principal effects include (i) the reduction in inter-granular bonding by sudden shock irrespective of the degree of saturation. (ii) The direct mechanical effect of horizontal acceleration and (iii) the cyclic loading which weakens the inter-particle bonding causing liquefaction.

### **3.3.3.3 Manmade activities**

Road construction and cultivation activities are the major manmade activities responsible for destabilization of slopes in mountainous areas. Road construction can involve slope cutting by blasting or by mechanical means, which is being done in unplanned manner. The Excavation of loose slope materials is dumped on down slopes which forms unstable slope mass. Manmade activity which mainly contributes for slope instability is cultivation practice of hill slopes. For cultivation steep slopes are cut into gentle slopes, thus change in natural slope geometry may result into slope instability (Raghuvanshi et al., 2015).

## **3.4 Landslide hazard zonation and evaluation**

Although by definition the term landslide is used for mass movements occurring along a well-defined sliding surface, it has been used in literature as the most general term for all kinds of mass movements, including some little or no true sliding, such as rock falls, topples, and debris flows. The term zonation refers to the division of the land surface into areas and ranking of these areas according to degree of actual or potential hazard (Leulalem Shano et al., 2020; Anbalagan, 1992; Raghuvanshi et al., 2014). Hence, landslide hazard zonation provides potential hazard of landslides or mass movements on a map, displaying the spatial distribution of hazard classes. In general, three basic principles or fundamental assumptions guide all zonation studies (Varnes, 1984).

- The past and the present are keys to the future: natural slope failures in the future will most likely occur where geologic, geomorphic, and hydraulic situations have led to past and present failures. Thus, there is a possibility to estimate the features of potential future failure. The absence of past and present failures doesn't mean that failures will not occur in the future.
- The main conditions that cause landslides can be recognized: the basic causes of slope failure can be recognized, are fairly well known from several case studies and the effects of them can be weighed. It's possible to map and correlate the contributing factors to each other.

- Degrees of hazard can be estimated: If the conditions and processes that promote instability can be identified, it is often possible to estimate their relative contribution and give them some qualitative or semi-quantitative measure.

### **3.4.2 Terminology used in the studies of landslide hazard assessment**

According to [Varnes \(1984\)](#) and [Guzzetti et al. \(2005\)](#) in the study of landslide assessment, terminologies used are defined as follows:

**Landslide zonation:** is the task of division of the land surface into areas and the ranking of these areas according to degrees of actual or potential landslide on slopes

**Landslide spatial prediction (landslide susceptibility assessment)** is to assess the spatial probability of potential landslide occurrence related to a set of affecting factors within a given area ([Guzzetti et al., 2005](#)).

**Landslide hazard assessment** is to assess the possibility of landslide occurrences within a specified period of time in a landslide prone area.

**Landslide risk assessment** is to assess the expected number of human lives lost and people injured, property damages, or economic activities disruption caused by landslide occurrences in a given area.

### **3.5 Landslide hazard zonation Approaches**

Landslide hazard zonation is a significant step in landslide hazard investigation and landslide risk management. The term zonation is defined as the process of division of land surface into areas and ranking of these areas based on the degree or potential hazard from landslides or other mass movements ([Raghuvanshi et al., 2014](#); [Anbalagan, 1992](#); [Varnes and IAEG, 1984](#)). According to [Gutierrez et al. \(2010\)](#) there has been important advancement in both landslide actions mainly those induced by human activities and in number of landslide investigations in different parts of the world. Landslide hazard zonation mapping has been carried out in different parts of the world over last three decades. For landslide hazard zonation mapping, several

techniques or approaches have been developed. These approaches are inventory-based mapping, heuristic approach, probabilistic assessment, deterministic approach, statistical approach and multi criteria decision making approach (Leulalem Shano et al., 2020; Gemechis Chimindi et al., 2017; Tilahun Hamza and Raghuvanshi, 2017; Birhanu Ermias et al., 2017; Fikre Girma et al., 2015; Raghuvanshi et al., 2014).

Numerous landslide susceptibility assessment methods are offered in the literature. These methods can be grouped into qualitative (direct) and quantitative (indirect) methods (Leulalem Shano et al., 2020; Van Westen et al., 2006). In indirect method, the researchers use either statistical models or deterministic models to predict landslide prone areas, based on the information obtained from the interrelation between landslide controlling factors and landslide distribution. However, in direct method, the researchers determine the degree of susceptibility based on her or his knowledge and experience (Leulalem Shano et al., 2020; Raghuvanshi et al., 2014; Van Westen et al., 2003). Further, qualitative approaches for landslide hazard zonation mapping include distribution analysis, geomorphic analysis and map combination approaches. These techniques have much subjectivity in the preparation of various thematic data layer (Leulalem Shano et al., 2020; Fikre Girma et al., 2015; Raghuvanshi et al., 2014), which are integrated to the generation of landslide hazard zonation map of the areas.

### **3.5.1 Qualitative methods**

Qualitative assessment methods evaluate the landslide hazard without landslide inventories. This method is mainly based on the actual landslide on the spatial distribution of landslide governing factors. This method is dependent on the experience and skill of the expert in preparing the map. It requires a prior knowledge on the factors controlling landslides (Leulalem Shano et al., 2020; Raghuvanshi et al., 2014). Heuristic method is an example of qualitative methods (Soeters and Van Westen, 1996). The main disadvantage of expert evaluation method is the subjectivity in the decision making (Leulalem Shano et al., 2020; Raghuvanshi et al., 2014; Van Westen et al., 1997; Leroi, 1997), because the landslide hazard maps produced by different researchers based on expert evaluation can be very different (Carrara et al., 1992). However, unique advantage of expert evaluation techniques is that they are more based on the actual field data and the

experience of an evaluator on the understanding of various governing parameters and their relative influence in inducing instability to the slopes (Raghuvanshi et al., 2014).

### **3.5.2 Quantitative method**

Quantitative method includes statistical and deterministic modeling of landslide susceptibility combining landslide inventory and landslide controlling factors (Leulalem Shano et al., 2020; Van Westen et al., 1997). Physically based models are based on the sound knowledge of the physical models and are capable of predictive landslide analysis. They render information on landslide hazards. However, these methods need high accuracy of input parameters. These predictive models are difficult to evaluate. It comprises complex modeling and is hard to do at smaller scales (Soeters and Van Westen, 1996).

#### **3.5.2.1 Statistical Approaches**

Statistical methods are based on the statistical determination of the combinations of different variables that were responsible for instability of slopes in given area (Dai and Lee, 2001). In last few years the approach towards landslide hazard zonation has been changed from knowledge-based approach to statistical to minimize subjectivity in weightage assignment procedure and produce more objective and reproductive results (Leulalem Shano et al., 2020). Methods based on statistical analysis of geo-environmental factors related to landslide occurrence are preferred (Kanungo et al., 2009). The limitation of statistical methods is gathering of large data on landslide distributions and various factors which require considerable time, resource and manpower (Leulalem Shano et al., 2020; Van Westen et al., 1997). Another constraint is quality and quantity of data on landslide frequency and various factors on which statistical correlations are established. Thus, the findings are highly influenced with the volume of the data gathered and its quality (Fall et al., 2006). The statistical methods for landslide hazard zonation can be grouped into two: bi-variate statistical analysis and multi-variate statistical analysis (Leulalem Shano et al., 2020).

### **3.5.2.1.1 Multi-variate statistical approach or techniques**

Multi-variate statistical models for LHZ were developed in Italy (Carrara, et al., 1990; 1991; 1992; 1995). Multivariate statistical analyses of important causal factors controlling landslide occurrence may indicate the relative contribution of each of these factors to the degree of hazard within a defined land unit (Gorsevski, et al., 2006). When using these methods all parameters at sites of instability can be analyzed by multiple regression techniques or parameter maps are crossed with landslide distribution maps and the correlation is established for stable and unstable areas using discriminant analysis (Lulalem Shano et al., 2020; Yin and Yan, 1988; Carrara et al., 1991; Dai et al., 2002; Van western, 2000).

Although multivariate techniques can be applied to different scales of landslide zonation, their use become quite bounded at the regional scale, where exact input map of landslide occurrences may not be available and most of the causative factors cannot be collected with satisfactory accuracy. At macro scales, several factors will have to be used. Therefore, the medium scale is supposed most appropriate for multivariate analysis. In recent years, the multivariate techniques have been elaborated with various approach of sampling. Basically, logistic regression and Artificial Neural Network methods are two commonly practiced multivariate modelling methods (Lulalem Shano et al., 2020).

### **3.5.2.1.2 Bi-variate statistical approach**

This method for landslide hazard zonation compares each data layer of causative factor to the existing landslide distribution (Kanungo et al, 2009). In bivariate statistical method, each factor influential in landslide is overlaid with the landslide inventory map, and in view of landslide densities weighting values are calculated for each class. In order to compute the weighting values, there are many significant methods of bi-variate statistical methods such as; information value method, frequency ratio method, weights of evidence model, weighted overlay model etc. (Lulalem Shano et al., 2020; Kanungo, 2006). The main disadvantage of bivariate statistical method is, independency between different parameter maps with respect to possibility to landslide occurrence, due to the assumption of conditional independence (Van Westen et al., 1997).

Some of bivariate analysis methods are discussed in the following paragraphs;

**Frequency ratio analysis:** This method is based on the concept of the favorability function (Chung and Fabbri, 1993; Fabbri et al., 2003). It adopts that the probability of landslide occurrence can be measured by statistical relationship between past landslides and specified spatial data sets. The relationship between the landslide occurrence area and the landslide related factors could be deduced from the relationship between areas where landslide had not occurred and the landslide related factors. The probability likelihood (frequency ratio) is the ratio of the probability of an occurrence to the probability of non-occurrence for given features (Leulalem Shano et al., 2020; Bonham-Carter, 1994). Frequency ratio for each subclass of individual causative factor is calculated based on their relationship with landslide occurrence. Finally, landslide susceptibility index is calculated by summing of frequency ratio values of each factor (Lee, 2005).

**Weights of Evidence (WofE) Method:** Among the bivariate statistical analysis, the weights of evidence modeling method is broadly used as it offers a flexible way of testing the importance of input factors for landslide susceptibility and can be used as a supporting tool in expert-based mapping (Lee, et al., 2002; Suzen and Doyuran, 2004b; van Westen et al., 2003). This method was developed at the Canadian Geological Survey (Atterberg et al., 1990; Bonham-Carter et al., 1989) and was applied to the mapping of mineral potential. Sabto, (1991) applied the method for landslide hazard analysis. The method consists of reducing each set of landslides correlated factors on a map to a pattern of a few distinct states. In its simplest form, the pattern for a feature is binary, representing its presence or absence within a pixel. It calculates both unconditional and conditional probability of landslide hazards. This method is based on calculation of positive and negative weights to define degree of spatial association between landslide occurrence and each explanatory variable class (Leulalem Shano et al., 2020). This method has been used for landslide susceptibility since 1990's (Blahut et al., 2010). Different combinations of landslide causative factors are used in order to describe their interrelation with landslide distribution.

**Weighted overlay method:** This method is a simple bivariate statistical method wherein weights are assigned based on the relationship of landslide causative factors with on the relationship frequency. Numerical weights are assigned to causative factors on the basis of their relationships

to the landslide distribution. Finally, the data layers are overlaid to produce the landslide hazard zonation map (Sarkar et al., 1995).

**Information value model** is a bivariate statistical analysis method which was developed from information theory. In this model, information values of predisposing factors are used for characterizing the possibility of landslide occurrence. The information values are determined for each subclass of landslide related parameter on the basis of presence of landslide in the given mapping unit. The triggering factor maps are combined with landslide map to get weight of each class. These models have the advantage of assessing landslide susceptibility in an objective way. The model allows the quantified prediction of susceptibility by means of a score, even on terrain units not yet affected by landslide occurrence. Each instability factor is combined with the landslide distribution, and weighting values based on the landslide densities are calculated for each parameter class, as it happens with all bivariate statistical methods. Negative value of information value shows that the presence of the variable is not relevant in landslide development whereas the positive value indicates a relevant relationship between the presence of the variable and landslide distribution (Yin and Yan, 1988).

### **3.6 Previous studies about landslide in Ethiopia**

Ethiopia is a country with great geographic diversity with mountains, high plateaus, deep gorges, river valleys, and lowland plains (Aregay Waktola, 1999). Landslide is very common in the mountainous areas of the country and along the rift margin. These landslides are caused by many influencing factors such as geology, human activities, topography, heavy rain fall, land use conditions and also seismicity (Raghuvanshi et al., 2014; Birhanu Ermias et al., 2017; Kifle Woldearegay., 2013; Dai and Lee., 2000). Landslides have become a common problem which can even cause life loss. Due to this problem, landslide hazard studies become mandatory. Many researchers have been conducted in different parts of the country using various approaches or techniques to evaluate the causes and factors that can cause landslide.

A brief summary of some studies carried out in past in different parts of Ethiopia is presented in the following paragraphs;

Filagot Mengistu et al. (2019) conducted landslide hazard zonation and slope instability assessment by using Optical and InSAR remote sensing: the case of Arbaminch- Gidole road, southern Ethiopia. In this study to carry out landslide hazard zonation information value Bi-variate statistical method was followed. The results of this study showed that 36.3% area fall within very low hazard zone, 34.2% of the area fall with low hazard zone, 6.6%, 15.4% and 7.5% of the area falls into very high hazard, high hazard and moderate hazard zones, respectively.

Tilahun Hamza and Raghuvanshi (2017) conducted a research with the title of landslide hazard zonation around Jeldu district, central Ethiopia using GIS based statistical and probability approach. Aspect, slope, elevation, litho-logy, soil and land use were used as conditioning factors. In this study to carry out landslide hazard zonation frequency ratio Bi-variate statistical method was followed. The result showed that 8% of the study area falls under very high hazard zone, 21% fall under high hazard, 32% falls in moderate hazard, 27% as low hazard and 12% falls under no hazard zone.

Gemechis Chimidi et al. (2017) conducted a study to carry out landslide evaluation and zonation in and around Gimbi town in western Ethiopia. GIS-based statistical method was followed to conduct this study. The result indicated that 12.2% of the area falls in very high hazard, 30.7% in high hazard, 24.3% in the moderate hazard, 23.3% in low hazard, and the rest 9.5% in no hazard zones.

Birhanu Ermias et al. (2017) conducted about landslide hazard zonation around the route from Alemketema Town to Ambat Village, North Shewa, Ethiopia. Slope stability susceptibility evaluation (SSEP) rating scheme was applied in this study. The prepared LHZ map was has identified two zones, namely high hazard (66.6) and Moderate hazard (33.1%). When LHZ map was overlaid by Past landslide events data out of 80.3 have fallen in High Hazard zone.

Tilahum Hamza and Raghuvanshi (2017) delineated Jeldu district area in to the degree of slope susceptibility and evaluate all the causative parameters which are responsible for failure using GIS based statistical approach for Landslide hazard zonation map. The result showed that 12%

fall in no hazard, 27% fall in low hazard, 32% in moderate hazard, 21% in high hazard, and 8% in very high hazard zone.

[Tsion Aragaw \(2017\)](#) carried out the research by using an integrated expert evaluation and statistical approach for landslide hazard zonation mapping in Alemketema-Fetera route corridor, in central Ethiopia. The result shows that, in terms of area coverage 85% area is covered by high hazard in original SSEP landslide hazard zonation map where as in landslide hazard zonation may by integrated approach high hazard covers 72% of the area. in terms of total high hazard both methods provided almost similar results; original SSEP landslide hazard zonation map 85% and intergrated approach 82%.

[Fikire Girma et al. \(2015\)](#) carried out a study on landslide hazard zonation in Ada Berga district, central Ethiopia using GIS based statistical approach. In this study to carry out landslide hazard zonation frequency ratio Bi-variate statistical method was followed. Elevation, aspect, slope, curvature, and soil and litho-logy, land use and land cover and hydrogeology were considered as causative factors of the study area. the result of this study showed 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.

[Zerihum Dawit \(2016\)](#) conducted a study on landslide hazard evaluation and zonation in the area Kindo Didaye Woreda, south west Ethiopia. The approaches that was followed to conducted this study were integrated SSEP and a raster based information value model approach. The result showed that the cultivation, deformation and modifying the slopes by manmade activities in addition with the high rainfall and groundwater are the most influential parameter for the occurrence of landslide in the area.

[Raghuvanshi et al. \(2015\)](#) conducted a study in Meta Robi district, Oromiya Ethiopia by using grid overlaid and GIS modeling approaches to prepare LHZ map. The result showed grid overlay method is more tedious and time consuming approach and GIS modeling produced better landslide hazard zonation map.

[Raghuvanshi et al. \(2014\)](#) performed their study on landslide hazard zonation by developing slope stability susceptibility evaluation parameter (SSEP) expert approach in Wurgessa Kebelle

of north Wollo Zonal Administration, Amara Regional State in Northern Ethiopia. The result indicates that 8.33% of the study area shows moderate hazard, 83.33% fall in high hazard and 8.34% fall under very high hazard areas

[Shiferaw Ayele et al. \(2014\)](#) have delineated landslide hazard zones in the Gohatsion- Degen section by using remote sensing and GIS approach. In this study to carry out landslide hazard zonation Analytical hierarchy process method was followed. Slope, structures, aspect, geology, Groundwater, land use and land cover, and drainage were used as causative factors. The landslide hazard zone map shows that 67% of the past landslide locations lie within the maximum hazard zone.

[Engdawork Mulatu et al., \(2009\)](#) carried out landslide hazard zonation mapping around Gilgel-Gibe II, southwestern Ethiopia. In this study to carry out landslide hazard zonation Landslide hazard evaluation factor rating scheme (LHEF) - expert evaluation technique proposed by [Anbalagan \(1992\)](#) was followed. They have classified the landslide hazard areas into high hazard zone, moderate hazard zone, and low hazard zone.

[Jemal Saed \(2005\)](#) presented an inventory of landslide mainly along the road alignment between Gohatsion and Dejen towns. This inventory on landslides indicated 17 critical slope sections. Further, he used limit equilibrium method to assess the stability condition of critical slope sections. The result showed that 4 sections were having planar mode of failure, 2 wedge mode of failure and 3 were soil sections having a circular mode of failures.

[Samuel Molla \(2011\)](#) has studies slope stability analysis on a selected slope section along the road Gohatsion to Degen. The deterministic slope stability analysis approach was followed. The results of the slope stability analysis clearly show that the slope section stable only for the dry condition under static state with a FOS of 1.28. For the other conditions under static and dynamic state, the slope section will be unstable with a FOS less than 1.0. The factor safety for the dynamic state for the worst condition is even less than 0.5. Thus, the finally based on the slope stability analysis findings for existing and anticipated worst conditions suitable remedial measures were worked out

### **3.7 Genesis of methodology for the present study**

The methodology followed for the present study is based on the principle of the past is the key for future. This method is statistical approach which is most commonly used technique for landslide susceptibility and hazard zonation, because of having minimum degree of subjectivity (Filagot Mengistu., 2019; Tilahum Hamza and Raghuvanshi., 2017; Fikre Girma et al., 2015; Kanungo et al., 2006; Raghuvansh et al., 2014; Leulalem Shano et al., 2020). The statistical analysis approaches are based on statistical determination of combination of contributing factors in a given area. Based on the analysis for the interrelationship of the governing factors and the invented landslide activities quantitative estimations are made. For the present study bivariate statistical techniques, especially, information value model was followed. Information values (IV) of different factors can be used to find out the possible areas of landslide occurrence which may make possible in the landslide hazard zonation (Yin and Yan., 1988: Leulalem Shano et al., 2020). The advantages of information value method (IVM) are involvement of less time and cost against the accurate result, easy and free from complex mathematical analysis (Sarkar et al., 2013).

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## **Chapter - 4**

## **METHODOLOGY**

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### **4.1 Introduction**

Over the last three decades landslide hazard zonation mapping has been carried out in different parts of the world (Pardeshi et al., 2013; Kanungo et al., 2006; Raghuvanshi et al., 2015; Birhanu Ermias et al., 2017). For landslide hazard zonation mapping, several approaches have been developed such as; heuristic approach, inventory-based mapping, probabilistic assessment, statistical analysis, deterministic approach, and multi criteria decision making approach (Leulalem Shano et al., 2020; Pathak, 2016; Acharya and Pathack, 2017; Dahal et al., 2008; Lee, 2007; Guzzetti et al., 1999). In the present study, statistical method is used for landslide hazard zonation mapping. It is based on determination of combination of causative variables in a given area. Based on the analysis for the interrelationship of the invented landslide activities and the governing factors, quantitative estimations are made. Such evaluation techniques make easy to allocate weights to the governing factors and it uses to rate the governing parameters which are used for the preparation of landslide hazard zonation map (Fall et al., 2006). This method is based on principles that “past is the key for the future” (Carrara et al., 1991).

### **4.2 Methodology adopted in the present study**

In this study, bivariate statistical method especially information value method was used. In the bivariate analysis, for the determination of weighted value of the classes that are used to classify each parameter, the landslide density is used in each individual class. Therefore, in this method, the individual factors are compared to the landslide inventory map (Aleotti and Chowdhury, 1999). This method needs the selection and mapping of significant parameters and their categorization into a number of applicable classes, landslide inventory mapping, overlay mapping of the landslide inventory map with each parameter map, determination of the density of landslide in each parameter class and definition of weighted values, and assignment of weighting values to the various parameter maps (Suzen and Doyuran, 2004). Finally, the degree of vulnerability of each land unit is determined and calculated after overlay mapping and calculation of the final hazard value of each identified land unit as operations (Yalcin, 2008).

According to Yin and Yan (1988), Jade and Sarkar (1993), Van Westen (19997), Lin and Tung (2003) Information value model 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 this method, a pixel was selected as a land unit and the relationship between effective factors in landslide occurrence and landslide dispersion was considered and the landslide hazard is evaluated. Based on this evaluation, the weight and the role of these classes and parameters were calculated with the following relationship.

The method was originally proposed by Yin and Yan (1988) and slightly modified by Van Westen (1993). Equations for the Information value calculation are as follows:

$$\text{Conditional probability (CP)} = \frac{N_{\text{Pix}}\{\text{SBi}\}}{N_{\text{Pix}}\{\text{Bi}\}} \quad \dots\dots\dots\text{eq.4.1}$$

$$\text{Prior probability (PP)} = \frac{N_{\text{Pix}}\{\text{TS}\}}{N_{\text{Pix}}\{\text{A}\}} \quad \dots\dots\dots\text{eq.4.2}$$

$$\text{Weight of factor class (WBi)} = \frac{CP}{PP} \quad \dots\dots\dots\text{eq.4.3}$$

$$\text{Information value (IV)} = \log(\text{WBi}) \quad \dots\dots\dots\text{eq.4.4}$$

Where; ‘ $N_{\text{Pix}}\{\text{SBi}\}$ ’ is the number of landslide pixels within the factor class,  $N_{\text{Pix}}\{\text{Bi}\}$  is the number of pixels of a factor class, ‘ $N_{\text{Pix}}\{\text{TS}\}$ ’ is the total sum of pixels of landslide of the whole study area and  $N_{\text{Pix}}\{\text{A}\}$  is the total pixels of the whole study area.

The higher the weight value, the higher the possibility that a landslide occurs within a given area. The natural logarithm is used to give negative weights when the landslide density is lower than normal and positive weights when higher than normal. Positive  $W_i$  indicates direct correlation between predictor factor and landslide occurrence and it also represent the presence of predictor in landslide areas. Negative  $W_i$  indicates inverse correlation and absence of predictor in landslide areas (Yin and Yan, 1988). The weight value for each class of the causative factors was calculated by using the above equation (Shraban K et al., 2013). Therefore, the acquired

information values were assigned for each of the factors to prepare the weight causative factor maps. Later, the causative factor maps were computed by using the raster calculator to determine landslide susceptibility value for each pixel;

$$LSI = IV_{SLOPE\ MATERIAL} + IV_{LULC} + IV_{SLOPE} + IV_{ELEVATION} + IV_{ASPECT} + IV_{GROUNWATER} \dots\dots eq.4.2$$

Where; ‘LSI’ is the landslide susceptibility index, LULC is land use and land cover and ‘IV’ is the information value.

Lastly, LHZ maps was prepared and classified into five classes such as very high hazard (VHH), high hazard (HH), moderate hazard (MH), low hazard (LH) and very low hazard (VLH) zones

In order to perform the present study, three stages were followed.

#### **4.2.1 Desk study**

During the desk study many researches about landslide hazard zonation was red as a literature review. Under this stage, secondary data such as topographic map, geological map, and rain fall data were collected. Topographic map (1:50,000) was used in GIS environment to delineate facet map. Slope map, aspect map and curvature map were also prepared from DEM of 30x30. Besides, thematic layers on slope material and land use land cover were also prepared from secondary data and satellite images.

#### **4.2.2 Field investigation and Data collection**

Field work activities are the most important activity for any landslide hazard study. After collection of secondary data and preparation of pre field work maps, the study area is directly visited to collect primary data. Data collection was mainly carried out to have all pertinent information about past landslide distribution and to verify various parameter maps prepared during pre-field work activities. To collect past landslide activities of the study area GPS reading of each past landslide was recorded. Type of landslide, type of slope material involved, presence of water springs, possible triggering factors and land use activities were also collected. The data and information of all these aspects were carried out through visual observation, Hand GPS and through local community interviews. Land use and land cover units were also observed and

verified. Manmade activities like cultivation practices, excavations, construction of roads or building were recorded and identified during the field visit.

#### **4.2.3 Data preparation and analysis**

When the secondary and primary data or information was collected, the data has been systematically grouped and analyzed using available software and techniques. Past landslide polygons were created by overlying field GPS failure point data on Google earth image and the thematic map layers of causative factors were prepared using secondary and primary data in ArcGIS. Then the thematic maps of the causative factors and landslide inventory map were altered to raster to find pixel values in Arc-GIS software. In order to get the relationship between the factor classes and landslides in the study area analysis of the causative factors map and landslide inventory maps was carried out using information value model. The information value maps of the causative factors were prepared and added to prepare Landslide hazard zonation map of the study area. Finally, landslide hazard zonation map was validated using the landslide inventory data

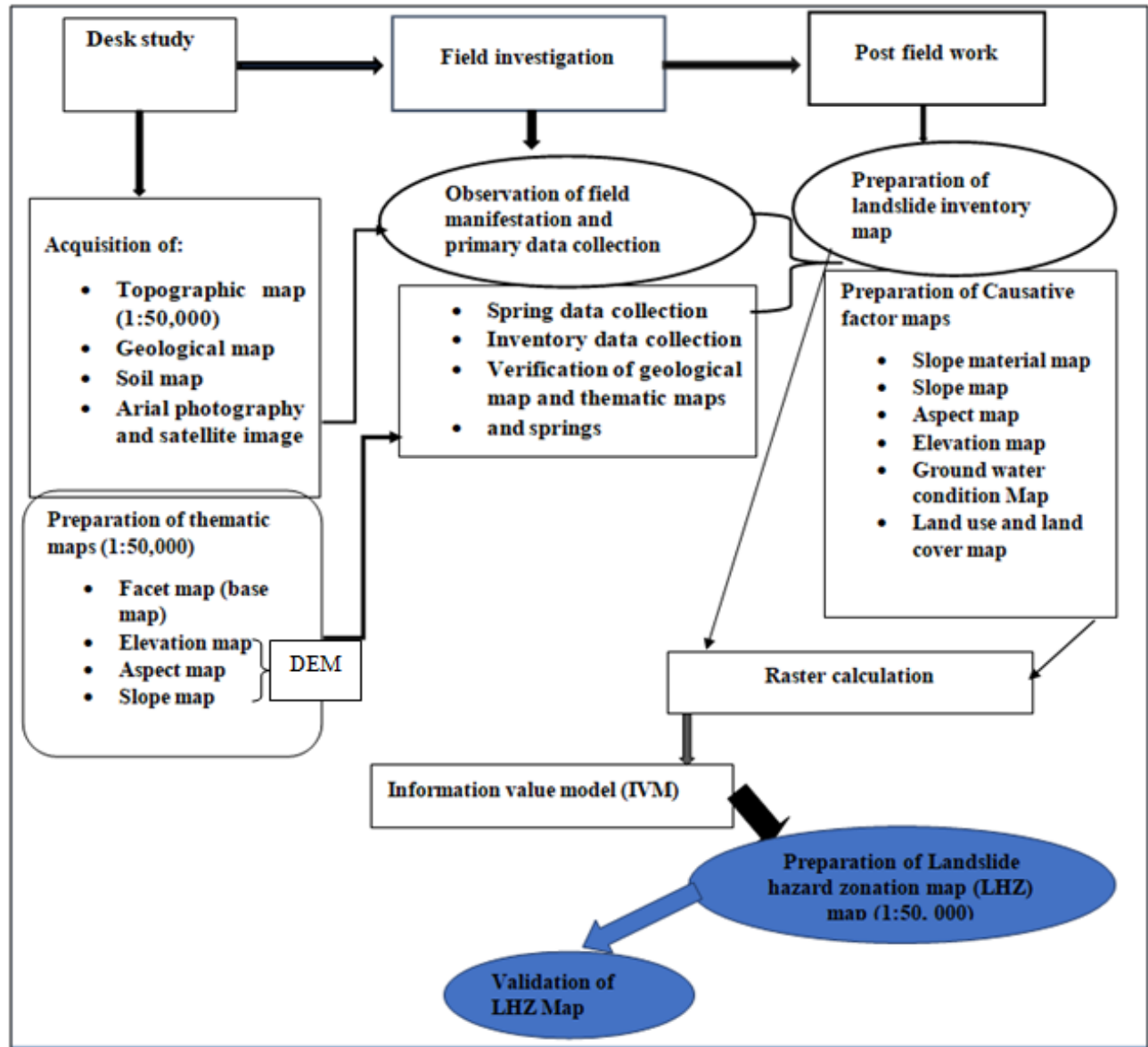


Fig.4.1 Methodology followed in the present study

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## **Chapter - 5** **ANALYSIS**

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## **DATA COLLECTION, PROCESSING AND**

### **5.1 Governing factors and distribution**

Landslides have caused multiple human and economic losses due to natural conditions or manmade activities (Fleming and Taylor, 1980; Guzzetti et al., 1999; Bekele Abebe et al., 2010; Tilahum Hamza and Raghuvanshi, 2017). The factors that influence landslide include slope angle, weathering, climate, vegetation cover, curvature, water content, slope materials and overloading (Subramani and Krishnan, 2015). The intrinsic causative factors which affect the stability conditions of a slope are slope materials, slope aspect, curvature, land use/land cover, and ground water conditions (Raghuvanshi et al., 2014a; Anbalagan, 1992). In the present study the causative factors considered for the evaluation of landslide hazard zonation are; slope material, slope, elevation, aspect, land use and land cover, and groundwater condition. These causative factors were considered based on their relative influence on slope instability in the area. The factors were extracted from the prepared spatial data base. Slope, aspect, elevation were extracted from DEM (30mx30m). The groundwater condition map was prepared from spring location and elevation of the study area. The land use and land cover were prepared from satellite image in ERDAS and ArcGIS software. The lithological map of the study area was digitized from geological map of Harar compiled by Geological Survey of Ethiopia at the scale of 1:250,000 appropriate modifications to this map were made through a field survey and suitable digitization was done with the help of satellite image. This map was prepared at the scale of 1:50,000. Therefore, evaluation of these causative factors with respect to past landslide distribution was made by conducting density analysis through raster maps overlay analysis and later information values were computed.

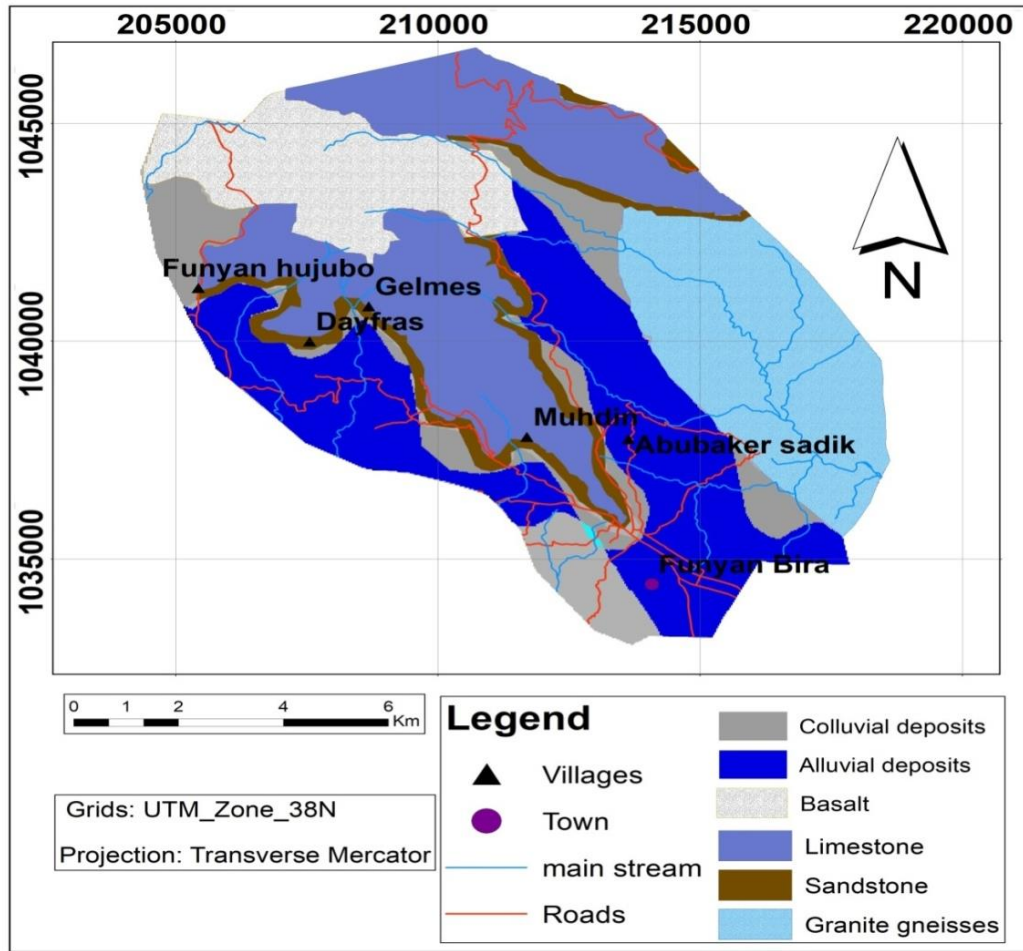
**Table 5.1** Thematic layers and their data source

Causative factors	Source
Slope Aspect Elevation	DEM data with 30x30m resolution ASTER elevation data set
Slope material	Soil map of Ethiopia from <a href="#">FAO (1986)</a> and geological map of Harar area with a scale of 1:250,000
Land use and land cover	Landsat image- 2018 and visual observation
Ground water surface trace (springs)	GPS data collected from the field

### 5.1.1 Slope materials

The slope materials are regarded as the one of the most important factors in landslide hazard assessment, because strength of the rocks, weathering and soil permeability are influenced by lithological characteristics ([Kavzoglu et al., 2014](#); [Henrique et al., 2015](#); [Anbalagan, 1992](#); [Raghuvanshi et al., 2014](#)). The permeability, porosity, strength and weathering conditions of lithology play a vital role in the stability of the slope and mostly it differs for different lithological units. However, this factor largely influences the probability of landslide occurrences ([Restrepo et al., 2003](#); [Anbalagan, 1992](#); [Raghuvanshi et al., 2014](#)). In case of soil, it is the most effective factors for landslide assessment. The tendency of soil to absorb moisture and increase of soil depth reduces the surface run off rate. On the other hand, shallow soil depth is considered to be more unstable and leading to landslide. Soil moisture also directly affects the slope material by which pore water pressure diminishes soil stability ([Sharma et al., 2012](#)).

The main slope materials present in the study area are; limestone, basalt, sandstone, Granite-gneisses, alluvial and colluvial deposits ([Fig 5.1](#)). The alluvial deposits constitute 25% of the study area and it covers mostly in western, southern and central parts of the study area. Limestone is mostly found in central and northern parts of the study area and it contributes 23% of the study area. 20%, 15%, 12%, 5% of the total study area is covered by granite-gneisses, basalt, colluvial deposits and sandstone, respectively ([Table 5.2](#)).



**Fig 5. 1** Slope material map of the study area

**Table 5. 2** Distribution on various Slope materials in the study area

Slope material	Area km <sup>2</sup>	Area (%)
Limestone	28	23
Alluvial deposits	30	25
Granite-gneisses	24	20
Basalt	18	15
Colluvial deposits	14	12
Sandstone	6	5
	120	100

### 5.1.2 Land use and land cover

Land use and land cover play a significant role in the stability of slope materials. The land covered by forest regulates continuous water flow and water infiltrates regularly whereas the cultivated land affects the soil slope stability due to saturation of covered soil (Matrika and Prakash, 2007; Anbalagan, 1992; Kifle Woldearegay, 2013; Vannnes, 1987; Raghuvanshi et al., 2014). A thick vegetation cover over a slope is an indication of stable condition as the vegetation cover prevents excess seepages of water into the slope (Arora, 1997). Roots of the plants bind the soil mass thus contributing to increase the shear strength of the soil mass (Turrini and Visintainer, 1998). Cultivation over slopes increases instability of slope by increasing in moisture of the slope material due to irrigation practice. Hill slopes are made flat and cut into terraced land for cultivation purpose (Raghuvanshi et al., 2014).

The land use and land cover of the present study area was prepared from LANDSAT-8 data through supervised classification using ERDAS imagine. It was classified into five classes namely; forest land, cultivated land, grass land, bare land and built-up area. In terms of percent area coverage, 13.3%, 29.6%, 30.1%, 20%, and 7% of the study area are covered by forest land, cultivated land (Plate 5.1), grassland, bare land and build-up area (Table 5.3; Fig. 5.2), respectively.

**Table 5.3 Land use and land cover classes and their area coverage**

Number	LULC	Area coverage km <sup>2</sup>	Percentage%
1	Forest land	16	13.3
2	Cultivated land	35	29.6
3	Grass land	37	30.1
4	Bare land	24	20
5	Build-up area	8	7
<b>Total</b>		<b>120</b>	<b>100</b>

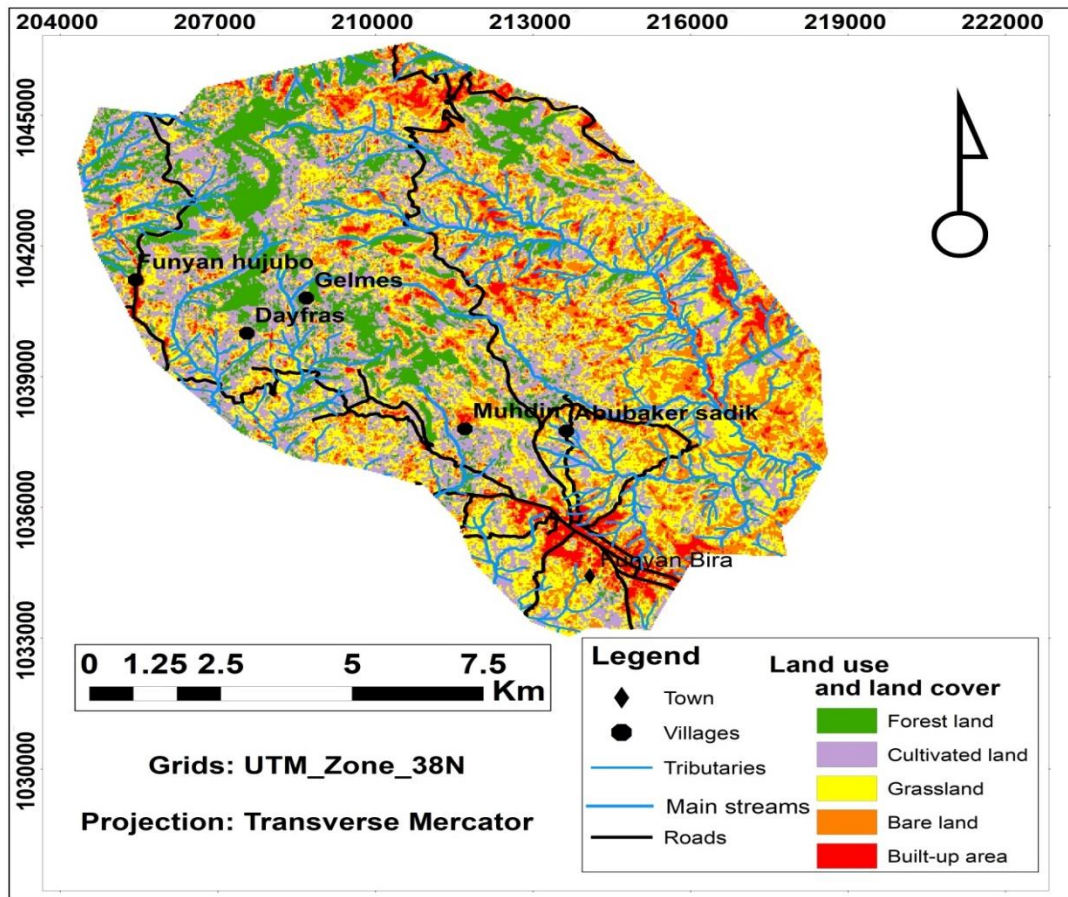


Fig 5. 2 Distribution of Land use and Land cover in the study area



Plate5. 1 (a) Cultivated area in the study area and (b) Cultivated gentle slope using gabion stabilized - affected by landslide

### **5.1.3 Groundwater homogeneous zones**

One of the primary causes of landslides is a slope saturated by water. It can occur in the form of intensive rainfalls, changes in groundwater levels, and water level changes along earth dams, and banks of lakes, reservoirs, canals and rivers. However, hydrogeology plays very important role in controlling the occurrence of landslide (Bekele Abebe et al., 2009; Tenalem Ayelew and Barbieri, 2004).

The present study area is located in Shabelle basin. It is characterized with many intermittent springs, perennial rivers and the upper part of this basin with high precipitation during rainy season. In the study area, there are many springs with high potential discharge and a number of low yielding springs common at the base of the slopes throughout the year. In order to incorporate the groundwater effect in landslide hazard evaluation, indirect surface manifestations of groundwater such as; springs were considered (Anbalagan, 1992). Springs over a slope may indicate groundwater proximity and relative saturation of the slope mass. It has also been observed that spring locations and landslides have direct correlation (Fikre Girma et al., 2005; Raguvanshi et al., 2015).

In order to delineate the groundwater homogenous zone spring (groundwater surface traces) and the elevation of the study area were considered for the present study. The total springs that have been observed and mapped with the help of GPS device were 20, as indicated through Table 5.5. In the present study area, the surface traces of groundwater were characterized as flowing, dripping, wet and dry areas. Flowing areas showed presence of spring on slope faces. Dripping zone indicated dripping of water through structural discontinuities. Wet areas indicated water marks on rock surface, some droplets along structural discontinuities, algal growth in shadow areas. Dry areas characterized as no water traces along structural discontinuities, dry rock face surfaces. Therefore, very high elevation areas were considered as dripping zone because water are dripping through structural discontinuities whereas high elevation areas were considered as flow zones due to presence of springs on slope faces. Moderate elevation areas were considered as wet zone due to water marks on rock surfaces, algal growth in shadow areas. Lastly, low elevation areas of the study area were considered as dry zone because of dry rock face surfaces, lack of water traces along structural discontinuity surfaces. The groundwater homogenous zones

map prepared for the present study area shows that 21.7%, 42.5%, 22.5% and 13.3% of the area is covered by Flow zone, Dripping zone, Wet zone and Dry zone, respectively (Table 5.5; Fig. 5.3).

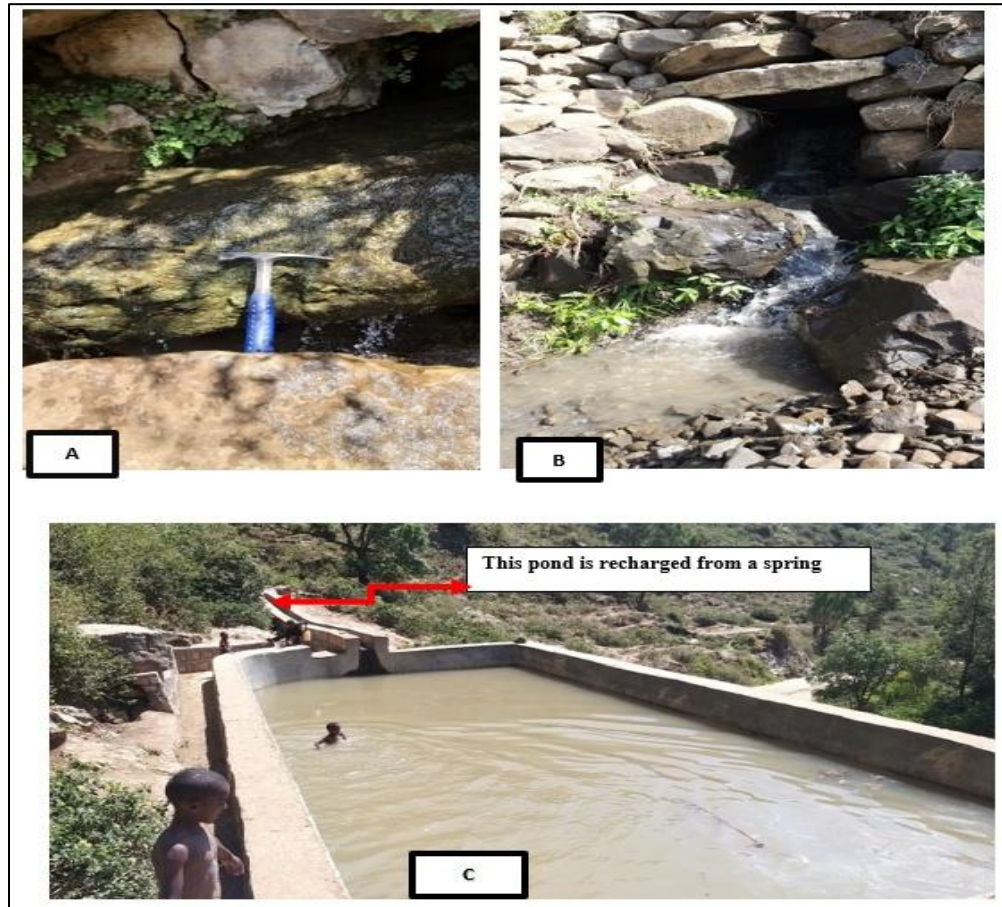


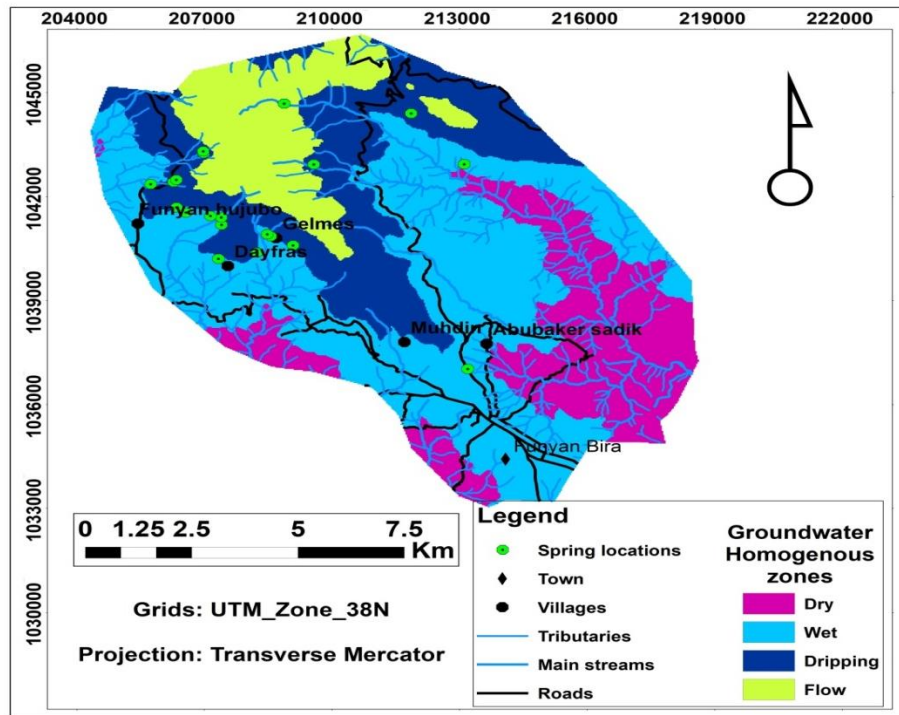
Plate5. 2 (A) North Funyan-hujubo spring, (B) Kundodo spring from basalt rock and (C) A pond captured from a spring at fractured limestone

Table 5. 4 Groundwater homogenous zone classes and their area coverage

Number	Groundwater homogeneous zones	Area coverage (km <sup>2</sup> )	Percentage (%)
1	Flow	26	21.7
2	Dripping	51	42.5
3	Wet	27	22.5
4	Dry	16	13.3
<b>Total</b>		<b>120</b>	<b>100</b>

**Table 5.5 Springs location in the study area**

<b>Numbers</b>	<b>Spring name</b>	<b>Easting</b>	<b>Northing</b>	<b>Elevation (m)</b>
1	Funyanhujubo	205734	1042359	2030
2	Harashi1	206275	1042423	2129
3	Harashi2	206334	1042483	2142
4	Kundodo1	206982	1043257	2297
5	Kundodo2	206970	1043307	2310
6	Onaya	209080	1040593	2134
7	Gelmes1	208556	1040854	2072
8	Gelmes2	208472	1040914	2084
9	Gelmes3	208222	1040386	2130
10	Defrays	207329	1040207	2077
11	Gollohumo	207402	1041184	2090
12	Maddagolla	207395	1041399	2068
13	Warosayu	207139	1041441	2075
14	Salto	206564	1041540	2042
15	Dinike1	206342	1041688	2095
16	Dinike2	213190	1037025	1971
17	Dinike3	208874	1044685	2090
18	Dinike4	213107	1042936	1990
19	Dinike5	211859	1044400	2009
20	Dinike6	209567	1042931	2199



**Fig 5. 3** Groundwater homogenous zones map of the study area

#### 5.1.4 Slope

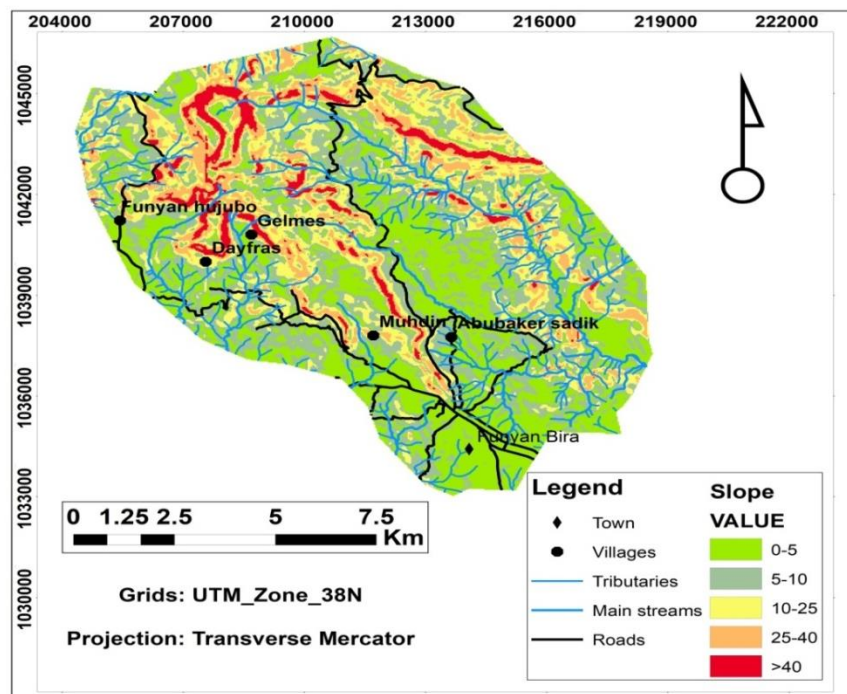
Slope is one of the main parameters in the slope stability analysis. Slope inclination has direct effect on landslide occurrences because the driving force of mass movement increases with increasing slope. However, variations in the soil thickness and strength are two factors which vary over a wide range of failure and non-failure sites (Borga et al., 2002).

The shape of a slope influences the direction and amount of surface runoff or subsurface drainage reaching an area (Dai et al., 2002). Morphology of slope can also have great effect on the susceptibility of a slope to landslide. If the slope is steep, there will be an increment in shear stress and the tangential component of the weight of the mass will increase while the perpendicular component of the weight will decrease. Thus, the slope mass will get tendency to slide down the slope, when the shear stress increases more than the resisting forces (Shimelis Ahmed, 2009; Raghuvanshi et al., 2014). Steeper the slope, tendency for failure will be more provided other instability contributing factors also favor sliding (Raghuvanshi et al., 2014).

The slope factor for the study area was extracted from the DEM using ArcMap-GIS tool. The slope angle in the study area generally varies from 0 to 70°. Further, the slope angle was classified into five classes. These classes are; 0-5°, 5-10°, 10-25°, 25, 40°, >40° (Fig 5.4). The slope classification map (Table 5.6) shows that 33.8%, 29.33%, 20.41%, 12.33% and 4.13% of area is covered by 0-5°, 5-10°, 10-25°, 25, 40°, >40° slope classes, respectively.

**Table 5.6** Slope classes and their area coverage

Number	Slope	Area coverage (km <sup>2</sup> )	Percentage (%)
1	0-5 <sup>0</sup>	40.5	33.8
2	5-10 <sup>0</sup>	35.2	29.33
3	10-25 <sup>0</sup>	24.5	20.41
4	25-40 <sup>0</sup>	14.8	12.33
5	>40 <sup>0</sup>	5	4.13
<b>Total</b>		<b>120</b>	<b>100</b>



**Fig 5.4** Slope map of the study area

### 5.1.5 Elevation

The influence of elevation may be attributed in terms of variation in humidity, rate of hydrate reaction, degree of weathering, erosion process and depth of weathering. Higher the elevation higher will be the intensity of erosion and weathering. Therefore, it is reasonable to consider elevation as one of the causative factors for controlling landslide process (Shimelis Ahmed, 2009). For the present study Digital elevation model (DEM) of the study area at a resolution of 30m was obtained from the ASTER data set.

Later, elevation map of the study area was prepared using ArcGIS software. For the present study the elevation was classified into 5 classes based on the topography of the study area namely; 1579-1873m, 1873-2074m, 2074-2299m, 2299-2572m, and 2572-2950m which show area coverage of 17.5%, 42.5%, 20%, 16.7% and 3.3% of the study area, respectively (Table 5.7).

**Table 5.7** Elevation sub-classes with area coverage in the study area

Number	Elevation (m)	Area coverage (km <sup>2</sup> )	Percentage (%)
1	1579-1873	21	17.5
2	1873-2074	51	42.5
3	2074-2299	24	20
4	2299-2572	20	16.7
5	2572-2950	4	3.3
<b>Total</b>		<b>120</b>	<b>100</b>

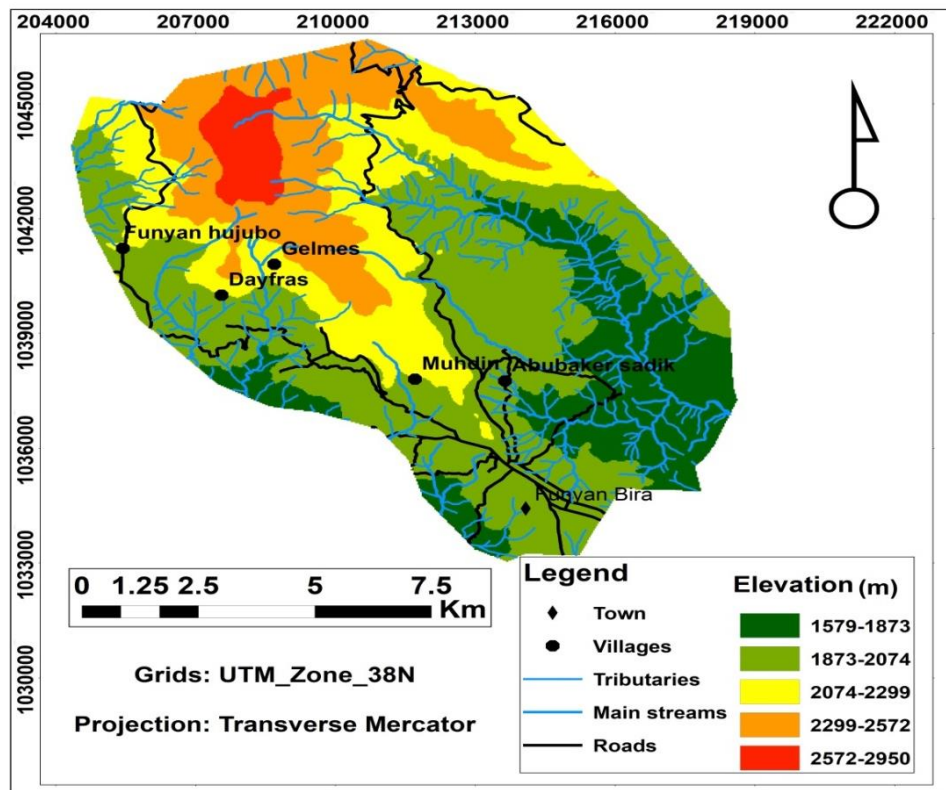


Fig 5.5 Elevation map of the study area

### 5.1.6 Aspect

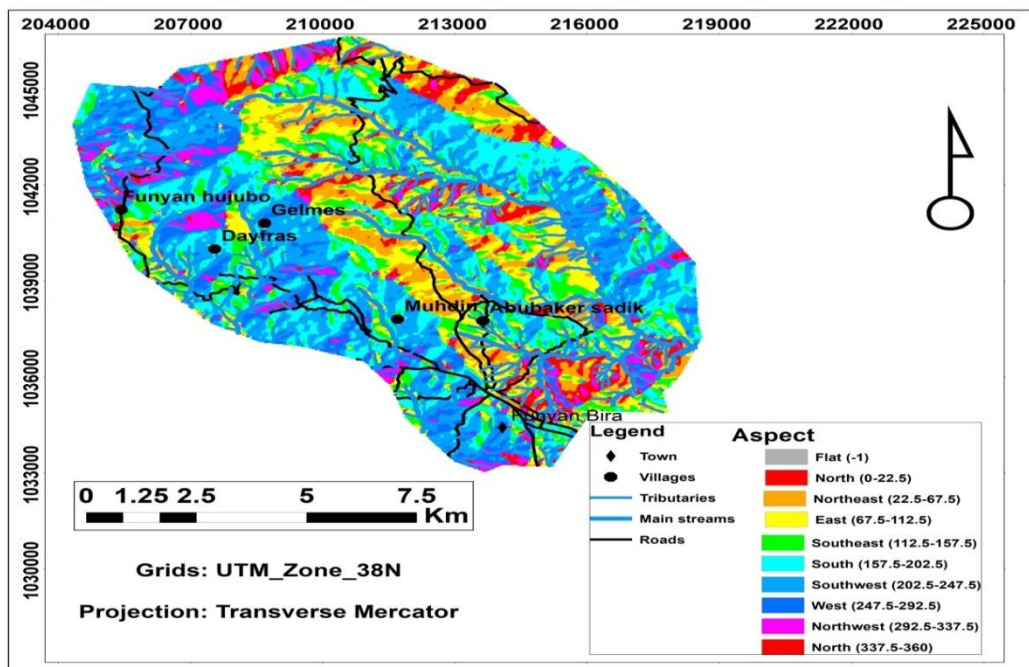
Aspect generally refers to the orientation to which a mountain slope faces. The aspect of a slope can make very significant influences on its local climate factors such as; amount of rainfall which in turn influences the occurrences of landslides. Further, its related parameters such as; exposure to sunlight, drying winds, rainfall or degree of saturation, and discontinuities may control the occurrences of landslides (Dai and Lee, 2002). Aspect has been considered as a landslide governing factor in several other studies (Saha et al., 2005; Yalcin, 2011; Anbalagan, 1992; Raghuvanshi et al, 2014).

The aspect map of the study area was derived from the DEM of the study area. For the present study the aspect was sub-divided in to all possible geographical directions namely; Flat ( $-1^{\circ}$ ), North ( $0-22.5^{\circ}$ ), North-east ( $22.5-67.5^{\circ}$ ), East ( $67.5-112.5^{\circ}$ ), South-east ( $112.5-157.5^{\circ}$ ), South ( $157.5-202.5^{\circ}$ ), South west ( $202.5-247.5^{\circ}$ ), West ( $247.5-292.5^{\circ}$ ), North-west ( $292.5-337.5^{\circ}$ ) and

North (337.5-360°). The distribution of various aspect classes in the present study area is presented in Table 5.8 and Fig. 5.6.

**Table 5.8** Aspect sub-classes and their coverage area

Number	Aspect Class	Area coverage (km <sup>2</sup> )	Percentage (%)
1	Flat (-1°),	0.07	0.05
2	North (0-22.5°),	5.6	4.66
3	North-east (22.5-67.5°)	17.2	14.33
4	East (67.5-112.5°),	17.7	14.75
5	South-east (112.5-157.5°),	14.8	12.33
6	South (157.5-202.5°),	21.4	17.83
7	South west (202.5-247.5°)	20.9	17.4
8	West (247.5-292.5°),	12	10
9	North-west (292.5-337.5°)	7.33	6.15
10	North (337.5-360°)	3	2.5



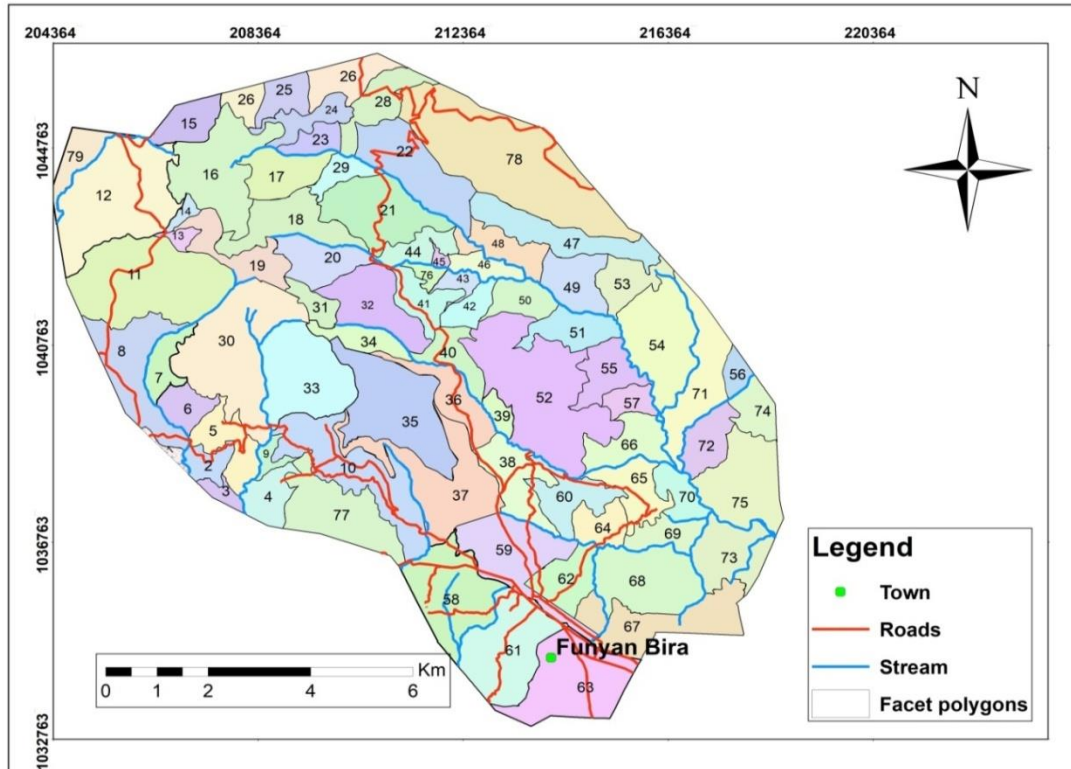
**Fig 5.6** Aspect map of the study area

## **5.2 Landslide inventory of the study area**

### **5.2.1 Introduction**

According to [Guzzetti et al. \(2012\)](#) landslide inventory maps describe the location, i.e. landslides are more likely to be triggered under the same conditions that had been found on earlier landslides, numbers and the other data of occurrence and the types of mass movements that have left discernable traces in an area. Preparation of inventory maps is an important part of landslide hazard zonation analysis for example the spatial distribution of landslide susceptibility. According to the interpretation of different data such as; field investigations, landslide events, and interaction with the local people about the landslide events and satellite images analysis, a landslide inventory map was prepared for the present study area ([Van Westen et al., 2006](#)).

Past landslides have some significant geomorphologic features which are easily identifiable with high resolution, especially in the 3D models, including decreases in the densely vegetated area and bare soil. The presence of flow materials along gullies, rims, and drainage networks with different erosion features and sedimentations are also other identifiable features of historical landslides ([Mallick et al., 2014](#)). In the initial stage, during the present study the study area was classified into facets. The facet map of the area was prepared by delineating major and minor hill ridges, streams and other topographic features on the basis of visual interpretation of topographic map and Arc-GIS software ([Anbalagan, 1992](#); [Raghuvanshi et al., 2014](#)). Thus, a total 79 slope facets were delineated as shown in ([Fig.5.7](#)).



**Fig 5. 7** Slope Facet map of the study area

There are several methods to identify landslides such as; through aerial photos, satellite images, and literature survey for the historical landslide records, Google Earth image interpretation, and from field observations (Raghuvanshi et al., 2014; Tlahum Hamza and Raghuvanshi, 2017; Anbalagan, 1992; Van Westen et al, 2006). In the present study the landslide inventory was carried out through Google earth image interpretation and from field observations or records using GPS point data along the past landslide boundaries. In the present study, 35 past landslides have been identified in the study area (Fig. 5.8). The majority of the landslides observed in the study area have occurred along cliff banks, roads, river banks and agricultural lands. The landslides in cliffs are often due to loss of land cover, steep slope topographic, and erosions. Road construction activity has caused many landslides in the study area.

### **5.2.1** Landslide distribution in the study area

The landslide hazard evaluation must start with a clear understanding on what has occurred in the past in the study area. Past landslide in the area gives useful information for possible

locations for future landslides. Therefore, the delineation of past landslide occurrences is significant for the prediction of future patterns of instability, directly from the past distribution of landslide occurrence (Raghuvanshi et al., 2015; Filagot Mengistu et al., 2019). All past landslides in the study area were identified through traverse mapping and important field observation during field investigations. The landslide distribution of the study area was also identified through image interpretation such as; Google earth and Land sat image. Inventory data of the study area was identified and verified during field investigation using GPS instrument. Location of landslide, type of failure, materials involved in the landslide was also recorded (Plate 5.3). After that, using Arc-GIS the recorded data locations were changed as a layer for analysis. Later, with the help of Google earth image polygon data was created to show the boundaries of past landslide in the study area (Fig.5.8).

### **5.2.2 Landslide manifestation in the study area**

According to USGS (2004, as cited in Birhanu Ermias, 2014) manifestation of landslides refer a change in morphology on the area and on any structures, which are found on the slopes. During field investigations for landslide hazard zoning major considerations are given to the evidence of past or recent landslide features such as; fresh rock falls, lithology and structures, engineering structures, cracks in the soils, geomorphology and slope setting, groundwater level, water flux during rainy season, land use, and also other anthropogenic factors such as manmade activities (Tenalem Ayenew and Barbery, 2005; Raghuvanshi et al., 2014).



(A) Landslide along road cut near Funyan-Hujubo, (B) Soil cracks ready to slide at the side of road around Muhyadin Kabele, (C) Mixture of soil and rock slides near kundodo, (D) Mass of earth flow slide along river, (E) Rotational soil slides along a road and (F) Rock falls in around Funyan-hujubo

**Plate 5.3** Landslide manifestations in the present study area

**Table 5. 9** Landslide inventory data of the study area

No	Location (UTM)		Elevation(ft)	Nearby place Name	Type of landslide	Dimension of slide	
	Easting	Northing				Length (m)	Width (m)
1	205514	1041421	6901	Funyan Hujubo	Rotational slide	60m	20m
2	205449	1041962	6807	Funyan Hujubo	Earthflow	85.1m	40m
3	206351	1042471	7196	Biyu-Negeya	Rockfall	93	56m
4	210732	1040588	7554	Sukaye	Rotational slide	30m	20m
5	210480	1042219	7297	Dinike	Translational slide	105m	78m
6	209333	1042240	7381	Dinike 2	Rock fall	25m	34m
7	208914	1042967	8501	Belensa	Earth flow	108m	90m
8	208660	1044182	9229	Kundodo East	Translational slide	29m	15m
9	208359	1044729	9256	North Kundodo	Rotational slide	89m	34m
10	208050	1045053	8918	North Kundodo	Rotational slide	50m	30m
11	207624	1043450	8570	South Kundodo	Translational slide	75m	56m
12	207616	1043799	7244	Top of Kundodo mountain	Earth flow	200m	150m
13	207822	1044688	9649	West Kundodo	Earth flow	240m	123m
14	207346	1044929	8305	Southwest Kundodo	Rotational slide	90m	35m
15	207409	1042693	6848	Harashi	Rock fall	25m	19m
16	206657	1042852	7230	Harshi	Rock fall	42m	23m
17	207072	1042468	8230	Hareshi	Earth flow	134m	68m
18	207834	1040092	6873	Dayfras	Translational slide	21m	20m
19	208242	1042134	8225	Dayfras	Rock slide	31m	20m
20	209500	1040318	7225	West Sukaye	Rotational	57m	34m

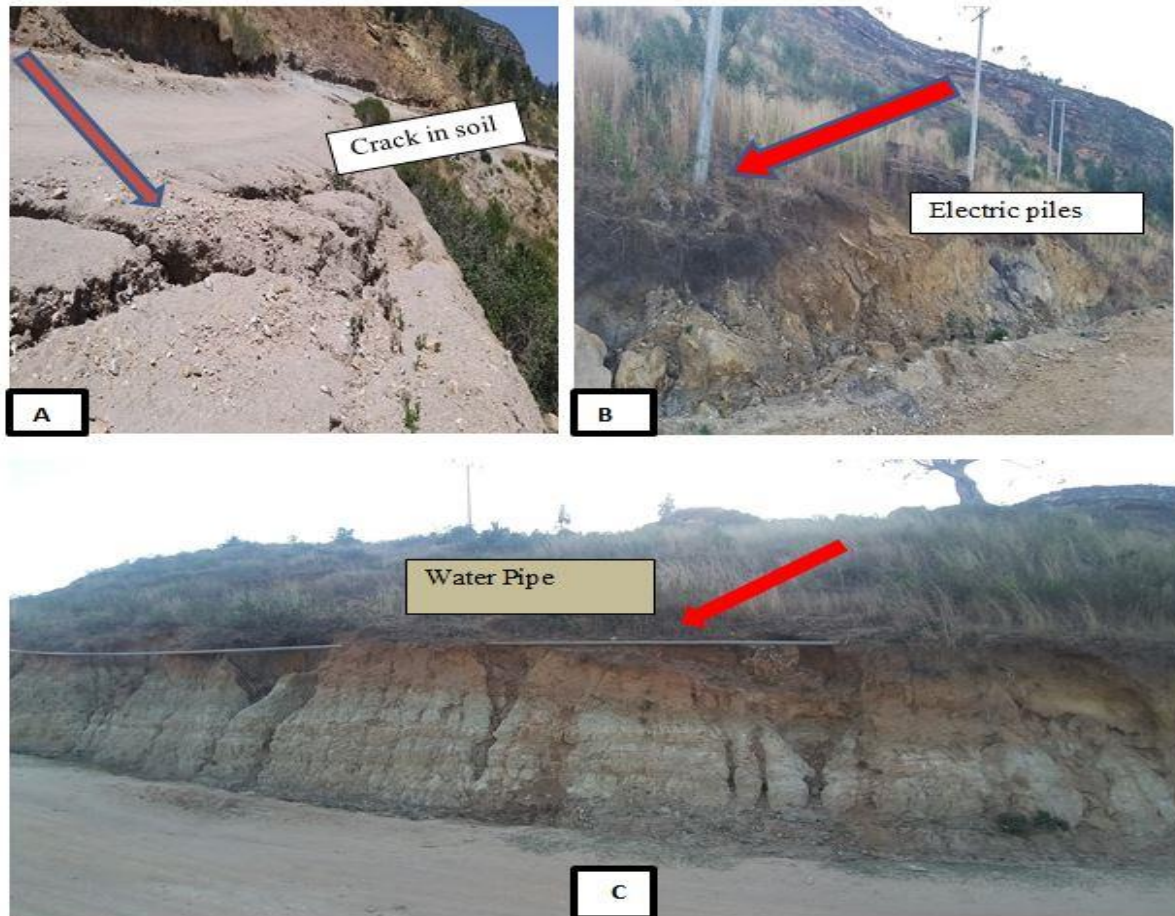
					slide		
21	209683	1040613	7723	Humo1	Earth flow	68m	23m
22	209721	1039783	7192	Humo2	Rotational slide	92m	53m
23	209839	1039268	6933	Humo3	Rotational slide	53m	23m
24	209898	1038683	6892	Gelmis1	Rock fall	32m	14m
25	210549	1038542	6723	Gelmis2	Rock fall	37m	23m
26	210819	1038389	7005	Gelmis3	Rock fall	23m	19m
27	211154	1037535	6824	Muhyadin	Earth flow	87m	43m
28	211272	1037992	6955	Muhyadin	Translational slide	45m	32m
29	211915	1037748	6741	Dinike	Earthflow	56m	23m
30	212015	1037641	6729	Goba	Rotational slide	211m	45m
31	212503	1037200	6766	Goba	Rotational slide	123m	50m
32	216505	1039612	5639	Goba River	Earth flow	175m	90m
33	216267	1041334	5732	Kebso	Rock fall	33m	12m
34	208910	1039280	6397	Day-Feres	Translational slide	190m	49m
35	209086	1038860	6538	Day-Feres	Rock fall	79m	35m

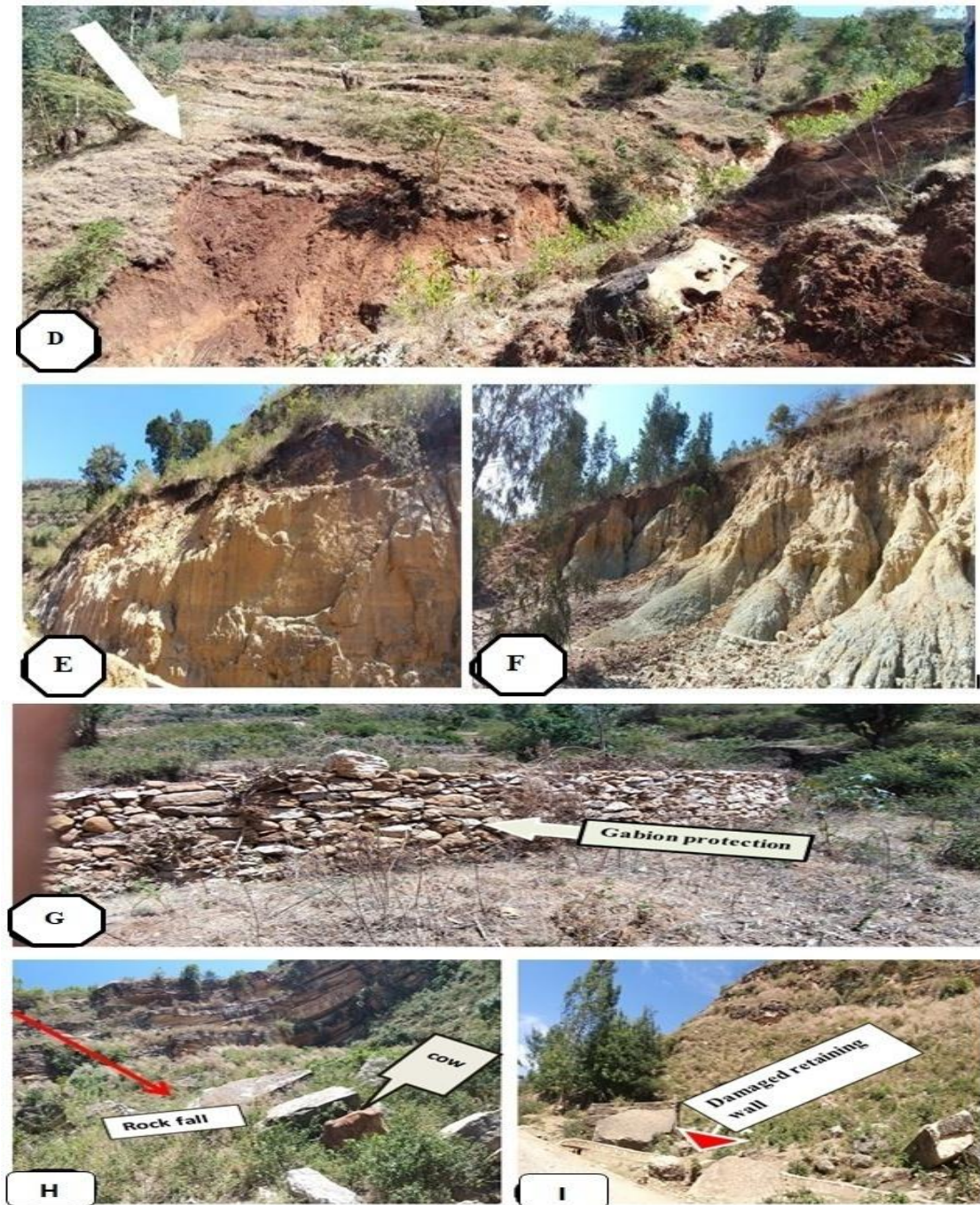
In the present study, different types of landslide manifestation were observed during field investigations. The observed manifestation of landslides are fallen rock blocks on gentle slopes, stream bank erosions, scarps of rock slides, bent trees, Cracks in soils, road side erosion and damages to man-made structures (Plate 5.3, 5.4 and 5.5).

### 5.2.3 Failure mechanisms in the study area

According to Fuchu et al. (1999) the failure mechanisms of landslides are controlled by number of factors. The type of slope materials dominantly observed on the slopes, slope geometry and causative factors and triggering factors dominantly involved in causing slope instability will determine the types of landslide's failure mechanisms. The occurrences of slide-debris flows have a close relationship with bedrock geology, slope gradient, vegetation cover, and micro land

forms. The sliding failure mechanisms which are observed in the study area indicate rotational and translational movement. However, the types of landslides triggered in the study area are translational slide, rotational, earth or debris flow and rock fall.





(A) Soil cracks near Abubaker Sadik village, (B) Electric pile damaged by landslide in Funyan Biro town and (C) Water pipe damaged by Erosion In north of Funyan Biro town (D) Rotational soil slide affected Agricultural land, (E) Disturbed slope due to road construction, (F) Gully erosion in Dinike area, (G) Limestone rocks used as gabion projections in agricultural land, (H) Showing large blocks of rocks fallen from the cliff and (I) showing retaining wall damaged by landslide

Plate 5. 4 Landslide manifestations in the study area

### 5.2.3.1 Transitional slide

This type of slide may progress over considerable distances if the surface of rupture is significantly inclined, in contrast to rotational slides, which tends to restore the slide equilibrium. The mass in a translational landslide moves out or down, outwards along a relatively planar surface with little rotational movement or backward tilting. It mostly fails along geological structures like joints, bedding surfaces, faults, and contacts between bedrocks and soil materials (Raghuvanshi et al., 2015).

Transitional type of slide is common in the study area where moderate gentle slope and gentle slopes are present. The materials in the slide in the study area are unconsolidated soils to extensive slabs of rocks or both. During field investigation, six (6) translational slides were encountered and most of them have occurred in colluvial deposits and sandstone units overlaid by limestone rock units. Along some slope sections reddish to yellowish horizontally bedded sandstone is exposed. Most of these landslides have affected in agricultural land and along road cuts.



a) Translational slides showing the surface of rupture at the debris-bedrock Boundary  
b) Translational slide along reddish to yellowish horizontally bedded sandstone

**Plate 5. 5 Translational slides**

### 5.2.3.2 Rotational slide

This type of slide occurs in the upper portion of the slope. Its surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to

the ground surface (Varnes, 1978). The movement is frequently, structurally controlled by discontinuities and variations in shear strength between layers of bedded deposits, or by the contact between firm bedrock and overlying detritus. These slides tend to be more superficial than compound (Bell, 1999; Varnes., 1978). Rotational slides were recorded in many parts of the study area. These types of landslide were found mostly in steep and gentle slopes of the study area. In this present study, ten rotational slides were recorded which were mainly found in north of Funyan Hujubo, Gelmeis, Dinike, Goba, north of Kundodo mountain, east and west of Kundodo areas and Muhyadin kebele. Cultivated areas of the study area are mostly damaged by rotational types of landslides. Soil slides were mostly present in the study area (Plate 5.6).



**Plate 5. 6 Rotational soil slide of the study area**

### **5.2.3.3 Rock fall**

In this failure rocks fall freely along a vertical or sub-vertical cliff, proceeds down slope through falling and rolling after they are firstly separated from the slope (Varnes., 1978).

In the present study area rock fall were observed, many roads are affected by rock fall. These rock falls were observed in road cut and Upper River cut exposures. Rock fall has also damaged many houses which were located in the gentler slopes of the study area. Moreover, during field visit rock fall activities were seen occurring suddenly. So, this shows that rock fall activities are

daily hazard activity in the study area. Large blocks of limestone, Basalts, and granite and also colluvial deposits are the fallen materials observed in the study area. Most of rock fall landslides have originated from the cliffs or ridges and they can be seen in the gentle and low slope areas in such as; Muhyadin, Dayfas, Hareshi, Funyan Hujubo, Dinike and Abubeker kebeles of the study area. In the study area, ten areas were recorded to be as rock fall affected areas. Illustrations for the observed rock fall are presented as Plate 5.7.



(A) Large block of rock damaged house around kundodo and  
(B) Rock fall damaged a gravel road from Funyan biro to Funyan-hujubo town

**Plate 5. 7 Rock falls in the study area**

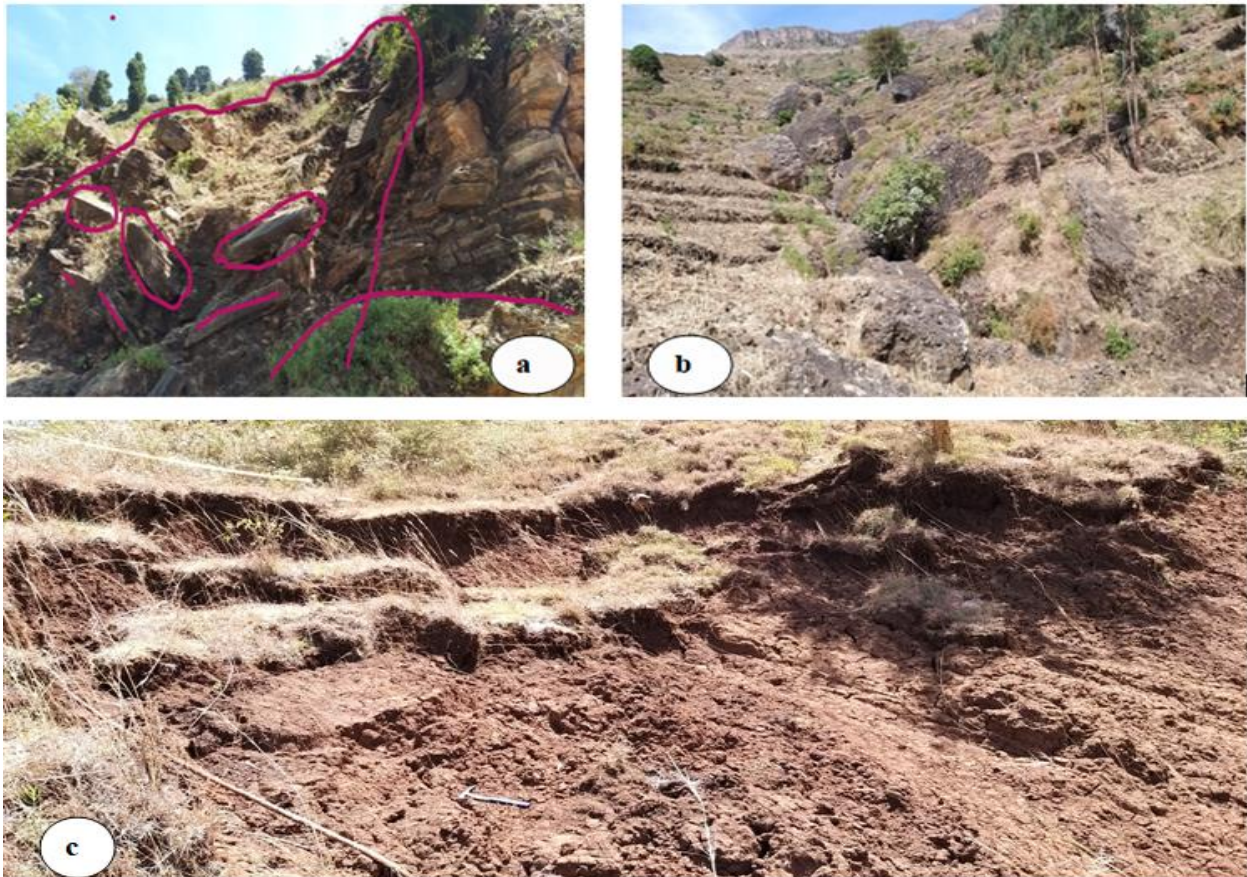
#### **5.2.3.4 Flow**

A debris flow is rapid movement in which a combination of rocks, loose soil, organic matter and water mobilizes as slurry that flows down the slope (Varnes., 1978). It is caused by intensive surface water flow, due to heavy rainfall (Lizunela, 2006; Hungr, et al, 2001).

In the present study area debris flows are amongst the various landslide activities which were observed in many parts of the study area. The major types of flow observed during the present field investigation in the study area were debris or earth flow type of movements. The debris flow which is observed in the study area is composed of sands, gravels, clays, and boulders with

plant roots. This type of landslides has caused much agricultural damages in the study area. At some places, debris flow is characterized large boulders of basalt, limestone with other unconsolidated materials such as soils with disintegrated rocks. They are mostly found in gentle or moderate slopes of the Kundudo Mountains and its surrounding woredas. This slope is main comprises of colluvial materials containing gravel to very big size basaltic rock fragments in clayey fine matrix overlying highly weathered limestone.

Earth flow is also common landslides that are observed in the study area. It is mainly concentrated on around Kundodo areas. Moderate, gentle and some low slope areas of the study area are occupied by earth flow especially slopes covered by soil materials. This type of landslide has damaged most in agricultural lands.



- a) Debris flow type of landslides; blocks of limestone with soil and plant roots north Funyan Hujubo
- b) Debris flow: Large blocks of basalt with alluvial deposits at Kundudo mountains
- c) Earth flow at low areas of Kundodo mountain-(Rotational slide-earth flow complex)

**Plate 5. 8 Debris flows in the study area**

#### **5.2.4 Landslide hazard zonation**

According to [Varnes \(1984\)](#) the term landslide hazard zonation applies, in a general sense, to divide the land surface into separate zones and ranking them according to the degree of actual or potential hazard from a landslide or slope stability based on an assessed significance of causative factors in including that instability. All landslide hazard studies carried out relies on following three fundamental assumptions;

- (i) The slope failures in future will most likely be similar to the terrain conditions that led to past and present failures
- (ii) The main conditions that cause landslide activity should be evaluated and identified.
- (iii) A summary of the degree of potential hazard in area can be built up depending on the factors present including the landslides, their severity and interaction.

Evaluating landslide hazard is the main objective of the method to produce a relative landslide hazard map that is used to provide one with a practical and cost-effective way to make further studies and various engineering constructions for the mitigation of the landslide occurrence in the future for the present study. These maps are very useful for identification of unstable zones.

For the present study past landslides were recorded. In order to prepare landslide hazard zonation map, statistical approach was followed. The main objective of this approach is to figure out the quantitative relationship between past landslides and factor classes in the study area. Six causative factors were used namely; slope, elevation, aspect, slope materials, land use and land cover, and groundwater condition were considered for landslide hazard zonation and evaluation. The maps of all these six causative factor classes and landslide inventory map of the study area were prepared in GIS environment in order to understand the quantitative relationship ([Guzzetti et al., 1999](#); [Dai and Lee, 2001](#); [Su'zen and Doyuran, 2004](#); [Gemechis Chimidi et al., 2017](#)). For the preparation of LHZ map the information value model was used. Finally, based on the information values for various causative factors landslide hazard index (LSI) was determined.

For the present study information value were assigned to each causative factor class to obtain weighted factor maps. These causative factors were summed up using raster calculator in Arc

Tool box to acquire landslide susceptibility index value for each pixel. The required LSI was calculated by using expression presented as equation 5.1;

$$LSI = IV_{SLOPE\ MATERIAL} + IV_{LULC} + IV_{SLOPE} + IV_{ELEVATION} + IV_{ASPECT} + IV_{GROUNWATER} \dots\dots eq.5.1$$

Where; ‘LSI’ is the landslide susceptibility index, LULC is land use and land cover and ‘IV’ is the information value.

Lastly, based on LSI values the LHZ maps was prepared and classified into five classes such as very high hazard (VHH), high hazard (HH), moderate hazard (MH), low hazard (LH) and very low hazard (VLH) zones.

## **Chapter - 6**

## **RESULTS AND DISCUSSIONS**

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### **6.1 Landslide inventory**

For landslide hazard assessment it is presumed that the conditions that has led to the historic landslides in the area if reoccur elsewhere in the given area, again landslides may occur (Dai et al., 2002; Raghuvanshi et al., 2015; Tilahum Hamza and Raghuvanshi, 2017). For the present study area, a detailed landslide inventory was undertaken based on field investigation, information gained from satellite image interpretation and from the secondary data. During field visit, 35 past landslides (Fig. 6.1) were recorded with the help of handheld GPS. Later, with this inventory information landslide polygons were created with the help of Google earth image. Moreover, unreachable areas of the study area such as; high cliffs, densely vegetated area, river gorges were identified on Google earth image only (Tilahum Hamza and Raghuvanshi., 2016).

Most of the past landslides in the study area have occurred in western, central and northwest parts of the area. In the present study, translational, rotational, rock falls and debris flow types of landslide were recorded. For the present study six causative factors namely; slope materials, slope, elevation, aspect, land uses and land cover, groundwater surface manifestations were considered. Later, information value was calculated based on relative influences of causative factors on past landslides of the study area. The distribution of landslide over each of the factor maps have been obtained and discussed. Weights for each of the classes within these factor maps have been obtained using the information value method.

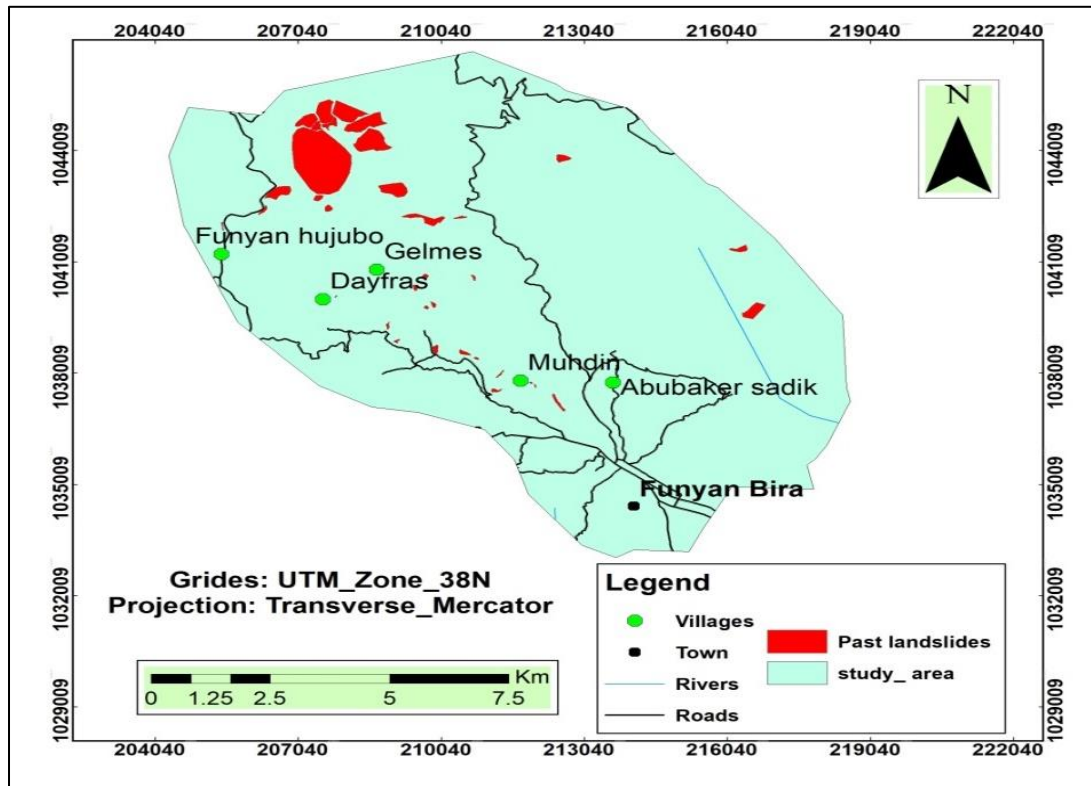


Fig 6. 1 Landslide inventory map of the study area

## 6.2 Governing factors influence and Hazard potential

### 6.2.1 Slope material

The lithological map of the study area was modified from Geological map of Harar sheet compiled by Geological Survey of Ethiopia (GSE, 2010) and through the present filed work activity (Fig.5.1, Chapter 5) (Tilahun Hamza and Raghuvanshi, 2017). The results indicates that (Table 6.7) 26%, 26%, 23%, 21%, 3% and 1% of the past landslide occurred in basalt, limestone, sandstone, colluvial soil alluvial deposits, and granite-gneisses in the study area. Further, the computed information values for basalt, limestone, sandstone and colluvial deposits are 0.209, 0.064, 0.258 and 0.393, respectively. This shows that these slope materials have high probability of landslide occurrences in the study area whereas Granite-gneisses and alluvial deposits have low probability of landslide occurrence with information value of -1.276 and -0.972, respectively. In the present study alluvial deposits show less percent coverage (3%) of past

landslide occurrence, as it is deposited in low lying areas of the study area. Furthermore, erosion is more in low lying areas of the study area including alluvial soil deposited areas.

**Table 6.1** Computed Information values (IV) for slope materials in the study area

Slope material	Npix{Bi}	Npix{SBi}	CP	Npix{A}	Npix{TS}	PP	WBi	IV
Limestone	28816	902	0.031	127503	3433	0.027	1.059	0.064
Alluvial deposits	30211	87	0.003	127503	3433	0.027	0.107	-0.972
Granite gneisses	21000	30	0.001	127503	3433	0.027	0.053	-1.276
Basalt	20127	880	0.044	127503	3433	0.027	1.619	0.209
Colluvial deposits	10987	733	0.067	127503	3433	0.027	1.471	0.393
Sandstone	16362	801	0.049	127503	3433	0.027	1.813	0.258
Total	127503	3433						

‘CP’ – Conditional probability; PP – Prior probability, WBi – Weight of Factor class; IV – Information value; ‘Npix{SBi}’ is the number of landslide pixels within the factor class, Npix{Bi} is the number of pixels of a factor class, ‘Npix{TS}’ is the total sum of pixels of landslide of the whole study area and Npix{A} is the total pixels of the whole study area.

## 6.2.2 Land use and land cover

Land use and land cover of the present study area was classified into five classes; forest land, cultivated land, grass land, bare land and built-up area. According to the results (Table 6.7), 57% of the landslides occurred in cultivated land. The information value (IV) of cultivated land as computed (Table 6.2) is 0.274 which indicates the highest probability of landslide occurrences. The rest of land use and land cover classes; forest land, grassland, bare land and built-up area shows 11%, 28%, 3% and 1% of past landslide. They indicate least probability of landslide occurrences and their information values are -0.095, -0.072, -0.816, and -1.128, respectively (Table 6.2).

**Table 6.2** Computed Information value (IV) for land use and Land cover

Landuse/ landcover classes	Npix{Bi}	Npix{SBi}	CP	Npix{A}	Npix{TS}	PP	WBi	IV
Forest land	18124	393	0.022	127503	3433	0.027	0.803	-0.095
Cultivated land	38674	1964	0.051	127503	3433	0.027	1.881	0.274
Grass land	42223	966	0.023	127503	3433	0.027	0.847	-0.072
Bare land	25000	103	0.004	127503	3433	0.027	0.153	-0.816
Build-up area	3482	7	0.002	127503	3433	0.027	0.074	-1.128
Total	127503	3433						

‘CP’ – Conditional probability; PP – Prior probability, WBi – Weight of Factor class; IV – Information value; ‘Npix{SBi}’ is the number of landslide pixels within the factor class, Npix{Bi} is the number of pixels of a factor class, ‘Npix{TS}’ is the total sum of pixels of landslide of the whole study area and Npix{A} is the total pixels of the whole study area.

### 6.2.3 Ground water condition

The groundwater condition of the study area was classified into four zones namely; Dry, wet, Dripping and flow. Based on the overlay analysis of past landslides over ground water surface traces, 53%, 38%, 6% and 2% of landslide occurred in dripping zone, flow zone, wet zone and dry zone, respectively. Most of the landslide occurred in dripping zone (53%) and flow zone (38%). These two zones (flow and Dripping zones) have the highest probability of landslide occurrences with information values of 0.391 and 0.463, respectively. Dripping zone is more susceptible to landslide or slope instability because most of the springs in the study area fall within this zone. The other two zones (wet and dry) show less probability of landslide occurrences with least information values (Table 6.3).

**Table 6.3** Computed information value (IV) for Groundwater surface traces

Slope material	Npix{Bi}	Npix{SBi}	CP	Npix{A}	Npix{TS}	PP	WBi	IV
Dry	27140	55	0.002	127503	3433	0.027	0.075	-1.125
Wet	55704	212	0.004	127503	3433	0.027	0.141	-0.851
Dripping	28095	1866	0.066	127503	3433	0.027	2.460	0.391
Flow	16564	1300	0.078	127503	3433	0.027	2.907	0.463
Total	<b>127503</b>	<b>3433</b>						

‘CP’ – Conditional probability; PP – Prior probability, WBi – Weight of Factor class; IV – Information value; ‘N<sub>pix</sub>{SBi}’ is the number of landslide pixels within the factor class, N<sub>pix</sub>{Bi} is the number of pixels of a factor class, ‘N<sub>pix</sub>{TS}’ is the total sum of pixels of landslide of the whole study area and N<sub>pix</sub>{A} is the total pixels of the whole study area.

### 6.2.4 Elevation

The overlay analysis of past landslides over elevation map of the present study area indicated that 34%, 29%, 30% 4% and 3% of past landslides occurred in 2074m- 2299m, 2299m-2950m, 1873m-2074m, 1579m-1873m elevation classes, respectively. As shown in (Table 6.4), the elevation classes 2572m-2950m, 2299m-2572m, and 2974m-2299m indicated the highest information values of 0.945, 0.249, and 0.234, respectively. These three elevation classes show the highest probability of landslide occurrences, as indicated by the information values. The rest two elevation classes (1873m-2072m and 1579m-1873m) show the least probability of landslide occurrences, as indicated by the information values.

**Table 6.4** Computed information value (IV) for elevation classes

Elevation classes	Npix{Bi}	Npix{SBi}	CP	Npix{A}	Npix{TS}	PP	WBi	IV
1579-1873	24275	91	0.004	127503	3433	0.027	0.139	-0.857
1873-2074	52714	131	0.002	127503	3433	0.027	0.092	-1.036
2074-2299	25372	1173	0.046	127503	3433	0.027	1.712	0.234
2299-2572	20759	995	0.048	127503	3433	0.027	1.775	0.249
2572-2950	4383	1043	0.238	127503	3433	0.027	8.814	0.945
Total	<b>127503</b>	<b>3433</b>						

'CP' – Conditional probability; PP – Prior probability, WBi – Weight of Factor class; IV – Information value; 'N<sub>pix</sub>{SBi}' is the number of landslide pixels within the factor class, N<sub>pix</sub>{Bi} is the number of pixels of a factor class, 'N<sub>pix</sub>{TS}' is the total sum of pixels of landslide of the whole study area and N<sub>pix</sub>{A} is the total pixels of the whole study area.

### 6.2.5 Slope

The result obtained (Table 6.7) indicates that the highest percentage of landslides (34%) occurred in slope class (25-40°) whereas 32% of the landslides have occurred in slope class (10-25°). Only 7% of landslides have occurred in slopes class (>40°). Slope classes (0-5°) and (5-10°) show less probability of landslide occurrences. The conditional probability of landslide occurrence in slope classes 0-5°, 5°-10°, 10°-25°, 25°-40°, Cliff (>40°) is -0.259, -0.524, 0.212, 0.459, and 0.102, respectively (Table 6.5).

**Table 6.5** Computed information value (IV) for slope classes

Slope classes	Npix{Bi}	Npix{SBi}	CP	Npix{A}	Npix{TS}	PP	WBi	IV
0-5°	42012	625	0.015	127503	3433	0.027	0.551	-0.259
5-10°	39318	318	0.008	127503	3433	0.027	0.300	-0.524
10°-25°	25272	1111	0.044	127503	3433	0.027	1.628	0.212
25°-40°	15308	1188	0.078	127503	3433	0.027	2.874	0.459
>40° (Cliff)	5593	191	0.034	127503	3433	0.027	1.265	0.102
Total	<b>127503</b>	<b>3433</b>						

'CP' – Conditional probability; PP – Prior probability, WBi – Weight of Factor class; IV – Information value; 'N<sub>pix</sub>{SBi}' is the number of landslide pixels within the factor class, N<sub>pix</sub>{Bi} is the number of pixels of a factor class, 'N<sub>pix</sub>{TS}' is the total sum of pixels of landslide of the whole study area and N<sub>pix</sub>{A} is the total pixels of the whole study area.

### 6.2.6 Aspect

The result of aspect as shown in Table 6.7 clearly indicate that landslide occurrence in the slopes inclined towards north is (22%, 26%) and southeast is 16% with the highest information values 0.67 and 0.121, respectively. Thus, slopes towards north and south-east wards are highly susceptible to landslides. The concentration of landslides in North and southeast directions may be related to the presence of higher elevation, some extent of cultivation practices and springs in

the area. Flat and south directions show no landslides activities. The rest of aspect slope classes indicated less probability of landslides occurrences, as shown in Table 6.6.

**Table 6.6** Computed information value (IV) for Aspect sub-classes in the study area

Aspect classes	Npix{Bi}	Npix{Sbi}	CP	Npix{A}	Npix{TS}	PP	WBi	IV
Flat	3438	0	0.000	127503	3433	0.027	0.000	0.000
North	5875	752	0.128	127503	3433	0.027	4.741	0.676
Northeast	17726	252	0.014	127503	3433	0.027	0.527	-0.279
East	18214	293	0.016	127503	3433	0.027	0.596	-0.225
Southeast	15423	550	0.036	127503	3433	0.027	1.321	0.121
South	22055	0	0.000	127503	3433	0.027	0.000	0.000
Southwest	24715	445	0.018	127503	3433	0.027	0.667	-0.176
Northwest	12399	232	0.019	127503	3433	0.027	0.693	-0.159
North	7658	909	0.119	127503	3433	0.027	4.396	0.643
Total	<b>127503</b>	<b>3433</b>						

‘CP’ – Conditional probability; PP – Prior probability, WBi – Weight of Factor class; IV – Information value; ‘N<sub>pix</sub>{Sbi}’ is the number of landslide pixels within the factor class, N<sub>pix</sub>{Bi} is the number of pixels of a factor class, ‘N<sub>pix</sub>{TS}’ is the total sum of pixels of landslide of the whole study area and N<sub>pix</sub>{A} is the total pixels of the whole study area.

## 6.2 Landslide hazard zonation and distribution

In the present study area landslide hazard zonation map was prepared by considering six causative factors and distribution of past landslides. The distribution of past landslide occurrences over each causative factor were acquired using the information value model. Each causative factor maps were added using raster calculator in Arc-Toolbox to compute the landslide susceptibility index (LSI) for each pixel. The results of weighting of all causative factors used in the present study area were calculated in ArcGIS and MS excel (Table 6.7). The relation analysis is the information value of the study area where landslides occurred to the total area, if the value is lower relative to other classes, it shows lower correlation; if higher, it shows a higher correlation (Filagot Mingestu et al., 2019).

For the present study the landslide hazard zonation map of the study area was grouped into five different potential zones namely; very low hazard, low hazard, moderate hazard, high hazard and very high hazard potential zones (Fig. 6.2). The landslide hazard zonation map of the study area (Fig. 6.2) revealed that 33% (40 km<sup>2</sup>) of the study area falls under very low hazard, 29% (35 km<sup>2</sup>) as low hazard, 23% (28 km<sup>2</sup>) as moderate hazard, 10% (11 km<sup>2</sup>) as high hazard, and the rest 5% (6 km<sup>2</sup>) as very high hazard area.

**Table 6.7** Information value calculated for causative factors

Causative factor class	Subclass	Pixel count sub-class in total area	Subclass pixel percentage (ratio %)	Pixel counts of subclass within landslide area	Landslide percentage (ratio %)	Weight	Information value (IV)
Slope materials	Limestone	28816	19	902	26	1.059	0.064
	Alluvial deposits	30211	26	87	3	0.107	-0.972
	Granite-gneisses	21000	15	30	1	0.053	-1.276
	Basalt	20127	18	880	26	1.619	0.209
	Colluvial deposits	10987	10	733	21	1.471	0.393
	Sandstone	16362	12	801	23	1.813	0.258
	<b>Total</b>	<b>127503</b>	<b>100</b>	<b>3433</b>	<b>100</b>		
Groundwater condition	Dry	27140	21	55	2	0.075	-1.125
	Wet	55704	44	212	6	0.141	-0.851
	Dripping	28095	22	1866	53	2.460	0.391
	Flow	16564	13	1300	38	2.907	0.463
	<b>Total</b>	<b>127503</b>	<b>100</b>	<b>3433</b>	<b>100</b>		
Land use/Land cover	Forest land	18124	14	393	11	0.803	-0.095
	Cultivated land	38674	30	1964	57	1.881	0.274
	Grass land	42223	33	966	28	0.847	-0.072
	Bare land	25000	20	103	3	0.153	-0.816
	Built-up area	3482	3	7	1	0.074	-1.128
	<b>Total</b>	<b>127503</b>	<b>100</b>	<b>3433</b>			
Elevation	1579-1873	24275	19	91	3	0.139	-0.857
	1873-2074	52714	41	131	4	0.092	-1.036
	2074-2299	25372	20	1173	34	1.712	0.234
	2299-2572	20759	16	995	29	1.775	0.249
	2572-2950	4383	4	1043	30	8.814	0.945
	<b>Total</b>	<b>127503</b>	<b>100</b>	<b>3433</b>	<b>100</b>		
slope	0-5	42012	33	625	18	0.551	-0.259
	5-10	39318	31	318	9	0.300	-0.524
	10-25	25272	20	1111	32	1.628	0.212
	25-40	15308	12	1188	34	2.874	0.459
	>40	5593	4	191	7	1.265	0.102
	<b>Total</b>	<b>127503</b>	<b>100</b>	<b>3433</b>	<b>100</b>		
Aspect	Flat	3438	3	0	0	0.000	0.000
	North	5875	5	752	22	4.741	0.676
	Northeast	17726	14	252	7	0.527	-0.279
	East	18214	14	293	9	0.596	-0.225
	Southeast	15423	12	550	16	1.321	0.121
	South	22055	17	0	0	0.000	0.000
	Southwest	24715	19	445	13	0.663	-0.176
	Northwest	12399	10	232	7	0.693	-0.159
	North	7658	6	909	26	4.396	0.643
	<b>Total</b>	<b>127503</b>	<b>100</b>	<b>3433</b>	<b>100</b>		

The information values of the six factors considered in this present study were listed in (table 6.7). In the present study, the result of litho-logical units demonstrates that the most susceptible classes were colluvial deposits, fractured basalt and limestone. These unit classes are mostly found in northern, western and central parts of the study area and they are covered by

agricultural land which may increase susceptibility to landslide as they have shown the highest information values. For land use and land cover, the most susceptible to landslide is cultivated land. This is due to irrigation and very loose litho-logy units in the slope of the study area. For the slope classes of the study area, the highest information values are calculated in slope class 10-25<sup>0</sup> (IV- 0.212) and 25-45<sup>0</sup> (IV-0.459) which showed the more susceptibility to landslide occurrences. These slope classes are mainly used as cultivated land and also many spring of the study area are found in these two slope classes. Slope class greater than 45<sup>0</sup> has also shown more susceptibility to landslide. In generally, slope instability increases as the slope angle increases on account of the increasing shear stress on the slope materials.

Elevation is considered as one of the important factors and the main reason of slope instability (Raghuvanshi et al., 2015). In the present study, most the past landslides have occurred in elevation classes 2074-2299m and 2572-2950m. One of the major reasons for dominance to landslides in these elevations is that most of slope in these elevations are occupied by agricultural land. The result of land use and land cover also showed that the highest information value was recorded with in the cultivated land.

With regards to aspect, the result of the present study indicated that the past landslides are dominant in the slopes oriented towards North and southeast directions. The highest weight and information values were obtained for slopes oriented towards North and southeast directions as compared to other aspect classes.

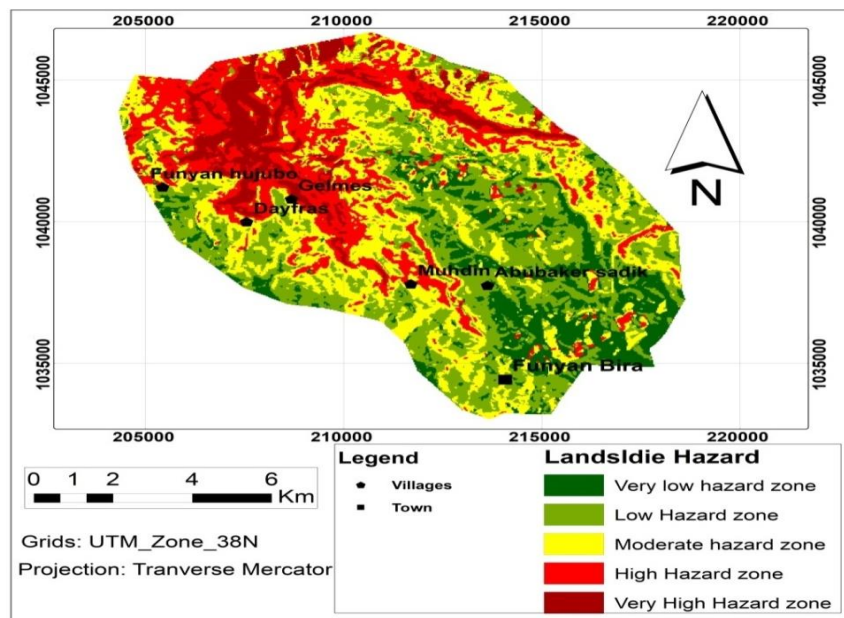
For Groundwater conditions, flow and dripping zones indicate the highest landslides susceptibility as the information values indicated in (Table 6.7). Dripping zone is mainly concentrated on north and northwest of the study area whereas the flow zone is mainly in central, northeast and somewhat west of the study area. Most of the past landslides have occurred within flow and Dripping zone. This is due more concentrations' of most of the springs in the study area.

**Table 6.8** Highest information value classes in the study area

Causative factors	Classes	Information value
Slope materials	Colluvial deposit	0.393
Land use/Land cover	Cultivated land	0.274
Groundwater surface	Flow	0.463
Elevation	2572-2950m	0.945
Slope	25 <sup>0</sup> -40 <sup>0</sup>	0.459
Aspect	North aspect	0.676

Distribution of several landslide hazard zones in the present study area prepared in this study was presented in (Fig-6.2). In the northern, northwest, and northeast part of the study area are distributed by very high and high hazard zones. Moderate hazard zone are mainly distributed in the southwestern, southern, northeastern and central parts of the study area. Very low and low hazard zone are mainly concentrated in the southeastern part of the study area.

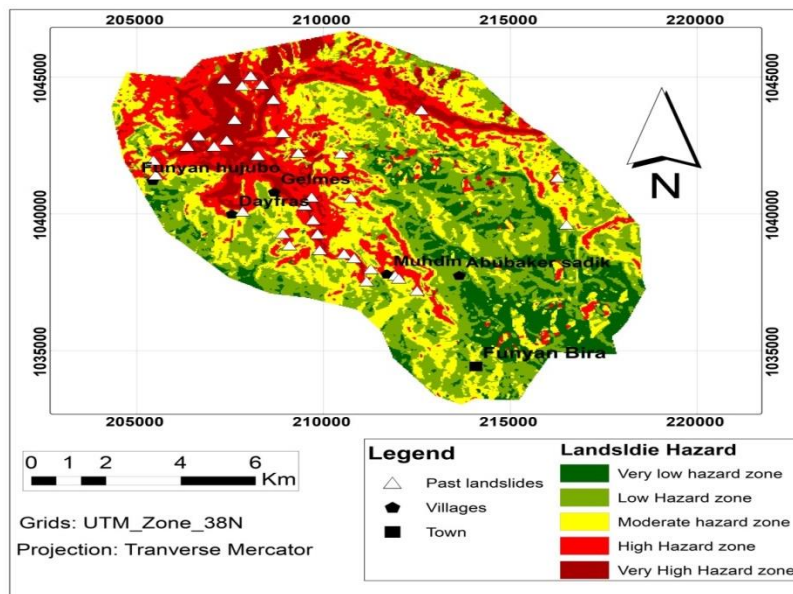
The areas of very high and high hazard zones of the study area are characterized by high elevation, cultivated land, more spring distribution, and high slope angles with highest information values as presented in (Table 6.8). Due to these, they show most probability of the landslide hazard occurrences. As per local community information, most of landslides in the area occurred during heavy rainy season. The study area also shows high annual rain fall.



**Fig 6.2** Landslide hazard zonation (LHZ) map of the study area

### 6.3 Validation of LHZ map

Validation of the prepared landslide hazard zonation map of the study area was conducted by comparing landslide hazard zonation map with past landslides in the area. Overlay analysis of past landslides and landslide hazard zonation map of the present study was used to validate the LHZ map. The result of overlay analysis of past landslide and LHZ map showed that 62.8% (22) of the past landslides occurred within very high hazard (VHH) zone whereas 34.2% of the past landslide fall under high hazard (HH) zone of landslide hazard zonation map of the present study area. Only 3% (1) of the past landslide fall within moderate hazard zone. Furthermore, no past landslides occurred under low and very low hazard zones. These results clearly shows (Fig 6.3) that 97% of the past landslide fall within high hazard (HH) and very high hazard zones (VHH). Thus, it can be safely said that the prepared landslide hazard zonation map has shown clear validation with the past landslides in the area. The factors considered and the model used to prepare landslide hazard zonation map in the present study is quite reasonable and may safely be applied for other areas. The delineated area under very high hazard and high hazard zones in the prepared LHZ map can be considered hazardous areas for existing and planned future activities. Further, these areas may require more detailed studies before implementing any developmental activities.



**Fig 6.3** validation of LHZ map with the past landslides of the study area

#### **6.4 Evaluation of causative factors based on the prepared LHZ map**

For the present study area the result of the spatial relationship between past landslides and six causative factors using information value model are given in (Table 6.7). It can be noted that in the present study area, each sub-class of the considered causative factors has a weight equal to or less or greater than zero, demonstrating that all factors bring about the possibility of landslide occurrence, yet to different extents (Sarda and Pandey, 2019). As shown in Table 6.7 the majority of landslide occurred in basalt (IV-0.209) , limestone (IV-0.064), sandstone (IV-0.258) and colluvial deposits (IV-0.393) with 26%, 26%, 23% and 21% of landslide occurrences, followed by Alluvial deposits (IV- -0.972) , granite-gneisses (IV- -1.276), respectively. The weight or information value of alluvial and granite-gneisses classes shows that it does not contribute much to the past landslides in the area. Among slope classes, the results shows that the largest weight values correspond to slope of  $25^{\circ}$ - $40^{\circ}$  (IV-0.459) and  $10^{\circ}$ - $25^{\circ}$  (IV-0.212) occupying about 34% and 32% of past landslide occurrences, respectively followed by slope  $>40^{\circ}$  (IV-0.102) covering about 4% of past landslides in the area. Litho-logically, these slope classes are covered by weathered basalt, fractured limestone and colluvial deposits. These lithological units in general are highly disintegrated and possess to high porosity and permeability (Raguvanshi et al., 2015, Filagot mengistu et al., 2019). In other two slope classes ( $0^{\circ}$ -  $5^{\circ}$ , ( $5^{\circ}$ -  $10^{\circ}$ ), the possibility of landslide occurrence is significantly less. In general, in the present study area the landslides have occurred in slopes ranging from  $10^{\circ}$  to  $40^{\circ}$ , about 66% of past landslides were observed in these slopes. In terms of land use/ land cover, landslides occurred within cultivated land with highest weighting (IV-0.274). The other four land use/land cover classes (forest land, bareland, Grassland and built up classes) of the present study area show less probability of landslide occurrences because their information values are less than zero. In case of ground water surface trace classes, dripping and flow classes have the highest information values of 0.391 and 0.463, respectively, while the dry and wet classes have the least weight of information value of -1.125 and -0.851, respectively. Most of the springs in the study area are situated within dripping and flow zone which means the areas are more susceptible to landslide occurrence.

Further, with regards to aspect, the result of the present study indicated that the past landslides are dominant in the slopes oriented towards North and southeast directions. The highest weight and information values were obtained for slopes oriented towards North and southeast directions as compared to other aspect classes. Similarly, the results of elevation classes for the present study shows (Table 6.7) that the highest weight of information value 0.945, 0.51 and 0.249 are for elevation classes 2572-2950m, 2229-2572 m and 2074-2299 m, respectively. Most of these elevation classes are within cultivated areas covered by fractured limestone, colluvial deposits and disintegrated limestone rocks. These elevation classes show more susceptibility for landslide. The other two elevation classes (1873-2074m and 1579-1873m) show less probability of landslide occurrences, as revealed from the weight of information value (Table 6.7). Instability of slope may be resulted from poor irrigation or unplanned cultivation practices such as terraced land which can lead to extensive recharge of groundwater (Raghuvanshi et al., 2014; 2015).

Finally, the highest information values as obtained for different causative factors are elevation (2572m-2950m), aspect (north aspect), groundwater condition (flow), and slope ( $25^{\circ}$ - $40^{\circ}$ ), Land use and land cover (cultivated land ) and slope materials (Colluvial deposits), respectively (Table 6.8). Furthermore, the information collected from the local respondents indicated that the landslides in the area have been triggered due to heavy rainfall.

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## **Chapter - 7**                      **CONCLUSION AND RECOMMENDATIONS**

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### **7.1 Conclusion**

The present study area is located in the eastern Hararghe zone of the Oromia region, Gursum District, Eastern Ethiopia, located about 581km from Addis Ababa. The area is characterized by very rugged topography with elevations that ranges from 1500 to 2950m. The topography of the study area is highland and margin rift which is prone to landslide occurrence. Furthermore, the area is highly populated therefore population and property is at high risk due to landslide hazard. The geology of the study area is characterized by Mesozoic sedimentary rocks, Precambrian rocks, Tertiary volcanic rocks and quaternary deposits.

The main objective of the present study was to evaluate landslide hazard and to prepare zonation map of Funyan Biro town and its surrounding areas. In order to prepare landslide hazard zonation map of the area, the past landslides that have occurred in the area were recorded. In the present study area 35 past landslides were observed from landslide inventory data and field investigation. For the present study, causative factors that were considered are; slope materials, slope, aspect, elevation, land use and land cover, and groundwater surface traces. The mode of the failure of past landslide in the area as observed was rotational slide, fall, translational and debris flow mode of failures.

For the present study bivariate statistical method especially information value model which is raster based method was used to prepare landslide hazard zonation map of the study area. The causative factors were classified into various sub-classes and for each subclass, based on the density analysis with past landslide inventory by using the pixel count, the information value for each factor sub-class was calculated. Later, by using information values for various sub-classes, landslide susceptibility index (LSI) was calculated. Further, by utilizing LSI values the LHZ map of the present study area was prepared.

The LHZ map was classified into five classes namely; very low hazard, low hazard, moderate hazard high hazard and very high hazard zones. The result of LHZ map of the study area revealed that 33% (40km<sup>2</sup>) of the study area falls under very low hazard (VLH), 29% (35km<sup>2</sup>) as low hazard (LH), 23% (28km<sup>2</sup>) as moderate hazard (MH), 10% (11km<sup>2</sup>) as high hazard (HH), and the rest 5% (6 km<sup>2</sup>) as very high hazard (VHH) area.

Later, the prepared LHZ map of the study area was validated by comparing it with the past landslides data of the study area. The result of overlay analysis of past landslide and LHZ map showed that 62.8% (22) of past landslides occurred within very high hazard (VHH) zone whereas 34.2% of the past landslide fall under high hazard (HH) zone of landslide hazard zonation map of the present study area. Further, only 3% (1) of the past landslide fall within moderate hazard zone. Furthermore, no past landslides occurred under low and very low hazard zones. Thus, the results clearly shows that 97% of the past landslide fall within high hazard (HH) and very high hazard zones (VHH). Thus, it can be safely said that the prepared landslide hazard zonation map has shown clear validation with the past landslides in the area. The factors considered and the model used to prepare landslide hazard zonation map in the present study is quite reasonable and may safely be applied for other areas.

## **7.2 Recommendation**

The landslides in the present study area have caused damage to developmental infrastructures, cultivated land, and settlements. Since the study area is highly populated area the landslides have also affected local people, their property and animals. This means that local people, property, and developmental infrastructures in the present study area are susceptible to landslide risk. Villages like Gelmis, Dayfras, Funyan hujubo, Dinke, Muhyadin and also local people around Kundudo mountain are at high risk in the study area. Therefore, following recommendations are forwarded;

- The effect of landslides in the study area can be minimized by avoiding those areas which has been delineated as high hazard zones in the present study. If the area can not be avoided more detailed studies must be made and proper mitigation and stabilization measures must be work out.

- The local government and planners needs to bring proper awareness among the local people for high landslide prone areas and preparedness related to this landslide risk.
- Before planning and implementing any infrastructure detailed investigation and slope instability study need to be mandatory in the study area.
- Avoding the landslide prone areas such as Kundodo mountain for settlement, agricultural land.
- Along some slopes of road cut such as; Road from Funyan Biro-Harashi-Muyadin-Gelmis-Dayfras-Funyan Hujubo require immediate rehabalitation by constructing retaing walls, and using proper surface drainage.
- To prevent landslide hazard immediate countermeasure actions should be taken before slope movements get worse by reshaping, decreasing of slope angles.
- Planting suitable trees in the study area is very important.

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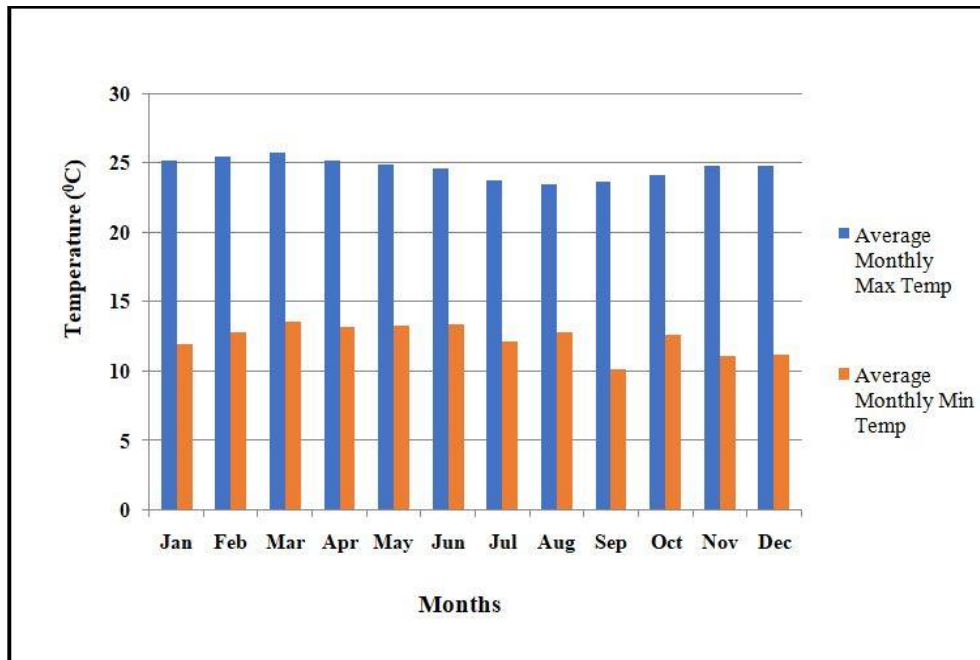
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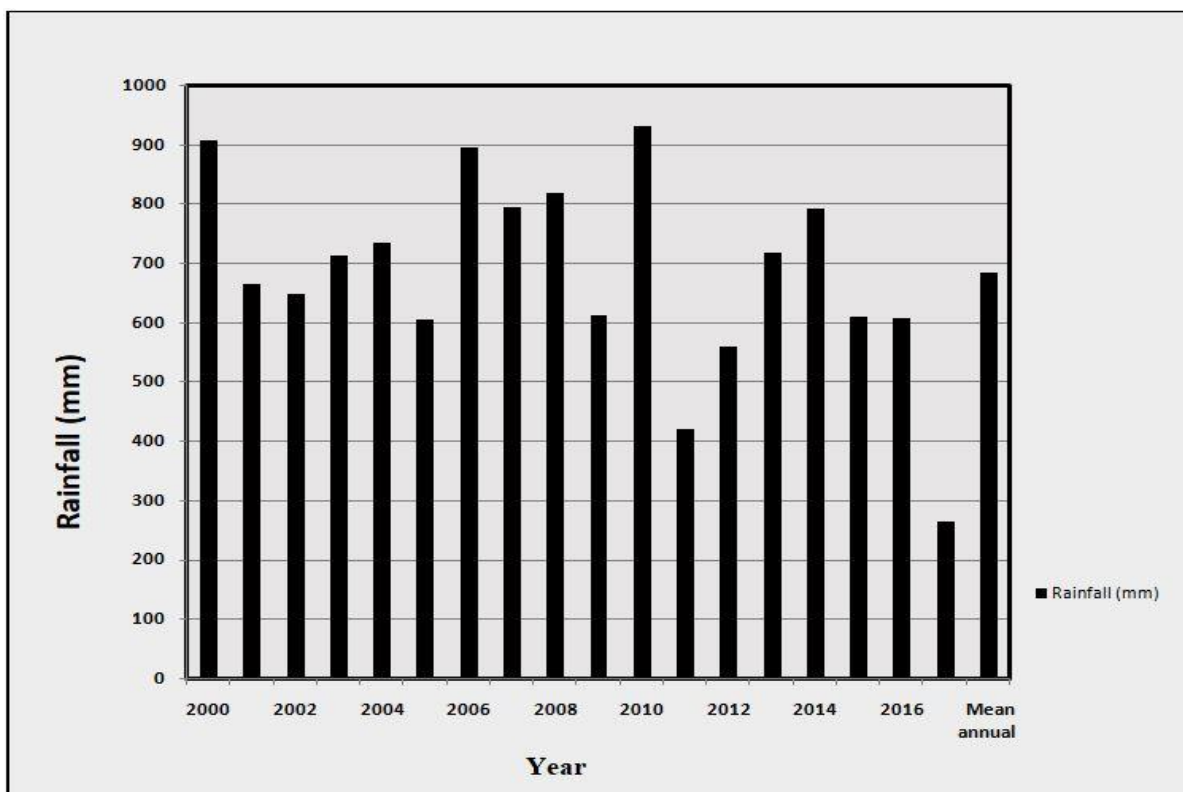
## List of Annexes

## Annex 1. 1 Maximum and minimum temperature in the study area from 2000 to 2107

Temp	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MAX	2000	24.1	27.56	28.02	26.93	24.16	24.75	23.84	23.1	23.98	24.17	25.03	25.17
MIN	2000	12.84	12.81	12.81	12.69	11.92	13.33	12.52	12.41	12.9	13.29	13.81	13.12
MAX	2001	25.42	25.94	25.39	25.78	24.26	24.34	23.66	22.88	24.25	24.38	25.5	25.66
MIN	2001	12.99	13.16	13.09	13.02	12.9	13.07	12.92	12.85	13.11	13.07	13.09	13.12
MAX	2002	25.47	26.07	25.9	25.43	25.58	24.78	24.46	23.94	24.33	24.77	25.57	25.2
MIN	2002	13.12	13.2	13.14	13.14	13.05	13.04	13.01	13.02	13.06	13.19	13.19	13.16
MAX	2003	25.37	25.95	25.84	25.28	25.43	24.65	24.43	21.24	24.02	24.48	25.13	24.43
MIN	2003	13.19	13.21	13.15	13.02	13.16	12.95	12.78	12.58	12.67	13.26	13.2	13.02
MAX	2004	0	25.15	25.29	24.04	25.36	24.63	23.53	24.01	24.12	24.23	24.33	24.17
MIN	2004	0	13.16	13.1	12.4	13.38	13.2	12.54	12.77	12.8	12.9	13.22	13.18
MAX	2005	23.96	0	25.34	24.97	23.19	23.19	23.19	23.4	23.77	24.32	24.62	24.94
MIN	2005	13.09	13.07	13.14	13	13.01	12.87	12.89	12.78	13.06	13.19	13.21	13.2
MAX	2006	26.08	27.04	25.94	25.12	26.2	25.97	24	23.69	0	24.18	24.37	24.05
MIN	2006	13.28	13.3	13.04	13.06	13.25	13.1	12.79	13.02	0	13.14	13.19	13.1
MAX	2007	24.7	25.61	25.65	23.62	23.39	23.21	23	22.99	22.55	23.57	24.84	25.64
MIN	2007	13.27	13.35	13.29	12.04	12.95	13.05	12.83	12.34	13.32	13.14	13.12	13.4
MAX	2008	26.18	26.42	26.58	25.59	24.05	23.6	23.11	22.34	22	23.56	23.12	23.98
MIN	2008	13.39	13.35	13.35	13.2	12.78	13.39	12.3	11.34	11.84	12.64	12.82	13.38
MAX	2009	24.46	25.29	25.97	24.46	24.52	24.72	23.56	23.37	23.4	24.48	24.89	25.5
MIN	2009	13.32	13.88	13.89	12.97	13.17	13.3	12.94	13.05	13.28	13.39	13.44	13.5
MAX	2010	26.27	25.32	24.49	24.12	23.7	25.08	24.4	24.03	24.33	24.77	25.8	22.1
MIN	2010	13.6	12.96	13.28	12.95	12.61	13.1	13.11	13.11	13.26	13.77	11.1	11.29
MAX	2011	23.38	23.47	25.27	25.2	23.63	23.94	23.2	23.39	0	23.33	24.45	0
MIN	2011	11.53	13.34	13.4	13.2	13.8	13.56	13.03	13.05	0	12.92	13.3	0
MAX	2012	23.08	23.94	25.06	25.38	25.21	25.09	23.05	23.51	23.57	0	24.66	24.76
MIN	2012	12.5	13.38	13.65	12.96	13.45	13.28	12.89	13.03	13.36	13.91	14.37	14.36
MAX	2013	25.48	26.18	25.58	23.62	24.24	24.47	22.79	23.39	23.14	0	0	24.51
MIN	2013	14.36	14.38	13.55	12.55	13.16	13.52	12.5	13.13	12.94	0	0	14.44
MAX	2014	0	24.56	24.45	24.44	25.12	25.48	24.93	24.3	23.22	23.56	24.73	25.19
MIN	2014	0	14.42	14.34	14.27	14.44	14.36	13.71	13.04	12.53	13.48	14.34	14.4
MAX	2015	25.6	25.56	25.62	25.57	25.2	24.5	24.39	24.49	24.83	25.55	25.64	0
MIN	2015	14.34	14.51	14.42	14.39	14.01	13.4	13.38	13.45	14.17	14.54	14.55	0
MAX	2016	26.52	26.56	28.17	28.03	26.6	25.79	23.8	23.47	0	23.7	0	25.99
MIN	2016	14.26	14.49	15.08	14.77	14.4	14.38	13.41	13.4	0	13.19	0	14.67
MAX	2017	25.62	0	25.56	24.84	24.4	24.51	0	0	0	23.63	0	0
MIN	2017	15.54	0	14.83	13.94	13.6	13.41	0	0	0	13.9	0	0



**Annex 1.2** Average monthly Max and Min temperature of the study area from 2000 to 2017



**Annex1.3** Mean Annual rainfall of Gursum (Funyan Biro) from 2000 to 2017

