



ADDIS ABABA UNIVERSITY
COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES
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**MAPPING AND ANALYSIS OF UNSTABLE SLOPES USING
FREQUENCY RATIO AND INSAR:
A CASE STUDY OF DEEP-SEATED LANDSLIDES IN DEBRESINA, ETHIOPIA**

A Thesis submitted to
The school of Graduate Studies of Addis Ababa University
In partial fulfilment of the requirements for the Degree of Master of Science in Engineering
Geology

by:
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May 2024

**Mapping and Analysis of Unstable Slopes Using Frequency Ratio and
InSAR:
A Case Study of Deep-seated Landslides in Debresina, Ethiopia**

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ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
ENGINEERING GEOLOGY PROGRAM

This is to certify that the thesis prepared by Getnet Meshesha Tefera ID No GSR/6309/15, entitled: “*Mapping and Analysis of Unstable Slopes Using Frequency Ratio and InSAR: A Case Study of Deep-seated Landslides in Debresina, Ethiopia*” and submitted in partial fulfilment of the requirements for the Degree of Master of Science (Engineering Geology program) complies with the regulations of the University and meets the accepted standards concerning originality and quality.

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ABSTRACT

This research focuses on studying landslides in the Ethiopian highlands, particularly along the edges of the Main Ethiopian Rift. The region's complex topography and tectonic activity have historically made it susceptible to landslides, with significant events recorded in September 2005. Recently, shallow landslides have been observed reactivating along the remnants of older, deep-seated landslides, causing significant damage to agriculture, infrastructure, and residential areas.

The study area's lithological composition includes the Tarmaber formation, making up 37% of the terrain, known for its moderate to extensive fracturing and varying degrees of weathering, with an average uniaxial compressive strength (UCS) value of 243.6 MPa. The Alaje formation, comprising 36%, is characterized by its highly fractured and weathered nature, with weaker UCS values of 79.2 MPa. Additionally, 21% of the area is composed of eluvium-colluvium deposits and 7% of alluvial deposits. These strata overlay an impermeable layer with hydraulic conductivity ranging from 0.0018 to 0.002 cm/sec, consisting of medium to dense sandy silt, which is an altered component of the Alaje formation.

The main focus of this research is to map and analyze instabilities using frequency ratio (FR) and Interferometric Synthetic Aperture Radar (InSAR) methodologies, aiming to create a comprehensive landslide susceptibility map and a displacement map. Six causative factors: aspect, slope, elevation, proximity to streams, and lithology were selected for the input process, tailored to the unique conditions of the site. Results from the FR analysis indicate that lithology, particularly the eluvium-colluvium and alluvial deposits, is the main causative factor for instability.

Furthermore, processing two descending Sentinel-1 Interferometric Wide Single Lock Complex (S1A_IW_SLC) images from 2014 and 2024 via the Sentinel Application Platform (SNAP) facilitated the preparation of the displacement map. InSAR analysis revealed a displacement trend towards the rift margin, ranging from 0.80m to 1.172m over the ten years.

The integration of FR and InSAR analyses demonstrates a strong correlation between displacement and susceptibility, particularly concerning deep-seated landslides, emphasizing the critical nature of these factors in landslide prediction and risk management.

Keywords: Frequency ratio, InSAR, Landslide susceptibility, Displacement, causative factor

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List of Acronyms

ASF	Alaska Satellite Facility
BEM	Boundary Element Method
BPM	Bonded Particle Model
BTF-1	basaltic tuff
DEM	digital elevation model
DInSAR	Differential interferometric synthetic aperture radar
EEC	Ethiopia Engineering and Construction Company
FR	Frequency ratio
GIS	Geographic Information System
InSAR	Interferometric synthetic aperture radar
LL	Liquid limit
LSI	landslip susceptibility index
LSMs	landslide susceptibility maps
LSZ	landslide susceptibility zonation
LULC	Land use land cover
MER	main Ethiopian rift
NMC	natural moisture content
PFC	Particle Flow Code
PI	plasticity index
PL	plastic limit
S1A_IW_SLC	sentinel 1 A intensity wide single lock complex
S1TBX	Sentinel-1 tool box
SAR	Synthetic Aperture Radar
SNAP	Sentinel Application Platform
USCS	Unified Soil Classification System
USGS	United States Geological Survey
UTM	Universal Transverse Mercator

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CHAPTER - ONE

INTRODUCTION

1.1. General

Fundamentally, a "landslide" is a gravity-driven, slow-to-fast movement of unstable rock and debris masses downward (Cruden, 1991, Abebe et al., 2010). Landslides can be classified into different categories based on their failure mechanism and types of mass movements including creep, slides, flow, topple, and falls, each with its characteristic features, and taking place over timescales from seconds to years (Cruden, 1991, Novotný, 2013). In Ethiopia, slope instability caused by both natural and man-made factors is a major concern, and landslides are a common hazard everywhere (Woldearegay, 2008). Along the rugged and mountainous terrain of Ethiopia's highlands particularly Debresina (Tarmaber districts), slope instability is a significant issue (Mebrahtu et al., 2021).

As reported by (Woldearegay, 2008), The largest landslide occurred in September 2005 in the Yizaba and Shotel Amba districts, displacing almost 3,000 people from their homes, destroying 1500 hectares of farmland, 1250 residential buildings, and one school. The instability issue is still significantly present, with multiple small-scale landslides on top of this deeply buried landslip (Mebrahtu et al., 2021). It was initiated after a long time of invisible creeping and large sliding masses took place from 2005 to 2006. Most of the displaced people due to the effect of this deep-seated landslide need to be properly resettled and back to their origins and need to avoid uncertainties of instability issues to build homes, schools, and roads. So, to minimize such damages and avoid uncertainties, identifying unstable slopes or risk areas and detailed analyses for probable instabilities to occur shortly play a crucial role.

This study is focused on specific localities of Yizaba and Shotel Amba districts with a large-scale analysis approach by selecting the study area according to the administrative boundary situation and for an adequate understanding of current deformation and instability conditions, the remote sensing techniques InSAR (Interferometric synthetic aperture radar) and susceptibility mapping a GIS-based bivariate statistical Frequency ratio (FR) method is applied.

1.2. Problem Statement

In September 2005, a significant landslide occurred in the Yizaba and Shotel Amba districts. This event led to the displacement of approximately 3,000 people and destroyed 1500 hectares of farmland, 1250 residential buildings, and one school (Woldearegay, 2008). Following the incident, several investigations were carried out by different researchers using various methods such as 2D slope stability analysis (Mebrahtu et al., 2021), Hazard assessment zonation with (SSEP) Rating Scheme methods (Tadele, 2014), GIS-based landslide mapping, and Global Limit equilibrium method (Hagos, 2012), as well as an expert evaluation approach method (Enigda & T, 2021).

Most of these investigations utilized medium-scale (1:50,000) analysis methods. The recommendations from these studies emphasized the necessity of further research, specifically focusing on slope stability evaluations through the use of 3D modeling analysis, detailed drilling works, field monitoring, and other techniques. There were suggestions for more comprehensive geotechnical investigations, geophysical surveys, and topographic surveys. Furthermore, recommendations were made for the complete evacuation of residents from the Yizaba and Shotel Amba localities (Hagos, 2012). Despite these recommendations, there has been a rise in the number of people residing in this area and constructing internal gravel roads without adequate investigation or the placement of warning signs in these potentially unstable areas.

The issues of instability restricting from the deep-seated landslides, along with subsequent minor landslides, persist. The majority of the displaced people require proper resettlement. To mitigate uncertainties and minimize unexpected damage to the area, it is essential to have a comprehensive understanding of unstable slopes or at-risk areas. Detailed analyses for potential instabilities should be conducted promptly.

1.3. Research Questions

The research questions ultimately initiate from the actual condition of its past deep-seated landslide history and the existence of active unstable slopes at the failure plane and toe of the sliding bodies, to answer the following questions:

1. What are the geotechnical properties of unstable slope rock and soil concerning instabilities?
2. What are the main causative factors of instability in the study area

3. Which areas are unstable and What/who are at risk?
4. What is the displacement condition of the study area?

1.4. Research objective

1.4.1. General Objectives

The main objective of this study is to map and analyze instabilities and understand the displacement condition of Shotel Amba and Yizaba Weyn localities, Debresina - Ethiopia

1.4.2. Specific Objectives

The specific research objectives are:

1. Determining the geotechnical properties of landslide-prone soil and rock.
2. Prepared different causative factor maps and analyzed their contribution to instability
3. Producing a landslide susceptibility mapping and identifying critical zones using frequency ratio methods
4. Producing a displacement map with a time series InSAR analysis method

1.5. Scope of the Study

- Within the scope of this study, first of all, a detailed literature survey including slope instability analysis and identification of failure-prone areas and mapping methods.
- Proper field investigation, landslide inventories, sampling, and required laboratory testing for the required input data preparation
- Produce a large-scale map (1:25,000) of the study area and asses landslide-triggering factors and prepare input maps of six causative factors with the scale of the study are for the FR model and evaluate the relation of contribution for instability.
- Prepare landslide susceptibility map and susceptibility zonation using frequency ratio values
- Mapping of the displacement condition using InSAR and assessing the level and cause of deformation.
- Based on the final map, forward a recommendation which can serve to the local community or that can be at risk

1.6. Significance of the Study

As a master's student, conducting research for a thesis holds significant importance. It can be seen as a step towards earning a master's degree, advancing in one's career, or acquiring a higher social position. Additionally, it equips individuals with the knowledge of how to conduct research and serves as a foundation for further studies. This research contributes to our understanding of unstable slopes, aiming to minimize the negative impacts of slope failure on the environment, natural resources, and society, prevent unplanned construction and settlement, and address factors leading to instability. Specifically, in regions with deep-seated landslides along rift boundaries and in highland terrains, this study may provide valuable insights into slope instability and related hazards.

1.7. Thesis Structure

Chapter One: Introduction including problem statements, research questions and objectives, scope of the study area, significance of the study, and methods and approach of the study.

Chapter Two: Literature review about the general theoretical review of slope type and comment slope failure, landslide triggering factors, previous studies and landslide mapping approach.

Chapter Three: Describe and analyze the study area based on location, physiography, spring and seepage conditions, mass movement conditions, discuss and describe the tectonic setting, geological setting, and structural setting of the site with a regional perspective, landslide inventories, encountered failure types, and geotechnical properties.

Chapter Four: deals with methods and procedure, preparation of factor maps such as aspect, slope, elevation, distance stream and LULC and described in detail frequency ratio methods and InSAR Procedures.

Chapter Five: Discuss the result of displacement and susceptibility map, comparison of the results, validation, verification and correlation of the two results

Chapter six: Conclusion and Recommendation

CHAPTER – TWO

LITERATURE REVIEW

2.1. Introduction

Landslides are common in Ethiopia and often cause significant damage to persons and property (Mersha & Meten, 2020). According to (Abebe et al., 2010), Ethiopia's highlands and mountainous regions, including the Blue Nile Gorge, the Lower Wabe-Shebele River valley, the Gilgel Gibe River, the Tarmaber districts, the Kombolcha-Desie road, Sawla's Uba Dema village, the Wondogenet area, and many more, frequently experience landslide-related issues. Past landslides and several conditioning factors, including slope morphology, hydrogeology, and local geology, must be integrated within a GIS framework to quantify and assess the landslide vulnerability of a particular area (Mersha & Meten, 2020).

To determine what relevant works or methodologies are available and what isn't in the topic of interest, a literature review is a crucial first step in research initiatives (Hagos, 2012). To conduct this research, a comprehensive examination of the literature on slope types and failure mechanisms, landslide triggering factors, and landslide mapping and analysis methods will be conducted. In addition to this a search of satellite images to produce a displacement map and for the digital elevation model (DEM), compilations of structural, topographical, and hydrological data, and a thorough investigation of any available information on landslides in the study area.

The deformation and displacement rate are mapped and detected utilizing time series InSAR analysis using Sentinel Application Platform (SNAP) software based on the deformation behavior and sentinel image data. To apply landslide mapping and analysis appropriately, a detailed understanding of the triggering factors, landslide inventories, geology, hydrology, failure mechanisms, geotechnical properties of soil and rock, Landslide mapping and analysis methods, identification of failure type, and, a detailed review of previous works is required (Wolde, 2013).

2.1. General theoretical review slope failure

2.2.1. Types of slopes and movements

There are two types of slopes on earth: natural slopes, which are formed naturally and can be found in hilly areas; man-made slopes that are found on the sides of cuttings, the slopes of embankments built for roads, railroads, canals, and other infrastructure, and the slopes of earth dams used for water storage (Murthy, 2002). Slopes can be infinite (long slopes found on a mountain face) and finite (slopes like embankments and earth dams slopes have a limited area) they may be man-made or natural (Murthy, 2002).

Based on Varnes, 1978 and updated by (Ho, 2007), (Novotný, 2013) and (Hung et al., 2014), Slope failures often occur in areas with moderate to steep slopes, conducive geology, and high precipitation, and generally, it is classified according to the type of movement and the type of material involved where the types of material included in the first term: rock, earth, soil, mud, and debris, and the types of movement including in the second term: fall, topple, slide, spread, flow, and complex with combining the two terms gives classifications such as: Rockfall, Rock topple, Debris slide, Debris flow, Earth slide, Earth spread, etc (Novotný, 2013) as shown in Figure 2.1.

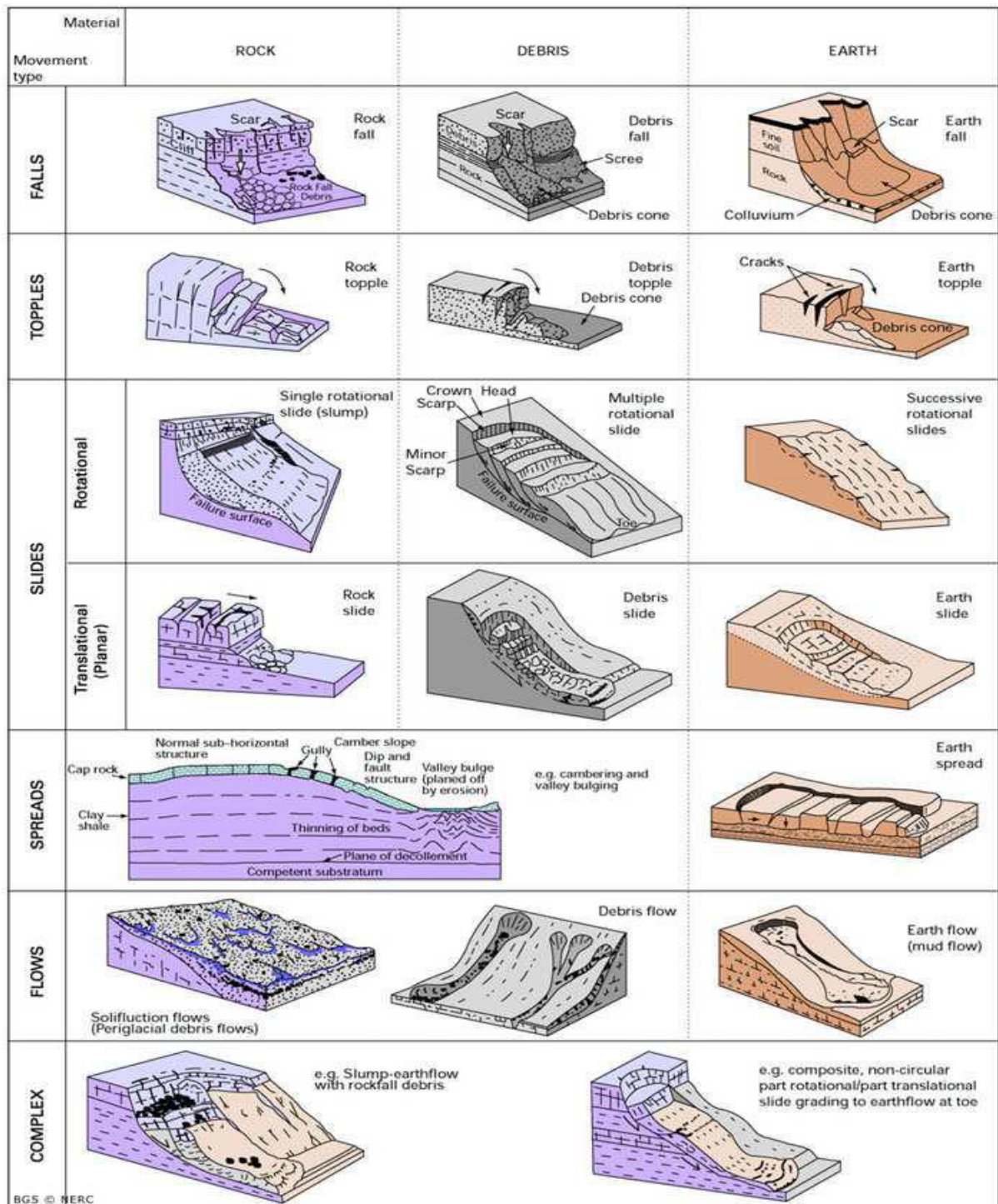


Figure 2.1. Classification of slope movements based on Varnes' (1978) updated by (Ho, 2007) (Novotný, 2013), (Hungr et al., 2014), (Report, 2015).

2.2.2. Common types of slope failures

Common types of failures in rock and soil slopes are; Rockfall, Toppling, Circular (rotational) failure, Wedge failure, Translational failure (Plane failure), and Compound Failure (Hoek, 2009), ("Types of slope failure," 2018).

i. Rockfall

According to (Volkwein et al., 2011)

The process of rockfall occurs quickly to very quickly and spreads over large areas. The rock mass can separate in any quantity from a high cliff or steep slope along a surface with little to no shear displacement. It primarily falls into the air by rolling, leaping, bouncing, or free-falling. Usually, the pressures acting on a rock are altered as a result of a biological or environmental event. The infiltration of rainfall, the surrounding material eroding during heavy downpours, freeze-thaw cycles in cold climates, the weathering or chemical degradation of the rock, the growth of roots or their leverage in strong winds, etc. can all cause the pore pressure to rise. In an environment where construction is continuing, the likelihood of mechanically igniting a rockfall is probably one or two orders of magnitude higher than the previously indicated biological and climatic beginning events [Figure 2.2](#) presents the rock fall view.

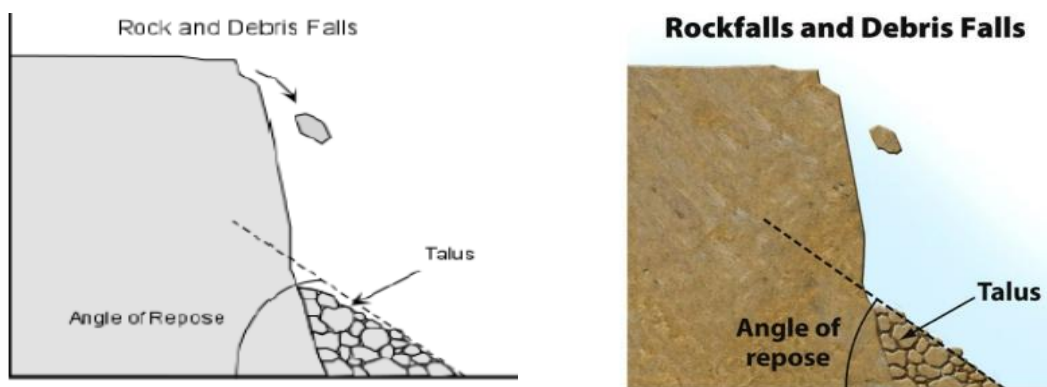


Figure 2.2. Typical view of Rockfall (Volkwein et al., 2011), (Theodoridis & Kraemer, n.d.).

ii. Toppling

Toppling failure occurs when a rock block resting on an inclined plane has its weight vector fall outside of the block's base (Wolde, 2013). According to (Wyllie & Mah, 2017), (Liu, Li, & Kang, 2019) The most common places for toppling failure are in rock masses that are broken into several slabs or columns composed of a sequence of fractures that intersect the slope face almost parallel and fall deeply into the rock mass. The three most prevalent toppling failures

are block toppling, flexural toppling, and block flexural toppling (Alejano et al., 2010) as shown in Figure 2.3.

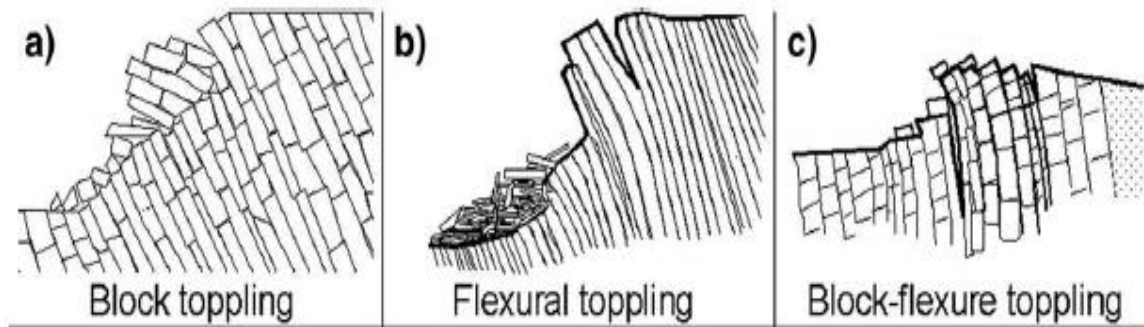


Figure 2.3. Common toppling failures (Alejano et al., 2010).

- a) Block toppling occurs in hard rock when columns or individual blocks are made up of two regular joint sets, the main set of which dips sharply into the face,
- b) Flexural toppling occurs when continuous, sharply dipping rock columns flex and tilt forward towards the slope,
- c) Block flexural toppling is a complicated mechanism that is distinguished by pseudo-continuous flexure along large blocks that are split by several cross-joints (Wyllie & Mah, 2017; Alejano, 2021).

iii. Circular (Rotational) failure

This form of failure mostly affects soils, although it can also happen to weak rock with finite slopes and a single discontinuity surface it rotates along a slip surface, creating a curved slip surface, and the failed surface slides downhill and outward (“Types of slope failure,” 2018). Circular failure is likely to occur when the tiny particles within a mass of soil or rock are so little in comparison to the slope's size that their form inhibits them from interlocking (Hoek, 2009). According to (“Types of slope failure,” 2018),

in homogeneous soils, the shape is circular while in the case of non-homogeneous soils, it is non-circular. Rotational failure may occur as a Face failure, a toe failure, and a base failure. Face failure occurs when soil above the toe contains a weak stratum and the failure plane intersects the slope above the toe, Toe failure is the most common failure in which the failure plane passes through the toe of the slope, Base failure occurs when there is a weak soil stratum under the toe and failure plane passes through the base of slope (Figure 2.4).

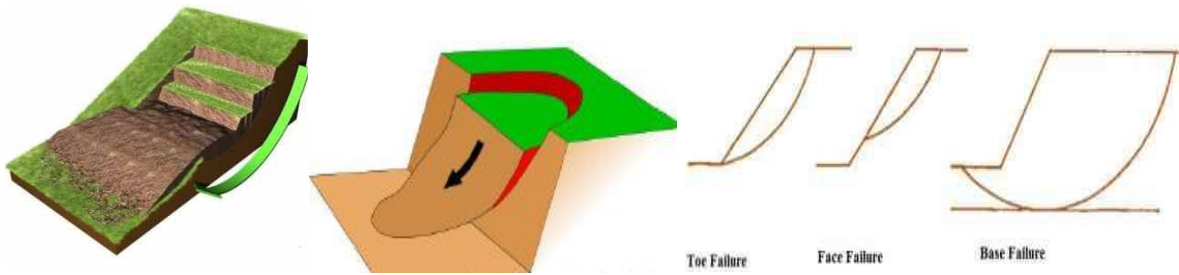


Figure 2.4. Types of Circular/Rotational Failures (Hoek, 2009, “Types of slope failure,” 2018)

iv. Wedge failure

Wedge failure occurs when there are discontinuities like fissures, joints, or weak soil layers in the slope, or when a slope is made of two different materials (Kumsar et al., 2000). Wedge failure sometimes referred to as block failure or plane failure, results in an inclined failure plane (“Types of slope failure,” 2018) (Figure 2.5). While wedge failure can happen on both infinite and finite slopes, translational failure can only happen on infinite slopes (G3soil works, 2020). When rock wedges are positioned on discontinuities, they will slide along the junction's line if the inclination is substantial and higher than the friction angle (Wolde, 2013). According to Smith & Arnhardt (2016) and Scheer et al., (2001) the minimal description of the structural prerequisites for wedge failure are: (1) the intersection line's trend should roughly follow the slope face's inclination direction, (2) the intersection line should also daylight in the slope if its plunge is less than the slope face's inclination, (3) the intersection line should also equal or exceed the angle of friction of the intersecting surfaces (discontinuities), and (4) Cohesion (C) should equal zero.

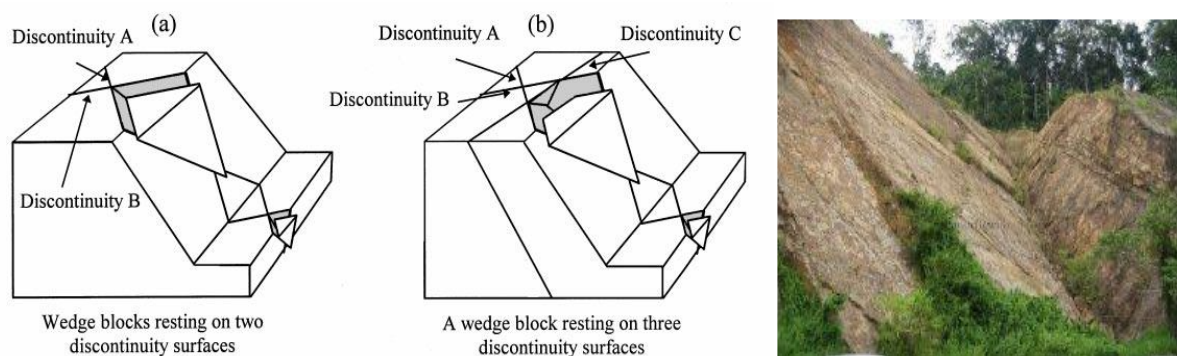


Figure 2.5. Types of wedge failures (Kumsar et al., 2000, “Types of slope failure,” 2018)

v. Translational failure (Plane failure)

When there is a planar failure the mass moves along a surface that is either gently undulating or roughly planar (Figure 2.6). Usually, the movement is structurally controlled by Surface weakness includes features like joints, faults, bedding planes, and differences in shear strength

between layers of bedded deposits and it includes the point where hard bedrock meets worn rock on top (Sharma et al., 1995).

Conditions for the appearance of planar failure: The strike of the slope doesn't differ more than $\pm 20^\circ$ from the strike of the weakness plane, the toe of the failure plane has to cross the slope between the toe and crest, the dip of the failure plane must be less than the dip of the slope face, and the internal angle of friction for the discontinuity must be less than the dip of the discontinuity (Wolde, 2013)

According to ("Types of slope failure," 2018),

When there are infinite slopes, translation failure happens, and in this situation, the failure surface is parallel to the slope surface. When a slope has no defined boundaries and the soil beneath the free surface has the same characteristics down to the same depths, the slope is said to be infinite. As indicated before, when the soil along the slope has comparable qualities up to a certain depth and soil below this layer is a strong or hard stratum, the weak topsoil will produce a parallel slip surface when failed. This type of failure can be detected in slopes of layered materials or natural slope formations.

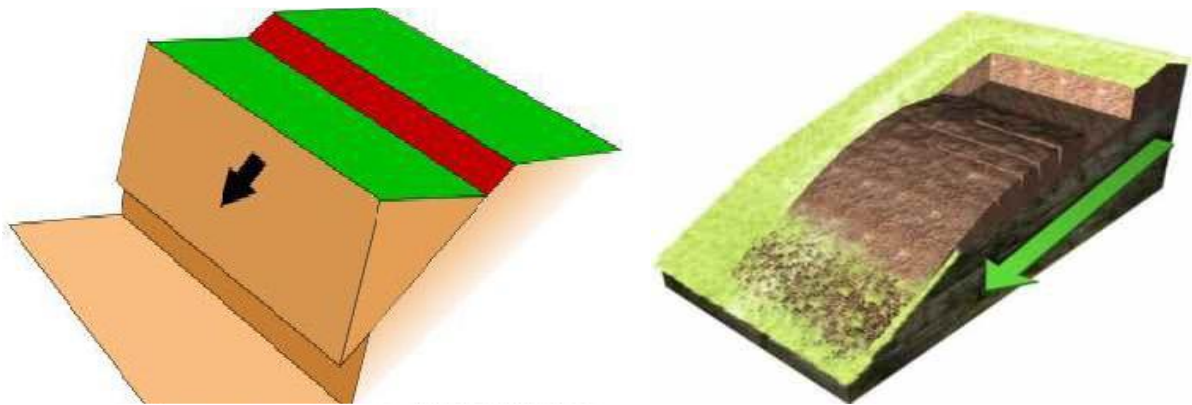


Figure 2.6. Planar/Translational Failure (Hoek, 2009), ("Types of slope failure," 2018)

vi. Compound Failure

According to (G3soil works, 2020), The result of both translational and rotational slippage is a compound failure, and here, the slip surface is curved at both ends, resembling a rotating slip surface, and flat in the middle, resembling a translational failure. The slip surface flattens

whenever there is a hard soil layer at a considerable depth beneath the toe (Figure 2.7) (“Types of slope failure,” 2018).

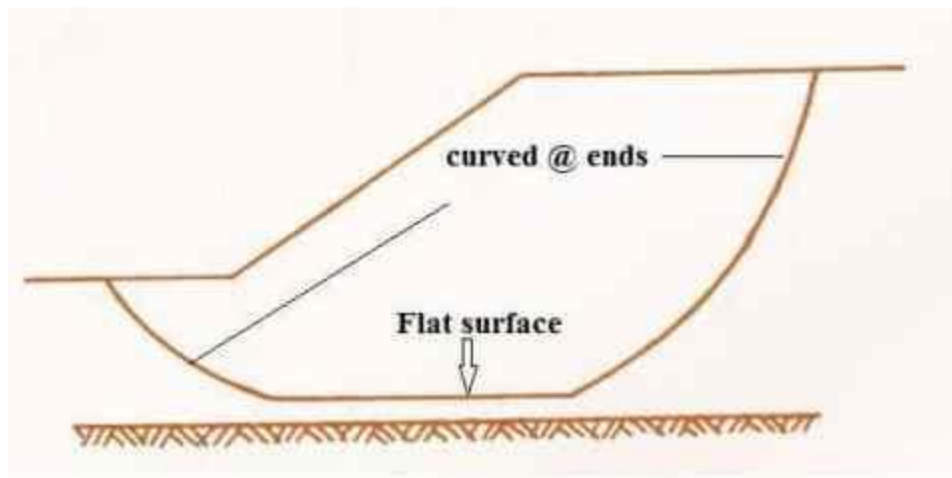


Figure 2.7. Compound failure (“Types of slope failure,” 2018)

2.3. Factors influencing slope stability

Numerous factors, including the force of gravity, hydraulic factor, dynamic force, land cover change, geologic factors (lithology, geological structures, Geotechnical properties), Geomorphic factors like (slope gradient, slope aspect, and shape and elevation), Anthropogenic (human) factors and land cover change all have an impact on slope stability (Karkar & kanungo, 2006, “factors affecting slope failure,” 2020, Kumar & Kumar, 2022).

This causative factor may be classified into two broad classes which is internal factors such as Lithology of slope material, Structural features, Geomorphology, Vegetation, Hydrogeologic conditions and external factors such as, Seismicity, Climate, Undercutting by river, Anthropogenic factors (Land use change and Unplanned construction) (Nelson, 2013). Any of these elements changed separately or in combination could lead to slope failure by altering the slope's steady state condition and decreasing its stability (Wolde, 2013). The following is an explanation of the primary component influencing slope stability according to (Civil Engineering Terms, 2012), (Nelson, 2013), (Kumar & Kumar, 2022). A summary of the causative factors is shown in (Table 1).

2.3.1. Geologic factors

i. Geotechnical properties

The important geotechnical properties affecting the stability of a slope are the shear strength of the material, particle size distribution, density, permeability, moisture content, plasticity, angle

of repose, strength of the rock mass (Kumar & Kumar, 2022). The normal stress on the slip surface, cohesiveness, and internal angle of friction are the three main shear strength characteristics that determine the shear strength of soil material where friction is a resistive force between two surfaces, and cohesiveness is the result of a particle's surfaces being connected soil (“factors affecting slope failure,” 2020). It depends on a number of variables, including as the characteristics of the material, the rate and direction of the applied force, the drainage conditions within the mass, and the amount of the confining pressure (Wolde, 2013). Depending on the size, form, and gradation of the soil as well as its density, the permeability of the soil influences the water levels and seepage patterns in the slope, which in turn can alter the material's shear resistance (“factors affecting slope failure,” 2020). The angle of repose of loose material is dependent on the size and shape of the particles, suggesting that smooth and spherical particles have a lesser angle of repose than angular and rough particles and coarse fragments may support a steeper slope than fine fragments (“factors affecting slope failure,” 2020).

ii. Geological structures

Geological structures that are potentially weak planes in a slope include bedding, joints, foliation, cleavage, and faults have lower strength than that of the nearby unbroken rock (Wolde, 2013). The tectonic context of the region, includes foliation structures, faulting, jointing, and fractures, because fracture and fault zones are areas of weakness that may also be unstable and where failures typically occur, it is crucial to understand how these zones are oriented with respect to slope angle, direction, and strength (Kumar & Kumar, 2022).

iii. Lithology

The term "lithology" describes the physical, chemical, and weathering aspects of rocks and soils, as well as additional features that impact permeability, shear strength, and other physicochemical properties (Fikadu, 2021). “Slope instability and lithology are closely related due to rock mass contact, water percolation, weathering processes” (Wolde, 2013).

2.3.2. Hydrologic factor

Slope stability is affected by water in two ways which are produced by groundwater, and the precipitation infiltration that penetrates the surface and flows downward (“Factors affecting slope failure,” 2020). It is associated with local precipitation patterns, terrain, adjacent water bodies, and the geo-hydrological properties of the rock mass (Wolde, 2013). Failures of the slope may happen When surface water (overland flow) from flooding soaks into slopes, the banks of streams and rivers are undercut (Highland & Bobrowsky, 2008). How rapidly water

percolates into the slope is another crucial element to consider; some slopes can become unstable even with little water penetrations, while others are more susceptible to significant waterfalls over time (Ashkan & Alborz, 2015). Water pressure acting within a discontinuity reduces the effective normal stress acting on the plane, improving pore water pressure in granular media, decreasing cohesion in soils, and increasing the weight of the slope and these effects reduce shear strength along a plane (Ashkan & Alborz, 2015).

2.3.3. Seismicity

According to (Kumar & Kumar, 2022), Seismic waves passing through rock add stress which could cause fracturing in the rock mass. Landslides are more likely to occur during earthquakes in steep places where landslides are prone to occur because of the liquefaction of vulnerable sediments, the dilatation of soil components produced by shaking, or both, and the latter permits water to seep quickly into the ground (Highland & Bobrowsky, 2008). Events such as blasts and earthquakes have two separate effects on rock slopes over different time intervals; The rock immediately separates from a slope face co-seismically as the initial effect and the second effect, which happens over a longer period, involves the opening of fissures and the fracturing of rock, which could eventually cause rock dislodgments (“factors affecting slope failure,” 2020). The impacts of seismicity on rock slopes are contingent upon the specific conditions present within the rock mass. The area's geological and topographic features may also regulate how susceptible a rock slope is to failing under the impact of seismicity and depends on the shaking of the ground rather than on the actual magnitude of the earthquake (Wolde, 2013), (“factors affecting slope failure,” 2020).

2.3.4. Land Use Land Cover

Worldwide, land cover is one of the main variables influencing the frequency of rainfall-induced slope failures (Ho, 2007). Unconsolidated materials are held together and erosion is prevented by the robust interlocking network that plants produce. Shear strength is also increased by plants since they are highly efficient at extracting water from the soil (“factors affecting slope failure,” 2020). Lastly, by attaching the soil to the bedrock or one another, root systems operate as slope-stabilizing components (Ho, 2007). A slope that has lost vegetation due to grading, logging, overgrazing, or fire may erode more quickly and experience failures involving surficial (shallow) material (Ho, 2007).

2.3.5. Anthropogenic (human) factors

Human activity in reaction to slope changes is referred to as anthropogenic influences (Wolde, 2013). In the process of constructing roads and highways, humans may undercut and change the slope. When slopes are crowded during mining and quarrying operations, the probability of a slope collapse increasing (Meusburger & Alewell, 2008)

2.3.6. Geomorphic factors

Geomorphic factors including topography and slope, including its gradient, aspect, elevation, plane curvature, and shape have a significant impact on the onset of slope instability (Wolde, 2013). Materials slide more readily down the slope when the slope gradient rises because of the increased shear stress brought on by gravity.

i. Slope gradient

As the slope increases, the tangential or shear stress component of gravity increases while the perpendicular component of gravity decreases (Nelson, 2013). Hence, steep slope angles that raise shear stress and decrease shear strength have an impact on a material's downslope movement (Kumar & Kumar, 2022). Tectonic tilting, undercutting, erosion activities, and the removal of lateral support can all increase a material's shear stress (Wolde, 2013). Rock's natural properties, such as the angle of internal friction, cohesiveness, and the binding force of plant roots between particles, determine shear strength (“factors affecting slope failure,” 2020).

ii. Aspect

Aspect is the ground surface's directional slope, or slope orientation, expressed in degrees ranging from 0 to 360 (Fikadu, 2021). It is important to landslide research because it controls the amount of sunlight that the slope receives, the direction of the wind, the amount of rainfall (and its saturation), and the discontinuity conditions (Fikadu, 2021). Because slope shape concentrates or disperses surface and primarily subsurface water in the landscape, it has a significant impact on the slope stability of steep terrain (Wolde, 2013).

iii. Plan curvature

Plan curvature is the curvature of a line formed by the intersection of an imaginary horizontal plane with the ground surface, or the curvature of topographic contours. It is a negative plan curvature (concave) denotes flow concentration, a positive plan curvature (convex) denotes flow divergence and Straight contours are referred to as planar regions (Fikadu, 2021).

iv. Distance from the stream

The distance from the drainage axis was taken into consideration when evaluating the influence of drainage on landslide incidence. Previous studies have shown that being adjacent to a stream has a significant impact on the occurrence of landslides, as extensive gully erosion is frequently the source of mass wasting. The slope's proximity to the stream course is an important determinant of the area's landscape evolution as well as an indicator of landslides and other erosional issues (Fikadu, 2021).

2.3.7. Natural Factors

i. Gravity

The primary cause of shear stress and its relationship to slope stability is the force of gravity and the slope's gradient (“factors affecting slope failure,” 2020). The forces of gravity consist of two components: a component that acts perpendicularly to the slope and a component that acts tangentially (Nelson, 2013).

ii. Rain falls

Water from precipitation and snowmelt adds to the slope's weight by penetrating into rock cracks and discontinuities and replacing air in pore spaces and soil voids. It results in an increase in effective stress, which blows up the slope (“Factors affecting slope failure,” 2020).

iii. Erosion

Erosion such as large-scale erosion which is caused by a river at the foot of a slope and local erosion is more localized and is brought on by surface runoff or groundwater (“factors affecting slope failure,” 2020). Removing material close to a potential slide's toe reduces the confining tension that might be stabilizing the slope, and localized erosion of the joint filling material or areas of weathered rock can effectively lessen the interlocking between adjacent rock blocks (“factors affecting slope failure,” 2020).

Table 1. Summary of factors influencing slope stability (“Factors affecting slope failure,” 2020)

No	Parameters	Details	Effects
1	Natural Factors	Force of gravity Climate Weathering Erosion	✓ Pulling everything in a direction toward the centre of the Earth. ✓ Decrease confining stress ✓ Reduce shear strength
2	Hydrologic factors	Rain falls, Groundwater, Drainage pattern, Permeability, Aquaifers,	✓ Increases the weight of the soil, ✓ Change the angle of repose, ✓ Reducing the strength of the soil, ✓ Reduce the cohesion between the mineral grains ✓ Liquefaction problems. ✓ Increase the fluid pressure ✓ Decrease shear strength and reduce confining stress
3	Dynamic forces	Tectonics, Earthquake, Blasting, Volcanoes	▪ The lower soil layer became liquefied. ▪ Causes fracturing in the rock mass
4	Land cover change	Deforestation	✓ The slope becomes more vulnerable to intense rain and erosions.
5	Anthropogenic (human) factors	Undercutting and altering the slope During construction.	✓ Slope collapse risk may occur
6	Geologic factors	Geological structures,	✓ Bedding, joints, foliation, cleavage, schistosity, and faults are potentially weak planes in a slope
		Geotechnical properties,	✓ The properties of shear strength of the material, particle size distribution, density, permeability, moisture content, plasticity, and angle of repose
		Lithology	✓ Due to its rock mass contact, water percolation, and weathering processes
7	Geomorphic factors	Slope gradient	✓ Exhibit varying degrees of water infiltration
		Aspect, and shape	
		plane curvature	
		Distance from the river.	✓ If slope gradient rises shear stress will be increased by gravity.
		Slope morphometry,	
		Relative relief etc.	

All of the factors mentioned above may be divided into two groups based on shear properties (1) the factors that lead to an increase in the shear stresses; (Weight of water causing saturation of soils, Surcharge loads, Seepage pressure, Steepening of slopes either by excavation or by

natural erosion), (2) the factors that lead to a reduction in the soil's shear strength are; (Rise in water content, Rise in pore water pressure, Seismicity, Shock, or cyclic load)(“Slope stability,” 2020).

2.4. Landslide Mapping Approaches

For many years, researchers have regularly employed landslide susceptibility maps (LSMs) to estimate the likelihood of landslides (JRC, 2007). The term "landslide susceptibility" describes the ability to anticipate the geographical distribution of landslides based on both external and internal factors related to landslides and the main goal of landslide mapping is to pinpoint locations where landslides are likely to occur within a region based on this variety of internal and external causal factors (Tadele, 2014). Geographic Information System (GIS) has been used extensively in recent years by many researchers to create landslide susceptibility maps, and the statistical technique which includes logistic regression, weights of evidence, and frequency ratio is currently the most widely used method for assessing landslide susceptibility (Thapa & Bhandari, 2019). A summary of landslide susceptibility mapping approaches is shown in Table 12.

Table 2. Mapping methods concerning types and scales (Tadele 2014), (Sarkar & Kanungo, 2006)

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

2.4.1. Frequency ratio

The frequency ratio model performs well with high accuracy, is easy to use, and can offer the contribution of each causative factor class for landslide occurrence, several researchers have recently employed frequency ratio methods to build landslide susceptibility maps (Fayez et al., 2018; Thapa & Bhandari, 2019; Elfriede et al, 2019; Mersha & Meten, 2020; Fikadu, 2021; Youssef et al, 2023, Javad et al, 2014). In frequency analysis, the normalized frequency distribution of landslides per unit area in each category of individual factors is determined manually or in a GIS system, overlying each thematic data layer with the landslide layer (Sarkar & Kanungo, 2006). The FR technique is based on the conditional probability principle, which states that the stronger the association between factor classes and landslides, and vice versa, the larger the ratio and to get the final landslide susceptibility index (LSI), the frequency ratio was then added (Fikadu, 2021). Frequency ratio methods are highly applicable for hilly and rugged topography areas (Meten, 2020)

2.4.2. InSAR (Interferometric Synthetic Aperture radar)

According to (Pepe & Calò, 2017), With the use of InSAR, one can quantify the deformations of the Earth's surface brought about by both natural and man-made processes. (DInSAR) techniques use the microwave properties of radio waves to determine the rate of ground movement with millimeter accuracy (Necula et al., 2021). Since the study area is located at the margin of the main Ethiopian rift (MER), its deformation behavior remained undetected for a long time using conventional approaches (Kiros et al., 2020). Based on time series InSAR using sentinel-1 data and analysis by SNAP software was used to map and detect instabilities or slow-type slope movements.

2.4.3. SNAP (Sentinel Application Platform)

The SNAP program includes the Sentinel-1 toolbox (S1TBX), which facilitates reading, displaying, processing, and writing of data from different remote sensing satellites, including Sentinel-1 (García et al., 2020). Numerous polarimetric and interferometric tools for data conversion, calibration, co-registration, speckle filtering, sub-swath merge, subset, multilook, and other tasks are included in the toolbox. Researchers in the field of satellite remote sensing frequently utilize the Sentinel-1 toolbox in conjunction with Sentinel-2, Sentinel-3, SMOS, and Proba-V toolboxes (García et al., 2020).

2.5. Previous work

Previously the area was investigated by Woldearegay 2008, Abay & Barbieri 2012, Hagos 2012, Tadele, 2014 Kropá~ & Va 2015, Kiros 2020, Enigda & T. 2021, (Mebrahtu et al., 2022) and Agegnehu 2023 with a medium scale (1:50,000) of analysis. The first authors of the area (Woldearegay, 2008) evaluate the characteristics of a large-scale landslide triggered by heavy rainfall in the Tarmaber area, central highlands of Ethiopia, and report that about 35km of the localities “Yizaba Wein” and “Shotel Amba” area, were completely affected by a single major deep-seated landslide that took place in 2005 and that “displaced more than 3000 and demolished 1250 dwelling houses, 1 church, and 1-elementary school.

After the first authors, (Abay & Barbieri 2012) determined four landslip susceptibility classes: very high susceptible (0.7%), high susceptible (22.7%), moderate susceptible (65%), and low susceptible (11.6%) utilizing GIS techniques, the frequency ration model (FR), and the kinematic slope stability method. Using the GIS-based Overlay Mapping method (OM), Frequency Ratio method (FR), and Analytical Hierarchical Process (AHP) method, identified four landslip hazard zones: very high susceptible zone (32%), high hazard zone (33%), moderate hazard zone (26%), and low hazard zone (9%). The three approach outcomes were shown to have a reasonable prediction rate based on a comparison with field conditions. It also implies that assessing the relative importance of the many causative factors for the landslide implied by the FR approach was crucial. In conclusion, it was suggested that the Shotel Amba and Yizaba Weyn areas be completely evacuated.

Tamene Tadele 2014, also by adopting the “Slope Stability Susceptibility Evaluation Parameter (SSEP)” rating scheme, a facet map was prepared from the topographic map (1:50000) and classified into three zones. Kropá~ & Va 2015, using "Remote Sensing for Characterization and Kinematic Analysis of Large Slope Failures" of the region, they identify the stable area in the lower portion of the slope, the shallow landslides surrounding the main landslide body, which increased the area to 8.5 km², and the main landslide, which covers an area of 6.5 km² and they assume that “precipitation accumulated over several months was the main triggering factor for such a large landslide”. Elias Assefa Enigda & T. 2021 also, adopt a methodology of “integration of an Expert Evaluation Approach with the statistical method of Slope stability susceptibility evaluation parameter (SSEP) rating scheme”. The result of the two methods shows different values and in terms of effectiveness, the SSEP method was good.

A detailed investigation was carried out using a “multidisciplinary approach based on geological, morpho-tectonic analysis, geomorphological, hydrogeological, hydrogeochemical, isotopic, geophysical (seismic refraction and vertical electrical sounding) and geotechnical (kinematic analysis and numerical modeling)” investigations by (Kiros 2020). According to the authors (Kiros 2020) “The steep terrain and the pressure created by precipitation, tectonic uplift, the complex slope morphology, and its high relief energy, the presence of closely spaced normal fault segments with steep slope angles, and the deepening action of the streams” are the primary causes of the landslide. For further research, he emphasized the need for more studies on slope stability evaluations employing, detailed drilling works and field monitoring techniques. The study conducted by (Natnael Agegnehu 2023) also focuses on "Landslide Mapping Using InSAR and GIS Techniques"; to conduct the InSAR analysis, the weighted linear combination (WLC) method was used for landslide susceptibility mapping, and SARPROZ software was utilized to generate a landslide displacement map using PS-InSAR. The results of the GIS analysis classify landslide into four zones while the InSAR shows a displacement of -12 to 12 mm/yr.

2.6. Adopted Methods and Lessons Learned

The frequency ratio and InSAR methods are adopted for the current study. The methods are selected based on the recommendations and performance of previous works. In the study area, two detailed studies with a medium-scale analysis of PhD thesis are done by Asmelash Abay 2012 and Tesfaye Kiros 2020. The frequency ratio methods perform well and show a reasonable prediction performance and are more important than the other methods to analyze the relation between landslides and positive factors. Since the study area topography has hilly rugged features, the Frequency ratio method is highly applicable for such hilly and rugged topography areas (Meten, 2020). According to the recommendation of (Kiros 2020), for field monitoring purposes, instead of Physical techniques like extensometer, displacement sensor, and other physical methods which are relatively expensive; the InSAR analysis method is adopted.

On the other hand, the area was investigated with a medium scale (1:50,000) of analysis, and determining the scale of analysis is an important consideration for the method of landslide susceptibility methods (Anbalagn, 1989 and 1992). The bivariate statistical method with the scale of analysis has a better application to the large scale (1:25,000) as shown in Table 2. Mapping methods concerning types and scales (Tadele 2014), (Sarkar & Kanungo, 2006)

CHAPTER - THREE

DESCRIPTION OF THE STUDY AREA

3.1. Location of the Study Area

The study area is situated in Amhara Regional State, North Shewa zone of Tarmaber woreda, in Ethiopia's central-western highlands, along the Main Ethiopian Rift escarpment border. It is approximately 193 km away from Addis Ababa. Specifically, it is located 3km northeast of Debresina town. To determine the boundary of the research area, landslide bodies (prior prone deep-seated landslide areas) and the administrative boundaries are taken into account. It includes all the two localities of Yizaba Weyn and Shotel Amba area. Its geographic coordinates are from the north UTM 1090881m N to 1098881m N and from the east 578265m E to 590265m E and it covers 54 km² areas as shown in (Figure 3.1) which is extracted from Landsat 9 image with true color band (4-3-2) composite view.

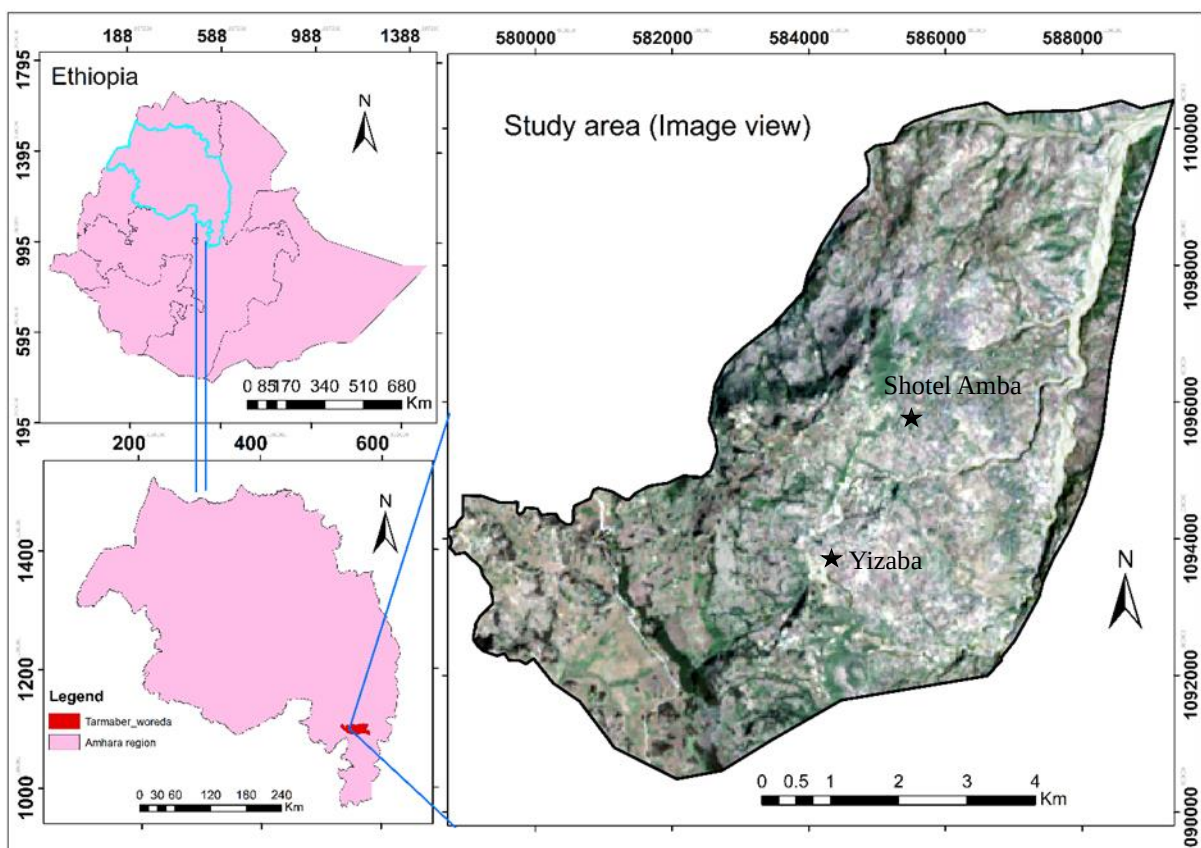


Figure 3.1. Location map of the study area

3.2. General mass movement condition

Ethiopia's highlands and mountainous regions, including the Blue Nile Gorge, the Lower Wabe-Shebele River valley, the Gilgel Gibe River, Tarmaber, the Kombolcha-Desie road, Sawla's Uba Dema village, the Wondogenet area, and many more, frequently experience landslide-related issues (Abebe et al., 2010, Mersha & Meten, 2020). As reported (Woldearegay, 2008), “The largest landslide occurred in September 2005 in the Yizaba and Shotel Amba districts, displacing almost 3,000 people from their homes, destroying 1500 hectares of farmland, 1250 residential buildings, and one school” and the instability issue is significantly continued, with multiple small scale landslides on this deeply seated landslide (Mebrahtu et al., 2021). It was initiated after a long-time small creeping and large sliding mass took place from 2005 to 2006. Numerous tension cracks have formed in the area, and these cracks are indicators that further slides are likely to occur soon (Kiros et al., 2020). The landslide distribution condition around the study areas is shown in Figure 3.2

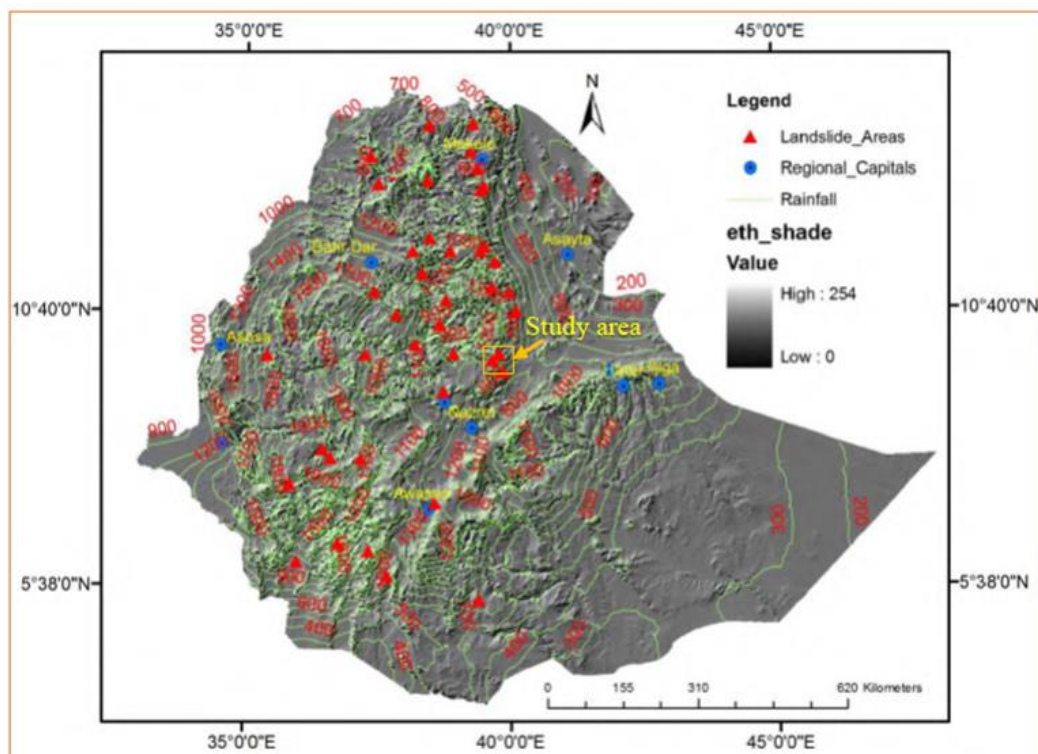


Figure 3.2. Landslide distribution of Ethiopia, modified from (Woldearegay, 2013)

3.3. Tectonic Setting

Since the study area is located along the margin of the Main Ethiopian Rift (MER) as shown in (Figure 3.3), which is a tectonically active area considering the tectonic action is important. Along the Gulf of Aden, the Red Sea, and the Main Ethiopian Rift, the Arabian-Nubian Shield broke apart, causing the Nubian, Arabian, and Somalian Plates to separate (Beyene &

Abdelsalam, 2005a). Tectonically Ethiopia is characterized by Precambrian tectonics, and Phanerozoic tectonics (Late Palaeozoic to Cretaceous tectonics and Cenozoic tectonism). The study area is vulnerable and related to the Cenozoic tectonism which is the separation and broken of the Afar depression, the Main Ethiopian Rift, and the Ethiopian Plateau. Active extensional tectonics that support the relative movement between the African and Somalian plates at a rate of approximately 6-7 mm/year characterize the MER (Tadesse Alemu, 2012 and Beyene & Abdelsalam, 2005a)

3.3.1. Precambrian Tectonics

The Precambrian of Ethiopia consists of litho tectonic terranes that are juxtaposed along north-south sheared thrust contacts between low-grade meta volcano-sedimentary sequences of the Arabian-Nubian Shield and high-grade gneisses of the Mozambique Belt and these contacts are identified by arc-like ophiolite sequences and the belts of Moyale, Adola, Bul Bul (Southern Ethiopia), and Tulu Dimtu (western Ethiopia) are the principal representatives of these litho tectonic terranes (Tadesse Alemu, 2012).

3.3.2. Phanerozoic tectonics

The tectonic evolution of the country during Phanerozoic can be thought of as relating to the polyphase break-up of Gondwanaland, which was accomplished, in general by reactivation along the Precambrian structures (Tadesse Alemu, 2012; Beyene & Abdelsalam, 2005). The Phanerozoic tectonics can broadly be divided into; (a), Late Palaeozoic to Cretaceous, and (b), Cenozoic tectonics (Tadesse Alemu, 2012).

- a) Late Palaeozoic to Cretaceous tectonics; are related to the early rifting of Africa from East Gondwana, which led to the formation of multiple rift basins and the deposition of terrestrial and marine sediments in central and eastern Africa (Rowland et al., 2007; Tadesse Alemu, 2012). The Ogden, Abay, and Mekelle Basins are presumed to be intracontinental rift basins formed as a result of extensional stresses induced by the break-up of Gondwanaland in the Late Palaeozoic (Tadesse Alemu, 2012, Beyene & Abdelsalam, 2005)
- b) Cenozoic tectonism: in Ethiopia, it is related to the final stage of Gondwanaland rifting and is represented by: The Afar Depression, The Main Ethiopian Rift, and The Ethiopian Plateau (Rowland et al., 2007; Tadesse Alemu, 2012).
 - i. The Ethiopian Plateau: The Afro-Arabian Rift System divides the Ethiopian Plateau into its eastern and western shoulders (Tadesse Alemu, 2012, Beyene & Abdelsalam, 2005a) the Tana Basin, a faulted depression situated between the tectonic western Afar

Margin, which overlooks the Afar Depression to the east, and the erosional Tana escarpment to the west, is part of the northwest Ethiopian Plateau (Tadesse Alemu, 2012).

- ii. The Main Ethiopian Rift: The Main Ethiopian Rift (MER) is a sector of the East African Rift system that extends from the Afar Depression at the junction of the Red Sea and the Gulf of Aden to the Kenya Rift (Tadesse Alemu, 2012). It trends generally northeast.
- iii. The Afar depression: This tectonic depression is still active today, resulting from the Afro-Arabian plateau breaking apart during the Oligocene-Miocene period and there is evidence of continuous extensional deformation in the area due to the recent faulting, shallow earthquakes, and ongoing volcanism (Tadesse Alemu, 2012; Rowland et al., 2007). According to these reasons tectonic is one of the causative factors for the study area located along the main Ethiopian escarpment that involves active extensional movement in the region (Figure 3.3)

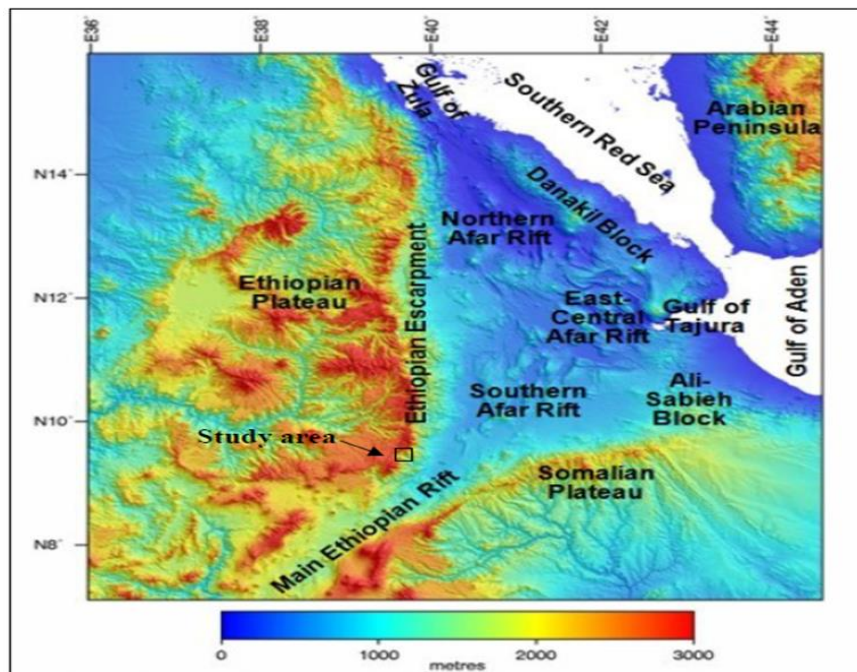


Figure 3.3. DEM of the Afar area showing geomorphological and structural divisions (Source (Afar Rift consortium, n.d.), Beyene & Abdelsalam, 2005, Hagos, 2012)

3.4. Geological Setting

3.4.1. Regional Geology

Ethiopia's geology is characterized by three main groups of rocks: Cenozoic volcanic rocks and related sediments, Palaeozoic–Mesozoic sedimentary rocks, Precambrian rocks, and range in

age from Precambrian to Recent (Tadesse Alemu, 2012). Three litho-stratigraphic units which are (i) Precambrian crystalline rocks; (ii) Mesozoic sedimentary rocks; and (iii) Tertiary-Quaternary volcanic rocks with minor lacustrine sediments, volcanic ash, and surface deposits represent the geology of central Ethiopia (Kiros et al., 2020).

i. Precambrian crystalline rocks

The Precambrian rocks are the earliest basement rocks of Ethiopia which are a diverse range of intrusive, volcanic, and sedimentary rocks with varying degrees of metamorphism (Hagos, 2012). These are primarily linear belts with a northward trend that contain low-grade mafic-ultramafic and volcano-sedimentary rocks. In between are gneisses and migmatites of varying grades (Tadesse Alemu, 2012). The Precambrian formations in the south and west of the country have been more strongly metamorphosed than those found in the northern section of the country (Hagos, 2012).

ii. Palaeozoic–Mesozoic sedimentary rocks

Ethiopia experienced continuous uplift for a large portion of the early Palaeozoic era, which resulted in extensive erosion overall but the northern provinces, where deposits partially originating from glaciers have been observed towards the end of this period (Tadesse Alemu, 2012), (Hagos, 2012). The Mesozoic era saw subsidence, which resulted in the formation of a sizable shallow sea that first covered the province of Ogaden before gradually moving further to the north and west as the land continued to sink (Hagos, 2012). The ancient land's surface was covered with sandstone, and when the water's depth rose, mudstone and limestone deposits happened (Tefera et al., 1999). Following this order, lake beds were generally raised and dried out, leaving behind precipitates of gypsum and anhydrite (Hagos, 2012).

Widespread volcanism and faulting were brought on by regional tectonic activity linked to rifting episodes in the late Tertiary that occurred in the Red Sea, Gulf of Aden, and East African Rift Valley (Hagos, 2012). Along the Nubian and Arabian borders of the southern Red Sea, massive amounts of flood lava series peaked between roughly 31 and 29 Ma, resulting in the emplacement of up to 2000 meters of lavas and ignimbrites (Wolfenden et al., 2005).

The Ethiopian volcanic rocks were divided into two main series: Trap Series or Plateau Series and Rift Volcanic (Mohr, 1971), (Zanettin et al., 1974), (Kiros et al., 2020). Large volumes of ash and coarser fragmentary material erupted along with it, creating the Trap Series and rift

volcanoes that were likewise composed of fragmented rock and alkali basalts formed along the eastern border of the Lake Tana depression (Hagos, 2012).

iii. Cenozoic volcanic rocks and associated sediments

Volcanism began in the Eocene-late Oligocene with the eruption of flood basalts, which have been linked to one or more mantle plumes impinging on the lithosphere's base beneath the rifts in the Afar or Northern Kenya (Tadesse Alemu, 2012). These traps are heavily weathered and fractured by faults (Beyene & Abdelsalam, 2005b). In the central part of the northwestern plateau, the volcanic rocks are classified into the Ashangi Formation, Aiba basalts, Alaji Formation, and Tarmaber basalt (Zanettin et al., 1974, Kiros et al., 2020) as shown in (Figure 3.4).

a) Ashangi basalt

The Ashangi basalt is the earliest example of fissural flood basalt that is mostly composed of slightly alkaline basalts with rare rhyolites, inter-bedded pyroclastic, and frequent injections by dolerite sills and dykes (Zanettin & Justin-Visentin, 1974). Lacustrine deposits are interbedded with lignite seams in the upper, more tuffaceous portion (Kiros et al., 2020). The Ashangie basalts are distinguished by severe fracturing and crushing, columnar jointing, significant weathering, and tilting in diverse directions (Tadele, 2022).

b) Aiba basalts

The Aiba basalts consist of massive transitional flood-basalt flows, with intercalated agglomerate beds, and the flow is often formed of dense, black, fine-grained olivine basalt, which is typically columnar and is between 15 and 50 m thick (in extreme situations pounding to 100 m) (Mohr & Zanettin, 1988), (Tadele, 2022).

c) Alaje Formation

The majority of the Alaji Formation is made up of aphyric flood basalts associated with rhyolite, ignimbrites, and subordinate trachytes that rest conformably on the Aiba basalts; however, in certain locations, such as the Kesem and Muger valleys and the majority of outcrops on the Southeast Plateau, it is directly on top of Mesozoic sediments (Mohr & Zanettin, 1988), Kiros et al., 2020).

d) Tarmaber formation

The Tarmaber-Megezez Formation is a grouping of fissural eruption products that followed the shield volcano's products in the southern portion of the northwest plateau (Kiros et al., 2020). According to (Kieffer et al., 2004) like flood volcanoes, shield volcanoes are bimodal and contain sequences of alternating basalts, rhyolite, and trachytic lava flows, tuffs, and

ignimbrites, especially near their summits. This unit is the most recent of the flood basalts with a tholeiitic composition that forms one of the prominent landmass shield volcanoes (Kieffer et al., 2004). They are composed of scoriaceous lava flows, peralkaline rhyolites with a maximum thickness of 1,000m around the centers, and lenticular, frequently zeolitized, alkali basalts with many tuffs (Mohr & Zanettin, 1988)

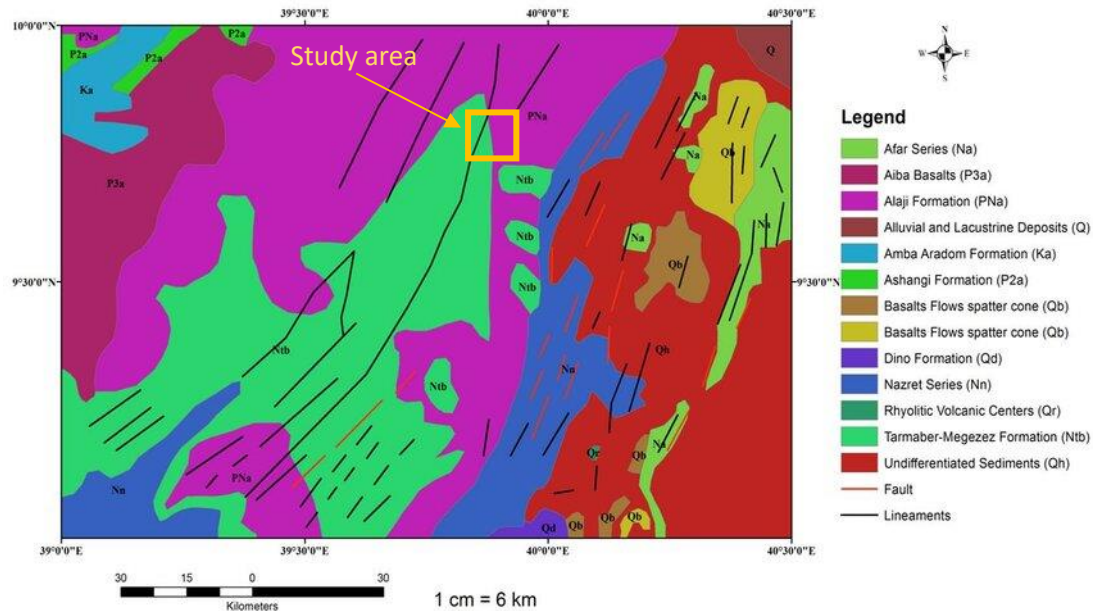


Figure 3.4. Regional geological map of Debre Birhan map sheet after (Mengesha Tefera et.al 1996) (Kidane & Nugsse, 2016)

3.4.2. Local Geology

The study area comprises four geological units with variable thicknesses of the Tarmaber basalt, Alaje basalt, alluvial deposits, and Eluvium-colluvium deposits. This layer is underlined by a light grey to dark and impermeable ignimbrite/tuff layer which is a part of Alaje formation. The rugged mountainous and high elevated eras are covered by highly weathered and fresh, highly fractured to massive Tarmaber basalt. The gentled slop areas are covered by highly fractured, highly jointed, flattened, and layered Alaje basalt. The lower elevated areas are also covered by Eluvium-colluvium deposits which is a part of Allaje formation. The alluvial deposits are encountered along the river section. Alaje formation contains the Alaje basalt, tuff, and Ignimbrite, which are highly fractured and weathered and cover 36% of the area. About 37% of the area (20km) is covered by Tarmaber basalt, 21% is covered with Eluvium-colluvium deposits, and 7% of the study area is covered by Alluvial deposits (Figure 3.5)

It is widely acknowledged that lithological changes greatly affect the strength and permeability of rocks and soils, which in turn determines the occurrence of landslides and are taken as one

of the costive factors (Hagos, 2012, Mersha & Meten, 2020). The lithological map of the study area is prepared with the same scale of the study area from the field survey, and Google Earth images, and supported by a 1:250,000 scall regional geological map of the Debrebirhan sheet (Figure 3.6).

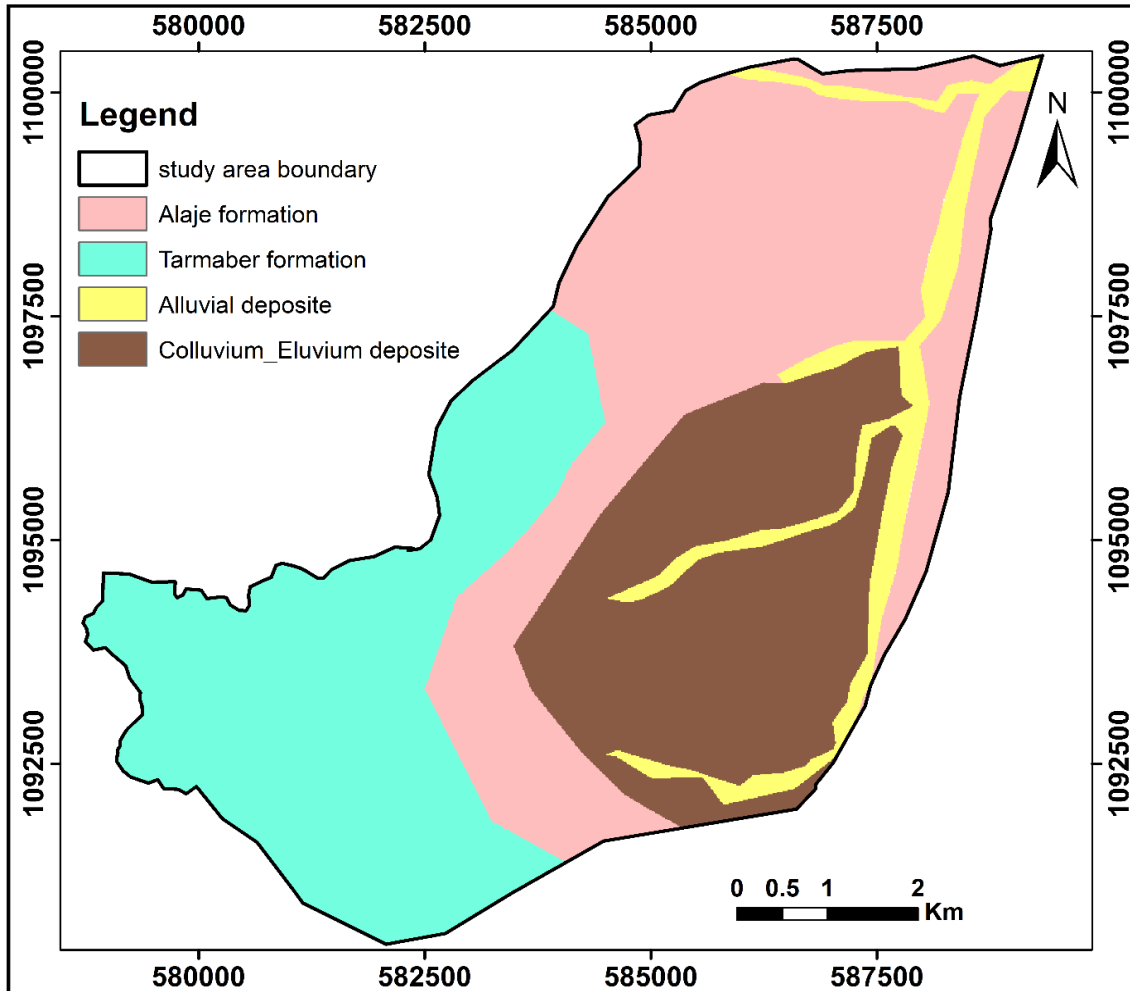


Figure 3.5. Lithology map

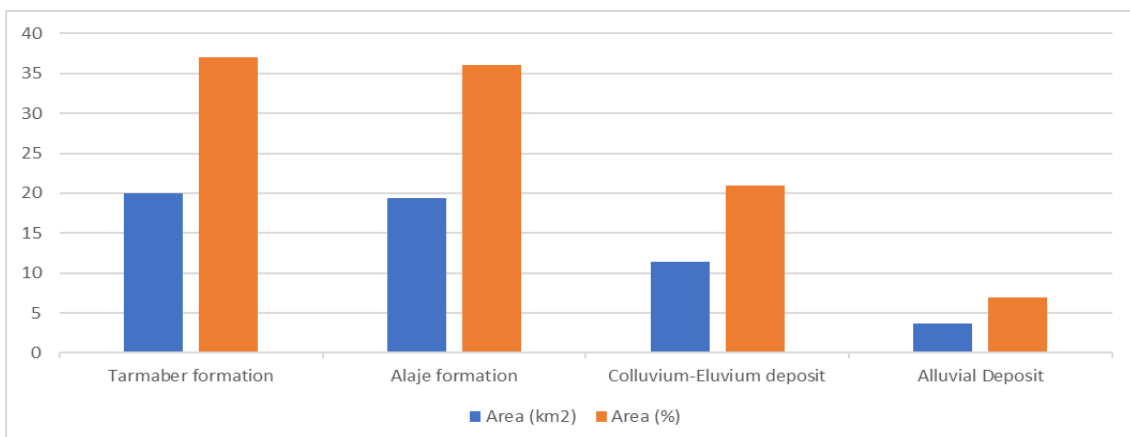


Figure 3.6. Lithology and area coverage

i. Tarmaber basalt

Tarmaber basalt covers the west and southwest parts of the study area. It forms a rugged topography and also linear ridges with high steep mountains. It is underlined by Alaje Ignimbrite and has sharp contact with the underlying layer. At the top of the Tarmaber basalt, it is covered with a variable thickness of dark grey silty clay soil. The basalt is characterized by medium to coarse-grained, dark grey fresh color, pale brown to brown weathered color, and with aphanitic to porphyritic texture. It shows different phases of flows as observed marked by the exposed paleo-soils in (Figure 3.7B). springs are drained through these contacts into the lower Alaje and colluvium-eluvium deposits aggravate erosions and cause instability.

ii. Alajie Formation

The part of the Alajie Formation is covered the north and northeast of the study area. This formation contains alternating layers of basalt, ignimbrites, and tuff with a variable thickness. The rock layer is exposed in relatively gentle sloping areas in contact with the Tarmaber basalt. This rock layer is highly jointed and fractured which is the most unstable layer in the study area of Jibgur, Kese, Weyraafaf, and Gedamareh areas. Almost all rock fallers are derived from this formation. The rock is characterized by fine-grained, grey, irregularly fractured, highly jointed, slightly weathered, and rarely shows a block and massive appearance that forms a cliff (Enigda & T, 2021) (Figure 3.7A).

The Tuff unit also forms gentle to very cliffs, isolated hills, and elongated ridges as exposed along the river banks and eroded areas. It is characterized to be fine to medium-grained, light grey to dark color, and slightly to highly welded Ignimbrite. This layer is mostly exposed at the river bed and bank, fault scape, and eroded areas (Figure 3.7 C&D). This layer is very susceptible to weathering when the overlying layer is removed by erosion and is also highly susceptible to erosion (Enigda & T, 2021). It observed that it is a main cause for adjacent rock and soil sliding due to its erodibility.



Figure 3.7. Alaje basalt (A), Weathered Tarmaber basalt with two flow phases (B), Dark tuff forming cliff (C) and light gray tuff with eluvium-colluvium deposits (D)

iii. Alluvial soil

The alluvial soil is encountered along the main rivers especially, along the Demaytemash, Aynemaryam, and Graramba Rivers (Figure 3.8a). The deposits can be characterized by rounded to sub-rounded shaped boulders, cobbles, and coarse grain gravels with some sand composition that gradually decreases their size down the river due to slope gradient, transportation distance, and force. It is also exposed in some flat areas which consist of dominantly fine to medium silt and sand deposits (Figure 3.8b). This material is derived from the above plateau areas of the Alaje and Tarmaber formations.

iv. Colluvium-eluvium deposit

The colluviums-eluvium deposit is exposed at the lower part of the study area which is the foot of cliffs and ridges of Alaje Formation. This formation covers all the areas of 2005 landslide bodies. This formation is composed of gravel, boulders, and fine soils near the cliffs gradually dominated by gravel, sand, clay, and silt composition. It is also good and fertile soil for agricultural purposes. During rainy time runoff and seepage, that drain from the plateau seep into this thick deposit, and springs are developed at the lower morphological breaks. This formation is the most susceptible to river bank erosion, gully and slope toe erosion, and landslide. The thickness of the deposit can be estimated to range from 10m to 50m as observed

in the river gorges ([Figure 3.8c](#)). Eluvium soil is encountered along the plateau areas forming flat and gentle morphology. It is derived from the in-situ weathering and gravitational movement of the Alaje formation ([Figure 3.8c&d](#)).



Figure 3.8. (a), Coarse grain alluvial deposit, (b) fine soil alluvial deposit, (c) Eluvium deposit and (d) eluvium colluvium deposit.

3.5. Structural setting

Geological structures like joints, lineament, surface cracks, and faults are identified from field observation and the DEM of SRTM images. These structures are areas of weak surfaces that may cause potential landslide surfaces.

3.5.1. Lineaments

Lineaments trends in the direction of SE-NW which is along the Tarmaber mountain, SW-NNE following the Belbela, Slasegedeam, and Weja mountain, and SE-NE along the stream direction are identified as shown in ([Figure 3.9](#)).

3.5.2. Fault

Hence the study area is located along the margin of MER and Consequently, the study area is more prone to tectonic activities. According to the field observations and the digital elevation model (DEM), major Active faults oriented in the SW – NE direction and other small-sized faults are identified in the area where the major 2005 landslide occurred ([Figure 3.9](#))

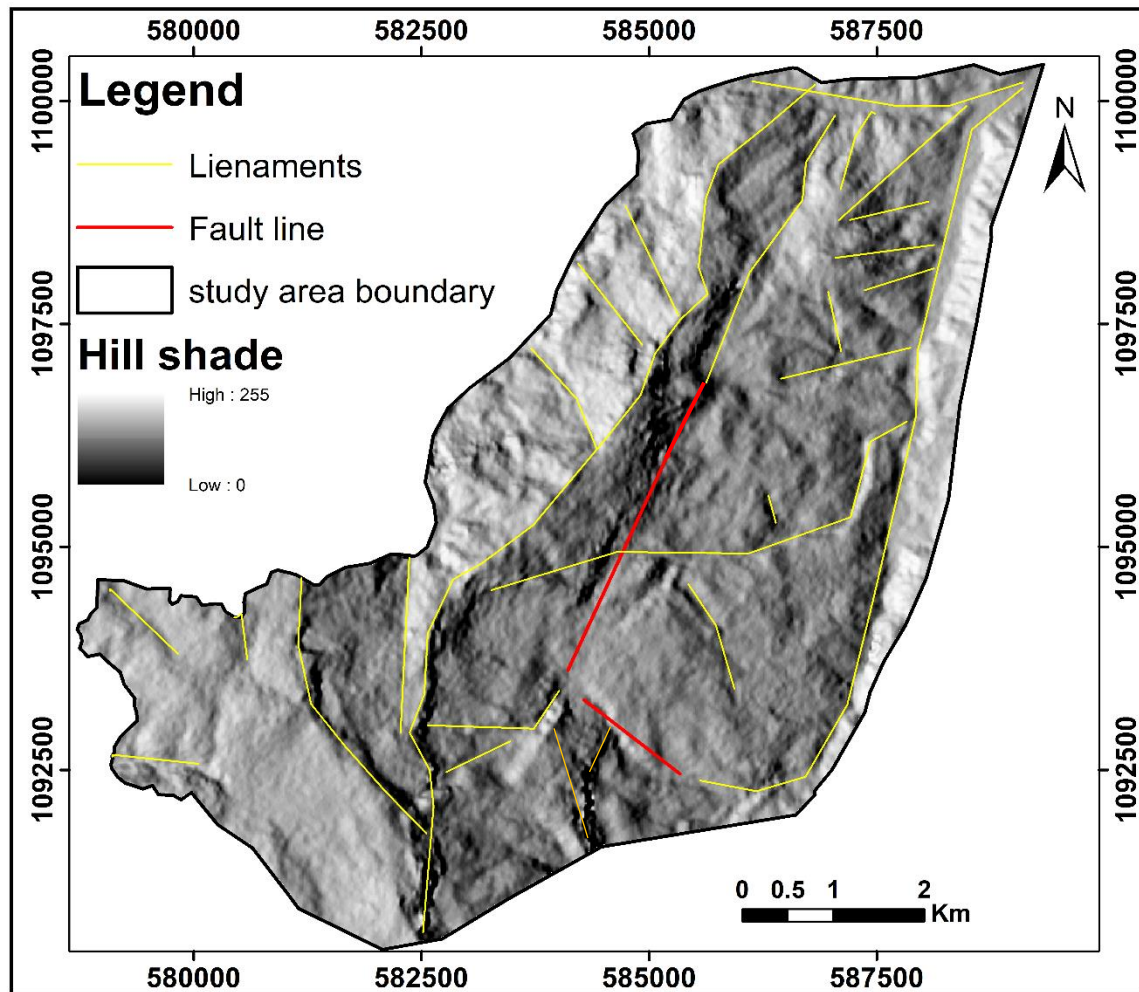


Figure 3.9. Major faults and lineaments

3.5.3. Joints and fractures

In the study area, most of the joints and fractures are observed in Alaje basalt. The joint sets have variable orientation and spacing. It is observed that wide and vertical joints with cm to meter width in the active rock slide areas. In the Tarmaber and Alaje basaltic Formation discontinuities with vertical orientation, variable spacing, and aperture are observed.

3.5.4. Surface crack

In the study area, surface and tension cracks are observed in Alaje rock units and colluvium-eluvium deposits. In the Alaje rock formation, large tension cracks are created due to the sliding body being sated on unstable loose tuff formation as observed around Jibgur and Weyra-Afaf area (**Figure 3.10 a & c**). Most of the surface cracks were observed in gentle slope areas of loose alluvial soil and weathered rocks near the stream and gullies (**Figure 3.10e**). In some areas springs and run-off have disappeared along with this surface and tension cracks. New

bulging structures where the soft ground is moved toward stable ground along the sliding body were also observed during site investigation work (Figure 3.10d).

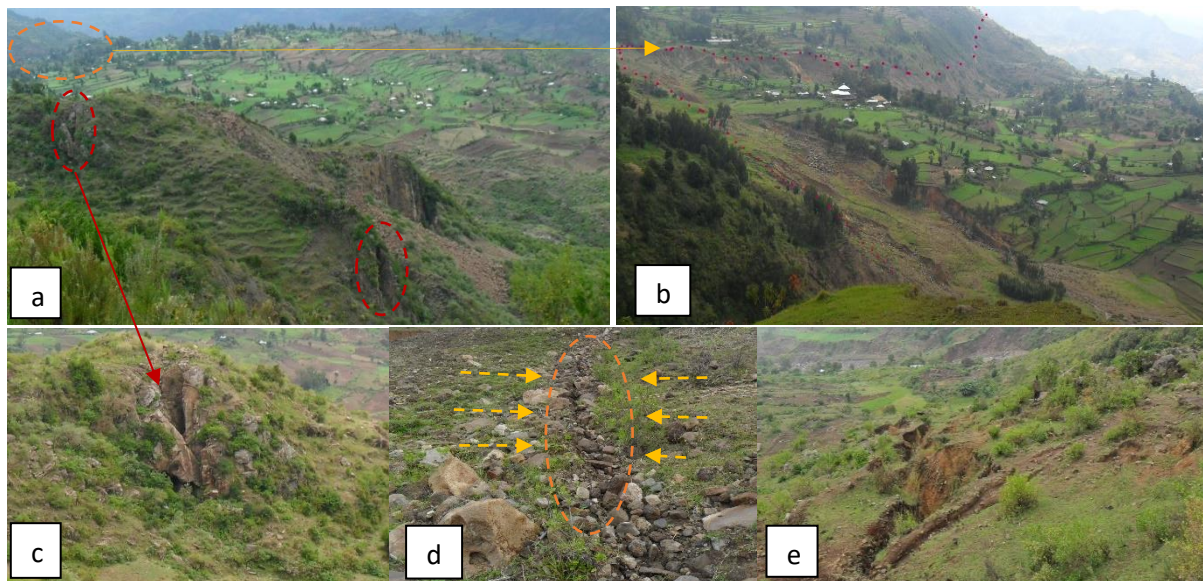


Figure 3.10. (a &c), Tension cracks on Alaje basalt, (b) Fault scraps along the Yizaba area (d), Bulging structures, (e) Surface cracks at Eluvium deposits near the Aynemaryam stream

3.6. Geotechnical properties

To understand the general geotechnical properties of soil and rock of landslide-prone areas, some selected major critical prone areas are sampled and laboratory tests have been carried out on the selected samples in the geotechnical laboratory of Ethiopian Engineering Corporation. Two soil samples from the altered black color basaltic tuff (BTF-1) and light color tuff (TF-2) formation are collected from the major critical landslide areas. Two representative rock samples from Alaje and Tarmaber basalt are also sampled and tested. The summary of executed activities and results are shown in (Table 3).

Table 3 Collected samples and corresponding test results

Soil sample															
No	Critical slope areas	Sam ple code	Atterburg Limit			N M C %	Free swel l %	Bulk dens ity (g/c c)	Direct Shear		Grain size analysis				USC
			LL %	PL %	PI %				C	σ	Gravel %	San d%	Silt %	Clay %	
1	Jibgure	BTF -1	51	32	19	21	20	1.79	16.0 8	11.8 1	0.00	60.2 9	39.0 1	0.70	SM
2	Yizaba	TF - 2	62	42	20	34 .5	20	1.56	5.63	15.7 3	0.36	64.8 0	32.1 8	2.66	SM
Rock sample															
	Location		Sample code						Bulk unit weight (g/cc)		Point load strength (Mpa)				
3	Gedam Areh		A-1 (Alaje basalt)						2.53		3.30				
4	Ayna		T-2 (Tarmaber basalt)						2.55		10.15				

(LL=liquid limit, PL= plastic limit, PI=plastic Index, USC= unified soil classification, NMC=natural moisture contents=silty sand)

3.6.1. Geotechnical Properties of Rocks

Irregular shape rock samples were collected from the Alaje basalt and Tarmaber basalt units. Bulk unit weight and Point load tests are performed on the collected samples in the laboratory to understand the rock strength properties. The point load test is performed using a standard test method of ASTM D5731 and the bulk unit weight is done following the standard test method of ASTM D7263. The point load test result is changed into unconfined compressive strength values. The value of converted UCS Tarmaber basalt is about 243.6MPa and Alaje basalt is about 79.2 Mpa. According to The International Society for Rock Mechanics (ISRM) standard, UCS from 0 to 5 MPa is very low, from 5–25 MPa is low, from 25–50 MPa moderate, from 50–100 MPa is medium, from (100–250 MPa) is high, and more than 250 MPa is very high. Based on the result Alaje basalt is considered to be medium strong and Tarmaber Basalt is highly strong. Most rock slides and rock toppling are encountered in the Alaje basalt. The bulk unit weight of the Alaje basalt is also less than from Tarmaber basalt and this indicates that the weathering condition of Alaje basalt is more than Tarmaber basalt.

3.6.2. Geotechnical Properties of Soil

Index or indication laboratory tests such as grain-size distribution analysis, Natural moisture content, bulk density, free swell, Atterberg limit, and strength tests like direct shear tests were performed on the collected soil samples from critical landslide-prone areas to understand the physical and geotechnical characteristics of the soil.

i. Index properties of the soil

The Atterberg limits (LL, PL, and PI), Free swell, bulk density, and grain size distribution are referred to as index tests because they enable an indication of different physical properties of the soil (Hagos, 2012). This test is performed following a standard method of ASTM D4318 in the Ethiopian Engineering Corporation. The test result indicates that the soil has a Liquid limit (LL) of 51%-62%, a plastic limit (PL) from 32% to 42%, and a plasticity index (PI) ranging from 19 to 20%. The natural moisture content (NMC) was also performed following a standard method of ASTM D2166 and the result ranged from 21%-34.5%. The result of the free swell test is 20% which is done by following the standard methods of IS 2720. The bulk density of the soil ranges from 1.56g/cc to 1.79 g/cc.

According to the plasticity index (PI) can be classified as Non-Plastic (0), low-plastic (1-7), medium plastic (7-17), Highly plastic (>17) (Advanced Engineering Geology & Geotechnics, 1960), (Falowo et al, 2020). Thus, the laboratory test result indicates that the plasticity result is more than 17 and that the soil is highly plastic and exposed to plastic deformation. This is aligned with the deep-seated landslide that occurs in a slow movement in the study area.

Grain size distribution of the soil is done with the standard method of ASTM D422 at this laboratory and the result is shown in (Table 3) which is further classified by the Unified Soil Classification System (USCS) which is SM (silty sand) soil type.

ii. Shear strength parameters

The direct shear test is performed by following the standard method of ASTM-D3080 in the laboratory of the Ethiopian Engineering Corporation (EEC) to evaluate the shear strength of the soil. The shear test result shows that cohesion (c), the value of the soil area in the range of 5.63 Kpa to 16.08kpa and the angle of internal friction (ϕ), is in the range from 11.81 degrees to 15.73 degrees as shown in (Table 3)

iii. Permeability of soils

The permeability of the landslide-prone soil is estimated based on the Hazen formula. This formula is mostly used by different researchers for determining the conductivity of the soil based on the grain size distribution curve (Hagos, 2012).

$$C=K(d_{10})^2 \quad \dots\dots \quad 3.1$$

Where C = Hazen's factor ($\text{cm}^{-1} \text{sec}^{-1}$), which = 100,

K = hydraulic conductivity (cm/sec),

d_{10} = particle diameter corresponding to 10 percent finer on the grain size distribution curve (cm):

The diameter of the particle corresponding to 10 percent finer from the current grain size distribution curve is 0.0372mm and 0.0377 which is equal to 0.372cm and 0.377cm respectively. According to the above equation, the hydraulic conductivity of the critical landslide-prone soil is estimated to be 0.0018 to 0.002 cm/sec. According to Darcy's law, silty sand or silty soil having a k(cm/sec) value in the range interval of 0.01 to 0.001 is low permeable soil.

3.7. Topographic and hydrologic condition

3.7.1. Topography

The physiography of the area forms a rugged topography with major mountains like Tarmaber, Belbela, Weja, Slasegedam, and Aynemariam areas ([Figure 3.11](#)). The Weja Mountain is a water-divided zone where rivers flow towards the Tegero River. This mountainous area is characterized by steep slopes which are composed of weak to strong, highly weathered to fresh Tarmaber basalt. The gently sloped areas are characterized by fractured and jointed Alaje formation and colluvium-eluvium deposits that most of the rock failure and slides are encountered. These steep and rugged valleys and mountain chains drain into lower-elevation areas. Due to this effect, the low-elevation areas of Colluvium-Eluvium deposits are highly dissected by major rivers and streams characterized by deep and wide valleys and gorges. The topographic map is prepared from 12.50m DEM of SRTM image obtained from Alaska Satellite Facility (ASF) and the drainage pattern is produced with a spatial analysis tool of hydrology in ArcGIS10.8.

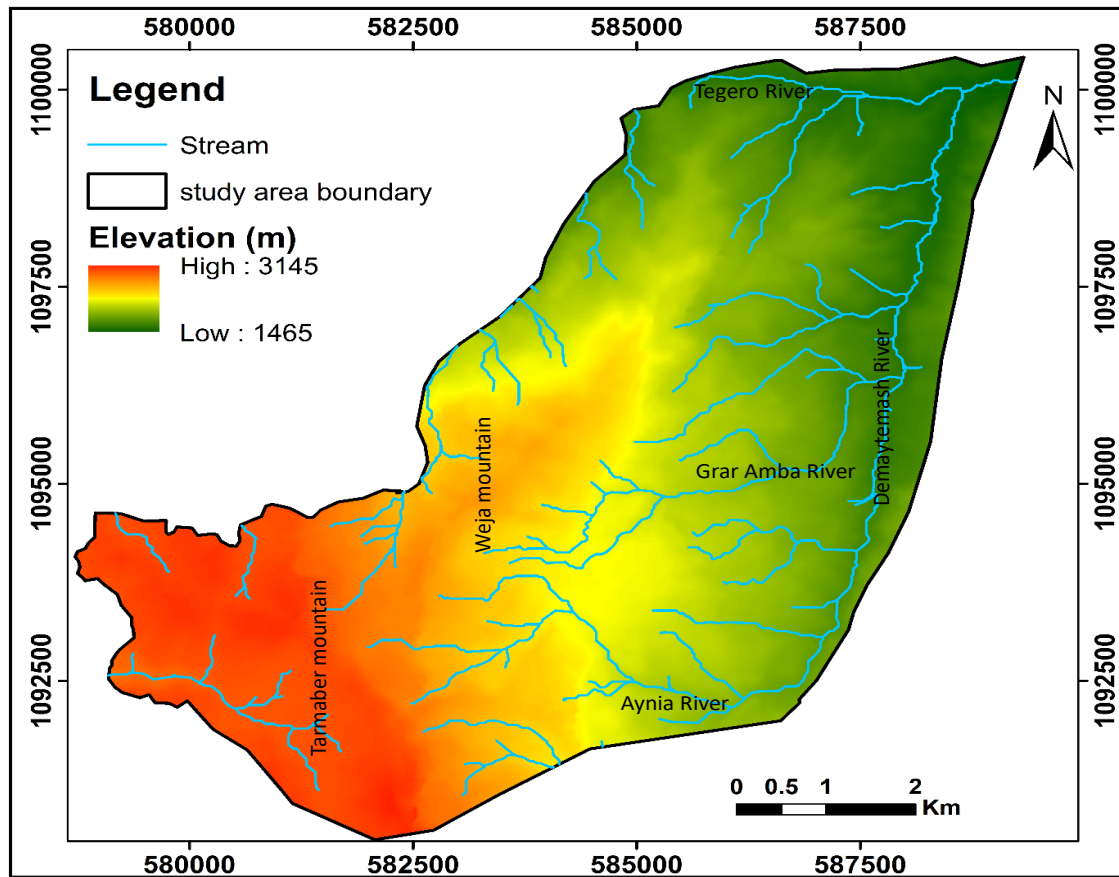


Figure 3.11. Topographic and drainage patterns map

3.7.2. Climate and Rainfall

The climate of the area experiences Dega to Weyna Dega with a mean annual rainfall of ranges from 1736 to 1812 mm/year and temperature varying between an average minimum of 10°C and maximum of 25°C that fluctuates with seasonality having a maximum in summer and minimum in winter (Tadele, 2014, Kiros et al., 2020). The study area falls in the regions with significant high rainfall area, which experiences bimodal rainfall, with peak precipitation occurring from June to September and minor precipitation occurring from February to May (Hagos, 2012). Most of the landslides occurred during the time of June to September which is during the high rainfall session as understood from the interviews of the local people. The deep-seated landslide was also initiated in September 2005 which was at the end of the high rainfall season. Especially debris flows have occurred during the summer season when there is a peak rainfall.

3.7.3. Spring and Seepages

During the fieldwork, a detailed assessment and inspection of the effect of the study area's springs, rivers, and seepage conditions is carried out. Large yield springs are seeps following the contact between the Alaje and Tarmaber formations and from the upper fractured layer of Tarmaber basalt. Small yield springs also seep through the body of lower formation or from the gentle slope area formation of eluvium-colluvium deposits and along the fault line ([Figure 3.12](#) & [Figure 3.13](#)). The vertical permeability condition of the study area is characterized by fractured and permeable Tarmaber basalt, Alaje formation, and Quaternary deposits at the top and an impermeable tuff layer at the bottom. The underlined impermeable tuff layer retard the vertical flow and encourage lateral flow along the slope direction and this allows the build-up of water pressure within the slope's face. Hence the steep to medium gentle sections areas are composed of highly fractured and permeable Tarmaber and Alaje formations that encourage recharge and lower elevating areas are composed of fine to medium coarse colluvium-eluvium deposits which have relatively low permeable and retard drainages and hence allow to rise in water during rainy time. During this time pore water pressure is developed and the weight of the slope will increase and decrease in shear strength which leads to increased instability on the slopes.

The manifestation of springs and seepages are observed during site investigation following the fractures and the contact between the lithology where the permeable layer overlays on the impermeable layer at different elevation levels as shown in [Figure 3.1 c & d](#). Some of the new springs that seep along the new fault lines are used as mineral water (Tebel) by living people around there as shown in [Figure 3.1d](#). In the study area, about 98% of the drinking water is supplied from the springs.

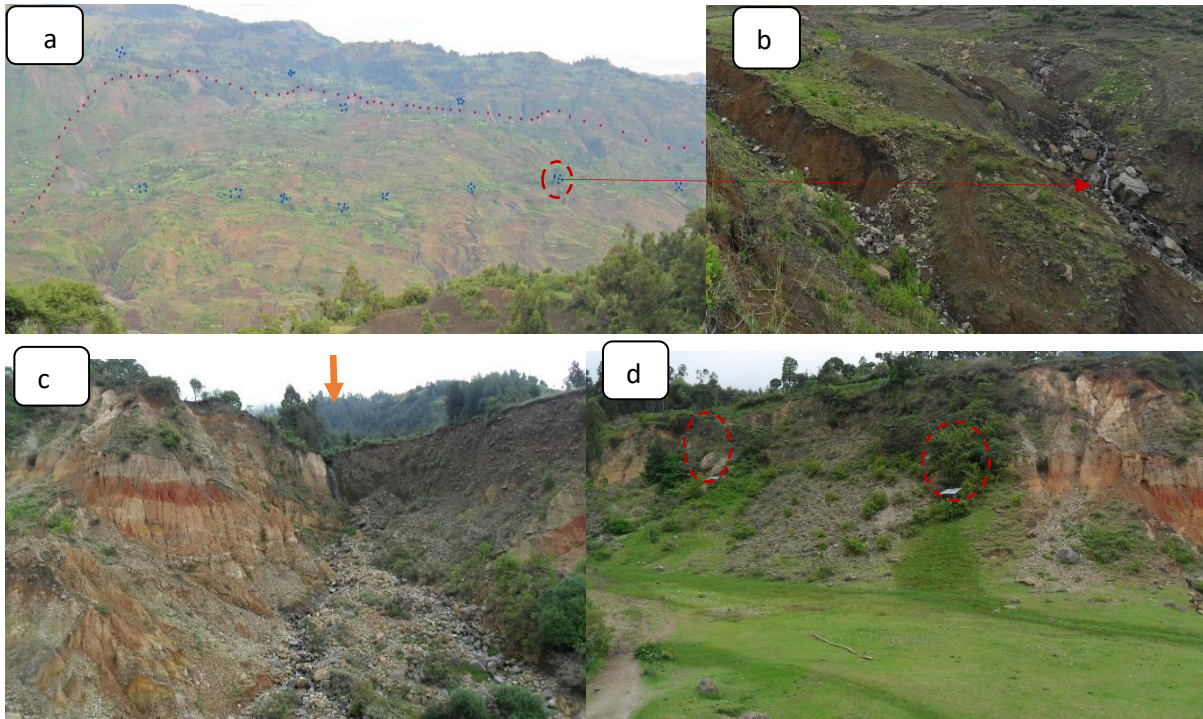


Figure 3.12. Aligned spring on the old slide bodies, (a & b), springs from the Lithology contacts (c & d).

Most of the contact springs in the study area erode the underlying soil and increase the slope height above and its surroundings by making dip gorges which can cause instability as shown in [Figure 3.12 b & c](#). The availability of several aligned springs around the foot of the sliding body and above it as shown in [Figure 3.12 a & b](#), with their aggressive erosion, indicate the occurrence of extra landslides in the study area.

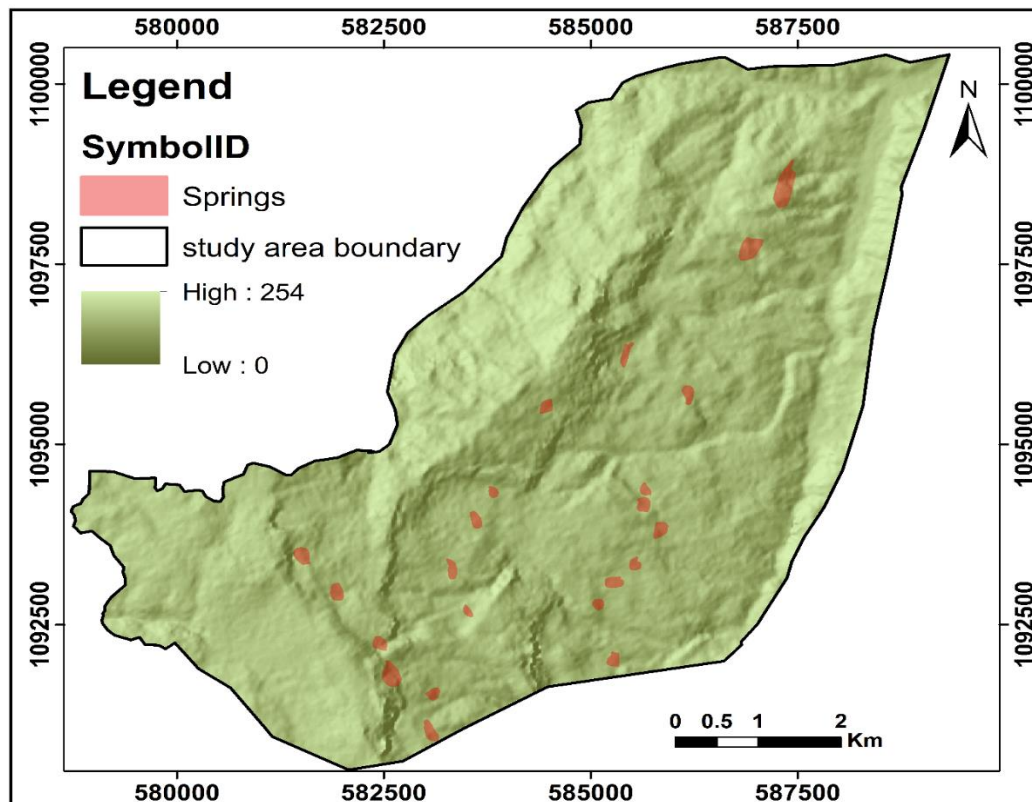


Figure 3.13. Spring distribution in the study area

3.8. Landslide inventory

Landslide inventory is important to identify and delineate the past landslide occurrences that enable to predict the future patterns of instability (Hagos, 2012). Aiming to this, the distribution of landslides in the study area is investigated from field survey and digitizing from Google Earth and Landsat images using ArcGIS10.8. About 62 Landslides in the study area which are 35 debris slides, 22 earth slides, 4 rock slides, and one debris flow are identified. Active landslides in the study area were identified along the river banks, the fault scraps, and the 2005 sliding bodies during site works. The cause of the failure is related to lithology, topography, geological structures, seepages, and continuous dipping of erosion by the Aynemariyam, Demaytemash, and Garar Amba rivers. Some representative landslides are presented in the following (Table 4.). Most of the landslide locations are taken with handheld GPS and some of them are taken from Google Earth images. The dimension which is the length that is covered along the sliding direction and the width that is covered horizontally perpendicular to the sliding direction is determined and measured from Google Earth and Landsat images as tabulated in (Table 5).

Table 4. Major landslide encountered in the study area (the detailed description is shown in below (Table 5))

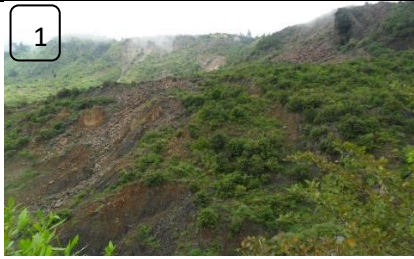
Landslide along the fault scrap		
1 	2 	3 
4 	5 	6 
Landslide along the River banks		
7 	8 	9 
10 	11 	12 
Landslide along the 2005 sliding bodies		
13 	14 	15 

Table 5. The detailed description of the above Table 3 pictures

Picture No.	Type	Dimension		Location		Local Name
		Length (m)	width (m)	Easting	Northing	
1	Rock and debris slide	320	500	84427	92690	Jibgur
2	Rock slide	360	270	84265	92373	„
3	Earth slide	70	100	84131	94099	Yizaba
4	Rock slide	340	250	84171	93152	Gedam-Areh
5	Debris slide	150	512	83971	93652	Gulimit-mesk
6	Debris slide	110	670	84360	94508	Gosh-gudba
7	Debris slide	250	570	84795	92489	Wadyat
8	Debris slide	120	200	85168	92412	Kese-Amba
9	Debris slide	70	200	85371	94829	Grar- Amba
10	Debris slide	60	100	85111	94569	korontos
11	Same area with No-1					Jibgure
12	Debris slide	50	300	85700	94890	Korontos
13	Debris flow	925	300	86664	93481	Weyn/medina
14& 15 are part of the earth's flow						„

The landslide distribution of the study area which is investigated from field survey and digitizing from Google Earth and Landsat images was mapped using ArcGIS10.8 with the same scale as the study area (Figure 3.14). This inventory map is used for analysis and verification of the landslide occurrences prediction in the areas. The location and the area coverage of the landslide are determined with the ArcGIS special analysis tool by calculating the area polygons.

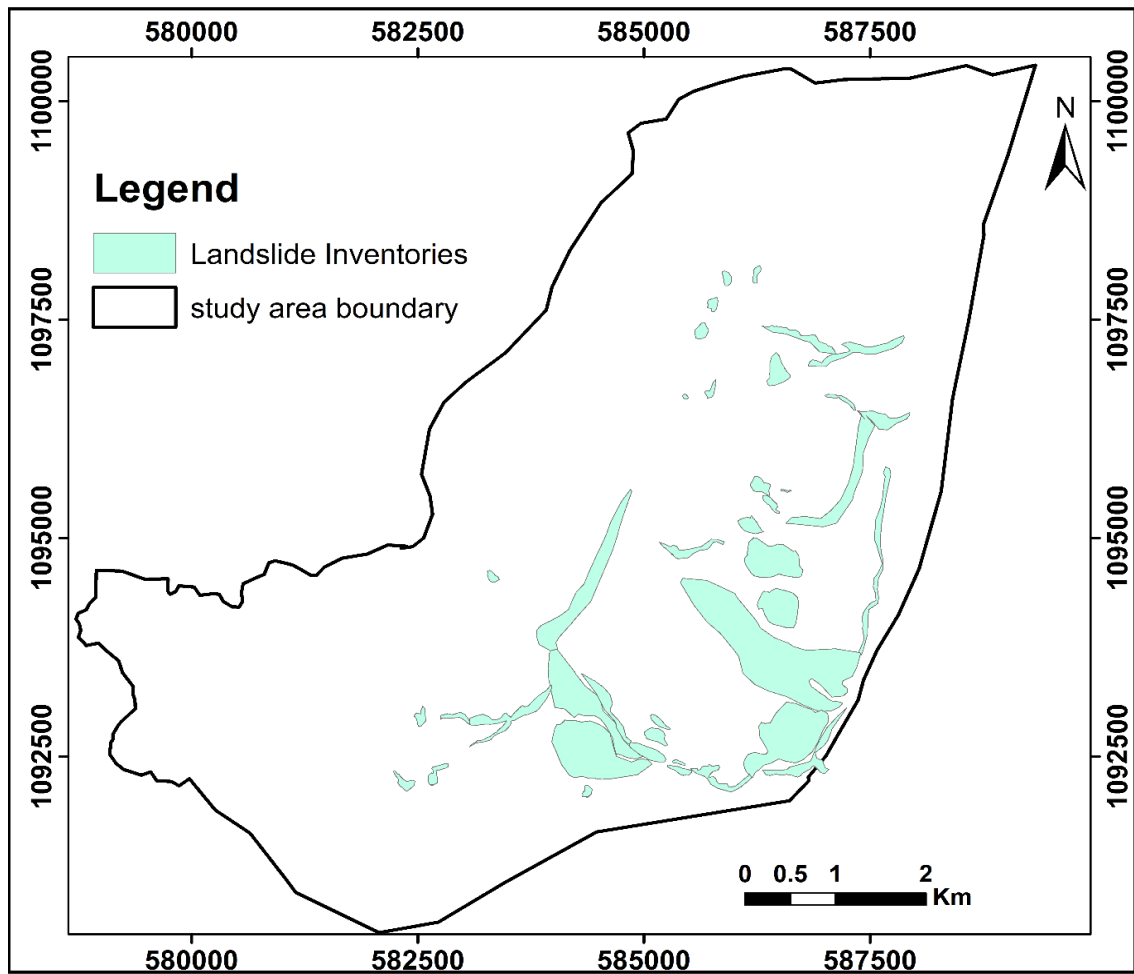


Figure 3.14. Landslide inventory map

The random distribution of the landslide inventories shows that the maximum area coverage is about 0.68 km^2 and the minimum is 0.01 km^2 . the landslide covers a total of about 4.27 km^2 from the total 54 km^2 of the study area (Figure 3.15).

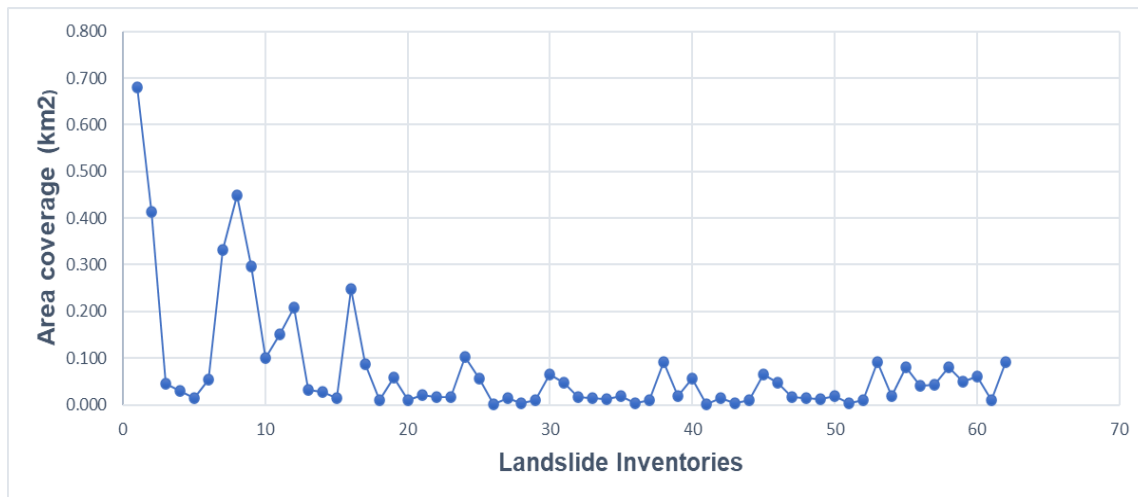


Figure 3.15. Landslide area coverage and Landslide Inventories

3.8.1. Types of slope failures encountered in the study area

According to Varnes's (1978) classification system, rotational debris and earth slides, translational rock slides, and rockfalls are the most common landslides in the study area (Figure 16). The movement of translational failure is structurally controlled by surface weakness including features like joints, faults, bedding planes, and differences in shear strength between layers of bedded deposits and it includes the point where hard bedrock meets worn rock on top (Sharma et al., 1995). This type of slide in the study is encountered along the main scrap of the 2005 landslide of the local name Jibgure and Gedam Areh area (Figure 3.16a & c). It occurred due to the continuous dipping and undercutting by the Aynemariyam River at the bottom of the formation. The formation of the bottom layer including the river bed is comprised of weak and altered Alaje Ignimbrite. This makes the overlying Alaje fracture and jointed basalt layer unstable. The rock in the frontal of the slide falls and bounces into the river. Most of the rock failure is observed at the fractured and jointed Alaje rock layer.

Circular (Rotational) debris and earth slides are encountered along the river banks due to the action of the river that cuts and erodes the toe of the slop (Figure 3.16 b & d). This failure is very active in the eluvium-colluvium deposits because this formation itself and the underline formation are highly susceptible to erosion.

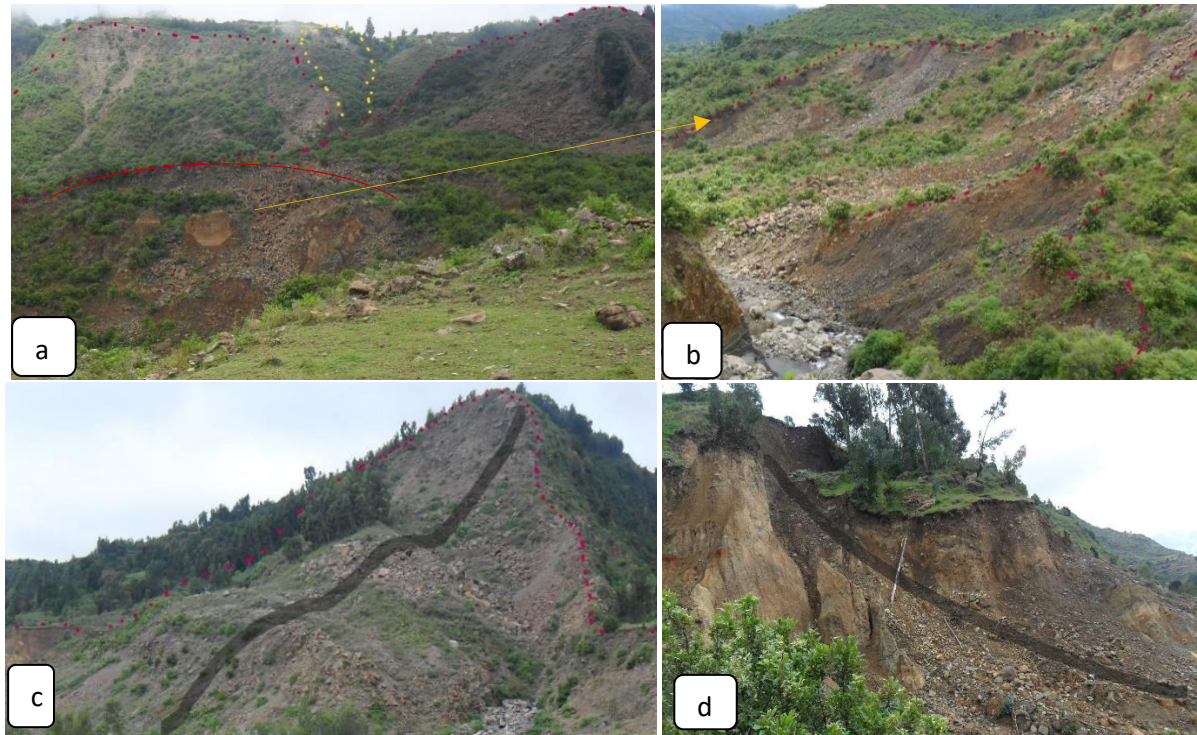


Figure 3.16. (a & b), Translational rock slide & debris slide, (b) rotational debris slide, (d) rotational Earth slide.

CHAPTER - FOUR

METHODS AND PROCEDURES

4.1. Introduction

In this section, the methods which are used in the current research, including data collection via fieldwork and remote sensing, laboratory testing, data analysis and evaluations using Arc GIS-based Frequency Ratio (FR), identification of current deformation through InSAR data analysis and finally generate landslide susceptibility map and displacement map are discussed. The general method of organization is presented in [\(Figure 4.1\)](#).

4.1.1. Remote sensing data collection

Google Earth images with field investigation have been used to prepare landslide inventory by searching their distribution and visually interpreting causative factors. SRTM images of the ALOS Phased Array L-band Synthetic Aperture Radar (ALOS PALSAR) Digital Elevation Model (DEM) with a Spatial Resolution of 12.5m obtained from the Alaska Satellite Facility (ASF) were used to map the elevation, aspect, and distance to stream, slope of the study area. Landsat-9 images (2024) obtained from the United States Geological Survey (USGS) used for mapping land use land cover (LULC) and two Sentinel-1 Interferometric Wide Single Lock Complex (S1A_IW_SLC, 2014 and 2024) images downloaded from (USGS) processed with Sentinel Application Platform (SNAP) to prepare the displacement map.

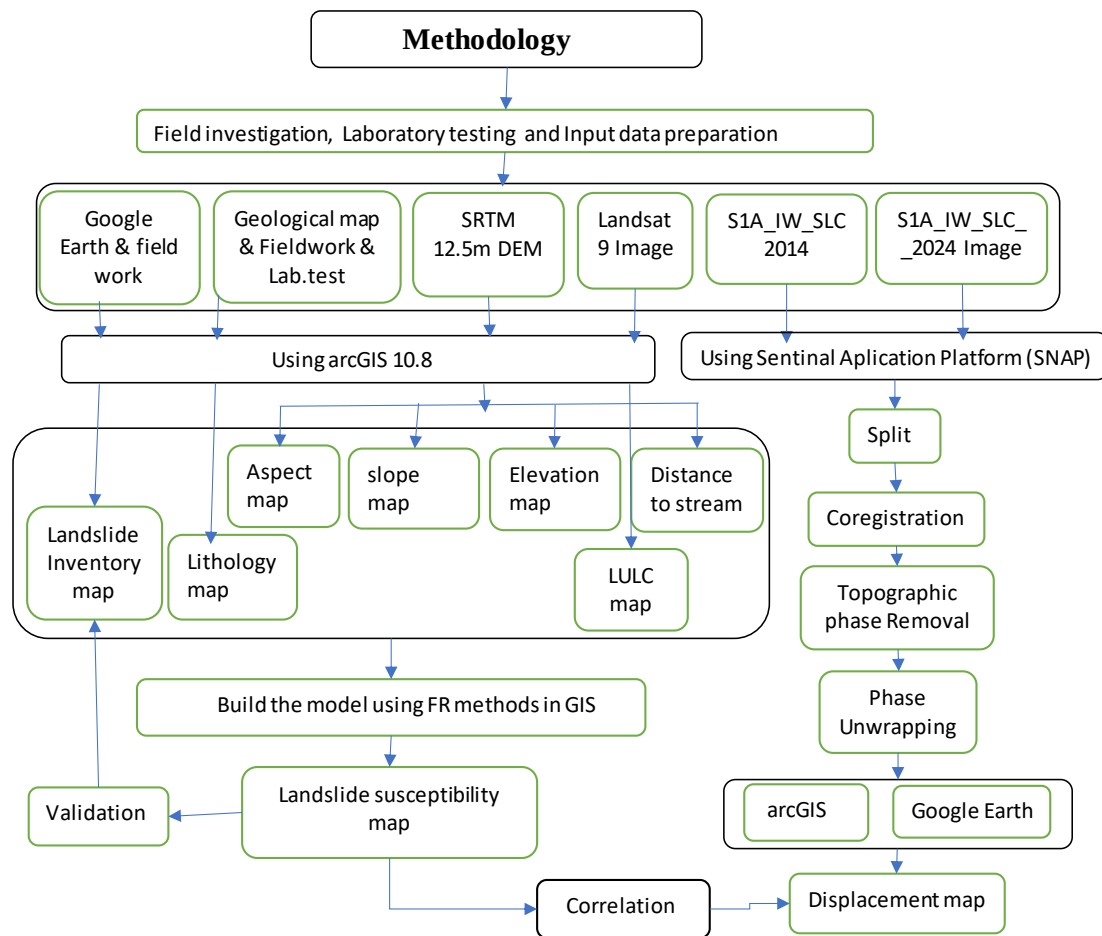


Figure 4.1. follow chart of general methodology

4.1.2. Landslide Susceptibility Mapping and procedures

4.1.2.1. Frequency ratio methods

To map the study area landslide susceptibility, frequency ratio modeling methods are employed. The frequency ratio model performs well with high accuracy, is easy to use, and can offer the contribution of each causative factor class for landslide occurrence recently several researchers have employed it to build landslide susceptibility maps (Thapa & Bhandari, 2019; Mersha & Meten, 2020; Thapa & Bhandari, 2019; Fikadu, 2021). According to the site conditions and previous literature, six causative factors such as slope gradient, slope aspect, elevation, lithology, land use land cover (LULC), and distance from the river are selected to prepare the input factor map for the models of LSM and to understand the degree of impact for each causative factor. This input factors map are generated and the FR index of each landslide causative factor has been determined using ArcGIS 10.8. The FR model is the ratio of occurrence probability to non-occurrence probability for a given attribute and it is a well-liked quantitative technique that has been used recently in multiple projects aiming to build landslide susceptibility maps with positive outcomes (Abay & Barbieri, 2012). This allows for a

quantitative description of the relationship between the causative variables and past landslide occurrences. The FR method was then used to create the study area's landslide susceptibility map using the weighted sums of the FR values of all classes as shown.

4.1.2.2. procedures

Detailed landslide inventories are done with the help of Google Earth images, satellite images, and actual fieldwork investigation. The lithology map was also prepared from fieldwork investigations. Slope aspect maps, slope gradients, and elevation maps are prepared from the digital elevation model of SRTM with 12.5-pixel resolution. Distance from stream and land use land cover maps are prepared from Landsat 9 image downloading from USGS all as shown in Figure 4.2. After all the required input maps were prepared and created, the FR was calculated for each class of the parameter by dividing the area of landslides in the class by the area of all landslides for the area of the class by the entire map.

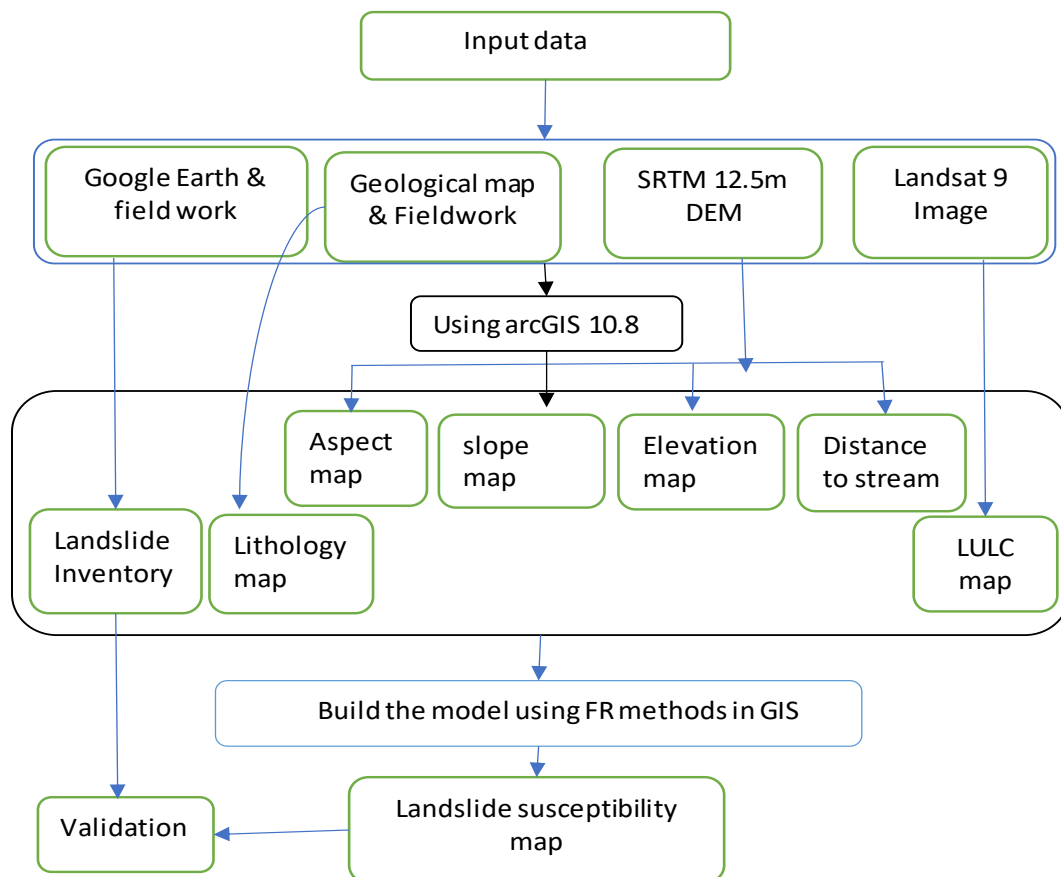


Figure 4.2. A flowchart of the frequency ratio approach

4.1.2.3. Input map preparation

The landslide triggering factors of the study area as an input map are evaluated according to the frequency of six causative factors of aspect, slope, elevation, distance to stream, Land use land cover, and lithology, and the inventory map is used for analysis and verification of the

landslide occurrences prediction in the areas. All factor maps are prepared with the same scale and equal pixel size as the study area.

According to (Rengaswamy & Suresh, 2022), there are different data classification systems like Equal Interval, Quantile, Natural Breaks (Jenks), and Standard Deviation in the ArcGIS platform. Each classification has its advantages and disadvantages for the applications that are employed. The equal interval system classifies the range of attribute values into equal-sized and the quantile scheme is used for evenly distributed data. The Standard Deviation is also used for evaluating the attribute value that varies from the mean. The Jenks Natural Breaks are Natural groupings that are present in the data and serve as the foundation for classes to determine breakpoints, ArcMap selects the class breaks that maximize the differences between classes and best group comparable data that the limits are determined by the locations of comparatively large data value jumps (Rengaswamy & Suresh, 2022). Hence the data used in this study and the inventories are not evenly distributed and Natural Breaks (Jenks) classification methods are adopted including classification of slope, aspect, and elevation.

i. Slope

The slope map is prepared from 12.50m DEM of SRTM image obtained from Alaska Satellite Facility (ASF) using slope spatial analysis tool in arcGIS10.8 with the same and equal pixel size of the study area. Slope gradient is commonly used in different kinds of literature because landslide is mostly related to slope angle (Mersha & Meten, 2020). The map is a kind of raster with the same pixel size as the digital elevation model. A slope classes are created by dividing the slope angles into five different classes by natural breaks which are class-1 (0-10), class-2 (10-18), class-3 (18-26), class-4 (26-37), and class-5 (>37) (Figure 4.3)

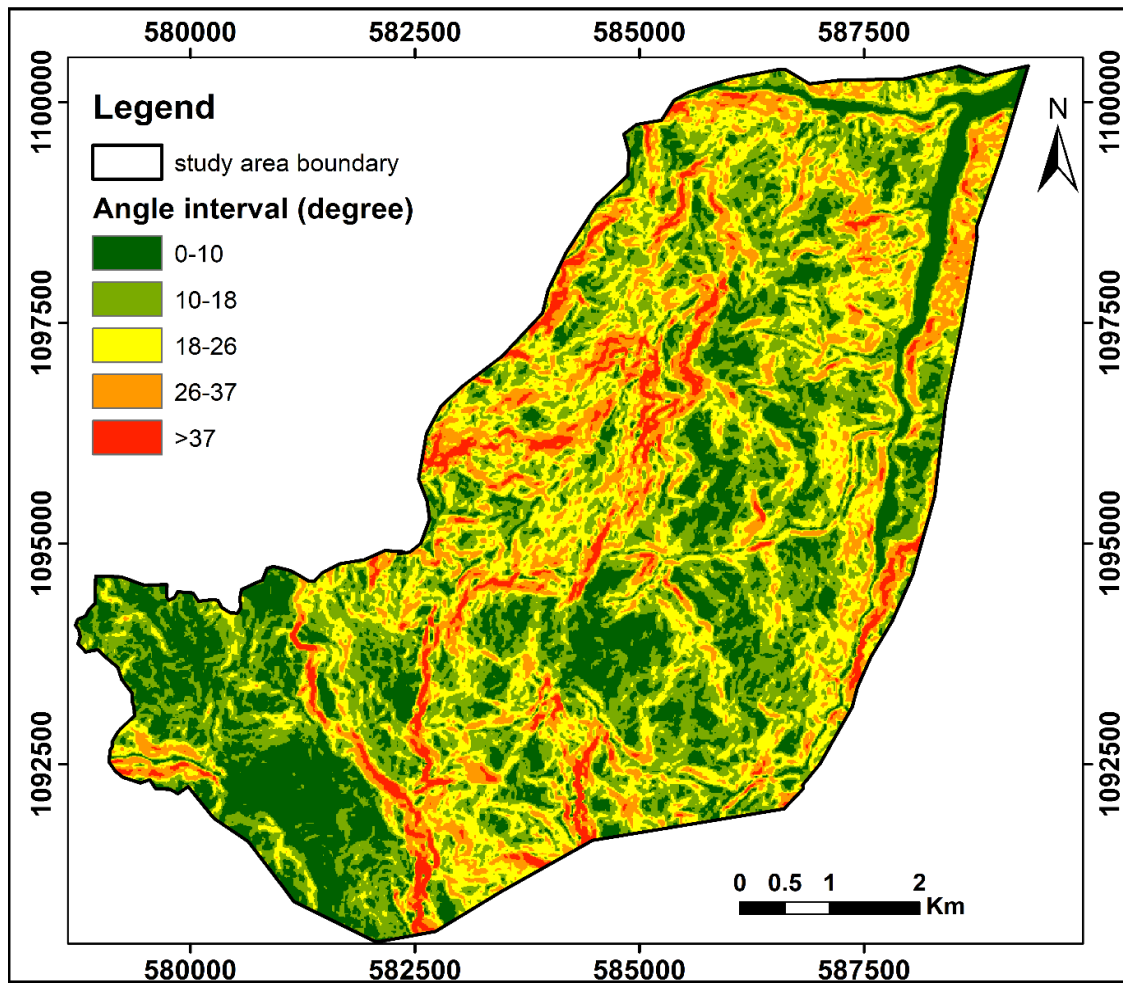


Figure 4.3. Slope map

The slope class-1 (0-10 degrees) covered 23% of the study area. Slope class-2 an angle interval from 10-18 degrees covers (32%) most of the area. Slope class -3 (18-26 degrees) also covered 26% of the area and slope class -4 and slope class covered a small area which is 14% and 4 % of the study area (Figure 4.4).

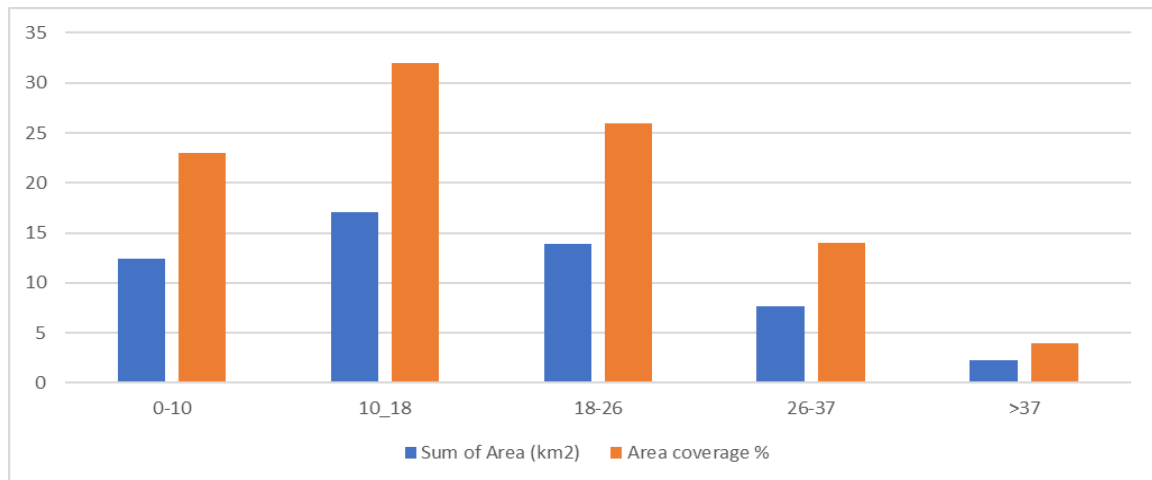


Figure 4.4. Slope angle interval and area coverage

ii. Aspect

Aspect is also like slope it is considered one of the landslide causative factors and applies to landslide studies. The slope aspect of the study area is prepared from 12.50m DEM of SRTM image obtained from Alaska Satellite Facility (ASF) using the aspect spatial analysis tool in arcGIS10.8. The derived map was then further reclassified into 9 distinctive classes by the natural break (Figure 4.5). In the study area, 25% of landslides are encountered along the east (80-120 degrees). 78% of the area is covered by aspect degree of N (0-40), NE (40-80) and E (80-120) (Figure 4.6).

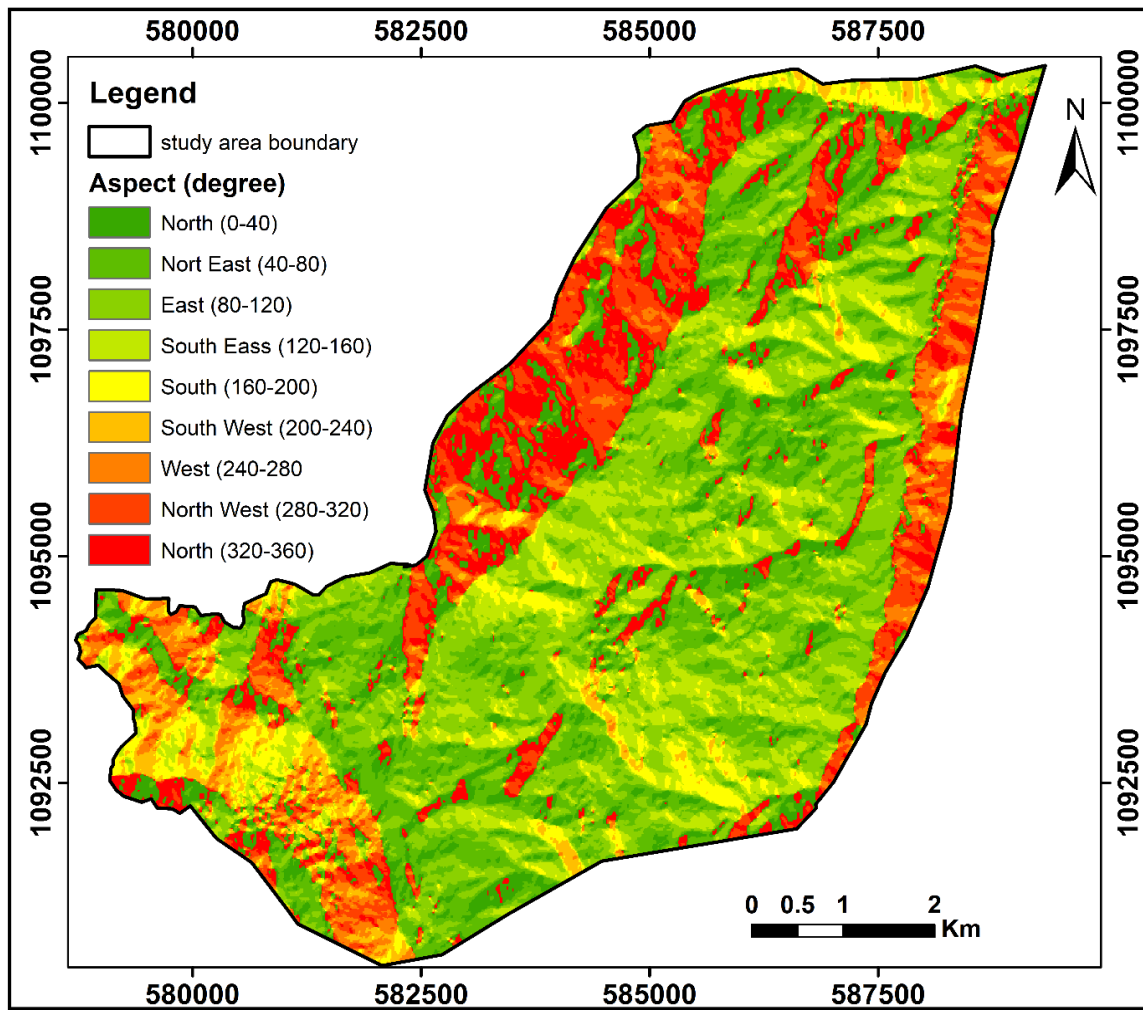


Figure 4.5. Aspect map

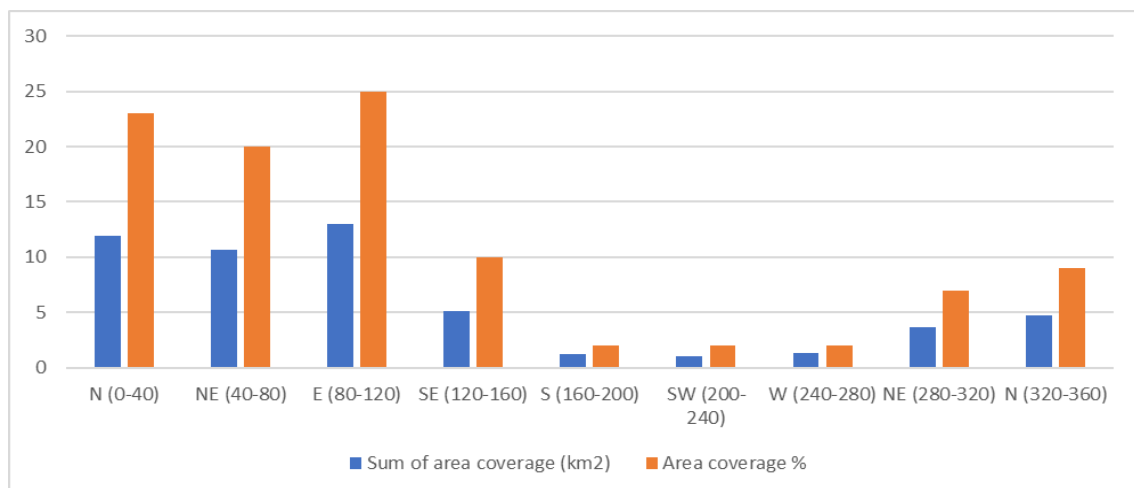


Figure 4.6. Aspect gradient distribution and area coverage

iii. Elevation

The elevation of the study area is prepared as the same aspect and slope map from the 12.50m DEM of SRTM image obtained from Alaska Satellite Facility (ASF) using elevation spatial analysis tool in arcGIS10.8 and classified into 5 classes using a natural break (Figure 4.7). It is prepared with the same scale and pixel size as the study area. The area is characterized by an elevation difference of about 1680m ranging from 1465m to 3145m above sea level. The elevation intervals show a continuous pattern of increase vertically and this type of inclination is susceptible to erosion and landslides. The slope of the area is characterized to be a gentle to moderately steep slope. Most of the area (82%) lies in the slope angle interval 0° to 26° as shown in Figure 4.8.

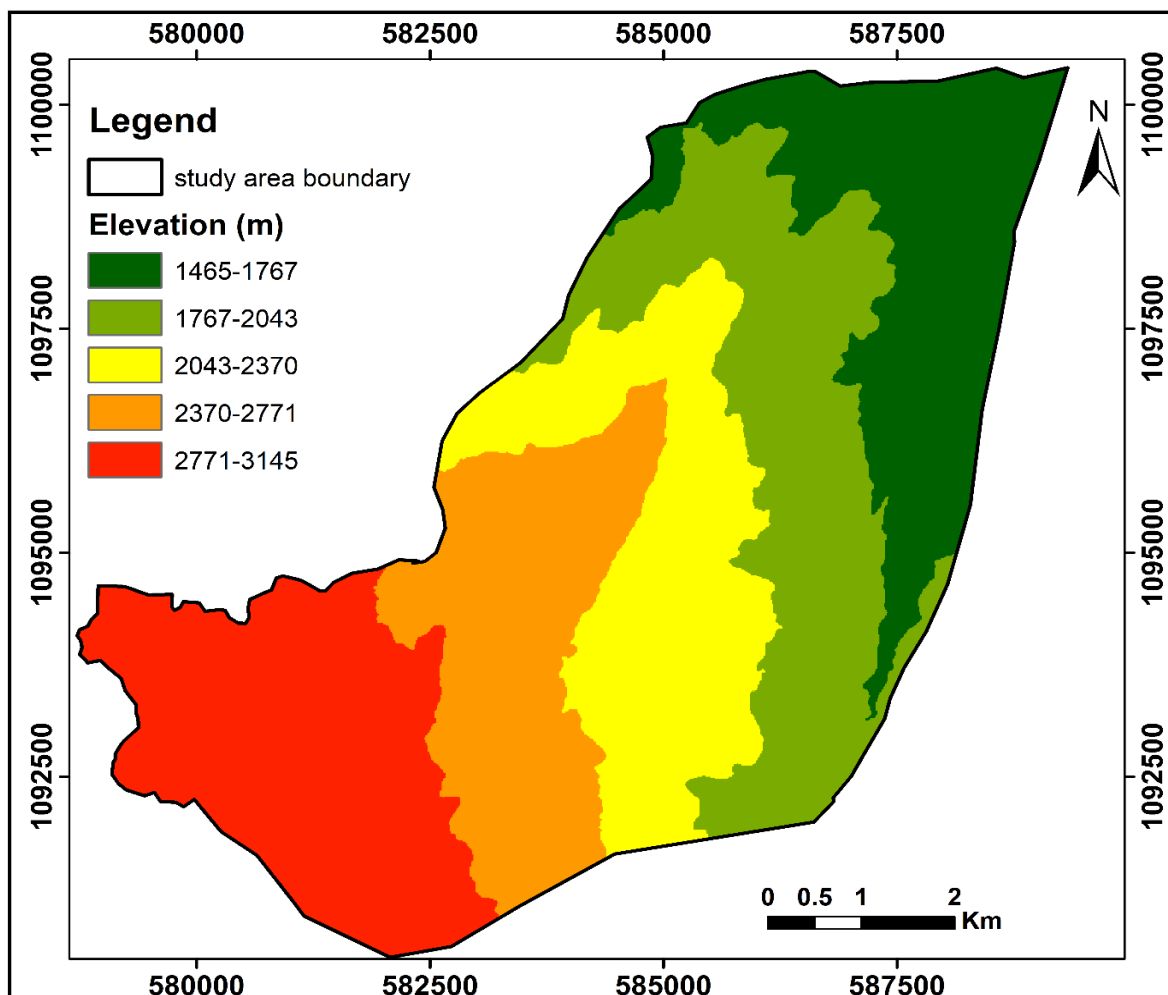


Figure 4.7. Elevation map

The maximum area of the study (42%) is covered by an elevation interval from 2065-2365m (Figure 4.8). most of the landslide is encountered along elevation ranges from 1767 to 2370m.

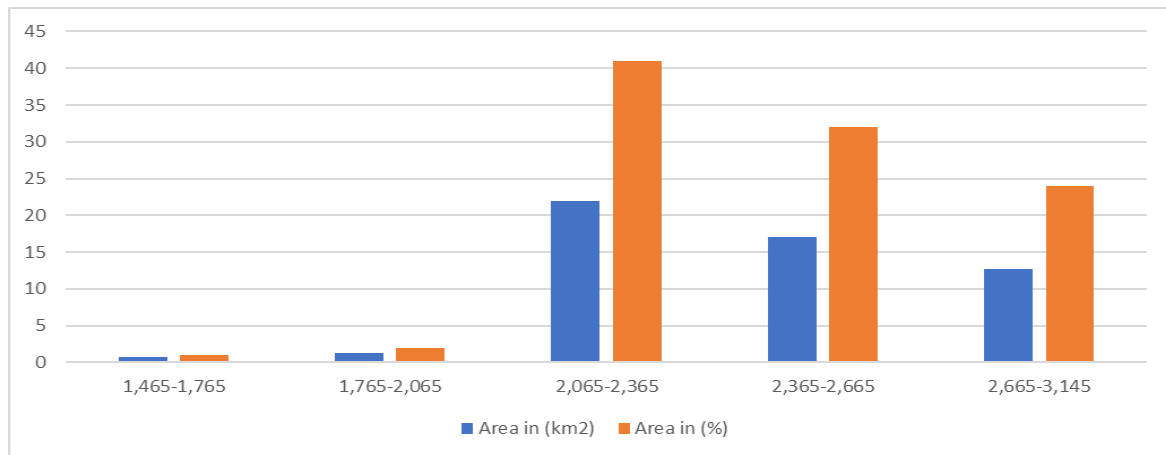


Figure 4.8. Elevation interval and area coverage

iv. Distance to drainage

The distance to the river map of the study area is prepared as the same aspect and slope map from the 12.50m DEM of the SRTM image obtained from the Alaska Satellite Facility (ASF) with the Euclidean distance buffering method in the spatial analyst tool of ArcGIS 10.8. It is also prepared with the same scale and pixel size as the study area. Most of the study area drainage systems were created along the geological structures. The lower elevated study area of the eluvium-colluvium deposit is highly susceptible to erosion as observed during site investigation work. Due to this reason, distance to drainage is considered one of the factors in the study area. The area was divided into five distance ranges depending on the literature and site conditions (Figure 4.9.). About 61 % of the study area encountered a distance of up to 200m and most of the earth slide is encountered along this distance (Figure 4.10.).

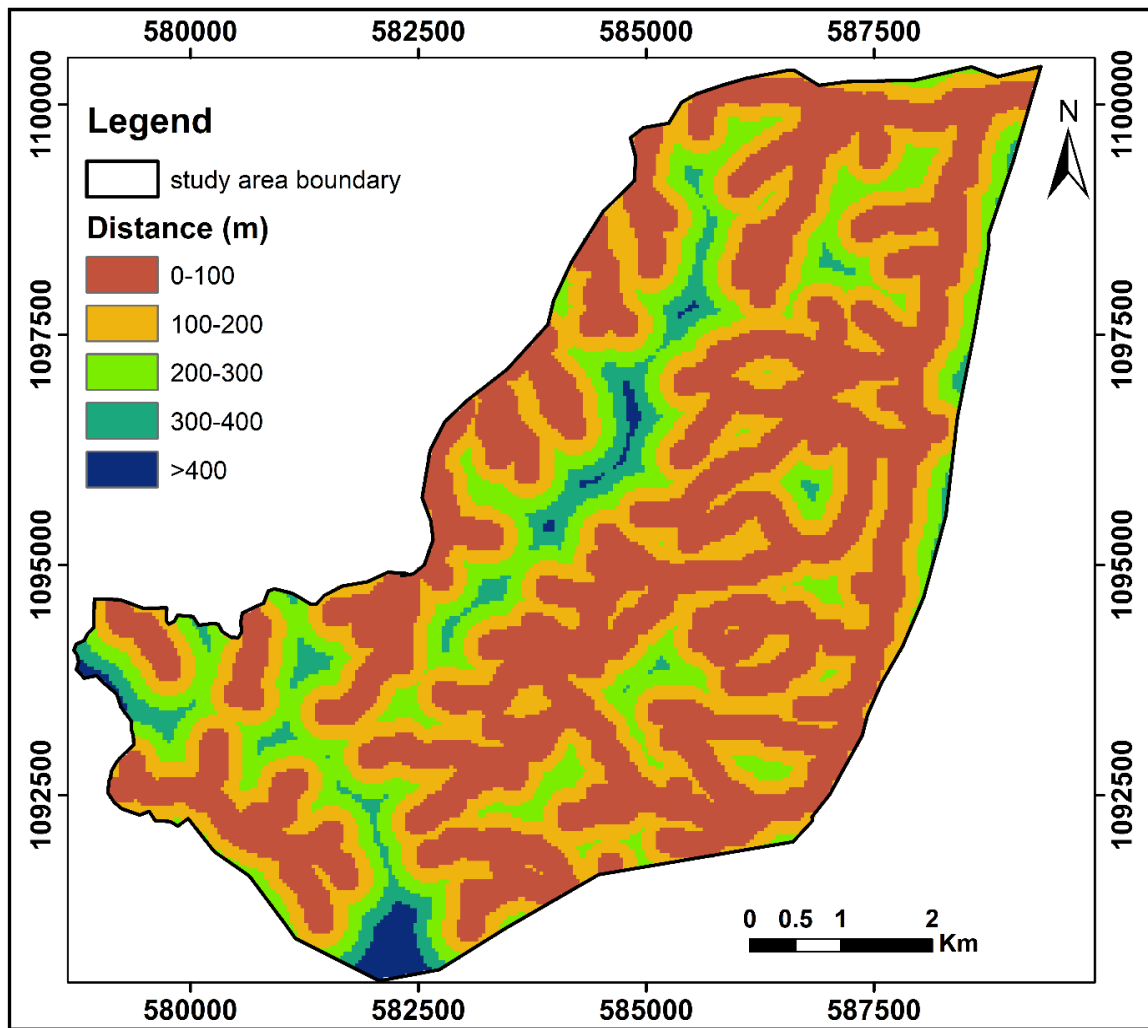


Figure 4.9. Distance to drainage map

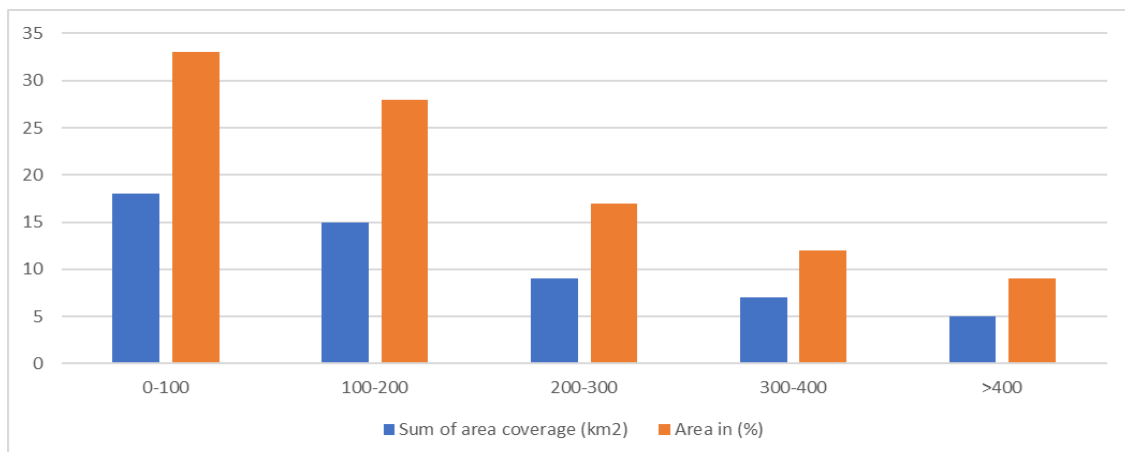


Figure 4.10. Distance from the river and area coverage

v. Land use land cover (LULC)

To prepare the LULC which is considered one of the other causative factors of the area, Landsat 9 image, Google Earth and field surveys have been used. It is also prepared with the same

scale and pixel size as the study area using ArcGIS 10.8 (Figure 4.11). supervised classification system was used to classify the land coverage by defining the known pixel and the signature file was created. Then the pixels are changed into polygons and the area is calculated. The study area is covered about 67% by arable land, 25% by Bush and shrubs, 5% by forest, and 2% by river (Figure 4.12).

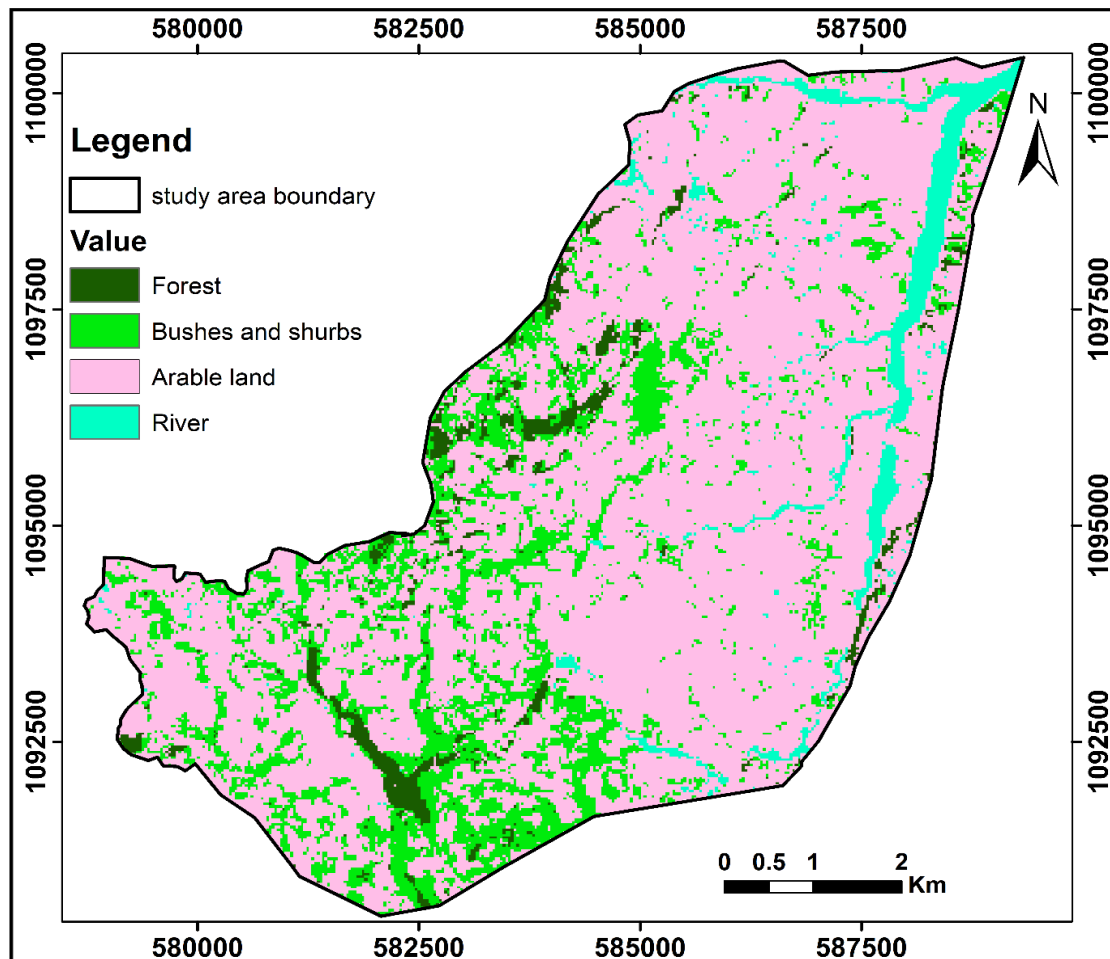


Figure 4.11. Land-use and land-cover map

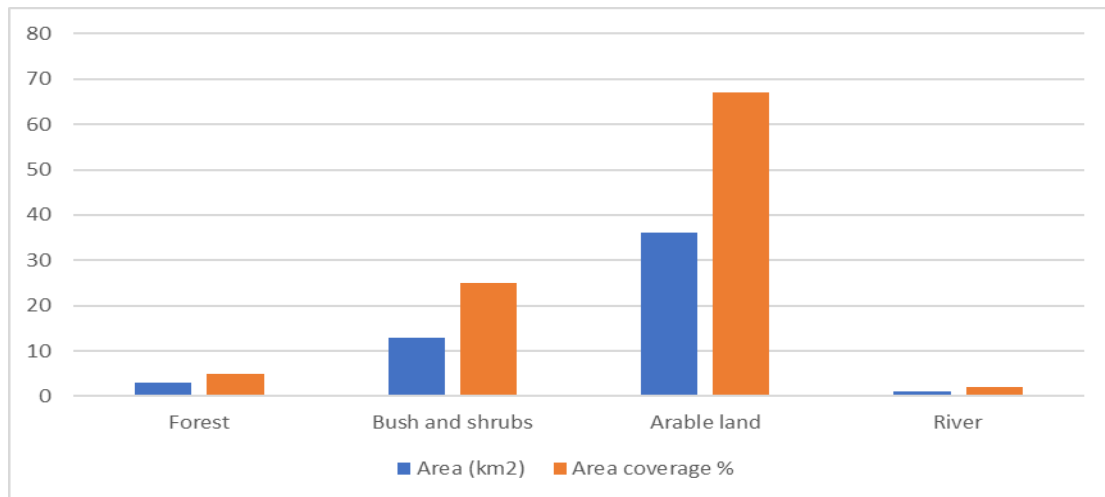


Figure 4.12. Land-use and land-cover and area coverage

4.1.3. Displacement mapping

4.1.3.1. InSAR techniques

Interferometric synthetic aperture radar (InSAR) techniques are employed to produce the landslide displacement map processed with Sentinel Application Platform (SNAP). Interferometric synthetic aperture radar (InSAR) techniques are employed to understand the area's displacement condition. The time series InSAR analysis method is used to map unstable areas, detect active slope deformation, and obtain surface displacement information (Shi et al., 2020, Wang et al., 2023). In difficult terrain, the InSAR analysis method based on SAR data visibility can also serve as a reference for detecting and assessing active landslides (Anjasmara, Yulyta, & Taufik, 2020).

The method is adopted using sentinel-1 products, a Space component of the Copernicus program of the European Commission and the European Space Agency (ESA). Its mission is formed by a constellation of two twin satellites faced at 180°. It is an active sensor working on the C-band including a right-looking faced array antenna providing fast scanning elevation and azimuth and also providing data for a short cycle of six days with different imaging modes. there are four imaging modes with swath and resolution which are stripping (SM), Interferometric wide swath (IW), Extra wide swath, and wave mode. Each mode has also four products which are Level-0 RAW, Level-1 SLC, Level-1 GRD, and Level-2 OCN. For this study, an acquisition mode interferometric intensity wide (IW) which is a land application mode with Single lock complex (SLC) products used downloading USGS and processing

through the free and open scalable platform of sentinel application platform (SNAP) provided by research and user support for sentinel core products (RUS) website. The interferometric intensity wide (IW) product comprised of three swaths which are IW-1, IW-2, and IW-3, and nine bursts.

4.1.3.2. Procedures

Two descending Sentinel-1 Interferometric Wide Single Lock Complex (S1A_IW_SLC, 2014 and 2024) images were downloaded from USGS and processed with Sentinel Application Platform (SNAP) to prepare the interferogram and displacement map (Figure 4.13). In the first step, both products are split into a specific swath to know which sub-swath belongs to the study area. The split products are composed of an IW-2 swath and three bursts which are near the study area. After splitting the image, both images are co-registered into a stack for interferometric processing and to ensure that each ground target contributes to the same pixel in both that select as one a master and the other as a slave image and putting the two images together (Meyer, 2019, García et al., 2020). In the 3rd stage interferogram formation and coherence estimation are performed by cross-multiplying the master image with the complex conjugate of the slave (Meyer, 2019, García et al., 2020). In the 4th step apply TOPS Deburst to join all bursts in a swath into a single image and in the 5th stage apply topographic phase removal to remove the topographic phase contribution (Meyer, 2019, García et al., 2020). Step 6th applies Multi-looking and Phase Filtering to reduce noise and enhance the appearance of the deformation fringes (Meyer, 2019).

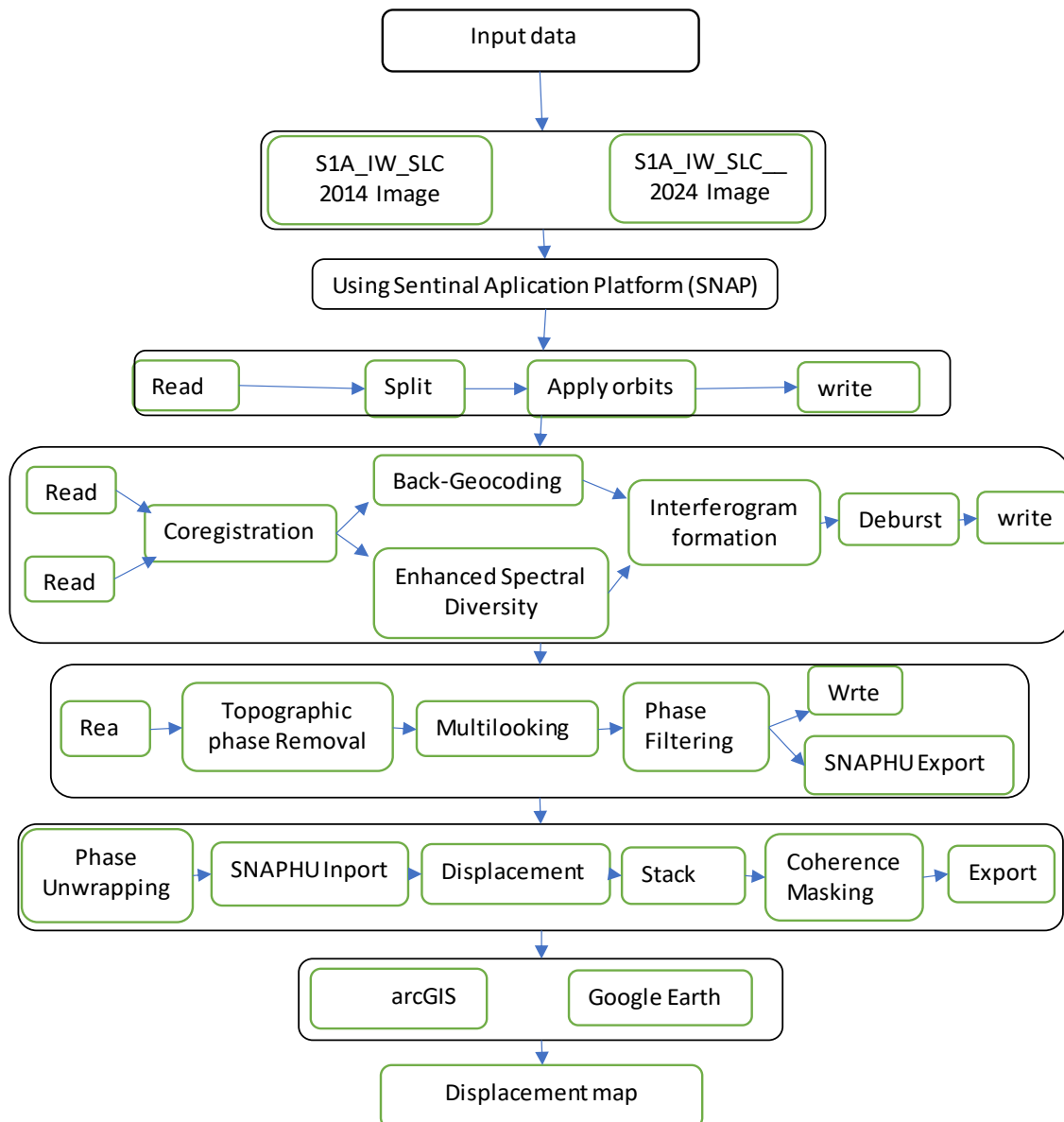


Figure 4.13. Workflow in SNAP software (source <https://youtu.be/w6ilV74r2RQ>, Alaska Satellite Facility, 2019)

At the 7th stage, run the Phase unwrapping process to resolve the ambiguity and obtain the absolute change of phase or continue the phase distribution using SNAPHU Command which is developed by Curtis Chen and Howard Zebker at Stanford University, a statistical-cost, network-flow algorithm for phase unwrapping (Mellors, Lindsey, & Feigl, 2017, Alaska Satellite Facility, 2019). Finally, perform geocoding and export in a format of ArcGIS and Google Earth KML file. A DEM-assisted geocoding step must be used to project the interferometric phase image into a geographic coordinate system for the data to be useful for further processing (Meyer, 2019). A series of detailed processes that shows all the steps in the SNAP software is given in Figure 4.13.

CHAPTER – FIVE

RESULT AND DISCUSSION

5.1. Frequency ratio

The areal coverage of landslide occurrences in each class of causative factors is calculated by crossing with the inventory map using ArcGIS. FR was calculated for each class of the parameter by dividing the area of landslides in the class by the area of all landslides for the area of the class by the entire map by the same equation as (Hagos, 2012, Mersha & Meten, 2020).

$$FR = \frac{\text{area of landslide in class} / \text{area of all landslide}}{\text{area of class} / \text{entire map}} \dots\dots\dots 5.1$$

According to (Hagos, 2012) (Fayez et al., 2018) (Youssef et al, 2023), next to this, the Frequency ratio is calculated using the ratio of the area occupied by landslides in each class (X in%) divided by the total area occupied by landslides in each class (Y in%). The FR values of the six chosen landslide causative parameters are shown in Table 6. According to (Hagos, 2012, Mersha & Meten, 2020) and (Elfriede et al, 2019), the values resulted in the table that $FR < 1$ indicates a lower correlation than average, $FR > 1$ indicates a stronger correlation than average, and $FR = 1$ indicates comparable to average. The ratios of each factor's type were summed to calculate the Landslide Susceptibility Index (LSI) using the equation

$$LSI = \Sigma FR \dots\dots\dots 5.2$$

where LSI = Landslide Susceptibility Index

FR = Frequency Ratio of each causative factor of the classes.

Table 6. Summary of frequency ratio results

Factors	Class	Class pixel	% class pixel	landslide pixel	% landslide pixel	FR
Slope	0-10	80392	23.523	4854	18.008	0.766
	10-18	108630	31.786	9401	34.877	1.097
	18-26	88963	26.031	7670	28.455	1.093
	26-37	49372	14.446	3743	13.886	0.961
	>37	14401	4.214	1287	4.775	1.133
	Total	341758	100	26955	100	5.050
Elevation	1465-1767	66050	19.327	2742	10.173	0.526
	1767-2043	78303	22.912	12621	46.822	2.044
	2043-2370	66099	19.341	8903	33.029	1.708
	2370-2771	59016	17.268	2502	9.282	0.538
	2771-3145	72290	21.152	187	0.694	0.033
	Total	341758	100	26955	100	4.848
Aspect	N	41548	12.157	2071	7.683	0.632
	NE	61377	17.959	5848	21.695	1.208
	E	76651	22.428	9473	35.144	1.567
	SE	43593	12.756	5763	21.380	1.676
	S	19558	5.723	1575	5.843	1.021
	SW	12649	3.701	434	1.610	0.435
	W	18555	5.429	262	0.972	0.179
	NW	31618	9.252	703	2.608	0.282
	N	36209	10.595	826	3.064	0.289
	Total	341758	100	26955	100	7.289
Distance to Stream	0-100	162093	47.429	16321	60.549	1.277
	100-200	107268	31.387	6879	25.520	0.813
	200-300	53957	15.788	2958	10.974	0.695
	300-400	15160	4.436	660	2.449	0.552
	>400	3280	0.960	137	0.508	0.530
	Total	341758	100	26955	100	3.866
Lithology	Alaje formation	127121	37.196	2880	10.684	0.287
	Tarmaber formation	105534	30.880	371	1.376	0.045
	Alluvial deposit	20944	6.128	4176	15.492	2.528
	Colluvium deposit	88159	25.796	19528	72.447	2.808
	Total	341758	100	26955	100	5.668
LULC	Forest	11688	3.420	184	0.683	0.200
	Shrub	60560	17.720	3779	14.020	0.791
	Arable land	255058	74.631	20569	76.309	1.022
	River	14452	4.229	2423	8.989	2.126
	Total	341758	100	26955	100	4.139

5.1.1. Correlation Landslides Causative Factors and FR results

5.1.1.1. Slope

The Slope angle of 10-26 degrees and more than 37 degrees have frequency ratio values >1 , indicating a strong relation with landslide probability of occurrences. The Slope angle from 26-37 degrees and 0-10 degrees shows a lower correlation to the probability of landslide occurrence as shown (Table 6 and Figure 5.1).

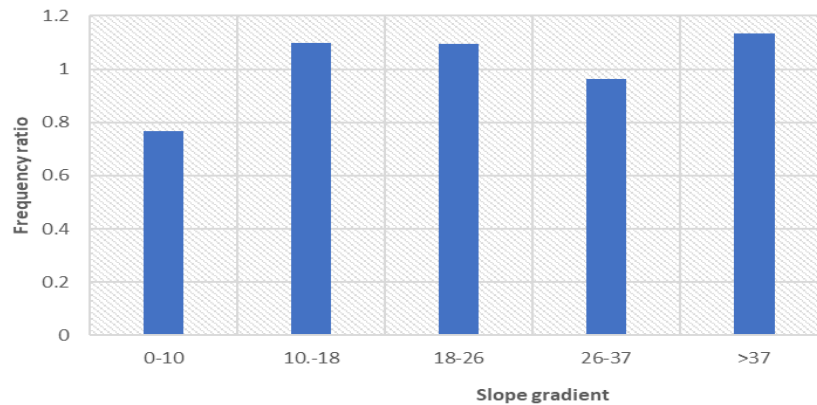


Figure 5.1. FR versus slope gradient

5.1.1.2. Elevation

The middle area of the elevation which is from 1767m to 2370m has FR values of more than 1.5 indicating a very high correlation with the probability of landslide occurrence. The low elevated area from 1465m to 1767m and the high elevated areas from 2370m to 3145m have FR values less than one and show low correlation probability (Table 6 and (Figure 5.2).

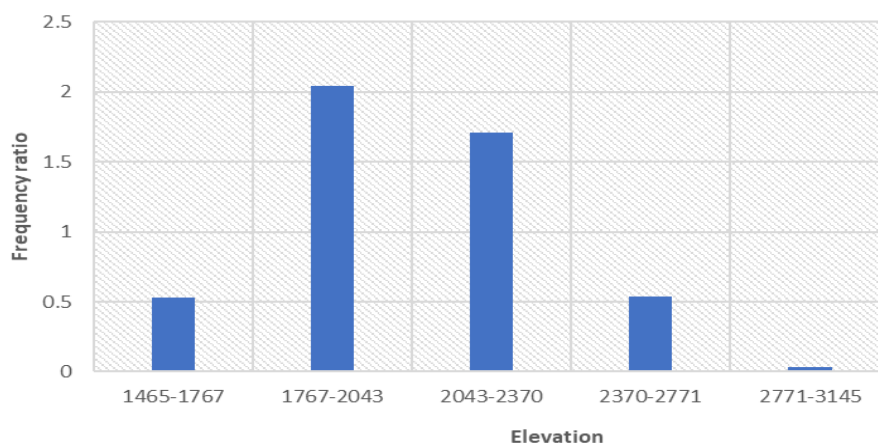


Figure 5.2. FR versus Elevation

5.1.1.3.Aspect

According to the aspect of the study area, southeast-facing (120° - 200°), east-facing (80° - 120°), and northeast (40° - 80°) have FR values of more than one and indicate high strong to medium-strong correlation respectively. The slope aspect facing south (160° - 200°) has an FR value close to one which indicates moderately comparable for the frequency of landslide. The rest of the aspect FR values have less than one and indicate with low probability (Table 6 and Figure 5.3).

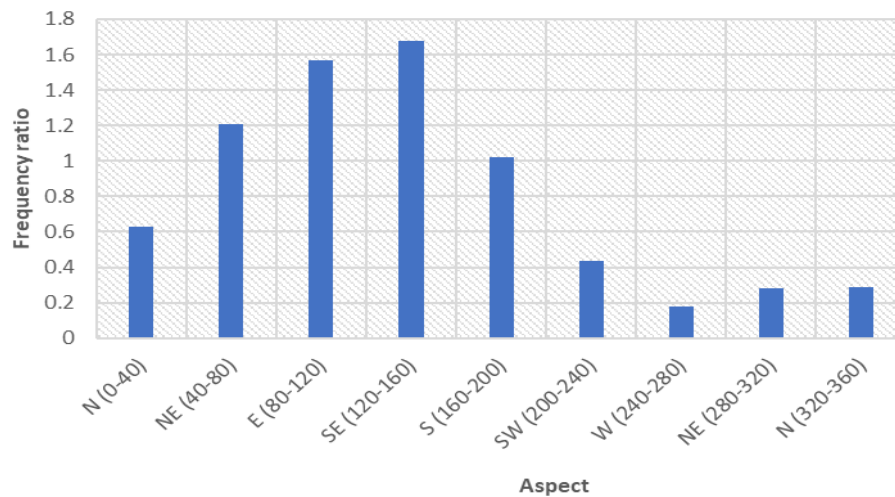


Figure 5.3. FR versus Aspect

5.1.1.4.Distance to stream

The nearest distance from the stream (0-100m) has a strong correlation with the probability of landslide occurrence. More than 100m distance from the stream, the value of frequency ratio is below one and also gradually decreases away from 100m distance indicating landslide susceptibility also gradually decreases far away from the stream (Table 6 & Figure 5.4).

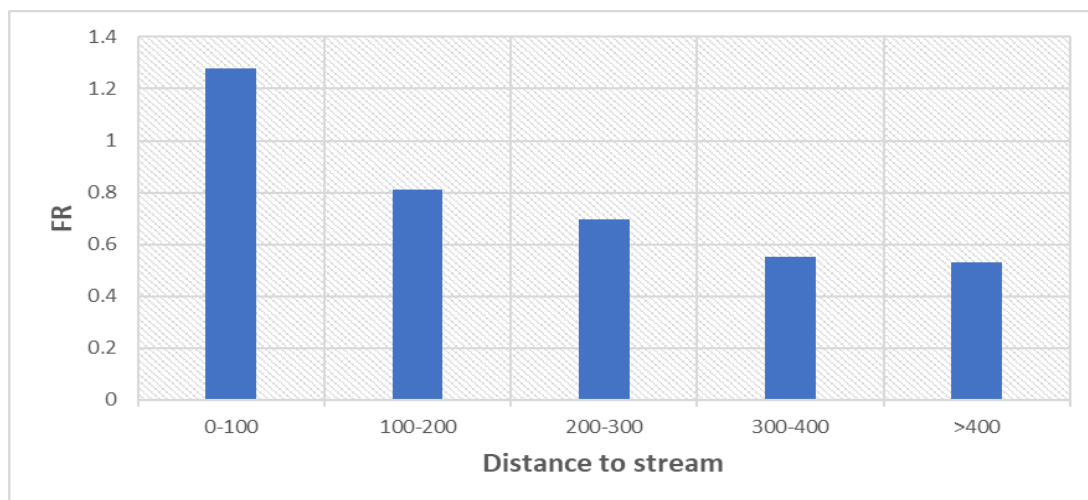


Figure 5.4. FR versus Distance to stream

5.1.1.5. Lithology

The Lithology of colluvium-eluvium deposits and alluvial deposits show an $FR > 1$ which is 2.8 and 2.5 respectively which indicates a powerful correlation with the probability of occurrence of a landslide. On the other side, the Tarmaber basalt shows a very low correlation with landslide susceptibility. Alaje formation also shows a low correlation with landslide probability of occurrence (Table 6 and Figure 5.5).

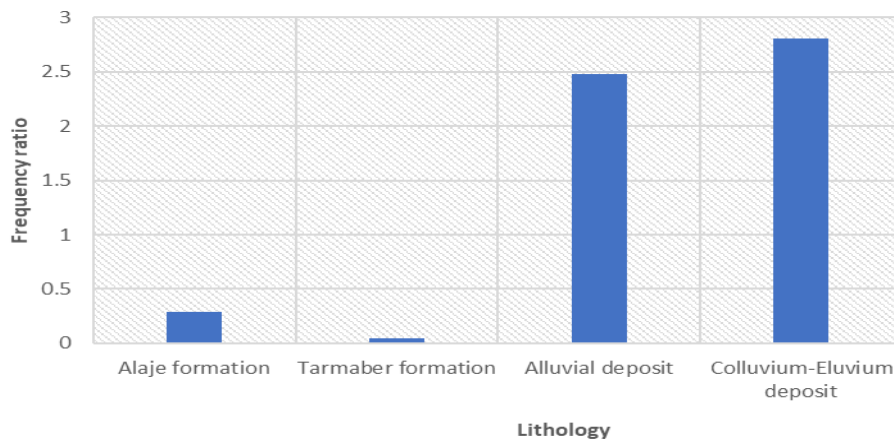


Figure 5.5. FR versus Lithology

5.1.1.6. Land use land cover (LULC)

In the case of LULC, the area covered by the river has a frequency value of greater than one which indicates that it is strongly correlated with the probability of landslide susceptibility. Areas covered by arable land have FR values close to one which indicates moderately comparable for the susceptibility of landslide. The areas covered by shrubs and forests have a low to very low correlation respectively to landslide occurrence (Table 6 and Figure 5.6).

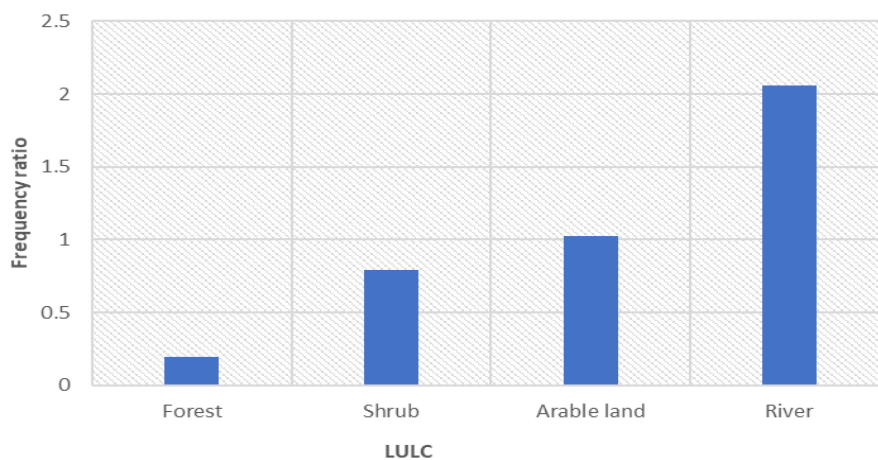


Figure 5.6. FR versus LULC

5.1.1.7. Comparison of all stronger values

Lithology is the most dominant and has a relatively very high correlation to the landslide probability of occurrence the FR value is more than 2.5 that of the six causative factors. the LULC (river coverage) and elevation (1767m to 2043m) have also a high correlation with an FR value of about 2. Distance to stream, slope, and aspect have a medium correlation to landslide susceptibility (Table 6 and Figure 5.7)

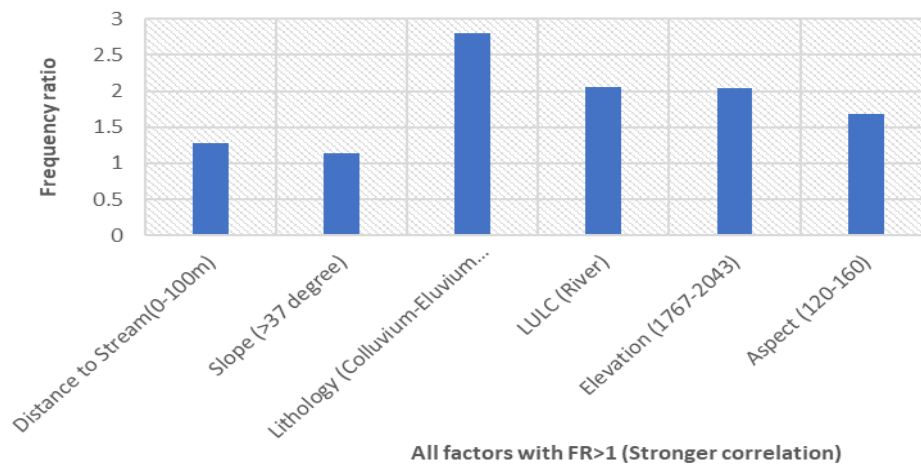


Figure 5.7. FR versus all factors of FR>1

Finally, the landslide susceptibility map was created using ArcGIS's raster calculation and map overlay tools to do the weighted sum using (Equation 5.2). There are different boundary classifier approaches as discussed above like Equal Interval, Quantile, Natural Breaks (Jenks), Standard Deviation, and manual classification. there is no common rule using such classification methods (Hagos, 2012). Researchers used different classification methods based on their expert judgment e.g. (Hagos, 2012) used a manual classification system, (Wubalem, 2021) adopt a quantile classification system, (Youssef et al., 2023 and Mersha & Meten, 2020, Javad et al, 2014) adopt a natural break classification system. For this research, a natural break classification was adopted because the data is not evenly distributed and then the LSI values are classified into five different susceptibility zones of the study area namely very high, high, moderate, low, and very low susceptibility zones as shown in Figure 5.8. As indicated in Figure 5.9 also, 18.52% of the area is covered by very high susceptibility, 12.96% by high susceptibility, 11.11% by medium susceptibility, 29.63% by low susceptibility, and 27.78% by very low susceptibility.

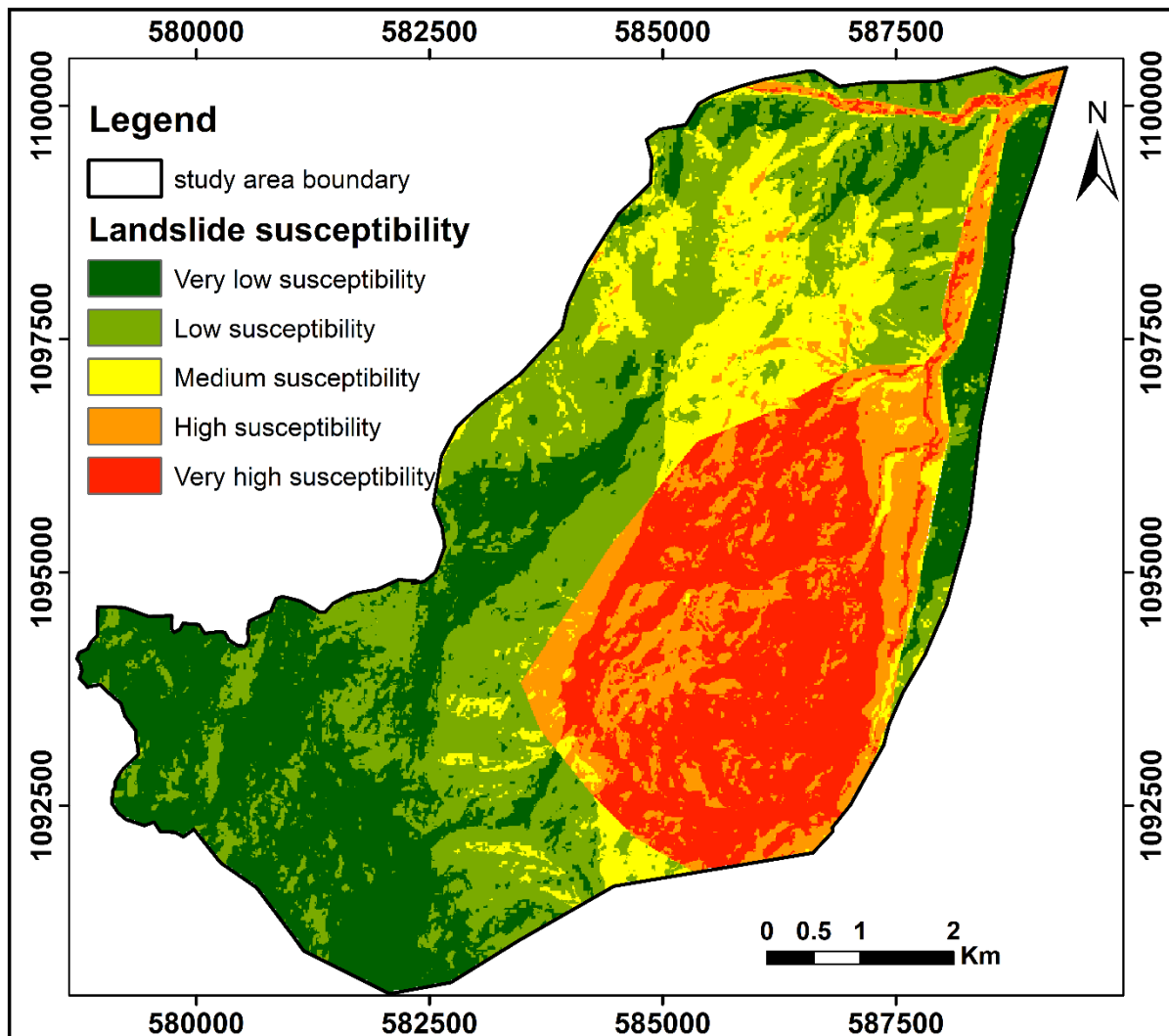


Figure 5.8. Landslide susceptibility zonation map

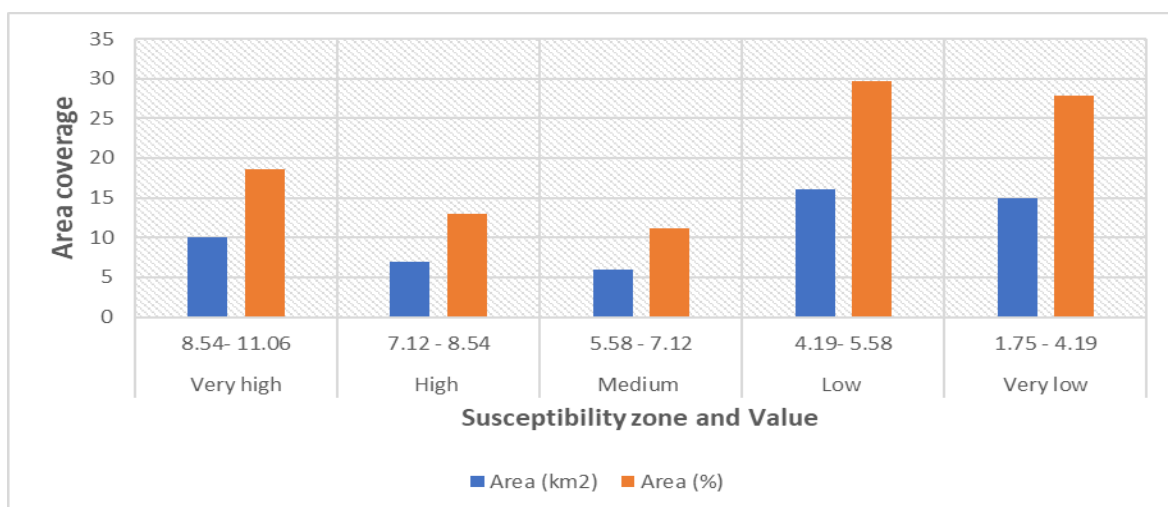


Figure 5.9. Landslide susceptibility zonation area coverage (%)

5.1.2. Validation

The output of this method shows that the very high susceptible zones are located along the high number of landslide inventories encountered areas and low susceptibility zones also lay with low landslide inventories area as shown in (Figure 5.10). The deep-seated landslide that occurred in 2005 also fits with the very high landslide susceptibility zone. From the total of 62 landslide inventories, 45 landslides include 4 main rock slides, 1 debris flow, 24 earth slides, and 19 debris slides which is about 72.5% found within the very high to high susceptible zone. According to this, it is quite significant and reasonable for prediction rate as compared with the field condition and to evaluate the contribution of the various causative factors to the landslide. The result of verification with the displacement is given below in the next section.

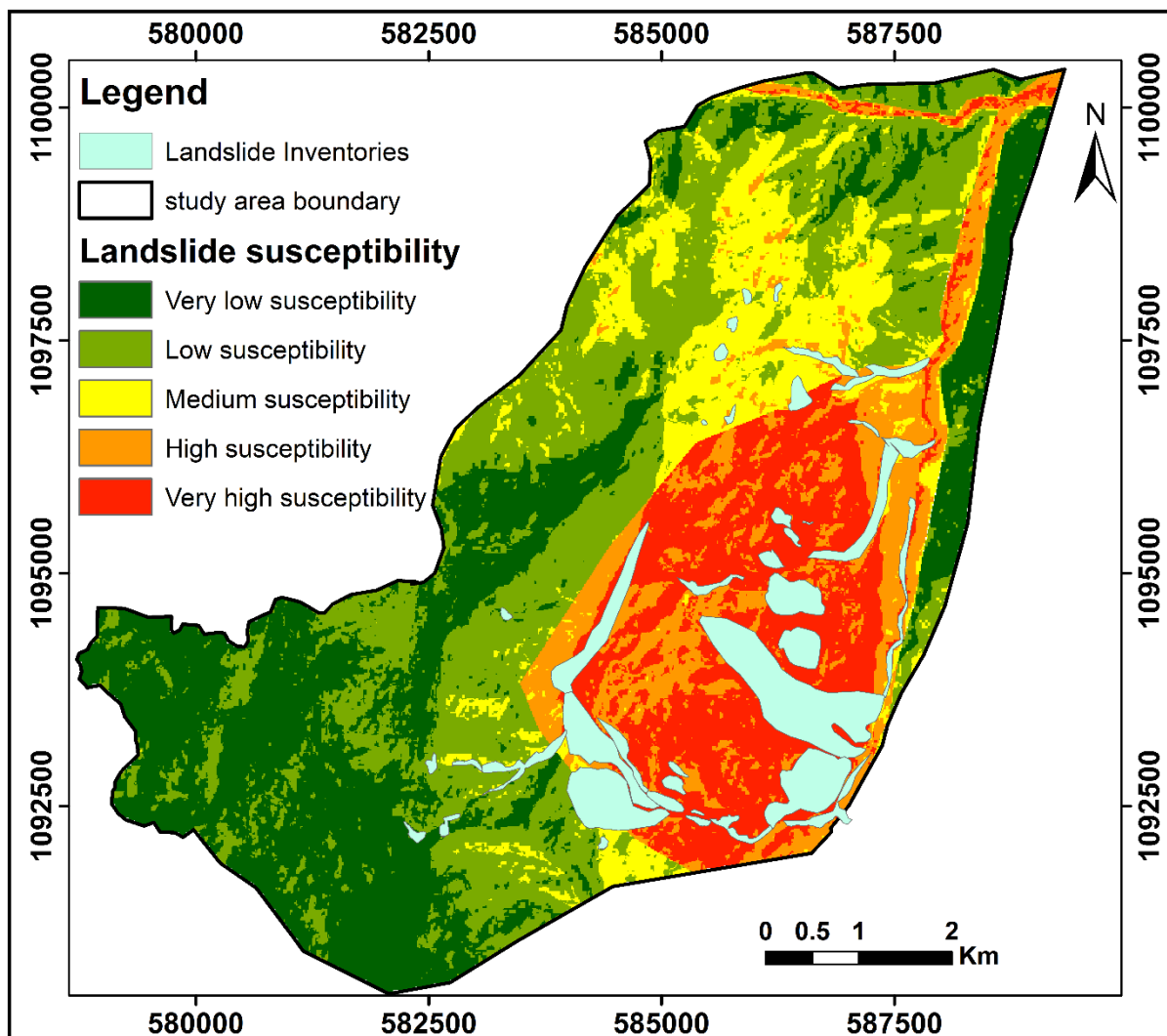
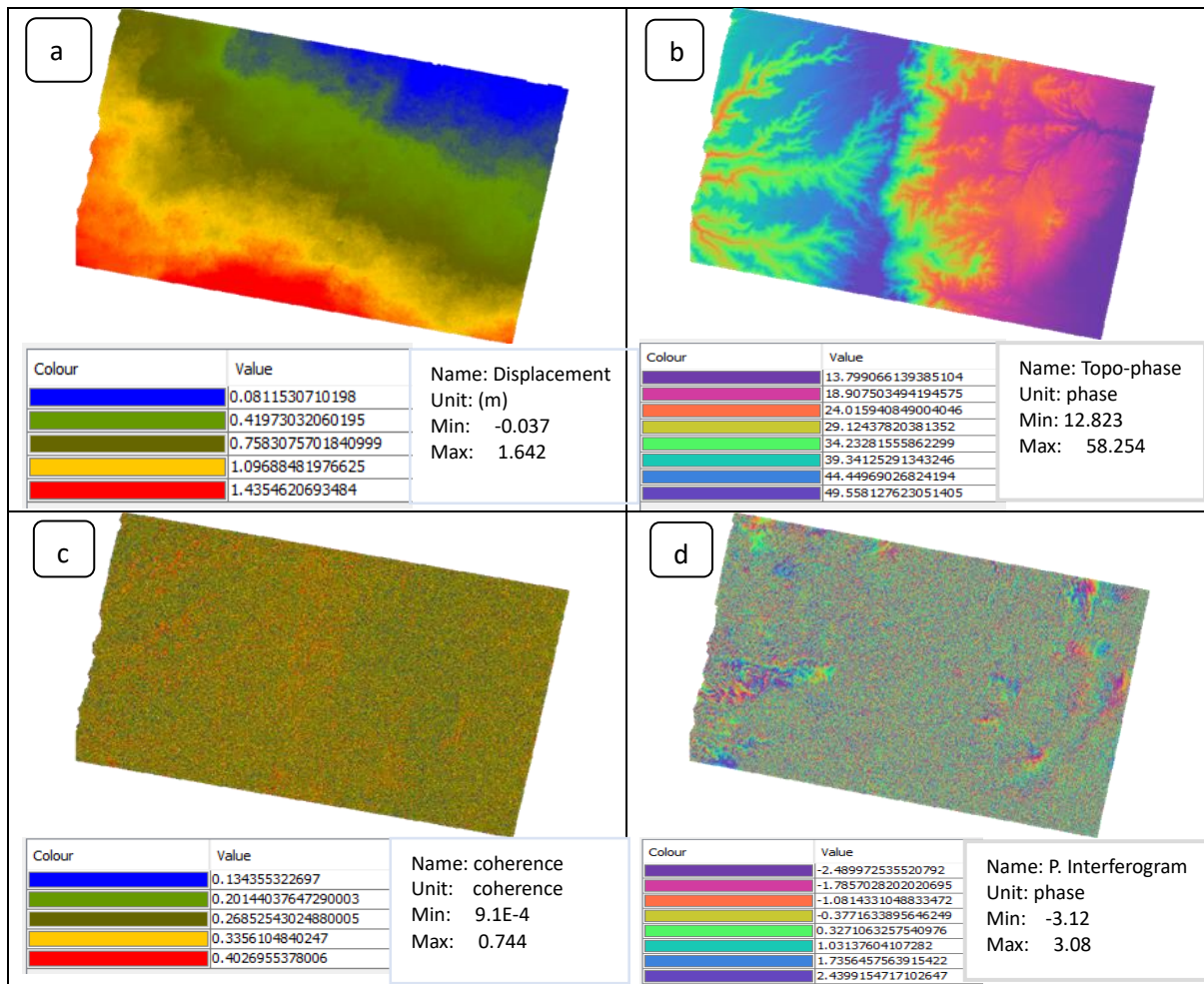


Figure 5.10. Landslide susceptibility validation map

5.2. InSAR

After proceeding with all the above procedures, the following products that contain all results of S1A_IW_SLC_split_Orb_Stack_Ifg_Deb_DInSAR_ML_Flt_TC_msk_Stack are produced (Table 7). This result contains displacement, Topophase, coherence, and phase interferogram.

Table 7 SNAP analysis products (a) Displacement, (b) Toppo phase, (c) coherence, (d) phase Interferogram.



The displacement result shows that the region is displaced from a minimum of -0.037m and a maximum of 1.642 from 2014 to 2024 years (Table 7 a). The change in the top phase is from a minimum of 12.823 to a maximum of 58.254m (Table 7 b). The coherence, which is the correlation between a master and a slave's images, has a result of 0.1 to 0.744 (Table 7 C). SAR image which has values close to one shows a high difference and close to zero shows a low difference. The phase interferogram is created by the interferometry of two radar images over the same area with the same geometry. The deformation or phase difference results from a minimum of -3.12 and a maximum of 3.08 (Table 7 d). In this case, the result is close to one

indicating that the image is more coherent. the interferometric phase consists of fringes of one cycle color which measure from 2π (-3.14 to +3.14). After this process, the products are exported with Geo tiff and KML and processed in ArcGIS extracted by mask special analysis tool with the same scale of the study area with their information values to evaluate the specific site condition (Figure 5.11)

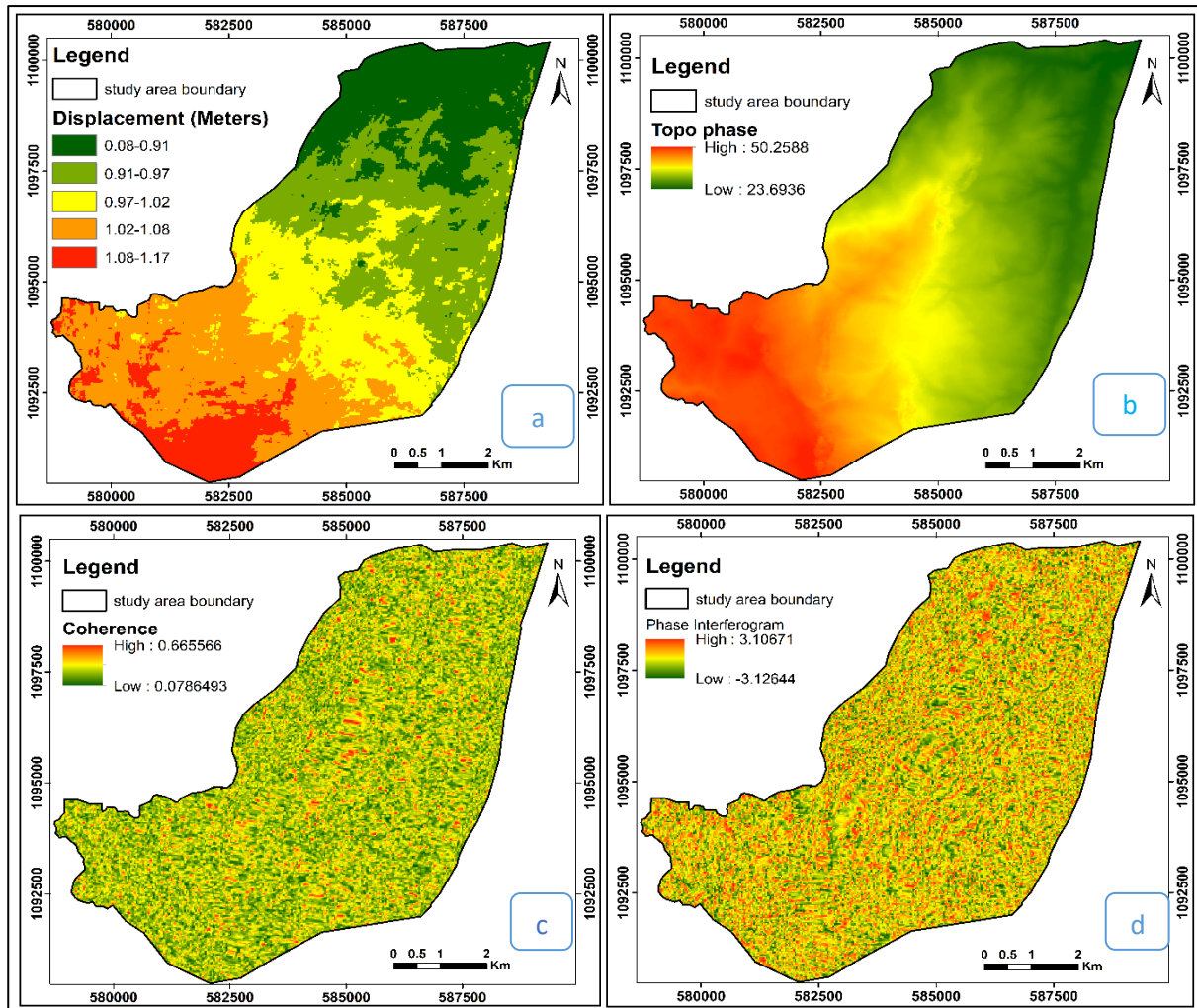


Figure 5.11. SNAP analysis products (a) Displacement, (b) Toppo phase, (c) coherence, (d) phase Interferogram.

The displacement map is reclassified with ArcGIS 10.8 based on the size of the study area as shown in (Figure 5.11a). The displacement range is classified using a natural break classification system similar to the frequency ratio method of susceptible zone classification to understand the correlation between the two methods. In the study area, the change in the top phase is from a minimum of 23.69 to a maximum of 50.26m (Figure 5.11b). The coherence has a result of 0.078 to 0.66 (The deformation or phase difference results from a minimum of -3.126 and a maximum of 3.106 which indicates medium coherence (Figure 5.11 c& d). The

following (Figure 5.12) shows the full process which includes the three bursts and IW-2 image with the Google Earth view and the area location.

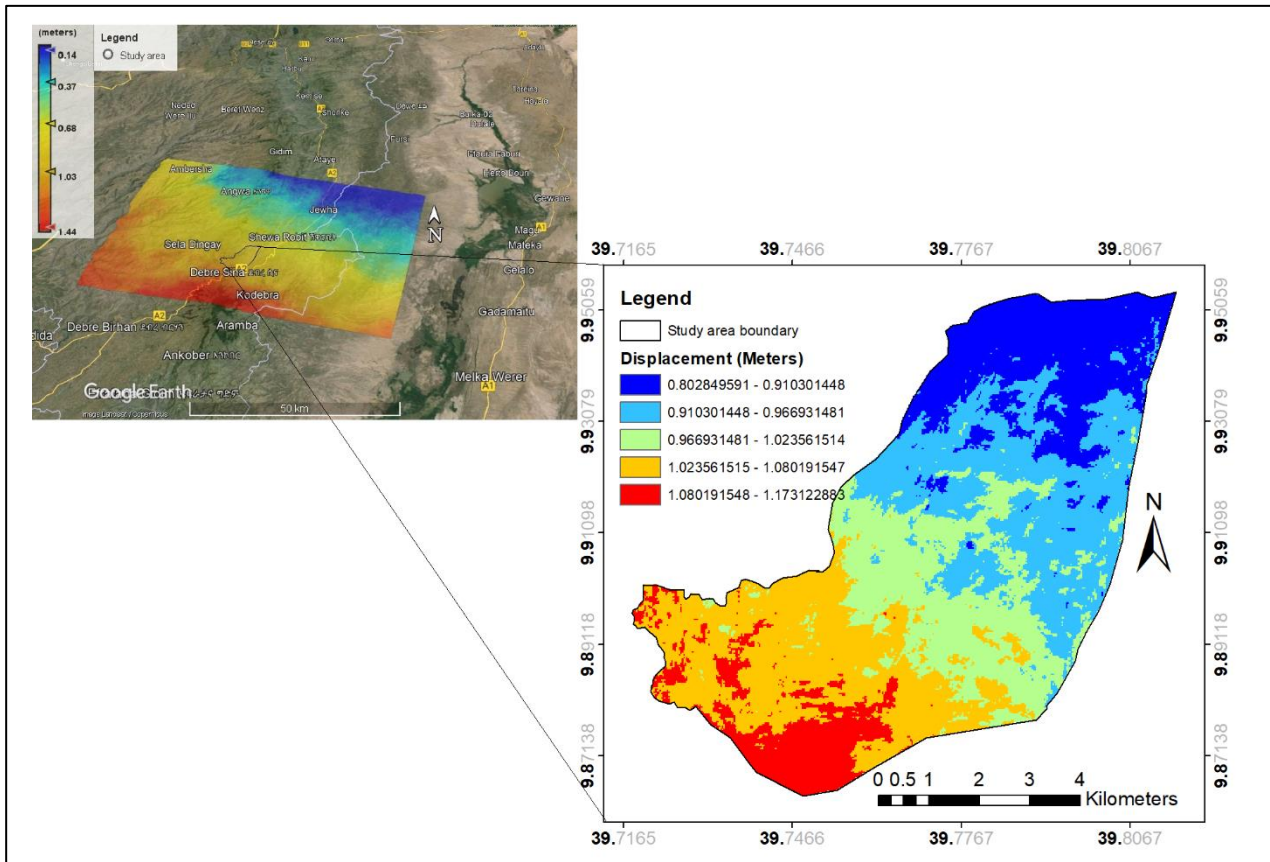


Figure 5.12. Displacement map

The highly displaced area covered about 9% of the study area. Medium to high displaced area is covered from 22% to 25% and low to very low displaced area is also covered from 26% to 18% respectively (Figure 13).

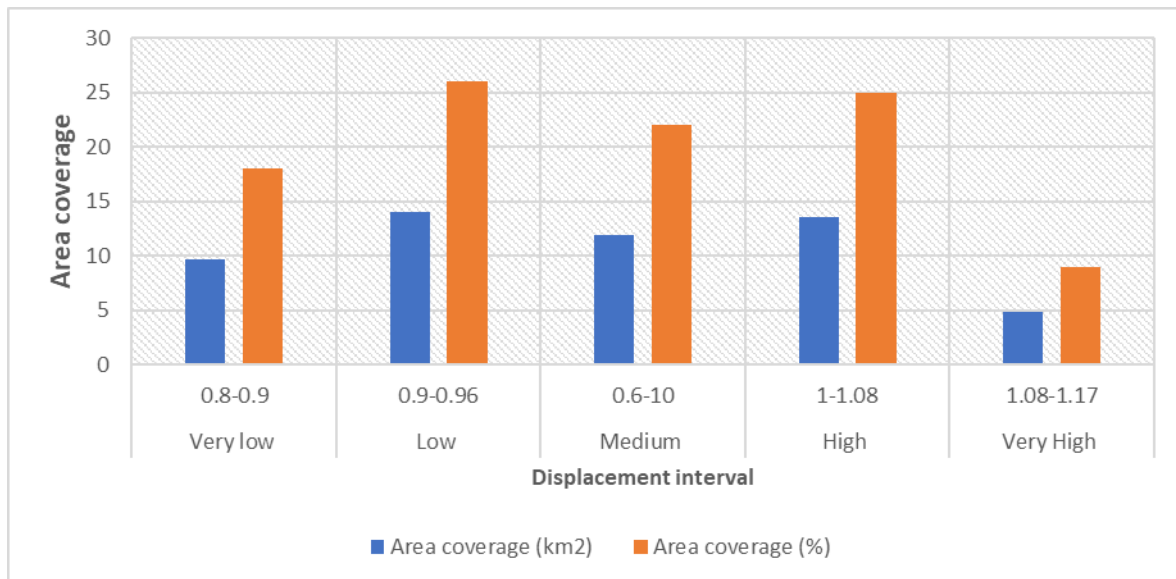


Figure 5.13. Range of Displacement area coverage (%)

The displacement map result shows that the study area is displaced from 0.8m to 1.17m (from 2014 to 2024) towards the satellite or to the east of the main Ethiopian rift. This means the image was taken from the descending products of sentinel-1 that the satellite observed from the east. On the other hand, negative or small values of displacement are referred to as movement away from the satellite, and large values or positive values indicate that the movement is towards the satellite.

The displacement is increasing away from the main Ethiopian rift towards the plateau areas. This is due to the active extensional tectonics discussed in chapter 3 of the tectonic section that the relative movement between the African and Somalian plates at a rate of approximately 6-7 mm/year characterize the MER (Tadesse Alemu, 2012 and Beyene & Abdelsalam, 2005a). This movement is very significant as the site's actual conditions. There is an indication and report of movements along the existing roads around the Armaniya, Agamber, and Ankober areas.

5.3. Verification and Correlation of the Results

The two mapping methods show similar boundary classifications but with different rates of values with having a good relation. the boundary both methods are classified by natural break classification in the ArcGIS 10.8. The low landslide susceptibility zone in the FR method remains with low displacement values. Some parts of medium landslide susceptibility also remain with a medium rate of displacement values as shown in Figure 14. The very high landslide susceptible zone, which is the main body of the 2005 deep-seated landslide lies with

a medium scale of displacement values for the time range of 2014 to 2024. The higher elevated areas encountered in the very low and low susceptibility zone of the FR model show relatively very high to high displacement values. This happened due to the effect of deep-seated landslides that occurred in lowland areas undercut the highland areas and led to reducing the confining stress of the area. This implies that the higher elevated areas show relatively high displacement values.

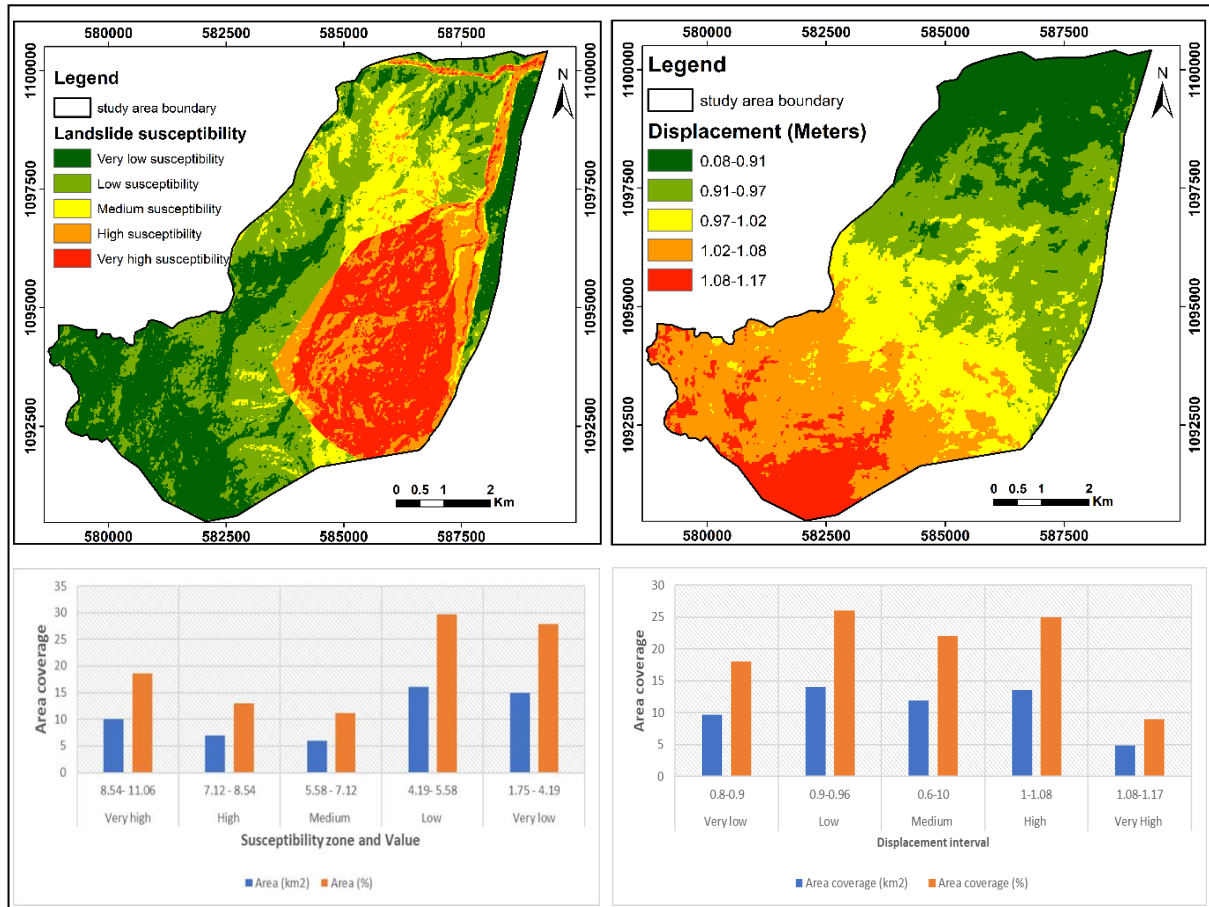


Figure 5.14. Susceptibility and displacement maps and graphs with the area coverage charts.

CHAPTER - SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusion

The study area is located along the main Ethiopian rift margins Ethiopian highland which is frequently affected by landslides. Deep-seated landslides that occurred in September 2005 highly affected the study area. New reactivated shallow landslides occur and damage massive agricultural lands, crops, and local houses.

This study is focused on mapping and analysis of instabilities based on determining the geotechnical properties of landslide-prone soil and rock by laboratory tests, preparing different causative factor maps and analyzing their contribution to instability, producing a landslide susceptibility mapping and identifying critical zones using frequency ratio methods, and producing a displacement map with a time series InSAR analysis method.

The methods and approaches employed in this research included:

- Literature reviews and data collection through field works including landslide inventories and collecting satellite data.
- Producing landslide susceptibility map using frequency ratio methods by preparing input maps including; landslide inventory map and six causative factor maps (a) Lithology map, (b) LULC map (c) distance to stream map (d) slop map (e) aspect map and (f) elevation map.
- Laboratory analysis of some landslide-prone soil and rock's geotechnical properties.
- Produced displacement map of the study area by using InSAR analysis methods using two sentinel-1 satellite images with the software Sentinel Application Platform (SNAP)

During fieldwork investigation and through Google Earth image interpretation, 62 landslides are identified and failure types like translational rock slide & rock fall, rotational debris slide, and rotational Earth slide are identified. The study area's lithological composition includes the

Tarmaber formation, making up 37% of the terrain, known for its moderate to extensive fracturing and varying degrees of weathering, with an average uniaxial compressive strength (UCS) value of 243.6 MPa. The Alaje formation, comprising 36%, is characterized by its highly fractured and weathered nature, with weaker UCS values of 79.2 MPa. Additionally, 21% of the area is composed of eluvium-colluvium deposits and 7% of alluvial deposits. These strata overlay an impermeable layer with hydraulic conductivity ranging from 0.0018 to 0.002 cm/sec, consisting of medium to dense sandy silt, an altered Alaje formation component.

The result of frequency ratio methods is classified into five susceptible zones by natural classification method which is (1) very high with an FR value of 8.54 to 11.06 and area coverage of 18%, (2) high with an FR value ranging from 7.12 to 8.54 and area coverage 14%, medium with FR value ranges from 5.58 to 7.12 and area coverage 11%, low with FR value ranging from 4.19 to 5.18 and area coverage of 30 %, and very low susceptible zones with FR value from 1.75 to 4.19 and area coverage of 27%. According to the correlation causative factors to landslide susceptibility, Lithology is the most dominant and has a relatively very high correlation to the landslide probability of occurrence in the study area. Finally, the result is validated by overlying with the known landslide inventory map and the actual site condition which results in high landslide inventory areas that are fit with the very high and high susceptible zones and low landslide inventory areas also fitting with the low susceptible areas.

The output of the InSAR analysis shows that the study area is displaced from 0.8m to 1.173m from 2014 to 2024 years interval towards the mean Ethiopian rift. The displacement rate indicates that it is high above the crown of the 2005 deep-seated landslide and low below the toe of the landslide. This indicates that the effect of deep-seated landslides that occurred in lowland areas undercut the highland areas and led to reducing the confining stress of the area. There is an indication of wide tension cracks observed above the fault scraps. It is important to use the two approaches together in such areas having a deep-seated movement or creeping to understand all instability processes.

In general, the combined effect of high rainfall in the area, the high concentration of springs along the Eluvium-colluvium deposits, and the contact between the Alaje formation, the geological setup which is the permeable underlined by impermeable and plastic tuff layer, the highly dissected gully structures and rugged topography, the behavior of constantly dipping and eroding action of the river and the tectonic effects makes the area unstable.

6.2. Recommendations

People living in very high susceptibility areas especially at the foot of landslide scrap around Yizaba Maryam, Korentos Kidanemhret, and immediately above the landslide scrap like Aynemaryam church are at risk condition because new tension cracks are observed around this area and the displacement condition is still active. Crops and local houses that are near the river with a distance of 100m are at risk conditions. It is observed that evacuation from the sliding bodies area is still a problem due to the creation of new tension cracks along the fault scrap and above it that continuously damage and disconnect the path.

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Distribution of landslide inventories type and locations. Their dimensions and area coverage are described in (Figure 3.).

Picture No.	Type	Location	
		Easting	Northing
1	Rock and debris slide	84427	92690
2	Rock slide	84265	92373
3	Earth slide	84131	94099
4	Rock slide	84171	93152
5	Debris slide	83971	93652
6	Debris slide	84360	94508
7	Debris slide	84795	92489
8	Debris slide	85168	92412
9	Debris slide	85371	94829
10	Debris slide	85111	94569
11	Debris slide	85169	92991
12	Debris slide	85700	94890
13	Debris flow	86664	93481
14	Rock slide	87103	97242
15	Rock slide	87635	96279
16	Debris slide	87749	97168
17	Debris slide	87601	95119
18	Debris slide	86656	93279
19	Debris slide	86699	94055
20	Debris slide	86714	94588
21	„	85458	94781
22	„	86146	95145
23	„	86418	95371
24	„	86281	95555
25	„	86490	96791
26	„	86237	97924
27	„	85895	97954
28	„	85770	97602
29	„	85632	97299
30	„	85765	96627
31	„	86504	96821
32	„	87084	95188
33	„	87152	93242
34	„	86724	92271
35	„	86271	92449
36	„	85169	92991
37	„	84583	93318
38	„	84429	92015
39	„	84845	92345
40	„	84785	92653
41	Earth slide	84129	93450
42	„	84543	93318
43	„	84216	93265
44	„	83827	93107
45	„	82403	92228
46	„	82834	92381
47	„	82728	92215

48	„	82589	92949
49	„	82967	92988
50	„	83298	92923
51	„	83993	93891
52	„	84313	94271
53	„	84514	94697
54	„	84782	95284
55	„	85348	94850
56	„	84238	93003
57	„	87416	93962
58	„	87560	94507
59	„	86555	95570
60	„	84259	93946
61	„	84340	92750
62	„	84296	92412