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School of Civil and Environmental Engineering



M.Sc. in Geodesy and Geomatics Program

Landslide Hazard Zonation by Using Geospatial Based Multi-Criteria Decision Analysis Techniques: The Case of Worra Jarso District, Central Ethiopia

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Addis Ababa, Ethiopia

DECLARATION

This is to certify that this thesis entitled “**Landslide Hazard Zonation by using Geospatial Based Multi-Criteria Decision Analysis Techniques: The Case of Worra Jarso District, Central Ethiopia**” is my original work completed under the supervision of **Dr. Hamere Yohannes**, and that it has not been submitted for a degree at any other university, and all sources of materials used for this thesis work have been properly acknowledged.

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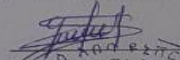
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Table of Contents

DECLARATION	i
ACKNOWLEDGEMENTS	ii
ABSTRACT	viii
CHAPTER ONE	1
1. INTRODUCTION.....	1
1.1 Background of the study	1
1.2 Statement of the problem	3
1.3 Objectives.....	4
1.3.1 General Objective.....	4
1.3.2 Specific Objectives.....	5
1.4 Research Questions	5
1.5 Scope of the study	5
1.6 Significance of the Study	5
1.7 Limitation of the study	6
1.8 Structure of the Thesis	7
CHAPTER TWO	8
2. LITERATURE REVIEW.....	8
2.1 Background	8
2.2 Concept of Landslide	8
2.3 Landslide Classification and Processes.....	10
2.3.1 Landslide Classification	10
2.3.2 Landslide Processes	13
2.4 Landslide Influencing Factors.....	15
2.4.1 Landslide Causative Factors.....	16
2.4.2 Landslide Triggering factors	19
2.5 Landslide Inventory Mapping	20
2.6 Landslide Hazard Zonation Mapping Techniques	20
2.6.1 Expert Evaluation Methods.....	20
2.6.1.1 Landslide Inventory Mapping Method.....	21
2.6.2 Statistical Methods.....	21
2.6.2.1 Bivariate Statistical Method	21
2.6.2.2 Multivariate Statistical Method.....	21

2.6.3 Deterministic Method.....	22
2.6.4 Multi Criteria Decision Analysis Techniques	22
2.6.4.1 Analytical Hierarchy Process	22
2.6.4.2 Weighted Linear Combination	23
2.7 Landslide Model Validation.....	24
2.8 Application of Geospatial Technologies in Landslide Hazard Zonation	24
2.9 Recent Studies on landslide in Ethiopia.....	26
2.9.1 Recent Landslide studies around study area.....	28
CHAPTER THREE.....	30
3. MATERIALS AND METHODOLOGY	30
3.1 An Overview of the study area.....	30
3.1.1 Description of the study area.....	30
3.1.2 Drainage pattern of the study area.....	31
3.1.3 Physiographic Situation of the study area	32
3.1.4 Climate condition	32
3.1.4.1 Rainfall.....	33
3.1.4.2 Temperature	34
3.1.5 Seismicity	36
3.1.6 Population and Human Activity	36
3.1.7. Geology	36
3.1.7.1 Regional Geology.....	36
3.1.7.2 Lithology of the Study Area.....	37
3.1.7.3 Geological Structures in the study area.....	39
3.2 Research Design.....	40
3.3 Data sources and Materials	40
3.3.1 Data sources and Types.....	40
3.3.2 Material and Software's	41
3.4 Methodology	42
3.4.1 Data Collection.....	42
3.4.2 Data Preparation.....	42
3.4.3 Data Analysis	44
3.5 Landslide causative factors	46

3.5.1 Slope.....	47
3.5.2 Lithology	47
3.5.3 Drainage Density.....	48
3.5.4 Soil Type	48
3.5.5 Land Use Land Cover	49
3.5.6 Elevation	50
3.5.7 Curvature.....	50
3.5.8 Aspect.....	51
3.7 Weighted Linear Combination.....	53
3.8 Validation of landslide hazard zone map.....	53
3.8.1 Landslide Inventory	53
3.8.2 Landslide Inventory Data.....	54
CHAPTER FOUR.....	56
4. RESULTS AND DISCUSSION	56
4.1 Landslide Hazard Zonation	56
4.1.1 Slope.....	56
4.1.2 Lithology	58
4.1.3 Drainage Density.....	59
4.1.4 Soil Type	61
4.1.5 Land use/Land cover	63
4.1.6 Elevation	64
4.1.7 Curvature.....	66
4.1.8 Aspect.....	68
4.2 Assigning Factor Weights	69
4.3 Weighted Linear Combination Using Weight Overlay Analysis.....	70
4.4 Landslide Hazard Zone Map.....	71
4.5 Validation of Landslide Hazard Zone Map.....	72
4.5.1 Landslide Inventory Map	72
4.5.2 Landslide Inventory Data.....	74
4.6 Discussion	75
CHAPTER FIVE.....	78
5. CONCLUSION AND RECOMMENDATIONS.....	79
5.1 CONCLUSION.....	79

5.2 RECOMMENDATIONS	81
References	82
Appendices	86

ABSTRACT

The present study area is located in the Northern Shewa Zone of the Oromia Region, Worra Jarso District, Central Ethiopia, which is far 186km from Addis Ababa. Landslide is among mega geo-hazard that pose a significant damage to civil infrastructure, property, and loss of life. It can be induced by natural phenomena like heavy rainfall, earthquakes and volcanoes. As well, by human action such as deep excavation for mining, road network, building, urbanization, deforestation, unscientific slope cutting and improper agricultural practice. Therefore, the main aim of this study was to delineate landslide hazard-zones using Geospatial based Multi-Criteria Decision Analysis methods. To achieve the stated objective, the eight causative factors were identified namely; elevation, slope, aspect, curvature, soil type, lithology, land use/land cover and drainage density. These factors were identified and the weights were assigned based on the Expert opinion, literature review and nature of the study area. Accordingly, the assigned weights were computed using pair wise comparison matrix of Analytic Hierarchy Process (AHP) method. The spatial distribution of landslide was mainly influenced by slope angle $>45^{\circ}$, limestone lithological unit, high drainage density, shallowness of leptosol, expansion of agricultural land on steep slope, falling of elevation class in between 1575m-2100m, concave slope curvature and northwest facing of slope aspect. Later, the landslide hazard zone map was produced by using Analytic Hierarchy Process and Weighted Linear Combination in Geographic Information System (GIS) weighted overlay analysis environment. The produced landslide Hazard Zone map shows that 0.001% (0.014km²) area fall within low hazard zone, 46.66% (555.25km²) of the area fall within moderate hazard zone, 50.02% (595.13km²) and 3.32% (39.48km²) of the area falls into high hazard and very high hazard zones respectively. Moreover, validation of landslide hazard zone map with 49 past landslide inventory data reveals that 85.7% of the known landslide events were falls in very high hazard and high hazard zone. Thus, the landslide hazard map produced by Geospatial based Multi-Criteria Decision Analysis Approaches with careful identified factors proved to be valuable tool for providing fundamental information about hazard assessment, land use planning, infrastructure development and disaster preparedness of the area.

Key Words: *Analytic Hierarchy Process, Causative Factors, Landslide, Weighted Linear Combination*

LIST OF TABLES

<i>Table 1: Data type and Source</i>	41
<i>Table 2: Material and Software</i>	41
<i>Table 3: Factors to be considered for Landslide Susceptibility Mapping with their rating values</i>	45
<i>Table 4: The preference scale of rating influence of factors in AHP (Saaty, 1980)</i>	52
<i>Table 5: Slope Class and Area Coverage</i>	56
<i>Table 6: Lithological Unit and Area Coverage</i>	58
<i>Table 7: Drainage Density Class and Area Coverage</i>	60
<i>Table 8: Soil Type and Area Coverage</i>	62
<i>Table 9: LULC class and Area Coverage</i>	63
<i>Table 10: Elevation Class and Area Coverage</i>	65
<i>Table 11: Curvature Class and Area Coverage</i>	67
<i>Table 12: Aspect Class and Area Coverage</i>	68
<i>Table 13: Analytical Hierarchy Process Weight Assignment</i>	70
<i>Table 14: Landslide Hazard Zone and Area Coverage</i>	72

LIST OF FIGURES

<i>Figure 1: Rock fall</i>	11
<i>Figure 2: Topple</i>	11
<i>Figure 3: Debris Avalanche (A), Debris flow (B), Earth flow(C) and Creep (D)</i>	12
<i>Figure 4: Rotational slide (A), Transitional slide (B)</i>	12
<i>Figure 5: Lateral Spread</i>	13
<i>Figure 6: Location map of the study area</i>	30
<i>Figure 7: Drainage map of the study area</i>	31
<i>Figure 8: Physiographic map of the study area</i>	32
<i>Figure 9: Monthly Rainfall data on Filiklik Station</i>	34
<i>Figure 10: Monthly Rainfall Data on Gohatsion Station</i>	34
<i>Figure 11: Graph of maximum, minimum and mean monthly temperature on Filiklik station</i>	35
<i>Figure 12: Graph of maximum, minimum and mean monthly temperature on Gohatsion station</i>	35
<i>Figure 13: General Methodological workflow of the study</i>	55
<i>Figure 14: Slope map of the study area</i>	57
<i>Figure 15: Lithology map of the study area</i>	59
<i>Figure 16: Drainage Density map of the study area</i>	61
<i>Figure 17: Soil Type map of the study area</i>	62
<i>Figure 18: LULC map of the study area</i>	64
<i>Figure 19: Elevation map of the study area</i>	66
<i>Figure 20: Curvature map of the study area</i>	67
<i>Figure 21: Aspect map of the study area</i>	69
<i>Figure 22: Landslide Hazard Zone map of the study area</i>	71
<i>Figure 23: Landslide Hazard Zone with Areal Coverage</i>	72
<i>Figure 24: Landslide Inventory Map of the study area</i>	73
<i>Figure 25: Landslide Inventory Data overlaid with Landslide Hazard Zone map for validation</i>	75

LIST OF ABBREVIATION AND ACRONYMS

AHP Analytic Hierarchy process

ANN Artificial Neural Network

Arc GIS Aeronautical Reconnaissance Coverage Geographic Information System

CSA Central Statistical Agency

DEM Digital Elevation Model

EOS Earth Observatory Satellite

ERDAS Earth Resource Data Analysis System

ESRI Environmental System Research Institute

GIS Geographic Information System

GNSS Global Navigation Satellite System

GPS Global Positioning System

IVM Information Value Model

ICTZ Inter-Tropical Convergence Zone

JICA Japan International Corporation Agency

LHEF Landslide Hazard Evaluation Factors

LHM Landslide Hazard Map

LHZ Landslide Hazard Zone

LHZI Landslide Hazard Zone Index

MCDA Multi-Criteria Decision Analysis

MoWIE Ministry of Water, Irrigation and Energy

NMA National Meteorological agency

RS Remote Sensing

SRTM Shuttle Radar Topographic Mission

USGS United State of Geological Survey

UTM Universal Transverse Mercator

WLC Weighted Linear Combination

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the study

The surface of the earth is always under ceaselessly change as a result of various geodynamics process those pose a major threat to human being and other animals worldwide (Abay et al., 2012). The majority of geodynamics process have been caused by geo-hazard like landslides, earthquakes, volcanoes and tsunamis associated with human action. Comprehensively these hazard killed more than 0.75 million people in the 21st century with total economic loss of \$ 0.5 trillion(Rees et al., 2012). Among these, Landslide is one of the most worldwide hazard which causes the loss of tens thousands of people and costing billions of dollars every year (Mason, 1998). Mainly, the mountainous communities are extremely vulnerable to the geo-hazard as natural set up motivate plate tectonics. Since the rugged morphology has been subjected to the earthquake and prolonged rainfall as it built-up from immense gravity. Globally, landslides caused numerous impacts upon loss of life, injury, property damage, economic crisis, social crisis and environmental damage in mountains part of the world.

Landslides are the downward slope movement of soil, rock and debris when the force of gravity exceed the force of resistance. Landslides are the revolutionary factors of downward mass movement and destruction of the landscape evolution in mountainous and hilly topographic areas of world. Landslide is the most serious environmental problem in the world (Crozier and Glade, 2012, Crozier and Glade, 2005 Franco Mantovani, Robert Soeters, 1996). Similarly, Ethiopia is sharing common problem due to complex topography like mountains, high plateaus, deep gorges, river valleys, and lowland plains (Waktola, 1999). Landslide hazard is defined as a probability of occurrence of a landslide of a given magnitude within pre-defined period of time in given area (Varnes et al., 1996). Landslide hazard is becoming serious environmental constraints for the developmental activities in the highlands of Ethiopia. Expansion of infrastructural development with poor land management system, it is predictable that the frequency and magnitude of landslide and losses due to these hazards would continue to increase (Abebe et al., 2010).

Landslide hazard assessment and susceptibility maps are a basis for strategic and regional landslide hazard mitigation work planning (Anbalagan, 1992; Mengistu, 2018; Shano, Raghuvanshi and Meten, 2020; Ali, 2021). Landslide hazard assessment is the most significant progress in identifying landslide prone areas, and guarantee the safety of people's lives and avoid negative impacts on the regional and national economy. In this context, landslide study intends to assess the nature of hazards and the losses to human life, agricultural land, roads, buildings, and other properties (Singh and Hassan, 2014). Landslide hazard map provides information for government agencies, planners, decision-makers, treasured and local landowners to make emergency plans to reduce the negative effects on infrastructure, superstructure, and human life (Dahal, 2017). The hilly and mountainous terrains of the highlands of Ethiopia, which are characterized by variable topography, geology, hydrology and land-use conditions, are frequently affected by rainfall-triggered slope failures though earthquake triggered landslides are little considered (Woldearegay, 2013).

Nowadays, the remarkable role of Geospatial Technologies like Global Positioning System (GPS), Remote Sensing (RS) and Geographic Information System (GIS) has become an effective tool that helps to assess, identify, evaluate, examine, recognize, map, analysis, interpret, manage, prevent, and mitigate the landslide hazard and other geo-environmental hazards with an exact spatial location. This manifest profound improvement of the technological progress that can provide a detailed information on a timely basis with low cost in extensive areal coverage. Moreover, Spatial and temporal thematic information derived from remote sensing, thematic maps and ground-based information needs to be integrated. Several researchers have visualized Geospatial technologies for landslide hazard zonation (Rai et al., 2014).

1.2 Statement of the problem

Landslide hazard is one of the main geo-hazard problems that pose several damages to both natural and built-up environments worldwide. Landslide is geo-environmental catastrophic event that mainly challenged the community living in the mountainous, hilly, rugged morphology, ground shaking, heavy rainfall, steep slope environments are extremely susceptible to direct, and indirect losses. Similarly, the present study area is sharing the common characteristics; Since the Worra Jarso is a well-known landslide prone site in Shewa plateau. The area has a long period history of occurrence or recurrence of the landslides. Hence, the area initiates the landslide events due to the nature of landscape evolutions. In spite of this, landslide and landslide-generated failure is a common geo-hazard in northern, southern, western and rift margin Ethiopian highlands. The ultimate causative factors of slope failures are heavy rainfall, high relative relief and complex fragile geology with increased manmade activities (Abebe et al., 2010). Heavy rainfall is the first and foremost trigger factor of road corridor failures along Gohatsion to Dejen town. As a result, landslides damage several road corridors along this way after heavy rainfall events. Destruction of road corridor threaten the lives and property of the inhabitants and leads to direct and indirect losses. Slope failures are the most critical reason for both trigger and causative factors to induce the landslide in the Abay Gorge. Slope failures in the northern section of the Abay Gorge basin occurred in 1960 had destroyed the Gembechi village property and lost 45 people (Ayalew, 1999). The area is subjective to the landslide hazard events due to its topography found in deep gorge. Accordingly, extensive damages upon; road corridor from Addis Ababa to Bahir Dar, damage on natural environments, constructed environment, economic losses, physical destruction, social destruction, property damages, maintenance costs, injuries, loss of life, damage of houses, damage on agricultural lands and other infrastructures are exposed to the problems. Several authors were made numerous efforts around present study area including Researchers from industry, Academic area and Japan International Corporation Agency (JICA) were conducted the studies in Abay Gorge along main road from Gohatsion to Dejen Town. Many of them were concentrated on the geological, geophysical and geotechnical aspects of slope instability monitoring using non-geodetic techniques. Despite extensive studies were carried out around the area, only few of them assessed on the landslide susceptibility and hazard using

GIS and RS. For instance, the study conducted by (Woldegiorgis et al., 2014) was putted the basis for mapping landslide hazard zone using expert evaluation technique in area found between Gohatsion town and Abay River. However, they did not consider causative factors such as soil type, aspect and curvature. In their study only five factors were considered are relative relief, slope morphometry, geology, groundwater and land use/land cover. Moreover, the method they used relied on expert experience. Hence the relative contribution of one factor may not be the same for the other geographical area. On other hand, Yechale (2021) was tried to identify susceptible area along Gohatsion-Dejen road corridor passes through Abay River Gorge using GIS-based IVM for evaluation of landslide susceptibility mapping. Although He did not consider factor like soil type and curvature, which has a paramount for slope instability. In general, the previous studies have factors, method and area gaps.

Therefore, the main objective of this study was to delineate landslide hazard zones by using Geospatial based Multi-Criteria Decision Analysis (MCDA) with Analytic Hierarchy Process (AHP) and Weighted Linear Combination (WLC) Techniques in the Worra Jarso District of North Shewa Zone located in Oromia Regional State. To achieve this objective, eight causative factors were considered are; elevation, slope, aspect, curvature, soil type, lithology, land use/land cover and drainage density. The MCDA Approaches is basically emphasis on how combination of multi-causative data layers into a single map (El Jazouli et al., 2019). These methods are significant in providing landslide hazard information that could help to guide the local and national awareness of the hazard situation for the extraction of, fast and accurate results that will help in decision-making and improve potential response for land use planning.

1.3 Objectives

1.3.1 General Objective

The main objective of this study was to delineate landslide hazard zones by using a Geospatial based Multi-Criteria Decision Analysis (MCDA) with Analytic Hierarchy Process (AHP) Techniques in Worra Jarso District, Central Ethiopia.

1.3.2 Specific Objectives

- ✚ To identify the major landslide causative factors of the study area
- ✚ To produce a landslide hazard zonation map of the study area
- ✚ To validate a produced landslide hazard zonation map of the study area

1.4 Research Questions

The present study was aimed to response the following questions:

- ✚ What are the major causative factors responsible for the landslide occurrence in the study area?
- ✚ How to produce a landslide hazard zonation map of the study area?
- ✚ What is the level of reliability of the produced landslide hazard zonation map of the study area?

1.5 Scope of the study

This study was focused on the delineation of landslide hazard zones using Geospatial Technology integrated with Multi-Criteria Decision Analysis (MCDA) methods based on eight causative factors, such as; elevation, slope, aspect, curvature, soil type, lithology, land use/land cover and drainage density. The study was geographically limited to the Worra Jarso District of North Shewa Zone located in Oromia Regional State. The study was not consider vulnerability and risk assessment of landslide studies.

1.6 Significance of the Study

Broadly, this study will serve to assess the effectiveness of Geospatial Technology integrated with Multi-Criteria Decision Analysis through an Analytic Hierarchy Process and Weighted Linear Combination methods to produce a landslide hazard zonation map. Since, landslide is a common geo-hazard that has been occurring almost everywhere in the world. Similarly, the problem has been pronounced in Ethiopia. Particularly this study will contribute many geoscientific achievements, accordingly; the study will serve as input and to call further studies for the concerned discipline in a particular area and as a whole in the country in terms of both location and subject matter. The second role is to alert the local community about

landslide occurrence at different stages. The third contribution is selecting an appropriate site for construction, agriculture, transportation, and other development activities.

The fourth contribution is use to information as a baseline for a policy maker to give attention for land resource as it has a remarkable role for sustaining life of all living things on physical environment. Therefore, the study has an essential role to identify the spatial and temporal probability of landslide occurrence for safer strategic planning of future developmental activities. The fifth contribution is to evaluate the capability of Geospatial technology that play a tremendous role for landslide studies to identify, classify, map, monitor, mitigate and predict the hazard by considering magnitude and frequency of occurrence with least cost. Thus helps to minimize the physical loss, socio-economic loss, upon natural and constructed environmental damage due to landslide. As a result of natural and anthropogenic activities. Generally, the main significance of this study will show the spatio-temporal variation of landslides that helps to reduce the hazard associated with landslide by identifying, predicting, and indicating the extent of hazard and revealing appropriate corrective measures to call for an action upon issues in risky for a public at large, private, government office and concerned institute.

1.7 Limitation of the study

The major limitation of this study was:

- ✚ Absence of peace and stability in the study area make a detail survey work remain
- ✚ Absence of previous study in the entire area
- ✚ Subjectivity of weight assignment
- ✚ Lack of responsible body to obtain adequate information about physical loss, economical loss and social loss.
- ✚ Lack of adequate data availability

Despite these limitation, the present study was made with all possible efforts in collecting a substantial input datasets. Thus make the study reasonable to provide the relevant information in landslide studies of similar geographical setting.

1.8 Structure of the Thesis

This thesis was organized into five chapters. Chapter one focuses on the introduction that includes the background, statement of the problem, objectives, research questions, scope, significance and the limitation of the study. Chapter two briefly discuss review on landslide hazard zonation using a geospatial based on multi-criteria decision analysis with analytical hierarchy process. Chapter three provides description of study area, data sources, applied software's, materials used, data collection, data preparation, data analysis, identification of landslide causative factors, adopted method, general methodological work flow and model validation. Chapter four clearly presents results and discussions of identified factors map, landslide hazard zone map, validation of LHZ map and incorporated with finding of the study. Chapter five gives Conclusion and Recommendation made based on the result of the study.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Background

As defined by Hammad (2020) “Geohazard is a natural phenomenon containing all the different geological processes and geographical features that are capable of triggering catastrophic events or natural disasters that threaten human beings and damage property, critical infrastructure and the natural environment in the areas where they occur”. Geohazard are inclusiveness of natural and human-induced hazards. Namely; landslides, earthquakes, floods, tsunamis, volcanic eruptions, tornadoes, severe storms and droughts are categorized under natural hazards. Human-induced hazards are; urbanization, deforestation, expansion of agricultural practices on steep slopes, cutting and deep excavations on slopes for buildings, roads, canals and mining in the landslide-prone areas(Genene, 2020). Landslide is one of the most serious natural hazard which causes the loss of tens thousands of people and costing billions of dollars every year(Mason, 1998). Landslides and related hazards are causing several damages all over the world without any geographical boundary between developed and developing countries (Abay et al., 2019). In fact, the extent of damage is not similar between developed and developing countries due to various reasons in different locality. Particularly, mountains parts of the world that reside in developing countries are extremely susceptible to landslide hazard. Similarly, Ethiopia is frequently affected by this hazard. More specifically, northern, southern, western and rift margin highland part of Ethiopia severely posed to continuous threat due to environmental setting are highly subjective to both natural and human-induced catastrophic events.

2.2 Concept of Landslide

Cruden (1991) defined landslide as the movement of mass of the rock, debris, or earth down a slope. Varne (1984) defined a landslide as a downward and outward movement of slope forming materials under the influence of gravity. A mass wasting is any downward movement of mass, within which the surface is worn away. Mass wasting include rock-falls and the flow of shore deposits called alluvium. Landslide can be occur when gravitational and other types of shear stresses within a slope exceed the shear strength (resistance to shearing) of the

materials that form the slope (Xue et al., 2014). Shear stress can be fortified within a slope due to a numbers of processes consists of excessive steepening of the base of the slope, such as by natural erosion or excavation, and loading of the slope, such as by an inflow of water, a rise in the groundwater table, or the accumulation of debris on the slope's surface. Short-term stresses, such as those imposed by earthquakes and rainstorms, can likewise contribute to the activation of landslides. Processes that weaken the shear strength of a slope's material also can activate landslides. Shear strength is dependent mainly on two factors: frictional strength, which is the resistance to movement between the slope material's interacting constituent particles, and cohesive strength, which is the bonding between the particles. Coarse particles like sand grains have high frictional strength but low cohesive strength, whereas the opposite is true for clays, which are composed of fine particles. Another factor that affects the shear strength of a slope-forming material is the spatial disposition of its constituent particles, referred to as the sediment fabric. Some materials with a loose, open sediment fabric will weaken if they are mechanically disturbed or flooded with water. An increase in water content, resulting from either natural causes or human activity, typically weakens sandy materials through the reduction of inter-particle friction and weakens clays through the dissolution of inter-particle cements, the hydration of clay minerals, and the elimination of inter-particle tension (Xue et al., 2014). Landslide is the most crucial environmental problem in Ethiopia, as it is causing loss to human life and damages property. A common incidence in the tectonically fragile and sensitive mountainous terrains of Ethiopia. The spread of landslide distribution in Ethiopian highland is mostly related to the occurrence of several factors such as, high relief, rugged topography and the nature of the soil and rocks (Abebe et al., 2010).

In several landslide studies, there are various terms commonly used in landslide studies, such as; landslide hazard, landslide susceptibility, Landslide vulnerability, and landslide risk (Catan and Casagli 2005; Diskshi tet al. 2007). Even though, these terms have various stages of study, own application, mapping scales and data types, they commonly used in many landslide studies. Sometimes, these terms used as interchangeable. In fact, these terms are not offer the same meanings. The proper definitions suggested by specialists in landslide studies are given under here accordingly:

Landslide hazard is defined as the probability of landslide occurrence with a particular intensity within a given area and period of time (Varnes, 1984).

This definition encompasses both spatial and temporal probability of landslide occurrence into account. Thus, explicitly incorporates the concepts of location, time, and magnitude of landslide hazard.

Landslide susceptibility refers to spatial probability of landslide occurrence (Nsengiyumva et al., 2018). According to this definition, only the spatial component of the hazard taken into account. Thus, emphasis more on causative factors those leads to landslide occurrence or reactivation based certain conditions(Hammad, 2020).

Landslide Vulnerability concerns to the potential for loss and damage from landslides. It clearly differentiates from human vulnerability which focus on the potential number of deaths and injuries (Hammad, 2020). The socio-economic vulnerability refers to direct damage to infrastructure, the disturbance of the economic activity and the disturbance of some social functions such as health and education (Hammad, 2020). The value of landslide vulnerability ranges from 0, i.e. no damage, to 1, i.e. total damage (Hammad, 2020).

Landslide Risk indicates the expected annual cost of landslide damage over all the affected area through incorporating both of the probability information from a landslide hazard map and the vulnerability analysis information of all possible consequences like loss of lives, injuring of people, property damage, environmental damage and loss of service (Hammad, 2020).

2.3 Landslide Classification and Processes

2.3.1 Landslide Classification

The term "landslide" describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these thematic maps (Varnes 1984; Highland and Bobrowsky, 2008). The materials may move by falling, toppling, sliding, spreading, or flowing. The various types of landslides can be differentiated by the kinds of material involved and the mode of movement.

Rock fall: Rock falls are abrupt movements of masses of large rocks or boulders which are detached from their parent rock. They usually fall along steep slopes or cliffs. Separation occurs along discontinuities such as fractures, joints, and bedding planes and movement occurs by free fall, bouncing, and rolling. Gravity, mechanical weathering, and the presence of interstitial water usually influence falls. It is common in steep slopes, or vertical slopes also in coastal area, along rocky bank of river and streams, road cuts, and jointed, fractured and weathered bedrock (Wachal and Haduk, 2000).



Figure 1: Rock fall

Topple: Topple failure encompasses the forward spinning and movement of huge masses of rock, debris and earth from a slope (Varnes, 1984) This type of slope failure takes place around an axis near or at the bottom of the block of rock. It is usually caused by cracks or fracture in the bedrocks. The rate of movement ranges from extremely slow to extremely rapid and it can be destructive especially when failure is sudden (Highland and Bobrowsky, 2008).



Figure 2: Topple

Flow: Flows can be occurred in many ways such as debris flow, debris avalanche, and mudflow, creep and Earth flow. Debris flow involves the rapid downhill movement of loose earth material usually with water. Debris Avalanche is similar to debris flow but has a more rapid flow. In an Earth flow, the earth material is finer and is washed away leaving a

depression bowl at the head. Mudslides are made up of fine silt, sand and clay material saturated with water and flowing very rapidly. Creeps are slower in nature and can be evident when electric poles and roads bend slightly. They are commonly caused by intense surface water flow, due to heavy precipitation or rapid snowmelt, which erodes and mobilizes loose soil or rock on steep slopes (Highland and Bobrowsky , 2008).

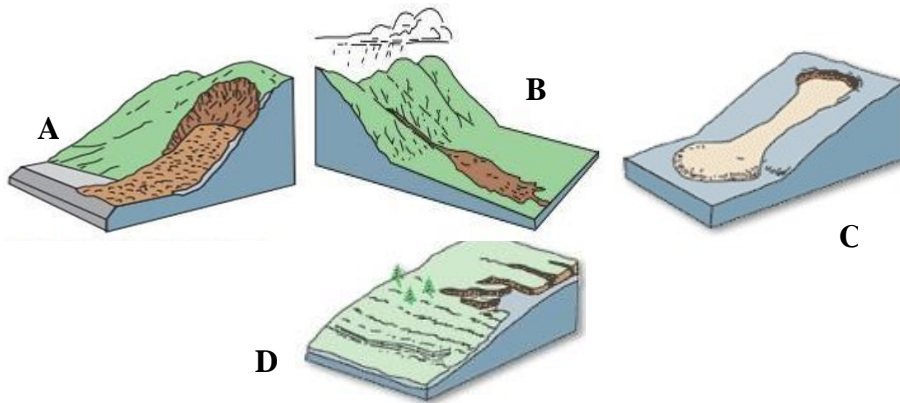


Figure 3: Debris Avalanche (A), Debris flow (B), Earth flow (C) and Creep (D)

Slide: This is a kind of mass movement whereby the sliding material breakaways from underlying stable material. Slides may be translational or rotational. In a translational slide the landslide mass moves along a roughly planar surface with little rotational or backward tilting. In a rotational slide, a slide in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide (Varnes, 1978). It occurs in unconsolidated soils and rate of movement ranges from extremely slow to moderately fast and it can damage structures but not life if the movement is slow (Highland and Bobrowsky, 2008).



Figure 4: Rotational slide (A), Transitional slide (B)

Lateral Spread: is distinctive because they usually occur on very gentle slopes or flat terrain. The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction, the process whereby saturated, loose, cohesion less sediments sands and silts are transformed from a solid into a liquefied state. Failure is usually triggered by rapid ground motion, such as that of experienced during an earthquake, but can also be artificially induced. When coherent material, either bedrock or soil, rests on

materials that liquefy, the upper units may undergo fracturing, extension and then subside, translate, rotate, disintegrate, or liquefy and flow off. Lateral spreading in fine-grained materials on shallow slopes is usually progressive. Lateral spreads typically damage pipelines, utilities, bridges, and other structures having shallow foundations (Highland and Bobrowsky, 2008).

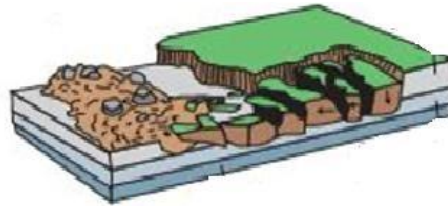


Figure 5: Lateral Spread

Complex type of movement: A combination of two or more types of failure happens in a single slope. This type of combination of failure may happen at the same time or during the life time of a slope failure (Cruden and Varnes, 1996).

2.3.2 Landslide Processes

“The processes involved in slope movements comprise a continuous series of events from cause to effect” (Varnes, 1978). Varnes distinction that the three broad types of landslide processes such as; increase shear stresses, contribute to low strength and reduce material strength. Several types of landslide have varied way of occurrence or recurrence mechanisms, as suggested by Varnes which broadly defined under three landslide processes.

1. Increase shear stresses

Shear stresses can be increase by processes that lead to removal of lateral support, by the imposition of surcharges, by transitory stresses resulting from explosions or earthquakes, and by uplift or tilting of the land surface.

a. Removal of support: The toe of a slope can be removed by erosion, steepening the slope. Typical agents are streams and material at depth within the displacing mass results in its extrusion or, if the base of the spread has liquefied, in its outward flow.

b. Imposition of surcharges: The addition of material can result in increases of both the length and the height of slope. Water can be added by precipitation, both rain and snow; by the flow of surface and groundwater into the displacing mass; and even by the growth of glaciers. The movement of landslides onto the slope add surcharges can 30, by volcanic activity, and by the growth of vegetation. Anthropogenic surcharges include construction of fills, stockpiles, and waste dumps; structural weight; and water from leaking canals, irrigation system, reservoirs, sewers, and septic tanks.

c. Transitory stresses: The local stress field within a slope can be greatly changed by transitory stresses from earthquakes and explosions (both anthropogenic and volcanic). Smaller transitory changes in the stress field can result from storms and from human activity such as driving and the passage of heavy vehicles.

d. Uplift or tilting: Uplift or tilting may be caused by tectonic forces or by volcanic processes. In either case, this type of increased shear stress may be associated with earthquakes, which themselves can trigger landslide. The melting of the extensive Pleistocene ice sheets has caused widespread uplift in temperate and circumpolar regions. Uplift of an area of the earth's surface generally causes steepening of slopes in the area as drainage responds by increased incision. The cutting of valleys in the uplifted area may cause valley rebound and accompanying fracturing and loosening of valley walls with inward shear along flat-lying discontinuities. The fractures and shears may allow the buildup of pore-water pressures in the loosened mass and eventually lead to land sliding.

2. Contribute to low strength

Low strength of the earth or rock material that make up a landslide may reflect inherent material characteristics or may result from the presence of discontinuities within the soil or rock mass.

a. Material characteristics: Material may be naturally weak or may become weak because of common natural processes such as saturation with water. Organic material and clays have low natural strengths. Rocks that have decomposed to clays by chemical weathering (weathered volcanic tuffs, schists, and serpentines). Besides the material of the individual

particles of which the material is composed, the arrangement of these particles (the fabric of the material) may cause low material strengths. Sensitive of material, which lose strength when disturbed, generally have loose fabrics or textures.

b. Mass characteristics: The soil or rock mass may be weakened by discontinuities such as faults, bedding surfaces, foliations, cleavages, joints, fissures, shears, and shear zones. Contrasts in bedded sedimentary sequences - such as stiff, thick beds over-lying weak, plastic, thin beds or permeable sands (or sandstones) alternating with weak, impermeable clays are sources of weakness.

3. Reduce material strength

Clays are particularly prone to weathering processes and other physico-chemical reactions. Hydration of clay minerals result in loss of cohesion, a process often associated with softening of fissured clays. Fissuring of clays may be due to drying or to release of vertical and lateral restraints by erosion or excavation. The exchanges of ions within clay minerals with those in the pore water of the clays may lead to substantial changes in physical properties of some clay. Electrical potentials set up by these chemical reactions or by other processes may attract water to the weathering front. The effects of extremes of temperature caused by severe weather are not confined to clays. Rocks may disintegrate under cycles of freezing and thawing or thermal expansion and contraction. Dry weather may cause desiccation cracking of weak or weather rock along preexisting discontinuities, such as bedding planes. Wet weather may dissolve natural rock cements that hold particles together. Saturation with water reduces effective inter-granular pressure and friction and destroys capillary tension.

2.4 Landslide Influencing Factors

Landslides are extensively accelerated by the following geo-environmental factors such as; geomorphological factors, geological factors, hydrological factors and land use/land cover. These factors are known as landslide causative factors. Hence, they are an internal factor. Causative factors are the reason why a landslide occurs at a particular area and accountable to the vulnerability of the slope instability (Basith, 2011b). In addition to this, trigger factors like earthquakes, volcanic eruptions, intense rainfall and human activities are known as landslide triggering factors. Since they are an external factor that initiates the occurrence or reactivation

of landslide event due to stimulus characteristics of a single factor. Particularly, the internal causative factors that affect landslide are; slope geometry, slope material, structural discontinuities, land use, land cover, and groundwater. Conversely, seismicity, rainfall, and manmade activities are considered as external triggering factors (Ermias et al., 2017). The environmental factors are a collection of data layers that are expected to have an effect on the occurrence of landslides and can be utilized as causal factors in the prediction of future landslides (Corominas and Mavrouli, 2011). Causative factors that are used as an input for the landslide hazard evaluation include lithology, proximity to the fault, land use, slope steepness, aspect, elevation and proximity to drainage (Abay et al., 2019).

2.4.1 Landslide Causative Factors

Intrinsic parameters are the causative parameters that define the favorable or unfavorable stability conditions within the slope. These intrinsic parameters are slope geometry, slope material, Structural discontinuities, land use and land cover and groundwater (Woldegiorgis et al., 2014). The considered causative factors mainly determine landslide includes; slope material, slope, aspect, elevation, land use, land cover and groundwater-surface traces (Kumar et al., 2015).

Elevation: Elevation is another factor that plays an important role in landslide susceptibility assessments considered in several researchers (Dai et al., 2002). The influence of elevation may be attributed in terms of degree of weathering, variation in humidity, rate of hydrate reaction, erosion process and depth of weathering (Girma et al., 2015). The main assumption is that the intensity of exogenous processes increases with rising altitudes. Exogenous processes disrupt the slope surface which leads to lower stability (Kova et al., 2017).

Slope: Slope is an important factor with regard to landslide initiation. In most studies of landslides, the slope steepness is taken into account as the major causative factor of the landslide (Abay et al., 2019). Slope morphometric maps define slope categories based on the frequency of occurrence of particular angles of slope. The geomorphological history of the area determines the distribution of the slope categories as the angle of slope of each unit reveals a series of localized processes and controls which have been imposed on the facet (Woldegiorgis et al., 2014).

Aspect: Aspect is defined as the direction of the maximum slope of the terrain surface with reference to the north. The aspect of a slope can influence landslide initiation because it affects moisture retention and vegetation cover, and in turn soil strength and susceptibility to landslides (Kumar et al., 2015).

Curvature: The term curvature is theoretically defined as the rate of change of slope gradient or aspect, usually in a particular direction (Gallant and Wilson, 2000). Morphology of the topography can be defined by curvature values. If the surface is upward concave at that raster cell the curvature is negative whereas if the surface is upward convex at that cell the curvature is positive. If the surface is flat, curvature value will be zero. The chances of landslide activity increase with an increasing negative value of curvature. According to the topographic type, the value is higher in the hilly and mountainous areas and low in flat areas (Lee and Min, 2002).

Proximity to Lineament: Lineaments are map-able linear features present on the surface of the earth, which indicates the zone of weakness and structural discontinuities in a rock. Lineaments affect surface material structures, have a significant influence on topography permeability, and thus slope stability. Proximity of a slope to these features influences its stability, increasing the susceptibility of landslides occurrence (Samanta, 2016). Geological fault and joint areas are in general, highly susceptible to landslides because the surrounding rock strength decreases due to tectonic breaks (Chen et al., 2017). Therefore, the lineaments can cause landslide formation and the hazard is decreased with increasing distance from lineament structures.

Proximity to drainage: The closeness of the slope to drainage structures is another important factor in terms of slope stability. Streams may adversely affect stability by eroding the slopes or by saturating the lower part of material until resulting in water level increases (Dai et al. 2001; Yalcin, 2005). Distance to stream is one of the controlling factors for the stability of a slope (Reis et al., 2012). They can lead the failure of banks because of the sub-quotation of slopes, and the modification of the ground caused by gully erosion may also influence landslide initiation (Dai et al. 2002).

Lithology: Lithology is one of the most important parameters in landslide studies because different lithological units have different susceptibility (Dai et al., 2002). Since it needs to be considered. Lithology significantly influences the occurrence of landslides, because lithological variations often lead to a difference in the strength and permeability of rocks and soils (Abay et al. , 2019).

Soil properties: Soil properties influence landslide occurrences. It could happen when the soil moisture content exceeds the liquid limit in the field. This event generates dangerous and prospectively devastating results as the soil becomes visible to be stable and then when distressed can unexpectedly break away. Increase in soil moisture content decreases soil strength by diminishing capillary cohesion (Handy and Spangler, 2007).

Proximity to road: Road-cuts are usually sites of anthropologically induced instability. A given road segment may act as a barrier, a net sources, as net sink or a corridor for water flow, and depending on its location in the mountains, it usually serves as a source of landslides. Some slope failures start above roads but are often intercepted by them (Ayalew and Yamagishi, 2004).

Land Use and Land Cover: Land cover is the physical material at the surface of the earth. Land covers include grass, asphalt, trees, bare ground, water, etc. whereas land use involves the management and modification of natural environment or wilderness into built environment such as settlements and semi-natural habitats such as arable fields, pastures, and managed woods (Gebremicheal, 2017). The land cover may also describe the potential for instability of slopes. Sparsely vegetated areas and barren areas demonstrate more erosion, thus greater instability as compared to reserve or protected forests, which are thickly vegetated and are less prone to mass wasting processes. The agricultural lands represent areas of repeated water charging for cultivation purposes and as such may be considered stable since agricultural practices are made on relatively gentler slopes (Mulatu et al., 2011). Land-use and land-cover is a key factor for landslide occurrence. Regions with dense vegetation are found to be prone to landslide than sparse vegetation, agriculture, and urbanization (Girma 2013; Raghuvanshi, and Atnafu, 2014).

2.4.2 Landslide Triggering factors

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

Rainfall: The frequency and magnitude of rainfall events, together with other factors such as lithology, topography, and land cover, influence the landslide occurrence. Heavy rainfall is indicated as the main triggering factor for almost all landslides (Broothaerts et al., 2012). The intensity of rainfall has a direct relation with the slope instability problems. For this reason, only most of the landslides occur during the rainy season (Dai et al. 2001; Ayalew and Yamagishi, 2004). Rainfall can result in surface erosion and also it can recharge groundwater which ultimately saturates the slope material (Woldegiorgis et al., 2014).

Seismicity: Earthquakes are a major cause of landslide in many parts of the world and have caused tens of thousands of deaths and billions of dollars in economic losses. Earthquake shaking is one of the agents that can cause landslide due to ground shaking, liquefaction of susceptible sediments, or shaking-caused dilation of soil materials (Highland and Bobrowsky 2008). Ground shaking decreases the shear resistance of slope material and generates the high excess pore water pressure, which adds slope instability condition (Highland and Bobrowsky 2008).

Volcanic activity: several types of volcanoes make them productive starting points for occurrence or recurrence of landslide events (Adugna, 2020). Hence, volcanic activity makes unstable surfaces that initiate landslide event. Even if the volcano is inactive.

Man-made Factors: (Abebe et al., 2010) and (Woldearegay, 2013) explained that the demand for new land for settlement, infrastructure and agriculture are primary causes that contribute to slope instability conditions caused by human interferences. Human activities like changing or disturbing drainage pattern, destabilizing the slopes, removing vegetation, overstepping of slopes by undercutting the bottom slope, loading the top of slope and irrigation may result directly or indirectly initiate the slope instability condition (Highland and Bobrowsky, 2008).

2.5 Landslide Inventory Mapping

Landslide inventory mapping is one of the simplest qualitative approaches of landslide susceptibility mapping. Landslide details are obtained through historical records, field survey mapping, aerial photo interpretation, and satellite images. Landslide inventory map also refers to slope failure by a single event or they may show cumulative effects of many events (Guzzetti et al.2005; Raghuvanshi et al., 2014).

The landslide hazard assessment must begin with a clear understanding of what has happened in the past in the area. This is to know what type of landslides have occurred and with what mechanism these were triggered. There needs to be a clear understanding of the possible causative and triggering factors that might have possibly resulted in landslides (Kumar et al., 2015).

2.6 Landslide Hazard Zonation Mapping Techniques

Landslide hazard zonation is used to identify potential landslide hazard areas or other mass movements, establish a relationship between landslide and triggering factors, ranking according to the degrees of actual or potential landslide susceptibility, and to predict the landslide hazard in the future. (Ayenew and Barbier, 2005; Hamza and Raghuvanshi, 2017). Over last three decades' landslide, hazard zonation has been carried out in different parts of the world. Several approaches have been developed for landslide hazard zonation such as; inventory-based mapping, heuristic approach, probabilistic assessment, deterministic approach, statistical analysis and multi criteria decision making approach (Raghuvanshi et al., 2014; Chimdi, Hamza and Raghuvanshi, 2017).

2.6.1 Expert Evaluation Methods

This method provides landslide hazard zonation depends on the past experience obtained over causative factors conducted by field specialists and their contribution to the instability of slopes in the area(Hammad et al., 2020). Qualitative method includes landslide inventory method, heuristic, landslide hazard evaluation and slope instability factor parameter. Moreover, expert evaluation techniques are more practical, simple in application and provide much more realistic field data well supported by experience of an expert in relatively less time (Woldegiorgis et al., 2014).

2.6.1.1 Landslide Inventory Mapping Method

Inventory based mapping is one of the simplest qualitative approaches of landslide hazard zonation mapping. In this analysis, landslide inventory maps are produced which reveal spatial and temporal patterns of landslide distribution, type of movement, rate of movement, type of displaced material (earth, debris or rock) etc. Landslide data are obtained through field survey, historical records, satellite images and aerial photo interpretation. Landslide inventory map also shows a slope failure by a single event or they may show cumulative effects of many events (Cruden 1991; Guzzetti et al. 2005; Barbier 2005; Raghuvanshi et al., 2014).

2.6.2 Statistical Methods

In the last few years the approach towards landslide hazard zonation has been changed from heuristic (knowledge based) approach to data driven approach (statistical approach) to minimize subjectivity in weight assignment procedure and produce more objective and reproducible results (Kanungo et al., 2009). Methods based on statistical analysis of geo-environmental factors related to landslide occurrence are preferred. The statistical methods for landslide hazard zonation can be grouped into two; bivariate statistical analysis and multivariate statistical analysis. The statistical methods are used to evaluate spatial landslide instability based on relationship between the landslide activities and their causative factors (Carrara et al. 1992; Hamza, and Raghuvanshi, 2017).

2.6.2.1 Bivariate Statistical Method

Bivariate statistical approach for landslide hazard zonation compares each factor map (slope, geology, aspect, elevation, land use and land cover) to the existing landslide distribution (Kanungo et al., 2009). Weights to the landslide causative factors are assigned based on landslide density. Frequency analysis approach, Information Value Model (IVM), weights of evidence model, weighted overlay model etc. are important bi-variate statistical methods used in Landslide Hazard Zone(LHZ) mapping.

2.6.2.2 Multivariate Statistical Method

Multivariate techniques for landslide hazard zonation correlate all the factors among themselves and factors with the landslide occurrence simultaneously (Kanungo et al., 2009). These methods calculate percentage of landslide area for each pixel and landslide absence or

presence data layer is produced followed by the application of multivariate statistical method for reclassification of hazard for the given area. Logistic regression model, discriminate analysis, multiple regression models, conditional analysis, Artificial Neural Networks (ANN) are commonly used methods for LHZ mapping (Brenning 2005; Kanungo et al., 2009).

2.6.3 Deterministic Method

The deterministic method provides landslide hazards in absolute values in the form of safety factors, or probability (Raghuvanshi, 2014; Kumar et al., 2015). Deterministic analyses are quantitative and are applied to small to medium size areas at large to medium scale mapping. They also require a large amount of detailed input data and they may lead to oversimplification if such data are only partially available (Woldegiorgis et al., 2014).

2.6.4 Multi Criteria Decision Analysis Techniques

The MCDA is focused on how to combine information from various data sources based on several criteria to form single index evaluation as stated by (Feizizadeh and Blaschke, 2013). GIS-MCDA can be believed of as a process that transforms and combines geographical data and value judgments based on favorites for decision-maker to obtain information for decision-making. GIS and MCDA have synergetic potential one can see the benefit for advancing theoretical and applied research on GIS MCDA (Malczewski, 2006). GIS-MCDA based landslide analysis allows to combine information derived from heterogeneous data layers to support landslide hazard assessment. One of the multi-aspect techniques which have been integrated into the GIS-based landslide analysis approach is the Analytical Hierarchy Process (AHP) originally introduced by Saaty (1977). Weighted Linear Combination (WLC) and Analytic Hierarchy Process (AHP) are the two most common Multi-Criteria Decision Analysis approaches.

2.6.4.1 Analytical Hierarchy Process

Analytical Hierarchy Process (AHP) is one of the most commonly used Multi criteria evaluation techniques that incorporated into GIS-based for landslide hazard analysis. It is originally introduced by Saaty (1977) for decision serving tool to focus with complex and multi-criteria decisions. AHP may assist the decision makers to set preferences and make the best decision and helps decision makers arrive at the best decision in a case of multiple

conflicting criteria's (Abay et al., 2019). AHP is a multiple attribute decision-making method that permits subjective as well as objective factors to be considered in the decision-making progress (Adugna, 2020). The designed AHP pair wise comparison table is depending on the rating of relative importance for two criteria at same time. Comparison is focus on importance of one factor over other, using a scale range from 1 to 9 values as this: {1/9, 1/8, 1/7, 1/6, 1/5, 1/4, 1/3, 1/2, 1, 2, 3, 4, 5, 6, 7, 8, 9}. The values range from 1/9 representing the least important (than) to 1 for equal importance and to 9 for the most important. The range of numbers like 2, 4, 6 and 8 represents an intermediate value. AHP has been successfully incorporated with GIS-based MCDA since the early 1990s. Analytic Hierarchy Process with GIS based Multi-criteria decision analysis (MCDA) provide a rich collection of techniques for landslide susceptibility mapping (Hamdouni et al., 2022). It has tendency to make hierarchical structures based on specific criteria and sub-criteria during weight assignment. GIS based AHP has gained popularity due to its capacity to integrate a large quantity of heterogeneous data, and because obtaining the required weights can be relatively straightforward, despite for a large number of factors (Adugna, 2020). AHP has obtained popularity because of its diversified applicability in landslide analysis, land suitability analysis, site selection, flood analysis and regional planning (Abay et al., 2019).

2.6.4.2 Weighted Linear Combination

The Weighted Linear Combination method (WLC) is one of the most effective and commonly used with GIS based MCDA to combine the multiple factors to produce a single map (Ghamgosar et al., 2011). WLC method is a popular method that is employed in diversified GIS application and flexible combination of maps (Feizizadeh et al., 2011). The tables of scores and the map weights can be adjusted to reflect the judgment of an expert in the domain of the application being considered (Debru, 2020). The WLC method starts with a comparison of the data-layers corresponding to the landslide causative factors, and the landslide inventory map and involves the computation of the landslide density so as to assign primary-level weights for each class of a particular parameter (Gizawu, 2020). In general, this method makes a combination of all the weighted layers into a single map. Then, the classified scores of the map turn to landslide susceptibility map. MCDA approach helps for overlaying massive data or map.

2.7 Landslide Model Validation

Any potential area of landslide event which could be resulted in to geo-environmental constraint should be assessed to set values of losses whether qualitatively, quantitatively or both at a time. Any means of influence that turn to landslide susceptibility, hazard and risk have to be modeled on space and time. Several validation model are suggested to evaluate the effectiveness of used methodology in particular area on landslide susceptibility, hazard and risk. These are; simple overlay, relative error, relative landslide density index(R), landslide density, Receiver operating characteristics, landslide percent comparison column chart, success and predictive rate curve.

2.8 Application of Geospatial Technologies in Landslide Hazard Zonation

An integration of Geospatial technologies like Geographic Information System (GIS), Remote Sensing and Global Positioning System (GPS) are extremely important for site identification, suitability analysis, hazard analysis, disaster management and propose an effective mitigation measure for identification of landslide prone areas. Especially, active landslide areas, which shows prospective occurrence of future landslide events. In spite of this, combining GIS and Remote sensing based mapping through GPS field survey of affected landslide areas have a crucial role in preparing landslide inventory and causative factors map. Moreover, prepare landslide hazard zone map of hotspot areas.

Geographic Information System (GIS) is a computer-based system for data capture, input, manipulation, transformation, visualization, combination, query, analysis, modeling and output, with its excellent spatial data processing capacity, has attracted great attention in natural disaster assessment (Carrara, 1983). GIS from science point of view; defined as science used to analyze spatial based information. This makes it possible to take data stored in one form and combine with data entered and stored in some other form (Church, 2002). It has become possible to efficiently collect, manipulate and integrate a variety of spatial data such as geological, structural, surface cover and slope characteristics of an area, which can be used for hazard zonation using GIS techniques. GIS techniques have used for preparation of causative factor map production and then make classification for each causative factors that have a critical role for obtaining information from each of factors. Thus, leads served for

producing single final map as it verified by weight rate of each causative factors. In addition to this, GIS integrate both spatial and non-spatial data for better analysis. Basic parameter preparation and rasterization is rudimentary for the spatial estimation of the data value for unknown location. Multi-criteria decision analysis methods like AHP and WLC are simple fitted with GIS environments. The data from remote sensing is the input for the GIS data analysis. Geographical Information System is widely used in landslide hazard assessment especially for generation of thematic data layers, computation of different indices, weight assignment, data integration and generation of Landslide hazard zonation maps. In hazard assessment, GIS provided to model and rank hazard risk occurrence according to its distribution or intensity and output visualization in various format. However, geographic information system supports as geo-database, geo-visualization and geo-processing views to support decision-making process. To sum up, GIS is a powerful tool that used to delineate the landslide hazard zone based on landslide occurrence pattern on the landslide influencing spatial feature and produce the disaster prone area map. Various researchers were used GIS based statistical analysis for landslide hazard zonation, the application of GIS was found vastly useful for thematic data layer generation and for their spatial data analysis, which involved complex operations (Sarkar and Kanungo, 2004). The main advantages of using a GIS in assessing landslide hazards include improving the hazard occurrence model in slope stability analysis by varying the input parameters and evaluating the results in an iterative process of trial and error (Baban and Sant, 2005).

Remote sensing technique was used to collect past landslide events of inaccessible area from Google earth image. Moreover, aerial photographs are employed to acquire cost-effective information with timely basis in vast areal coverage's. Remote sensing techniques are widely implemented in landslide susceptibility assessment in both generation of landslide factors thematic layers and the production of landslide inventory map (Kouli, 2009). Remote sensing method is more effective tool aid for detecting, mapping, analysis and monitoring geo-environmental hazards as a whole and particularly for landslide.

Global Positioning System (GPS) instrument was used to collect the ground truth data of accessible past landslides. GPS was an effective instrument that used to identify the location

of the known landslides(Gizawu et al., 2020). GPS also used for landslide mapping with an exactly known location.

In general, Geospatial technology has become more effective and efficient tool in assessing landslide susceptibility, hazard and risk starting from early warning to reactivation of an event. Hence, incorporation of one technique with other fit the constraint of another technique.

2.9 Recent Studies on landslide in Ethiopia

Several researchers have attempted to conduct the study on landslide. Since landslide is a one of catastrophic geo-hazard problems for the development of the country like Ethiopia, particularly the northern, western, central, southern highlands and rift margin are more prone area of landslides. The distribution of landslides within the area relies on different factors, which are complex and weathered geology, unstable soil cover, rugged morphology, heavy rainfall, high relief energy, hydrogeology, earthquake, volcanic eruptions and anthropogenic activities as a whole. As pointed out by the following researchers (Girma 2015; Hamza and Raghuvanshi 2017; Mengistu 2019; Debru 2020; Gizawu 2020; Ali 2021). The increased man-made activities in the recent past years such as road, building and other construction works have resulted increment of landslides in Ethiopia. Different research works have been conducted using various qualitative and quantitative techniques to assess the causes that induce landslides in the different part of Ethiopia. Various studies on landslides in Ethiopia are presented below:

Girma, (2015) made a study on landslide hazard zonation in Adea Berga District, central Ethiopia using a GIS-based statistical approach. In this study, the considered landslide causative factors are lithology, soil deposit, slope, aspect, elevation, curvature, land use/land cover, and groundwater.

Meten et al., (2015) carried out a study in Debresina GIS-based frequency ratio and logistic regression modeling for landslide susceptibility mapping of Debresina area central Ethiopia. To discuss this and to prepare landslide susceptibility mapping landslide inventory and nine causative factors including lithology, land use, distance from river and fault, slope, aspect, elevation, curvature and annual rainfall were considered. After various rasterization of causative factor thematic maps and landslide inventories for both logistic regression and

frequency regression model the success and prediction rates 75.7%, 74.5% and 74.8%, 73.5% were produced respectively. The prediction rate and therefore the validation rates are almost similar, therefore based on this they concluded that the model is acceptable.

Kumar et al., (2015) conducted the research in Meta Robe district, Oromia Ethiopia using grid overlay and GIS modeling approaches to prepare landslide hazard zonation map. The research showed that GIS modeling produced a better landslide hazard zonation map. In addition, the grid overlay method is a more tedious and time-consuming approach.

Dawit, (2016) made the study on landslide hazard evaluation and zonation in Kindo Didaye Woreda, southwest Ethiopia. In this study landslide, hazard zonation of the study area was carried out by using two methods: Integrated slope stability susceptibility evaluation parameter and a raster-based information value model approach. The findings show that the deformation, cultivation and modifying the slopes by manmade activities in addition to high rainfall and groundwater are the most influential causative parameter for the occurrence of a landslide in the study area.

Chimdi et al., (2017) conducted landslide hazard zonation mapping in Gimbi town; western Ethiopia using GIS based statistical approach entitled which was by landslide hazard evaluation and zonation in Gimbi town and its surroundings, western Ethiopia a GIS-based statistical approach. In this study, nine causative factors were considered for the landslide hazard zonation map preparation including slope material, elevation, slope, aspect, curvature, land-use/land-cover, groundwater, and distance to road and distance stream. From this study, five hazard zones and fifty past landslide sites were identified. The authors concluded that 75% of the past landslides fall within very high and high hazard zones; as a result, future planning and development of the town should consider this hazard.

Hamza and Raghuvanshi, (2017) conducted the study on landslide hazard evaluation and zonation in Jeldu District in Central Ethiopia. The considered governing factors in this study are aspect, slope and elevation, lithology, soil and land use/land cover. The results revealed that 12% of the study area falls under no hazard, 27% as low hazard, 32% as a moderate hazard, 21% as high hazard and the rest 8% as very high hazard.

Filagot Mengistu (2019) made study on Landslide Hazard Zonation and Slope Instability Assessment by using Optical and InSAR Remote Sensing: the case of Arbaminch Gidole Road, Southern Ethiopia. In order to identify landslide hazard zones in this study area six causative factors were considered are; aspect, slope, elevation, NDVI, lithology, and land use/land cover. The information value method was used. Thus produced 92.3% of study area was fall under high and very high hazard zones.

Endashaw Debru (2020) conducted the study on Landslide hazard zonation map and time series deformation map in the Birbir-Mariam Area of the Southern Regional State that were generated using techniques AHP and PS-InSAR techniques by using eight causative factor maps. Such as Slope, Elevation, LULC, Lineament density, and Drainage density, NDVI, Lithology and Aspect. The outcome of the data processing by making use of the AHP technique shows that 40.5 % of the study areas belongs to high and very high hazard zone.

Fayera Gizawu (2020) made study on landslide hazard zonation using Geospatial and multi-criteria decision analysis techniques in Gechi district western Ethiopia. The validation result revealed that 82.7% of past landslide events were falls in maximum landslide hazard zones.

2.9.1 Recent Landslide studies around study area

Various researchers were tried to conduct the studies in Abay Gorge along main road corridor of Gohatsion to Dejen from geological and geophysical point of view, due to the landscape evolutions. This road corridor is very important linkage that connect central Ethiopia to Northern part, due to that various individuals and institution conduct detail investigations more than anywhere in Ethiopia. The present study was situated in the Worra Jarso district of North Shewa located in Oromia region. No one was conducted the study in this district as a whole, however two authors were conducted the studies in partial part of this district that found in area lies between Gohatsion Town and Abay River Gorge.

Henok Woldegiorgis (2014) conducted a landslide hazard zonation by utilizing expert evaluation technique in area lies between Gohatsion Town and Abay River Gorge. In this study, they have attempted to delineate the area into landslide hazard zones by utilizing landslide hazard evaluation factor rating scheme. The considered causative factors were relief, slope morphometric, geology, groundwater and land use/land cover. Based on the causative

factor scheme the hazard has low, moderate and high levels. According to the final overlay, analysis of hazard zonation result showed the main road passes through moderate and high hazard zones. According to these authors, detailed investigation was recommended to suggest the remedial measures or to realign the main road.

Shiferawu Ayele (2014) undertaken study using GIS and Remote sensing techniques with Fuzzy for landslide disaster management in the area fall between Gohatsion Town and Dejen Town along road corridor of Abay River Gorge. The researchers were used the following causative factors geology, groundwater condition, land use land cover, drainage, structure, aspect and slope. In order to delineate landslide hazard zones. A comparison of the landslide hazard map with actual landslide events of the area showed that 67% of the area falls under maximum hazard zone.

Mihret Manaye (2018) made study on two and three dimensions' slope stability because of failures colluvial materials. The study focused on prior data for monitoring slope instability from Geological and Geophysical standing point.

According to the recent study conducted by Yechale Ali (2021) in the Abay River Gorge along main road from Gohatsion to Dejen town using GIS based statistical analysis for evaluation of landslide susceptibility mapping through considering seven causative factors such as; lithology, elevation, slope, aspect, land use/land cover, proximity to road and proximity to stream. The Information value method was used to produce causative factors map. Validation of the prepared susceptibility map showed that 87.1% of past landslides fall in high susceptible class of the prepared landslide susceptibility map. Based on finding of this study, many road corridors passes along high landslide susceptibility class which need a further investigation. Hence, it subjected to slope failures, which initiate occurrence and reactivation of landslides along main road from Gohatsion Town to Dejen Town.

Therefore, the present made on Landslide Hazard Zonation by using a Geospatial based Multi-Criteria Decision Analysis through AHP and WLC Techniques based on eight causative factors such as; elevation, slope, aspect, curvature, soil type, lithology, LULC and drainage density in the Worra Jarso District of North Shewa Zone located in Oromia Regional State.

CHAPTER THREE

3. MATERIALS AND METHODOLOGY

3.1 An Overview of the study area

3.1.1 Description of the study area

The study area is found in the Worra Jarso District of North Shewa Zone located in Oromia Regional State, Central Ethiopia. The area is far away 186km from Addis Ababa. The capital town of district is Gohatsion, which is found along the main highway road in between Tulu Milk and Filiklik town. It is bordered on the south by Kuyu, on the west by the Muger River, on the north by the Abay River, on the northeast by the Jemma River and on the east by Hidabu Abote. Geographically the area is defined by 9°0'0''N to 10°10'0''N latitude and 38°0'0''E to 38°30'0''E longitude with covering a total surface area of 1198 Km². The study area forms a part of the Abay River Basin with elevation ranges from 926m to 2602m.

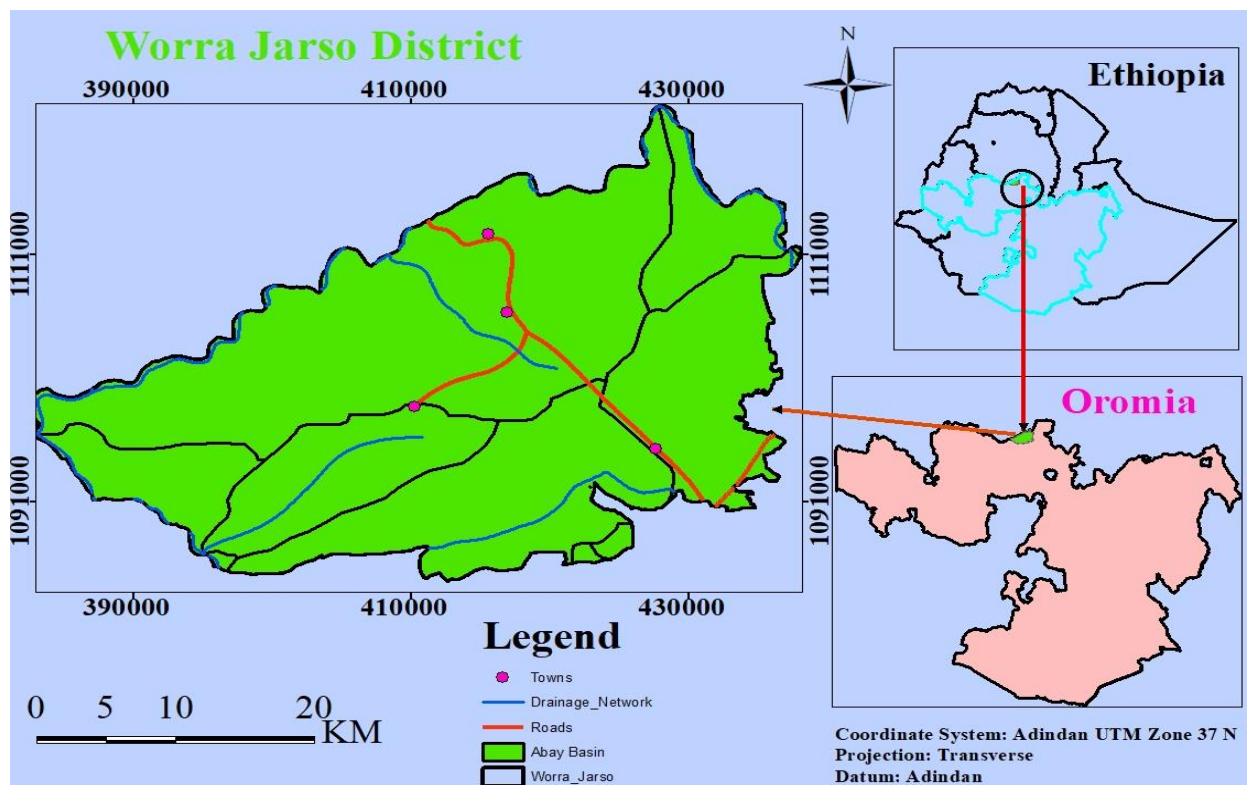


Figure 6: Location map of the study area

3.1.2 Drainage pattern of the study area

The study area is situated at the main Ethiopian rift margin of Shewa plateau in the northwestern highland drainage system, with elevation ranges from 926m to 2602m above mean sea level. Many rivers like Abay, Muger and Jemma are border of the study area, which initiate the slope instability because of weathering and erosion as the area is near to rivers network. In this area, most of the rivers originate from the highland plateau and characterized by dendritic to sub parallel drainage patterns. All flows are finally drain to Abay River. The existence of many drainage network exposed the area for massive gully erosion particularly in a lower slope. Thus are mostly resulted from unconsolidated colluvium and alluvial deposits. As a result, landslide frequently damage the main road corridor that passes through this terrain.

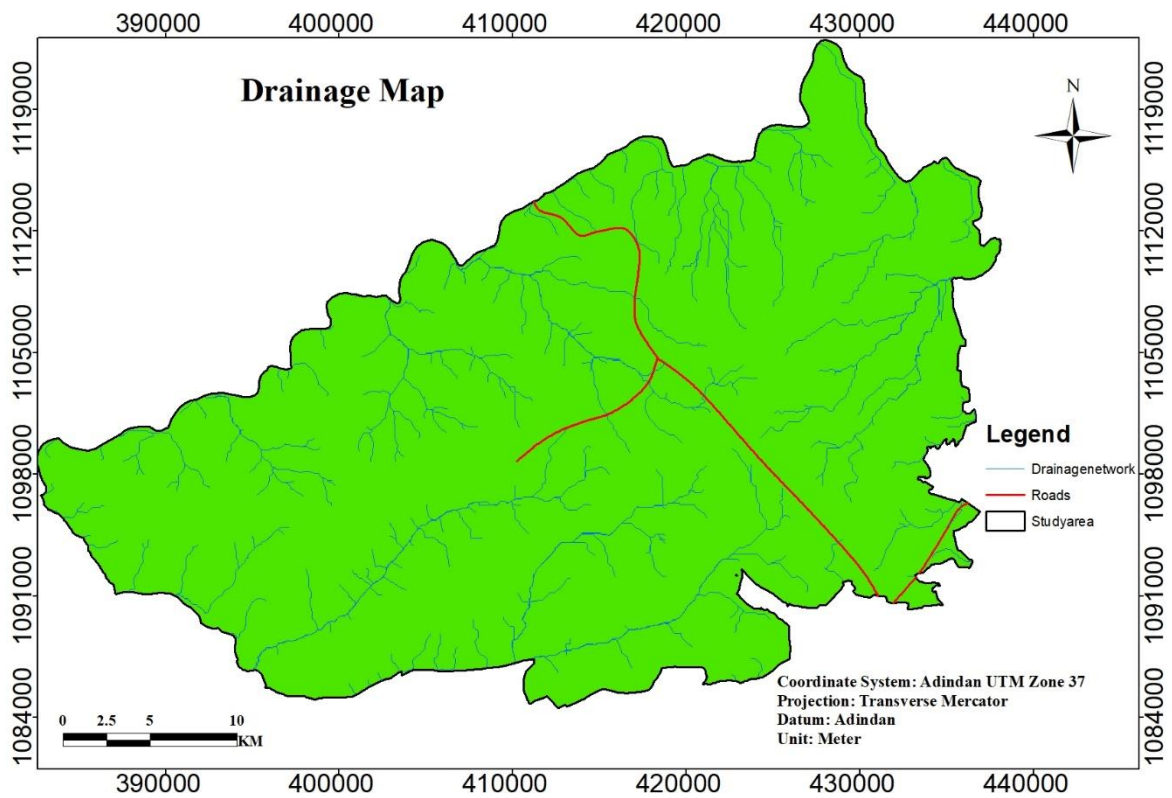


Figure 7: Drainage map of the study area

3.1.3 Physiographic Situation of the study area

The topographic pattern of the study area is the propensity to be adversely affected by the geological formation associated with tectonic setup, as the area is a succession of Mesozoic sedimentary rocks underlain by basement rock and overlain tertiary basalt volcanic rock. Accordingly, the area shows more than 1600m altitudinal variations. Since the lowest altitude is 926m and the highest altitude is 2602m. The physiographic pattern of the study area is undulated, which are a reflection of the past geological and denudation process that dissected by the deep gorges. This situation is mainly a result of surface erosion, ground movement and interlinked with geodynamic processes.

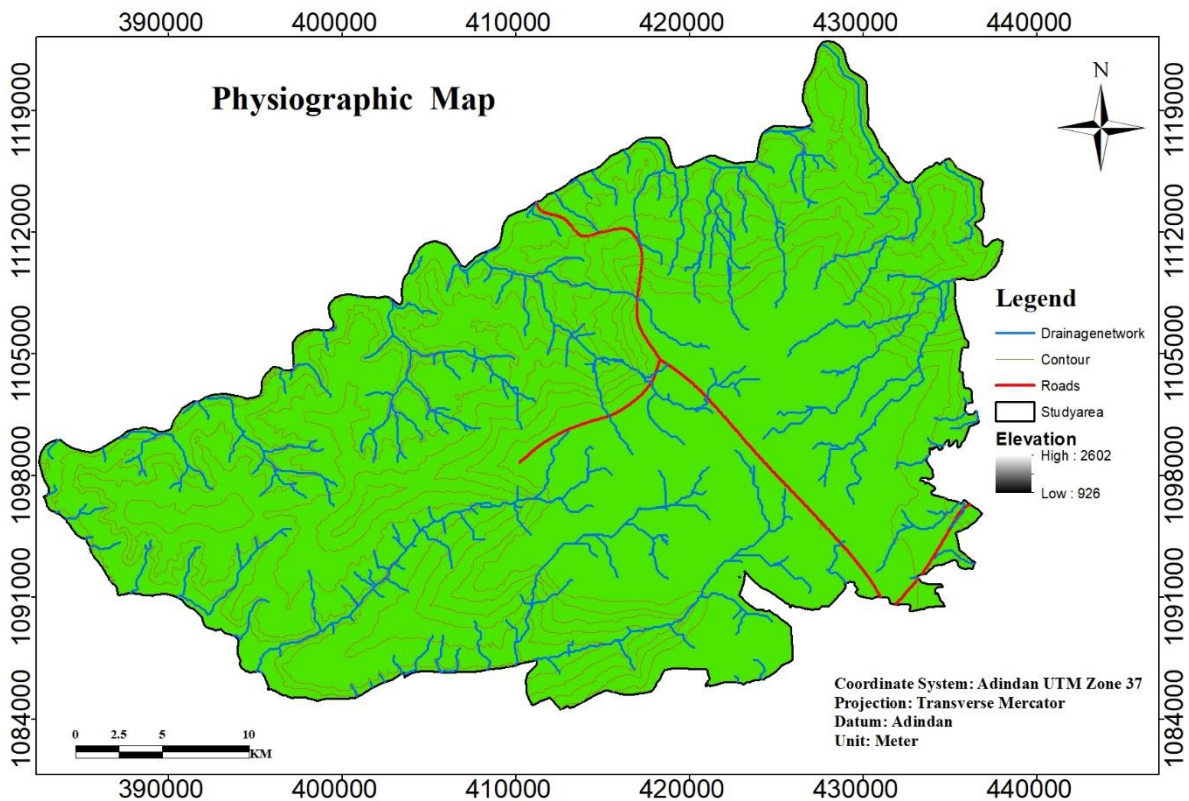


Figure 8: Physiographic map of the study area

3.1.4 Climate condition

The climate situation of Ethiopia is highly controlled by the seasonal variation of the Inter-Tropical Convergence Zone (ITCZ) following the sun's position with respect to the earth and the associated atmospheric circulation (NMA, 2001). Moreover, the climate condition has been affected by the altitudinal variations. The present study area lies in three climatic zones

such as Tropical (kola), Sub-tropical (weynadega) and Temperate (dega). Since it is altitudinal variations lies in between 926m to 2602m. In this study, two main elements of climate condition is considered for overall analysis rather than serving as an input dataset for preparation of landslide hazard zonation map. These are rainfall and temperature.

3.1.4.1 Rainfall

Rainfall is one of the main triggering factor for landslide initiation. Landslide has an erratic nature that makes it difficult to control and predict. Landslides are downward mass movement of rock, soil and debris under the influence of gravity. Rainfall factor is directly initiate the landslide incidence, even though the other causative factor initiate slope failures. The variability of surface water or groundwater level is one of the critical consequence of amount rainfall. Rainfall and landslide have direct relationship with respect to slope geometry and materials. Rainfall did not consider in the present study, because the study area has only two meteorological stations that cover the small area. Hence, it is a regional factor, which is not suited for microclimate study. There are two metrological stations situated in the study area namely Filiklik and Gohatsion. The record of long time rainfall data was obtained from National meteorology Agency (NMA) of Ethiopia. Despite, the data was not full and some year's data was missed. To compensate the missed data, the result interpretation solely depends on full data. Specifically, rainfall data of 33 years (1990-2022) and 31 years (1990-2020) for Filiklik and Gohatsion station respectively are used. Repeatedly the many landslides are occur in the study area during the rainy seasons from July to September since the amount of rainfall reached the peak at 858.1mm in the month of august, 2018 and followed by 529.8mm in the month of July, 1993 for Filiklik station. Similarly, for Gohatsion station the amount of rainfall reached the peak at 468.5mm in the month of July, 1993 and followed by 464.33 mm in the month of July, 2017. The mean annual rainfall recorded at these stations were 1175.42mm/33yrs, 1137.87mm/31yrs respectively (appendix3a&3b). This result showed that the amount of rainfall increases, simultaneously the landslide hazard occurrence also increase. As rainfall reached the peak in the months of July and august.

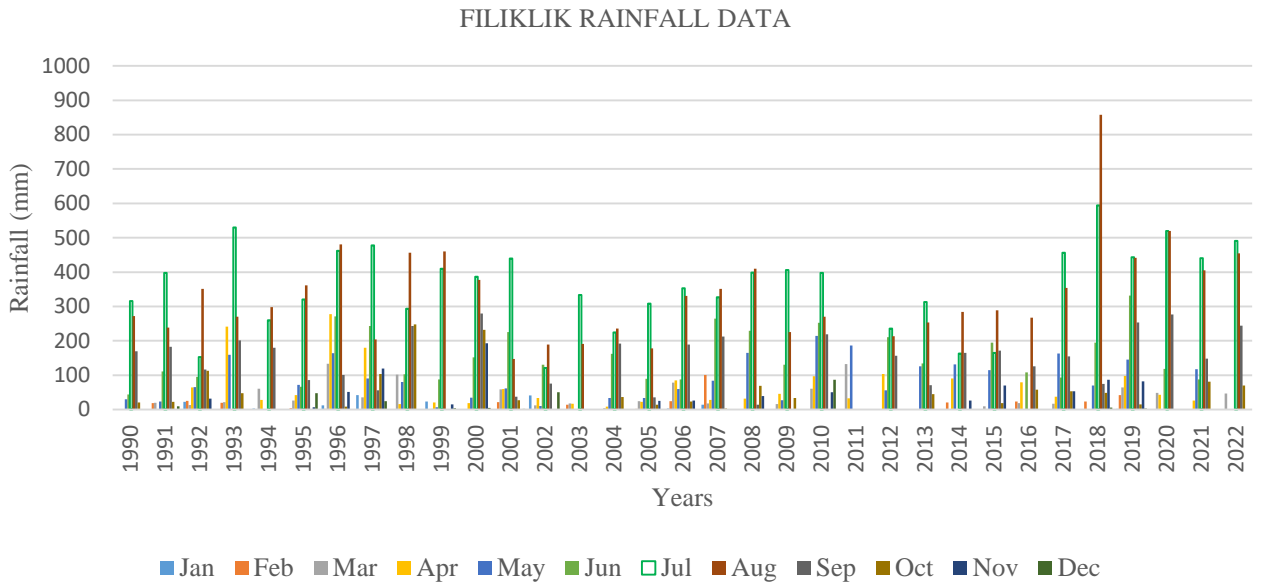


Figure 9: Monthly Rainfall data on Filiklik Station

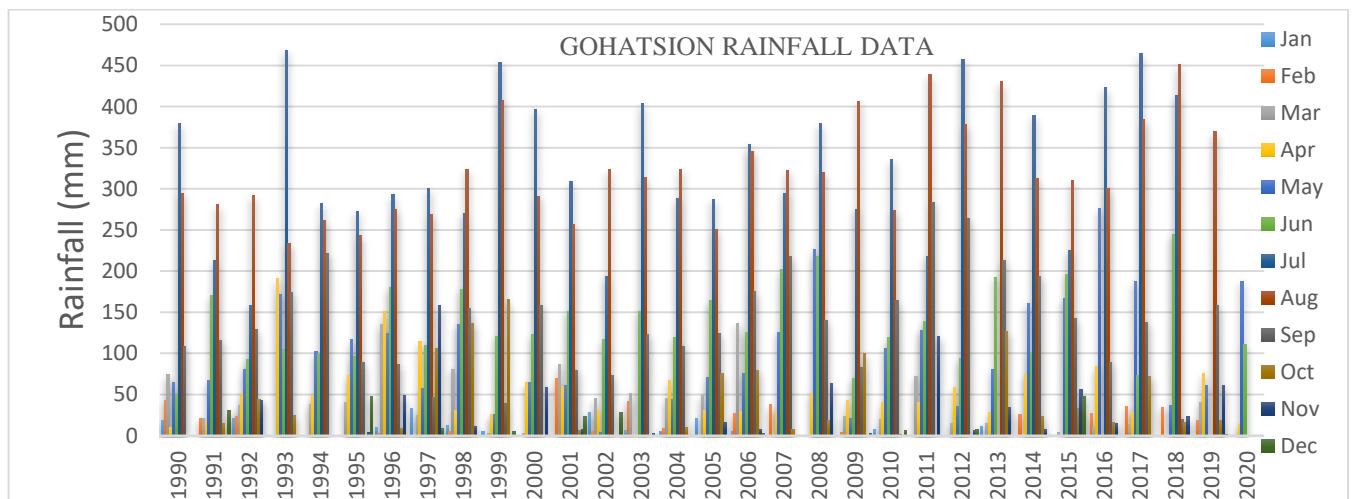


Figure 10: Monthly Rainfall Data on Gohatsion Station

3.1.4.2 Temperature

Temperature is another element of climate condition. The fluctuation of temperature can affect the stability of a slope in a various way. As it can change the extent of vegetation cover and groundwater. In the present study, temperature is not taken into account for mapping of landslide hazard zone. Two meteorological stations used for collection rainfall data is similarly serve for temperature data collection. Accordingly, the temperature data of 32 years (1990-2022) for Filiklik station with fully missed data of 2003 year. As well as, the

temperature data of 31 years (1990-2021) for Gohatsion station with fully missed data of 2020 year. The data for both stations was acquired from National Meteorological Agency (NMA) of Ethiopia. Based on record of NMA, generally the maximum mean monthly temperature was recorded from February up to June in the present study area for both stations. Specifically, the maximum mean monthly temperature of Gohatsion station reached the peak at 23.9°C in the month of May, 2002. Moreover, the maximum mean monthly temperature of Filiklik station reached the peak at 27.1°C in the month of February, 2009. On the other hand, the minimum mean monthly temperature was recorded as 12.75°C and 15.3°C for Filiklik and Gohatsion respectively (appendix3c&3d).

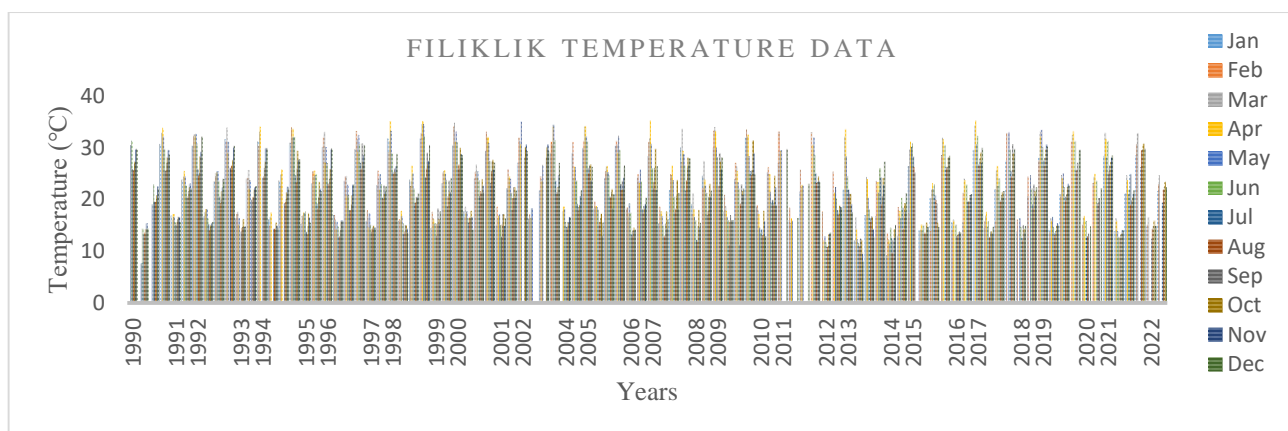


Figure 11: Graph of maximum, minimum and mean monthly temperature on Filiklik station

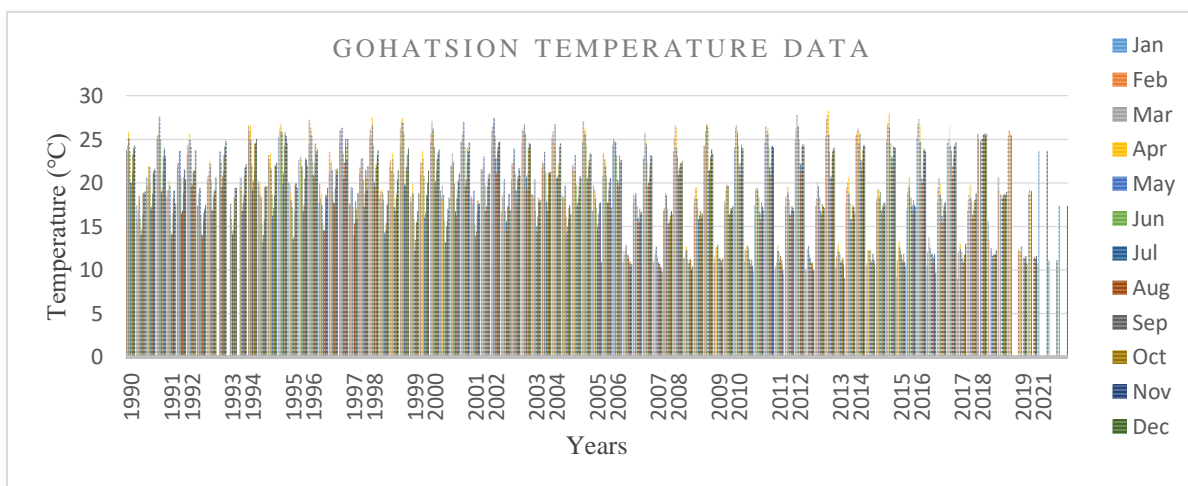


Figure 12: Graph of maximum, minimum and mean monthly temperature on Gohatsion station

3.1.5 Seismicity

The earthquake is one of the most critical triggering factors of geo-environmental hazard that caused by the motion of ground acceleration at the earth's surface, it has a great impact on existing natural conditions, civil infrastructures and public safety. The earthquakes are common in the active plate boundaries and rift margin areas. However, the seismic hazard zone map of present study area manifests the seismic free based on map released by Ethiopian Building Code Standard (EBCS, 1995). Therefore, the present study did not consider the earthquake as an influencing factor.

3.1.6 Population and Human Activity

According to the Central Statistical Agency (CSA) reported in 2007 a total population of Worra Jarso district is 141,426, out of this population 70,787 were men and 70,639 were women. Among this population around 10,531 or 7.45% were urban dwellers. The majority of the inhabitants were Orthodox, which account 93.55%, while 4.65% were Protestant, and 1.46% were Muslim. With an estimated area of 1198 square kilometers. Agriculture is one of the most source of livelihoods in this district, with dominant crop production such as sorghum, wheat, maize, teff and sugarcane. Among different land use type characterized in this district, agricultural land is a very sensitive to landslide occurrence or reactivations. Since practiced by many people in this study and almost no covered with forest that minimize the extent degradation.

3.1.7. Geology

3.1.7.1 Regional Geology

The present study area is located in the Blue Nile Basin (Abay River) is one of the main East African sedimentary basins found in Ethiopia (*Assefa*, 1991). Besides, Mekele, Ogaden, Gambela and Rift basins. Those five basins cover 33% of the Ethiopian Surface (*Ahmed*, 2008). Among those basins the northwestern part sedimentary basin covers most part of the country and characterized by highland relatively 1500m to 4000m and the southeastern plateau occupied by Ogaden Basin relatively lies below 1000m which is characterized by descending to the Indian Ocean (*Getaneh Asefa et al.*, 1991). The history of Mesozoic sedimentation related to the beginning of break-up of Gondwanaland during Paleozoic

Jurassic times which were largely fault-controlled (Ayalew and Yamagishi, 2014). Blue Nile Basin is created during the intra-continental rift stage which related to the beginning of Gondwanaland break-up (Russo et al., 1994). Blue Nile basin has 1200 meters thick and capped by Tertiary flood basalt lava flows.

3.7.1.2 Lithology of the Study Area

Geology plays a crucial role in slope instability initiation that leads to landslide occurrence. Hence, it manifests the different lithological units and geological structures associated with surface soils deposit. The study area is the composed of Paleozoic, Mesozoic and Cenozoic geological era. As the study area is located around Abay Gorge, it is character is associated with stratified sedimentary rocks capped by Tertiary basaltic volcanic rock. The stratigraphic sequence starts with the oldest being Paleozoic sedimentary rocks at the bottom followed by subsequent younging upward sequence of Mesozoic sedimentary rocks and Tertiary basaltic rocks. In this regard, it encompasses four geological formations that found in mentioned geological time. These are Abay formation, Adigrat formation, and Ashangi formation and Antalo formation with different lithological units. Different types of rock are manifested in the area are; Paleozoic sedimentary rocks with Abay sandstone unit, Mesozoic sedimentary rocks are lower sandstone unit, gypsum unit, limestone unit and upper sandstone unit, Tertiary rocks are dominated by basalt lava flows and quaternary age are the recent deposits that extensively found in the form of alluvial sediments and as slope deposits.

Sandstone; Adigrat Formation

Sandstone unit is the oldest within the study area that belongs to Adigrat formation that uncomfortably overlies on Paleozoic sediments. Adigrat formation has 290m thickness on the Gohatsion side. Sandstone unit intercalated with mudstone, siltstone and shale within the lower part, and conglomerate within the upper part (JICA and GSE, 2010).

Abay Formation; Middle Jurassic

This formation is composed of Jurassic limestone, mudstone, gypsum, siltstone and shale. This formation has 320 m thickness on the Gohatsion side.

Mudstone unit

The mudstone forms flat-lying, gentle slope to moderate slope topography occupied occasional steep slope topography with a 40m maximum thickness on top of the sandstone. The mudstone is massive, partly laminated and bedded vertically jointed and faulted (JICA and GSE, 2012). Fine-grained silica-clastic rocks and subordinate evaporate beds dominate it.

Gypsum unit

Gypsum unit is intercalated dolomite, limestone, shale and subordinate silt and mudstones with 130 m thickness (JICA and GSE, 2010). The dominant lithology within this member is gypsum. Gypsum forms flat-lying, moderately steep topography. It lies between the lower shale unit and overlying upper shale unit, which is not observed along main road. However, intercalated layers are suffered from deep weathering. This will cause slope instability. Lower part of this formation contains massive gypsum, limestone, thinly bedded shale, siltstone and sandstone. Middle part of this formation shows massive gypsum, thin limestone and thin shale. Upper part of this formation constitute mainly gypsum with slightly thin limestone and shale.

Siltstone and Shale Units

The siltstone and the shale layers are interceded with underlying sandstone (Adigrat Formation) and overlying limestone and gypsum (Abay Formation). The thickness of the units are about 120 m on the Gohatsion side. They are observed as an alternating layer in limestone and gypsum units. The siltstone unit is comprise of silt and clay particles. It is interceded with shale, mudstone and sandstone with calcite or gypsum veins. The shale is a clastic sedimentary rock that contains many clay minerals. The shale between underlying sandstone (Adigrat Formation) and overlying gypsum. The shale between underlying siltstone and overlying limestone (Antalo Formation). Even though “the upper shale unit is not observed along the main road due to weathering and erosion. In the present study area, a gentle slope was formed by removal of soil deposit and experienced many landslide occurrence. Shale is vulnerable to weathering and erosion that is finally changed to clay by denudation. The lower part of the shale is not subjective to weathering and erosion, subsequently the silt and shale area indicate

almost flat surface and/or gentle slope (JICA and GSE, 2010). Thus, the lowest rate were given for these lithological units in this study, with respect to slope instability.

Limestone; Antalo Formation

The limestone is horizontally bedded which is topped by the trap series basalts with 400m thickness formations. The unit comprises of dolomite, mudstone, shale, and carbonated clay and marl intercalations. Despite the limestone unit is dominant. The form of limestone layer creates steep slope cliffs and escarpments. The limestone is more susceptible to weathering and erosion due to closely spaced minor vertical joints(JICA&GSE, 2010).

Basalt; Ashangi Formation

The thickness of the Ashangi formation is 380m intercalated with pyroclastic layers (JICA&GSE, 2012). The lower part of this unit is characterized by a massive basaltic lava flow associated with colluvium deposit whereas the middle part is composed of basaltic lava and pyroclastic rocks. The top of this unit capped by columnar joints while the bottom flows are massive with huge blocks.

Surface Soils

The study area is experienced with massive amounts of surface soil covering the bedrocks. Namely residual, alluvial and colluvial deposits. The amount of depositions are mainly relies on altitudinal variations. In this scenario, basalt, limestone, gypsum and sandstone layers generally form steep cliffs, and pyroclastic rock, siltstone and shale form gentle slopes due to the susceptibility to weathering and erosion in the area. The pyroclastic unit and the shale unit are covered by huge amount of surface soils, which characterized many landslide forms(JICA&GSE, 2012).

3.1.7.3 Geological Structures in the study area

The normal faults that strike towards NE-SW and NW-SE within study area. The normal faults observed in gypsum beds of the present study area. Many part of the study area encompasses the three well-developed joint sets namely the bedding plane, which is nearly horizontal, and two other joint systems (j1 and j2). Major of them are trending towards NW and the other

NE, respectively. Many columnar joints in the study area is basalt rock mass. Moreover, the surface cracks are observed in the study area on colluvial deposit around Filiklik town (Ali, 2021).

3.2 Research Design

The present study was used Explanatory and Descriptive research design. Explanatory research design was used to quantify spatial data. Descriptive research design was served to analyze non-spatial data that comes from expert interview. In addition to this, this study was used a semi-quantitative approach encompassing both qualitative and quantitative. The qualitative approach was used to analyze non-spatial data from qualitative data sources and a quantitative approach was used to quantify spatial data. In general, this study was used mixed research design and approach.

3.3 Data sources and Materials

3.3.1 Data sources and Types

In order to achieve the objective of this study, the data of eight causative factors were collected. These factors are slope, lithology, drainage density, soil type, land use land cover, elevation, curvature and aspect. These factors were identified due to significant contribution to landslide occurrence (Girma 2015; Hamza and Raghuvanshi 2017; Mengistu 2019; Debru 2020; Gizawu 2020; Ali 2021). These data are available on different platform. Accordingly, different data types were collected from different sources in different data type. The major data used in this study are Inventory data, Remote Sensing, Soil and Geological data. All the above data that were collected from different data source in different types are collected, manipulated, and analyzed in GIS and RS environment to serve for delineation of potential landslide hazard zones. Thus helps to identify and predict the landslide-prone areas. In general, the different data type and sources that was used in this thesis presented under here:

Table 1: Data type and Source

No	Data Type	Data Format	Scale/Spatial Resolution	Purpose	Data Source
1.	Inventory data	Vector	Row data	Inventory and Validation maps Elevation, Slope, Aspect, Curvature, and Drainage Density Maps	Known Landslide, Field survey and Google Earth
2.	DEM (SRTM)	Raster	30m	Lithology Map	USGS(website)
3.	Geological map	PDF	1:250,000	LULC Map	JICA and GSE
4.	Sentinel-2A	Raster	10m	Soil Type map	ESRI(website)
5.	Soil data	Vector	1:50,000		MoWIE

3.3.2 Material and Software's

This study used different materials and software, in order to achieve the targeted objective. In this regard, the following materials was used for data collection, data organization, and data analysis and result interpretation. Like GPS, personal Computer, Printer, and digital camera. Similarly, both system and application software also serve for data pre-processing, preparation, visualization, manipulation, management, processing, and data analysis, editing and result interpretation of spatial and non-spatial data are presented below here.

Table 2: Material and Software

No	Materials/Software	Versions	Purpose
1.	Handheld GPS	Garmin 78	To collect landslide inventory data
2.	Google Earth Pro	Google Earth Pro 2019	To collect landslide Inventory data and conduct LULC accuracy assessment
3.	ArcGIS Software	10.4.1	To prepare thematic and location map of the study area
4.	TerrSet (AHP plugin)	2020	To calculate weights for each factors based on relative importance value

3.4 Methodology

Several approaches have been suggested for Landslide Hazard Zonation such as inventory-based mapping, heuristic approach, probabilistic assessment, deterministic approach, statistical analysis and multi-criteria decision analysis approach (Mengistu et al., 2019). After the carefully inspection of nature of the entire study in conformity with previous studies, a Geospatial based MCDA with AHP method was developed for delineation of landslide hazard zones.

3.4.1 Data Collection

Collecting a precise and an accurate data has a paramount is of importance in any scientific study for a realistic output of proposed study. While combining a data from different sources have own drawback. In this regard, for this study, the data was collected from different governmental office and downloaded from satellite data sources. Besides, the ancillary data was used. Since the data was collected from different sources, they data formats, projections and types were different. Accordingly, Lithology map was prepared from Geology map in pdf format that were prepared by JICA and GSE, SRTM DEM image with 30m resolution was downloaded from USGS to extract elevation, slope, aspect, curvature and drainage density, Soil data was obtained from Ministry of Water, Irrigation and energy (MoWIE) to extract soil type. Sentinel-2A image of 10m resolution was downloaded from ESRI to prepare land use land cover of the study area.

3.4.2 Data Preparation

The identification of causative factors and preparation of respective thematic data layers has a vital role in delineation of potential landslide hazard zones. Similarly for present study, data preparation is a primary task to preprocessed and prepared collected data for further analysis. In this manner, all datasets were converted into the same spatial reference system, which means the Universal Transverse Mercator (UTM) projection of Adindan datum was used for all the data set. All dataset was resampled to the same spatial resolution of a 30m. Moreover, lithology map, and soil map of vector data type were converted to raster data type. Then, spatial reference, spatial resolution and data types are well-suited for further data analysis.

Preparation of Elevation dataset: The SRTM DEM with 30m resolution image of the study area was downloaded from USGS. Then, the digital elevation model (DEM) of the study area was extracted by shape file of the study area. Then after, the missing DEM was filled using hydrology tool of ArcGIS 10.4.1 software. The filled DEM of the study area was used to prepare the Elevation map, Slope map, Aspect map, Curvature map and Drainage network map of the study area.

Preparation of Slope dataset: the slope dataset was prepared from unclassified elevation dataset using symbology tool of Arc GIS environment. The generated slope dataset was prepared for further reclassification of slope angle.

Preparation of Aspect dataset: the aspect dataset was prepared from unclassified elevation dataset using symbology tool of Arc GIS 10.4.1 software. The generated aspect dataset was prepared for further reclassification.

Preparation of Curvature dataset: the curvature dataset was prepared from unclassified elevation dataset using symbology tool of Arc GIS 10.4.1 software. The generated curvature datasets was prepared for further reclassification.

Preparation of Drainage network dataset: Drainage network dataset was extracted from elevation map of the study area by using hydrology tool of ArcGIS software. The prepared drainage network dataset was used to generate drainage density map through line density and further reclassification was done.

Preparation of Soil dataset: Soil dataset was obtained from ministry of water and energy of Ethiopia. The soil dataset was acquired in vector data type, then clipped using shape file of the study area. The most relevant attribute for deriving soil information was soil type classes. The soil type map was converted into raster format using conversion tool of ArcGIS software for further reclassification and analysis.

Preparation of Land use Land cover dataset: The sentinel-2A images of 2022 of the LULC dataset with 10m resolution was downloaded from ESRI website containing four bands such as 2, 3, 4 and 8, blue, green, red and Near infrared red respectively. Those bands are

purposefully used for preparation of land use land cover classification map of the study area. For further analysis the prepared LULC map was reclassified and resampled to 30m.

Preparation of Lithology dataset: To prepare lithology dataset of the study area, the lithological map of the study area is adopted from existing geological map published by Japan International Corporation Agency (JICA) and Geological Survey of Ethiopia (GSE), 2012 in pdf. The map in Pdf format was imported to GIS software and digitized within shape file of the study area. Then, it was georeferenced and saved in tiff format. This was done with the geo-referencing tool bar in ArcGIS Environment. The prepared lithology map has geological information incorporated with its lithological unit. The prepared lithology map was projected to the same spatial resolution and spatial reference system to be compatible with other dataset.

3.4.3 Data Analysis

The data for present study was analyzed through the semi-quantitative methods incorporated with geospatial based software's. Particularly, the study was used Multi-criteria Decision Analysis (MCDA) with Analytic Hierarchy Process (AHP) and Weighted Linear Combination (WLC) to analysis multiple factors. The eight relevant causative factors considered for this study are slope, lithology, drainage density, soil type, land use/land cover, elevation, curvature and aspect. These factors were evaluated and analyzed based on a given weight through AHP method to delineate the landslide hazard zone qualitatively. All factors were resampled to spatial resolution of a 30m and with Adindan UTM Zone 37N spatial reference. Moreover, all vector data format was converted into raster format. Then, these factors was reclassified to a common measurement scale and new values were assigned to each factor. Reclassification and rating of sub-class of each factor was assigned based on expert judgment, nature of the study area, international and national standards obtained from different literatures. In this regard, the classes of each factor that have the maximum impact of landslide was assigned the maximum value, conversely classes with less influence of landslides were assigned with a minimum value(Gizawu et al., 2020). The assigned values are expressed as 1(very low), 2(low), 3(moderate), 4(high) and 5(very high) for probability of a landslide occurrence. These values were assigned to each sub-class of the major factors used throughout this study. Thus served to prepare landslide susceptibility map of the proposed area.

Table 3: Factors to be considered for Landslide Susceptibility Mapping with their rating values

Factors	Class Categories	Rated value	Sources
Elevation	1497–1696 m	1	(Hamza & Raghuvanshi, 2017)
	1696–1821 m	5	
	1821–1954 m	4	
	1954–2126 m	3	
	2126–2426 m	2	
Slope	(0–5°)very gentle slope	1	(Debru et al., 2020)
	(5–12°)gentle slope	2	
	(12–30°)moderately steep slope	3	
	(30–45°)steep slope	4	
	>45° escarpment	5	
Drainage Density	0 – 0.049 (km/km ²)	1	(Adugna, 2020)
	0.049 - 0.12(km/km ²)	2	
	0.12 – 0.19(km/km ²)	3	
	0.19 – 0.25(km/km ²)	4	
	0.25 – 0.40(km/km ²)	5	
Aspect	Flat	1	(Gizawu, 2020)
	North-Northeast	2	
	East-Southeast	3	
	South-Southwest	4	
	West-Northwest	5	
Lithology	Abay Formation	2	(JICA&GSE, 2010)
	Adigrat Formation	3	
	Ashangi Formation	4	
	Antalo Formation	5	
Curvature	-7.9	5	(Gizawu et al., 2020)
	0	2	
	0-6.7	4	

Soil Type	Eutric Regosols	2	(Adugna et al., 2020)
	Eutric Cambisols/Pellic		
	Vertisols/Eutric Nitosols	3	
	Leptosols	4	
LULC	Bush Land	6	(Chimidi et al., 2017)
	Forest Land	2	
	Densely vegetated land	1	
	Sparsely vegetated	5	
	Water body/springs	6	
	Irrigated wetland	4	
	Cultivated land	7	

3.5 Landslide causative factors

The following geo-environmental factors were used for this study are; topographic factors (elevation, slope, curvature and aspect), geological factors (lithology and soil type), anthropogenic factor (LULC) and hydrological factor (drainage density). More specifically, the eight major causative factors were identified are elevation, slope, curvature, aspect, lithology, soil type, LULC and drainage density. Even though there is no clearly defined standard to identify the most influencing landslide factors. The factors that initiate the landslide occurrence in the study area were identified based on field observation, purpose of the study, scope of the study, scale of the study, previous study in the area, review of different literature, availability of the data, nature of the study area, proposed time, interview with local community and expert knowledge. As especially identification of major factors and weight assignment was conducted through an interview made with an expert of Geological institute of Ethiopia under ministry of Mines (Appendix 1). The carefully identification of relevant factors is a critical steps to prepare landslide hazard zonation map of the study area. Hence different factors have varied degree of susceptibility to landslide. For the sake of clarity, all factors used in this study were treated as causative factors throughout whole study.

3.5.1 Slope

Slope angle is a critical factor that is regularly used in landslide susceptibility and hazard mapping studies. As a steeper slopes are more prone to landslides due to the increased gravitational forces pulling down the slope material like rock type, structures, soil type and its texture. Even though the landslides are occur in gentle slopes depend on the others environmental factors (Abay et al., 2012). The slope factor of the study area was derived from SRTM DEM of 30m resolution using spatial analyst tools of ArcGIS 10.4.1 software. The generated slope map ranges from 0° to 63° in degree. The generated slope map was reclassified into five classes as (0-5°, 5-12°, 12-30°, 30-45°, and 45-63°). The slope angle represented in terms of topography as very gentle (0-5°), gentle(5-12°), moderately steep(12-30°), steep(30-45°), and escarpment(45-63°). The values were rated based on the relative contribution of each slope class with respect to probability of a landslide occurrence depend on the expert experience and review of different literatures.

3.5.2 Lithology

Lithology is one of the most causative of geological factor that induce a landslide occurrence in landslide susceptibility and hazard studies. Hence the different rock type have different physio-chemical and engineering properties in terms of its lithological units. Thus leads to a difference in the strength and permeability of rocks and soils (Abay et al., 2012). The subjectivity of each rock type to be erodible depends on degree of weathering and its strength. The rocks which retain high strength are relatively more resistant to erosion (Tadele, 2014). For present study, the lithological map of the study area is adopted from existing geological map published by (JICA&GSE, 2012). In the present study area four geological formations was observed. These geological formations have seven lithological units. These geological formations are Adigrat, Abay, Antalo and Ashangi. The following lithological units are found in these formations namely Sandstone, Siltstone, and Shale, Gypsum, Limestone, Surface Soils (residual soil, alluvial soil and colluvial deposit), Basalt and pyroclastic rock. These lithological units are classified into four groups in four geological formations from landslide occurrence perspective. These are limestone, siltstone and shale are found in the Antalo formation, basalt and pyroclastic is lies in the Ashangi formation, sandstone, conglomerate with siltstone and shale are existed in the Adigrat formation, gypsum, limestone, siltstone and

shale are found in the Abay formation. The seventh lithological unit is surface deposits which includes residual soils, alluvial and colluvial deposits are found in this study area. However, surface soils was not studied in this study separately as individual lithological unit rather it's incorporated with all formations.

3.5.3 Drainage Density

Density of stream channel associated with unstable slopes have a significant role in landslide studies (Che et al., 2011). Since the slope failure and erosion are frequently occur along the water courses like rivers, lakes and streams (Basith, 2011). In the same fashion, the present study considered the drainage density as one of the most influencing causative factors of the landslides. The stream/river associated with dense drainage networks have high probability of landslide occurrence, as they erode the slope base and saturate the slope forming materials (Ali, 2021). The drainage density factor was derived from SRTM DEM of 30m resolution using hydrology in ArcGIS spatial analyst tool. Drainage density factor was done through line density of spatial analyst tool in ArcGIS 10.4.1 environment. Then the map was classified into five classes in meter per meter square as 0-0.13m/m², 0.14-0.27m/m², 0.28-0.4m/m², 0.41-0.53m/m² and 0.54-0.66m/m². Then after, the new values were assigned for each class of distance.

3.5.4 Soil Type

A soil type is an important causative factor in landslide studies such as landslide susceptibility, hazard and risk assessment. Since soil type determines the potential of soil particles to resist forces of slide against driving forces. As a ground movement has been controlled by the earth materials it made-up from (Adane et al., 2022). A soil type with large particles like sandy soils are the most cohesive whereas clayey soils with fine particles almost cohesiveness due to the low permeability and high water retention capacity. Driving forces are relied on the load placed on the soil surface. The greater the load placed on the soil surface, the higher possibility of landslide occurrence or reactivation. Hence the driving force is greater than the resisting force. For this study, the soil map was obtained from the Ministry of Water, Irrigation and Energy, then it was clipped with an extent of study area shape file. It was rasterized to 30m. Five types of soil was found in the study area namely Eutric Regoils, Eutric Cambisols, Pellic

Vertisol, Eutric Nitosol and Leptosol. Then after, the new values were assigned to each soil type.

3.5.5 Land Use Land Cover

The LULC is one of the most anthropogenic factor that influence the landslide occurrence. The effect of LULC depends on soil depth, slope, types of plant, rocks and weather condition in the area as slope instability relies on certain local conditions (*Debru, 2020*). It plays a crucial role in provoking slope instability, hence the less vegetation cover areas are more prone to erosion rather than dense vegetated cover. Roots of vegetation cover support soil capabilities to resist erosion and stabilize slopes. For the sake of clarity, the LULC was treated as a causative factors of landslide occurrence rather than anthropogenic factor in this study. Many landslides occur mainly due to the improper land use practices like deforestation and increasing of the urbanization over a period (*Busha, 2019*). The Sentinel 2A satellite imagery of multi-spectral bands with resampled spatial resolution of 30m was used to prepare the LULC map of the study area. Then it was classified using maximum likelihood supervised image classification of pattern recognition method such as agricultural land, built-up area, rangeland, bare land, and forest and water body. Then after, it was processed by using ArcGIS software. In order to reduce the geometric errors, the raw image was georeferenced, different bands were stacked together as single layer and the area of interest subsetted within study area shape file.

Accuracy Assessment

Thematic map without an accuracy assessment don't offer the complete information. Hence the remote sensing data has been always contains some sort of errors resulted from many aspects. Therefore, the carefully attention should be given to accuracy assessment to ascertain the correctness of the prepared LULC map. In spite of this, the accuracy assessment was conducted in ArcGIS software using accuracy assessment tool. The points for each land use/land cover were selected from field survey and Google earth image of the study area using stratified random method. Subsequently, the 120 points were selected. The overall classification accuracy was computed by the total number of correctly classified pixels (the

sum of the diagonal cells) divided by the total number of pixels in the entire error matrix based on the formula indicated under here.

Overall accuracy (OA) = Total number of correctly classified pixels/Totals number of reference pixels.....equation (1)

Producer Accuracy (PA) = each diagonal element/total column*100.....equation (2)

User Accuracy (UA) = each diagonal element/total row*100.....equation (3)

Kappa coefficient (KC) = Total pixels*correctly classified pixels-sum of all (column total*row total)/square of total pixels-sum of all (column total*row total).....equation (4)

The value of kappa coefficient is used for the analysis of classified image with respect reference. Thus can helps to analysis the values that lies between the 0 and 1 corresponds with chance of agreement.

3.5.6 Elevation

Elevation is one of the most influencing topographic factor as it associated with slope angle, lithology, weathering, precipitation, ground motion, soil thickness and land cover of the environmental setting (Adugna, 2020). The area lies in higher elevation experienced steeper slope with high amount of rainfall intensity, which increases the probability of a landslides occurrence. Since it influences the gravitational forces acting on a slope. The elevation factor of this study was prepared from a SRTM DEM of 30m resolution downloaded from USGS website. The prepared elevation map ranges from 926m to 2602m above mean sea level. Then, it was classified into five elevation classes as (926m-1430m, 1430m-1575m, 1575m-2100m, 2100m-2480m, 2480m-2602m). And the values were assigned for each elevation class based on the degree of susceptibility to landslide occurrences according to expert opinion and review of different literature in line with nature of study area.

3.5.7 Curvature

The curvature values refers to a shape of the land surface in which area the topographic terrains showed as flat, convex and concave surface that leads to acceleration of flow. The acceleration of flow play an important role in increasing the potential of streams/rivers to

transport particles along curved surfaces (*Gizawu, 2020*). Thus can make a convex or concave surface more subjective to the landslide occurrence. The curvature factor was derived from SRTM DEM of a 30m resolution using spatial analyst tools of ArcGIS 10.4.1 software. The curvature map ranges from (-10° to 10.7778°). Then, it was classified into three curvature classes as Concave (0° to -10°), Flat (0°) and Convex (10.7778° to 0°).

3.5.8 Aspect

Aspect is an important topographic causative factor that manifest the orientation to slope instability happen. The aspect of a slope can be affected by microclimatic factors of the study area such as amount of the rainfall, direction of sun light, soil conditions, drying winds, and vegetation cover (*Hammad, 2020*). The area experienced of less vegetation cover, expose to sun light and higher amount of rainfall more subjective to landslides occurrence (*Basith, 2011a*). For the present study, the aspect factor was derived from SRTM DEM of a 30m resolution using spatial analyst tools of ArcGIS 10.4.1 software. The generated aspect map ranges from (-1°) to (360°) in degree. The aspect map of the study area was generated as Flat (-1°), North (0-22.5°), Northeast (22.5-67.5°), East (67.5-112.5°), Southeast (112.5-157.5°), South (157.5-202.5°), Southwest (202.5-247.5°), West (247.5-292.5°), Northwest (292.5-337.5°) and North (337.5-360°). Then, it was reclassified into five classes as (Flat, North–Northeast, Northeast–East–Southeast, Southeast–South–Southwest and Southwest–West Northwest). The values were given for each aspect class with respect to probability of a landslide occurrence depending on the expert experience and reviewed of different literatures.

3.6 Assigning Factor Weights

In this study, AHP method was used to assign relative importance value of each causative factor. The method provide percentage of influence based on expert judgment from Geological Institute of Ethiopia (Appendix 1). In addition to this, an interview was made with concerned stakeholders from road and logistics office, climate change and environmental protection office, disaster and risk management office, local community incorporated with review of different literatures to map landslide hazard zone. Thus, serves to calculate the factor weight. The GIS-based AHP method was applied to calculate weight for each factor using TerrSet Geospatial monitoring and modeling software. In this scenario, the weight of eight

causative factors were assigned using AHP model based on standard proposed by (Saaty, 1980) with respect to relative contributions to the landslide occurrence. The following causative factors were considered for this study are slope, lithology, drainage density, soil type, land use land cover, elevation, curvature and aspect. As developed by Saaty the rating scale can be ranges from 1 to 9, reciprocal numbers ranges start from 1/9, 1/7, 1/5 shows less importance and vice versa for more importance. Whereas 1 and 3 indicates equal and moderate importance respectively.

Table 4: The preference scale of rating influence of factors in AHP (Saaty, 1980)

Intensity of importance	Definitions
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance
2, 4, 6, 8	Intermediate values
Reciprocals	Value for inverse comparison

In order to fit the aimed objective, first the pair-wise comparisons of the relative importance of factors was prepared in matrix table. Then it was normalized with corresponds to each factor. Then after the weights of each factor was obtained. Further progress goes on like calculation of consistency index (CI), Principal Eigen vector (λ_{max}), Random Consistency Index (RI) and Consistency Ratio (CR). Calculation of CR is used to assure the reliability of judgment whether it's logical or not. For more than four factors CR must be less than 0.1. Unless reviewed. Consistency Index (CI) can be calculated as:

$$CI = \frac{\lambda_{max} - n}{n - 1} \dots \dots \dots \text{equation (5)}$$

Where, λ_{max} is principal or largest Eigen value and n is the number factor. Eight factors was considered for this study (n=8). The RI value is 1.41 for eight factors as proposed by (Saaty, 1980). $\lambda_{max} = 8.346$, n = 8

$$CI = \frac{(8.346-7)}{(8-1)} = \frac{(0.346)}{(7)} = \mathbf{0.049}$$

The CR can be calculated as below:

$$CR = CI/RI \dots \dots \dots \text{equation (6)}$$

$$CR = (0.049) / (1.41) = \mathbf{0.035}$$

The consistency ratio must be less than 0.1 for more than four factors, so the present study was assigned a reasonable weight for identified factors. Thus safely serve for delineation of a landslide hazard zones.

3.7 Weighted Linear Combination

One of special feature of GIS is to have tendency to combine spatial and non-spatial data of multi-attribute dataset. Weighted Linear Combination is well known method of MCDA which is compatible to use, flexible and repeatedly used to aggregate different digital layers in GIS environment (Malczewski, 2006). This study used GIS based MCDA method to integrate eight causative factors to produce a single landslide hazard zonation map by weighted linear combination. At the end, the Landslide Hazard Zone Index (LHZI) value for each factor pixel was calculated by summation of eight factors weight multiplied by class weight of each factor pixel as showed below:

$$LHZI = \sum_{i=1}^n (W_i R_j) \dots \dots \dots \text{equation (7)}$$

Where LHZI = Landslide Hazard Zone Index, n = number of factor (n=8), W_i = Weight of each factor and R_j = Rating value of each sub-class of particular factor. In this manner, the landslide hazard zone map of the study area was produced. The produced landslide hazard zonation map was classified into four hazard classes as low, moderate, high and very high

3.8 Validation of landslide hazard zone map

Different scholars proposed various method to assure the reliability of the produced landslide susceptibility, hazard and risk map (Wubalem, 2021). Basically there are two method used for validation of prepared map, namely field and model based validations. The present study was used the field based validation.

3.8.1 Landslide Inventory

Landslide inventory is a beginning for any landslide studies that helps to identify and map all landslide events happened in the past (Ermiyas, 2014). Preparation of landslide inventory provides a sign of slope instability. Because having information about past occurrence, spatial distribution, size and type of landslides will enable us to identify and known its occurrence

(Abay et al., 2019). In this concern, it gives basic clue to predict the future patterns of instability. Hence, landslides likely occur under similar geographical conditions with past. Landslide inventory can be prepared from field survey, aerial photography, satellite image, digital elevation model, community report and archive studies (Westen, 2008). For present study landslide inventory was prepared from digital elevation model and archive studies

3.8.2 Landslide Inventory Data

A landslide hazard analysis result is validated using known landslide locations (Woldearegay, 2005). In the present case, the past record of known landslide location with spring water point was used for this study to validate the produced the landslide hazard zone map. Accordingly, 45 existing inventory data of known landslide location with 4 landslide of spring water was used in this study to assure the reliability of a produced landslide hazard zone map. Total 49 point location of inventory data was obtained through handheld GPS survey of past landslide occurrence incorporated with Google earth image and review of previous studies (Ali, 2021). Then, verification of the result was conducted through cross-checking a landslide inventory data with landslide hazard zone map. Finally, an inventory data was overlaid with prepared landslide hazard zone map. The general methodological workflow employed in the current study was presented (Figure 13).

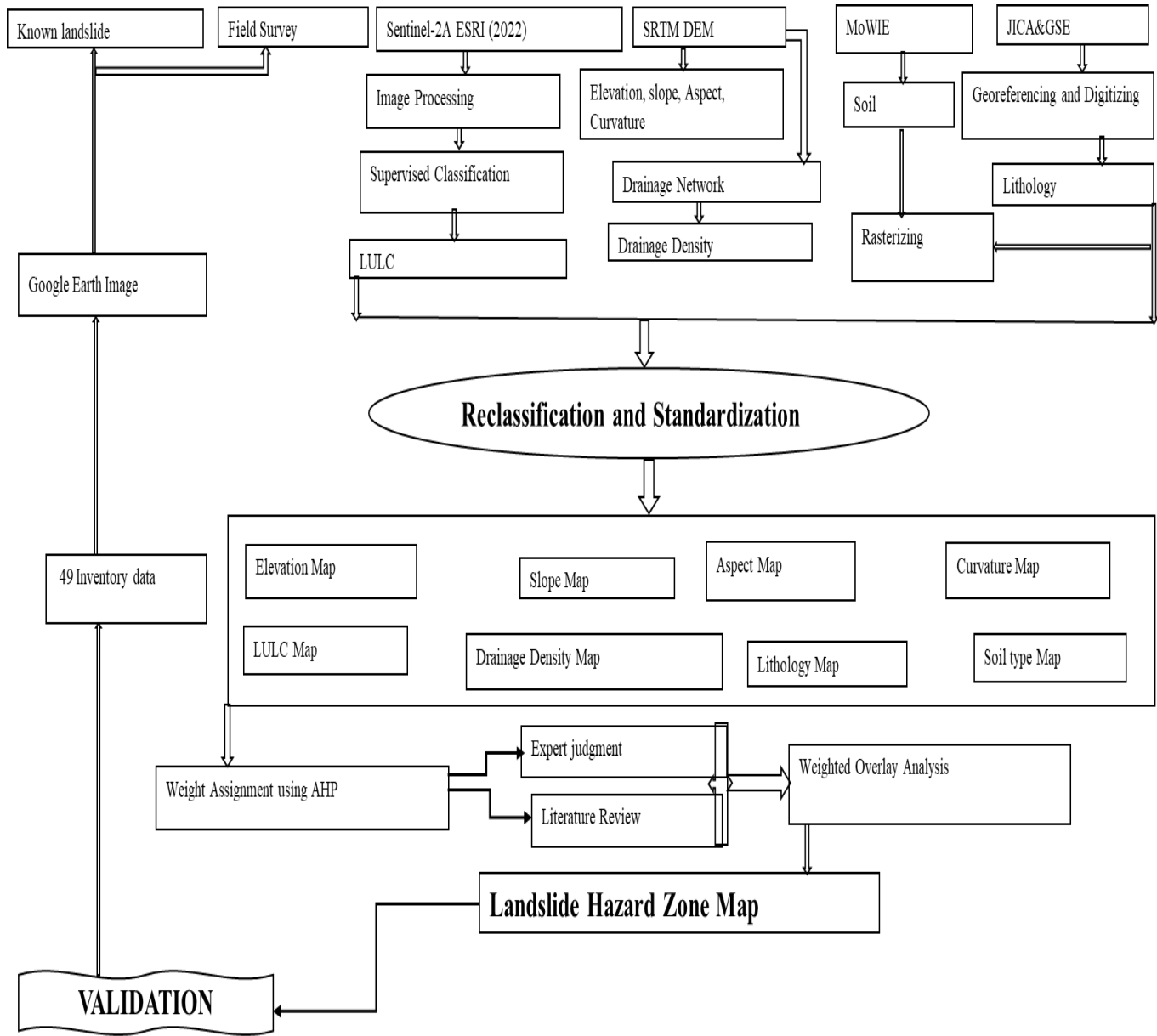


Figure 13: General Methodological workflow of the study

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1 Landslide Hazard Zonation

Landslide hazard zonation is the process of classifying landslide surface into the different degree of hazard level based on an actual or potential loss with time interval (Westen & Asch, 2014). It has a significant progress in landslide hazard mapping. Hence the hazard mapping is serves for identifying and predicting landslide prone areas. In the present study eight landside causative factors were identified are slope, lithology, drainage density, soil type, LULC, elevation, curvature and aspect. The values were assigned to each sub-class based on national and international literature standards incorporated with nature of the study area (Table 3).

4.1.1 Slope

In the present study the slope map was classified into five classes and their areal coverage was calculated (Table 5). In addition, the value was assigned to each slope class based on the relative contribution to the landslide occurrence. The area characterized by small slope angle has less impact on landslide occurrence as it is made up from consolidated materials (Dawit, 2016). Accordingly, the relative contribution of each slope class are given as 1, 2, 3, 4 and 5 with corresponds to 0-5⁰, 5-12⁰, 12-30⁰, 30-45⁰ and 45-63⁰ slope angle respectively. The area found in slope class greater than 30⁰-45⁰ and 45⁰-63⁰ shows high and very high susceptibility to landslide respectively. Due to this classes are mainly covered by limestone, highly weathered basalt and colluvial deposit. While the slope class lies in ranges of 0⁰-5⁰ is very low susceptible to landslide as it composed from consolidated materials. Thus, the result manifests an agreement with(Woldegiorgis et al., 2014).

Table 5: Slope Class and Area Coverage

S.No	Slope Class(degree)	Value	Susceptibility	Area (km ²)	Area (%)
1	0-5	1	Very low	377.89	31.53
2	5-12	2	Low	361.90	30.20
3	12-30	3	Moderate	391.06	32.63
4	30-45	4	High	63.62	5.31
5	45-63	5	Very high	3.88	0.32
Total				1198.34	100.0

As showed in the table above, the moderate steep slope was the dominant class of slope ranges from 12° - 30° covering of 32.63% of the total area. The spatial distribution of this slope class almost cover the whole part of the study except the southern side of Kuyu District along main road. A very gentle slope was the second dominant class of slope ranges from 0° - 5° with areal coverage of 31.53% from total area. Similar with moderate steep slope class, it is distribution was densely found in almost all direction of the study area towards the water flow except to the area of Gohatsion town. The third dominant class was manifested by gentle slope of ranges from 5° - 12° with areal coverage of 30.20% from total area. From spatial distribution aspect, it was similar with two of above mentioned. The fourth class was lies in steep slope of ranges from 30° - 45° covering of 5.31% of the study area. It is sparsely distributed in the study area mainly around entry of cliff and water flow. The left class was rarely present in the study area with areal coverage of 0.32% which settle in very steep slope of ranges from 45° - 63° .

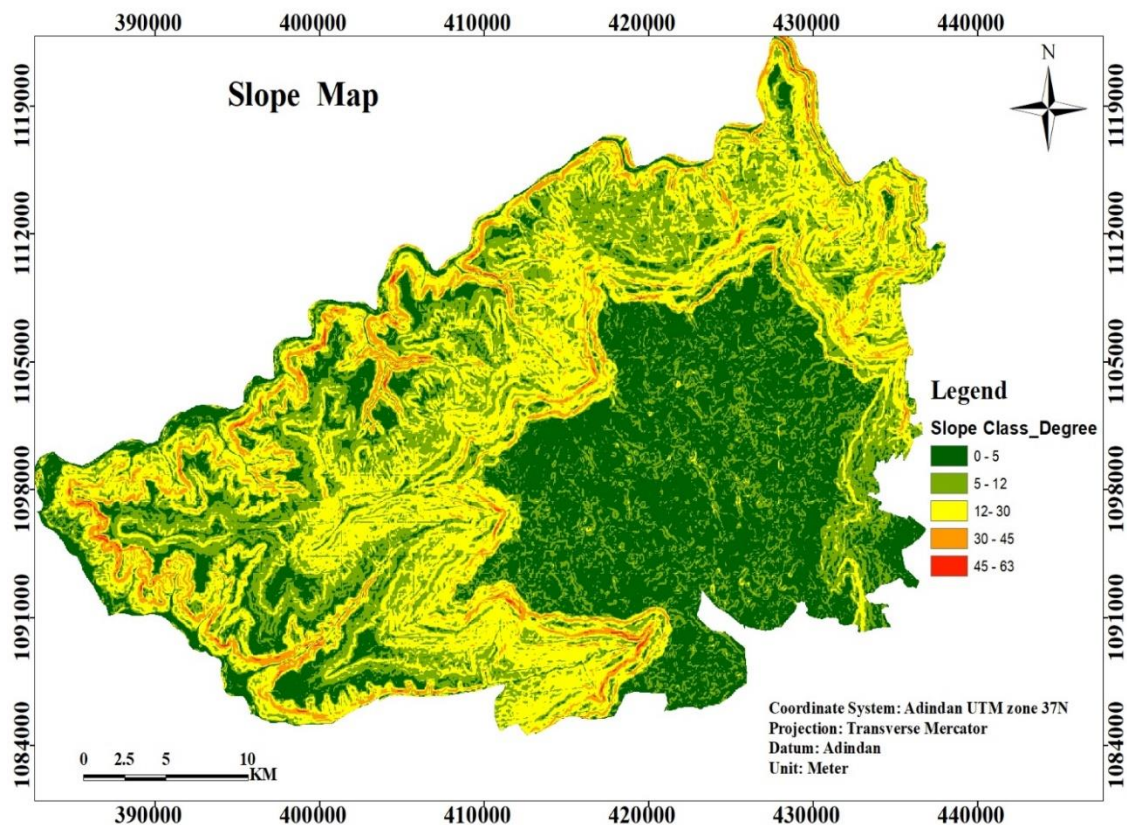


Figure 14: Slope map of the study area

4.1.2 Lithology

In the present study area four geological formations was observed and their areal coverage was calculated (Table 6). As well, the value was assigned to each formation based on the relative contribution to the landslide occurrence. The area characterized with the distribution of Gypsum, Limestone, Siltstone and Shale in the Abay formation, followed by the area with the distribution of Sandstone, Siltstone and Shale in the Adigrat formation were assigned 2 (low) and 3 values (moderate) respectively. Since they are situated at low elevations of Abay Gorge. The area with the distribution of Basalt and Pyroclastic rock in the Ashangi formation, followed by the area with the distribution of Limestone, Siltstone and Shale in the Antalo formation were assigned 4 (high) and 5 (very high) values respectively. Because, the presence of basalt load exerted on limestone interbedded with weak materials like marl and shale makes Antalo formation to be very high susceptible to landslide. On the other hand, Ashangi formation is high susceptibility to landslide due to the nature of basalt unit is deeply weathered and easily affected by various geological structures, which make it vulnerable to slope instability through reducing the shear strength of slope materials. The result indicates a good agreement with previous study by (Getachew & Meten, 2021).

Table 6: Lithological Unit and Area Coverage

S.No	Formation	Lithological unit	Value	Susceptibility	Area (km ²)	Area (%)
1	Abay	Gypsum, Limestone, Siltstone and Shale	2	Low	258.60	21.58
2	Adigrat	Sandstone, Siltstone and Shale	3	Moderate	351.17	29.30
3	Ashangi	Basalt and Pyroclastic Rock	4	High	340.00	28.38
4	Antalo	Limestone, Siltstone and Shale	5	Very High	248.58	20.74
Total					1198.34	100.00

As indicated in the table the Adigrat formation is the most dominant which covers about 351.17 km² (29.30%) of the total area. The second dominant is Ashangi formation with total

area of 340 km² (28.38%). Third dominant formation is Abay that covers 258.60km²(21.58%) of the total area. And the last dominant formation is Antalo which covers 248.58km²(20.74%). All formations are evenly distributed in the study area, therefore all lithological units found in this formations have own contribution on occurrence of landslide. On the contrary, the different rock type have different physio-chemical and engineering properties in terms of its lithological units. Thus leads to a difference in the strength and permeability of rocks and soils. So, a result come up with a good as pointed in (Abay et al., 2012). The subjectivity of each rock type to be erodible depends on degree of weathering and its strength.

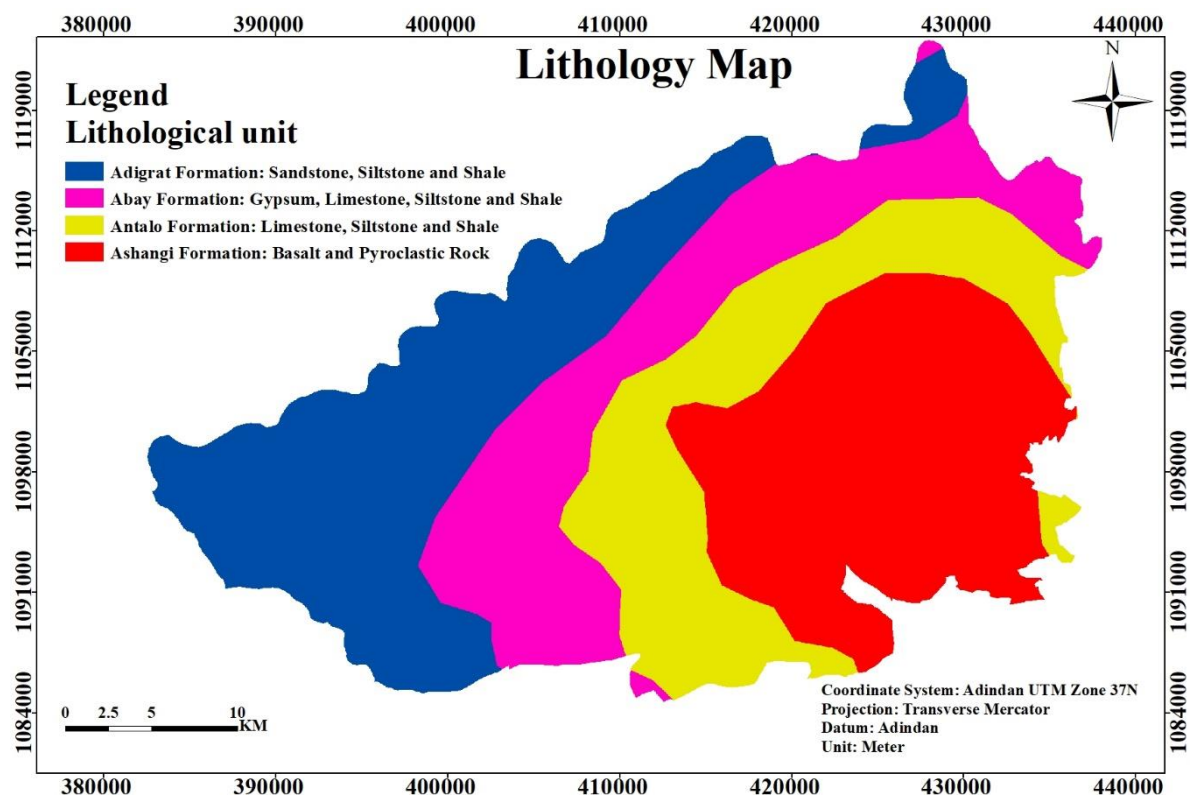


Figure 15: Lithology map of the study area

4.1.3 Drainage Density

For this study, the drainage density was categorized into five classes and their areal coverage was calculated (Table 7). Moreover, the values were assigned based on the relative contribution to landslide occurrence. The area experienced with a low drainage density is less susceptibility to landslide. Whereas the area experienced with a high drainage density is more susceptibility to landslide. As landslide and drainage density have a direct relationship. In this

regard, the following values were assigned for drainage density as; (1) very low, (2) low, (3) moderate, (4) high and (5) very high. The very low and low value were assigned to drainage class situated at the lower elevations. As the area receive small amount of rainfall compared to higher elevations. The moderate value was assigned to drainage rested on moderate elevations area. High and very High values were assigned to drainage located at the higher elevations. As far as amount of rainfall is concerned. The study shows a conformity with previous study by (Busha, 2019).

Table 7: Drainage Density Class and Area Coverage

S.No	Drainage Density Class (m/m ²)	Value	Susceptibility	Area(km ²)	Area (%)
1	0-0.13	1	Very Low	837.00	69.85
2	0.14-0.27	2	Low	251.07	20.95
3	0.28-0.4	3	Moderate	95.94	8.00
4	0.41-0.53	4	High	12.23	1.02
5	0.54-0.66	5	Very High	2.10	0.18
Total				1198.34	100.00

As manifested in the above table, the most of the study area was characterized by very low drainage density with covering 69.85% of the total area. The area was situated around the north of Gohatsion town in the Abay gorge at low elevations. It is unevenly distributed in the study area. The second dominant class is low drainage density which cover 20.95% of the total area. This class was scattered in all directions and located at different elevation levels throughout the study area. While, moderate, high and very high drainage density accounts 8%, 1.02% and 0.18% respectively. The moderate drainage density is located at the South East of the study area. High and very high drainage density are found in the South, West, South West and North West of the study area.

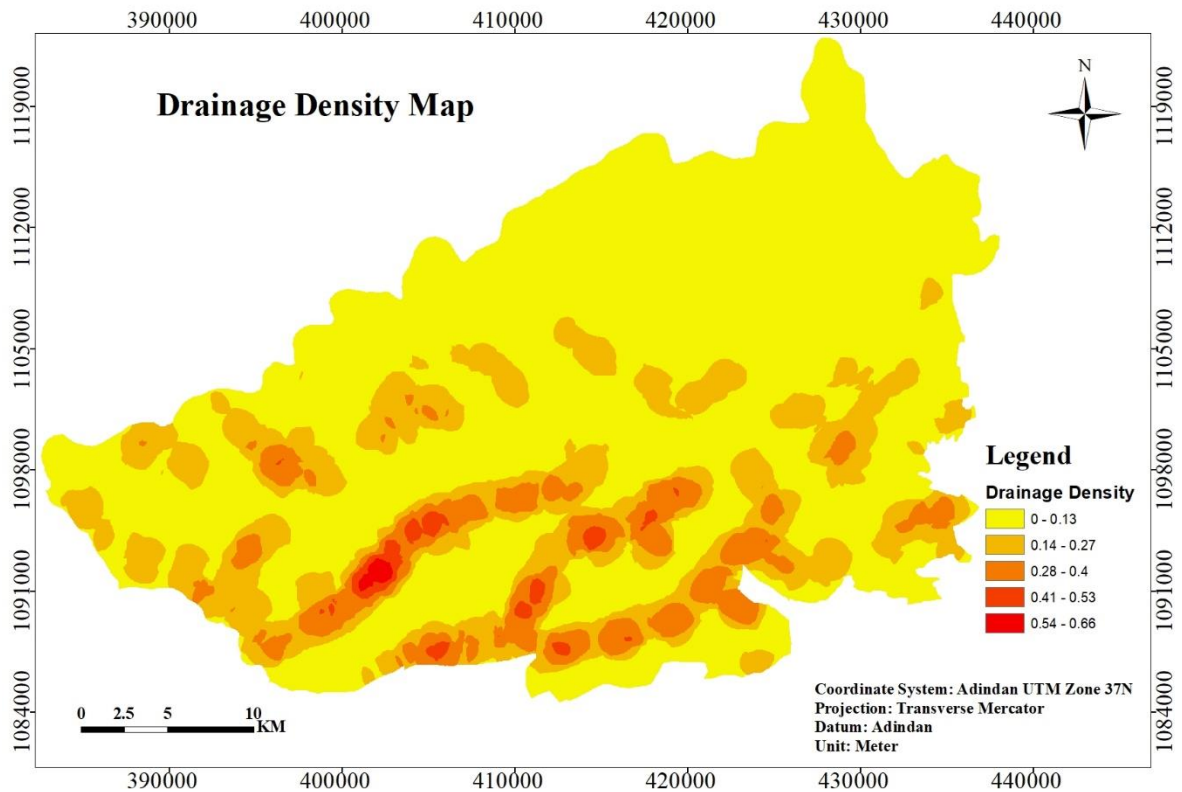


Figure 16: Drainage Density map of the study area

4.1.4 Soil Type

In the present study area five type of soils were identified and their areal coverage was calculated. In addition, the relative contribution values were given to each type of soil with corresponds to landslide occurrence. As different types of soil have different degree of strength and permeability (Melkamu, 2019). In spite of this, soil type presented in this area was reclassified into three classes based on degree of susceptibility to landslide occurrence. These classes are Eutric Regosols, Eutric Cambisols/Pellic Vertisols/Eutric Nitosols and Leptosols. The area with the distribution of Regosols did not show the previous landslide, in this sense the low value (2) was assigned to this type of soil. The area characterized by Eutric Cambisols/Pellic Vertisols/Eutric Nitosols were assigned moderate value (3) due to clay rich nature and strong structures, which make them relative stables and moderate susceptible to landslides. Leptosol was assigned a high value (4). Because of shallowness, low permeability and weak structure. These properties of leptosol make more prone to saturation and

instability. Especially, during heavy rainfall events. The result revealed a good resemblance with (Adugna, 2020).

Table 8: Soil Type and Area Coverage

S.No	Soil Type	Value	Susceptibility	Area(km ²)	Area (%)
1	Eutric Regosols	2	Low	5.68	0.47
2	Eutric Cambisols/Pellic Vertisols/Eutric Nitosols	3	Moderate	1130.09	94.30
3	Leptosols	4	High	62.60	5.22
Total				1198.34	100.00

As observed from above table, the most of study area are characterized by Eutric Cambisols/Pellic Vertisols/Eutric Nitosols with 94.30% of the total area. These types of soil are evenly distributed in whole study area almost with massive coverage except on the higher elevations situated at Gohatsion town and surround main road towards south. While only 0.47% and 5.22% of total area was covered by Eutric Regosols and Leptosols respectively.

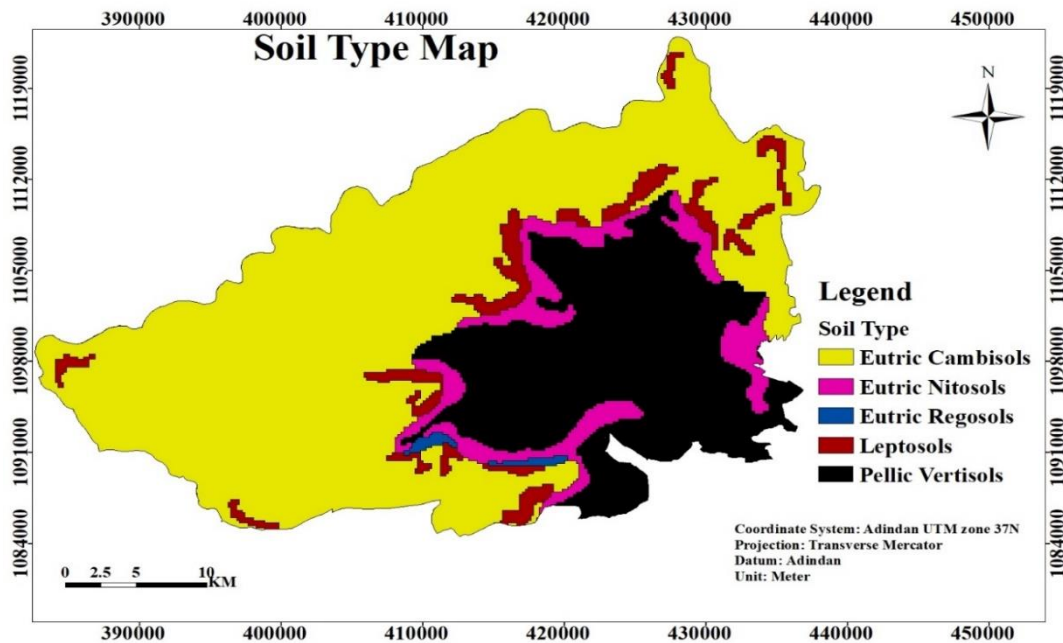


Figure 17: Soil Type map of the study area

4.1.5 Land use/Land cover

For this study, the land use land cover types was categorized into five classes and their areal coverage was calculated (Table 9). Namely as forest, rangeland, built-up area, agricultural land, water body and bare land. As well, the value was assigned to the each type based on the relative contribution to the landslide occurrence. The very low value (1) was assigned to forest, hence the existence of forest coverage decrease denudation process and surface run off (Busha, 2019). Low, moderate and high values were assigned to rangeland, built-up and water body/bare land respectively. Rangeland was assigned low value (2) due to the trees shaded the ground to the some extent, which decrease the degree of degradation. For built-up area the moderate value (3) was given due to the absence of massive construction of infrastructures that facilitate the ground deformation. For water body and bare land high value were assigned. Particularly for the water body; the existence of Abay River and its tributaries initiate the landslide occurrence or recurrence. Since the variability of rainfall condition has own impact upon both groundwater and surface water. The high value was assigned to bare land due to the predominant existence of bare land along main road and surrounding in the Abay gorge, as the gorge characterized by hills, cliff and rugged topography. While the very high value was assigned to agricultural land as it is easily eroded by flood, and different physical and chemical weathering. Hence the intensive farming activity is practiced by many people that settled at higher elevation capped by plains. As a result, 621 hectares of agricultural land was out of service due to landslide. Around 210 family were displaced from their home based on information collected during field work. The result of this study made a satisfactory agreement with (Mengistu et al., 2019b).

Table 9: LULC class and Area Coverage

S.No	LULC Class	Value	Susceptibility	Area(km ²)	Area (%)
1	Forest	1	Very Low	38.44	3.22
2	Rangeland	2	Low	587.90	49.04
3	Built-up Area	3	Moderate	40.40	3.38
4	Water Body/Bare Land	4	High	17.00	1.45
5	Agricultural Land	5	Very High	514.60	42.92
Total				1198.34	100.00

As presented in the above, the first dominant class of LULC was rangeland, which covers the 578.90km² (49.04%) of the total area. The second dominant class of LULC was agricultural land that covers the 514.60 km² (42.92%) of the total area. The area is located on the higher elevations having plains surface at the top. Whereas the remaining class represents 3.22%, 3.38% and 1.45% of forest, built-up area and water body/bare land respectively.

The accuracy assessment of the classification was calculated based of field data and Google earth image. The overall accuracy of the prepared LU/LC classification is 95% with a kappa coefficient of 0.932(Appendix 4).

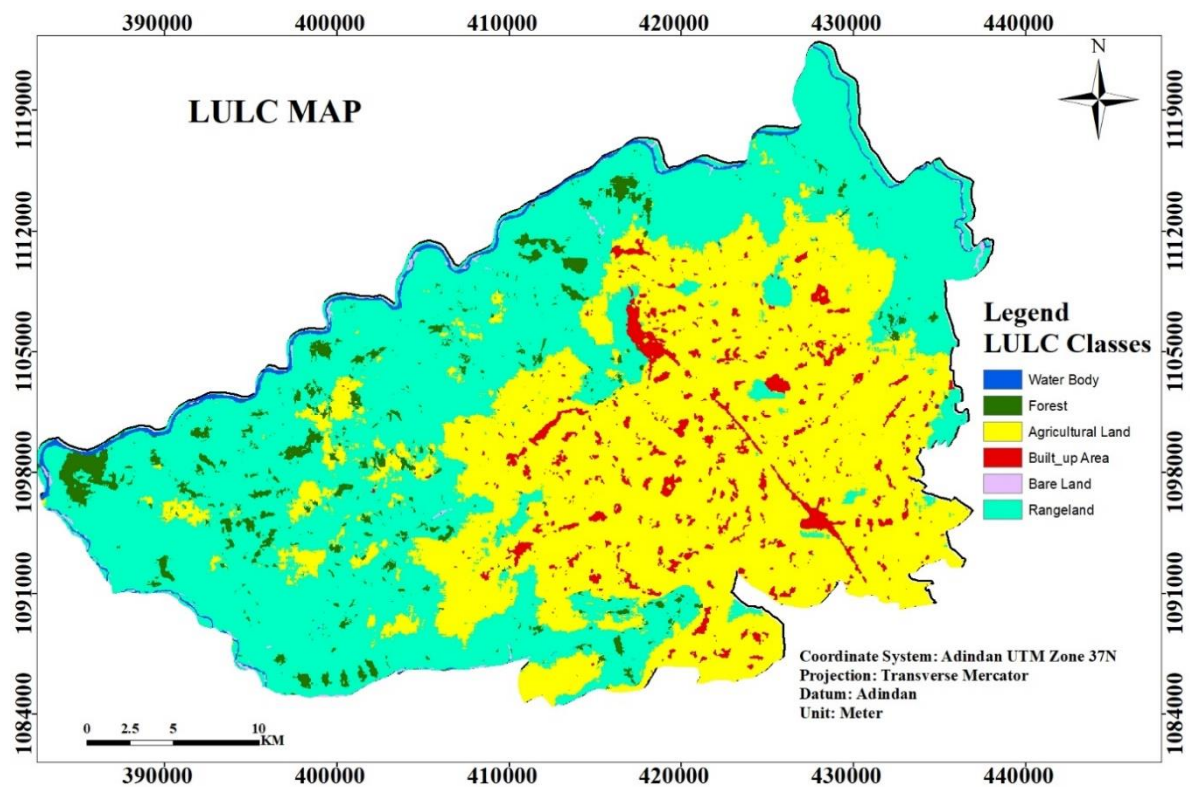


Figure 18: LULC map of the study area

4.1.6 Elevation

The elevation class of this study was classified into five classes and their areal coverage was calculated. The elevation of this study ranges from 926m to 2602m above mean sea level. Moreover, the value was assigned to each class based on the relative contribution to the landslide occurrence. The higher elevation is more susceptible to landslide with compared to lower elevation area. Accordingly; the very low value (1) was assigned to elevations ranges

from 926m-1430m. As lithological units found in this classes are highly consolidated. Low value (2) was assigned to elevations ranges from 2480-2602m due to the existence of residual soil and more clay that rested on flat area of Gohatsion town. The moderate value (3) was assigned to elevations ranges from 1430m-1575m. This class moderately affect the landslide since it built-up from soft and weathered materials. The high value (4) was assigned to elevations ranges from 2100m-2480m. Hence this class is intercalated with highly disintegrated basalts and pyroclastic materials. As well as the existence of colluvium deposit in this range with intensive farming activity are practiced in this class. The very high value (5) was given to elevations ranges from 1575m-2100m, due to the presence of dominant limestone unit of Antalo formation found in this class. As it intercalated with unconsolidated materials like marl and shale. since the many landslides were occurred in this class as justified in (Chimidi et al., 2017). Therefore, the result of this study shares the common characteristics with study conducted near to the basin in other area.

Table 10: Elevation Class and Area Coverage

S.No	Elevation Class(m)	Value	Susceptibility	Area(km ²)	Area (%)
1	926-1430	1	Very Low	283.06	23.62
2	1430-1575	3	Moderate	173.23	14.46
3	1575-2100	5	Very High	268.81	22.43
4	2100-2480	4	High	145.21	12.12
5	2480-2602	2	Low	328.04	27.37
Total				1198.34	100.00

As indicated in the above table, the most dominant elevation class was located in ranges of 2480m-2602m with 328.04km²(27.37%) of the total area. This class range was unevenly distributed in the area. The second dominant class is situated in ranges of 926m-1430m with 283.06 km² (23.62%) of the total area. The class found in this range was surrounded by water course. Sandstone, lower mudstone and gypsum are existed in this class. Due to the existence of lower elevation near to the Abay and other bounded rivers. The third dominant class is lies

in elevation ranges from 1575m-2100m with 268.81km²(22.43%) of the total area. The area was found in moderately steep slopes. Whereas; the elevation ranges from 1430m-1575m and 2100m-2480m were covered the total study area with 14.46% and 12.12% respectively.

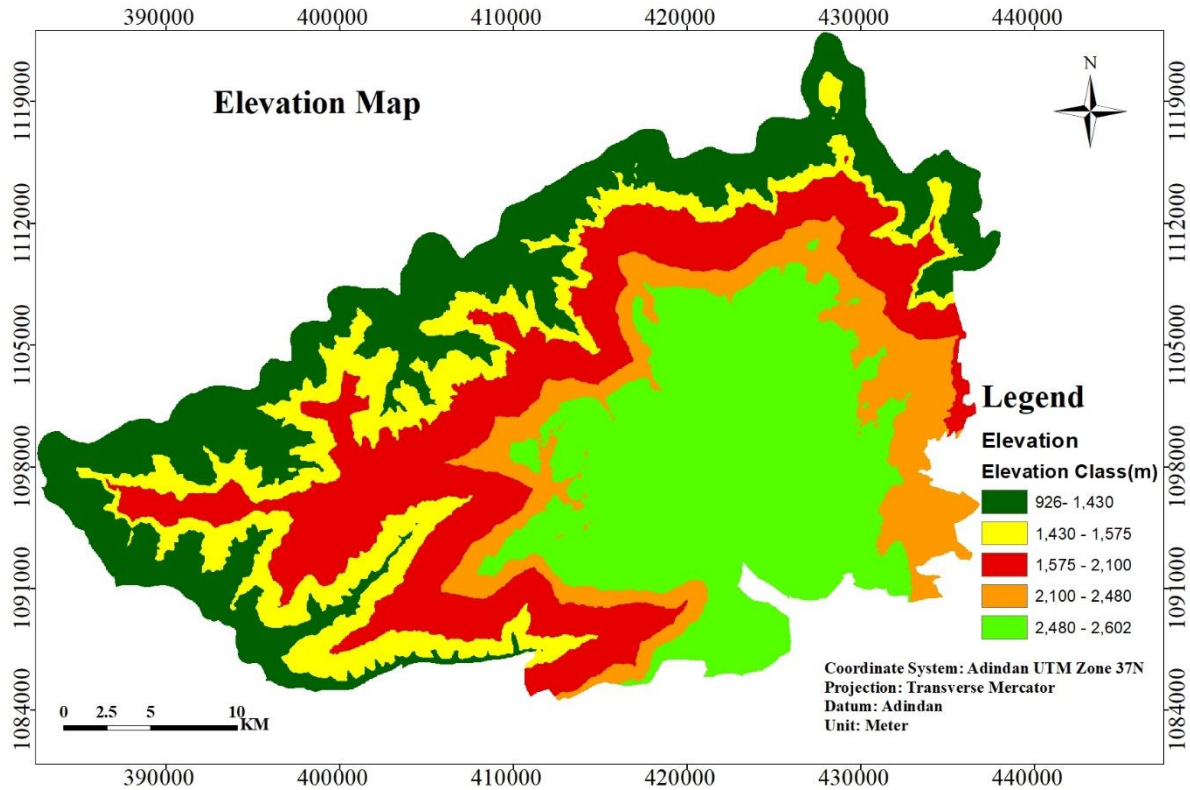


Figure 19: Elevation map of the study area

4.1.7 Curvature

The curvature class of the study area was classified into three classes and their areal coverage was calculated. The curvature classes are Concave (0° to -10°), Flat (0°) and Convex (10.7778° to 0°). Besides, the values were assigned to each class based on the relative contribution to landslide occurrence. The probability of landslide occurrence increases with an increasing negative and positive values of curvature (Gizawu, 2020). In this regard, the low value (2) was assigned to flat area. As it rested on low elevations. The high and very high values were given to convex and concave curvature class. As far as curvature class is concerned. So, the result of this study fitted with previous in the area (Meten et al., 2015).

Table 11: Curvature Class and Area Coverage

S.No	Curvature	Value	Susceptibility	Area(km ²)	Area (%)
1	Flat	2	Low	699.72840	58.391250
2	Convex	4	High	498.6153	41.608674
3	Concave	5	Very High	0.0009	0.000075
Total				1198.34	100.00

As shown in the above table, the most dominant curvature class was flat, which covers 699.72km²(58.39%) of the total area. The second dominant class was convex curvature with 498.61km²(41.60%) of the total area. While concave curvature class was rarely presented in the study area. Hence it covers the area with insignificant value as 0.000075% of the total area.

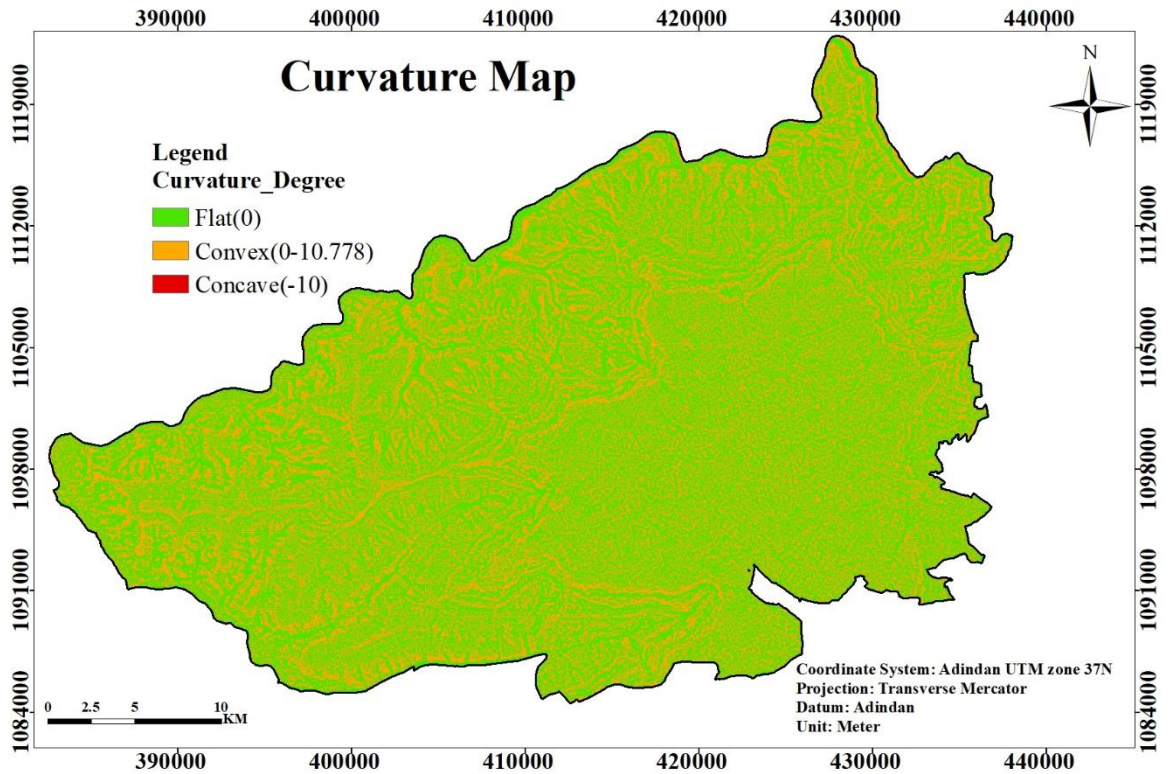


Figure 20: Curvature map of the study area

4.1.8 Aspect

The aspect class of this study was categorized into five classes based on common degree of susceptibility as flat, north-northeast, east-southeast, south-southwest and west-northwest. The values were assigned to each class depending on the probability of landslide occurrence. The slope direction has a significant effect on exposure to sunlight, wind and wave action (Meten et al., 2015). As well, the climate conditions has indirect impact towards occurrence of landslide. Accordingly, the very low and low values were given to flat and northeast aspect class. Whereas moderate, high and very high values were assigned to southeast, southwest and northwest respectively. Due to the distribution of maximum drainage density were manifested in this class. The result indicates satisfactory consensus with (Adugna, 2020).

Table 12: Aspect Class and Area Coverage

S.No	Aspect Class(degree)	Value	Susceptibility	Area(km ²)	Area (%)
1	Flat	1	Very Low	242.19	20.21
2	North-Northeast	2	Low	195.08	16.28
3	East-Southeast	3	Moderate	221.50	18.48
4	South-Southwest	4	High	216.93	18.10
5	West-Northwest	5	Very High	322.64	26.92
Total				1198.34	100.00

As analyzed from the above table, among the aspect class West-Northwest is the most dominant that covers 322.64km² with 26.92% of the total area. Flat was the second dominant aspect class, which covers 242.19km² with 20.21% of the total area. Whereas; 18.48%, 18.10% and 16.28% of the total area was covered by East-Southeast, South-Southwest and North-Northeast respectively. These classes were spatial distributed along moderate, high and very drainage density. Even if the extent of susceptibility is not the same. The result is in agree with study conducted by(Chimidi et al., 2017).

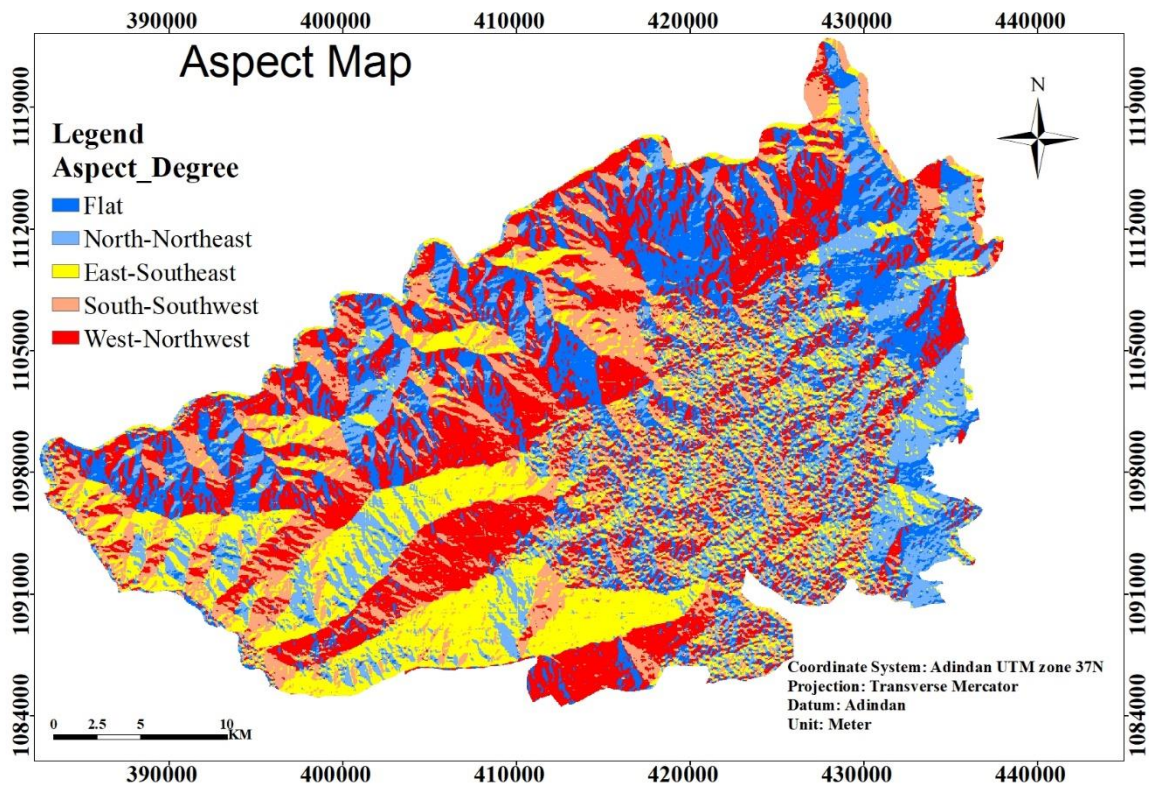


Figure 21: Aspect map of the study area

4.2 Assigning Factor Weights

After preparing the landslide susceptibility map of each factor based on the rate assigned that considered a common national and international standards (Table 3). Then, the weight of each factor was assigned in TerrSet Geospatial monitoring and modeling software using AHP method of a series pairwise comparison matrix table. At this stage, the influence of each factor to the each other was analyzed simultaneously with respect to landslide occurrence. The Saaty (1980) measurement scale was used, which ranges from 1 to 9 and 1/9 to 1 for more and less influencing respectively. The highest weight was assigned for more influencing factors. While the low weight was assigned for less influencing factors. The weight derived using AHP method has subjectivity nature. Hence the assigned values are used as input dataset for multi-criteria evaluation using weighted linear combination in GIS environment. Thus a produced landslide hazard zonation map could not be reasonable applied for safe disaster risk management. In order to reduce the subjectivity nature of AHP weight derivation. The

consistency ratio can be computed. If the value of consistency ratio is greater than 0.1, the assigned relative importance value of chosen factors is not consistent.

Table 13: Analytical Hierarchy Process Weight Assignment

Factors	SL	LG	DD	ST	LULC	EV	CV	AS	Weights	Weights (%)
SL	1	2	2	4	6	6	7	7	0.31	31
LG	1/2	1	3	4	4	4	6	6	0.25	25
DD	1/2	1/3	1	3	3	4	5	5	0.17	17
ST	1/4	1/4	1/3	1	2	2	3	3	0.09	9
LULC	1/6	1/4	1/3	1/2	1	2	3	3	0.07	7
EV	1/6	1/4	1/4	1/2	1/2	1	2	2	0.05	5
CV	1/7	1/6	1/5	1/3	1/3	1/2	1	1	0.03	3
AS	1/7	1/6	1/5	1/3	1/3	1/2	1	1	0.03	3
Total										100

(Where; SL = Slope, LG = Lithology, DD = Drainage Density, ST = Soil Type, LULC = Land use Land cover, EV = Elevation, CV = Curvature, AS = Aspect).

The **consistency ratio** (CR) for present this study is **0.035**, therefore an appropriate weight was assigned for each factor. **CR = 0.035**

The computed weight shows the relative contribution of identified factors in landslide hazard zonation. The most influencing factors are slope (31%), lithology (25%) and drainage density (17%), whereas the less influencing factors are elevation, curvature and aspect. Nevertheless, they have own contributions on landslide occurrence.

4.3 Weighted Linear Combination Using Weight Overlay Analysis

After all weights were assigned using AHP method of a series pairwise comparisons. Then, weighted linear combination method was used in GIS weighted overlay analysis environment to combine all susceptible maps of identified factors. Thus, helps to produce the landslide hazard zonation map. Finally, the weights of the identified factors were combined using weighted linear combination to produce the single landslide hazard zone index (LHZI), which classified into different degrees of potential hazard (Rahaman et al., 2014).

4.4 Landslide Hazard Zone Map

The Landslide Hazard Zone Map of the study area was prepared by using Analytic Hierarchy Process and Weighted Linear Combination in GIS weighted overlay analysis environment. The prepared landslide hazard zone was classified into four classes based on the class of weighted overlay analysis obtained from the computation. These are low, moderate, high and very high hazard level. The area coverage of a produced landslide hazard zone was calculated. Accordingly, low hazard 0.001% (0.014km²), moderate hazard 46.66% (555.25km²), and high hazard 50.02% (595.13km²) and very high hazard 3.32% (39.48km²) of the total study area. The result of the study revealed that the spatial distributions of landslide hazard are dominantly distributed in the moderate and high hazard zones of the study area. Despite the very high landslide susceptibility areas were mostly inhabited towards the central part of the study area. Moreover, the low hazard zone was insignificant presented in the study area. Due to the different factors have varied degree of influence.

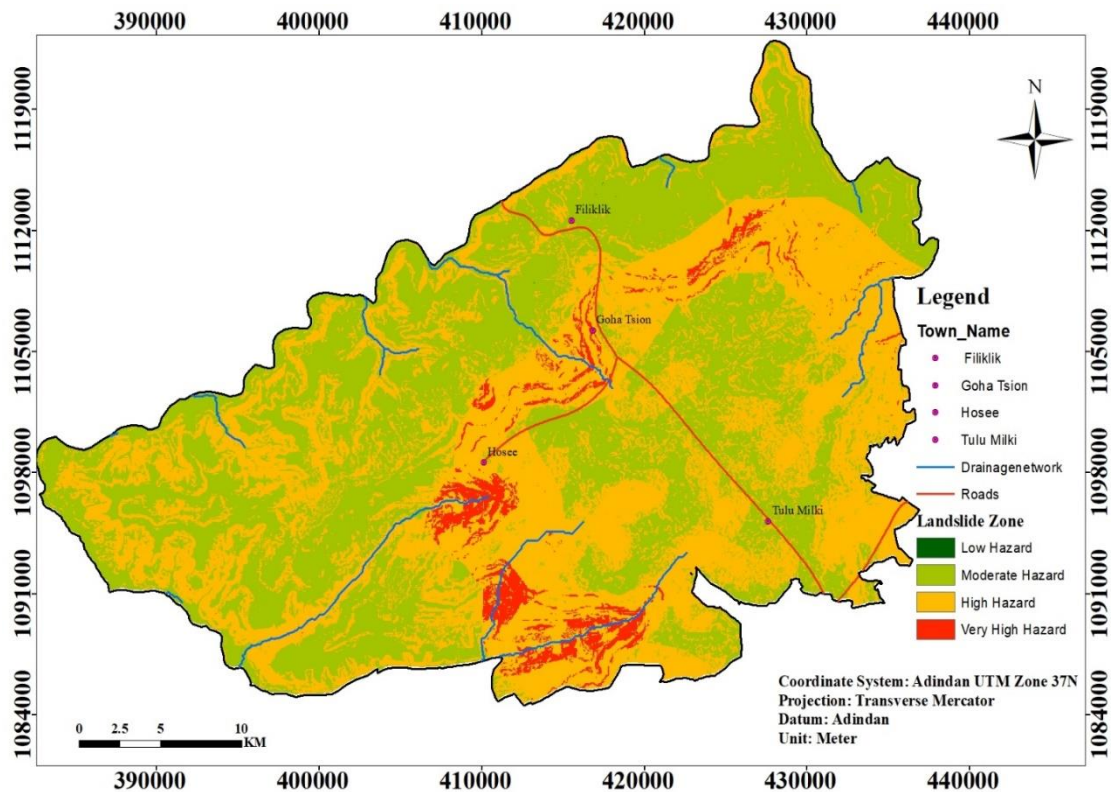


Figure 22: Landslide Hazard Zone map of the study area

Table 14: Landslide Hazard Zone and Area Coverage

S.No	Landslide Hazard Zone	Area(km ²)	Area (%)
1	Low	0.014	0.001
2	Moderate	555.25	46.66
3	High	595.13	50.02
4	Very High	39.48	3.32
Total		1189.87	100.00

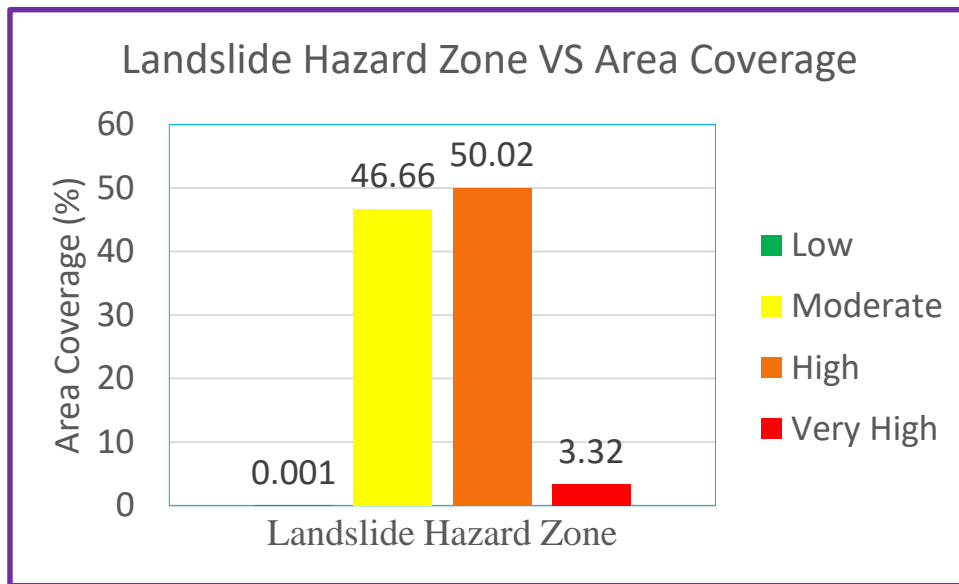


Figure 23: Landslide Hazard Zone with Areal Coverage

4.5 Validation of Landslide Hazard Zone Map

4.5.1 Landslide Inventory Map

Landslide inventory is a beginning for any landslide studies that helps to identify and map all landslide events happened in the past (Ermiyas, 2014). For this study a landslide inventory map was prepared from digital elevation model and review of previous study by (Ali, 2021). Different types of landslide occurred in the past was identified from historical record and supported by field visit. These are; debris, rock fall, topple, complex, rotational and translational. These slope instabilities were related to geological, topographical, hydrological

and anthropogenic factors. Consequently, they can often suit the prediction of particular location and the nature of future instability. A total 49 landslides was observed and out these 7 are debris, 4 are rock fall, 2 are topple, 23 are translational, 8 are rotational and 1 is complex. However, the types of 4 landslide induced due to the spring water was not clearly identified. Accordingly, translational is the most dominant type of landslide in the present area as identified by(Ali, 2021). Moreover, different villages of Worra Jarso district were identified based on susceptibility to landslide. Among those, frequently affected villages were Kola Jemo Gedera, Lencho Borsu, Kola Borsu and Gohatsion 02. Kola Jemo Gedera is the most dominant village that extremely affected by landslide as verified from previous study (Appendix2a&2b).

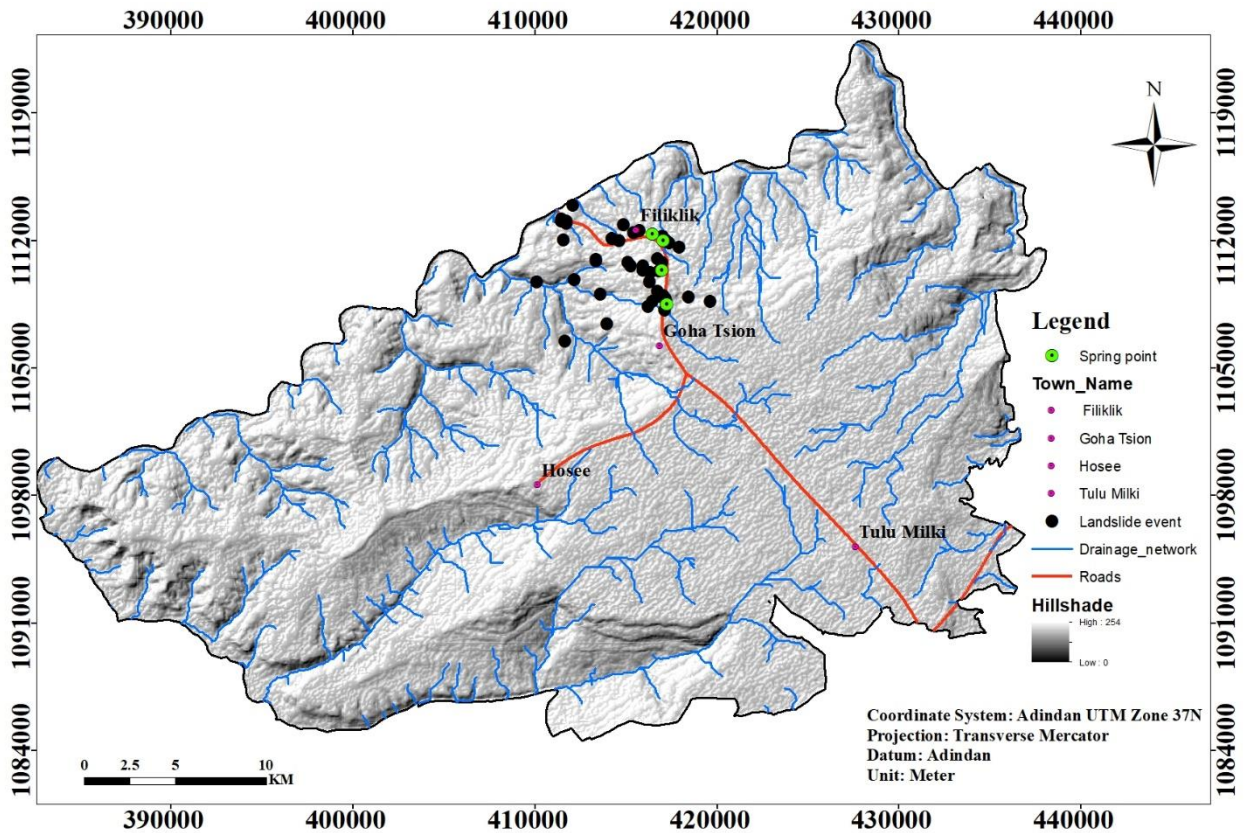


Figure 24: Landslide Inventory Map of the study area

4.5.2 Landslide Inventory Data

A landslide hazard analysis result is validated using known landslide locations (Woldearegay, 2005). In the present study about 49 point location data that manifesting the known landslide were collected (Appendix2a&2b). Specifically, 45 landslide inventory with 4 landslide of spring water was used for verification of landslide hazard zone map. Totally 49 inventory data was acquired through field survey, Google earth image and review of previous study conducted by (Ali, 2021). In order to validate the prepared landslide hazard zone map during the present study overlay analysis was made with the past landslide inventory data. The overlay analysis clearly revealed that out of 49 past landslides inventory data 11(22.44%) fall in very high hazard zone, 31 (63.26%) fall in high hazard zone, and only 7(14.3%) fall in moderate hazard zone whereas in low hazard zone no past landslide was observed. This reveals that 85.7% of the known landslide events were fall in high hazard and very high hazard zone (figure 25). Therefore, the most relevant factors were identified and the appropriate weights were assigned to map landslide susceptibility. As Geospatial based MCDA method shows satisfactory agreement with the prepared landslide hazard zone map. Further, the produced landslide hazard zone map provides fundamental information for hazard assessment, land-use planning, and infrastructure development and landslide disaster mitigation strategy.

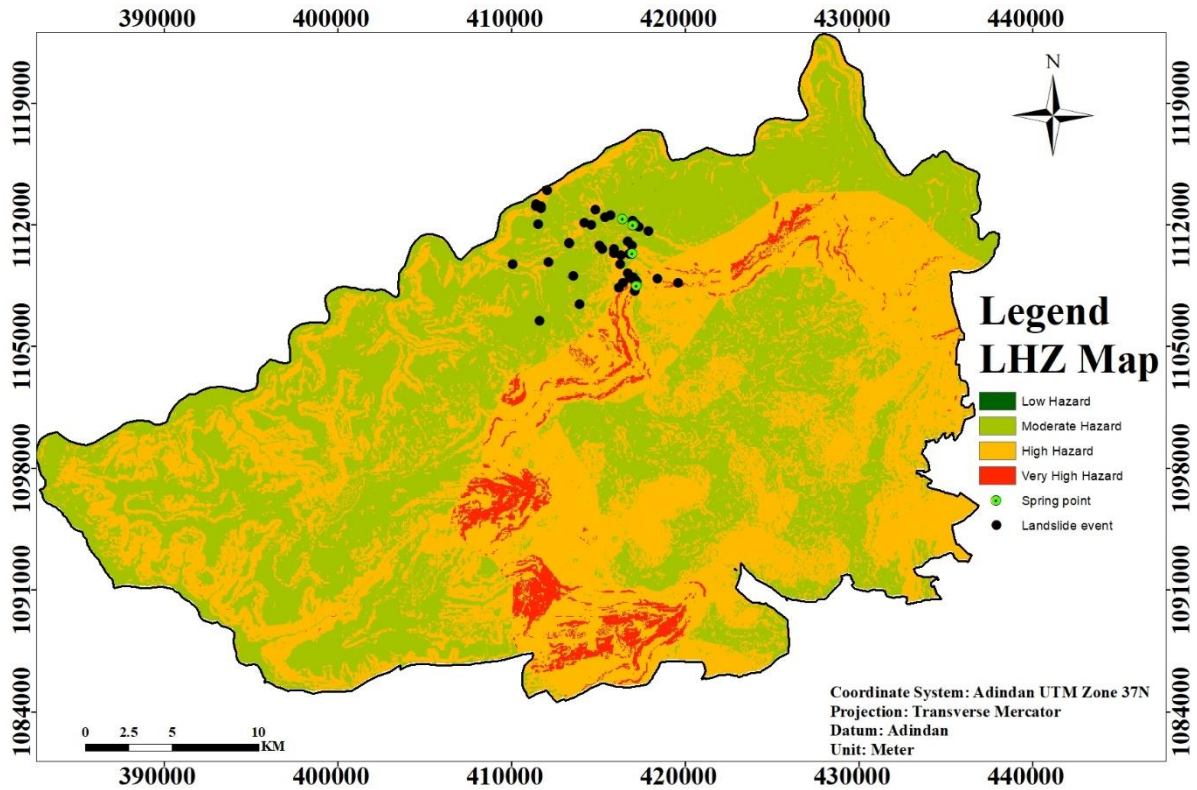


Figure 25: Landslide Inventory Data overlaid with Landslide Hazard Zone map for validation

4.6 Discussion

Landslide is a serious geo-hazard that pose a major threat to loss of life and property, damage to natural resources such as land, vegetation, soil and hamper infrastructure projects like roads, bridges and communication lines (Mengistu et al., 2019; Gemechis Chimindi et al., 2017; Tilahun and Raghuvanshi, 2017; Raghuvanshi et al., 2015). The same is true for present study as it located at the rift margin part of the Ethiopia. In landslide hazard mapping, identification of the most relevant factors that influencing landslide is very important, which significantly influence the results of models used. In this study, eight major landslide factors were identified based on expert opinion, nature of the study area and review of different literatures. Primarily analysis of landslide studies mostly goes with past landslide occurrence factors, which is the same true for quantitative techniques and analyze the probability of appearing again in the area(Shano et al., 2020). In this study, a geospatial based AHP and WLC was used to delineate the landslide hazard zones based on eight factors such as slope, lithology, drainage density, soil type, LULC, elevation, curvature and aspect.

The produced LHZ map manifests that 53.34 % of the study areas belongs to high and very high hazard zone. From this it is concluded that the spatial distributions of landslide hazard are distributed throughout the study area. Despite the very high landslide susceptibility areas were mostly inhabited towards the central part of the study area. Possible reason to be reached on this result; steepness of the topography ($>45^{\circ}$), slope modification, poor characteristics of limestone as it was found between 1575m and 2100m elevation ranges capped by unconsolidated colluvial deposits, extensive underground excavation of limestone, deeply weathered basalt unit situated in between 2100m and 2480m elevation ranges, shallow depth of leptosoil as it constituted from sand texture, high concentration of high drainage towards northwest facing aspect of slopes, expansion of many agricultural at the higher elevation near to drainage incorporated with steepness of slope, existence of bare land along main road, and surrounding and receive heavy rainfall especially from July to September which increase surface run-off (JICA&GSE, 2012). The low hazard zone is predominantly covered by forest, rangeland, situated at very low elevations (926m-1430m) covered by gypsum and sandstone unit those have capacity resist erosion, settled in elevation ranges from 2480m-2602m capped by residual soil and this zone is mostly in habited at low drainage density. As it receive small amount of rainfall and manifests low surface run-off (Getachew & Meten, 2021). In moderate zone all factors influenced in moderately.

The study, which was performed in the Gidole area (Mengistu, 2018) used information value method to asses landslide hazard zonation map. The paper presented six causative factor maps such as Slope, Elevation, Aspect, NDVI, Lithology and LULC. In her study, 23 % of the study area was under high and very high hazard zone. In that study the many landslides were observed in elevation class found in between 1821m and 1924m. Even though for the present study it lies in 1575m and 2100m. Almost there is a good agreement with present study.

The study made by (Debru, 2020) using AHP method to map landslide hazard zone undertaken in Birbir-Mariam Area of the Southern Regional State. The paper presented eight causative factors like Slope, Elevation, LULC, Lineament Density, Drainage Density, NDVI, Lithology and Aspect. Finding of this study showed that, 40.5% of the study area belongs to very high and high zones. In his study the dominant elevation class was found in 2170m and 3030m.

There is a difference with present study, but the previous study mainly covered by agricultural land on higher elevations. Thus assure similarity with current study as an elevation greater than 2000m was covered by agricultural land which makes the area more vulnerable to landslide.

The study conducted by (Gizawu, 2020) in Gechi district of western Ethiopia using AHP and WLC method based eleven factors like Slope, Lithology, Elevation, Aspect, Curvature, Land use land cover, Soil texture, Distance from lineament, Distance from drainage, rainfall and Distance from road. In his study, 20.2% of the area falls in very high and high zones. In that study the dominant elevation class was found in 1696m and 1821m. In comparable with present study it reveals a little bit the difference as environmental set-up is concerned.

A similar study, which was conducted in and around present study that lies in area between Gohatsion and Dejen Town (Ali, 2021) used information value method to investigate landslide susceptibility map. The paper presented seven causative factor maps such as lithology, elevation, slope, aspect, LULC, proximity to road and proximity to streams. In his study, 44.9% of the study area was under high susceptible class. His study showed the similarity with present study using different method. In that study the dominant elevation class was found in 1575m and 2100m. This shows similar agreement with present study. As environmental set-up matter goes beyond the method.

The study conducted by (Mewa & Mengistu, 2022) on Assessment of Landslide Risk in Ethiopia with its distributions, Causes, and impacts showed that 49.1% of Ethiopia's land surface is susceptible to landslides. So, the finding of the present study showed a conformity with their study as 53.34% susceptible to landslides.

According to the international landslide classification (Varnes, 1984) predominant types of the slope processes in the study area are debris, rock fall, topple, translational, rotational and complex. As identified from previous studies. The results of present study showed that the very high landslide susceptibility areas were mostly inhabited towards the central part of the study area within twenty three (23) villages out of thirty (30) villages found in district. These are Kola Jemo Gedera, Lencho Borsu, Dembeza Wole, Filiklik 01, Girmi Goba, Bitsino Dera, Gohatsion 01, Gohatsion 02, Haro Mikael, Shonkora Shashang, Kola Borsu, Hose, Hose 01,

Bobbe Liben, Bochese Silase, Tahe Tuti, Jemjem Mela, Lantu Wal-argi, Maliyu Chewa, Jemo Berdada, Nunu Gundini, Korgogo Lutu and Aware Golje. The above mentioned villages were identified based on the results of the study, local people interview incorporated with previous study. Although the degree of susceptibility are not the same as area is characterized different geo-environmental factors. Moreover, based on interview made with Busa Gonofa (Disaster and risk management) office, around 621 agricultural land was out of service due to the landslides that leads to displace 210 family, quarry mine exploitation and unscientific cutting of slope around asphalt road were identified as main causes of landslides in this area.

The drawback of this study is the weighting and ranking of factors which is highly subjective despite the expert's opinion and consistency ratio was assured. As well the lack of detailed field survey to identify the type, location and time of the occurrence of landslide and lack of well-organized records to quantify actual loss of element at risk to assess the risk assessment.

In general, the geospatial based MCDA approach using the AHP method proved to be a valuable tool for identifying landslide hazard zones characterized by deep gorge, mountainous terrain, heavy rainfall, soil erosion, improper land use practices, steep slopes and complex geology like Worra Jarso district. There is no contradiction among different studies with dominant class of slope. The landslide inventory map (Figure 24) showed that the northern part was experiencing landslides. As there is no information about previous landslides, in the southern, western and eastern areas. Since there is no previous work on landslide as whole. Accordingly, the current status of results of LHZ map cannot be compared to the prevalence of previous landslide in these areas. The proposed methodology can be applied to other regions with similar landslide susceptibility characteristics for providing valuable information about land use planning, infrastructure development and disaster preparedness.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This study demonstrates the potential of a Geospatial based MCDA to delineate the landslide hazard zones in hilly and mountains area like the Worra Jarso District. An attempt was made to map landslide hazard zones using AHP method with WLC in GIS weight Overlay Analysis environment. In the entire study area no previous attempts have been made to produce landslide hazard zone map.

Eight relevant landslide causative factors were identified are slope, lithology, drainage density, soil type, land use/land cover, elevation, curvature and aspect. These factors were reclassified and the values were assigned for each classes of the factors based on their relative contribution to landslide occurrence. Resampling technique was performed to be come all thematic maps into the same spatial resolution, reference system, and scale and data format. Their weights which was derived by analytical hierarchy process show that the influence of each factor for landslide occurrence in the study area. This has been done by a series pairwise comparison matrix of AHP method which is assigned based on expert opinion, literature reviews and nature of the study area. The obtained weight clearly identify that slope, lithology and drainage density are the most influencing factors whereas elevation, curvature and aspect are the least influencing factors in landslide occurrence.

The spatial distribution of landslides predominantly influenced by slope angle $>45^{\circ}$, Limestone lithological unit, high drainage density, shallowness of leptosol, expansion of agricultural land on steep slope, falling of elevation class in between 1575m and 2100m, concave slope curvature and northwest facing slope aspect. These, classes are very high susceptible to landslide occurrence. Later, the landslide hazard zonation map was produced by using Analytic Hierarchy Process and Weighted Linear Combination in GIS weighted overlay analysis environment. The produced map was classified into four hazard levels based on the computation of weight overlay analysis. Accordingly, the area was classified as low hazard zone 0.001% (0.014km²), moderate hazard zone 46.66% (555.25km²), high hazard

zone 50.02% (595.13km²) and 3.32% (39.48km²) of the study area was found to be within very high hazard zone.

Finally, validation of landslide hazard zone map with 49 past landslide inventory data shows that 85.7% of the known landslide events were falls in very high hazard and high hazard zone, and only 14.3% fall in moderate hazard zone whereas in low hazard zone no past landslide was observed. Therefore, the most relevant factors were identified and the appropriate weights were assigned to map landslide susceptibility. As Geospatial based MCDA method shows satisfactory agreement with the prepared landslide hazard zone map. Further, the produced landslide hazard zone map provides fundamental information for hazard assessment, land-use planning, and infrastructure development and landslide disaster mitigation strategy.

5.2 RECOMMENDATIONS

Based on the present study findings the following recommendations are forwarded:

- ✚ The most of the Agricultural land found in the central part of the study was exposed to landslide, which predominantly located at very steep slope, elevation greater than 2000m and towards northwest facing slope aspect. Therefore, agricultural practice which carried out at higher elevation and on the steep slope greater than 30° should be prohibited. Instead, the drainage system should be installed and forest conservation activity has to be take place so as to reduce landslide event.
- ✚ The area delineated as very high and high hazard zones in this study shows the possibility of for future landslide occurrence. In this regard, before taking any activity like; Road construction a detail study must be carried out. It is strongly recommended for further study to include Additional factors like distance to road and distance to lineament. Since the many landslides were observed near to main road.
- ✚ The detailed surveys must be conducted using existing and previously recorded landslide data, hence for present study only past landslides data were used. It is strongly recommended to use sophisticated instrument GNSS to known intensity of the deformation. Thus make the progress to easily predict future occurrence of event.
- ✚ The further study highly recommended to be conducted on landslide risk assessment using socio-economic data. To obtain information about physical loss, economic loss and social loss. Hence the present study did not consider.
- ✚ The local administrative of Worra Jarso district should take protective measures to stop underground excavation for exploration of limestone. As the main road corridor blocked due to nearness of limestone around the road. In this concern, an immediate response should be given for safety of road corridor. Then, the prepared map is used as basis for hazard assessment and disaster preparedness for this district.

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Appendices

Appendix 1: Questionnaire Prepared for Experts

My name is Adisu Mersha Yemane and I am a student of Addis Ababa University Institute of Technology, School of Civil and Environmental Engineering, Stream of Geodesy and Geomatics, Specialization in Geodesy. I am doing a research on the Landslide Hazard Zonation by using Geospatial based Multi-Criteria Decision Analysis Techniques: The Case of Worra Jarso District, Central Ethiopia. This research was used Multi-Criteria Decision Analysis of different factors those have influence for the occurrence of landslide. Therefore, the weighted overlay analysis method was employed using Satty's Analytical Hierarchy Process (AHP) for weight assignment of factors; I request your involvement in this research for identification of major factors and assignment of weights using pair wise comparison matrix. Your response is very valuable and will be held in utmost confidentiality. Thus will be used only for the purpose of this study.

I. Personal Information

1. Name.....Institute.....Position.....
2. Name.....Institute.....Position.....
3. Name.....Institute.....Position.....
4. Name.....Institute.....Position.....

II. Factors identification and Weight Assignment

Your contribution is highly significant for this study, in order to identify the major causative factors and rate the relative weight in considering geographically situations of the study area. Hence you are an expert of geological institute of the Ethiopia. Please identify the relevant factors and assign an appropriate weights of main class using the provided minimum and maximum values of a classes. Please assigned with scores ranging from 1 to 1/9 as per the Saaty scale. The continuous rating scale proposed by Saaty (1977) has been implemented accordingly.

Based on response of an Expert from Geological institute of Ethiopia under Ministry of Mines

S.No	Identified Factors	Assigned Weight	Assigned Weight (%)
1	Slope	0.31	31

2	Lithology	0.25	25
3	Drainage Density	0.17	17
4	Soil Type	0.09	9
5	LULC	0.07	7
6	Elevation	0.05	5
7	Curvature	0.03	3
8	Aspect	0.03	3

Appendix 2: Validation Data of a Produced Landslide Hazard Zone Map

Appendix 2a: Past Landslide Inventory Data

FID	Easting	Northing	Length(m)	Width(m)	Mode of failure	Occurred Kebele	Validation Result
1	414195	1112101	282	245	Debris flow	Kola Jemo Gedera	High
2	414845	1112857	144	880	Debris flow	Kola Jemo Gedera	High
3	411536	1112041	62	212	Debris flow	Kola Jemo Gedera	Moderate
4	413338	1110971	80	94	Debris flow	Kola Jemo Gedera	High
5	413346	1110898	77	122	Debris flow	Kola Jemo Gedera	High
6	415409	1112425	44	99	Debris flow	Kola Jemo Gedera	High
7	415713	1112557	145	75	Debris flow	Kola Jemo Gedera	Moderate
8	417113	1108161	41	35	Rotational	Gohatsion 02	Very High
9	417039	1108968	14	44	Translational	Lencho Borsu	Very High
10	417210	1108482	45	62	Rock fall	Kola Jemo Gedera	Very High
11	417210	1108702	98	22	Translational	Lencho Borsu	Very High
12	417169	1108816	39	46	Translational	Lencho Borsu	Very High
13	416955	1108973	72	23	Translational	Kola Jemo Gedera	Very High
14	416706	1109202	108	317	Rock fall	Kola Jemo Gedera	High
15	416849	1108922	35	83	Translational	Kola Jemo Gedera	Very High
16	416817	1108970	56	23	Rotational	Kola Jemo Gedera	Very High
17	416278	1109735	37	171	Translational	Kola Jemo Gedera	High
18	416778	1110317	221	233	Rotational	Kola Jemo Gedera	High
19	416312	1110243	21	94	Translational	Kola Jemo Gedera	High
20	414622	1112004	16	127	Translational	Kola Jemo Gedera	Moderate
21	419628	1108641	120	205	Translational	Kola Borsu	Very High
22	418411	1108903	95	114	Translational	Kola Borsu	Very High
23	416419	1108670	292	479	Complex	Kola Jemo Gedera	High
24	413920	1107411	125	248	Translational	Shonkora Shashang	Moderate
25	413584	1109064	78	79	Rotational	Kola Jemo Gedera	High
26	412166	1109842	71	125	Translational	Kola Jemo Gedera	High
27	412056	1113953	12	136	Toppling	Kola Jemo Gedera	High
28	411451	1113190	51	317	Rock fall	Kola Jemo Gedera	High

29	411712	1113052	30	56	Rock fall	Kola Jemo Gedera	High
30	411428	1113063	99	69	Toppling	Kola Jemo Gedera	High
31	411701	1112936	34	163	Translational	Kola Jemo Gedera	High
32	417363	1111885	55	45	Translational	Kola Jemo Gedera	High
33	417100	1112054	31	56	Rotational	Kola Jemo Gedera	High
34	417195	1111974	386	463	Rotational	Kola Jemo Gedera	High
35	417897	1111614	66	165	Rotational	Kola Jemo Gedera	High
36	416968	1110812	76	69	Translational	Kola Jemo Gedera	High
37	416714	1111015	57	1061	Translational	Kola Jemo Gedera	High
38	410090	1109708	56	64	Translational	Kola Jemo Gedera	High
39	416201	1108360	107	130	Rotational	Shonkora Shashang	Moderate
40	415228	1110597	157	582	Translational	Kola Jemo Gedera	High
41	415074	1110791	32	63	Translational	Kola Jemo Gedera	High
42	415914	1110605	105	262	Translational	Kola Jemo Gedera	High
43	415904	1110379	37	115	Translational	Kola Jemo Gedera	High
44	417000	1112241	35	74	Translational	Kola Jemo Gedera	High
45	411621	1106470	60	105	Translational	Kola Jemo Gedera	High

Appendix 2b: Location of past spring point

FID	Easting	Northing	Elevation	Occurred Kebele	Validate Result
1	416424	1112332	1756	Kola Jemo Gedera	High
2	417043	1111972	1714	Kola Jemo Gedera	High
3	416972	1110361	2131	Kola Jemo Gedera	High
4	417212	1108499	2139	Kola Jemo Gedera	Very High

Appendix 3: Climate Data

Appendix 3a: Rainfall Data on Filiklik Station for 33 years

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Rainfall(mm)
1990					29.3	43.7	315.6	272	169.2	20.6	0	0	850.4
1991	0	19	19.6	0	23.3	110.5	397.3	238.7	182.5	22	0	9.4	1022.3

1992	21.9	25.5	12.6	63.9	65.6	95	152.4	350.7	116.7	112.3	31.4	0	1048
1993	0	19.5	21.4	240.8	159.6		529.8	270	201.5	47	0	0	1489.6
1994	3	0	60.8	27.5			259.5	297.7	179.7	0	0	0	828.2
1995	0	4.1	26	42.1	71.9	66.2	320.2	361.2	85.8		6.5	47.3	1031.3
1996	12	2	133.3	277.5	163.5	270.6	462.1	480.2	100.8	8.7	51.4	0	1962.1
1997	41.5	0	35.6	179.6	90	242.7	478.2	203.7	55.6	103.6	118.9	24	1573.4
1998	0	0	101.7	15.7	80.2	102.7	293.3	456.8	242.6	248	0	0	1541
1999	23	0	2.2	20.9	6.4	87.3	410	460			14.4	4.1	1028.3
2000	0	0	0	18.4	34.8	152.1	386.2	377.6	279.3	231.9	192.5	4.6	1677.4
2001	0	21.4	59	59.5	61.7	225.6	439.7	146.9	37.1	27.1	0	2.1	1080.1
2002	40.7	0	11.8	33.3	10.1	130	120.6	188.7	75.7	0	0	49.8	660.7
2003	0	13.6	17.2	17			333	190.5	0	0	0	0	571.3
2004	0	0	4	8.2	33.3	161.6	224.1	235.7	191.7	36.5	0	0	895.1
2005	0	1.8	24.1	22.6	33.7	89.4	308	178	35.1	14.3	24.8	0	731.8
2006	3.2	24.5	78.1	84.8	59.3	87.5	352.9	330.3	188.7	23.5	26	0	1258.8
2007	13.8	100.1	17.6	28.1	84.1	264.2	326.6	351.4	211.9	2.4	0	0	1400.2
2008	0	0	0	32	165.2	228.9	398.2	409.6	14	68.9	39.1	0	1355.9
2009	0	0	16.1	45.3	26.8	129.9	406.1	225.2	0	33.6	0	0	883
2010	0	0	60.7	96.8	214.6	252.8	397.6	270.5	218.6	0	50.1	86.3	1648
2011	0	0	131.9	32.3	186.4								350.6
2012				103.3	56.3	210	235.6	213.3	156.6	0	0	0	975.1
2013	0	0	0	0	126	134.2	313.2	253.3	70.8	45.1	0	0	942.6
2014	0	20.7	0	90.2	131.3	0	162.6	284.5	165.2	0	25.7	0	880.2
2015	0	0	9.3	0	114.5	194.6	165	288.5	171	18.8	70.2	0	1031.9
2016	0	22.9	18.7	79.3		107.6		267.3	125.6	57.5	0	0	678.9
2017	0	0	16.7	37.2	162.7	93.1	456.6	354.3	155	53	53		1381.6
2018		22.8			69.7	194.8	594.5	858.1	74.2	48.8	86.6	5.3	1954.8
2019	1.4	41.8	64.5	98.2	144.9	331.1	442.9	441.5	253	15.3	81.9	2.5	1919
2020			48.6	43		118.3	519.3	519.3	276.5				1525
2021	0	0	0.6	25.8	117.4	87.1	440.1	405.5	148.2	81.2	0		1305.9
2022	0	0	46.9				490.8	454.8	244.1	69.7			1306.3
Average													1175.42

Appendix: 3b Rainfall Data on Gohatsion Station for 31 years

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Rainfall(mm)
1990	18.2	42.2	74.1	10.5	64.4	50.5	378.9	294.1	108.5	0	0	0	1041.4
1991	0	21.3	20.5	17.1	66.6	170.5	212.7	280.5	116	14.5	0.1	30.3	950.1
1992	20.9	23.4	36.2	51.1	79.8	93.1	158	291.5	128.5	43.6	43.1	0	969.2
1993				190.8	172.1	104.6	468.5	233.2	174.1	24.6	0	0	1367.9
1994	0	0	37.7	48.4	101.9	98.2	281.7	261.7	221	0	0	0	1050.6
1995	0		40.7	72.9	116.8	96	273	242.9	88.6	0	3.2	48	982.1
1996	10.3	2	135.3	150.3	123.7	179.4	292.8	274.9	86.5	9.2	48.8	0	1313.2
1997	32.8	0	23.8	115	57.9	109.7	300.3	269.4	46.4	106	158.2	9.3	1228.8
1998	11.7	5	80.8	30.5	135.3	178.1	270	323.9	154.8	135.8	11.2	0	1337.1

1999	5	0	2	25.6	25.9	120.9	454	407.4	39.4	165.2	0	5	1250.4
2000	0	0	3	64.6	64.7	122.7	397.1	291.3	158.4		58.8	0	1160.6
2001	0	69.7	87	59.5	60.6	150.9	309	256.6	79.7	6.3	8	22.8	1110.1
2002	28.6	5.2	45.5	31.1	4.1	116.8	193.8	323.4	72.8	0	0	28.4	849.7
2003	6	41.8	51.7		0	150.7	403.9	313.4	123	0	3	0	1093.5
2004	5.1	8.3	45	66.9	43.2	119.5	288.1	323.7	108.9	10.1	0	0	1018.8
2005	20.5	0	49.1	30	70.4	164.5	287.5	250.8	124.6	75.2	16	0	1088.6
2006	5	27.4	136.9	29	76	124.9	354.3	345.3	174.9	79	7.5	3	1363.2
2007	0	38	0	29.6	125.8	201.9	294.6	322.8	217.4	8	0	0	1238.1
2008	0	0	0	51.7	226.5	217.9	378.9	320.3	139.3	18.7	62.7	0	1416
2009	0	3.2	23.4	42.4	20.5	69.2	275.1	406.8	83	100.3	0	2.1	1026
2010	7.1	0	20.2	40.4	106.4	118.7	336.2	273.7	163.8	1.1	0	6	1073.6
2011	0	0	71.8	40.4	127.2	138.8	217.4	438.8	283.8	0	120.3	0	1438.5
2012	0	0	14.5	58.6	35.3	93.7	457.4	377.8	264	0	6.3	7.2	1314.8
2013	11	0	14.5	27.8	80.4	192.6		430.2	213.4	126.3	34.5	0	1130.7
2014	0	25.9		74.6	161.2	101.4	389.2	313.1	193.9	23.3	7.6	0	1290.2
2015	0	0	3.2	0	166.8	196.3	225.2	310.4	142.3	33.3	56.4	48.2	1182.1
2016	0	26.6	10.2	83.8	275.5		422.8	301	89.1	16.4	14.5	0	1239.9
2017	0	35.8	13.3	28.1	187.6	73	464.3	383.9	137.7	71.4	0	0	1395.1
2018	0	34.4			36.3	244.9	413.1	451.1	19.7	15.6	22.6	0	1237.7
2019	0	18.6	40.5	75.9	61			369.6	158.3	18.5	61.3	1.2	804.9
2020	0	0	0	12.9	187.5	110.8							311.2
Average													1137.87

Appendix 3c: Temperature Data on Filiklik Station for 32 Years

Temp(°C)	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MAX	1990					30.4	31.3	25.8	25.6	26.9	27.2	29.6	29.7
MIN	1990					7.7	14.4	13.2	13.6	13.3	14.3	15.4	14.4
MEAN						19.05	22.85	19.5	19.6	20.1	20.75	22.5	22.05
MAX	1991	30.7		32.9	33.8	32.1	29.7	25.5	25.6	27.1	28	29.5	28.6
MIN	1991	16.9		16.1	17.2	16.7	15.6	15	15.7	16.1	16.6	16.6	15.6
MEAN		23.8		24.5	25.5	24.4	22.65	20.25	20.65	21.6	22.3	23.05	22.1
MAX	1992	30.3	32.2	32.6	32.2	32.6	30.8	25.8	24.6	25.1	28.2	29.2	32.1
MIN	1992	16.7	16.8	17.6	18.2	18.2	16.3	15.2	14	14.8	15	15.4	15.7
MEAN		23.5	24.5	25.1	25.2	25.4	23.55	20.5	19.3	19.95	21.6	22.3	23.9
MAX	1993	31.6	31.2	33.9	29	31.1		26	26.5	26.1	27.5	30	30.3
MIN	1993	16.4	17.2	17.6	15.2	16.4		13.8	14.6	14.7	16.2	14.7	14.8
MEAN		24	24.2	25.75	22.1	23.75		19.9	20.55	20.4	21.85	22.35	22.55
MAX	1994	31.2	30.3	33.1	34			24.1	24.5	26.1	27.2	29.9	29.8
MIN	1994	16.1	15	16.6	17.5			14.3	14.4	14.2	15.5	15	14.5
MEAN		23.65	22.65	24.85	25.75			19.2	19.45	20.15	21.35	22.45	22.15
MAX	1995	30.9	33.9	32	33.6	32	32	24.6	23.3	25.9	29.3	27.6	27.7
MIN	1995	15.3	16.9	16.8	17.5	17.4	17.6	13.7	13.3	14.9	17.3	16.5	15.5
MEAN		23.1	25.4	24.4	25.55	24.7	24.8	19.15	18.3	20.4	23.3	22.05	21.6
MAX	1996	30.1	31.9	33	27.1	30.1	27	23	23	24	25.8	29.6	29.8
MIN	1996	17	17	16.1	14.3	15.7	14.8	12.8	12.9	14.1	15.7	16	15.8
MEAN		23.55	24.45	24.55	20.7	22.9	20.9	17.9	17.95	19.05	20.75	22.8	22.8
MAX	1997	29.7	33.2	31.6	29.2	32.4	30.7	27	25.9	30.8	27.2	28.5	30.5

MIN	1997	15.8	17.9	16.5	14.6	17.3	15.2	13.7	14.4	14.6	14.9	14.5	14.5
MEAN		22.75	25.55	24.05	21.9	24.85	22.95	20.35	20.15	22.7	21.05	21.5	22.5
MAX	1998	31.7	29.1	31.3	35.1	33.2	28.8	25.2	25	26	25.3	26.4	28.7
MIN	1998	15.9	16.2	16	17.8	16.8	15.4	13.3	13.8	15.1	15	14.4	13.6
MEAN		23.8	22.65	23.65	26.45	25	22.1	19.25	19.4	20.55	20.15	20.4	21.15
MAX	1999	31.7	32.8	34.6	35.1	34.5	32.1	24.2	26	29	26.7	27.4	30.4
MIN	1999	14.5	17.6	16.4	16.1	15.3	15.4	13	15.3	18.3	16.2	15.3	17.7
MEAN		23.1	25.2	25.5	25.6	24.9	23.75	18.6	20.65	23.65	21.45	21.35	24.05
MAX	2000	30.4	34.1	34.9	31.1	33.1	31	25.8	26.7	26	29.9	28.7	28.5
MIN	2000	17.7	16.6	18.6	17.3	17.7	16.4	15.5	16.5	16.4	17.8	16.6	14.2
MEAN		24.05	25.35	26.75	24.2	25.4	23.7	20.65	21.6	21.2	23.85	22.65	21.35
MAX	2001	29.3	33.1	31.8	32	30.9	27.4	23.1	25.4	27.4	27.6	25.7	27.1
MIN	2001	15	18.6	16.5	16.9	17.1	15.1	12.8	15.2	17.2	17.1	14.9	16.3
MEAN		22.15	25.85	24.15	24.45	24	21.25	17.95	20.3	22.3	22.35	20.3	21.7
MAX	2002	27.1	31.9	31.3	30.6	35				28.1	30	30.6	29.3
MIN	2002	16.3	17.1	16.5	16.4	18.3							
MEAN		21.7	24.5	23.9	23.5	26.65				28.1	30	30.6	29.3
MAX	2004	28.9	31.1	30.6	34	34.4	31.4	23.5	21.1	21.4	22.4	24.7	27
MIN	2004			17.8	18.6	18.1	15.7	14.7	14.5	15.7	15.4	16.6	16.5
MEAN		28.9	31.1	24.2	26.3	26.25	23.55	19.1	17.8	18.55	18.9	20.65	21.75
MAX	2005	29.9	31.3	34.1	34.1	32.1	31.2	26	25.1	26.5	26.7	23.6	26.3
MIN	2005	18.2	19.6	18.6	18.7	18.5	18	15.1	15.7	16.4	17.2	13	15.6
MEAN		24.05	25.45	26.35	26.4	25.3	24.6	20.55	20.4	21.45	21.95	18.3	20.95
MAX	2006	30.3	31.3	30.6	29	32.2	29.5	22.9	21.8	23.5	21.9	24.2	26.5
MIN	2006	18.1	18.4	16.7	17.4	19.2	17.4	13.2	13	14	14.5	14	14.2
MEAN		24.2	24.85	23.65	23.2	25.7	23.45	18.05	17.4	18.75	18.2	19.1	20.35
MAX	2007	28.3	31.1	31.8	35.2	30.7	26	22.1	23.4	26.1	29.7	21.8	26.4
MIN	2007	15.4	18.6	17.7	17.7	16.8	15	12.8	13	15.3	17.7	14.4	16.1
MEAN		21.85	24.85	24.75	26.45	23.75	20.5	17.45	18.2	20.7	23.7	18.1	21.25
MAX	2008	30	27.3	33.7	29.4	28.7	26.5	21.7	23.7	26.1	28	26.5	27.9
MIN	2008	19.1	17.2	21.2	18.2	16.7	16	12.2	11.8	14.9	17.9	14.6	15.5
MEAN		24.55	22.25	27.45	23.8	22.7	21.25	16.95	17.75	20.5	22.95	20.55	21.7
MAX	2009	30	33.3	34	33.1	30	28.1		22.6	28.9	27.2	25.8	28.1
MIN	2009	17.7	20.9	18.8	17.8	16.6	16	11.2	15.7	17	16	16	16
MEAN		23.85	27.1	26.4	25.45	23.3	22.05	11.2	19.15	22.95	21.6	20.9	22.05
MAX	2010	31.9	33.5	32.1	32.5	28.4	24.9	25.5	24.7	25.6	31.3	28.9	24.8
MIN	2010	18.6	18.9	17.9	17.2	14.5	13.6	14.2	13.1	13.1	17.8	15.8	12.9
MEAN		25.25	26.2	25	24.85	21.45	19.25	19.85	18.9	19.35	24.55	22.35	18.85
MAX	2011	27	33.1	29.3	29.3	29.5							29.64
MIN	2011	16	18.4	15.5	16.3	15.9							16.42
MEAN		21.5	25.75	22.4	22.8	22.7							23.03
MAX	2012		33		30.5	31.9	28.5	24.9	23.2	23.4	24.4	23.6	23.3

MIN	2012		17.7		12.2	12.9	11.8	10.9	10.8	11.1	13.2	13.5	13.6
MEAN			25.35		21.35	22.4	20.15	17.9	17	17.25	18.8	18.55	18.45
MAX	2013	21.9		32.1	33.5	28.3	24.5	21.8	20.5	21.1	21	19.1	17.5
MIN	2013	12.1		16.6	14.2	12.3	11.6	11	10.9	12.4	12.1	9.5	8
MEAN		17		24.35	23.85	20.3	18.05	16.4	15.7	16.75	16.55	14.3	12.75
MAX	2014	16.8	23.6	21.4	23.4	21.3	26	24.2	19.1	20.6	24.1	22.8	27.3
MIN	2014	9.2	13.5	12.3	12.2	11.5	14.5	12.5	9.7	12.1	14.3	12.6	15.1
MEAN		13	18.55	16.85	17.8	16.4	20.25	18.35	14.4	16.35	19.2	17.7	21.2
MAX	2015	26.4	17.5	29.7	31.1	30.1	30.8	28.2	26.3	25.2			
MIN	2015	14	10.3	14.2	15.2	14	15	13.3	13.6	13.4	15.5	14.6	14.7
MEAN		20.2	13.9	21.95	23.15	22.05	22.9	20.75	19.95	19.3	15.5	14.6	14.7
MAX	2016		28.6	32	31.6		30.4	26.2	26	26.2	28	28	28.4
MIN	2016	15.6	14.1	16.1	15.9		15.2	12.9	13.1	13.3	13.7	13.8	13.6
MEAN		15.6	21.35	24.05	23.75		22.8	19.55	19.55	19.75	20.85	20.9	21
MAX	2017	29.5		34.3	35.2	30.6	32.3	26.7	26.5	27.9	29	27.1	29.91
MIN	2017	14.5	15.8	16.9	17.6	14.7	15.8	12.7	12.7	13.8	13.8	13.5	14.7
MEAN		22	15.8	25.6	26.4	22.65	24.05	19.7	19.6	20.85	21.4	20.3	21.66
MAX	2018	27.5	32.8			32.9	29.5	25.4	24.5	30.7	28.8	27.7	29.7
MIN	2018	13.8	16.1			16.4	14.7	12.6	12.2	15.1	14.3	13.6	14.9
MEAN		20.65	24.45			24.65	22.1	19	18.35	22.9	21.55	20.65	22.3
MAX	2019	28	27.5	33.1	32.2	33.4	30.1	27.4	26.4	28	29.7	30.6	30.2
MIN	2019	14.1	13.7	16.4	15.9	16.7	14.7	13.5	13.1	13.9	14.9	15.4	15
MEAN		21.05	20.6	24.75	24.05	25.05	22.4	20.45	19.75	20.95	22.3	23	22.6
MAX	2020		31.2	32.5	33.1		31.2	25.6	25.6	27.1			29.47
MIN	2020		15.2	16.5	16.8		15.9	12.9	12.9	13.5			14.81
MEAN			23.2	24.5	24.95		23.55	19.25	19.25	20.3			22.14
MAX	2021	28.4		32.9	31.6	28.1	31.2	24.8	25.4	26.5	27.2	28.1	28.42
MIN	2021	13.9		16.4	15.9	13.9	12.7		12.6	13.2	13.5	14.1	14.02
MEAN		21.15		24.65	23.75	21	21.95	24.8	19	19.85	20.35	21.1	21.76
MAX	2022	28.5	30.7	32.8				26.3	29.5	29.7	30.7		29.74
MIN	2022	14.8	15.2	16.6				12.4	14.4	14.9	15.9		14.88
MEAN		21.65	22.95	24.7				19.35	21.95	22.3	23.3		22.31

Appendix 3d: Temperature Data on Gohatsion Station for 31 Years

Temp(°C)	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MAX	1990	23.8	23.5	24.3	25.8	25.1	23.6	20.1	19.9	21.2	23.3	23.9	24.2
MIN	1990	17.4	15.8	16.9	18	18.5	15.9	14	14.7	16.3	18.9	18.8	19
MEAN		20.6	19.65	20.6	21.9	21.8	19.75	17.05	17.3	18.75	21.1	21.35	21.6
MAX	1991	24.9	25.3	25.5	26.6	27.6	24.9	19	19.3	21.2	23	23.9	23
MIN	1991	18.4	19.1	19.1	20.2	19.7	16.3	14	14.2	16.5	18.3	19.1	17.6
MEAN		21.65	22.2	22.3	23.4	23.65	20.6	16.5	16.75	18.85	20.65	21.5	20.3
MAX	1992	23.3	24.3	23.9	25.6	24.9	24.1	19.6	19.8	21.2	21.4	21.4	23.7

MIN	1992	17.3	17.3	18.7	19.3	19.4	16.3	14.1	13.8	15.7	16.6	17	17.5
MEAN		20.3	20.8	21.3	22.45	22.15	20.2	16.85	16.8	18.45	19	19.2	20.6
MAX	1993				22.6	23.6	22.3	19.5	20.7	21.3	23.2	24.1	24.8
MIN	1993				16.3	17.6	15.8	14.1	14.6	15.8	18.3	19.4	19.4
MEAN					19.45	20.6	19.05	16.8	17.65	18.55	20.75	21.75	22.1
MAX	1994	25.1	26.5	26	26.6	24.9	22	19.2	20.2	21.3	24.5	24.5	25
MIN	1994	20.2	19.8	18.7	20.1	18.4	15.3	13.3	14	15.7	19.6	19.4	19.6
MEAN		22.65	23.15	22.35	23.35	21.65	18.65	16.25	17.1	18.5	22.05	21.95	22.3
MAX	1995	25.2		26.2	26.7	25.8	25.8	19.9	21.1	24.2	25.8	25.3	24.5
MIN	1995	20		19.8	18.8	18	17.2	13.5	13.8	16.7	19.8	19.9	19.4
MEAN		22.6		23	22.75	21.9	21.5	16.7	17.45	20.45	22.8	22.6	21.95
MAX	1996	24.4	27.2	26.3	26.1	25.4	22.4	20.9	20.7	22.2	24.5	23.4	23.8
MIN	1996	17.7	19.8	18.2	18.7	17.5	15.4	14.6	14.5	16.5	18.7	18.4	19.4
MEAN		21.05	23.5	22.25	22.4	21.45	18.9	17.75	17.6	19.35	21.6	20.9	21.6
MAX	1997	24.5	25.9	26	25.3	26.3	23.4	20.5	22.3	25	24.2	22.6	25
MIN	1997	17.6	17.5	19.5	18.7	19.4	17.2	14	15.3	17.9	17	15.8	18.8
MEAN		21.05	21.7	22.75	22	22.85	20.3	17.25	18.8	21.45	20.6	19.2	21.9
MAX	1998	25.2	26.1	25.2	27.5	26.6	24.2	20.1	19.6	21.7	22.1	23.1	23.7
MIN	1998	18.4	19	17.6	19.2	18.9	18	14.3	13.8	14.6	15.4	17.5	19.1
MEAN		21.8	22.55	21.4	23.35	22.75	21.1	17.2	16.7	18.15	18.75	20.3	21.4
MAX	1999	24.2	26.2	27	27.4	26.9	25.7	19.8	19.7	21.8	21.3	23.2	23.9
MIN	1999	17.7	18.4	17.8	19.8	18.8	15.8	12.3	13.4	15.4	15.6	16.7	18.8
MEAN		20.95	22.3	22.4	23.6	22.85	20.75	16.05	16.55	18.6	18.45	19.95	21.35
MAX	2000	24.7	25.6	27.1	25.8	26.2	24.1	20.2	19.4	21.4	22.7	23.4	23.8
MIN	2000	19.1	18.4	19.7	18	18.6	15.7	13.2	13.1	15	15.7	17	18.3
MEAN		21.9	22	23.4	21.9	22.4	19.9	16.7	16.25	18.2	19.2	20.2	21.05
MAX	2001	24.7	24.7	25.6	25.8	27	24.1	19.7	20.3	22.4	24	23.5	24.6
MIN	2001	18.4	18.1	17.5	18.3	19.1	15.2	13.9	14.4	16.6	18	17.5	17.6
MEAN		21.55	21.4	21.55	22.05	23.05	19.65	16.8	17.35	19.5	21	20.5	21.1
MAX	2002	24.1	25.9	26.5	26.8	27.4	25.3	22.8	21.1	23.5	24.1	24.6	24.7
MIN	2002	16.6	18.5	18.1	19	20.4	16.8	15.6	14.6	17.2	17.4	18.7	16.9
MEAN		20.35	22.2	22.3	22.9	23.9	21.05	19.2	17.85	20.35	20.75	21.65	20.8
MAX	2003	24.7	26.1	25.9	25.7	26.7	25.6	20.7	19.3	21.1	24	24.5	24.4
MIN	2003	18.7	18.6	18.5	18.3	20.4	16.7	15	14.3	16.1	18.3	17.8	18
MEAN		21.7	22.35	22.2	22	23.55	21.15	17.85	16.8	18.6	21.15	21.15	21.2
MAX	2004	25.1	25.8	24.9	24.4	26.7	23.4	20.6	20.6	20.9	22.2	24.1	24.5
MIN	2004	18.5	18.3	17.8	18.2	19.7	16.1	14.3	14.9	15.9	17.1	17.4	16.4
MEAN		21.8	22.05	21.35	21.3	23.2	19.75	17.45	17.75	18.4	19.65	20.75	20.45
MAX	2005	24.7	27	26	26.2	25.6	24.3	20.6	20.1	21.9	22.6	23.4	23.3
MIN	2005	16.8	19.7	19.3	19	18.2	17.1	14.8	15.2	16.5	17.6	17.7	10.9
MEAN		20.75	23.35	22.65	22.6	21.9	20.7	17.7	17.65	19.2	20.1	20.55	17.1
MAX	2006	24.3	25	24.8	24.4	24.7	23.1	20.3	19.7	20.1	23.1	22.4	22.6

MIN	2006	10.9	12.2	11.7	12.3	12.9	11.5	11.7	11.5	10.7	11	10.5	10.7
MEAN		17.6	18.6	18.25	18.35	18.8	17.3	16	15.6	15.4	17.05	16.45	16.65
MAX	2007	22.7	23	25.7	24.6	24.4	22.5	19.7	20	20.7	22.1	23.1	23
MIN	2007	10.9	11.1	11.9	12.3	12.7	11.5	10.9	10.7	10.7	10.3	10.3	9.8
MEAN		16.8	17.05	18.8	18.45	18.55	17	15.3	15.35	15.7	16.2	16.7	16.4
MAX	2008	23.6	25.1	26.6	26.2	24	22.9	20.9	21.6	21.8	22.3	22.1	22.5
MIN	2008	11.3	11.5	12.1	12.7	12.3	11.2	10.7	10.8	11.2	11.2	10.1	10.4
MEAN		17.45	18.3	19.35	19.45	18.15	17.05	15.8	16.2	16.5	16.75	16.1	16.45
MAX	2009	24.2	24.2	25.9	26.7	26.6	26.3	21.4	21.4	23	22.6	23.8	23.3
MIN	2009	10.8	11.5	12.6	12.6	12.9	12.9	11.4	11.4	11.1	11.1	10.3	11.3
MEAN		17.5	17.85	19.25	19.65	19.75	19.6	16.4	16.4	17.05	16.85	17.05	17.3
MAX	2010	24	26.2	26.6	26	25.7	24.2	22.1	20.9	22.4	24.4	23.9	23.9
MIN	2010	10.9	12.3	12.2	12.8	12.7	12.4	11.2	10.6	10.5	11.2	10.5	9.8
MEAN		17.45	19.25	19.4	19.4	19.2	18.3	16.65	15.75	16.45	17.8	17.2	16.85
MAX	2011	24.6	26.4	25.9	26.2	25.6	24	21.8	20.9	22.5	24.1	24.2	24
MIN	2011	10.1	10.4	10.9	12.8	12.2	12	11	11.6	11.1	10.6	10	9.6
MEAN		17.35	18.4	18.4	19.5	18.9	18	16.4	16.25	16.8	17.35	17.1	16.8
MAX	2012	24.9	26.2	27.8	26.3	26.5	24.9	22.2	21.2	22	24.2	24.4	24.2
MIN	2012	9.8	10.1	12.4	12.2	12.8	11.8	11.4	10.8	10.7	10.9	10.1	9.9
MEAN		17.35	18.15	20.1	19.25	19.65	18.35	16.8	16	16.35	17.55	17.25	17.05
MAX	2013	25.3	27.3	27.8	28.2	25.5	23.5	20.7	20.7	23	23.5	23.8	24
MIN	2013	10.2	11.5	12.3	13	12.1	11.8	10.9	11	11.1	11.4	10.6	9.1
MEAN		17.75	19.4	20.05	20.6	18.8	17.65	15.8	15.85	17.05	17.45	17.2	16.55
MAX	2014	25.3	25.6	26.2	25.9	24.5	25.6	22.6	21.6	22.4	23.8	24.3	24.3
MIN	2014	10.5	10.8	12.3	12.3	12.2	12.3	11.1	10.9	11.9	11.2	11.1	10.6
MEAN		17.9	18.2	19.25	19.1	18.35	18.95	16.85	16.25	17.15	17.5	17.7	17.45
MAX	2015	24.8	26.6	26.9	28	26.3	24.5	23	21.8	22.8	24.2	24	24
MIN	2015	9.2	11.1	12.5	13.3	12.6	12.1	11.8	11.1	10.8	11.9	10.9	10.4
MEAN		17	18.85	19.7	20.65	19.45	18.3	17.4	16.45	16.8	18.05	17.45	17.2
MAX	2016	25.2	26.7	27.3	26.5	24.7	24.6	20.5	20	22.4	23.9	23.7	23.5
MIN	2016	10.5	12.1	13.8	13	12.5	11.8	11.9	10.9	11.5	11.1	11.8	9.7
MEAN		17.85	19.4	20.55	19.75	18.6	18.2	16.2	15.45	16.95	17.5	17.75	16.6
MAX	2017	24.6	24.1	25	26.5	24.2	23.6	20.7	21.9	23	24.3	24.2	24.6
MIN	2017	9	12	12.3	13	12.4	12.1	11.4	10.9	11	11.7	11.8	13
MEAN		16.8	18.05	18.65	19.75	18.3	17.85	16.05	16.4	17	18	18	18.8
MAX	2018	25.6	25			24.8	25	25.2	25.5	25.6	24.9	25.4	25.6
MIN	2018	15.6	13.4			12.5	11.5	11.6	11.7	11.9	11.7	11.7	12.3
MEAN		20.6	19.2			18.65	18.25	18.4	18.6	18.75	18.3	18.55	18.95
MAX	2019	25.3	25.9	25.6	25.5	25.4							
MIN	2019	12.1	12.4	12	12.1	12.7			11.5	11.3	10.8	11.6	10.7
MEAN		18.7	19.15	18.8	18.8	19.05			11.5	11.3	10.8	11.6	10.7
MAX	2021	23.6											23.6

MIN	2021	11.1											11.1
MEAN		17.35											17.35

Appendix 4: Land Use Land Cover Accuracy Assessment

Classification	WB	FR	AG	BU	BA	RG	Total	UA (%)
WB	12	0	0	0	1	1	14	85.71
FR	0	6	0	0	0	0	6	100
AG	1	0	47	0	1	0	49	95.91
BU	0	0	0	7	0	0	7	100
BA	0	0	0	0	11	0	11	100
RG	1	0	0	0	1	31	33	93.93
Total	14	6	47	7	14	32	120	
PA (%)	85.71	100	100	100	78.57	96.87		
OA (%)								95
KC (%)								93.2

Where; WB= Water Body, BA= Bare Land, FR= Forest, AG= Agricultural Land, BU=Built-up Area, RG= Rangeland, PA = Producer Accuracy, UA = User Accuracy, OA = Overall Accuracy, KC = Kappa Coefficient.