



ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Landslide Assessment, Susceptibility Analysis and Recommendation of
Remedial Measures for Jimma-Chida Road Segment, South-West Ethiopia

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In Civil Engineering (Geotechnical Engineering)

By
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Advisor
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Addis Ababa, Ethiopia

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By: Lemenew Minale Tesfa

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DECLARATION

I hereby declare that this thesis entitled “**Landslide Assessment, Susceptibility Analysis and Recommendation of Remedial Measures for Jimma-Chida Road Segment, South-West Ethiopia**”, has been conducted by me under the advice and supervision of my advisor, Dr. Tezera Firew.

This thesis work is original and has not been submitted for any degree or diploma to any college, university or institution. Where materials and references have been used from any external sources it has been properly acknowledged.

A handwritten signature in black ink, consisting of stylized letters and a horizontal line, positioned above the printed name.

Lemenew Minale Tesfa

ABSTRACT

In Ethiopia, landslides, mostly demonstrated as rock fall, earth slide, debris, and mudflow, are prevalent in the central, south-southwest, and north-northwest highlands, especially after intense rainy season. Jimma-Chida road section which is studied in this paper is located in southern highlands and lies in Gibe and Gojeb River Basins where landslide incidence occurred frequently.

This work studied the active landslide areas along Jimma-Chida road by assessing their features, failure mechanism and extent of the landslides. Landslide susceptibility map is produced by weighting factors that contribute to the landslide using Analytical Hierarchy Process(AHP) method and integrating it with the existing landslide inventory data. For this purpose, key factors (lithology, elevation, rainfall, slope, slope aspect, land use/ cover, distance to stream, distance to road and curvature) are considered and weighted after dividing into sub-factors using AHP. Then the causative factor layers are overlaid using weighted overlay technique in ArcGIS environment to produce the landslide susceptibility map.

From the assessment of the existing landslide it is revealed that slope angle (9° - 14°), slope aspect(Northwest), elevation (2388-2732 m), curvature(flat), lithology (residual soil of upper basalt flow), distance to stream (50 m), distance to road (50 m), land use/cover (crops) and rainfall (1600-1675 mm) have higher contribution for the occurrence of the active landslide. Based on AHP for landslide susceptibility map, distance to the stream, distance to the road and rainfall are the most contributing factors with weight 0.203,0.197 and 0.199, respectively. The other influential factor is lithology with weight of 0.167, followed by slope angle, aspect, elevation, curvature, land use/cover with the weight 0.073,0.023,0.023 and 0.059, respectively. The landslide susceptibility map concludes that Jimma-Chida road section is classified as low (32.23%), moderate (62.87%), high (4.89%), and very low and very high susceptibility zones are covered a very small and localized areas.

Finally, modification of the slope geometry, provision of both surface and sub-surface drainage, provision of retaining structure and internal reinforcement of slope are recommended as a preliminary remedial measure for the area affected by landslide.

Key words: Landslide Susceptibility Map, ArcGIS, Analytic Hierarchy Process (AHP)

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LIST OF ABBREVIATIONS

AC -Asphalt Concrete

AHP-Analytic Hierarchy Process

AI-Artificial Intelligence

a.m.s.l-Above Mean Sea Level

AUC-Area Under Curve

CI-Consistency Index

CR-Consistency Ratio

DEM-Digital Elevation Model

ERA- Ethiopian Roads Administration

ERT-Electrical Resistivity Tomography

FPR-False Positive Rate

FR-Frequency Ratio

GIS-Geographical Information System

IV-Information Value

LHEF-Landslide Hazard Evaluation
Factor

LSM-landslide susceptibility map

MER-Main Ethiopian Rift

NDVI-Normalized difference vegetation
index

PRC-Prediction Rate Curve

RI- Random Index

ROC-Receiver Operating Characteristics
Curve

SE-Shannon Entropy

SSEP-Slope Susceptibility Evaluation
Parameters

SRS-Seismic Refraction Survey

TPR-True Positive Rate

UTM-Universal Transverse Mercator

VES-Vertical Electrical Soundi

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CHAPTER 1. INTRODUCTION

1.1. Background

The devastating landslides that previously occurred in Ethiopia have caused severe damage to infrastructures, destruction of households, environmental impact, disrupt the economic development and loss of lives. Landslides are the movement of a different types of soil, rock or debris. These movements happen down or along the slope (Serdarevic & Babic, 2019). These phenomenon usually occur on areas with mountainous and escarpment topography where the terrain is rough. There are many factors which are contributing to the initiation and aggravation of the landslide. Some of the factors are deforestation, active riverbank erosions leading to gully formations, intense and prolonged rainfall, the presence of recent unconsolidated soil deposits in areas, human activities such as construction of infrastructures and metropolitan expansions, and so on.

Based on the physical characteristics of the sliding materials and mode of movements landslides can be classified as falls, topples, slides, flows, spreads, or any mixture of these and occur either slowly or suddenly. Ethiopia, situated in the horn of Africa and constitutes the highlands plateaus, dissected valleys, escarpments, gentle slopes, and flat plains. Places dominantly constitute the mountainous and escarpment terrain are a convenient environment for the widespread incidence of landslide. Such locations are the mountainous areas of Ethiopia dominantly located in the north-northwest(N-NW), central and south-southwest(S-SW) highlands, and rift margins, which frequently receive high intensity of rainfall for long duration of the year (Mewa & Mengistu, 2021). As cited by (A. W. Azeze, 2019), the mountainous topography of Ethiopia is mainly characterized by a steep slope, deep gorge, frequent fault escarpment, highly weathered rocks, unconsolidated colluvium deposits, residual soil deposits, combined with intensive and extended rainfall which are favorable for the occurrence of slope movements and landslide hazards in most parts of the country (Tsige et al., 2017).

Many of the road infrastructures developed in the country has been regularly hit by landslide incidence and causes human loss as well as financial cost. Particularly, road infrastructure constructions with deep excavation and high fill sections on the most rugged regions of Ethiopia has long histories of landslide incidents.

Jimma-Chida road section is one of the corridor that was frequently affected by the landslide incidences and so far, the road network has not been investigated for its landslide susceptibility. The landslide on the road section extends from Jimma to Chida town has resulted in failure of existing gravel road at different locations, damage on multiple drainage structures and devastation of houses and farmlands. The Ethiopian Roads Administration(ERA) started the construction activity to upgrade the existing gravel road to Asphalt Concrete(AC) surfacing standard road. Prior to the commencement of any permanent construction activities, to reduce the devastating damage of landslide on the road section conducting detail geotechnical and geophysical investigations is important so that the cause of the failures can be identified and a viable remedial measures can be put in place. In addition to this, to identify the root causes of the active landslides and to avoid the occurrence of any additional incidence, conducting an integrated approach of landslide assessment, evaluation of possible failure causes and susceptibility analysis/mapping is essential.

Different researchers and practitioners around the world have used various approaches to conduct landslide susceptibility mapping. Particularly for road construction projects to minimize the risk of failure due to landslide incidence, It is important to conduct landslide susceptibility analysis during the route selection and detail engineering design phase targeting to identify landslide prone areas using existing landslide data. For this purpose, different professions in multiple streams of engineering and geology have implemented various approaches and techniques which mainly categorized as qualitative, quantitative or semi-quantitative approach.

Qualitative approach is widely used method which mainly characterized by its descriptive expression based on the subjective opinion of the professional conducting the analysis. The widely used qualitative methods for landslide susceptibility are Heuristic, Landslide Inventory, Landslide Hazard Evaluation Factor(LHEF) and Slope Stability Evaluation Parameter(SSEP)(Anbalagan, 2019; A. W. Azeze, 2019; Fell et al., 2008).

On the other hand, the quantitative approach unlike the qualitative one it mainly depends on the statistical scheme and the involvement of the professional judgement is not significant(Guzzetti et al., 1999; Kanungo et al., 2009). The most popular quantitative approaches used for the landslide susceptibility analysis are statistical and deterministic approaches.

In statistical method the result of landslide inventory are compared with the physical terrain factors influencing landslides(Casagli et al., 2004).Even though such methods are theoretically simple, they have limitations due to the high level of complexity in identifying the slope-failure processes, methodically collecting and representing all contributing factors related to land slide and applying geomorphological predictive model of failure over large areas (Guzzetti et al., 1999).In addition, there are also various local indicators(creeps, crevices and trenches)that are essential in the forecasting of a landslide event but are not included in the analyses(Casagli et al., 2004).This approach is not equipped to come up with the factor of safety, which can be used as quantitative information about the slope stability (Dou et al., 2015).On the other hand, deterministic approach has been used by engineers to assess the landslide susceptibility of the area using slope stability analysis intended to determine a safety factor. This approach can be used especially when the area under investigation is small and accessible to acquire the required data.

The semi-quantitative approach is the fusion of both the qualitative and quantitative approaches which currently used by the various researchers for the preparation of landslide susceptibility map(Panchal & Shrivastava, 2022).The semi-quantitative approach widely employed by the engineers and practitioners mainly on the area of road sector due to its powerful capability to weight the contribution factors with less landslide inventory data(Fell et al., 2008).

The present work used semi- quantitative approach to conduct landslide susceptibility analysis and mapping of the road section by integrating landslide inventory and landslide contributing factor rating of the area. Finally, a suggestions of preliminary remedial measures are given to avoid the occurrence and exacerbation of new and existing landslides, respectively.

1.2. Statement of the Problem

During the last five decades, significant number of road projects faced a complex problem during their construction and service period due to the occurrence landslides and related failures.

The attention given to landslide investigation and susceptibility mapping prior to the commencement of the construction work is inadequate comparing to the danger faced. Considering the landslide risk on the road networks, it requires detailed landslide studies before starting any construction activities and permanent engineering work. Identifying the factors that initiate and exacerbate the landslide is a great step forward to understand the types and mechanisms of failure and to produce the landslide susceptibility map. The findings of the landslide susceptibility analysis can be used as input by road construction engineers and governmental road asset administration bodies in project planning, route selection, engineering design preparation, construction works execution, road asset management, maintenance and rehabilitation activities. Provision of proper remedial measures for the active landslides also require sufficient understanding of the contributing factors.

The Jimma-Chida road section, that is characterized by the rough and hilly topography, has been affected by recurrent landslides and slope instabilities throughout its gravel road service period. The slope instabilities occur at various scales having different mode of failures and related to multiple factors, mainly the topography of the area, the surface drainage condition, thick residual soil formation, presence of subsurface water and prolonged rainy season.

According to the information gathered from locals, landslides with various extent and severity has happened along the road section at different period of the year especially during and after the rainy season. For example, landslide at km 30+600(JC/S/03) first occurred in August, 2000 and reactivated again in the same month of 2014. It embraces the complex, large scale, very active and rotational landslide.

Similarly, landslide at km 34+300(JC/S/04) first recorded on July, 2014 and recently the landslide is reactivated and propagated to the road prism on August, 2022. The recent landslide causes a total blockage of the road for three days before getting maintenance.

Recently on August 01,2023 night, a long and heavy rainfall reactivate a landslide at km 42+300(JC/S/07), which highly affect the road users by blocking the left side of the road. Temporary maintenance work has conducted just to provide access for the motorized vehicles and pedestrians.

Hence, the road section with multiple active landslide sites, needs a detailed study to evaluate the type and mode of failures, identify the triggering factors and conduct landslide susceptibility analysis by considering different factors which contributes for the occurrence of the landslide in order to mark areas which are prone for the landslide. Maximum attention shall be given for locations which demarcated as susceptible for landslide and special design and construction approach shall be adopted for such areas. Finally, for sections which are already affected by the landslide mitigation and remedial measures shall be proposed to stable the area.

1.3. Research Questions

The research is aimed to answer the following questions:

- What are the major landslide causative and triggering factors along the study road section?
- What are the existing landslide features along the study road section?
- What types of landslides and failure mechanisms characterize the failed road sections?
- How to conduct the landslide susceptibility analysis/map for the road section?
- What will be preliminary remedial measures for the landslide along the road sections?

1.4. Research Objective

1.4.1. General Objective

The main objective of this thesis work is to carry out detail landslide assessment, susceptibility analysis and mapping, and provide preliminary level remedial measures for landslides along Jimma-Chida road section.

1.4.2. Specific Objectives

- To conduct a landslide inventory and assessment along the study road section;
- To evaluate the possible causes of landslide along the study road section;
- To prepare a landslide susceptibility map (LSM) of the road corridor using Analytic Hierarchy Process (AHP) approach;
- To forward a preliminary level remedial measure for the road sections affected by the landslide.

1.5. Scope of the Research

The thesis addresses the described objectives and forward a preliminary level remedial measure. Landslide inventories and mapping are conducted along the road section by field data collection and satellite image analysis. The spatial distribution of the landslides and the contribution of different conditioning and triggering factors are studied systematically. The findings of detail desk study and site survey conducted to characterize the mode of failure, material type, hydrological condition, extent and severity of the landslide has utilized while conducting the landslide assessment and susceptibility analysis. The causative factors for the occurrence of the landslide are identified and preliminary remedial measures are recommended accordingly. The use of the findings and proposed remedial measures of this study are limited to the landslide section along Jimma-Chida road while the method of investigation and analysis can be adopted to other landslide prone areas.

1.6. Significance of the Research

Nowadays, it is obvious that landslide become an important issue and the most concerning problem for the practicing engineers during the project appraisal, route selection, engineering design and construction phase of the road project. Knowing the susceptibility of the proposed routes for the landslide prior to the commencement of permanent construction work will help to avoid or reduce the risk of failure due to the landslide. Similarly, for road sections which are already affected by the landslide it is very essential to evaluate the root causes and provide the viable remedial measures.

Utilizing all the available geotechnical, geological, hydrological, climate and environmental data to assess the existing landslide, analyze the susceptibility, determine the causative factors and provide a practicable remedial measure by combining a systematic multi criteria decision making approach and a powerful tool in ArcGIS environment contributes enormously to address the problem. The findings of this paper is not limited to the subject project, instead it can be used as an input for other road projects facing a landslide problem.

CHAPTER 2. LITERATURE REVIEW

2.1. Landslide

Interdisciplinary professionals such as Engineers, Geologists and Hydrologists often gives distinctive and diverse definitions for landslides and this diversity in definitions implicate the complex nature of the problem. For our purposes, landslide is a general term used to describe the downslope movement of soil, rock, and organic materials under the effects of gravity and also the landform that results from such movement(Crudén, 1991).

Throughout various spectrum of studies there are a several terminologies that are used synonymously with “landslide” such as slope failure, mass movement, landslip, mud flow and others(Highland & Bobrowsky, 2008).Though intense rainfall, earthquakes, volcanic activity, geomorphological and tectonic conditions of the area are the prime natural drivers of landslides, in multiple incidents, disastrous landslides are resulted mainly due to disturbance of natural rough topography during construction of engineering structures and other human activities(Arbanas & Arbanas, 2015, Fell et al., 2008).

2.2. Landslide Classification

A brief classification of landslide is an important part when studying and managing the hazard inflicted due to the landslide. Categorizing the landslide could be taken as the primary work when investigating the phenomena. Different variables have been used by various researchers while classifying the landslide. However, the landslide classification used by Varnes, 1978 is accepted by different researches and it is commonly used to this day. Hence, based on the type of movement, landslide activity, its extent and severity and the type of material involved, landslide can be classified into different types (Crudén, 1996; Popescu, 1994; Pradhan & Lee, 2010; Varnes, 1978). In general, landslides can be classified based on the material type of the affected area and mode of mass movement. For most of the areas, the sliding mass is either rock or soil (or both).The soil material is designated as earth when it mainly composed of sand size or finer material and when the soil mainly composed of coarser fragments it classified as debris(Gaurina-Medjimurec, 2014; Highland & Bobrowsky, 2008).

Other classification criteria has been used by geologists and engineers, such as the current state of activity(Popescu, 1994; Varnes, 1978), magnitude of the slide and depth of slide (Varnes, 1978).Some types of landslides are summarized as;

- a. Landslide classification based on types of material and mode of movement(Varnes, 1978).

Under this classification the name for the types of sliding material are used as rock, debris and earth. Similarly the mode of movement are divided into five types: falls, topples, slides, spreads and flows (Varnes, 1978).An additional sixth type of movement, complex, added by Varnes, 1978 to indicate the combined landslide modes of the mentioned five types of mass movement.

This classification system describes landslide using two nouns; the first one designates the material type and the second denotes the type of mass movement as indicated in Table 2-1 and Figure 2-1.

Table 2-1: Landslide classification(version of (Varnes, 1978), mass movements.

Mode of Movement		Slope Material Type		
		Rock	Residual/Transported Soil	
			Predominantly Coarse	Predominantly Fine
Fall		Rock fall	Debris fall	Earth fall
Topples		Rock topple	Debris topple	Earth topple
Slide	Rotational	Rock slide	Debris slide	Earth slide
	Translational			
Lateral Spread		Rock spread	Debris spread	Earth spread
Flows		Rock flow	Debris flow	Earth flow
			(Soil Creep)	
Complex		A combination of two or more principal types of movements		

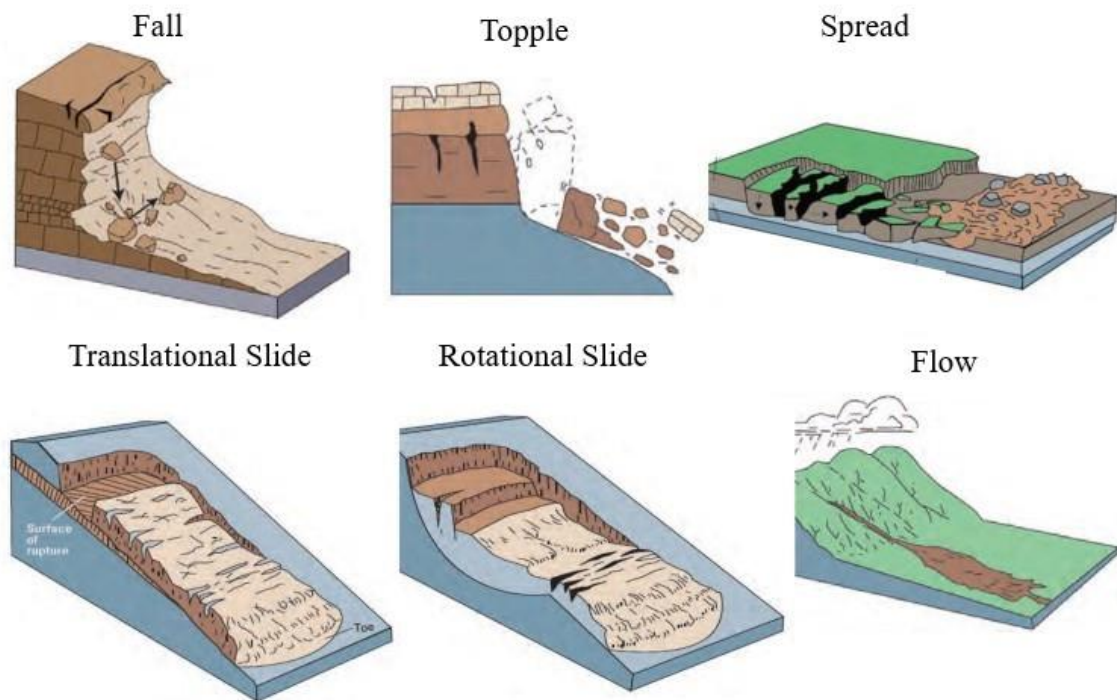


Figure 2-1: Types of mass movement (Cruden, 1996; Varnes, 1978(modified)).

- b. Landslide classification based on the current state of activity(Crudén, 1996; Varnes, 1978).

Considering the current state of activity landslide can be classified as preparatory, active, reactive, suspended, inactive (dormant, abandoned, repaired, stabilized and relict) (Cruden, 1996; Varnes, 1978).

- c. Landslide classification based on the rate of mass movement(Crudén, 1996; Varnes, 1978).

Depending the rate of moving mass, landslide can be classified as extremely rapid, very rapid, rapid, moderate, slow very slow and extremely slow.

- d. Distribution of landslide is also taken as a variable for landslide classification, (Cruden, 1996; Varnes, 1978).

Advancing, retrogressive, widening, enlarging, confined, diminishing and moving landslides can be taken as different types of landslides classified based on the distribution.

- e. Water content of the sliding material (Cruden, 1996; Varnes, 1978)

Moving mass with very wet, wet, moist and dry moisture content can be used as a classification feature of the landslide.

As per (Varnes, 1978) the landslide on any area can be classified using two nouns namely noun describing the sliding material and type of movement, respectively as presented in Table 2-1. (Varnes, 1978). For more complex case the naming of landslide can become more elaborative when sufficient information about the phenomena becomes available. For developing the more complete and explanatory designation of the sliding mass the mentioned descriptors are placed before the two-noun naming using the proper arrangement of terms. The order of descriptors provides a progressive narrowing of the emphasis of the descriptors, primarily by time and then by spatial location, starting with a view of the entire landslide, proceeding with portions of the movement on the area and finally describing the material and type of the landslide (Cruden, 1996; Varnes, 1978).

2.3. Landslide Features and Geometry

Proper characterization of the landslide features and geometry is very important to conduct a landslide assessment, prepare reliable susceptibility map and plan a viable remedial measure (A. Azeze, 2019; Highland (compiler), 2004). The benefit of using systematic approach for identification of landslide features and geometry extends to determining the triggering factors, severity and failure mechanism of the landslide. Most of the time the geometric features of landslide indicates the contributing factor behind, it is like a symptom for the underline health condition of the patient (Varnes, 1978). An schematic diagram indicating most of the features for a complex form of landslide is presented in Figure 2-2 (Varnes, 1978).

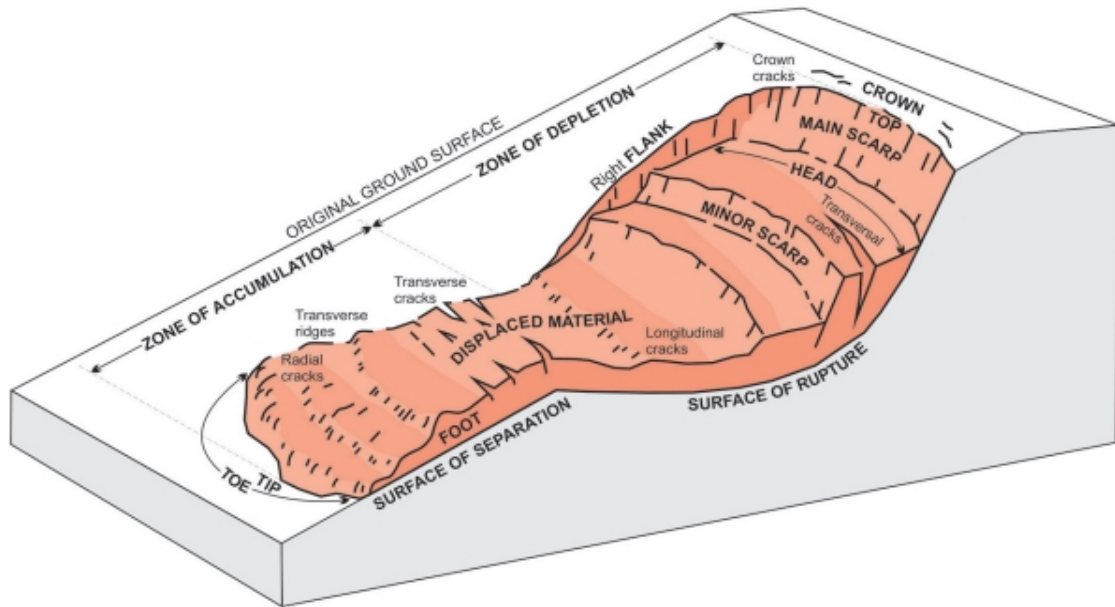


Figure 2-2: Representative diagram landslide features(Varnes, 1978) minor modification.

2.4. Contributing Factors of Landslide

There are several factors contributing for the occurrence of landslide including but not limited to geological, morphological, physical ,environmental and human(Alexander, 1992; Highland & Bobrowsky, 2008). By definition a trigger is an external stimulus such as intense rainfall, earthquake shaking, volcanic eruption, storm waves, or rapid stream erosion that causes a near-immediate response in the form of a landslide by rapidly increasing the stresses or by reducing the strength of slope materials(Arbanas & Arbanas, 2015). In some cases, landslides may occur without an apparent attributable trigger because of a variety or combination of causes, such as chemical or physical alteration of materials, that gradually bring the slope to failure. The requisite short time frame of cause and effect is the critical element in the identification of a landslide triggering factor.(Cruden, 1996; Popescu & Sasahara, 2005).

In general, the landslide causative factors can be classified as factors that contribute to a rise of the shear stress and that contribute to the decline of shear strength of a mass(Terzaghi, 1950; Varnes, 1978). Factors that increase shear stresses include removal of lateral support; surcharge/ overloading, transitory earth stress, regional tilting, removal of support underneath , and increase in lateral pressure(Highland & Bobrowsky, 2008; Popescu, 1994; Terzaghi, 1950).

On the other hand, factors that contribute to decrease the shear strength of slope material include initial state or inherent characteristics of materials and changing or variable factors (Cruden, 1996; Highland & Bobrowsky, 2008). The main factor contributing for landslide is water, the potential of water to cause landslide comes from its influence by either increasing or decreasing of shear stress and shear strength of a soil, respectively.

Even though various researchers classified landslide contributing factors using different parameters and requirements, the landslide causative factors can be classified into two broad groups namely internal and external factors.

I. Internal Controlling Factors

The internal governing factors of landslide are naturally inherent controlling characteristics that define the favorable or unfavorable condition within the slope (Anbalagan, 2019; T. Raghuvanshi et al., 2014). These factors include slope geometry, presence of physically incompetent (soft) earth materials that make up slope surfaces or elevated terrains and also effects of structural discontinuities in areas, potential failure plane (joint, fault, and shear plane), surface/ground water condition and land use.

The mentioned factors are contributing for the landslide by reducing the shear strength of the mass. Any kind of study on the landslide shall make thorough consideration on these and other related factors.

II. External Causative Factors

External factors may trigger slope movement by increasing driving force which exceed the shear strength of the sliding mass. These triggering factors include rainfall, change in water level of water bodies, , underline seismic activity, and human activity (T. Raghuvanshi et al., 2014). In case of the intense rainfall, landslides in soils and highly weathered rock mostly occurred on steep slopes during and after a long and intense rainfall season, and the combined effect of intensity and duration of the rainfall may be the main factor to trigger them. (Cannon & Ellen, 1983; Cruden, 1996). Similarly, the abrupt lowering of the water level (rapid drawdown) against the slope can lead to landslides in the manmade structures such as earth dam, canals and dykes as well as on natural features like along coastlines, lake banks and rivers. Following the flood stage rapid draw down can happen when the water level in the reservoir or canal fall abruptly.

The soil slope adjacent to the falling water level subjected to higher shear stresses and potential instability is imminent unless pore pressure dissipation mechanism put in place(Gaurina-Medjimurec, 2014; Nugraha et al., 2018; Terzaghi, 1943; Tsige et al., 2017).

An earthquake which cause strong ground movement has trigger strong landslide with various severity under different geologic and topographic setting. Rock fall, soil slides and rock slides are common types of landslide which mainly related with the seismic activity of the area.(Cruden, 1996).

2.5. Landslide Susceptibility Analysis

According to (Brabb, 1985), landslide susceptibility is the likelihood of a landslide happening in a region considering both intrinsic and extrinsic parameters. It provides information about “where” landslides are likely to occur. Similarly, landslide susceptibility maps are convenient tools to designate areas that are suitable for settlement, infrastructure development , agriculture, industry zone, town expansion or other purposes as well as to demarcate risk-prone areas that should be avoided, protected or rehabilitated before implementation of any developmental projects which could change the naturally stable condition of the area (Fell et al., 2008; Petschko et al., 2014).Landslide susceptibility analysis requires an inventory of the phenomena which are active in the boundary of the area under investigation and a sufficient knowledge of all the factors that may contribute their share for the occurrence of the landslide(Arbanas & Arbanas, 2015; Highland & Bobrowsky, 2008).

In the case of road design and construction works, landslide susceptibility analysis and mapping is useful tool to differentiate areas that are suitable for the road construction purpose as well as to mark risk-prone areas that should be investigated before the commencements of any permanent engineering works. After multiple researches and studies, various methods are developed for landslide susceptibility evaluation and mapping. These techniques are grouped into three main groups such as quantitative(statistical method), qualitative(expert evaluation method), and semi-quantitative(Crudén, 1996; Fell et al., 2008; Highland & Bobrowsky, 2008; Kanungo et al., 2009).

There are basic assumptions which should be taken in to account while conducting landslide susceptibility analysis and mapping.

- a) While preparing the landslide susceptibility map the combined importance of the past history and present condition of the area is enormously high. The landslide in future are more likely to happen under identical lithological, climate, geological, geomorphological and hydrological condition with landslide phenomena happens in the previous time. These conditions are the main factors for the last and present landslide incidences and external triggering factors should be considered since they are aggressive and unpredictable(Guzzetti et al., 1999; Kanungo et al., 2009).
- b) Landslide occurs under the unique geomorphological and geological features can be determined, categorized and mapped both through site investigation and image interpretation(Fell et al., 2008; Guzzetti, 2005).
- c) Most of landslide incidents happen in the past left with apparent geomorphological structures which are identifiable for mapping and classification during field survey or remote sensing .(Guzzetti et al., 1999; Serdarevic & Babic, 2019; Varnes, 1978).
- d) The landslide process affected by physical laws that can be defined in statistical, empirical or analytical approach. Factors that contribute for the occurrence of landslide with different degree of influence can be identified and analyzed to produce a predictive model of landslide susceptibility of the area(Guzzetti, 2005; Guzzetti et al., 1999).
- e) The occurrence of landslide across the study area can be anecdote from the expert evaluations, analyzed from contributing factors condition or drawn from the mechanical modelling. Hence, an area can be categorized into specific susceptibility zone based on different probabilities(Casagli et al., 2004; Guzzetti, 2005; Guzzetti et al., 1999).

2.5.1. Qualitative (Expert Evaluation) Method

In qualitative(Expert Evaluation) method, the data used are non-numeric and descriptive which significant proportion of subjectivity is used in the production of landslide susceptibility analysis of the area(Tyagi et al., 2022a).

This method mainly includes heuristic, landslide inventory mapping, landslide hazard evaluation factor(LHEF) and slope stability evaluation parameters. (SSEP).

a. Heuristic method

The Heuristic method is used the expert opinion of an individual who conduct the susceptibility analysis to produce the landslide susceptibility map(Fell et al., 2008).However, its subjectivity while rating the contributing factors is the main demerits of this method. The reliability of this method directly depends on the how well the expert demonstrates the geotechnical. geological, geomorphological and environmental process on the area(Guzzetti et al., 1999).

b. Landslide inventory method

The landslide inventory approach also known as distribution analysis method is the simplest and direct qualitative method of landslide susceptibility mapping. This method simply produced the susceptibility map directly from the collected landslide inventory data (Casagli et al., 2004).The landslide inventory data can be acquired from field survey, previous event record data, satellite imaginary and aerial photographs The major disadvantage of this method is the susceptibility study excludes the areas outside the existing landslide where there is no active landslide which can recognize during the study period(Guzzetti, 2005).This method is also not capable of giving information on the temporal changes in landslide distribution(Kanungo et al., 2009).

c. Slope Susceptibility Evaluation Parameters (SSEP)

The Slope Susceptibility Evaluation Parameter(SSEP) approach mainly use both intrinsic causative and extrinsic triggering factors in order to generate the landslide susceptibility map(T. K. Raghuvanshi et al., 2014).

d. Landslide Hazard Evaluation Factor

Unlike the SSEP approach, Landslide Hazard Evaluation Factor(LHEF) is exclusively relay on major intrinsic contributing factors such as geomorphology, ground water, hydrological and drainage condition of the area, land use/cover and lithology of the area(Anbalagan, 2019).Landslide causing factors such as rainfall and seismicity of the area under investigation are not part of the landslide susceptibility map.

2.5.2. Quantitative(Statistical) Method

Quantitative methods generates numerical estimates (probabilities) of the chance for the landslide phenomena in any hazard zone(Guzzetti et al., 1999). The statistically based methods assess the correlation between the landslide contributing factors (both intrinsic and extrinsic) and the existing landslide occurrence. Such approaches supported by geographic information system (GIS) expertise have been used to generate landslide susceptibility maps (L.Ayalew et al., 2005).This approach mainly rely on the association between every factors and the existing landslide distribution (Fell R et al., 2008).The statistical relationship then established between the mapped existing landslide during the landslide inventory and possible contributing factors.

Since the method is highly depends on the availability of the quality data, limitation raised for this method result from errors during mapping, inaccurate landslide inventory data and poor resolution of some data sets (Fell R et al., 2008). The main advantage of quantitative method over expert evaluation method is, the earlier method mainly relies on the mathematical model and expressions but less on the observation of the expert. This property makes quantitative method give a reliable result unlike the qualitative method (Kanungo et al., 2006).

Statistical method is one type of quantitative methods, which used the relationship between the old/existing landslide and the contributing factors to evaluate the spatial distribution of slope stability (Carrara A. et al., 1992).

The difficulty to find detailed and quality landslide factor data is one of the challenges of statistical method, which makes this method time consuming and cause logistical challenge to acquire over a large area. Statistical method further divided into two broad categories namely bivariate and multivariate method (Kanungo et al., 2006).In this analysis the use of GIS powerful tools are significantly useful.

a) Bi-variate Statistical Analysis

In bi-variate statistical analysis method, the existing landslide distribution layer prepared as landslide inventory data is associated to the selected landslide factor data layers. Using this method has enable to determine the contribution of each factor for the landslide phenomena at large which makes this method simple and precise(A. Azeze, 2019; Guzzetti et al., 1999; Remondo et al., 2003) .

The weight to the landslide causative factors are calculated based on the landslide densities computed for each factors. This computation involves the overlay of landslide distribution layer on each of landslide factor data layers, and calculation of landslide density accordingly(Kanungo et al., 2009).

The bi-variate statistical method outcome mainly depends on the correlation between each class of contributing factors and the active landslide distribution currently exists on the area(Fell et al., 2008). Especially on the weight assignment process of this method some degree of subjectivity involves and Multi-Variate Statistical Analysis approach is introduced.

b) Multi-variate Statistical Analysis

This method was developed in Italy mainly by (Casagli et al., 2004; Guzzetti, 2005) .Multi-variate approaches consider comparative influence of each causative factors data layer to the overall landslide susceptibility of the area (Kanungo et al., 2009).The method compute composition of the area with and without landslide for every pixel and multi-variate statistical method is introduced for reclassification of susceptibility class. (Paradeshi, Sumant, Atade, & Suchitra, 2013).

Unlike the bivariate statistical method, the multivariate statistical method enables to perform multivariate statistical analysis(A. Azeze, 2019). Different Multi-variate statistical techniques have been employed for various works of the landslide susceptibility mapping. The most known and practiced are discriminant analysis, linear and logistic regression, and neural networks(Dou et al., 2015; Guzzetti et al., 1999).

2.5.3. Semi-Quantitative Method

The semi-quantitative method is the widely used method which evolved from the qualitative approach(Corominas et al., 2014; Guzzetti et al., 2008).To improve the high dependency of the qualitative method on the expert evaluation and its subjectivity, the semi-quantitative method adopt the principle of ranking and weighting of the parameters which contributes for the occurrence of landslide(Corominas et al., 2014; Enigda & Suryanarayana, 2021; Guzzetti et al., 2008).Multi Criteria Decision Analysis(MCDA) is the very powerful semi-quantitative method used for the landslide susceptibility analysis.

A number of methods have been developed which used a multi criteria decision making approach such as fuzzy logic, analytical hierarchy process(AHP),weighted linear combination and ordered weighted average are well known and frequently used(Abay et al., 2019; Jazouli & Barakat, 2019; Panchal & Shrivastava, 2022; Tesfa, 2022).Analytical hierarchy process(AHP) is a multi-criteria and multi-objective decision making approach which used for selecting and ranking the landslide contributing factors in the possible rational mode(Arsyad & W Hamid, 2020; Mehmood et al., 2022; Panchal & Shrivastava, 2022).

2.5.3.1. Analytic Hierarchy Process (AHP)

Landslide susceptibility maps are essential tools which can help engineers and planners when designing and constructing engineering structures, in particular linear engineering structures on landslide prone areas (Panchal & Shrivastava, 2022; Tesfa, 2022).

The need for the landslide maps is raised since it shows the possibility of the occurrence of landslide along the road corridor(Panchal & Shrivastava, 2022). The final result of landslide susceptibility map is mainly relay on good understanding of the contributing factors of landslides, either intrinsic causative or extrinsic triggering factors. As indicated on the previous discussion, various approaches were developed to determine the weight of contributing factors for preparation of landslide susceptibility maps.

The Analytic Hierarchy Process(AHP), formulated by (Saaty, 1977),is well developed semi-quantitative method which employ a pair-wise comparison matrix of the different parameters for the occurrence of landslide(Kavzoglu, 2015). This approach serves as a systematic mechanism in breaking multi-objective, multi-criteria and complex problems in distinct simple criteria and weightage is given for all criteria based on their corresponding contribution for the occurrence of landslide. The development of powerful computer programs has been found to be incredibly helpful in the studies related to landslide phenomena. A geographical information systems(GIS) is one of such computer tools which collect, store, retrieve, display and transform spatial data(Burrough & McDonnell, 1998).Integrating various spatial data of different layers and define the influence of each contributing factors on the landslide occurrence becomes possible with the help of GIS (Intarawichian & Dasananda, 2010).

Nowadays, the Analytic Hierarchy Process method, is widely used in landslide susceptibility analysis as a quasi-quantitative approach. This method found to be the most precise approach for computing the proportion of the criteria and determination of relative amount of the subject factors using the pairwise comparison(Mehmood et al., 2022).The statistical comparison is used to indicate the importance of the given factor on the landslide susceptibility analysis by correlating with the other factor. The main advancement made by using AHP approach as a semi-quantitative method of landslide susceptibility mapping is that it is equipped with controlling mechanisms to assure the consistency of the decision taken regarding the weighting of the landslide causative factors. The consistency ratio(CR) is used to confirm the consistency used to construct a pair-wise matrix and avoid the inconsistent solutions(Jazouli & Barakat, 2019). The consistency ratio(CR) is defined as the ratio between the matrix's consistency index and random index(Intarawichian & Dasananda, 2010).Generally the AHP approach implemented the following steps like; construct a hierarchal structure of the problem, conduct binary comparison of the criteria against the main deliverables, formulate comparative multi-criteria matrix, compute priority vector, calculate the consistency ratio(CR),form a comparison of criteria, develop a sub-criteria based on the total number of criteria subjected, compute the performance of the relative value of each criterion by contribution to the value of the criteria, determine the performance of the value of each alternative by report to project aggregation and determine the final output(Jazouli & Barakat, 2019).

2.5.4. Deterministic Method

This method used a geotechnical approach which utilize a physically based model which demonstrate the physical mechanism leading to the occurrence of landslide based on simple mechanical principles(Pardeshi et al., 2013).The main advantage of this method over the statistical approach is it does not need historical data and become more applicable for areas without a landslide inventory records.

The geotechnical method is mainly relying on site investigation data in order to determine the engineering properties and extents of soil/rock material , surface and subsurface water condition, the slope geometry, distinct location of landslide, failure mechanism of the slide mass, depth and extent of the landslide(A. W. Azeze, 2019). These method is suitable for the slope stability analysis of the road projects enhanced with detailed geotechnical investigation.

By processing the findings of detail geotechnical investigation, the landslide analysis is carried out using different methods. Limit equilibrium and finite element methods are popular approaches adopted on the area of geotechnical method of landslide analysis.

The mountainous areas of Ethiopia with different topography, geological setting, hydrology (surface and ground water), climatic condition, land use/cover are repeatedly affected by landslides which triggered due to one or combination of the mentioned factors. Long duration of rainfall, especially heavy storms in summer followed by infiltration of water have played a vital role for various severe landslides and failures across the country. Such rainfall-induced landslides are the most frequent ones in many parts of Ethiopia such as Dessie, Abay Gorge, Tarmaber, Jemma Bain, Debresina, South-western Ethiopia and so on (Addis, 2022; A. W. Azeze, 2019; Enigda & Suryanarayana, 2021; T. K. Raghuvanshi et al., 2014; Woldearegay, 2013). Consequently, the landslide triggered due to the rainfall shall be studied thoroughly.

The limit equilibrium is one of the classic and popular analysis method that has been used routinely for geotechnical problems because of its simplicity and reliability (Matthews, C., Farook, Z. & Helm, 2014). The shortcoming of the limit equilibrium method is, it is not equipped with the capacity to determine the ground response under the applied stress.

On the other hand, Finite element method is capable of determining the response of the ground under stress, for this purpose the method is become more preferable by practitioners for the purpose of analyzing engineering problems in general and slope stability in particular. All the discussed approaches used for landslide susceptibility analysis is presented in the Figure 2-3.

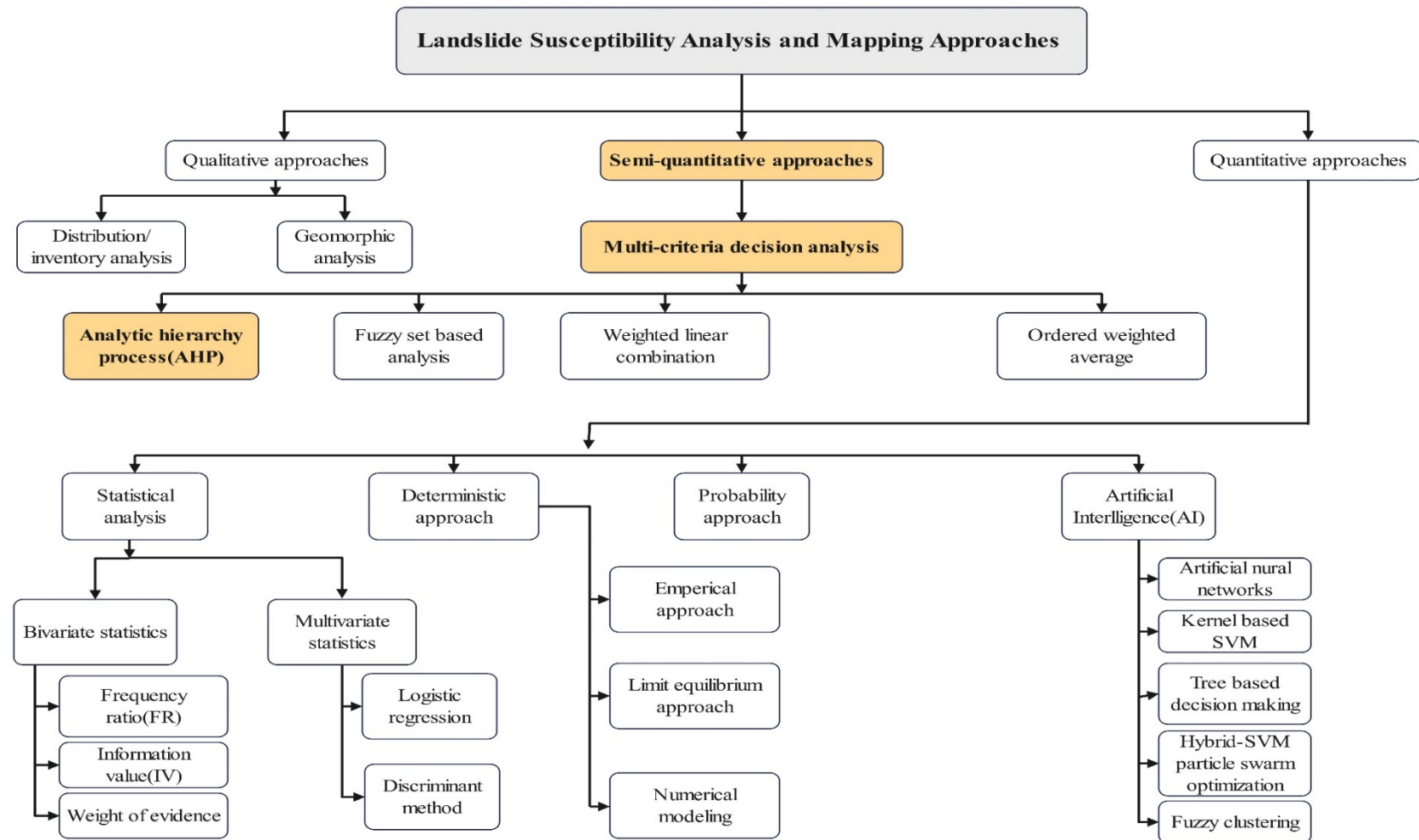


Figure 2-3: Landslide susceptibility analysis and mapping approaches(Shano et al., 2020)

2.6. Landslide Prevention and Remedial Measures

Landslide assessment and susceptibility analysis is a part of the landslide study to reduce the possibility of landslide incidence by conducting detail study of the given area. When the area is already affected by the landslide or has an imminent potential to fall, it requires viable remedial and mitigation measure to avoid or minimize the damage (Highland & Bobrowsky, 2008; Popescu & Sasahara, 2005). Seeking the recommendation of engineers is always advised when possible to avoid a catastrophic failure of engineering structures. When dealing with prevention of landslide due to road construction activities, the simplest solution is to evade road construction on hilly topography with rough terrain and sections with the scar of old or active landslides; however, this is not always practical. While trying to prevent the landslide, the route selection and engineering design process mainly rely on the finding of landslide susceptibility analysis, mappings and the characterization of the affected areas to reduce the occurrence of additional failure by landslide. In cases where landslides already affect serving structures or it is impossible to avoid its existence, physical controls can be used. Though there is not too much experience on the context of Ethiopia, monitoring and warning system could be effective for the avoidance and early mitigation of the landslide.

As previously witnessed on multiple incidences, water plays a vital role for the landslide. Controlling both the surface and sub-surface water could be the only viable remedial measure for some landslide sites. Some of the remedial measures related with water control methods are;

- Diverting the surface water away from areas affected by or susceptible for landslide;
- To reduce the potential for the ground water table rise, drain the ground water away from the landslide;
- To avoid the saturation of the landslide prone area, covering it with an impermeable membrane can be taken as a remedial measure;
- If possible, avoid irrigation work near the landslide susceptible areas.

Likewise, provision of physical support can be proposed as a remedial measure to stop the movement of the sliding mass and restrain it. Retaining walls are structures built to support a soil mass permanently without any major deformation.

They also used whenever right of way limitation make it impossible to extend the side or back slope of a fill or an excavation with flatter inclination. In addition, retaining walls are also used to protect the slope toe from erosion by river and surface water scour. However, these walls cannot be used as a measure to avoid the occurrence of landslide rather they are used as a corrective measure for the existing failure.

2.7. Previous Landslide Studies in Ethiopia

Though many researchers have work tirelessly to identify the nature, type, cause, and consequence of the landslide in a different parts of the country, there was a limitation on extending the practice toward landslide assessment and susceptibility analysis for road networks. On most of the routes that affected by landslides there was a gap on conducting detail and systematic landslide assessment and susceptibility analysis during the project planning, route selection and design phases. Due to this practice multiple landslides are encountered after the commencement of the construction work or during the service period of the road, which cause loss of human life and significant damage on the road asset. In general, various researchers were conducted numerous researches on the landslides occurred at various part of the country. However, most of the researches are conducted from geological perspective and there was a gap on using the findings of the studies for provision of innovative engineering remedial measures.

(Melese et al., 2022) used Analytic Hierarchy Process(AHP),Frequency Ratio(FR) and Shannon Entropy(SE) for landslide susceptibility mapping of Dejen district, Ethiopia. In their study the landslide inventory map is produced for a total of 87 landslides and a total of 12 landslide factors are used for the generation of the landslide susceptibility map. As per their study AHP is found to be the best method comparing to the other two approaches.

(Vařilová et al., 2014) has studied the selected four areas in Dessie town which affected by the frequent landslide. They conduct landslide inventory using the digital elevation model and a high resolution satellite image with in ArcGIS platform.

They describe the main causes of landslide along the selected section and concluded that the landslide continued to be a problem and appropriate planning, provision of proper drainage structures and giving maximum attention for the landslide event during the design phase of engineering projects shall be considered as a preventive measure.

Similarly,(Suryanarayana et al., 2021) has conducted landslide hazard assessment of Dessie town. Under his study the role of anthropogenic activities was recognized as one of the main decisive factors of landslide in the study area.(Temesgen et al., 1999) investigated landslide hazard of the slope in Dabicho Ridge, Wondo Genet area. Under this study, geological-geomorphological field investigation has conducted to determine the mechanism of landslide occurred at Dabich Ridge of Wondo Genet area.

Ayenew & Giulio, 2005 have done an inventory of landslides and susceptibility mapping of Dessie area using classical weighted overlay approach. They produced the landslide susceptibility map for hillside areas of Dessie which covers about 16 km². Based on their study it is concluded that the presence of loose unconsolidated material over highly weather basalt on the steep slope sections combined with high rainfall provides a suitable environment of the occurrence of landslide.

(Hearn, 2018) conducted a study regarding the slope hazards on the Ethiopian road networks. Under his publication he studied a landslides happen along Abay gorge, around Kombolcha area, Sodo district, Jimma zone, Debre Markos and Dire Dawa district. He concluded that reactivation of old landslide is a dominant cause of landslide in the country and triggered by alteration of the geometry and drainage condition of the areas.

(Wendim, 2023) has studied the causes, features and failure mechanism of landslide along Gedo-Dilb road corridor of Northern Ethiopia and produced susceptibility map employing Analytic Hierarchy Process(AHP) method. Under his study slope angle, distance to stream, distance to road, lithology of the area, land use/ cover and curvature are identified as the major factors contribution the landslide. Based on his study the study area is affected by a total of 103 active landslides composing 8.44 km² area.

Around 75% of the collected landslides fall in the high and very high landslide susceptibility class which also proven by the high Area Under Curve(AUC) value of around 0.82.

(Addis, 2022) used Information Value(IV) and Frequency Ratio(FR) approach to prepare the landslide susceptibility of Chemoga Watershade, Ethiopia. Under this study ten landslide conditioning parameters were chosen considering the data quality and accessibility. It is confirmed that both Frequency Ratio(FR) and Information Value(IV)

approaches are found to be simple, effective and reliable methods with the AUC value of 0.870 and 0.901, respectively.

The landslide hazard mapping and assessment around Debre Markos town using a GIS based statistical methodology were prepared by (Manderso, 2021). In his research lithology, slope, aspect, elevation, curvature, land use/ cover, distance to stream and distance to fault are identified as controlling factors. The result of model stipulate, 17.15% (40.60 km²), 25.53% (60.45 km²), 28.04% (66.39 km²), 18.93% (44.83 km²) and 10.36% (24.54 km²) area fall into very low, low, moderate, high and very high susceptibility zones respectively.

(Mulatu et al., 2009) have studied the landslide hazard zonation around Gilgel Gibe-II Hydroelectric Project, South-Western Ethiopia. Particularly, he studied the newly constructed road from Fofa town to Gilgel Gibe-II powerhouse in south western Ethiopia. For the study of this road section he utilized the landslide hazard evaluation factor rating scheme (LHEF) (Anbalagan, 2019). As per their study 54% of the road section fall in high susceptibility 34% categorized under moderate and the remaining 12% in low landslide susceptibility zones.

(T.K. Raghuvanshi et al., 2014) have studied the slope stability susceptibility evaluation parameter (SSEP) rating scheme for landslide hazard zonation. they consider the factors such as slope geometry, slope material, structural discontinuities, land use /land cover and ground water condition, seismicity, rainfall and manmade activities. (Asmare, 2022) has conducted the landslide hazard mapping and assessment around Debre Markos town using a bivariate statistical method. The susceptibility map indicates that 17.15% of the studied area classified as no susceptible zone, 25.53%, 28.04% and 44.83% of the area considered as low, moderate and high susceptibility zones respectively. The remaining 10.36% is a highly susceptible zone.

(Tesfa, 2022) has used GIS based Analytic Hierarchy Process (AHP) and Frequency Ratio (FR) methods to prepare landslide susceptibility mapping of Abay Gorge. He utilized both quantitative and semi-quantitative methods to produce the landslide susceptibility map of the Abay Gorge.

From his study the segment of Abay Gorge from Dejen town to the Renaissance Bridge is categorized into five susceptibility zones as extremely low, low, moderate, high and very high.

(Adem et al., 2020) have utilized GIS based Logistic Regression(LR) model for landslide hazard mapping of Ensaro District, North Ethiopia. On this study seven controlling factors were considered for landslide zoning, these are distance to stream, slope aspect, slope, elevation, land use/ cover, lithology and normalized difference vegetation index(NDVI). Using the Logistic Regression(LR) method 32.00% of the studied area is classified as highly susceptible zone.

From a review of previous landslide study in Ethiopia, the mostly occurring types of landslides are, earth/debris flow, rock/soil slide, rock/earth fall, rock toppling(Mewa & Mengistu, 2022; Woldearegay, 2013), and the factors causing the phenomena are complex geological condition, hydrological and hydrogeological condition, complex terrain surficial process, slope geometry change, rainfall and improper land use practices.

(Woldearegay, 2013) review the distributions and controlling factors of landslides in the Ethiopian highlands and concludes that the mountainous parts of Ethiopian are recurrently hit by landslides mainly after intense and prolonged rainy season which associated with the rise of ground water to shallower depth. Similarly,(Mewa & Mengistu, 2022) conduct an assessment of landslide as a catastrophic phenomenon in the Ethiopian context and prepares the landslide distribution map in the country. In addition,(Mewa & Mengistu, 2022) discussed the use of advanced technologies for hazard map preparation and landslide mitigation planning. The distribution of landslide in Ethiopia as per (Mewa & Mengistu, 2022; Woldearegay, 2013) is presented in Figure 2-4.

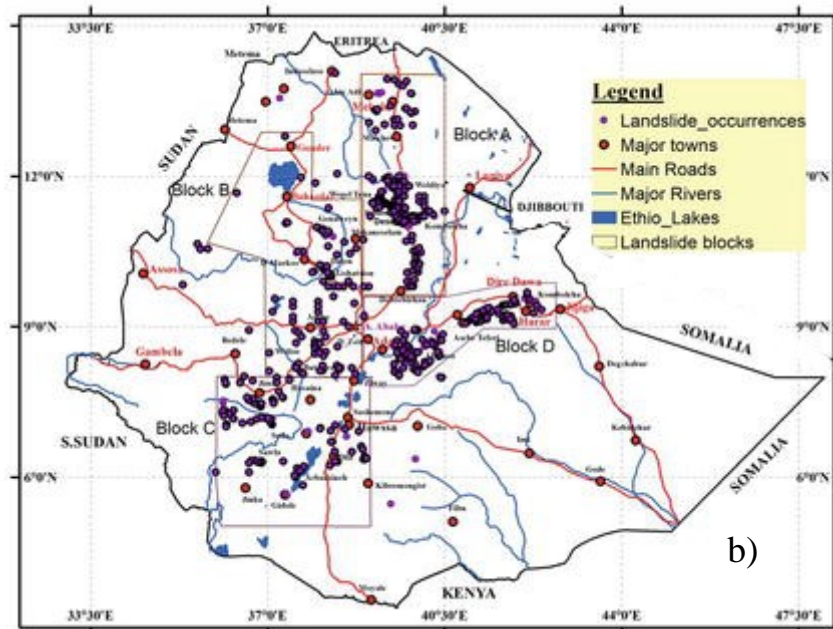
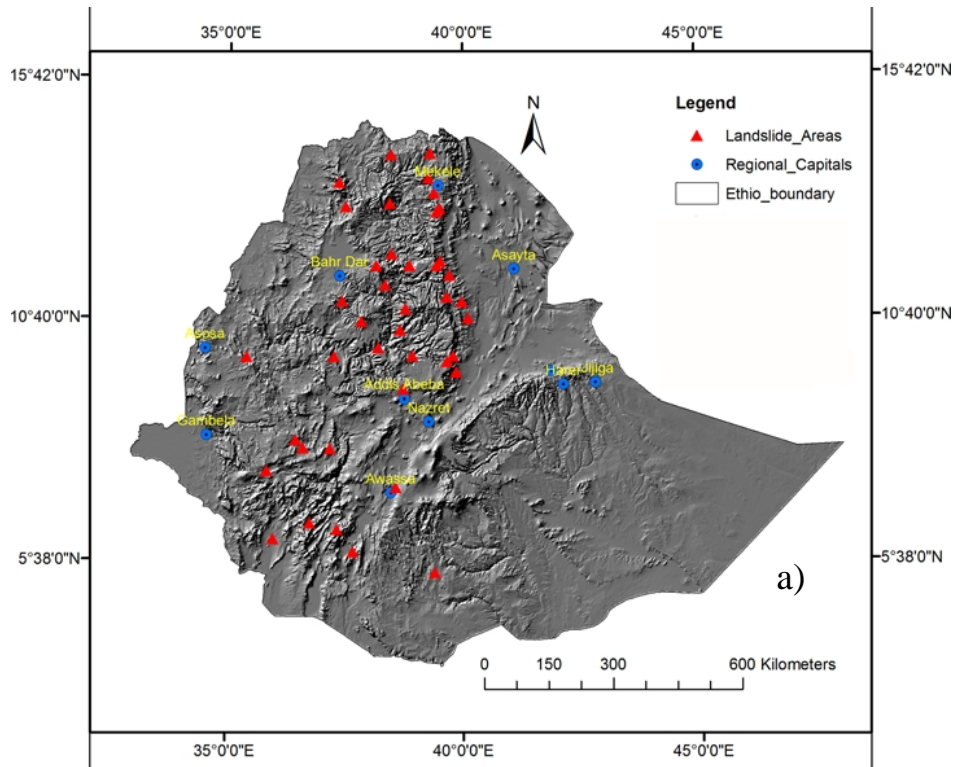


Figure 2-4: Landslide distribution in Ethiopia;

a)(Woldearegay, 2013) b)(Mewa & Mengistu, 2022)

2.7.1. Gaps on Previous Landslide Studies

During the past decades, the road network in Ethiopia has expanding enormously which leads to large volume construction activities on different topographic. Although various landslide researches has conducted at different parts of the country, their contribution for avoiding the problem prior to its occurrence was not satisfactory. There are also few works have done using a Multi Criteria Decision Making(MCDM) approaches to exploit the advantages of this method over the other on preparing the landslide susceptibility map. Particularly on the road construction projects the attention given to study the landslide susceptibility of the area and to include its findings into consideration during the design and construction phase has not match the scale of the problem. Rather, most attention has given to provide a remedial measure after the occurrence of landslide which has big financial implication.

Most of the researches conducted on the landslide susceptibility mapping are used either fully qualitative or quantitative approach which requires higher level of expertise judgement or large amount of landslide inventory data. For the road corridor study, gathering ample landslide data is a very challenging task and sometime not feasible. The analytic hierarchy process(AHP) method enable the researcher or practitioner to weight the contribution factor based on the pairwise comparison matrix and prepare the landslide susceptibility map.

The south-west region in general and Jimma-Chida road section in particular has been previously affected by multiple landslides. However, detail studies were not conducted for the area. Hence, this work mainly intended to conduct landslide assessment and produce landslide susceptibility map of Jimma-Chida road section.

CHAPTER 3. RESEARCH METHODOLOGY

The devastating effect of landslide on the road infrastructure leads to the loss of life, property damage and deterioration of living environment. Prior to the occurrence of the landslide the need for identifying the areas which are prone to the landslide phenomena is very essential. (Intarawichian & Dasananda, 2010).

To identify the type, contributing factors, extent and severity of the landslide and give feasible remedial measures, landslide assessment and susceptibility mapping is conducted along the road section. For the subject road corridor landslide assessment and susceptibility mapping has been carried out by utilizing all the in-situ survey, large volume of data collection and analysis. All works conducted for the intended purpose has common intention to provide landslide assessment and susceptibility analysis by employing systematic approaches to study the natural conditions of the area and combining all parameters contributing for the slope instability. Landslide mapping for engineering purpose (engineering geological map), landslide inventory survey, data collection, processing and analyzing the landslide controlling factors were conducted to meet the objectives of the study. The general research approach followed for this study in summarized in Figure 3-14.

3.1. Description of the Study Area

3.1.1. Location of the Road Section

Geographically, the road segment with a total length of about 80.0 km is located in the Seka Chekorsa and Dedo Woredas of the Jimma Zone in the Oromia, and the Konta Woreda of the Southwest Ethiopia Regional States. The area is part of the southern massive highland and particularly lies in the Gibe and Gojeb River Basins. The road starts at the junction of Jimma-Mizan Road at the outskirts of Jimma town which is about 346.0 km south-west of Addis Ababa and terminates at Chida town (Figure 3-1).

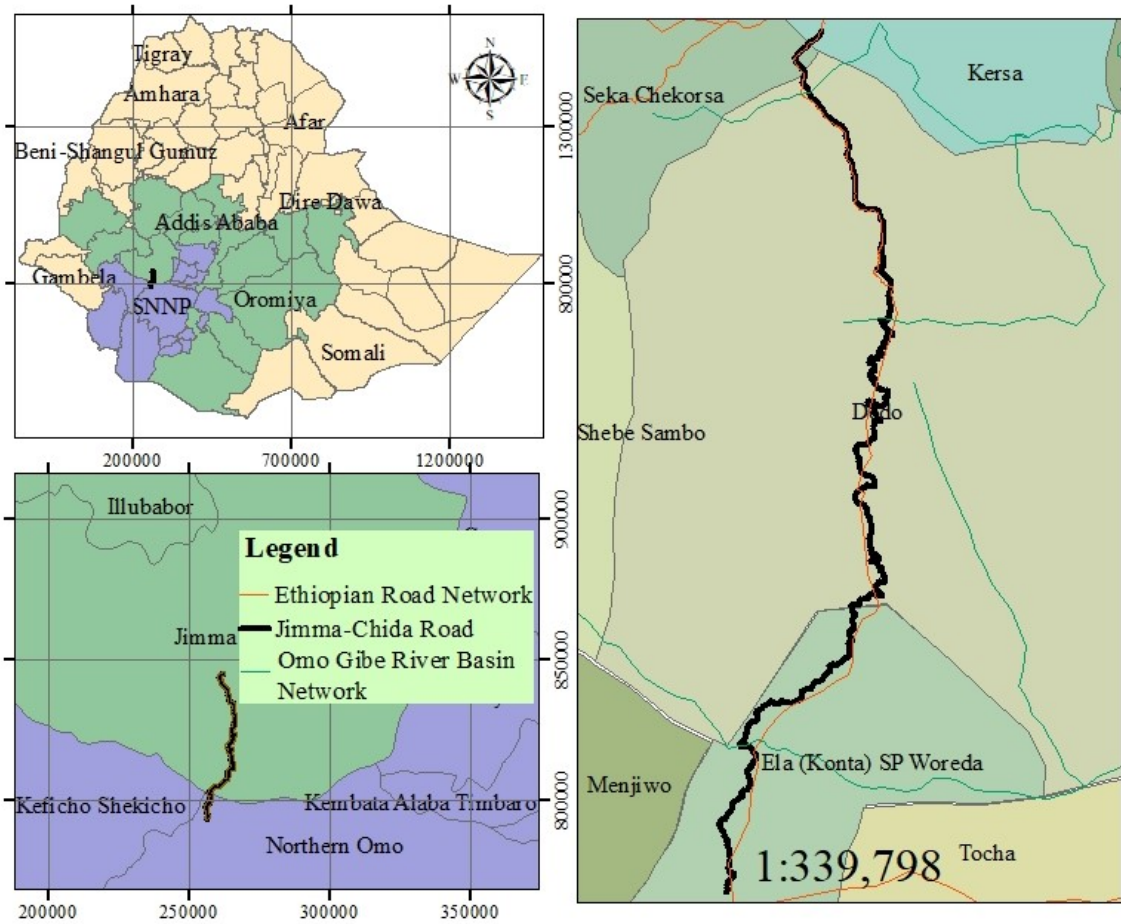


Figure 3-1: Location map of the road section.

3.1.2. Topography

From site reconnaissance and topographic map of the area produced from 30.0 m resolution Digital Elevation Model (Figure 3-2), the terrain traversed by the road is dominantly rolling topography (5-25 degrees) while the remaining section consists of mountainous terrain with short random flat stretches. The project road corridor is densely populated and intensively cultivated with some sections traversing forestlands and woodland areas.

The road section starts at an elevation of 1705 m a.m.s.l (at outskirts of Jimma town) and is 1765 m a.m.s.l at the end (near Sodo junction) in Chida town. The altitude rises from 1705 m to 2625 m a.m.s.l and again falls toward 1765 m after it passes Delbi town.

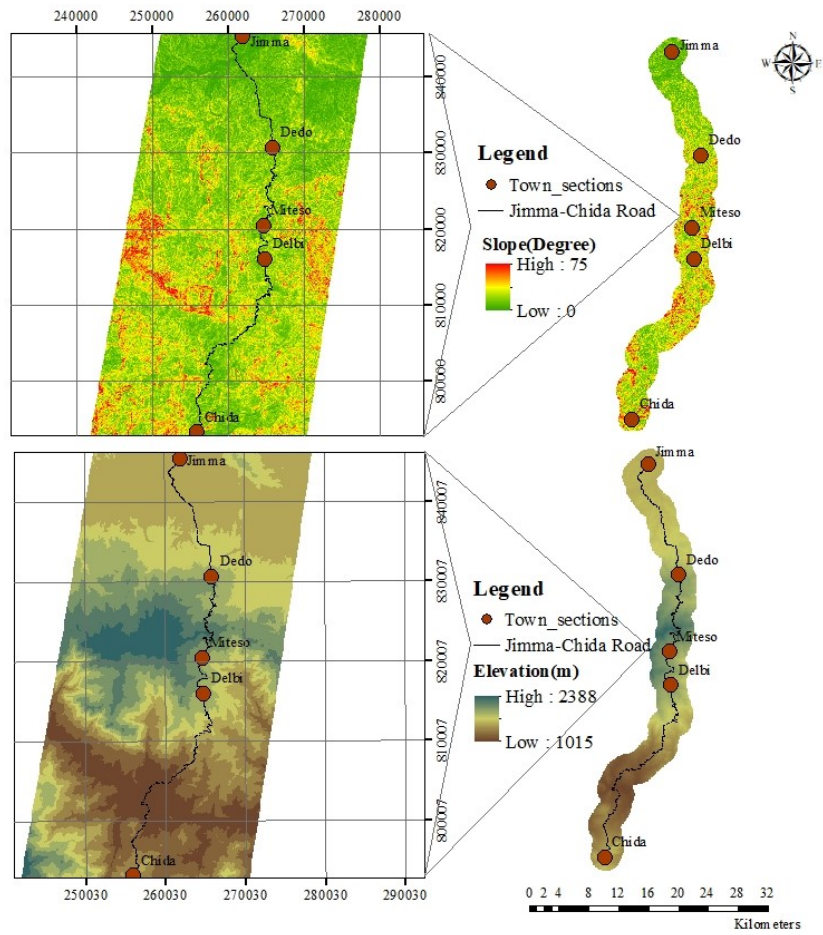


Figure 3-2: Slope map of the road section.

3.1.3. Geomorphology

The geomorphic setting along Jimma-Chida road corridor is primarily depends on the internal (tectonic and volcanic) and external forces that took place in the past geological time one event after the other. The project and its surrounding formed part of the central Ethiopia plateau and eastern most part of the rift margin and floor of the Main Ethiopian Rift (MER). The geomorphology of the present landscape of the study area is built up through sliding, erosion, volcanism and denudation processes(Geological Survey of Ethiopia(GSE), 2015). The geomorphological landforms in the area as indicated in Figure 3-3 are:

Volcanic land forms

The most part of the study area is covered by this geomorphological volcanic land forms. This land form type covers volcanic ridges, high lands, and other fissured eruptions forming trachyte and basaltic lava flows.

Structural land forms

This structural landform mainly comprises Grabens. Normal faults which are trending NW or SE direction forms Jimma Grabens. Jimma town is situated in these Grabens. The settlement area is flat to some undulating lowland.

Denudational land form

The area consists of denuded, well drained, steep and undulating to rugged landscapes. Regarding its lithology, it comprises mainly Trachyte, and Basalts.

Residual land forms

Residual land form is characterized by land-scape produced by disintegration of rock fragments and in-situ deposition. This landform principally forms the northwestern and northeastern parts of the area. This residual landform is the product of highly decomposed bed rocks such as basalt.

Alluvial land forms

These type of land forms are found around Jimma city and consists of quaternary alluvial deposits and is located mainly in WNW and SE of the area. It is composed of gentle to plain topography with silty clay to silty soil.

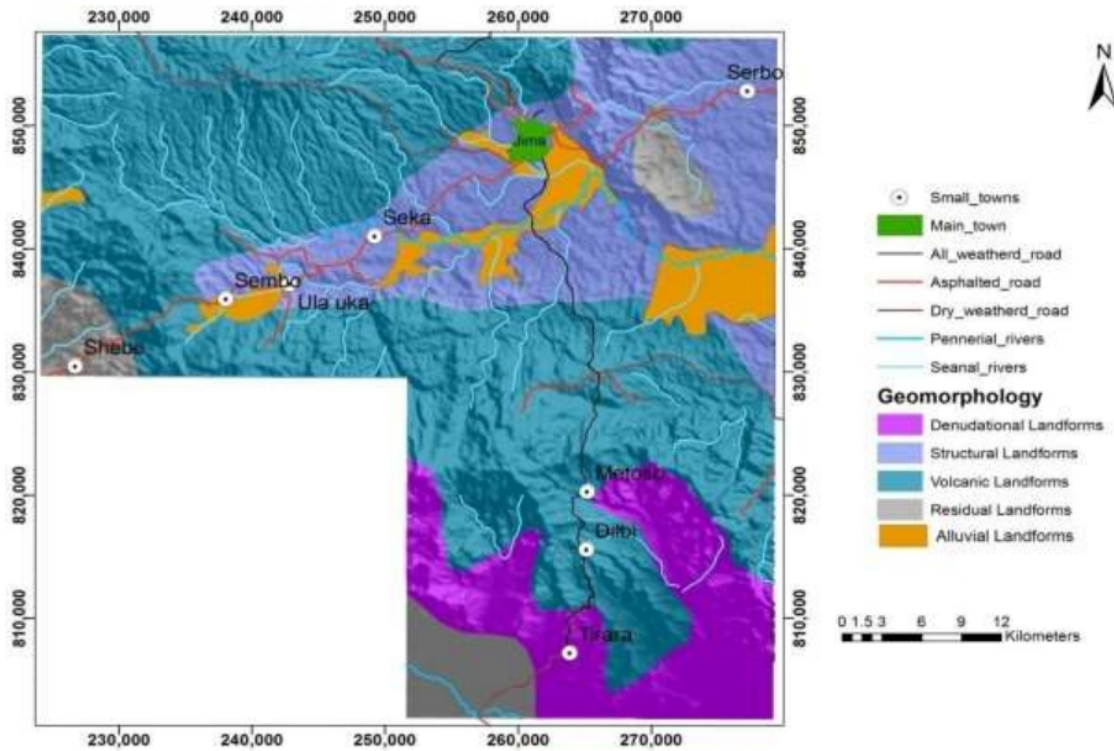


Figure 3-3: Geomorphological map of the region where the Jimma-Chida road section is located(Geological Survey of Ethiopia(GSE), 2015)

3.1.4. Climate

As per the data collected from (Ethiopian Metrological Agency,Climatic Data of Jimma Area, 2022),the annual rainfall of Jimma area ranges from 1143.8 to 1966.7 mm and it ranges from 1108.0 to 1944.6 mm for Chida area, the main rainy season along the area are months of June to September and April to May. The mean annual maximum temperature ranges from 27.4 °C to 28.4 °C and 25.7 °C to 27.5 °C for Jimma and Chida towns respectively.

Similarly, the mean annual minimum temperature ranges from 11.3 °C to 12.9 °C and 14.6 °C to 15.7 °C for Jimma and Chida towns respectively. The rainfall data collected from Jimma and Chida town is presented in Figure 3-4 and Figure 3-5.

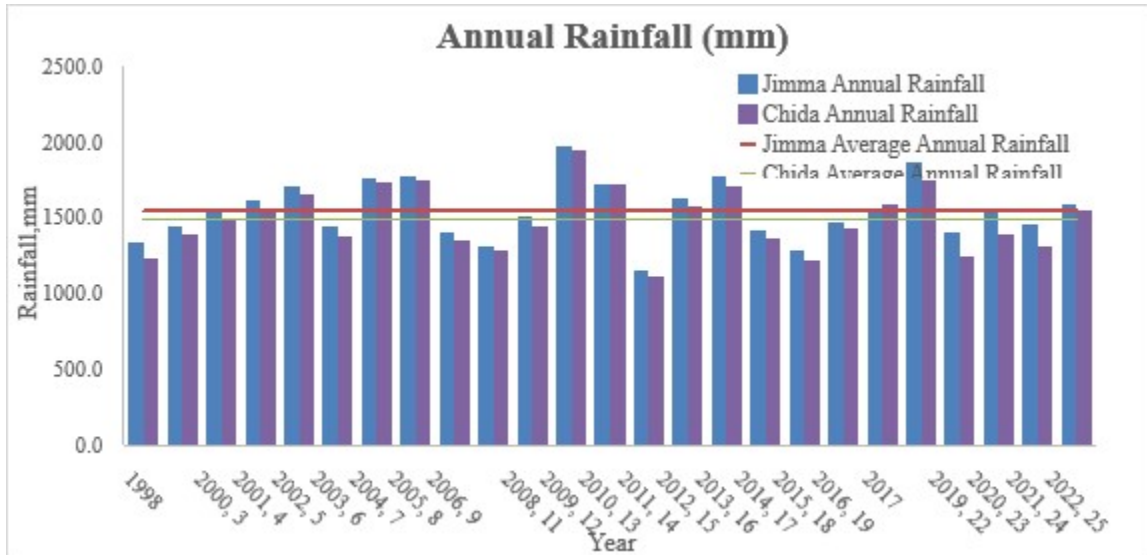


Figure 3-4: Annual Rainfall of Jimma and Chida Metrological Station

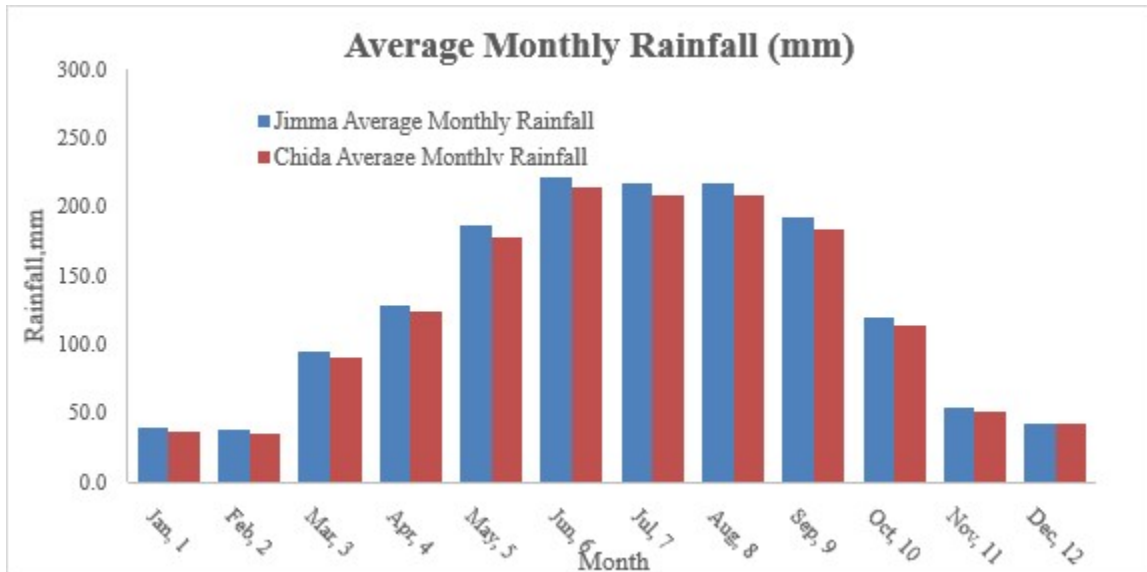


Figure 3-5: Average Monthly Rainfall of Jimma and Chida Metrological Station

3.1.5. Drainage

The Jimma – Chida road traverses two major drainage systems, namely Gibe River and Gojeb River catchments that are sub-basins of the Omo-Gibe River system/basin(Geological Survey of Ethiopia(GSE), 2015). The rivers and streams crossed by the road generally drain west-east direction(CORE Consulting Engineers PLC., 2021).

The project road crosses four major perennial rivers, namely Gibe, Offole, Unta and Gojeb rivers, which have substantial flows throughout the year. In addition, as shown by the drainage map generated from 30.0 x 30.0 m DEM of the area (Figure 3-6) the road section intercepts several small streams. The drainage type is mainly dendritic drainage type which implies a weak geology, i.e., thick soil cover.

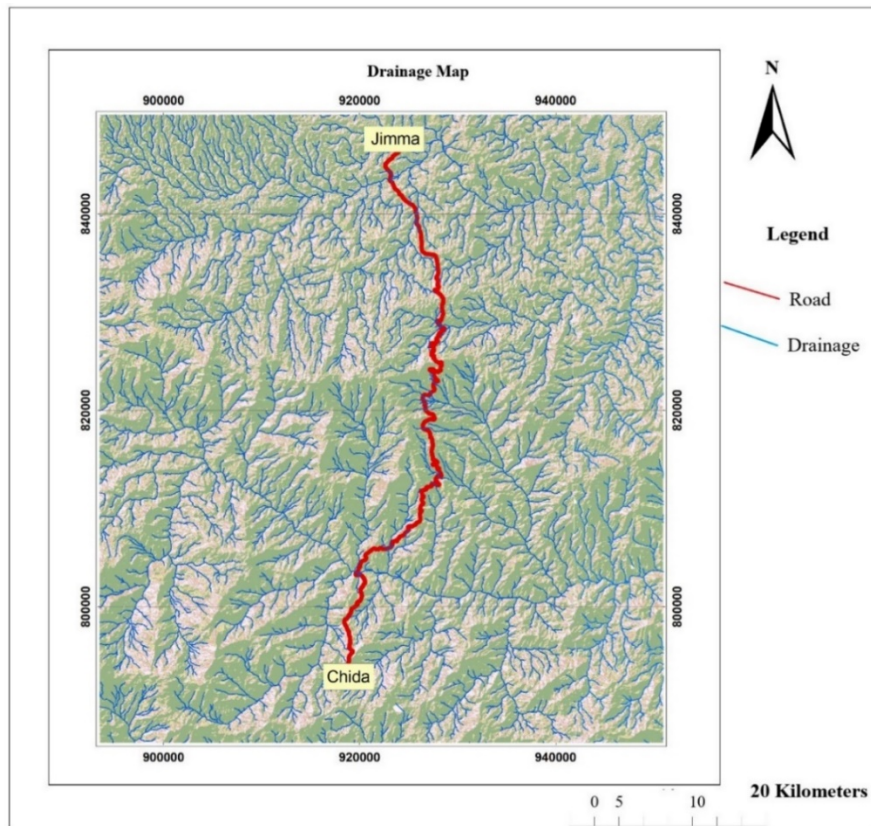


Figure 3-6: Drainage map of the area.

3.1.6. Geology

3.1.6.1. Regional Geology

The geological formation of the road section is dominated by the Jimma Volcanics which covers most part of southwestern Ethiopia, and the Nazereth Series. The Jimma volcanics are a thick succession of trachybasalts (lower part), and rhyolites (upper part)(Figure 3-7). According to the(Ethiopian Geological Survey(GSE), 1996),the geological formation of Jimma-Chida road corridor is characterized as;

- **Nazret Series:** Ignimbrites, un-welded tuffs, rhyolitic flows, domes and trachytes (Nn).
- **Jimma Volcanics (upper part):** rhyolite & trachyte flows and tuffs with minor basalt (Pjr).
- **Jimma Volcanics (Lower part):** flood basalt with minor salic flows (Pjb).

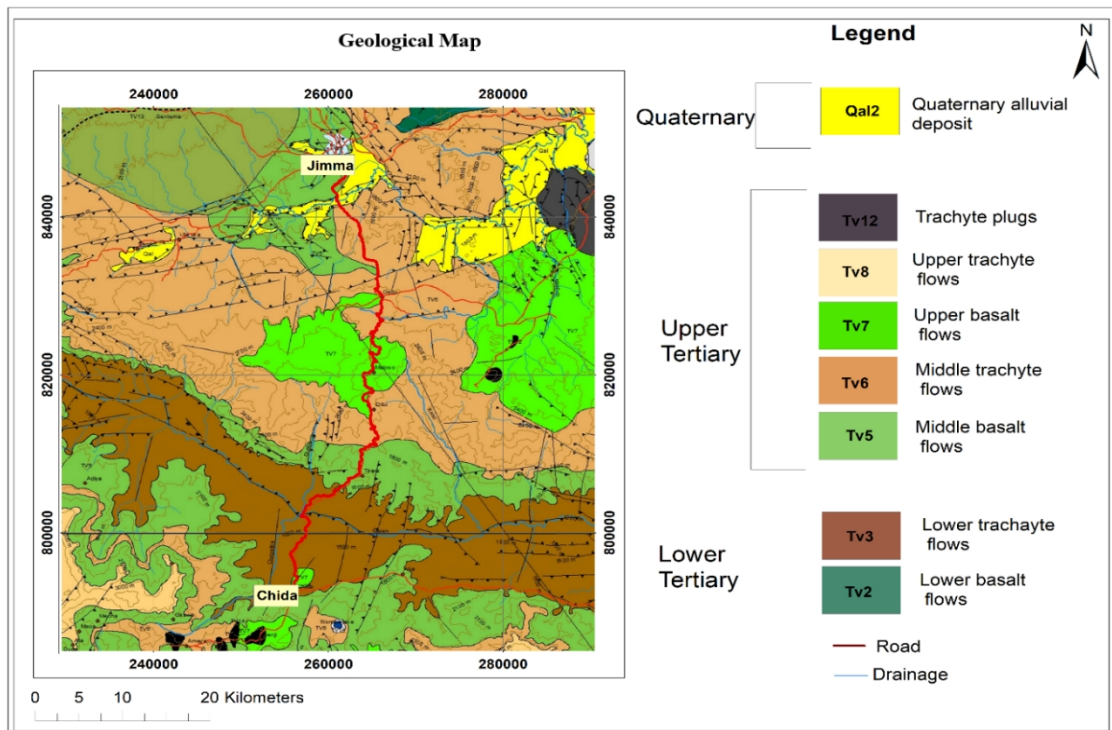


Figure 3-7: Regional geological map of Jimma area, 1:250,000(Ethiopian Geological Survey(GSE), 1996)

3.1.6.2. Local Geology

The type and characteristics of the slope material along Jimma-Chida road corridor mainly depends on the geological formations of the parent rock material followed by the physiographic conditions of the terrain, runoff, rainfall influences, and the transporting agent.

The majority of the road traverses through a highly weathered (with weak relict structures and fabric of the parent material still preserved) bed rock to completely decomposed bed rock(Figure 3-8 and Figure 3-9). The residual soils are derived from this weathered bedrock and, have not undergone transportation, i.e., they are deposited in-situ. Residual soils are an indication of high temperature and high rainfall in the area. These residual soil deposits are mostly observed along the rolling topography sections of the road corridor.



Figure 3-8: Highly weathered to decomposed rock along Jimma-Chida road section with relict structures and fabric still preserved



Figure 3-9: Residual soil along the road mostly covering the flat and rolling part of the corridor.

3.1.7. Tectonics

The geological structures in the region are described by normal faults and lineaments that are represented by fractures and /or joints of variable strike and length affected by normal faults giving rise to asymmetric graben(Geological Survey of Ethiopia(GSE), 2012).

As shown in Figure 3-10, the rift systems developed are two types. The major one, the Asendabo graben shows ENE trend along with Kische graben. Both grabens contain younger Quaternary stratified tuffs. The graben formation is analogous to the structure that formed the Main Ethiopian Rifts. Normal faults are prevalent in the study area and they generally trend to NE-SW direction. Some E-W and N-S trending normal faults are also traced from hill-shaded relief of the area(Abbate et al., 2015).

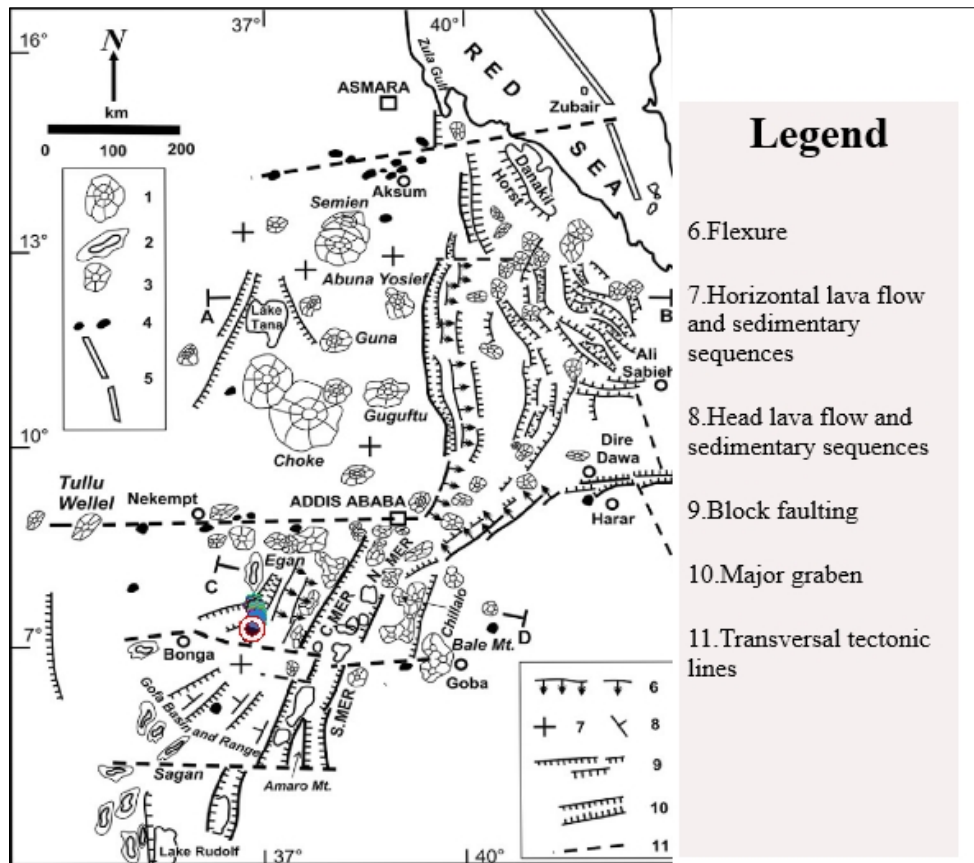


Figure 3-10: Structural sketch map of the Ethiopian and Somali plateaus, Afar depression, and Main Ethiopian Rift (Northern, Central, and Southern MER) with the main transversal tectonic line and major volcanic edifices (Abbate et al., 2015).

3.1.8. Seismicity

The seismicity of the study area has its origin from the development of the Ethiopian rift system. Thus, seismic condition of the area mainly related to the tectonic activities of the MER which is the extensional active continental rifting system in which strong tectonically and volcanic triggered earthquakes are expected. The seismic hazard map of Ethiopia is based on the peak ground acceleration (PGA) of the bed rock at the surface.

Part of the road section (from stn. 0+000 to ~51+800) which is where most of the active landslides are found are located within seismic zone-0 and the remaining section is located in the seismic zone-1 which indicates that the project area is located within seismic Zone-0 and 1 of Ethiopia's seismic hazard map, Figure 3-11, the entire length of the project fall on PGA of 0.0-0.04.

Based on (ES EN 1998:2015, 2015), as indicated on Figure 3-11, the landslide sections along Jimma-Chida road section belongs to zone 0 and 1. Thus, the role of the seismicity effect on the area for the landslide is insignificant and not considered as contributing factor in the landslide susceptibility analysis.

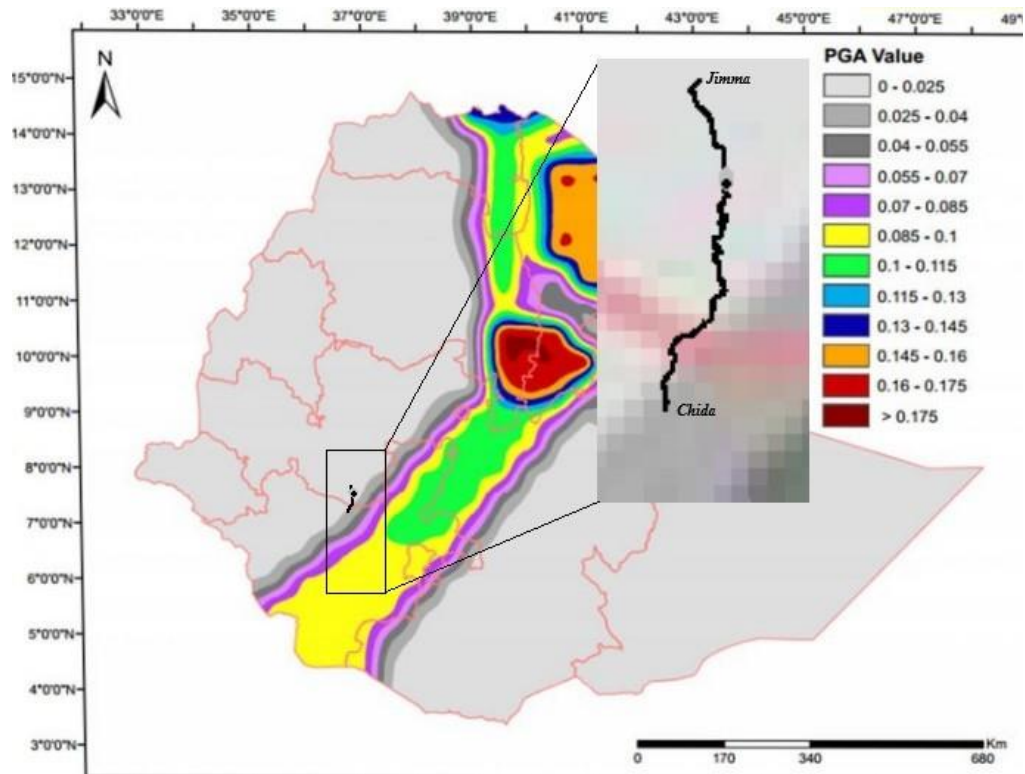


Figure 3-11: Seismic hazard map of Ethiopia for 100-year return period.

(Source; ES EN 1998:2015, 2015)

3.2. Data Collection and Processing

In order to conduct the landslide assessment and produce a precise landslide susceptibility map different tasks have been carried out during the study period. Data with wide spectrum and variable sources were collected such as DEM (30.0 x 30.0 m resolution), different satellite imaginaries, geological maps and reports of the study area, available metrological data, existing landslide data from the site inventory activity, information from locals and borehole data.

Landslide mapping for engineering purpose (engineering geological map) has prepared for the existing landslide areas based on an extensive site survey and Google Earth image visual analysis.

The landslide mapping helps to indicate the landslide features on the ground surface which resulted from the slope movement on the area (Arbanas & Arbanas, 2015). Lithology, Elevation, Slope, Slope Aspect, Curvature, Distance to the Stream, Distance to Road, Land Use/ Cover and Rainfall are selected as landslide contributing factors based on their contribution for the landslide occurrence and the site condition.

From 30.0 x 30.0 m DEM data slope, slope aspect, elevation, curvature and distance to stream data were extracted. The lithological data were acquired from the geological map of Jimma area accompanied by site survey. Similarly, the land use/ cover data is extracted from Google Earth and confirmed on the site. Laboratory test results such as atterberg limit, unit weight, specific gravity, grain size analysis and natural moisture content were reviewed during the landslide assessment, lithological map preparation and forwarding a preliminary remedial measure.

During the course of this study different instruments such as hand held GPS, geological hammers, measurement tapes, laptops and multiple softwares like Microsoft Office, Arc GIS 10.5, Google Earth Pro, Global Mapper 17 and Real Statistics in Excel were utilized. Similarly, various raster maps such as geological, geomorphological and topographic maps were also used as an input for this study.

3.3. Landslide Susceptibility Mapping using Analytical Hierarchy Process (AHP)

Landslide susceptibility map provides a predictive information about the potential of landslide to occur in a given area. In general, methods implemented for the landslide susceptibility analysis have their own qualities and shortcomings. For example, in case of qualitative methods a lot of professional subjectivity is involved in organization of various causative factor data layers contributing for landslide phenomena. In case geotechnical approach, the method uses geotechnical parameters to analyze the slope affected by the landslide but it is expensive (since it requires mobilization of extended crews and machineries) and cannot simulate the spatial distribution of the landslide (A. Azeze, 2019).

In this study, Analytical Hierarchy Process (AHP) which is a semi-quantitative approach is selected to prepare the landslide susceptibility map for Jimma-Chida road section.

This method analyzes the spatial distribution of landslides by combining all the intrinsic and extrinsic factors to characterize the current condition of the moving mass and the potential sliding area. The Analytical Hierarchy Process(AHP) is originally formulated by Thomas Saaty as a decision making procedure(T. L. Saaty, 1977,1987). Its prior use is to provide solutions to problems involving decision making in multivariate case, in which various options for attaining given objectives are compared under multiple criteria. The AHP establishes contributing weights for alternatives by organizing main objectives, criteria and sub-criteria in a hierarchic manner(Bernasconi et al., 2009) .This method is a semi-quantitative method having a tool which makes it the most reliable method for computing the weight of each criteria and determining the relative proportion of factors using a pairwise comparison with the input of experts judgement and experience(Mehmood et al., 2022).The AHP has very important application in the area of landslide susceptibility analysis and mapping by indicating the importance of a certain factor and correlating with other factors through a statistical computation.

The primary step in the landslide susceptibility mapping is constructing a spatial database for prominent landslide contributing factors. For this study a total of nine factors are identified. These factors are slope, aspect, elevation, curvature, lithology, distance to drainage, distance to road, land use/ cover and rainfall. These factors were analyzed and weights were given for all the variables based on their share of influence on triggering landslide using the AHP approach. After allocation the weight for all causative factors they are merged into a single assessment index (landslide susceptibility index) to generate landslide susceptibility map of the road.

Even though complex knowledge about movement on the area and the triggering factors plays a vital role while developing the susceptibility map, a fundamental challenge of the landslide susceptibility analysis is driving the weight for a set of factors according to their contribution(T. L. Saaty, 1977). The weight calculated using the Analytic Hierarchy Process (AHP) were applied to each thematic map of the causative factors based on their relative importance with the assistance of the spatial analysis tool of Arc GIS to give a single landslide susceptibility index.

Application of AHP method for weighting of landslide contribution factors incorporate several procedures. The method comprises decomposing the problem into a hierarchy which includes essential elements of the problem.

Then the data are organized by pairwise comparison of the factor elements against the objective, that is the main measurement element used in the AHP method(Dou et al., 2015).The comparative judgement matrix is established to calculate the priority vector.In addition the Random Consistency Index Value(RI) is referenced as per the number of the contributing factors.The average value(λ_{max}) and the Coherence Index (CI) are calculated to check the Coherence Ratio(CR).

The model with CR value of greater than 0.1 were omitted immediately and CR less than 0.1 shows the reasonable level of consistency in the pair-wise comparison matrix and accepted,

As presented in Table 3-1, the grading of contributing factors is conducted through assigning weight in range of 1 to 9.Where 1 represent the equivalent significance and 9 is the significant importance of one factor over the other.

Table 3-1: Scale of preference between two parameters in AHP (T. Saaty & Vargas, 2001)

Scale	Degree of preference	Explanation
1	Equally	Two activities contribute equally to the objective
3	Moderately	Experience and judgment slightly to moderately favor one activity over another
5	Strong	Experience and judgment strongly or essentially favor one activity over another.
7	Very strong	An activity is strongly favored over another and its dominance is showed in practice.
9	Extremely	The evidence of favoring one activity over another is of the highest degree possible of an affirmation.
2,4,6,8	Intermediate values	Used to represent compromises between the preferences in weights 1, 3, 5, 7 and 9.
Reciprocals	Opposite	Used for inverse comparison.

(Abay et al., 2019; T. L. Saaty, 2008) summarizes the steps to be followed in order to make the decision and priorities in an organized way using Analytical Hierarchy Process(AHP).

1. **Arrange the hierarchy from the top with the aim of the decision, then the objectives from a broad perception, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives).** This enables the complex decision to be arranged into a hierarchy from top to bottom order of overall objective to multiple criteria, sub-criteria and so on.
2. **Construct a set of pairwise comparison matrices** is the next step to follow when using the AHP method. This step involves the data for the subject problem contains pair-wise comparison matrices which includes elements of one rank that contribute to accomplish the objective of the next level at the top. The quantitative values used for the pair-wise comparison matrix are either of the set: $\{1,2,3,4,5,6,7,8,9,1/2,1/3,1/4,1/5,1/6,1/7,1/8,1/9\}$. Using this scale, the qualitative measurement for each pairwise elements is converted into quantitative values with the principle that the criteria receiving higher rating is taken as more contributor than the other one with lower rating.
3. **Calculate local weight and consistency ratio.** This step involves computing local weight of a matrix which is the normalized Eigen vector of the rated elements in the pair wise matrix. The procedure Eigen vector of the matrix involved the following operations;
 - i. The values in each column of the reciprocal matrix are summed up
 - ii. Every element in the matrix are divided by the total sum of the column total to compute the normalized pair wise comparison matrix with the sum of each column becomes 1.0.
 - iii. The average of the values in every row of the normalized matrix is computed by dividing the total sum of each row of the normalized matrix by the total number of criteria in order to calculate the relative weight of each comparing criteria taking consideration that the criteria with the highest weight is the most important one.
 - iv. The consistency ratio computed to confirm the consistency of the pair-wise comparison reciprocal matrix (Abay et al., 2019). Initially, the Principal Eigen value λ_{max} is computed by summing up the products of each elements a normalized pairwise comparison matrix and the sum of the

column of reciprocal matrix. Then the Consistency Index(CI) is computed for each matrix of order 'n' (3.1)

$$CI = \frac{\lambda_{\max} - 1}{n - 1} \quad (3.1)$$

Finally, the Consistency Ratio(CR) value of the reciprocal matrix is computed as (3.2).

$$CR = \frac{CI}{RI} \quad (3.2)$$

Where RI is the Random Consistency Index acquired from a numerous trials and studies which differentiate based on the order of matrix (Table 3-2).

Table 3-2: Random Consistency Index(RI) (R. W. Saaty, 1987; T. Saaty & Vargas, 2001)

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53	1.56	1.57	1.59

The decision making procedures using the Analytical Hierarchy Process(AHP) is summarized in Figure 3-12.

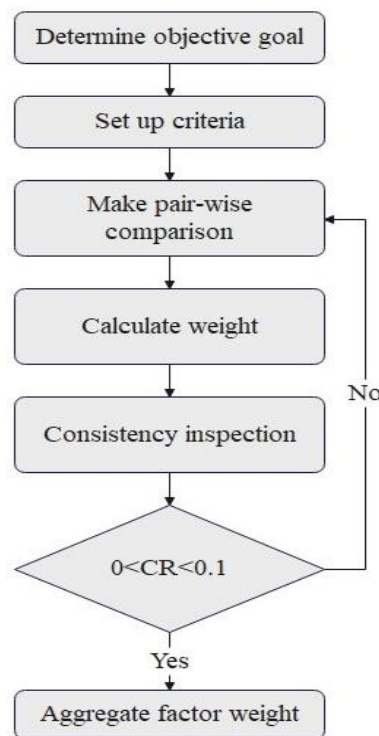


Figure 3-12: Landslide contributing factors weighting using Analytical Hierarchy Process

The final phase on preparation of the landslide susceptibility map using the Analytical Hierarchy Process(AHP) is aggregating the computed weight of the factors to generate the landslide susceptibility index(LSI) based on the weighted-overlay(WOL) using the raster calculation tool(3.3).

$$LSI = \sum_i^n W_j * R_{ij} \quad (3.3)$$

Where W_j :Weight for each of the landslide conditioning factor ; R_{ij} ;rating value of class i in landslide contributing factor j; n: number of landslide contributing factors.

3.3.1. Validation of Landslide Susceptibility Map(LSM)

The landslide susceptibility map produced shall be validated to verify the accuracy of the model. A feasible validation is carried out by comparing the actual existing landslide map along the study road section and the map produced using AHP approach. Different methods such as Landslide Percent Comparison, Prediction Rate Curve(PRC); Relative Error, Relative Landslide Density Index(R-Index) and Receiver Operating Characteristics Curve(ROC) are available to validate the landslide susceptibility map. For this particular study, Landslide Percent Comparison method is used for validation of the Landslide Susceptibility Map.

For the landslide percent comparison method, the landslide susceptibility map is validated using active and past landslide locations which were collected during the landslide inventory work. Then the actual landslide locations are overlain on landslide susceptibility map produced to observe if the produce map using the selected analysis model really match with the actual condition on the area. For this study a total of 11 landslide locations were used as an inventory data to validate the landslide map produced. The general workflow adopted for the landslide susceptibility analysis is presented in Figure 3-13.

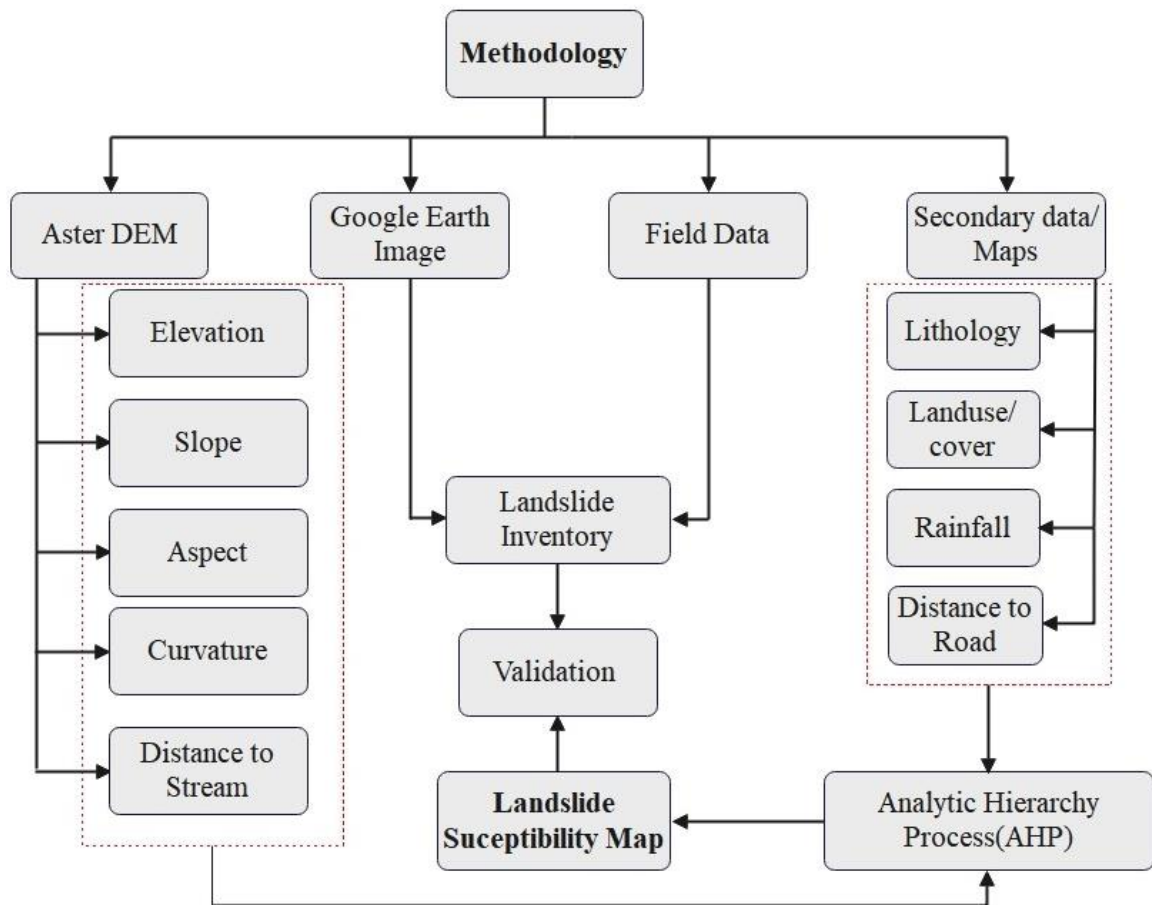


Figure 3-13: Workflow of landslide susceptibility analysis and mapping

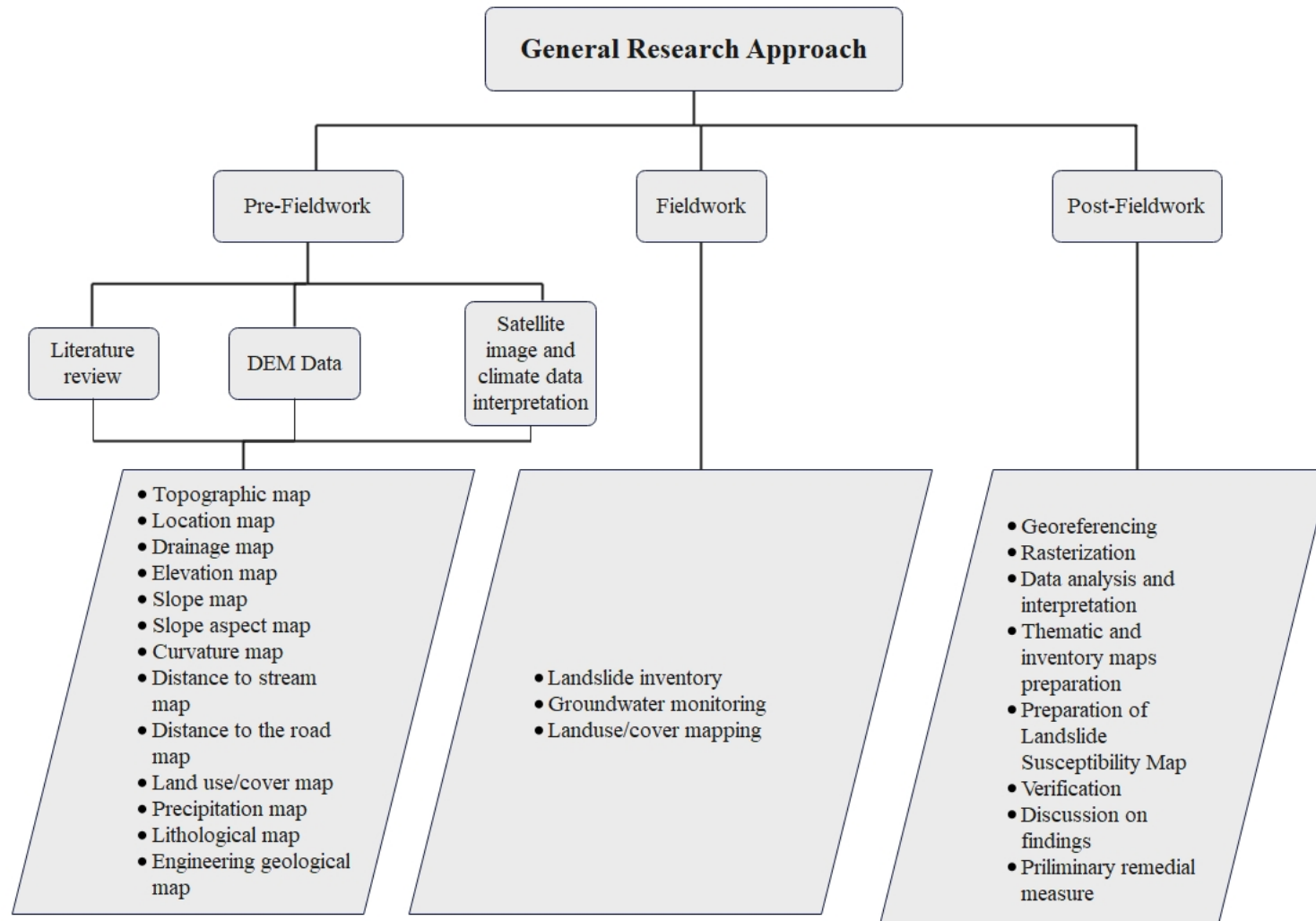


Figure 3-14: General research approach

CHAPTER 4. RESULTS AND DISCUSSIONS

4.1. Results

4.1.1. Landslide Inventory

Landslide assessment and inventory is a crucial step when studying the landslide susceptibility of a given area. The landslide assessment and inventory work comprises the collection and determination of landslide features along the affected section, studying the extent and severity of the existing landslide, determining the type of landslide and storing all the data collected in a spatially referenced digital information with their specific location and size by representing the landslides as a point or polygonal feature.

The landslide inventory work is conducted by site data collection along the route, measuring the actual landslide features during the field survey, interviewing the locals, using Google Earth imagery and referring some previously published papers.

After an intensive site survey, 11 locations were identified along Jimma-Chida road sections which were affected by the landslide. Most of the serious landslides are located on the road section from km 20+000 to km 45+000. The landslide dimension and extent of affected sites were gathered during site data collection work and landslide maps for engineering purpose were prepared accordingly. The assessment of each of the landslides along the route covered by the current study is presented in the following sections.

The assessment of the existing landslides is conducted based on the geographical location, general description of the landslide, geological formation of the affected area, drainage condition along the road corridor, distinct landslide features, and the possible causes of the existing landslides.

4.1.1.1. Landslide at km 23+200 (JC/S/01)

Coordinate: E- 265652 N- 826874

Projected Coordinate System: Adindan_UTM_Zone_37N

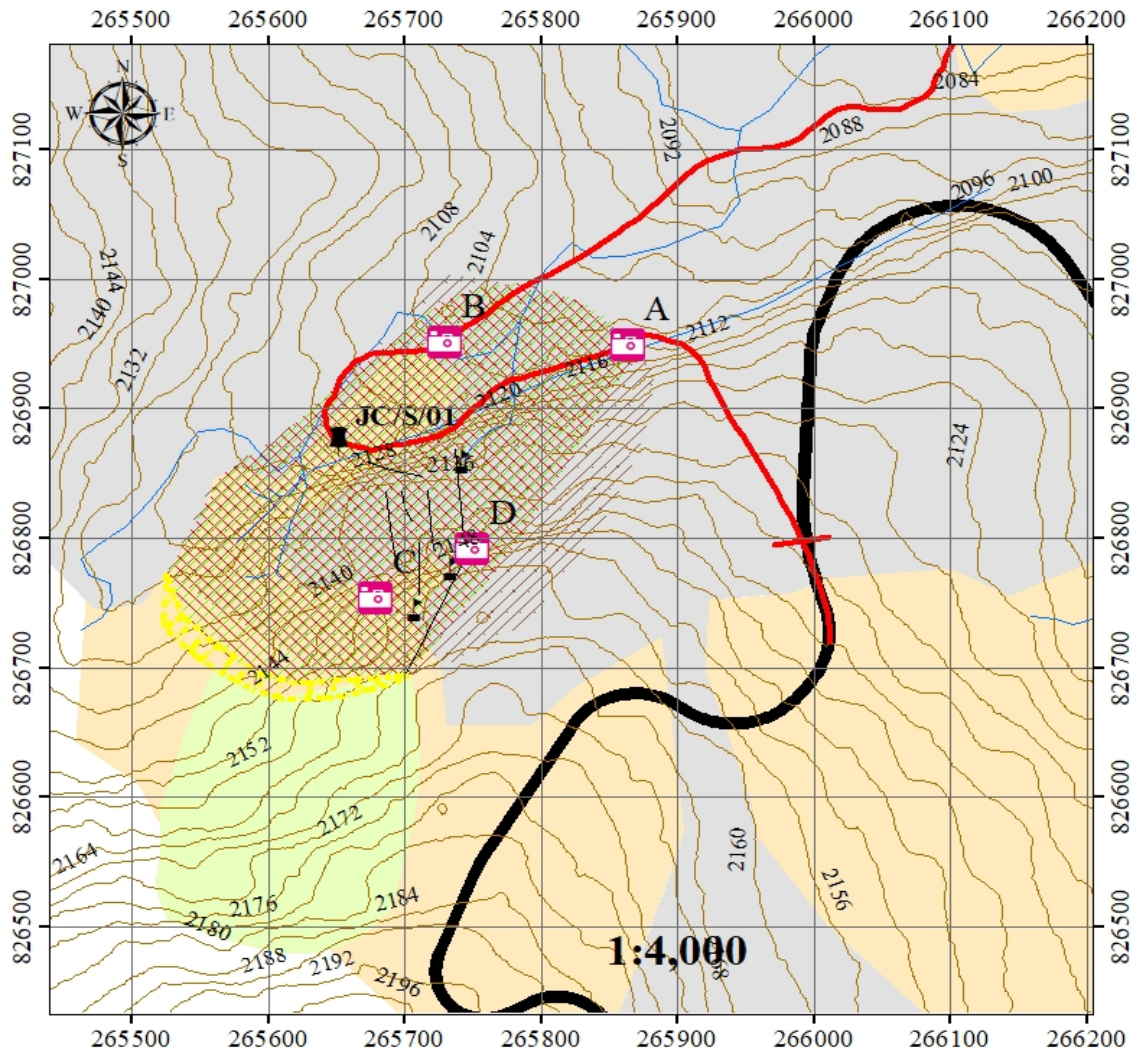
Description: The landslide located at this section is the largest in volume and most severe one. Figure 4-1 and Plate 4-1 presents the engineering geological map of this landslide. The landslide encroaches the sharp curve along the existing road causing severe failure which has been worsening through time.

Geology: The geological formation of the area is described as the upper basalt formation which is characterized by dark, slightly to moderately weathered, fine to medium grained aphanitic, deep river cut, closely spaced jointed plus fractured slightly weathered to fresh, massive basalt which altered to thick, brown silty clay soil underlain by decomposed basalt and decomposed basalt with thin top soil.

Drainage Condition: The stream on right side has encroached the alignment at many points contributing to the aggravation of landslide. Various springs were observed at the area which makes the slope material wet and weak.

Landslide Features: The active landslide is exacerbated by the dumping of the spoil material at its crown with the main scarp around 200 m above the existing road, and a series of minor scarps and extended transverse cracks to the failed mass. The slope and the existing road along this section is also marked by the appearance of springs and wet swampy area. The hard rock strata which is observed at the nearby river bed is contemplated as the possible slip surface of the landslide.

Possible Cause of Landslide: The combined effect of the spoil mass, river bank and bed erosion propagated to the slope, the steepness of the slope which marks an accumulation zone of a reactivated old landslide associated with uncontrolled surface water and shallow ground water saturation cause landslide.



Legend

- Landslide Locations
 - 📷 Photo
 - ⚡ Springs
 - ⋯ Scarp
 - Existing_Road
 - Tension Crack
 - Contour Lines
 - Streams
 - Jimma-Chida_Road
- Slope Material**
- Spoil Area
 - ▨ Old Landslide
 - ▩ Active Landslide
 - Thick, brown silty clay soil underlain by decomposed basalt
 - Decomposed basalt with thin top soil

Figure 4-1: Landslide map of JC/S/01



Plate 4-1: Landslide at site JC/S/01 A) Spoil mass triggering the landslide B) Slide mass toward the stream at the toe C)Wet area due to multiple springs D)Long tension cracks developed by moving mass.

4.1.1.2. Landslide at km 29+370(JC/S/02)

Coordinate: E- 265205 N- 823906

Projected Coordinate System: Adindan_UTM_Zone_37N

Description: As indicated in Figure 4-2 and Plate 4-2, at this section of the road failure is observed on the back slope in the right hand side of the road. The general slope geometry depicts the geomorphological processes of an older creeping movement that may develop to full scale landslide if there is further excavation work conducted on the area.

Geology: In this slope part, the majority of existing landslide section is covered with brown silty clay soil underlain by highly weathered basalt and in areas where the top residual soil is substantial, shallow sliding of this loose top soil over the bed rock of upper basalt formation which characterized by dark, slightly to moderately weathered, fine to medium grained, weathered, massive basalt.

Drainage Condition: Spring water is observed at various locations along this section of the road and the locals developed the water well for domestic use which indicates the presence of sub-surface water at shallow depth. The uncontrolled surface water without any surface drainage structures on the failed slope mass is also observed.

Landslide Features: In this section the failed mass is the back slope in the right hand side of the road. The active landslide observed at two separate locations along this section with a slow, creep movement of the thin, brown silty clay soil underlain by highly weathered rock back slope material at the first section and typical semi-circular rotational slide (150 m wide and 100 m long) with the main scarp located 100 m away from the road edge and the toe of the sliding mass extended to the right hand side of the road.

Possible Cause of Landslide: The possible causes are steepness geometry, loose material and saturated weak material, uncontrolled surface water coming from the hill side, lack of back slope drainage facilities that allows water to enter to the loose material and the presence of sub-surface water at shallow depth. The shallow sub-surface water is developed by the locals for household water source and when conducting shallow excavation work on the area the water encountered, indicating the presence of water which should be mitigate properly. In addition to that, the exposed and uncovered back slope material is eroded by surface water which diverted by settlers from the ridge of the mountain compromise the overall stability of the slope.

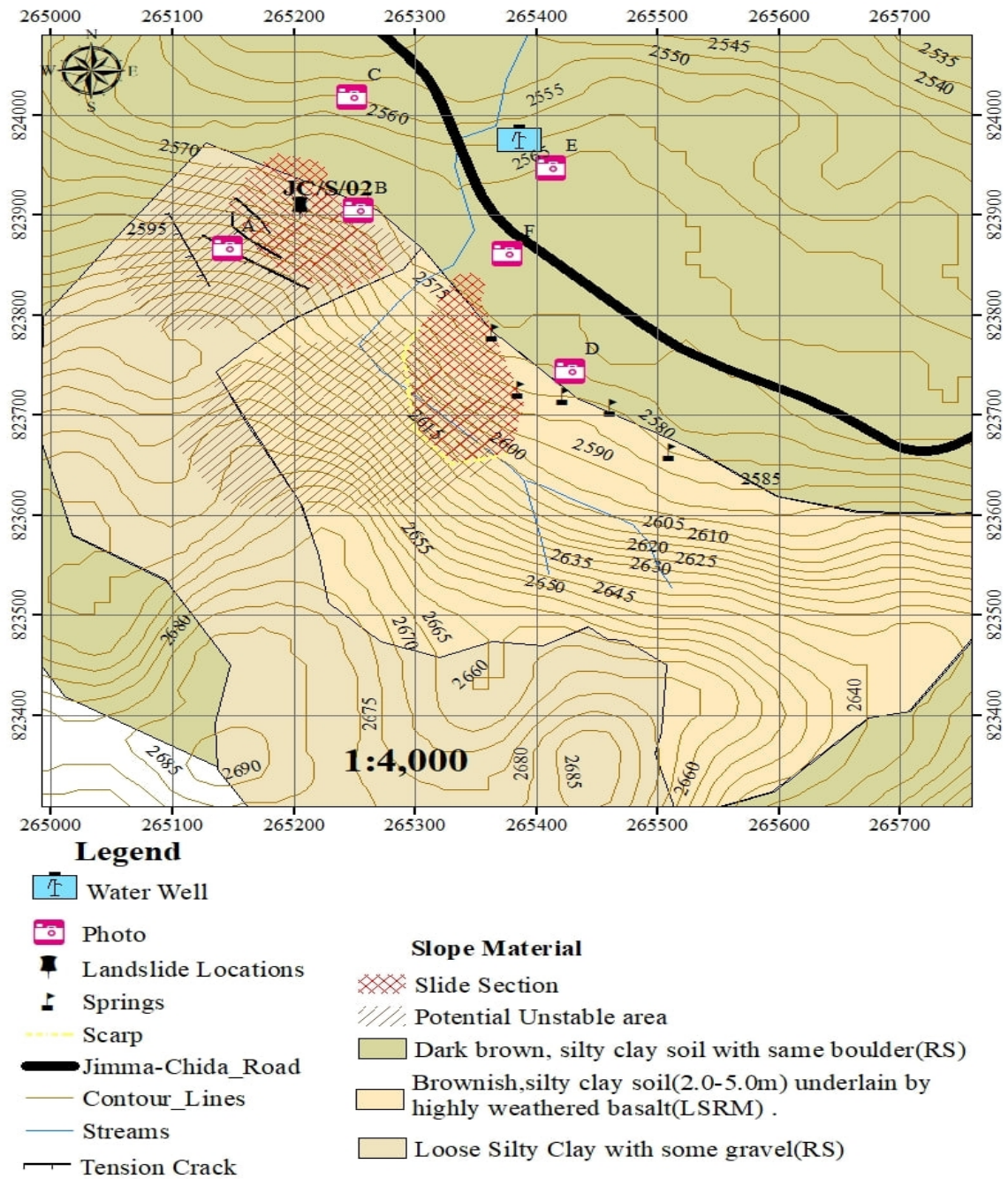


Figure 4-2: Landslide Map of JC/S/02



Plate 4-2: Landslide at site JC/S/02; A-C Slope movement of the brownish, loose silty clay soil with gravel at the back slope of the road D) Landslide at the back slope of the road E) Developed water well on the left side of the road indicating the presence of ground water at shallow depth F) Landslide of the back slope with prominent semi-circular scarp.

4.1.1.3. Landslide at km 30+600(JC/S/03)

Coordinate: E- 265797 N- 822920

Projected Coordinate System: Adindan_UTM_Zone_37N

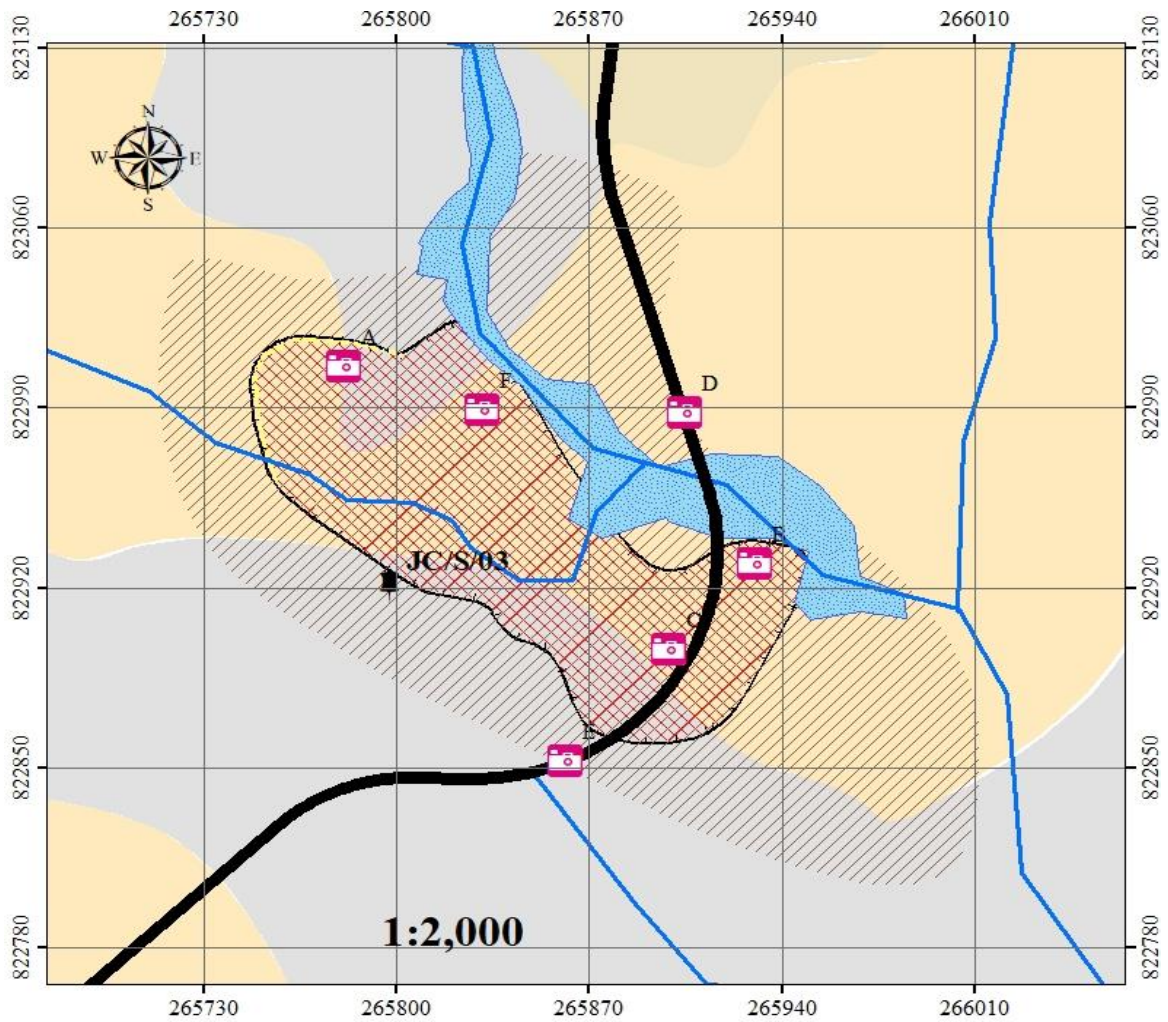
Description: As shown in Figure 4-3 and Plate 4-3, this section is characterized by big, deep seated, old landslide mass at the eastern foothill of a prominent ridge at excavated road sections made up of strongly weathered upper basalt covered by thick residual soil. There are prominent streams and gullies along the length of the landslide mass leading to reactivation of the landslide particularly above and below the existing route alignment

Geology: the existing road is aligned at the contact between the upper basalt ridge and the flatter surface underlain by the upper silicic rocks with the thick brownish silty clay residual soil.

Drainage Condition: This section characterized by the prominent gullies and streams. Mainly along the major landslide section two streams crossed the existing route causing multiple erosion gullies.

Landslide Features: This stretch crosses a big (200 m wide and 300 m long) old, deep seated, rotational landslide mass with visible scarps and slumps which has been reactivated multiple times as the road bed is on the flexure zone (toe of the rapture zone) of the old landslide where the convex valley above the road is the detachment zone (surface of rupture) while the concave bulged lobate mass on the left hand side is the accumulation zone of the displaced material.

Possible Cause of Landslide: The possible causes are weak, thick residual soil affected by valleys, various gullies, presence of sub-surface water and steep slope topography of the area.



Legend

- Landslide Locations
- Photo

- Jimma-Chida_Road
- Streams
- Failure due do gully development
- Scarp

Slope Material

- Active Land Slide Section
- Potentially Unstable area
- Thin, brownish silty clay soil underlain by decomposed basalt(LSRM)
- Dark, silty clay soil underlain by decomposed basalt(LSRM)
- Brown, silty clay underlain by decomposed basalt(LSRM)

Figure 4-3: Landslide map of JC/S/03



Plate 4-3: Landslide at site JC/S/03 A) Landslide from the top of the scarp) Crack on the left flank of the landslide extended to the side slope C) Depleted mass on the back slope side of the road D) The gravel wearing road near the failed section (toward Chida) E) Potentially unstable area near the active landslide F) Depletion on the back slope of the slide mass.

4.1.1.4. Landslide at km 34+300(JC/S/04)

Coordinate: E- 265209 N- 821707

Projected Coordinate System: Adindan_UTM_Zone_37N

Description: According to the witnesses (local residents) the small development of crack were occurred on July 2014 at the edge of the left hand side of the road where there is a highly erosive stream crossing structure is located. Since then the crack is propagating toward the road mainly during the rainy season and minor maintenance were carried out on yearly basis. As indicated in Figure 4-4 and Plate 4-4, the landslide at this section of the road is an inner gorge failure of silty clay soil sliding over underlying relatively impermeable clay and/or competent bedrock. The stream at this location severely erode the banks mainly along the downstream direction of the road. During the site survey it is observed that there is one major creek crossed by the road at the stream crossing location. This portion of the creek has developed quite deep cut gullies that are eroding and the stream channel developed quite deep cut gullies which are highly erodible. This deep cut erosion gully along the stream portion creates a steep slope, which cause the slope failure to spread toward the river banks. Additionally, there is some small old slide on the road near the active landslide section. This failure is the result of loose silty clay material that was brought about by subsurface water saturation of the slope.

Geology: The area is covered by top residual silty clay soil underlain by decomposed basalt, and brownish, loose silty clay soil with gravel size remnants of parent upper basaltic rock formation. Large portions of this slope section are covered in degraded basaltic rocks with thin top soil which varies in thickness from place to place.

Drainage Condition: Along the main landslide section the stream with deep bank traverses toward the eastern foothill of prominent ridge crossing the existing road. The highly erodible nature of the river bank material contributes for the development of various gullies mainly along the downstream side of the stream and causing the landslide. Similarly, the sub-surface water is observed at the localized old landslide section of the road.

Landslide Features: Along this stretch, active landslide (failed) masses are noted that are associated with riverbank and road embankment failures mainly along the downstream side of the stream in left hand side of the road.

A well-defined scarp and tension cracks in the river banks characterized the failure mass with cracks and surface water. The slope angle is increasing on downstream side of the stream due to down cutting of the stream side slope.

Possible Cause of Landslide: The steep side slope of the downstream and undercutting of the highly erodible silty clay soil by the stream water propagates to the road embankment. In addition, uncontrolled surface and sub-surface water plays a vital role for the initiation of landslide.

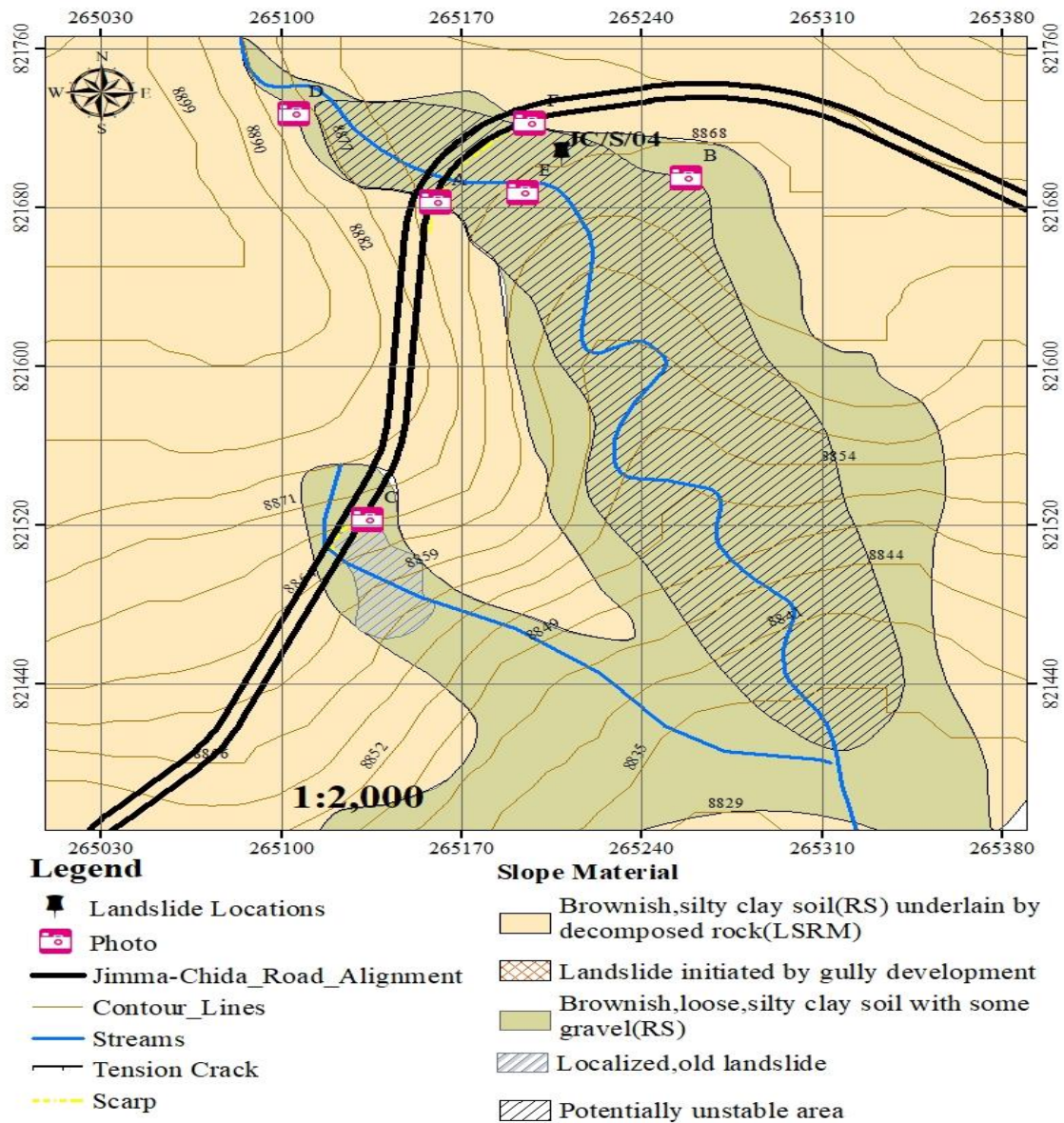


Figure 4-4: Landslide map of JC/S/04



Plate 4-4: Landslide at site JC/S/04 A)Severe erosion propagated to landslide B)Erosion of river bank on the downstream direction C)Localized old landslide propagating towards the road D)Erosion of the river bank on upstream side E)Toe erosion of the side slope by the water from the drainage outlet F)Land slide initiated by severe erosion propagating to the road.

4.1.1.5. Landslide at km 37+910(JC/S/05)

Coordinate: E- 264106 N- 819283

Projected Coordinate System: Adindan_UTM_Zone_37N

Description: The old landslide mass at the eastern foothill of a prominent ridge made up of strongly weathered upper basalt covered by thick residual soil mass; the existing route is aligned across the body of the old landslide mass, which is crossed by prominent streams and gullies along the length of the landslide mass leading to reactivation of the landslide particularly below the existing route alignment (Figure 4-5 and Plate 4-5). The crown and major scarp of the active landslide is on the right hand side of the road while several minor scarps and transverse cracks are observed across the upstream side of the stream. The existing movement is manifested on the surface as a failure of a pipe culvert structure on the left hand side of the road and back slope failure on right hand side. The failed drainage structure is founded at shallow depth on the moving reactivated mass (weak and easily erodible brownish silty clay soil mixed with gravel), and has been continuously displaced due to the movement of the foundation material.

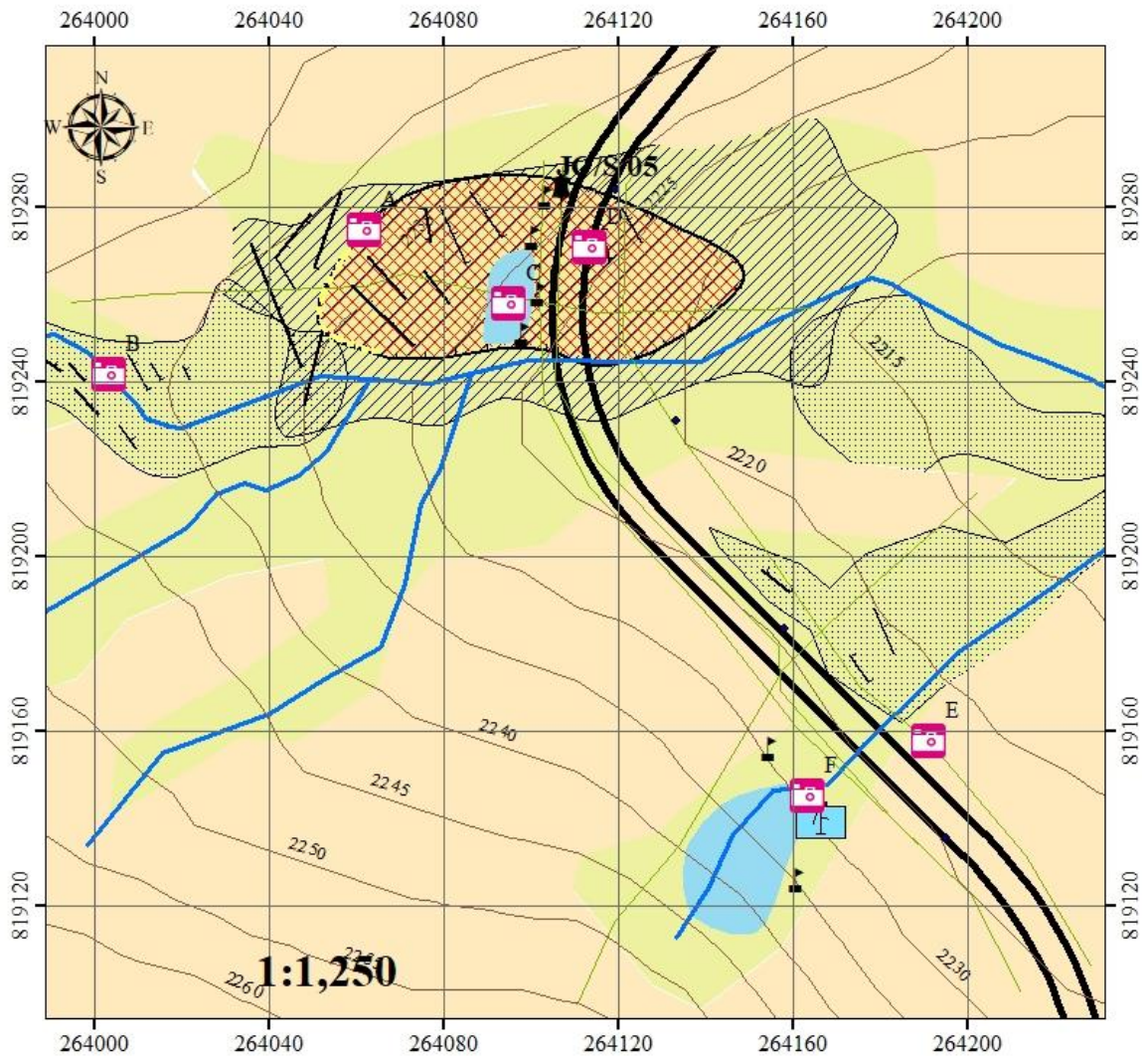
Geology: The area is characterized by residual brown silty clay soil underlain by decomposed upper basaltic rock and alluvial deposit (loose clayey silt with gravel) along the streams channel. The alluvial deposit material is predominant mainly along the steep gradient topography of the road is susceptible to erosion and it develops gully formations which associated with landslide movements particularly along the river banks.

Drainage Condition: The existing road along this section crosses two streams which contributes mainly for the activation of old landslide. The two streams are cause severe erosion across the road section and ample farmland areas mainly along the upstream side of the road. The combined effect of highly erosive nature of the alluvial deposit and perennial streams lead to the frequent activation of landslide along the road section. In addition to the streams, the presence of shallow sub-surface water is observed along this section of the road with development of water wells by locals on the side of the road.

Landslide Features: The movement of the slope is extended from the right toward the left hand side of the route causing vertical subsidence of the road which constructed on the sliding mass. The entire slope is failed due to the saturation of the area by streams and shallow sub-surface water with a clearly exposed slip surface along which the back and side slope have moved through the road. The road bed is located in the accumulation zone of the landslide mass and the movement is more pronounced in the upstream right hand side of the road as the old landslide mass has been frequently reactivated mainly during the rainy season evidenced by several extended longitudinal cracks and some disconnected but frequent transverse cracks. The crown and major scarp of the active landslide is on the right side of the road around 100.0 m away from the road edge while several minor scarps and transverse cracks are observed across the upstream side of the stream.

Possible Cause of Landslide: The presence streams and sub-surface water across the road section contributes for a complex set of movements. In addition, the formation of wide erosion gullies by the crossing stream cause undercutting of the stream side slope and result failure of the drainage structure and propagating toward the road.

For this location of the road multiple water wells which developed by locals for their household use were observed which indicates that there is a presence of sub-surface water at the shallow depth of the road causing the high saturation of the underneath soil stratum leading to reduction of shear strength. Any mitigation measure proposed for this location shall consider the provision of proper and integrated sub-surface drainage structures. The movement on the slope side will be more severe by the reactivation of the old landslide mass if there is any excavation work carried out at this location which could exacerbate an ongoing active landslide on the area. In addition to this, outflow from the clogged pipe culvert also contribute for the failure by saturating the road bed and foundation material of the area.



Legend

- | | |
|----------------------------|---|
| Landslide Locations | Slope Material |
| Pictures | Brown, silty clay soil(RS) underlain by decomposed rock(LSRM) |
| Tension Crack | Failures due to gully development |
| Scarp | Potentially unstable material |
| Water Well | Active landslide |
| Springs | Swampy area |
| Contour_Lines | Very loose, alluvial deposit(ALS) |
| Streams | |
| Jimma-Chida_Road_Alignment | |

Figure 4-5: Landslide map of JC/S/05



Plate 4-5: Landslide at site JC/S/05: A) Main scarp on the back slope B) Severely destabilized area of the river bank on the upstream C) Swampy area due to springs D) Sag on the existing road due to movement E) Failed drainage structure F) Water well developed from the spring indicating the presence of sub-surface water at shallow depth.

4.1.1.6. Landslide at km 39+170(JC/S/06)

Coordinate: E- 264743 N- 818330

Projected Coordinate System: Adindan_UTM_Zone_37N

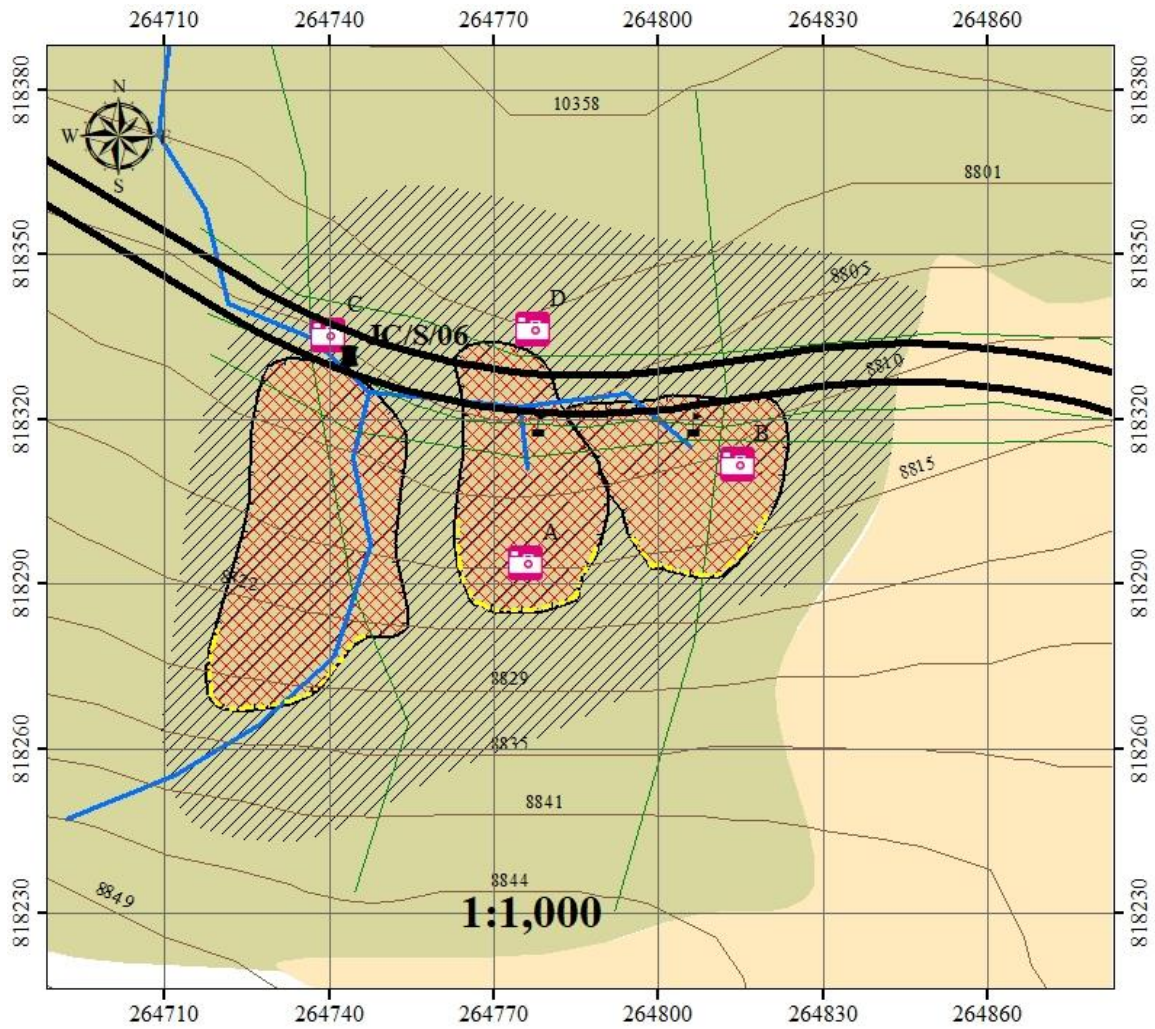
Description: As shown in Figure 4-6 and Plate 4-6 ,the area is generally composed of a relict(old) landslide mass of debris as well as brownish silty clay mixed with gravel residual soil (~100 m wide and ~150 m long) over a highly weathered upper basalt of low rock mass strength. In this section there are three (3) adjacent failed slope masses with the failure of the back slope is occurred on two (2) of them and the failure is initiated at the back slope side and extending through the road towards the side slope for the remaining one (1) location. According to the local residence before 5 years the mobilized landslide mass from the back slope side of the road damaged the trucks which were using the road and cause fatality of one driver.

Geology: The road section generally composed of a brown silty clay residual soil with gravel size remnants of parent rock which underlain by decomposed upper basalt of low rock mass strength.

Drainage Condition: The section is characterized by the presence of subsurface water at shallow depth marked by the wet area and spring development along the failed back slope part of the road. The uncontrolled surface runoff from the hilly catchment of the slope contributes for the erosion development and saturation of the slope material which consequently leads to the slope failure.

Landslide Features: The crown and the main scarp of the landslide is located 50.0 m away from the right edge of the road. A typical, shallow rotational slide is observed where the slip surface is located at the interface between the residual silty clay soil and decomposed basaltic rock and the former forms bulged concave lobate while the latter is nearly stable at vertical slope.

Possible Cause of Landslide: Saturation of the slope material, the presence of subsurface flow and uncontrolled surface water flow are the main causes of the landslide. The weak and saturated residual soil slope material is also plays a detrimental role for the reactivation of the landside at this section.



Legend

- | | |
|----------------------------|---|
| Landslide Locations | Slope Materials |
| Jimma-Chida_Road_Alignment | Active Landslide |
| Photo | Potentially unstable material |
| Springs | Brown, silty clay soil(RS) underlain by decomposed basalt(LSRM) |
| Scarp | Brown, silty clay soil with gravel(RS) |
| Streams | |
| Crack | |

Figure 4-6: Landslide map of JC/S/06



Plate 4-6: Landslide at site JC/S/06: A)The main scarp on the back slope B)Springs on the back slope C)Landslide area covered by trees D)Destabilized side slope on the left hand side of the road.

4.1.1.7. Landslide at km 42+300(JC/S/07)

Coordinate: E- 264962 N- 817740

Projected Coordinate System: Adindan_UTM_Zone_37N

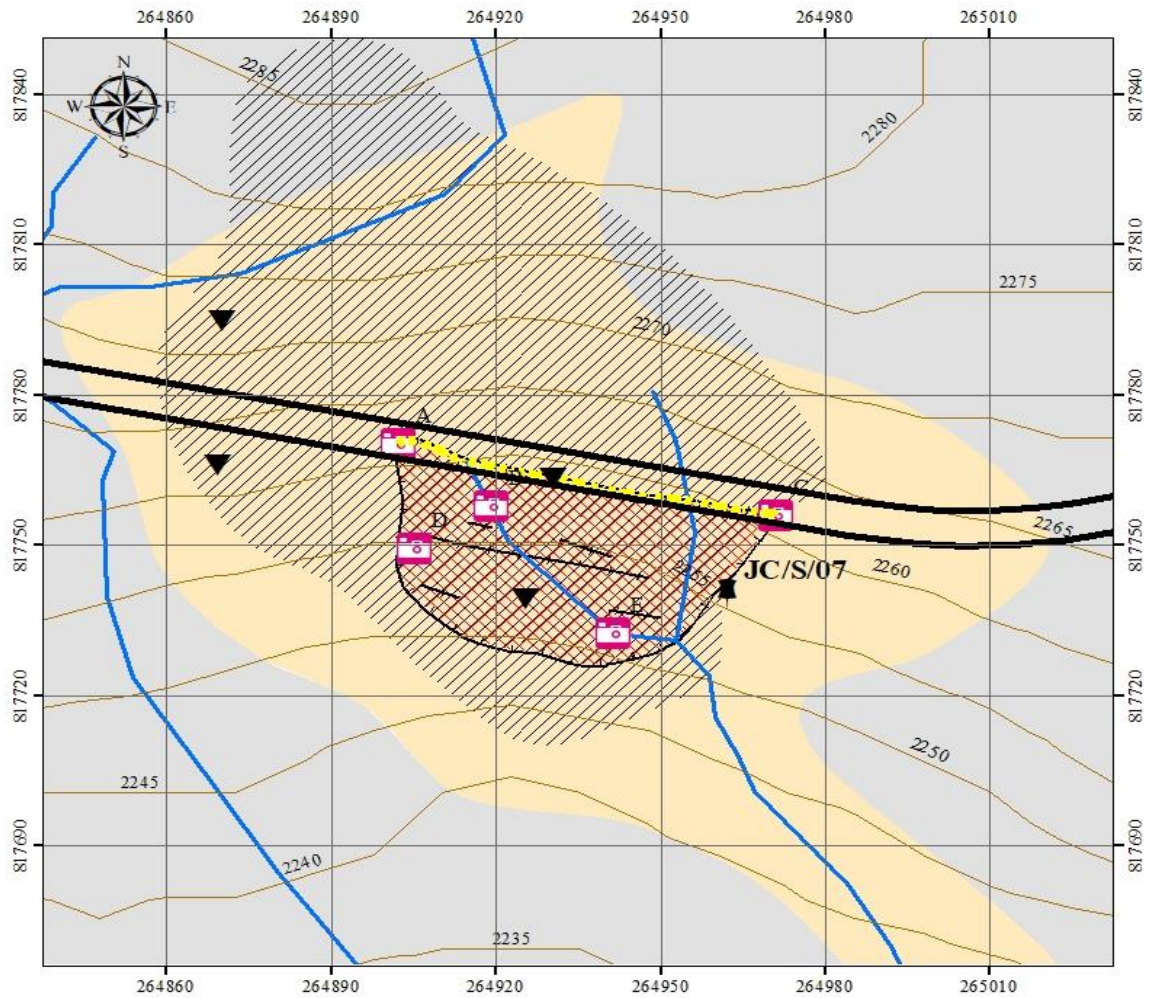
Description: As presented in Figure 4-7 and Plate 4-7, the area is composed of an old landslide mass (~75.0 m wide and ~100.0 m long) over a highly weathered trachy basalts and trachytes rocks. The landslide mass has been reactivated several times as can be observed from several generations of landslide scars and a complex hummocky structures particularly on the side slope of the current road section. Previously on July 31,2023 the landslide is activated and the road which constructed on the top of sliding mass itself is collapsed after a long and intense rain.

Geology: The road section generally composed of a highly weathered trachy basalts and trachytes rocks having a low rock mass strength which exposed on the back slope side of the road overlain by brown silty clay residual soil intercalated with gravel size remnants of parent rock.

Drainage Condition: One active stream traverse across the road section which progressively eroding the side slope. The runoff water discharged from the single cell pipe culvert which provided as cross drainage structure causes saturation and weaken the slope material.

Landslide Features: The crown and the, main scarp of the landslide is located at the edge of road left hand side while several minor scarp of the active landslide is observed at the side slope of the road. The left hand side slope is on the major accumulation zone of the displaced material which shows a different set of movements marked by variously oriented transverse and longitudinal cracks. The movement in this zone is also manifested in the deformed pipe culvert structure which have been constructed on the old landslide mass.

Possible Cause of Landslide: Saturation of the slope material and the presence of uncontrolled surface water flow are the main causes of the landslide. The weak and saturated residual soil slope material is also contributing for the reactivation of the landslide at this section.



Legend

- 📍 Landslide Locations
- ▼ Move direction
- Jimma Chida Road
- Scarp
- 📷 Photo
- Contour_Lines
- Streams
- Tension Crack

Slope Material

- ☐ Dark brown, thin, silty clay soil (RS) underlain by decomposed basalt (LSRM)
- ☐ Brown, silty clay soil (RS) underlain by trachyte basalt (LSRM)
- ▨ Old Slide Sections
- ▨ Potentially Unstable area

Figure 4-7: Landslide map of JC/S/07



Plate 4-7: Landslide at site JC/S/07: A)Backfilled material on the failed section B)Mobilized mass at the toe of the landslide C)Landslide from the side slope direction of the road D)Clogged cross drainage ditch on the downstream E)Main scarp on the road surface re-emerge on the July 31,2023.

4.1.1.8. Landslide at km 43+100(JC/S/08)

Coordinate: E- 264196 N- 817587

Projected Coordinate System: Adindan_UTM_Zone_37N

Description: Shown in Figure 4-8 and Plate 4-8, this section is composed of brown, loose, gravelly silty clay residual soil. It shows deep seated rotational slide and also bending of trees and destruction of houses. Frequent maintenance of the road by rock filling as a temporary solution is used for this road section. This stretch crosses an old landslide which has been reactivated during road cut as the road bed is on the accumulation zone of the old landslide. The landslide is stated from the hill side on the right hand side of the road where a slip surface is clearly exposed along which the back and side slopes have moved beneath the roadbed. As per the information gathered from the locals, the road section has exhibit movements during various times of its service since its first occurrence 9 years ago.

Geology: The section is located in the trachy basalt ridge and the failing mass is composed of erratic mass of debris, as well as residual (thick, soft, saturated, and highly plastic brown silty clay soil mixed with gravel) underlain by decomposed basalt.

Drainage Condition: This section of the road is crossed by one (1) stream and the side slope material is observed to be very wet and saturated due to the presence of subsurface water to the extent of spring development. The toe of the side slope has become very swampy by the ponding of both surface and subsurface water,

Landslide Features: The failure zone extends from the back up to side slope through the road bed and the failure is located at the entrance of Dilbi town. The crown and the major semi-circular scarp of the active landslides are located in the back slope of the road and houses have been constructed on depletion and accumulation zone of the active land slide leading to loading of the slope.

Possible Cause of Landslide: The saturation of slope material by the rainfall water and surface runoff combined with the presence of subsurface water at the toe of the slope cause the strength reduction of slope material which leads to the reactivation landslide.

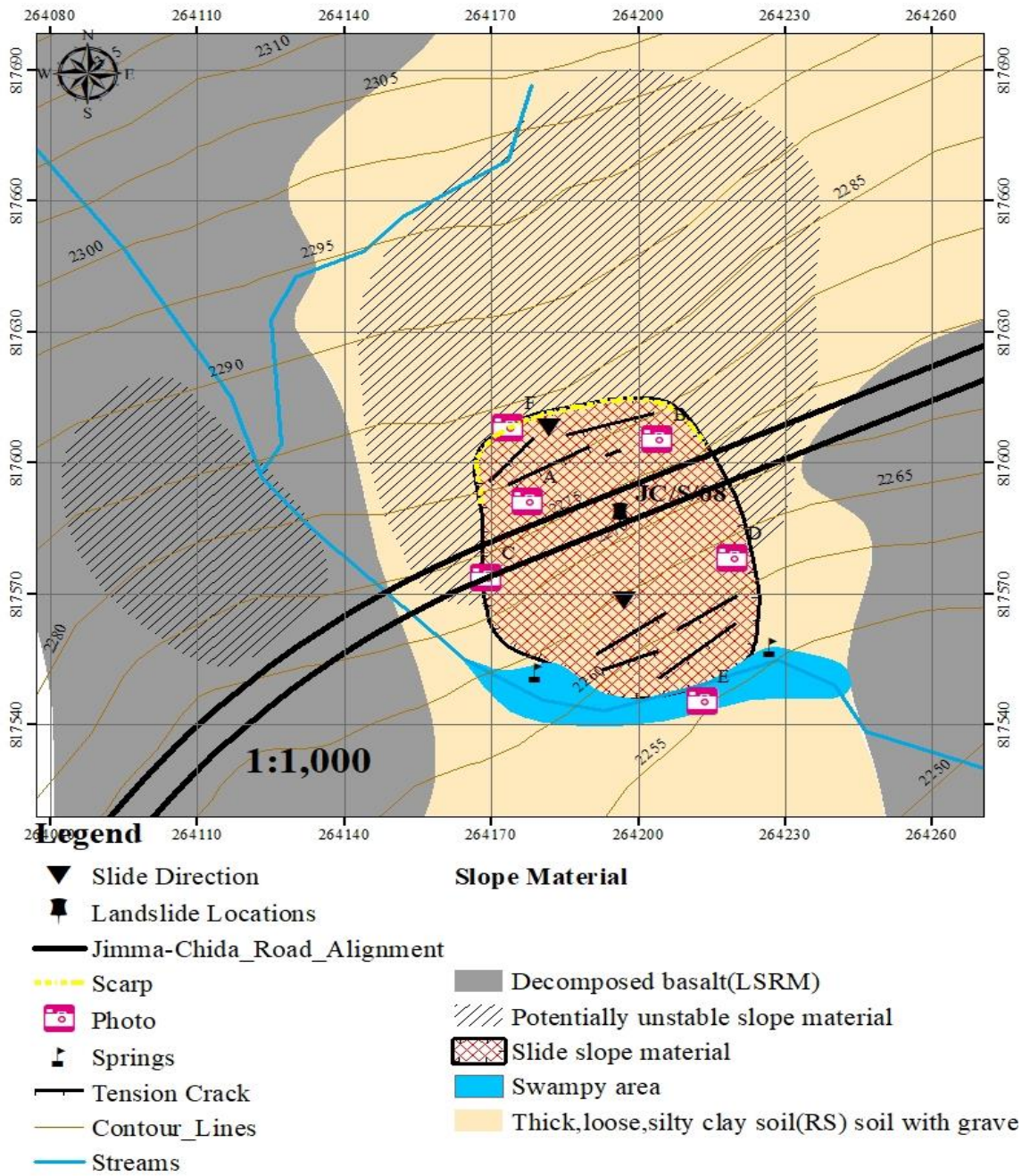


Figure 4-8: Landslide map of JC/S/08



Plate 4-8: Landslide at site JC/S/08 A)Landslide on the back slope of the road B) Multiple tension cracks on the slope C)House constructed on the sliding mass D)Destabilized mass on the side slope of the road E)Wet/swamp area at the toe of the side slope due to multiple springs F)Big tension cracks on main scarp on the top of the landslide.

4.1.1.9. Landslide at km 44+110(JC/S/09)

Coordinate: E-264120 N-816782

Projected Coordinate System: Adindan_UTM_Zone_37N

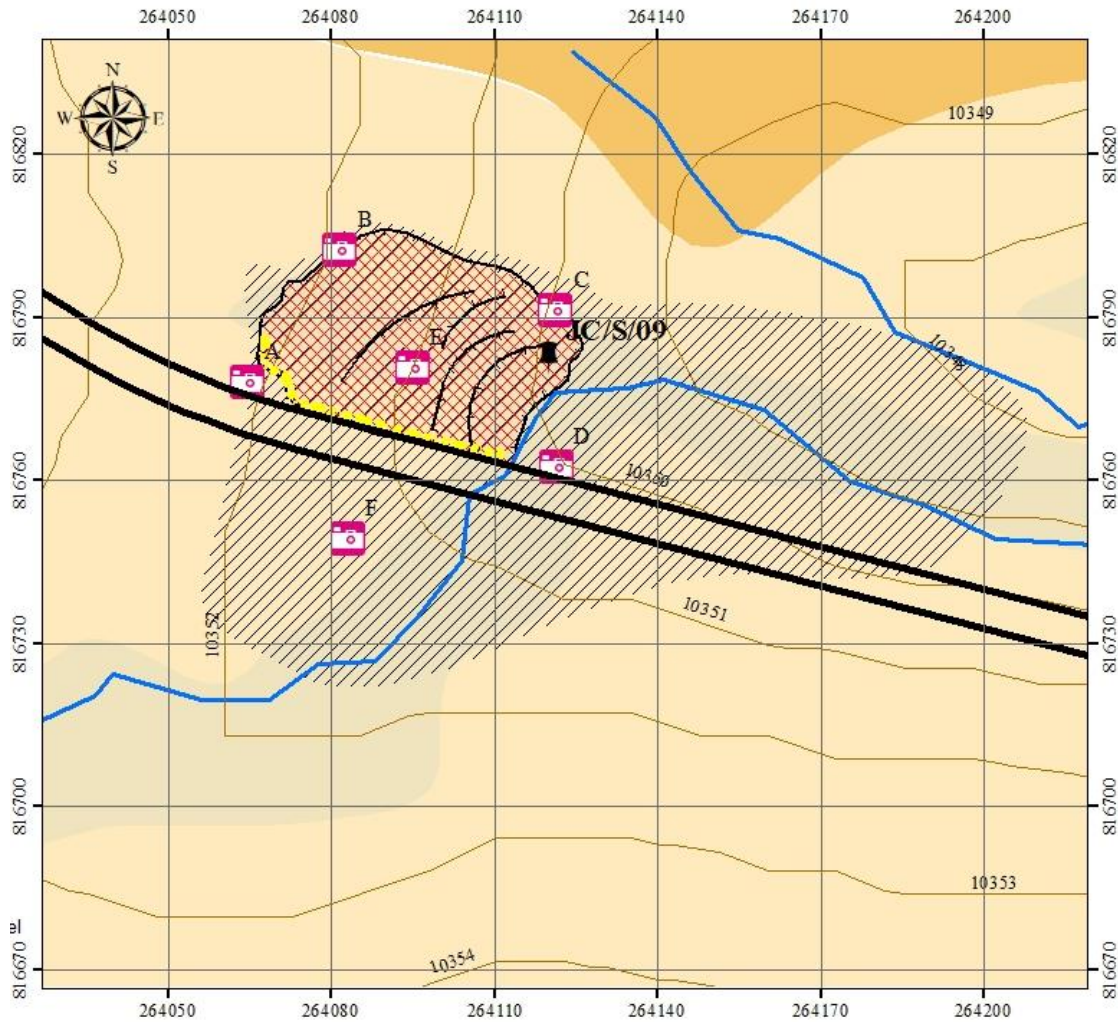
Description: Presented in Figure 4-9 and Plate 4-9, the section is characterized by a thick residual soil which is actively undercut by a prominent stream crossing the route from the ridge above the road section. The continuous riverbank erosion increases the instability of the road section and the problem has been exacerbating due to the inability to conduct a proper drainage and erosion protection work. The failure is more pronounced in the downstream direction of the road as the landslide mass cause failure on the existing cross drainage structure and embankment while propagating toward the road evidenced by several extended longitudinal cracks and some disconnected but frequent transverse cracks. There was an effort to mitigate the problem by backfilling the slide area with selected granular material, which was not successful.

Geology: The section is composed of brownish silty clay residual soil underlain by decomposed rock and loose, silty clay size alluvial deposit intercalated with gravel along the stream channel.

Drainage Condition: The main triggering factor for the landslide at this section is related with the active stream crossing this section of the road. The highly erosive stream crosses the road from the upstream ridge and cause severe toe erosion at the downstream side. Proper river bank protection work has not provided at the downstream side of the stream which leads to the occurrence of landside on the natural slope as well as on the embankment propagating towards the road.

Landslide Features: The failed mass is the entire side slope of the left hand side of the road where a slip surface is clearly exposed along which the slope material has moved toward the downstream, and the main crown and scarp of the slide is located at the left edge of the road. The side slope is characterized by active movement manifested in the form of vertical subsidence of the mass starting at the road edge, active side scraps (slip surfaces showing current movement) defining the moving mass, several minor scarps and transverse cracks, hummocky ground downslope, extended longitudinal cracks, and an active currently and moving (at moderate speed) rotational slide.

Possible Cause of Landslide: The toe erosion and undercutting of the natural slope material by the stream crossing the road is identified as the main cause of the active landslide. In addition, the saturation of the side slope material by rainfall and surface runoff water contribute for the strength reduction of the slope material which contribute for the landslide.



Legend













- | | |
|--|---|
| <ul style="list-style-type: none">  Landslide Locations  Jimma-Chida_Road_Alignment  Scarp  Tension Crack  Contour_Lines  Streams  Photo | <p>Slope Material</p> <ul style="list-style-type: none">  Brown silty clay soil underlain by decomposed basalt  Light brown silty clay soil  Loose, silty clay Alluvial deposit mixed with some gravel  Active landslide  Potential unstable section |
|--|---|

Figure 4-9: Landslide map of JC/S/09



Plate 4-9: Landslide at site JC/S/09: A)Landslide of road side slope B)Typical rotational landslide of the slope C)Cracks developed at the side slope of the road D)Landslide propagating towards the road corridor E)Moving slope mass F)Upstream side of the landslide section.

4.1.1.10. Landslide at km 58+750(JC/S/10)

Coordinate: E- 263066 N- 807147

Projected Coordinate System: Adindan_UTM_Zone_37N

Description: As indicated in Figure 4-10 and Plate 4-10, this section of the road is generally traverse through exposed sub-vertical cliff of the Lower Basalt. In addition weak, light grey, very closely jointed, moderately weathered basalt inter fingering with loose material is encountered at some section of the road mainly minor transitional landslide and low severity rock fall are observed along the mentioned section of the road. Further excavation of the slope and widening of the road section will destabilize the back and steep side slope below the road section. Minimizing any excavation work with provision of proper drainage structures are required to minimize such instability during and after road construction works.

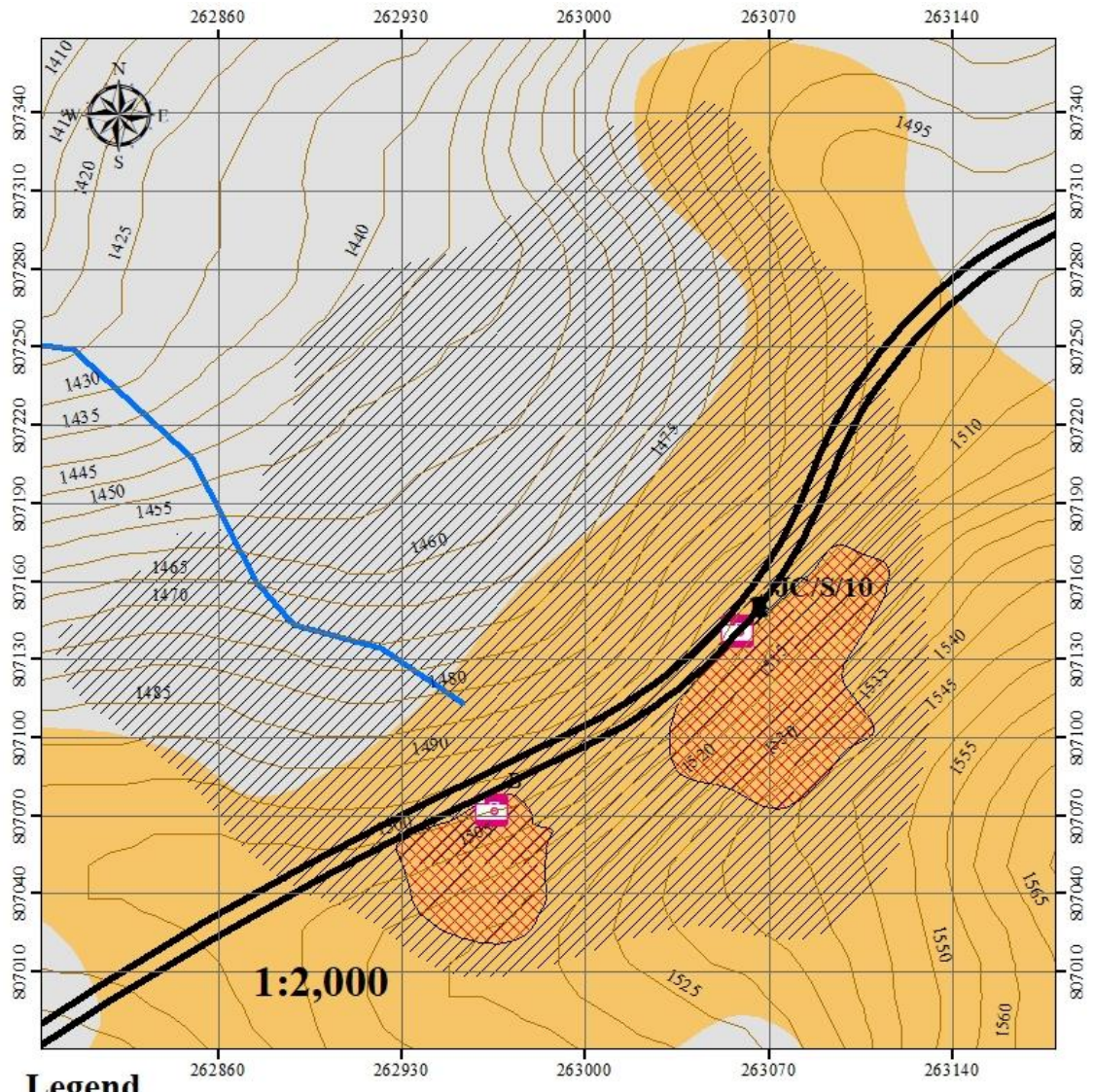
Geology: The section is composed of thin brownish silty clay residual soil intercalated with gravel underlain by highly weathered and fractures lower basalt. The highly fractured basalt cause low severity rock fall.

Drainage Condition: The surface runoff water from the catchment above the hill cause the erosion of the slope material leading to minor landslides. In addition, Springs also appeared at the side slope face.

Landslide Features: The minor rock falls from the strongly jointed, highly weathered lower basaltic rock forming the steep slope on the left hand side of the road while the road bed is on a stabilized ancient landslide mass. The slope side is very steep (nearly sub-vertical) accumulation of minor rock fall debris covered by residual soil.

In this section, the minor back slope failure occurred in left hand side of the road and it failed over a steep slope within the slope stake of the hill.

Possible Cause of Landslide: The failure was triggered by the steepness of the slope, surface water erosion and the presence of shallow groundwater saturation. Even though, there is no trace of tension cracks on the slope face or road, the slope failure due to continuous surface water erosion may eventually lead to loss of support at the base and subsequent failure. Thus, slope surface erosion protection and stabilization are considered as practical remediation actions.



Legend

-  Photo
-  Landslide Locations
-  Jimma-Chida Road
-  Contour Lines
-  Streams
-  Tension Crack

Slope Material





-  Dark brown silty clay soil(RS) underlain by decomposed basalt(LSRM)
-  Brown, thin, silty clay soil(RS) underlain by highly weathered and fractured basalt(LSRM)
-  Rockfall(Low severity) and minor landslide
-  Potentially unstable area

Figure 4-10: Landslide map of JC/S/10



Plate 4-10: Landslide at site JC/S/10: A)Steep back slope with low severity rock fall and minor slide B)The exposed, highly weathered and fractured slope material.

4.1.1.11. Landslide at km 79+350(JC/S/11)

Coordinate: E- 256086 N- 793553

Projected Coordinate System: Adindan_UTM_Zone_37N

Description: As presented in Figure 4-11 and Plate 4-11, the section is generally characterized by an old landslide mass below a steep slope made up of the trachybasalts layers. The road section is across a stabilized landslide body while downslope the landslide lobe forms a steeper, less stable mass incised by actively propagating gullies and swampy areas. The old landslide mass can potentially be reactivated if further slope steepening work is undertaken by excavating the backslope material.

Geology: The section is composed of highly weathered and fractured basalt underlain by fragmented trachy basalt formation. The weathered basalt material was previously used as borrow material for the road construction work. The dark brown silty clay soil underlain by decomposed basalt is observed at the toe of the steep side slope with the presence of springs.

Drainage Condition: The surface runoff water from the catchment above the hill cause the erosion of the slope material leading to minor landslides. In addition, the toe of steep side slope is observed to be swampy area with the development of springs and ponding of the surface water coming from the hill side.

Landslide Features: The minor rock falls from the strongly jointed, highly weathered trachy basaltic rock forming the steep slope on the left hands side of the road while the road bed is on a stabilized landslide body. The slope side is very steep (nearly sub-vertical) with the presence of subsurface water and development of erosion gullies.

Possible Cause of Landslide: Active infiltration of the surface water and erosion gully propagation on the slope are the main causes which could trigger the landside. The old landslide mass can potentially be reactivated if there is further steepening of the slope during excavation. The saturation of the side slope by the sub-surface water and infiltration of the surface water are the main causes of the landslide.

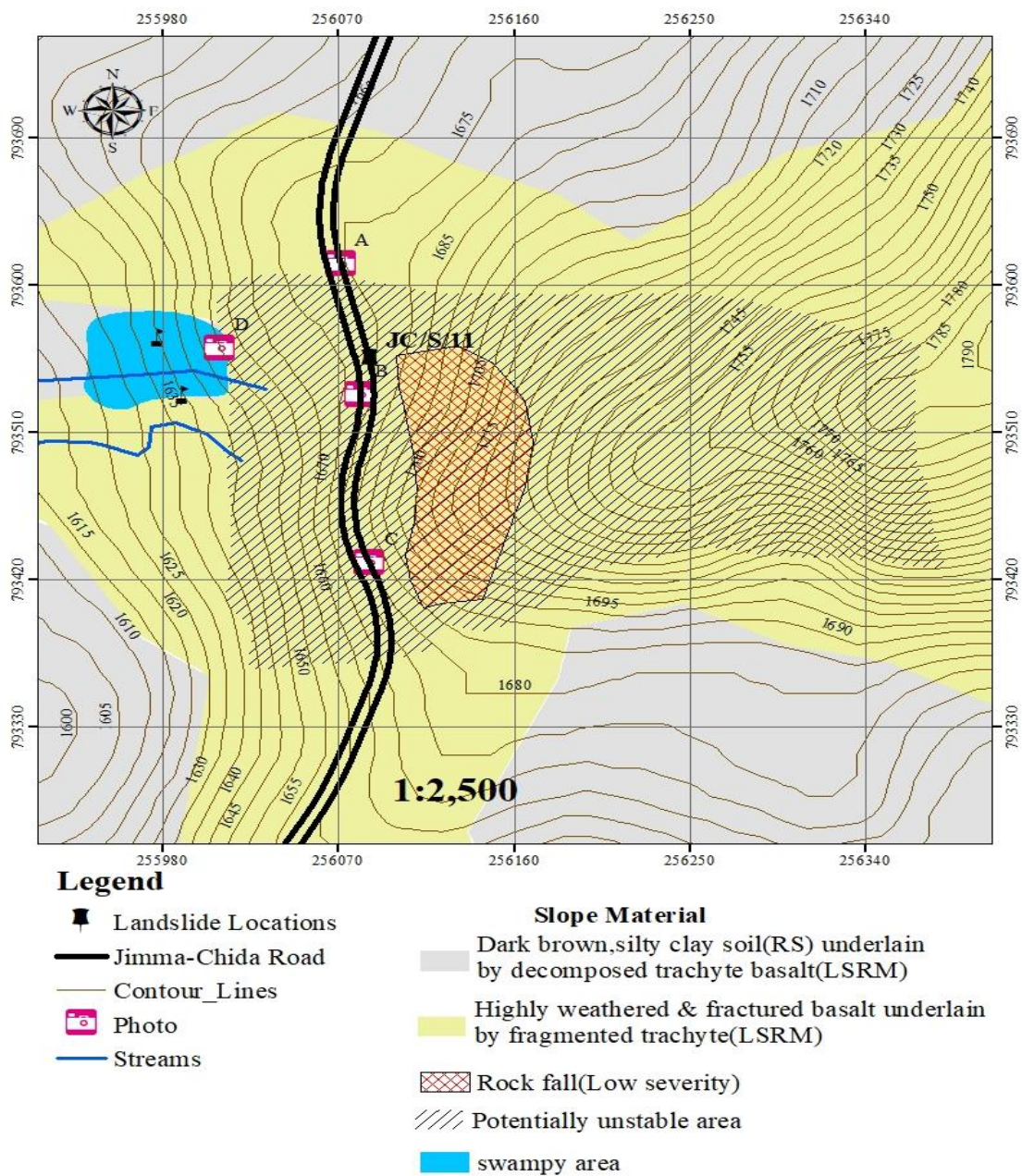


Figure 4-11: Landslide map of JC/S/11



Plate 4-11: Landslide at site JC/S/11: A-C steep back slope material of highly weathered and fractured basalt. D)Swampy area at right hand side of the downslope.

4.1.2. Landslide Contributing Factors

Identification, selection and evaluation of the landslide contributing and triggering factors has a critical importance in the accuracy of the final landslide susceptibility map(LSM) being produced. Various researchers have used different landslide factors for the preparation of landslide susceptibility map(LSM).There is no standard selection criteria for landslide triggering factors/parameters (T. Raghuvanshi et al., 2014).The geomorphological, geological , hydrological and human/manmade condition of the study area as well as the availability of data are main determinants for the selection of factors. The triggering factors that contribute for the occurrence of landslide in the study area have been studied through site investigation, field reconnaissance, literature review, and interview with residents.

The selected factor for landslide susceptibility mapping has to be measurable, unique, complete and practical (Melese et al., 2022). Based on the mentioned requirements a total of nine (9) landslide causative factors/parameters are selected for this study. Slope angle, elevation, slope aspect, curvature is taken as geomorphological factors; lithology as geological factors; distance to the stream and rainfall are taken as hydrological factors; and land use and land cover as human factors.

4.1.2.1. Slope Angle

Slope angle is one of the most essential contributing factor which influence the occurrence of landslide, the steeper the slope the likelihood of the landslide to initiate. By definition the slope angle is a parameter which indicates the degree of steepness and inclination with reference to the horizontal plane (Mehmood et al., 2022). As presented by different researchers such as (Ayenew & Giulio, 2005; Guzzetti et al., 1999; Wendim, 2023 and Woldearegay, 2019) significant numbers of the previous studies stipulated that majority of the landslide phenomena have taken place in locations having a slope angles in range of 15° to 45° (Woldearegay, 2019). The slope morphology of the area not only affects the driving stress inside the slope but also determines the weathering layer depth and the runoff water (Guzzetti, 2005). The principal idea here is the low possibility for the existence of landslides in flat and gentle slope is perhaps to be as a result of the corresponding increment in the safety factor of the slope and a water table at shallower depth will be required to trigger failure (Woldearegay, 2019). The other perspective is the nonexistence of major landslide phenomena on topography with steep slope gradients is associated to the very thin or even absence of unconsolidated deposits on such terrains because most of the steep slopes are composed of fresh to highly weather rock formations.

As mentioned previously the slope angle plays a vital role on the stability of the area. The natural slope angle of the area is altered by various factors through natural and artificial processes which in turn influence the possibility of landslide occurrence. The slope map of the Jimma-Chida road section is generated from DEM data using an Arc GIS spatial tool and classified into 9 (nine) classes as $<5^{\circ}$, 5° - 9° , 9° - 14° , 14° - 20° , 20° - 27° , 27° - 32° , 32° - 39° , 39° - 48° and 48° - 75° (Figure 4-12).

The topographic survey conducted along Jimma-Chida road alignment indicates that the route passes through 12.4% flat, 30.6% rolling, 52.0% mountainous and 5.0% escarpment terrain and around 70% of the route traverse along ridge top alignment section which has a favorable topographic nature for road since it optimizes the earth work and drainage structural quantities but is susceptible for the occurrence of landslide. Particularly the road section from km 20+000 to km 45+000 with a history of various occurrences of landslides is characterized by rolling to mountainous topography combined with other controlling factors like drainage, erosion gullies and intense rainfall. From Figure 4-13 it is indicated that majority of the existing landslides are occurred in a slope class 9° - 14° and 14° - 20° which composed 31.4% and 29.0% of the total landslides along the section of the road. The slope classes 5° - 9° , 20° - 27° , 0° - 5° , 27° - 32° , 32° - 39° and 39° - 48° are composed 14.3%, 13.6%, 5.9%, 4.1%, 1.4% and 0.3% of the total recorded landslides along the studied road section.

From this discussion it is indicated that majority of the existing landslides are occurred on the rolling and rolling to mountainous terrain which gives an information that the contribution of the slope angle exclusively for the occurrence of the landslide along the study road section is not that significant. Though slope angle is not the most influencing factor for the landslide triggered along the road, it has a cumulative effect combined with the other factors.

From the in-situ assessment of the existing active landslides, it is witnessed that the landslides occurred on the rolling and rolling to mountainous areas are triggered mainly due to either their proximity to streams distance to the engineered road (mainly on the high fill and deeper cut sections) or lithology and geological formation of the area combined with the comparative roughness of the local topography.

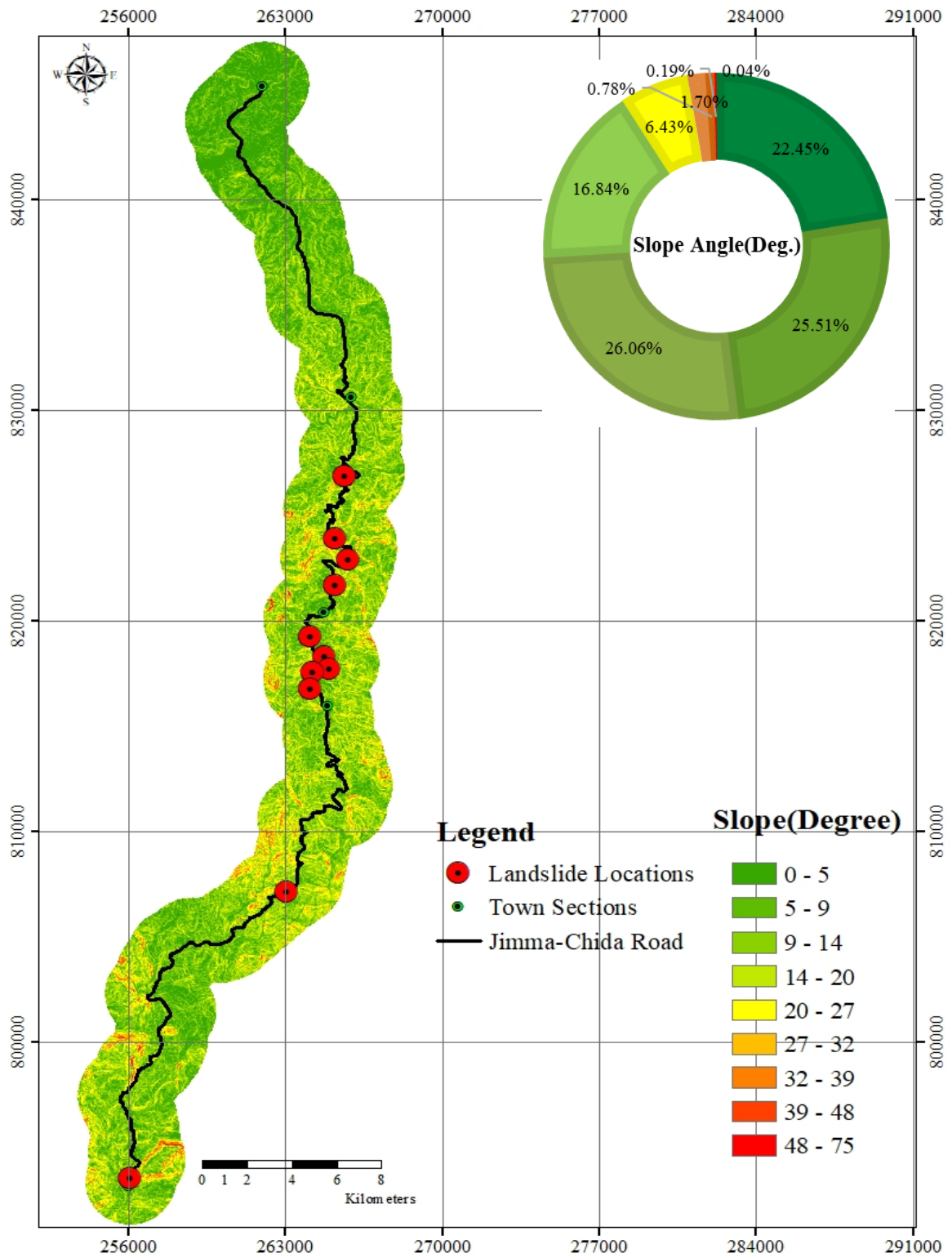


Figure 4-12: Slope map



Figure 4-13: Distribution of the slope angle factor classes for the existing landslides

4.1.2.2. Slope Aspect

The slope aspect is refers to the direction that the slope is facing (Tesfa, 2022). This feature of the slope mainly determine on the exposure of sunlight, rain shadow, forest cover, flow of surface water runoff, erosion behavior of the slope material and drying wind (Melese et al., 2022). The contribution of slope aspect for the occurrence of landslide can be related with the concentration of soil moisture. For this particular study the slope aspect is taken as one of the landslide triggering factor to represent the relationship between slope aspect facing and landslide. As indicated in Figure 4-14, the slope aspect map is prepared by utilizing aspect tool in ArcGIS software on the 30.0 m x 30.0 m DEM data. For the subject study area, the produced slope aspect map is classified into 9(nine) classes as flat, northwest(NW), west(W), southwest(SW), south(S), southeast(SE), east(E), northeast(NE), and north(N). Based in the analysis between the existing landslide sections and the slope aspect map (Figure 4-15) the majority of landslide occurred in the Northwest(NW), North(N), South(S) slope aspect classes each composed of 20.3%, 17.4% and 16.8% of the total landslides, respectively. The remaining slope aspect classes South(S), Southwest(SW), West(W), Northeast(NE), East(E) and Flat(F) accounted for 14.6%, 9.7%, 9.5%, 7.7%, 2.9% and 1.3% of the landslides, respectively.

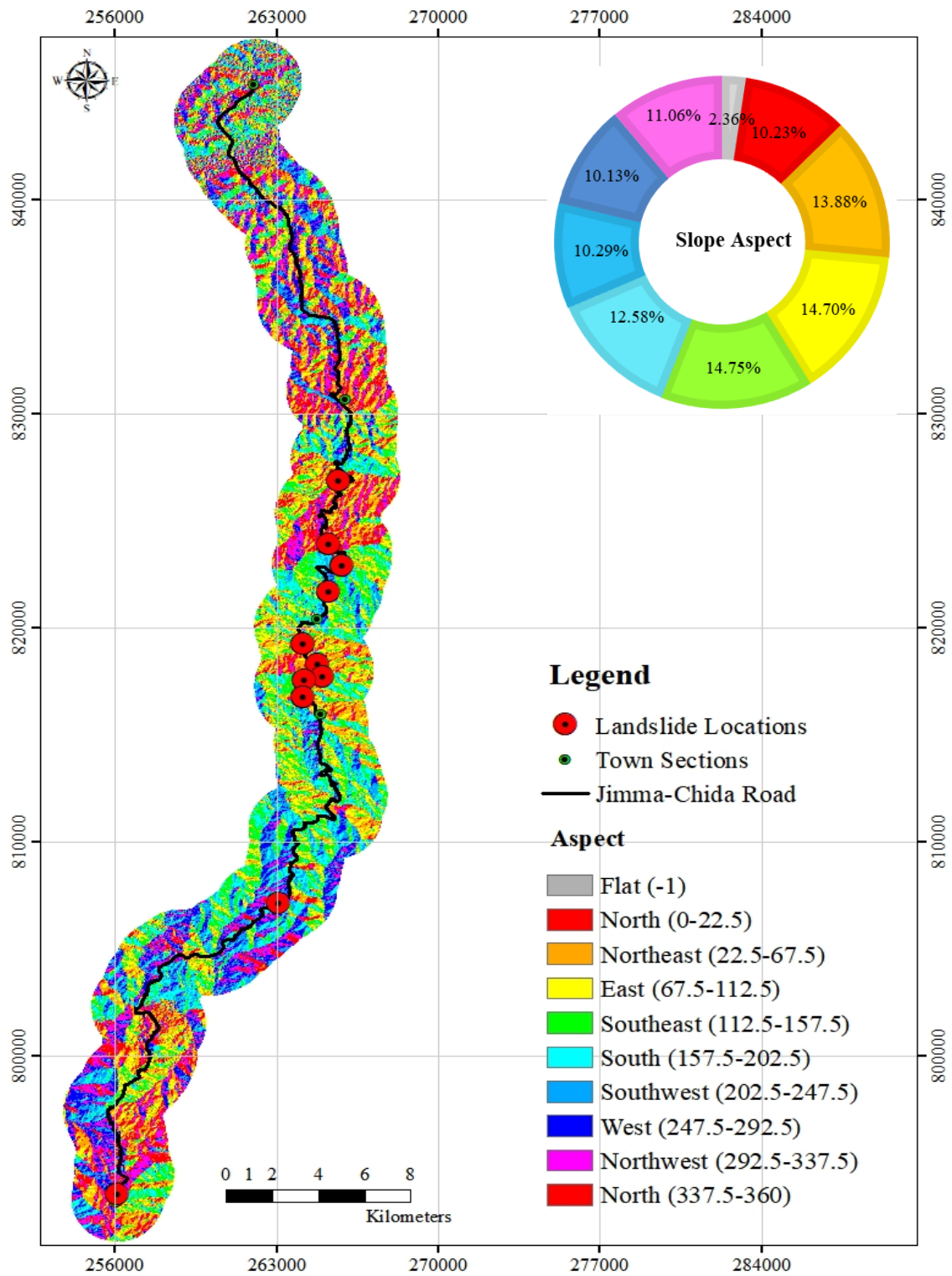


Figure 4-14: Slope aspect map

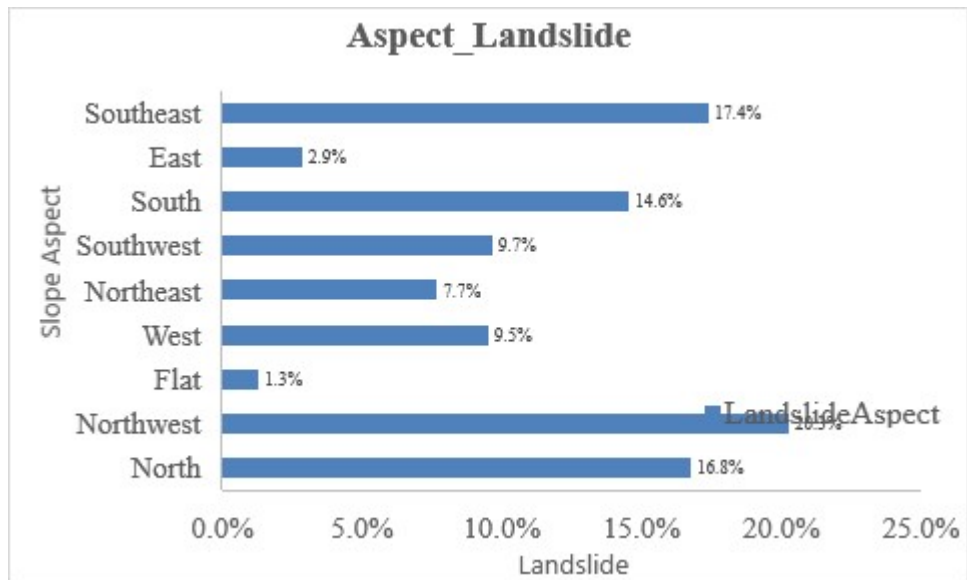


Figure 4-15: Distribution of the slope aspect factor classes for the existing landslides

4.1.2.3. Elevation

Elevation describes the height of the area relative to the sea level and mostly used by various researchers as contributing factor for analyzing the landslide susceptibility of the area. In principle, areas located at higher elevation have a higher landslide occurrence possibility. Elevation mainly related with different environmental conditions such as rainfall intensity received, the vegetation type and density of the area (Catani et al., 2013). The elevation of the study area was extracted and generated from a digital elevation model with a resolution of 30.0 m using the ArcGIS software tool. The elevation of the area ranged between 1015 m and 2732 m and reclassified into seven classes (Figure 4-16). The area with higher elevation value has higher precipitation, indicating that there is a higher possibility of landslide in this area and have a history of frequent landslide. Referring Figure 4-17, the elevation classes with the ranges of 2388.0-2732.0 m, 2198.0-2388.0 m, 1300.0-1580.0 m, 1580.0-1802.0 m, 1998.0-2198.0 m are composed 30.1%, 21.0%, 17.6%, 15.7% and 15.5% of the existing landslides, respectively.

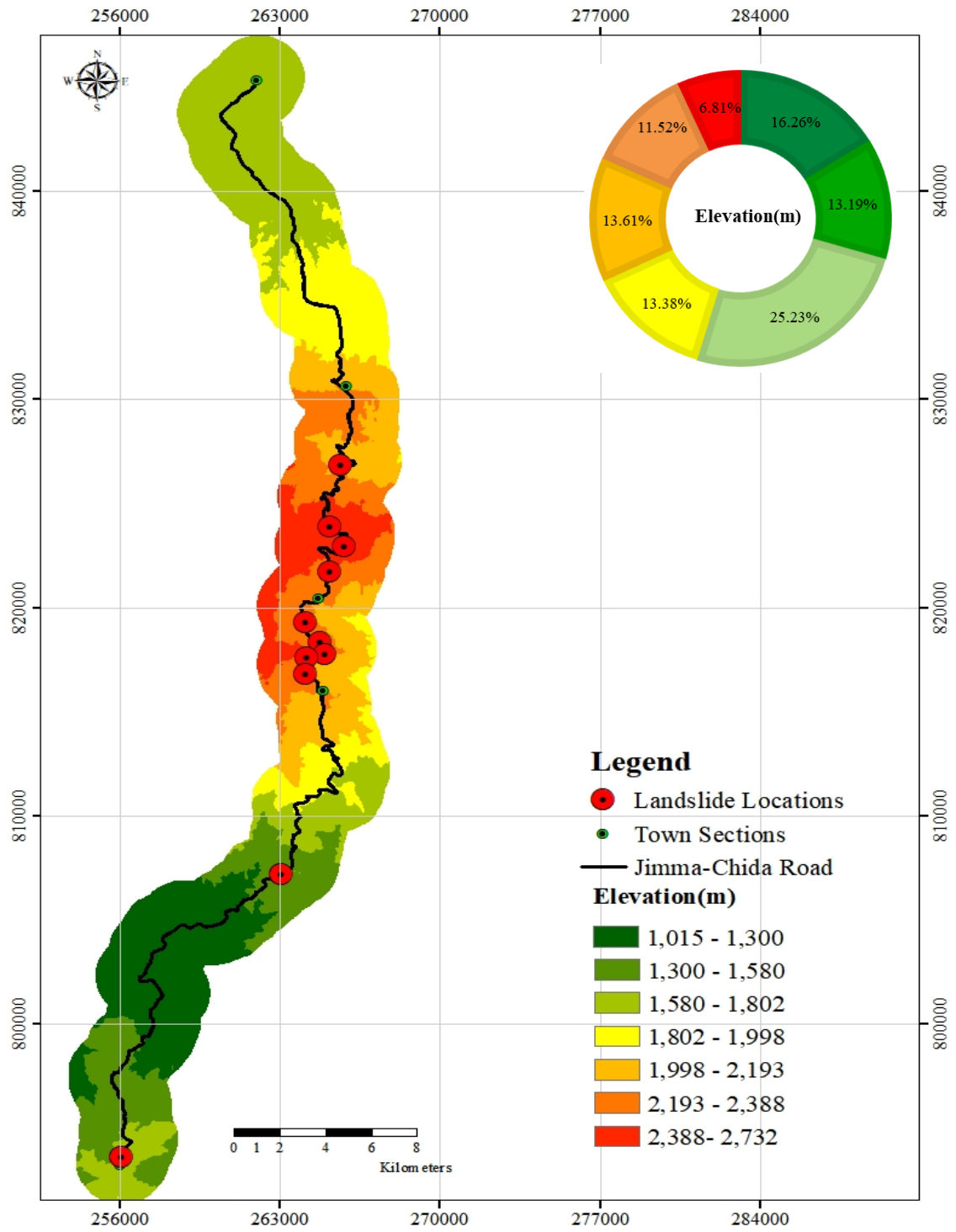


Figure 4-16: Elevation map

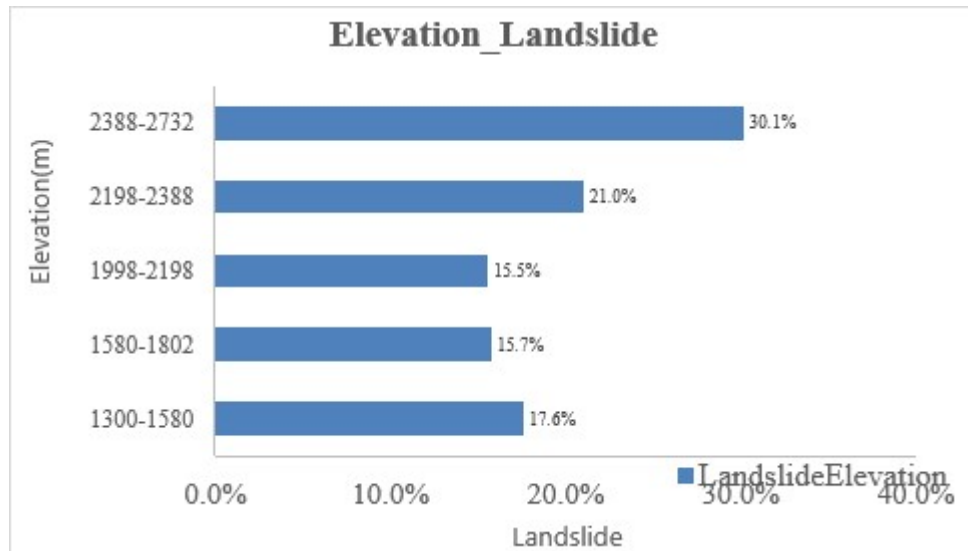


Figure 4-17: Distribution of the elevation factor classes for the existing landslides

4.1.2.4. Curvature

An important geomorphological index of topographic feature for the study area is characterized by the curvature of the slopes (M.Melesse, 2019, Fomelis et al., 2018). The curvature contribute for the occurrence of landslide while affecting the surface runoff which in turn affects the surface erosion. For instance, landslide occurred more frequently on concave slopes than on convex ones. The reason for this is slopes with concave slopes have a high tendency of holding more rainfall water; thus the water gets more time to infiltrate into the slope and enhance the possibility for the occurrence of landslide (Farhan et al., 2020). In addition, according to (Ohlmacher, 2007), curvature significantly affects the shear and resistance stresses of landslides.

Likewise, the curvature map of the study area was classified into three main classes. Negative curvature concave (< 0), zero curvature flat (0), and positive curvature convex (> 0) (Figure 4-18). A positive curvature represents that the surface is convex upward and a negative curvature indicates that the surface is concave upward at that cell. Similarly, a zero value of curvature shows that the surface is flat (Solaimani & Mousavi, 2012). From Figure 4-19, it is indicated that the flat curvature with composition of 39.7% followed by concave and convex curvature with 38.2% and 22.1% contribution, respectively are curvatures of the existing landslide along the Jimma-Chida road section.

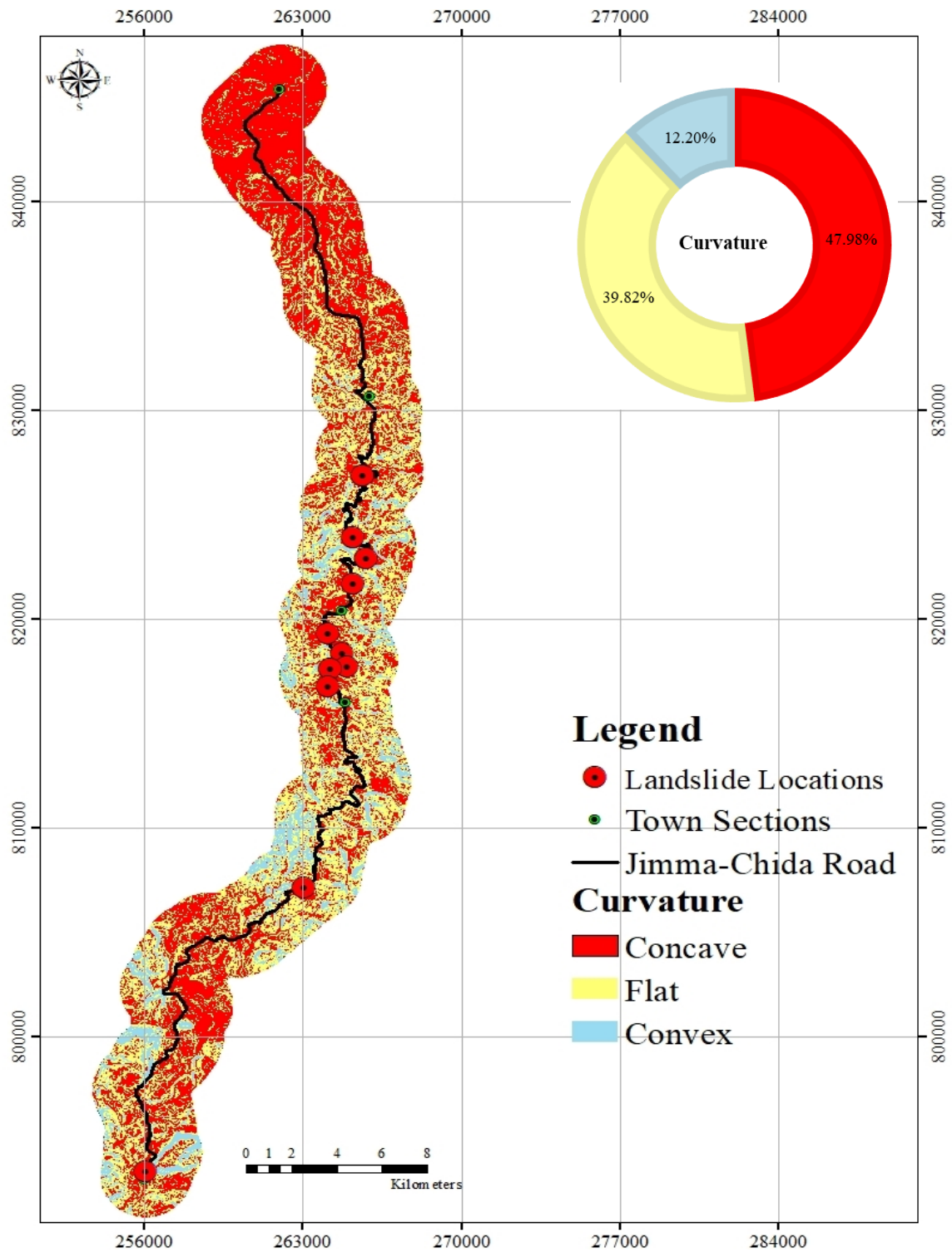


Figure 4-18: Curvature map

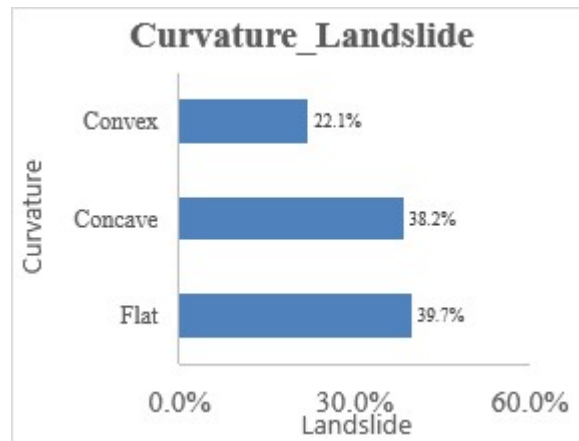


Figure 4-19: Distribution of the curvature factor classes for the existing landslides

4.1.2.5. Lithology

Lithology is one of the determinant factors not only for preparing landslide susceptibility map but also for determining the size and type of landslide. Hence degree of susceptibility, size, density and type of landslide for a given area is highly affected by the lithological formation it has (Dai et al., 2001; Yalcin, 2007). For that reason, the lithology as a contributing factor of landslide shall be taken into consideration. The influence of lithology on the degree of landslide susceptibility mainly associated with the fact that different formations have varies each other on their structures, composition, and hydraulic property which affects the material characteristics and strength (Hong et al., 2016). The combined effect of this parameter with the topographic, hydrologic and human intervention factors has a remarkable influence on the landslide incidences and shall be study well.

For the Jimma-Chida road the lithological map has been produced using Landsat images, Google Earth, combined with the existing Jimma area geological and geomorphological maps and field reconnaissance (Figure 4-20). The road section under study is represented by five major lithological units namely Alluvial deposit (Q_{al}), Lower trachyte flows (Tv3), Middle basalt flows (Tv5), Middle trachyte flows (Tv6) and Upper basalt flows (Tv7) (Geological Survey of Ethiopia (GSE), 2012).

The alluvial deposit formation mainly found around the outskirts of Jimma town and along the major river locations. This formation composed of the quaternary alluvial deposits with silty clay to silt soil on gentle to plain topography.

The Middle Trachyte(Tv6) formation is characterized by a medium to highly weathered, light grey to light pinkish in color, massive and laminated trachyte(Ethiopian Geological Survey(GSE), 1996). At some place small hill forming with laminated and bedded structures is observed and the formation has a low strength value. The residual soil originated from this formation is characterized as brown to grayish brown color, silty clay, high plasticity to medium plastic, high to medium dilatancy. This formation composed the road section at two segments ranging from km 5+000 to km 27+900 and km 46+880 to km 54+000. For the upper basalt flows(Tv7) its highly decomposed formation of this geology forms a residual soil with brownish, soft to firm to stiff, clayey silt/silty clay soil. The hydraulic properties of this residual soil formations are poor resulting low water permeability which leads to the development of excess pore water pressure which is the driving force causing the slope instability. Most of the landslides along the studied road section, JC/S/01 to JC/S/08 and JC/S/10, are located on this formation. This unit encountered on two segments of the road section ranging from km 27+900 to 46+880 and km 77+350 to Chida Town. Middle basalt flows(Tv5) formation is encountered for road segment from km 54+000 to 62+700 (Figure 5-20). The residual soil derived from middle basalt flows(Tv5) characterized by brown to dark brown color, silty clay, high to medium plastic having an expansive property. JC/S/10 at km58+750 is located at this lithological formation.

The lower trachyte flows(Tv3) is the light gray to pinkish,medium to coarse grained,closely spaced jointed to massive,sometimes randomly fractured trachytes which mainly exposed in the Gojeb river valley.This formation is encountered from km62+700 to entrance of Chida Town(km77+350) of the road section.

Regarding the composition of the lithological formation of the existing landslides as indicated in Figure 4-21, the upper basalt flows exists along majority of the landslide section with the percentage of 48.6% followed by middle basalt flows,alluvial deposit and middle trachyte flowa with composition of 18.1%,17.6% and 15.7%,respectively.

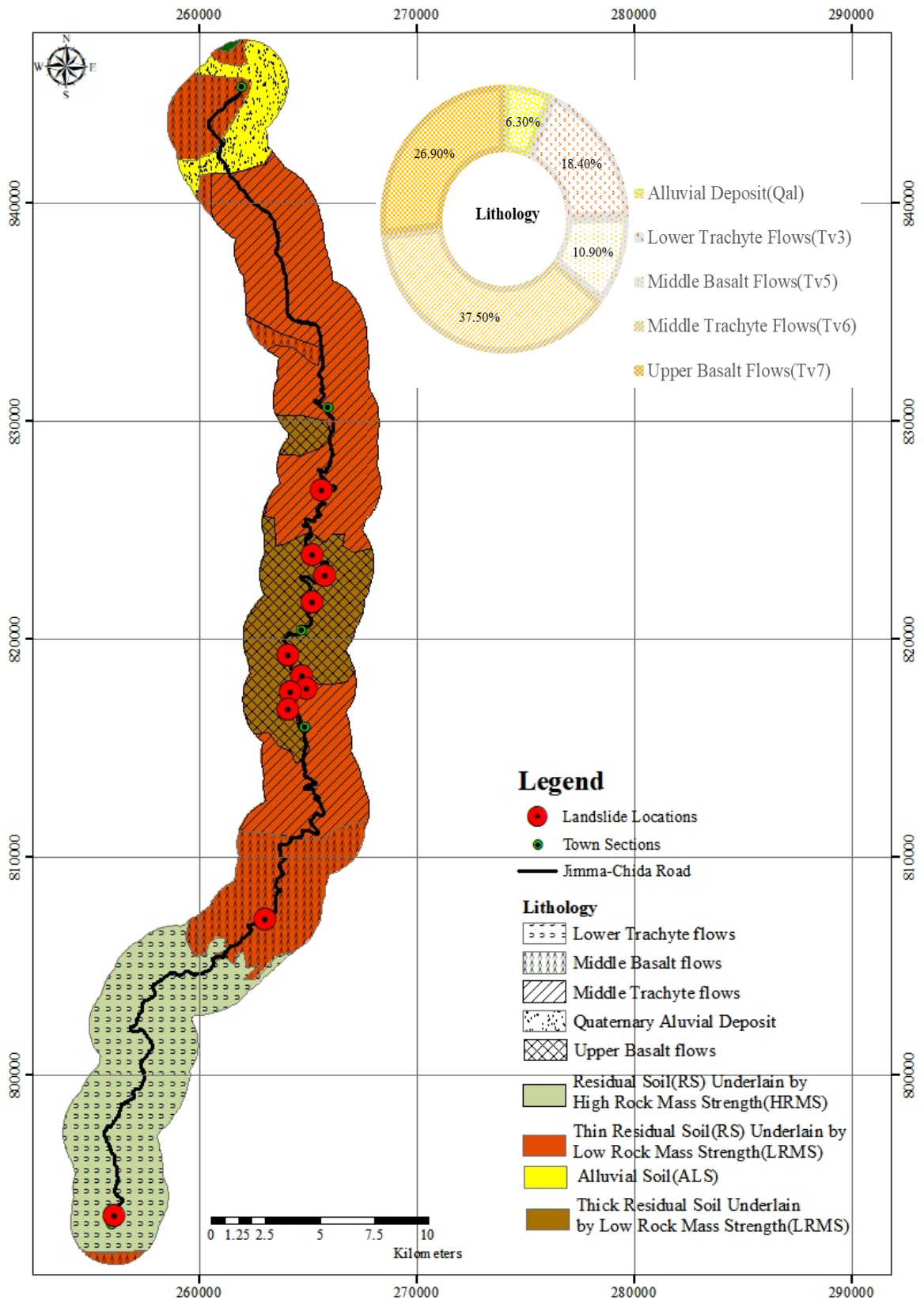


Figure 4-20: Lithology map

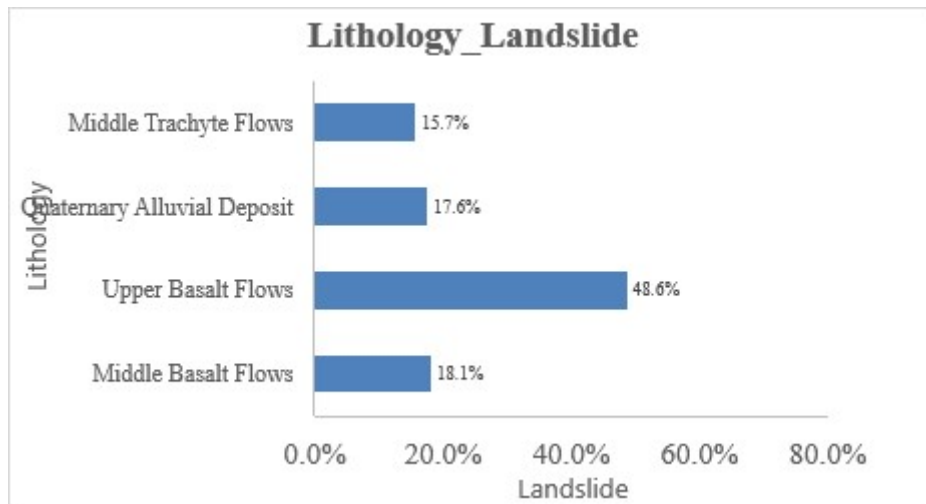


Figure 4-21: Distribution of the lithological factor classes for the existing landslides

4.1.2.6. Distance to Stream

The role of streams on the development of landslide is substantial. The potential of the stream to change the groundwater level and to erode the toe of the slope can lead to the failure of the banks and slope faces (Dai et al., 2001). On the other hand, the drainage pattern tremendously depends on the degree of stream channel surface material property and this can be manifest by when the stream network is denser it indicates that the slope material on the area is looser and highly erodible.

For Jimma-Chida road, most of landslides have occurred along streams and at the locations where cross drainage structures are constructed. For the present study, the drainage network was generated from 30.0 m x 30.0 m Aster DEM by utilizing Arc-Hydro tools in GIS environment. Four different proximity zones were produced to characterize the contribution of the drainage for the instability of the road section mainly traverse along the river bank slopes (Figure 4-22). The stream zones along the road corridor generated to analyze their contribution for the occurrence of landslide are 50 m, 100 m, 300 m and 1000 m and >1000 m. Presented in Figure 4-23, it is observed that the distance to stream of 50, 100, 300, 1000 and >1000 m have a distribution of 30.8%, 28.8%, 24.7%, 12.3% and 3.4% of existing landslide, respectively.

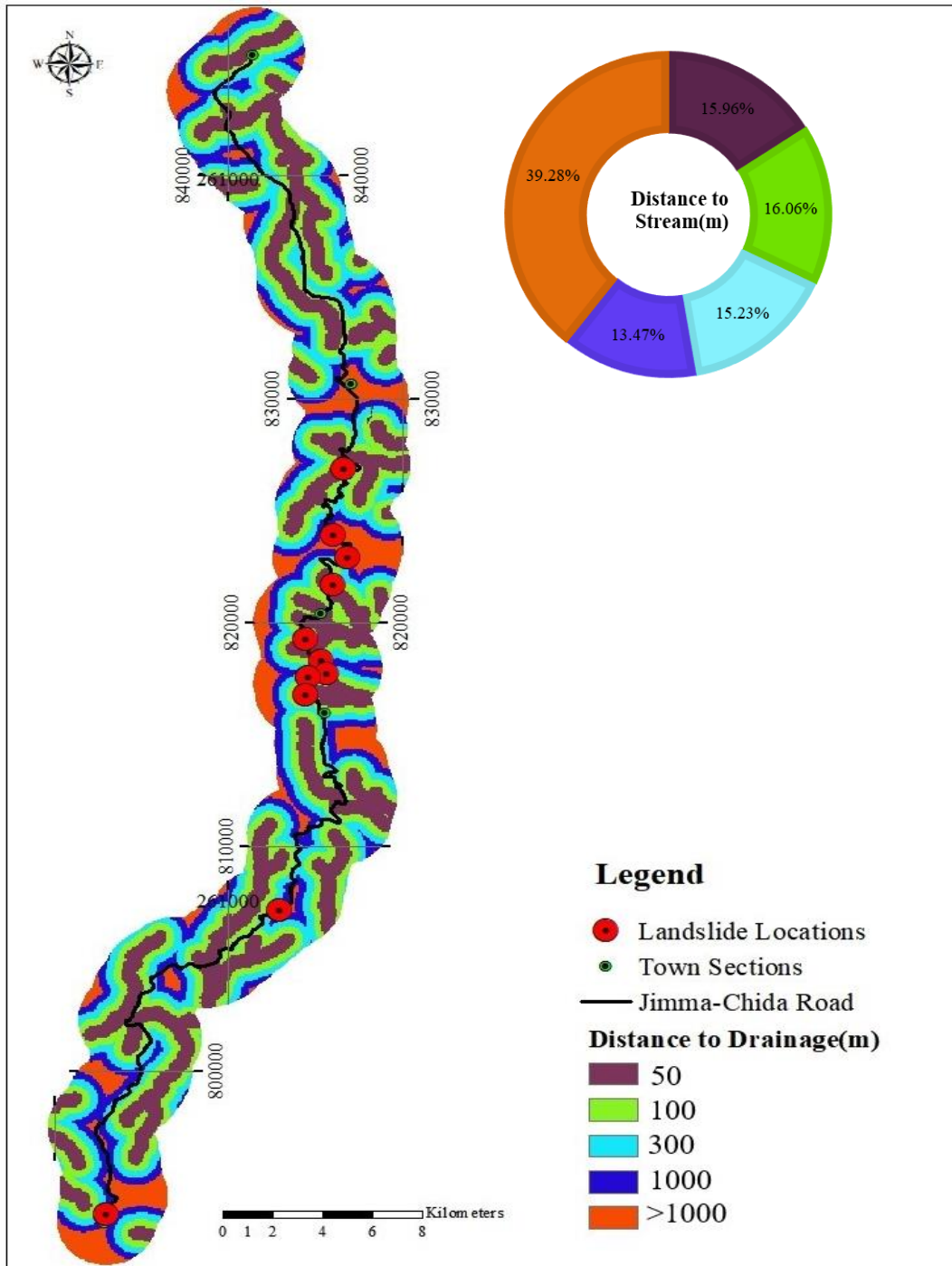


Figure 4-22: Distance to stream Map

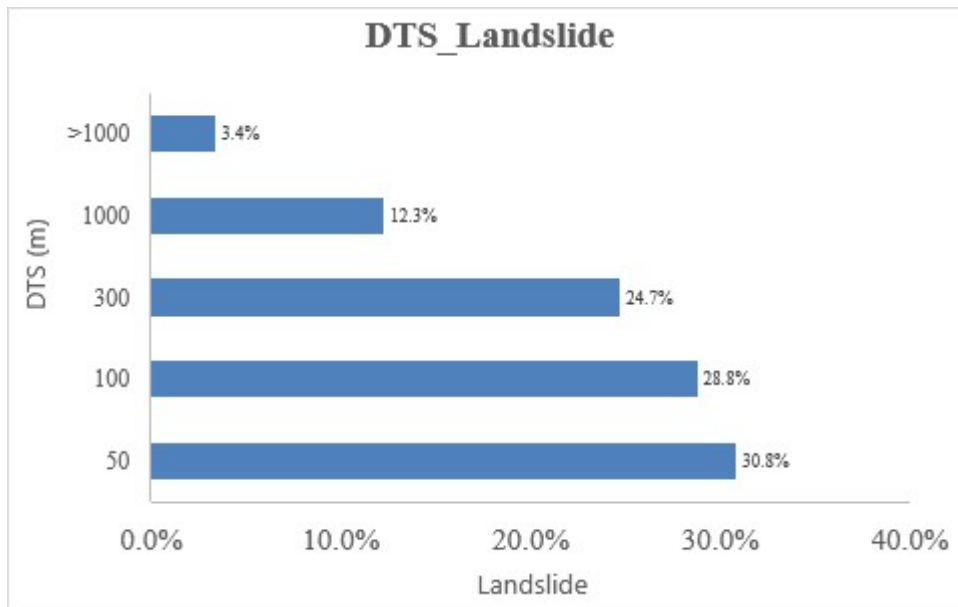


Figure 4-23: Distribution of the distance to stream factor classes for the existing landslides

4.1.2.7. Distance to Road

The relative distance of the given location from the road is taken as one of the main anthropogenic factor determining the existence of landslide on the area (Jazouli & Barakat, 2019). In case of Jimma-Chida road section the excavation activities on the mountainous and rolling section has a high contribution for the instability on the area by disturbing the natural slope. This cause the lack of support at the toe of the slope after excavation which reduce the resisting force leading to the mass on the upslope direction to slide toward the down slope. Construction of the road near the hill side raise the chance that the landslide will occur significantly. This is mainly observed on the residual soil slope material.

For Jimma-Chida road section five distinct buffer zones were produced and classified into 50, 50-150, 150-500, 500-1000 and, > 1000 m (Figure 4-24). The area located near the road corridor have more chance of landslide occurrence comparing with the areas located far from the road corridor.

As indicated on Figure 4-25, most of landslides are occurred within 50, 150 and 500 m distance from the road with their composition of 39.9%, 38.5% and 21.6%, respectively.

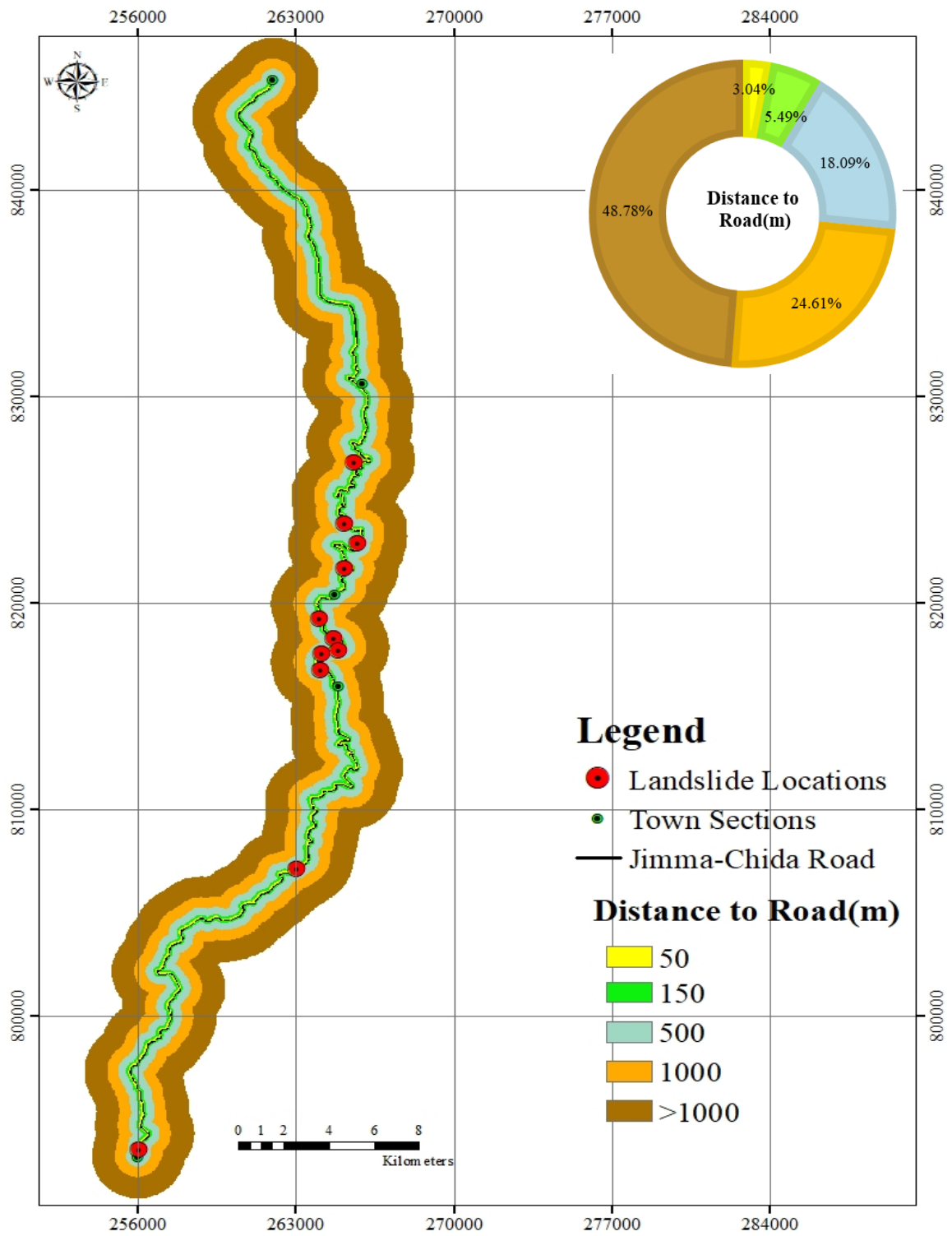


Figure 4-24: Distance to road map

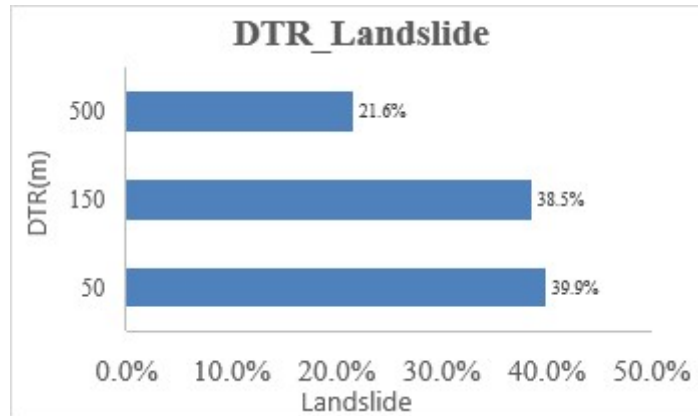


Figure 4-25: Distribution of the distance to road factor classes for the existing landslides

4.1.2.8. Land use/ cover

Land use and cover is the other important factor which contribute for the occurrence of landslide. Areas with rough topography and have a bare land or scattered vegetation cover are highly affected by landslide and a densely forested areas have less susceptibility for the landslide while comparing to the previous one. The Land use/ cover is highly related to the need of the population settled on the area. For example, the human intervention on the land use can be characterized by changing the dense forest area to urban center, conversion of the forest with unique ecological makeup into the farm land due to expanded demand and poor management of farmlands and altering the natural slope of the area for infrastructure development(Jazouli & Barakat, 2019).

The main land cover/use observed along the road section are water bodies, trees, flooded vegetation, crops, built areas, bare ground and range lands(Figure 4-26). Significant number of the landslides along the Jimma-Chida road section have occurred due to the intense erosion of slope faces and river banks which lacks vegetation cover. There are also active agricultural activities along the road section which practiced on a rolling to mountainous ground slope by cutting trees, which leads to the erosion of the slope material which highly contributes for the occurrence of landslide. Summarized in Figure 4-27, the areas covered by crops, built up towns sections, range lands, water bodies and trees are contribute for the existing landslides with distribution of 42.5%,27.5%,28.6%,1.3% and 0.2%, respectively.

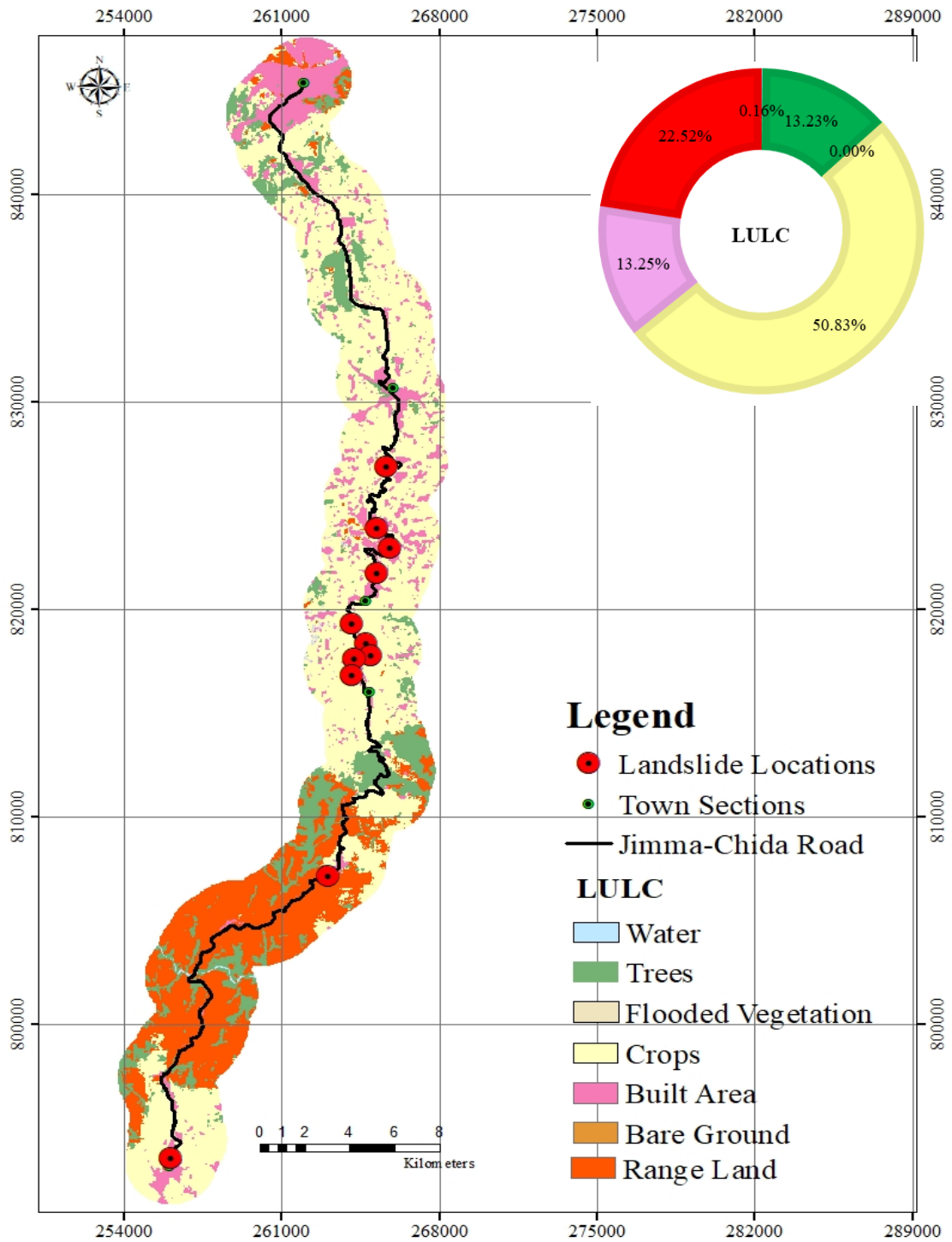


Figure 4-26: Land use/ cover map

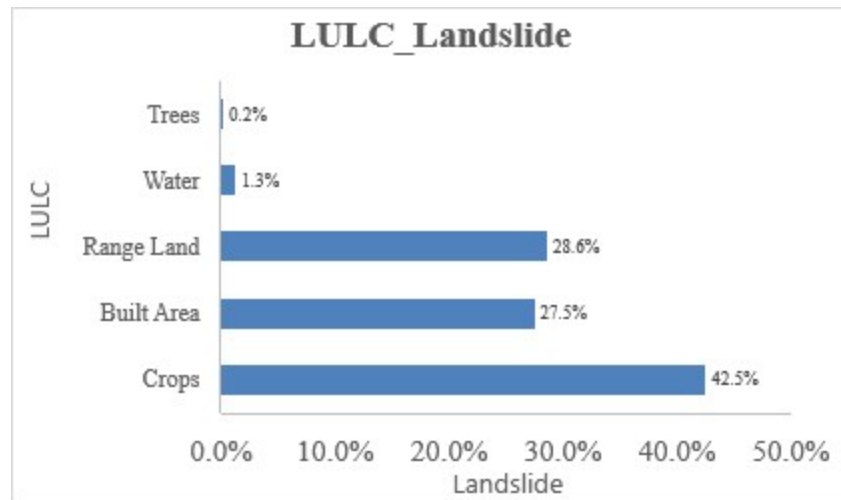


Figure 4-27: Distribution of the land use/cover factor classes for the existing landslides

4.1.2.9. Rainfall

Rainfall is one of the critical contributing parameter for most types of landslide because the large volume of rainfall in combination with all the other factors highly facilitate the instability of the area and destabilize the slope (Tešić, 2021). This is supported by the fact that most of landslides are initiated during and after the rainy season, when large amount of rainfall recorded on the area, and the slope surface becomes wet and heavy due to increased infiltration of water leading to significant reduction of shear strength and soil cohesion which induced instability.

In case of the study Jimma-Chida Road section most of the slope failures have been occurred in the month of July, August and mid-September when the study area receive intense and prolonged rainfall. The historic rainfall data from National Meteorological Agency of Ethiopia, the main rainy seasons of the road section are the months of June to September and April to May with the annual rainfall in Jimma area ranges from 1143.8 to 1966.7 mm and it ranges from 1108.0 to 1944.6 mm in Chida area.

However, the effect of the rainfall on the overall slope stability of the area is studied as a combined effect of the other contributing factor such as slope gradient, slope aspect, slope material type and potential of soil erosion. For Jimma-Chida road section the collected rainfall data has interpolated into 4 classes using spatial analysis tool in GIS environment (Figure 4-28). As indicated in Figure 4-29, existing landslides are occurred in the rainfall region of 1547-1600 mm and 1600-1675 mm with distribution of 38.1% and 61.9%, respectively.

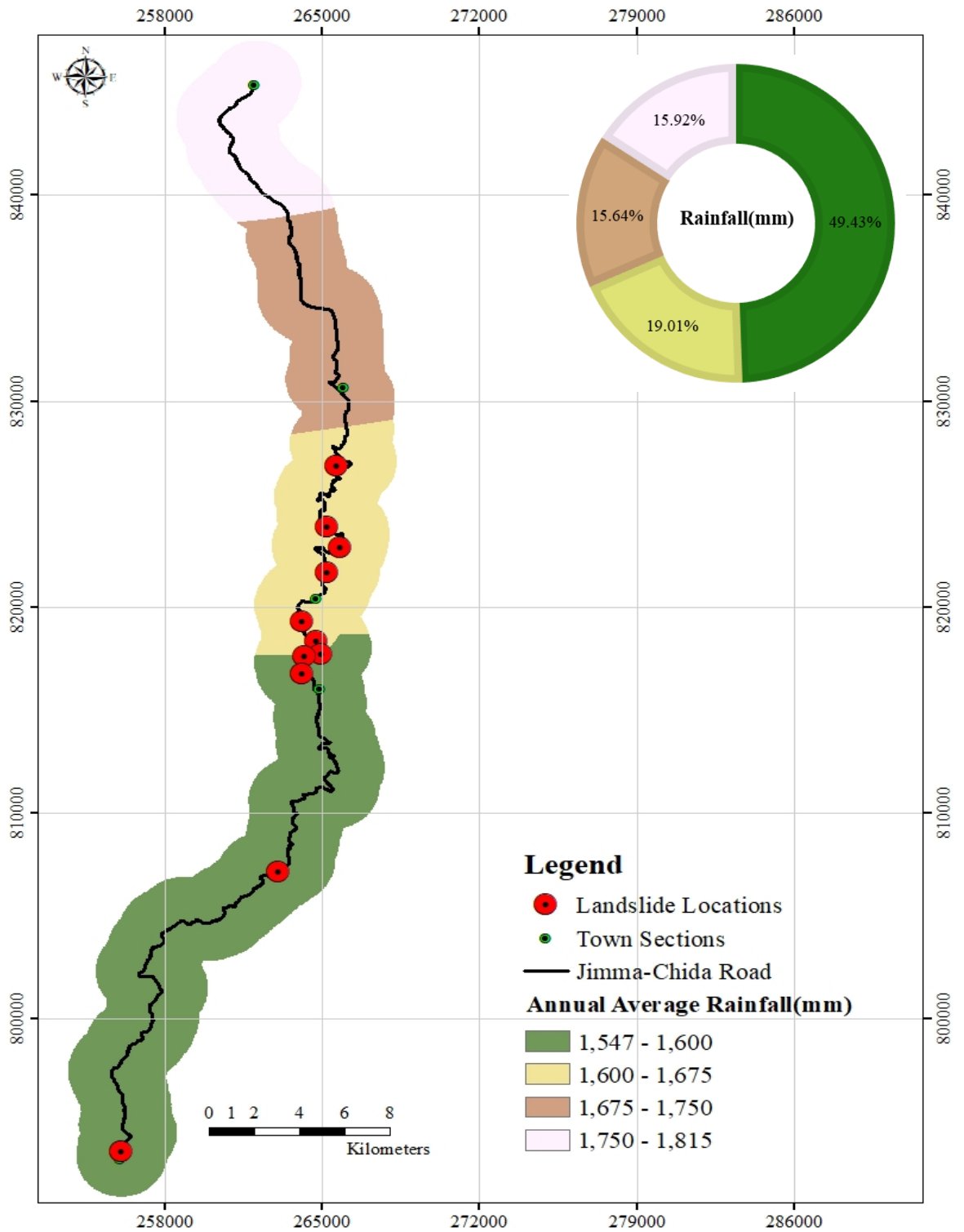


Figure 4-28: Rainfall map

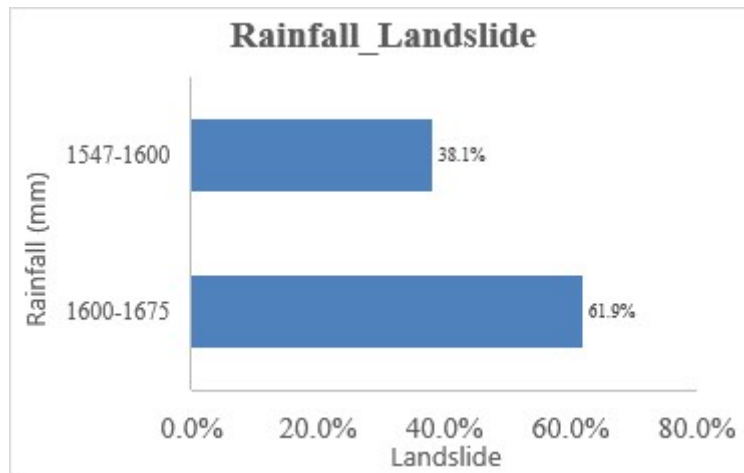


Figure 4-29: Distribution of the rainfall factor classes for the existing landslides.

4.1.3. Landslide Susceptibility Analyses

The weight of the corresponding causative factors of the landslide is computed using the Analytic Hierarchy Process(AHP) approach to determine the relative susceptibility of landslide occurrence along Jimma-Chida road section. Nine landslide triggering factors namely slope degree, aspect, curvature, elevation, lithology, land use/land cover, distance to road, distance to stream and rainfall were utilized to conduct landslide susceptibility analysis.

4.1.3.1. Landslide Contributing Factor Score using Analytic Hierarchy Process(AHP)

The spatial relationship between landslide contributing factor and location of landslide is key for analyzing the AHP model. Hence, the spatial analysis of all contributing factors and parameters as well as site observation were taken into account for rational judgement. The pair-wise comparison matrix for the factors and sub-factors are analyzed to produce their relative weight as indicated in Table 4-1.

Table 4-1: The pair-wise comparison matrix, factor weights, class weights (rating) and consistency ratio

Slope Angle(Deg.)		1	2	3	4	5	6	7	8	9	Weight
1	0-5	1									0.019
2	5-9	2	1								0.026
3	9-14	3	2	1							0.037
4	14-20	4	3	2	1						0.053
5	20-27	5	4	3	2	1					0.076
6	27-32	6	5	4	3	2	1				0.109

Slope Angle(Deg.)		1	2	3	4	5	6	7	8	9	Weight
7	32-39	7	6	5	4	3	2	1			0.154
8	39-48	8	7	6	5	4	3	2	1		0.218
9	48-75	9	8	7	6	5	4	3	2	1	0.307

CR 0.052

Slope Aspect		1	2	3	4	5	6	7	8	9	Weight
1	Flat	1									0.023
2	North	2	1								0.047
3	Northeast	7	4	1							0.203
4	East	4	2	1/3	1						0.083
5	Southeast	9	8	3	4	1					0.356
6	South	5	3	1/2	2	1/4	1				0.126
7	Southwest	4	2	1/4	1	1/5	1/2	1			0.080
8	West	3	1/2	1/4	1/2	1/7	1/3	1/2	1		0.047
9	Northwest	2	1	1/7	1/3	1/8	1/4	1/3	1/2	1	0.034

CR 0.034

Elevation(m)		1	2	3	4	5	6	7	Weight
1	1015-1300	1							0.030
2	1300-1580	2	1						0.043
3	1580-1802	3	2	1					0.065
4	1802-1998	4	3	2	1				0.098
5	1998-2198	5	4	3	2	1			0.146
6	2198-2388	6	5	4	3	2	1		0.213
7	2388-2732	8	7	6	5	4	3	1	0.406

CR 0.046

Curvature		1	2	3	Weight
1	Flat	1			0.106
2	Concave	5	1		0.633
3	Convex	3	1/3	1	0.260

CR 0.053

Lithology		1	2	3	4	5	Weight
1	Lower Trachyte Flows	1					0.118
2	Middle Basalt Flows	1	1				0.120
3	Middle Trachyte Flows	1/3	1/2	1			0.056
4	Quaternary Alluvial Deposit	1/2	1/3	1	1		0.056
5	Upper Basalt Flows	8	7	9	9	1	0.649

CR 0.051

Distance to Stream(m)		1	2	3	4	5	Weight
1	50	1					0.441
2	100	1/2	1				0.260
3	300	1/3	1/2	1			0.152
4	1000	1/5	1/3	1/2	1		0.099
5	>1000	1/7	1/5	1/3	1/3	1	0.049

CR 0.022

Distance to Road(m)		1	2	3	4	5	Weight
1	50	1					0.481
2	150	1/2	1				0.268
3	500	1/4	1/2	1			0.134
4	1000	1/8	1/4	1/2	1		0.082
5	>1000	1/9	1/8	1/4	1/4	1	0.035

CR 0.044

Land use/ cover		1	2	3	4	5	6	7	Weight
1	Water	1							0.379
2	Trees	1/7	1						0.045
3	Flooded Vegetation	1/5	3	1					0.077
4	Crops	1/6	1	1/2	1				0.048
5	Built Area	1/3	4	4	4	1			0.262
6	Bare Ground	1/3	2	2	2	1/5	1		0.098
7	Range Land	1/5	2	2	2	1/5	1	1	0.090

CR 0.064

Rainfall(mm)		1	2	3	4	Weight
1	1547-1600	1				0.057
2	1600-1675	3	1			0.122
3	1675-1750	5	3	1		0.263
4	1750-1815	7	5	3	1	0.558

CR 0.066

Factors	Slope Angle	Slope Aspect	Elev.	Curv.	Litho.	DTS	DTR	LULC	Rain	Weight
Slope Angle	1									0.073
Slope Aspect	1/4	1								0.023
Elev.	1/2	3	1							0.056
Curv.	1/4	1	1/3	1						0.023
Litho.	5	6	4	5	1					0.167
DTS	3	6	4	7	2	1				0.203
DTR	4	8	3	9	2	1	1			0.197
LULC	1/2	4	2	3	1/4	1/5	1/4	1		0.059
Rainfall	4	6	2	8	1	1	2	4	1	0.199
CR	0.056									

4.1.4. Landslide Susceptibility Mapping(LSM)

Using the Analytic Hierarchy Process(AHP) approach the landslide susceptibility map of the study road section was generated by combining the thematic raster map of nine contributing factors with their calculated weightage.

Recalling (4-3), the weighted raster maps are summed using the weighted overlay tool in spatial analysis to generate the landslide susceptibility index(LSI) (4-1);

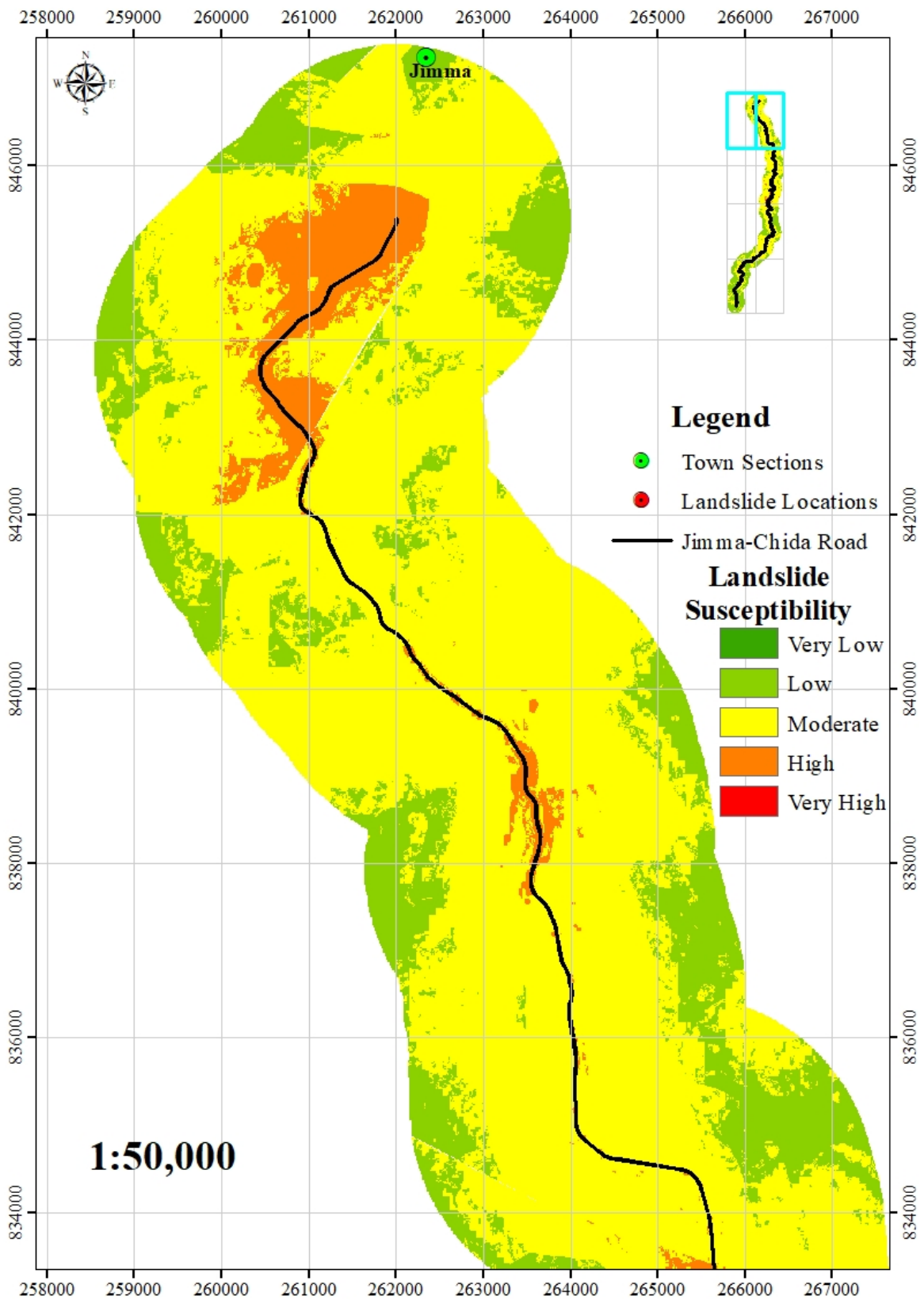
$$LSI = \sum_i^n W_j * R_{ij} \quad (4-1)$$

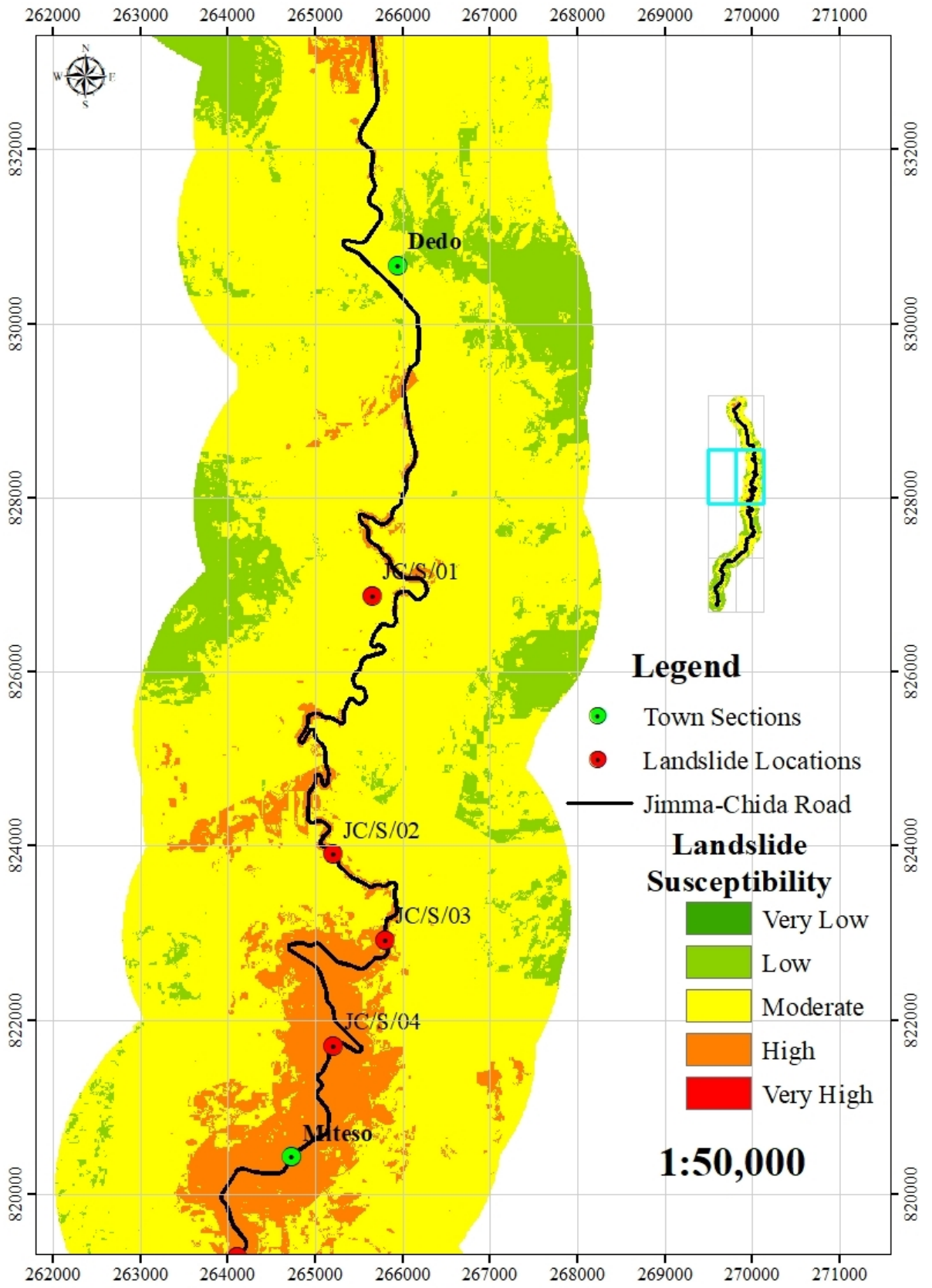
Where W_j :Weight for each of the landslide conditioning factor ; R_{ij} ;rating value of class i in landslide contributing factor j; n: number of landslide contributing factors.

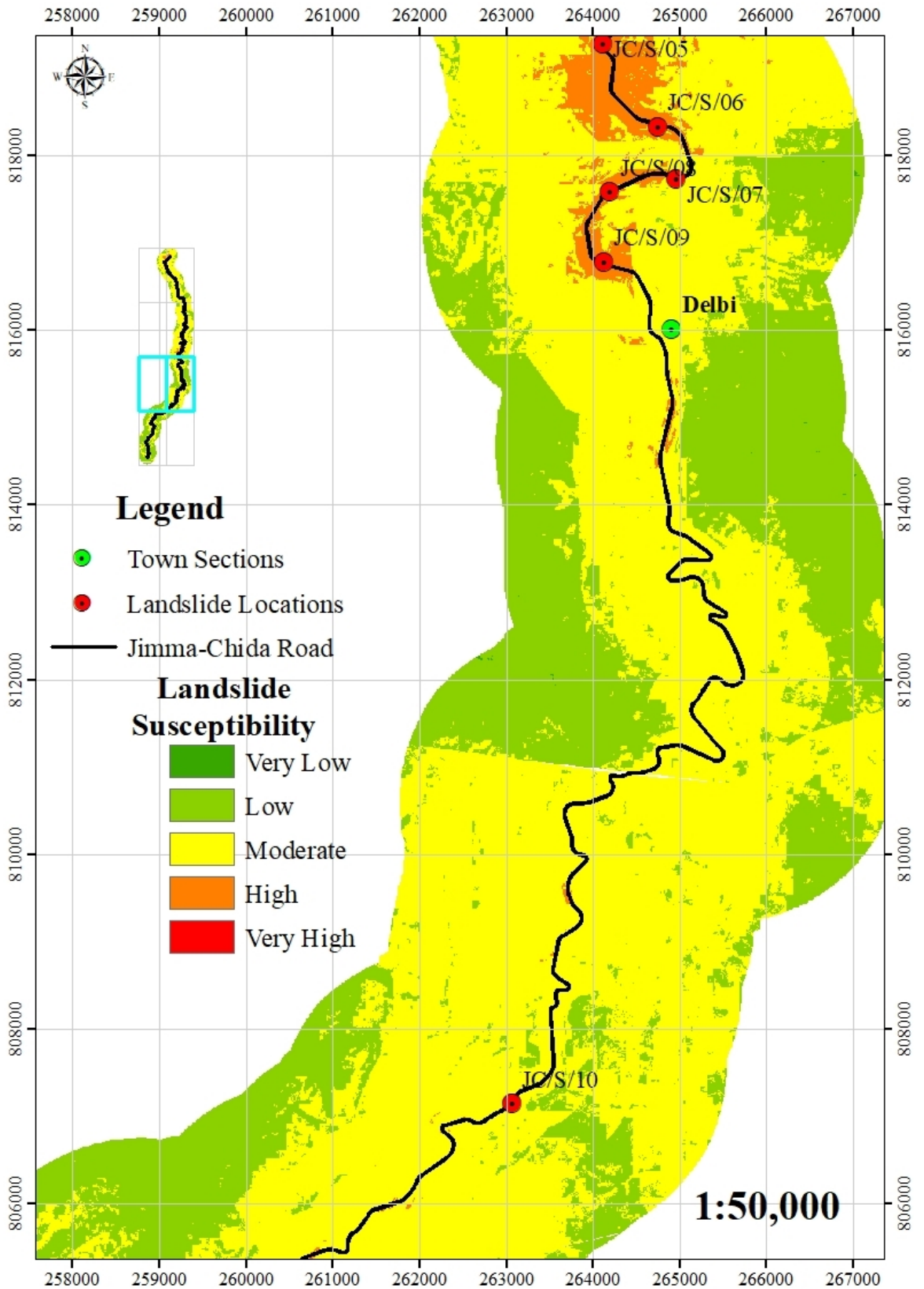
$$LSI = 0.073 * Slope + 0.023 * Aspect + 0.056 * Elevation + 0.023 * Curvature + 0.167 * Lithology + 0.203 * Distance\ to\ stream + 0.197 * Distance\ to\ road + 0.059 * Land\ use/cover + 0.199 * Rainfall$$

The landslide susceptibility index then reclassified to five landslide susceptibility classes of very low(VLS), low(LS), moderate(MS), high(HS) and very high(VHS) as indicated in Figure 4-30. The final landslide susceptibility map indicates that majority of the road section 62.87% traverse through areas having a moderate degree of susceptibility for the occurrence of landslide which requires consideration during the design and construction work. Distance to road, streams and rainfall are the most contributing factors followed by the lithological formation, the slope angle, elevation and the land use/ cover along the road have moderate contribution for the occurrence of landslide and the role of the slope aspect and curvature is least important factors. Here, it is worth mentioning that the listed less important contributing factors could trigger the landslide under a particular situation(He & Beighley, 2008).For example ,though the land use/land cover of the study area has comparatively low contribution for the initiation of landslide any human or natural activity which alter the land coverage could lead to the activation of additional landslides.

Moreover, in the case of Jimma-Chida road section the landslide recorded are located near to the road corridor which resulted from the road construction activity demanding large volume of earth work, streams collected from their natural channel and channelized by drainage structures across the road and expansion of settlement along the road corridor leading to deforestation.







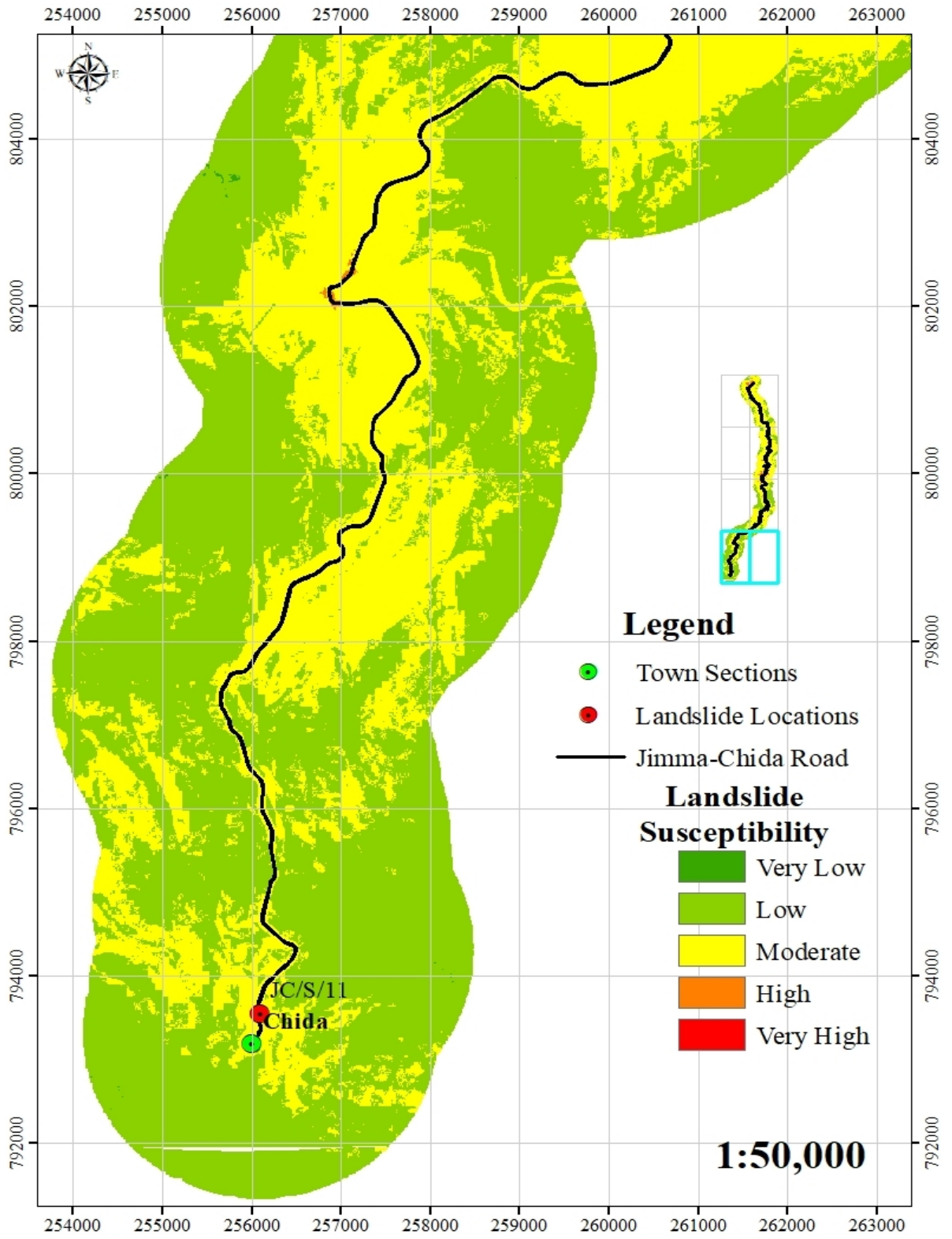


Figure 4-30: Landslide susceptibility map of Jimma-Chida Road Section.

For the road corridor along Jimma-Chida section the landslide susceptibility has been classified in to five(5) susceptibility classes namely very low(VLS), low(LS), moderate(MS), high(HS) and very high susceptible(VHS) classes .

Based on the result of landslide susceptibility map generated using the Analytic Hierarchy Process(AHP) presented in Table 4-2, majority of the road corridor 62.87%(167.0 km²) is classified under moderate susceptibility class and the rest 32.23%(85.6 km²),4.89%(13.0 km²),0.01%(0.03 km²) and 0.0005%(0.0012 km²) of the road section falls under low, high, very low and very high susceptibility classes respectively.

Table 4-2: Landslide susceptibility classes, landslide area and percent.

S.No	LSP	%LSM	LSM Area(km ²)	Description
1	311	0.01	0.03	VLS
2	856051	32.23	85.60	LS
3	1669734	62.87	167.70	MS
4	129790	4.89	13.00	HS
5	12	0.0005	0.0012	VHS

Where; LSP-landslide susceptibility pixel, LSMA-landslide susceptibility map area, VLS, LS, MS, HS and VHS means very low, low, moderate, high and very high landslide susceptibility, respectively.

According to the landslide susceptibility map similar to the existing condition on site road sections classified as highly susceptible for landslide are located mainly between km 25+000 to km 45+000 in the watershed along valleys close to the drainages with steep slope topography which highly contribute for the occurrence of erosion and landslide. The road section at the outskirts of Jimma town up to Gibe river with is also labeled as a highly susceptible area due to the presence of residual soil deposit underlain by a parent low strength rock mass which crossed by multiple streams and traverses along the rolling terrain. Similarly, as clearly noted in the landslide susceptibility map, landslide mainly abundant on the upper basalt flow formation which overlain by reddish brown to brownish silty clay soil especially locating on steep riverbank slopes. The areas covered by clay formation are deforested by the local farmers for crop cultivation which results on the vulnerability of the area for the occurrence of landslide.

4.1.5. Model Validation of the Landslide Susceptibility Analysis

The landslide susceptibility analysis result has to be verified by contrasting the existing landslide location data acquired from the landslide inventory with the produced landslide susceptibility map. For this study, the landslide susceptibility analysis model has validated by utilizing landslide percent comparison method. In addition, the produced landslide susceptibility map was actually validated by site observation along the study road section,

particularly in the highly susceptible zone. Active landslides are witnessed in the areas that designated as highly susceptible area, km 20+000 to km 45+000.

4.1.5.1. Landslide Percent Comparison

By comparing the existing landslide collected during the landslide inventory with the output of the landslide susceptibility map, around 86.2% of the existing landslides are located in the high susceptibility class of the predicted landslide susceptibility degree, which means that the choice of the models was accurate (Table 4-3 and Figure 4-31).

Table 4-3: Comparison of the landslide event location with generated landslide susceptibility map

Landslide Inventory	Landslide Susceptibility Class
JC/S/01	HS
JC/S/02	MS
JC/S/03	HS
JC/S/04	HS
JC/S/05	HS
JC/S/06	HS
JC/S/07	HS
JC/S/08	HS
JC/S/09	HS
JC/S/10	MS
JC/S/11	MS
	VLS
	LS
	MS
	HS
	VHS

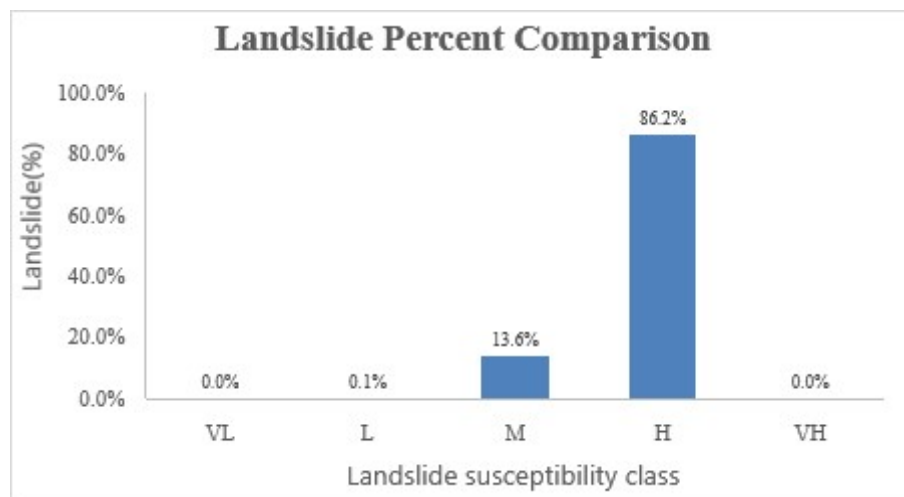


Figure 4-31: Landslide percent comparison

4.2. Discussion

The landslide susceptibility map for Jimma-Chida road section were prepared taking into account the relationship between the landside contributing factors and the existing landslide. The main principle considered in the preparation of the landslide susceptibility map is different locations on the given area with similar internal and external environmental setting and history of landslide are similarly susceptible for the occurrence of landslide in the future (Tyagi et al., 2022b).

For the purpose of this study Analytical Hierarchy Process(AHP) model is utilized considering the relationship of contributing factors and the occurrence of landslide. A total of nine contributing factors were used as the possible landslide triggering factors, which are slope aspect, slope angle, curvature, elevation, lithology, distance to stream, distance to road, land use/land cover and rainfall considering the existing active landslides and availability of data. The role of influencing factors for the occurrence of predicted landslide from the generated landslide susceptibility map is presented as follow.

As discussed in section 5.2.1, slope is one of the main contributing factor for the occurrence of landslide. For the study road section using the AHP model a weight of 0.073 is given for the contribution of the slope angle. As a result of the landslide susceptibility map majority of the highly susceptible landslides (25.77%) are predicted to occur on the slope class from 9° to 14° and around 15.45% of the total highly susceptible areas are located in slope angle ranging from 14° to 20° . Similar to the highly susceptible areas for the road sections which are moderately susceptible, most of the landslides (26.54%) are predicted to occur in the slope angle between 9° to 14° followed by the slope angle range of 5° to 9° (Figure 4-32 (a)). As discussed in section 5.2.1, the possibility of the occurrence of landslide on flat laying and gentle slope areas are very less while comparing with areas at the steep slope topography. The finding of the susceptibility map solidifies the previous statement by indicating around 70.74% of the areas which designated as a very low susceptible area located on the flat topography with slope angle of 0° to 5° .

From the landslide susceptibility map, it is clearly stipulated that even though most of landslides have happened on the terrain with steep slope angle but there are multiple incidents that the landslides occurred on topography having gentle slope. This could be a cumulative result of other triggering factors such as gully development on the streams

mostly traversing at toe of slope, saturation of the slope by rainfall, alteration of the natural slope by excavation and deforestation of the natural slope which leads to slope erosion and landslide development.

Slope aspect is one of the influential factor for the landslide. Regarding the slope aspect, it a weighed of 0.023 is assigned for the landslide susceptibility map. The slope aspect direction southeast and south has a higher contributes for the landslide susceptibility of the road section under study. As indicated in (Figure 4-32 (b)), Around 23.26% and 17.06% of the area which designated as a highly susceptible have a slope aspect direction of southeast and east direction. Similarly, both southeast and east slope aspect direction are accounted for 16.13% and 15.10% of the predicted landslide susceptibility. The northwest, west and southwest slope aspect direction has attributes for the low susceptibility area.

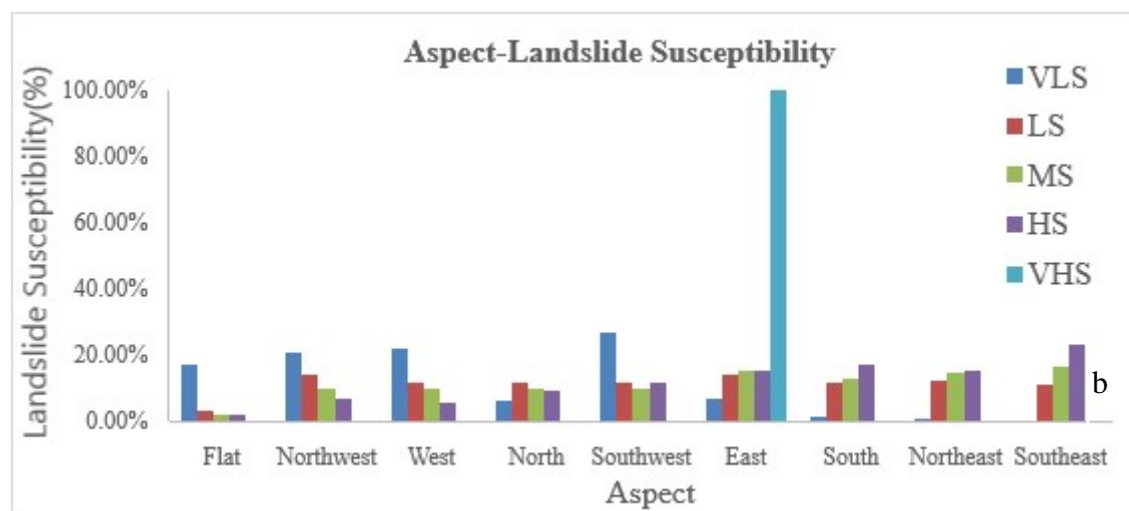
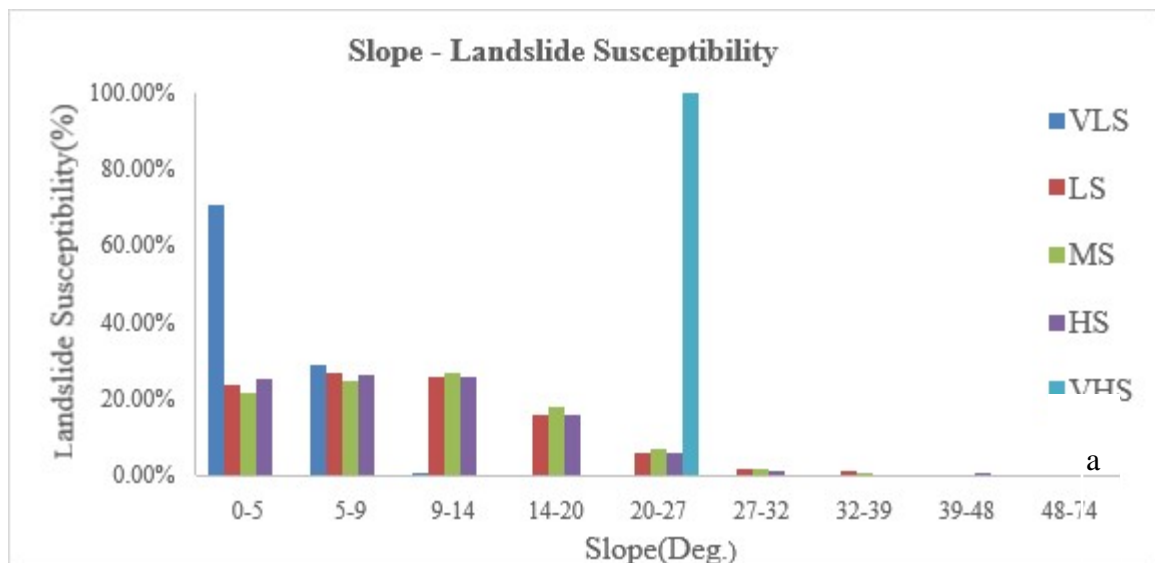


Figure 4-32: a) Slope-Landslide susceptibility b) Aspect-Landslide susceptibility

In case of elevation, Figure 4-33(a) indicates that the elevation from 2198 m to 2388 m has a significant effect on the landslide with around 43.51% of the highly susceptible area which consolidate the general understanding that areas located on the higher elevation are more susceptible for the occurrence of landslide. The elevation from 1580 m to 1802 m has covered majority of the road corridor under study with composition of 25.23% and accounted for around 31.07% of the highly susceptible road section. Similarly, the elevation ranges of 1580-1802 m and 1998-2198 m has a significant effect on the moderately susceptible area with composition of 27.20% and 14.41%, respectively.

The curvature of the given slope mainly controls the mode and characteristics of surface runoff which in turn has an effect on the occurrence of landslide. The curvature along Jimma-Chida road section are categorized into concave, convex and flat curvature with around 47.98% accounted for concave curvature(Figure 4-33 (b)).

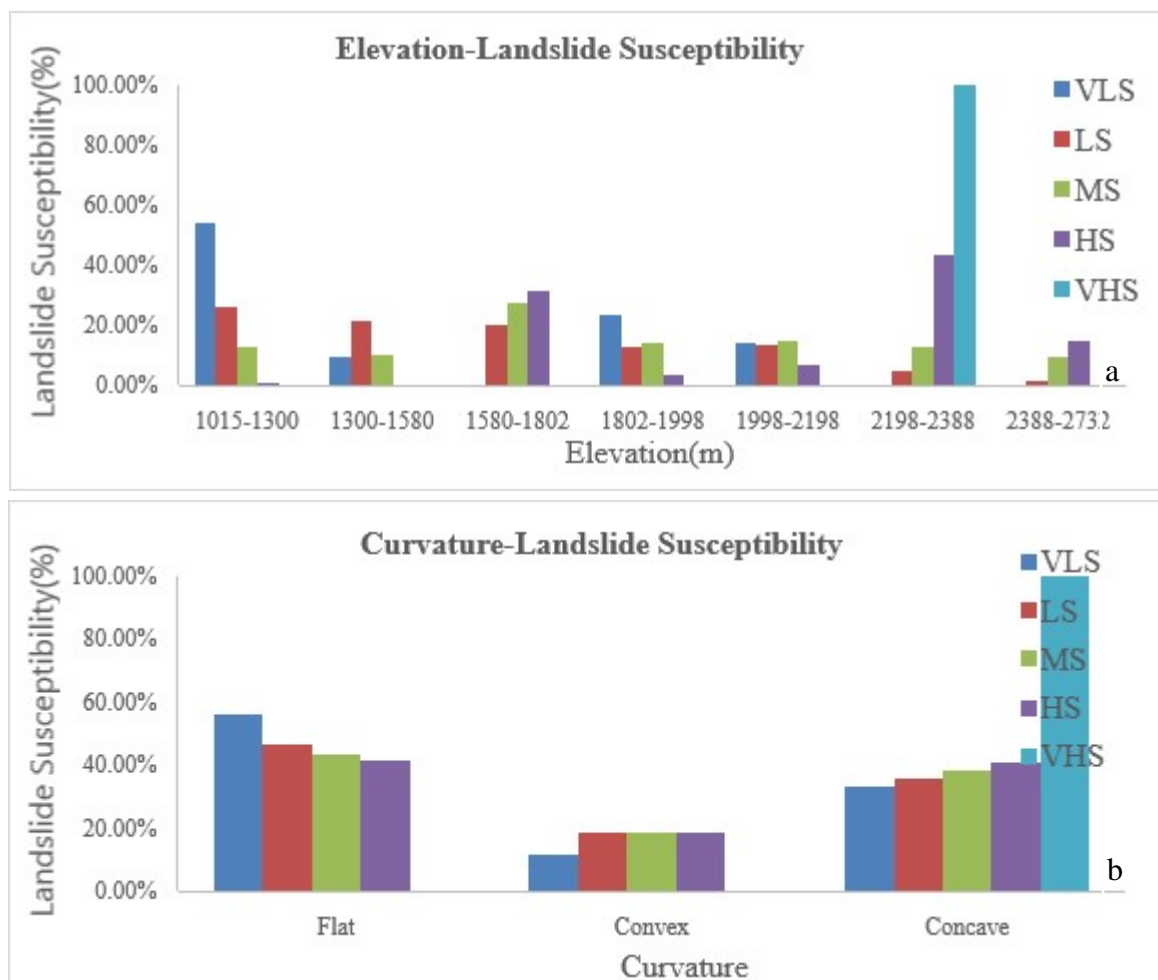


Figure 4-33: a)Elevation-Landslide susceptibility b)Curvature-Landslide susceptibility

The contribution of the site lithology for the landslide to initiate could not be over stated and it plays a vital role and depends on both the inherent (mineralogy, formation process and engineering characteristics) and surface condition. As indicated on the lithological map (Figure 4-34 (a)) of the study road section middle trachyte flows cover a majority of the road section which amount 37.50% of the entire road segment. Upper basalt flow is the other prominent lithological formation which mostly characterized by a residual soil underlain by a low strength rock mass unit covers around 26.90% of the study road segment and it is where most of the active landslides were occurred.

From the landslide susceptibility map produced, the upper basalt flow formation which identified on site with various depth of the residual soil underlain by highly weathered to decomposed, low strength rock mass dominantly accounted for the predicted highly susceptible area with a percentage of 62.41%. Middle basaltic flow followed by middle trachyte flows are contributes for the highly susceptible areas with a proportion of 28.56% and 8.11%, respectively. The remaining two formation alluvial deposit and lower trachyte flows are the least lithological formations contributing for the highly susceptibility of the predicted landslide.

Similarly, the middle trachyte flow is covered around 39.26% of the moderately landslide susceptible areas followed by middle basalt flow, upper basalt flow, lower trachyte flow and alluvial deposit with the composition of 20.14%,19.57%,15.01% and 6.01%, respectively.

From the field observation and the desk study on the geological formation, soil extension, borehole and geophysical investigation data of the study road section, the residual soil with variable thickness underlain by the highly weather to decomposed, low strength upper basaltic flow rock formation is responsible for the occurrence of multiple landslide combined with other triggering factors.

The proximity of the road section for the prominent streams which traverses along and across the route is an essential and critical factor which related with the occurrence of majority landslide along the study area. Streams plays an immense role for the initiation of landslide by either eroding the slopes and river banks or saturating the slope material especially the one at the toe of the slope. In case of the study road section most of the landslides are happened at close proximity of the streams and related with the erosion gully cut formed. During the site survey it is observed that, the weak, highly saturated and shear

zones along the areas affected by the landslides are formed following the stream and erosion gullies on the road section. The highly erodible, mostly silty clay residual soil were increasingly eroded by the prominent streams and their tributaries adding to the prolonged and intense rainfall on the area. The distance to stream of the area were considered as the most influential factor for the occurrence of landslide and weighted with 0.203 for the preparation of the landslide susceptibility map. Consolidating the observation made during the site survey, 55.78% of the area which designated as highly susceptible for landslide is located with 50 m radius of the stream. Similarly, 25.94%,13.52%,3.55% and 1.20% of the highly susceptible areas are located within the distance of 100 m, 300 m, 1000 m and greater than 1000 m of the streams. Regarding the areas marked as a moderately susceptible, majority of them (36.05%) are located within a 50 m distance from the stream and the remaining parts which accounted for 29.39%,18.40%,9.56% and 6.59% are located within 100 m, 300 m, 1000 m and more than 1000 m of the stream, respectively (Figure 4-34 (b)).

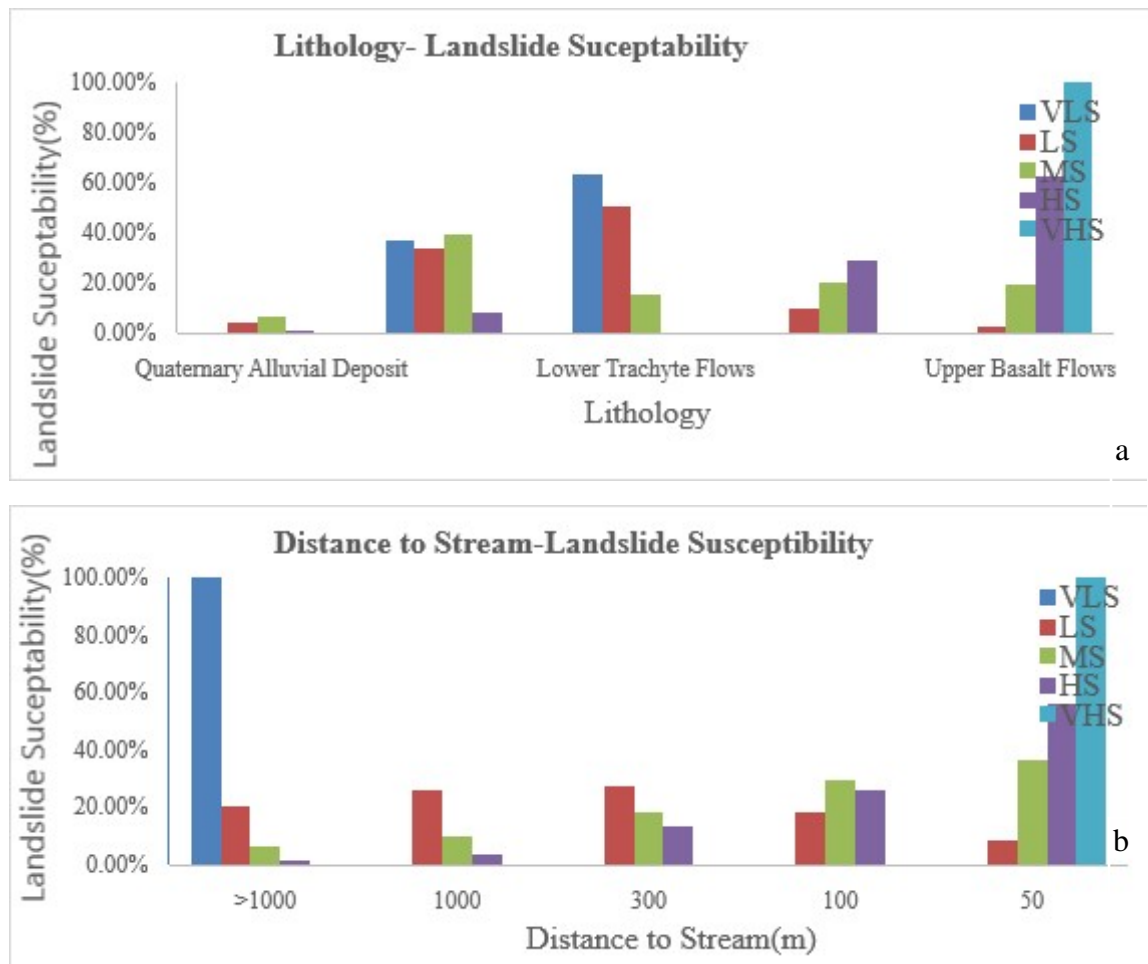


Figure 4-34: a) Lithology-Landslide susceptibility b) Distance to Stream-Landslide susceptibility

Road construction is a human intervention which encourages the occurrence of landslide on area either it has a history of landslide or not. Especially, roads on the rough mountainous and escarpment terrains requires a large amount of earth work due to the geometric demand. Such kind of excavation works frequently cause instability on the road slope which sometimes become catastrophic for the road, its users and the surrounding community.

Considering this a proximity of the road is taken as a causative factor and assign with a weight of 0.197 after AHP analysis. Hence, based on the landslide susceptibility map, the areas located at 50 m distance from the road are accounted for 19.69% of a high susceptibility areas and areas at the 500 m offset of the road is where majority of the predicted landslide occurs. This is mainly due to the collective effect of other factors and the occurrence of landslides within the distance range of 50-500 m on both side of the road majorly between the road and end of the slope. Similarly, the entire areas labeled as a very low and very high susceptible for landslide are located within the distance of greater than 1000 m and less than 50 m from the road prism, respectively(Figure 4-35 (a)).

In addition to the large infrastructure development works currently ongoing on the road corridor, land use/cover of the area across the study road section plays a vital role for the emergence of slope stability problems. On areas which are covered with dense forest and vegetation the potential of the landslide to occur is minimized due to the enhancement of soil strength by root reinforcement. The contribution of the land use/cover for the preparation of landslide susceptibility map is considered and it is taken as a factor with weight of 0.059. From the site survey and land use/cover map of the road corridor it is observed that crops of multiple varieties including Maize, Sorghum, Coffee, Enset and Chat are widely cultivated by locals who lives alongside the road corridor which accounted for 50.83% of the area. Similarly, 13.23% of the road corridor is covered with multiple trees such as Eucalyptus, Juniperous(Tid), Ficus(Sholla), Podocarpus(Zigba), Cordia (Wanza), Hagenia (Kosso) and so on. From the slope stability point of view most of the mentioned trees are deep rooted and helpful for the stabilization of the slope mass.

From the landslide susceptibility map, areas covered by crops are cover majority of the zones designated as a highly susceptible for the landslide with share of 50.26%. This is mainly due to the intervention of local settlers by cutting trees for the purpose of farming and expansion of settlement leading to deforestation.

Similarly, crops lands are majority of the area marked as a moderate susceptibility for landslide constituting 52.03% of the class(Figure 4-35 (b)).

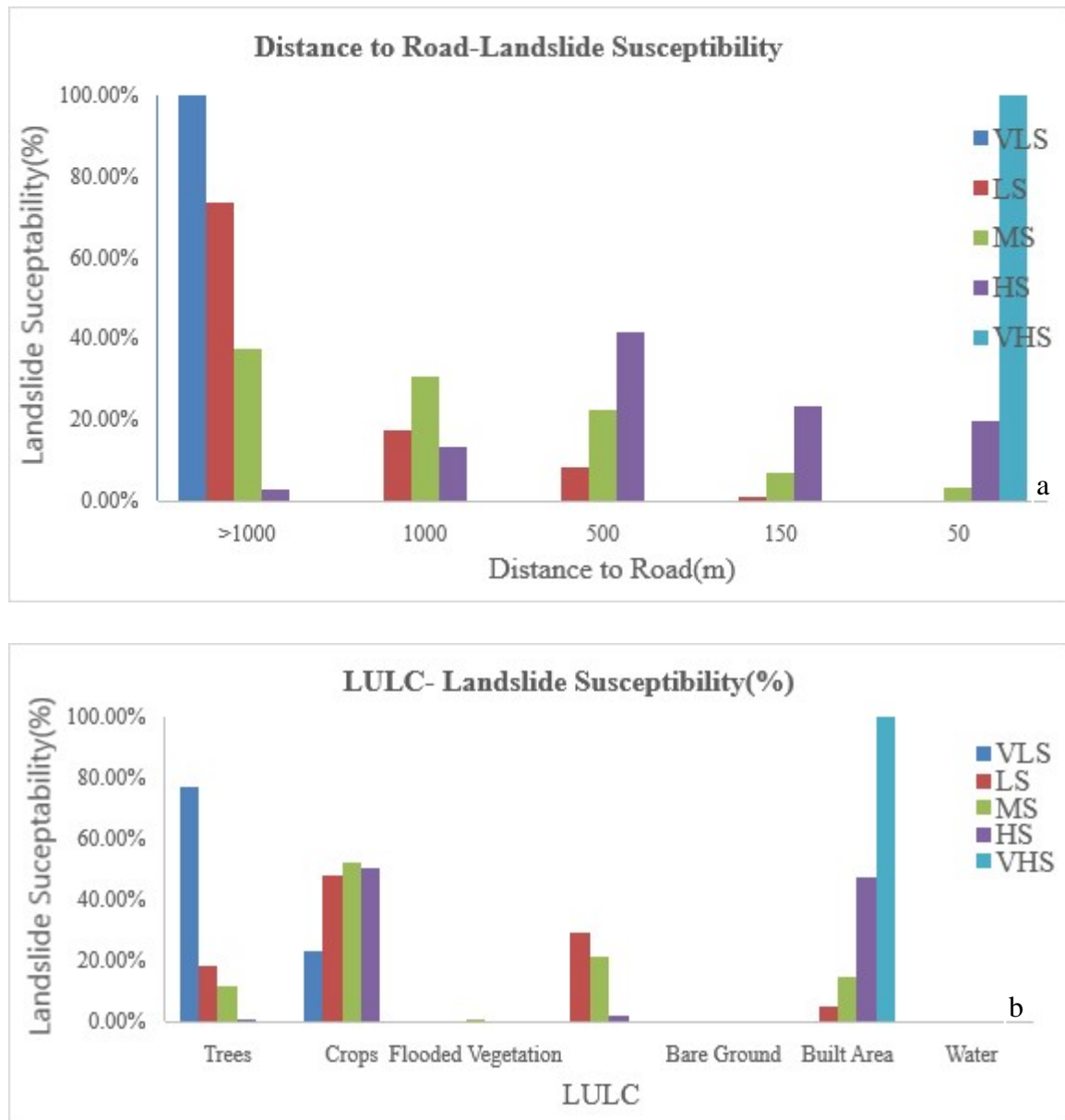


Figure 4-35: a)Distance to Road-Landslide susceptibility b) LULC-Landslide susceptibility

Rain fall is one of the most influential and crucial triggering factor for almost all kind of landslides. Especially on areas which receive intense rainfall for long duration and frequency, the rainfall shall be considered as a prominent factor contributing for the landslide and all analysis and remedial measures shall take it into consideration.

For the Jimma-Chida road section the average annual rainfall data of the last 25 years, since 1998 to 2022, have been collected from Ethiopian Metrological Agency(EMA) and

the rainfall map was produced by utilizing the interpolation tool in ArcGIS environment. The weight of 0.199 is allocated for the contribution of the rainfall after conducting analysis using a semi-quantitative, multi-criteria evaluation approach by AHP model.

Based on the landslide susceptibility map generated, areas with the rate of high susceptibility mainly located in the average annual rainfall range 1600-1675 mm which compose 59.47% of the susceptibility class. Around 30.60% of the highly susceptible zones are received an average annual rainfall of 1750 to 1815 mm. Only 4.92% of areas with the rate of high susceptibility are located on the locations which receives an annual rainfall of 1547-1600 mm, Figure 6-7.

For areas with low susceptibility for landslide, 76.56% of them are located in zone which has a record of average annual rainfall ranging from 1547 to 1600 mm. This solidifies that the area which receive less rainfall have less potential for the landslide while comparing with the one with the highest maximum rainfall.

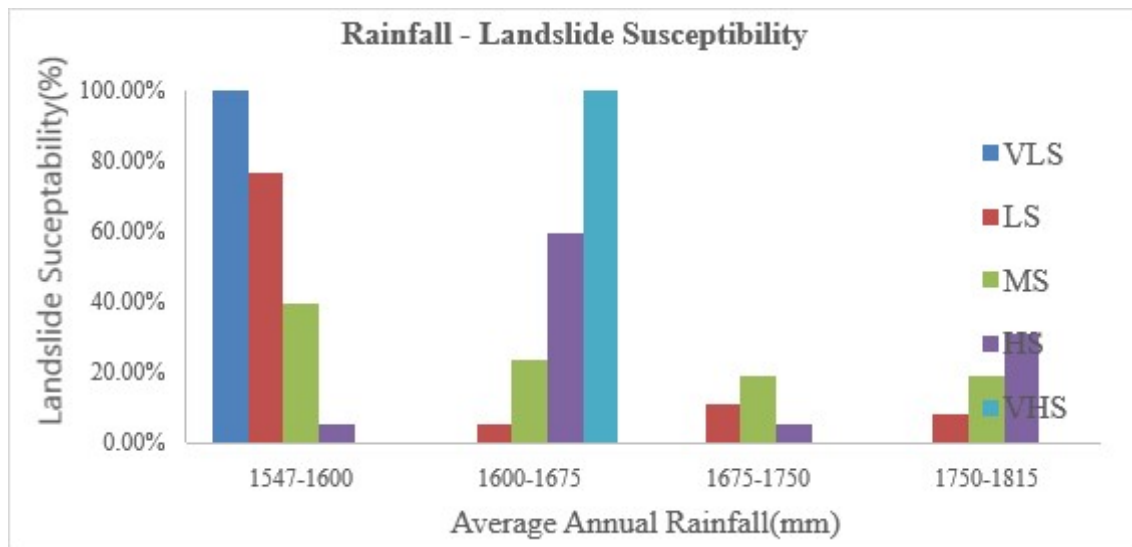


Figure 4-36: Rainfall -Landslide susceptibility

Based on the analysis, the contribution of the factors is different based on the actual environmental(external) and internal condition of the study road section. Some of the factors and factor classes in a particular factor contributes highly for the occurrence of landslide than the other one. However, the final susceptibility class of the given location is utterly depends on the combined contribution of all factors engaged.

This clearly explained by the fact that, there are cases where landslide occurred on area situated at the gentle slope topography with far distance to the stream which triggered by the collective effect of the other triggering factors.

4.2.1. Preliminary Remedial Measures for Landslides along Jimma-Chida Road Section

Landslide remediation measures are intended to provide permanent stability of the area from existing and probable instability in the slope (Cornforth 2005). The general approach for remediation of landslide along the study road section is mainly consider using one or a combination of the following measures.

(Terzaghi, 1950) mentioned that, "if a slope has started to move, the means for stopping movement must be adapted to the processes which started the slide". For example, if the presence of sub-surface water is the main cause of landslide, the effective remedial measure shall provide a feasible means to expel the subsurface water.

I. Modification of slope geometry

a) Cutting and Flattening of Slope

Cutting(mass removal) and flattening work is used to remove mobilized landslide mass and to decrease the load, and hence driving force, at the head of a landslide area(Nippon Koei Co.Ltd & OYO International Corporation, 2007).There are key points to be taken into consideration while implementing this measure for a particular landslide location.

- i. The cutting (mass removal) work shall be execute only at the head of landslide which cause a driving effect on the downslope side of the slope. No excavation(cutting) work has to be conducted at the toe of the slope;
- ii. Cutting on destabilized mass is not feasible if the landslide is continuous;
- iii. Maximum care has to be taken to avoid instability of the adjacent slope behind the removed slope mass due to lack of support;
- iv. In addition to removal of the moving(unstable) mass integrated slope protection work by utilizing vegetation covering of the slope face and provision of surface drainage should be considered simultaneously.

In case of Jimma-Chida road, cutting of the unstable material at the back slope integrated with vegetation cover and surface drainage structures is recommended as a remedial

measure for landslide sections JC/S/02, JC/S/06, JC/S/08, JC/S/10 and JC/S/11. The main features of the mentioned landslides are typical rotational failure with the scarp of the moving mass located on the back slope.

b) Fill support construction

Provision of support for the moving mass by construction of fill at the toe of the slope can be considered as one of the remedial measure. While considering fill construction as the remedial measure for the landslide, there are some considerations which shall be taken in to account;

- i. Fill shall be construct as the resisting mass only at the toe of the landslide location; otherwise it could be cause exaterbate the problem by causing additional driving force;
- ii. Due to the mobilization of the high volume of mass from depeletion and accumulation zone the material at the toe of the landslide is often disturbed and weak. Hence, the bearing capacity of the foundation material for the construction of fill shall be investigated properly;
- iii. Thorough consideration shall be given to avoid the driving force caused by the fill material which could cause subsequent landslide on the adjacent slope on the downside of the the existing landslide;
- iv. Filling work especially using fine, cohesive material may block the flow of sub-surface water which could lead to the development of positive pore water pressure. Hence, proper drainage mechanism to dissipate the subsurface water from the fill shall be consider.
- v. Unless it is properly designed and constructed, the fill slope itself could fail and cause additional instability. The stability of the fill shall be check and proper fill slope has to be recommend.

In case of Jimma-Chida road, construction of fill at the toe of the moving slope integrated with provision of drainage mechanism shall be considered as a viable remedial measure for landslide sections JC/S/04 and JC/S/07. The main features of the mentioned landslides are typical rotational failure with the scarp of the moving mass located on the back slope.

II. Drainage

Provision of surface and sub-surface drainage for saturated soils widely implemented as a viable mitigation for landslide, since they are economical and effective than other types of remedial measure and suitable for a multiple case, even for deep seated landslides when provision of structural measure is not meet the demand(Popescu & Sasahara, 2005).

a) Provision of surface drainage

One of the prominent causes of landslide is the uncontrolled surface water which contribute for the development of erosion gullies and saturation of the slope material leading to the initiation of landslide by inducing a hydraulic thrust. There are different types of surface drainage structures which has been used as the remedial measure for landslide such as collector drain, chute, furrow ditch, side ditch, berm drain and toe drain(Nippon Koei Co.Ltd & OYO International Corporation, 2007).The common objectives of all the mentioned drainage structures are to minimize the occurrence landslide by avoiding infiltration of precipitation or re-permeation of water from subsurface and marshy areas. The effect of surface water on the existing slope can be stipulated by mainly considering the flow of surface water on the face of the slope and infiltration of water into the soil mass through tension cracks on the head of the cut(Hulagabali et al., 2020).Effective and an integrated surface drainage scheme has a high contribution for the treatment of the either existing or potential landslides. There are some considerations which needs to be addressed seriously while providing surface drainage structures for the remedial of landslide.

1. Collector drain are intended to collect the surface water mainly from upslope catchment by lined ditches along the slope, which are then interconnected to chutes and drainage channels which used to expel the collected surface water from the landslide area effectively.
2. Surface drainage structures which construct in area of active landslide should have sufficient strength and easily maintainable. Any damage on the drainage structure due to the mass movement should be maintain quickly before become severe.

In case of Jimma-Chida road, provision of surface drainage structures shall be considered solely or in combination of other remedial measures for all locations affected by landslide.

The contribution of controlling the surface water for the stabilization of the slope cannot be overstressed. Especially the back slope failure at JC/S/02, JC/S/06 and JC/S/08 can easily mitigate by providing the surface drainage at the crown of the hill to control the runoff from upper catchment.

b) Provision of sub-surface drainage

The use of sub-surface drainage is become essential to reduce the development of a driving positive pore water pressure in the subsoil and as a result to increase in effective stresses and shear strength of the sliding soil mass(Popescu & Sasahara, 2005).The performance of the sub-surface drainage structures highly depends on the permeability of the drained soils. The main source of ground water for the area along the Jimma-Chida road section is recharging the ground water by infiltration from the prolonged rainfall. When the area receives high rainfall volume for extended period and significant amount of water evaporates and lost through the transpiration of green plants. The remaining water from the rainfall is surface runoff and infiltrates to the subsurface to recharge the ground system. Along the study road section, it is observed that the depth of water table is shallow and has thin unsaturated zone which wet enough to shed excess water.

Provision of horizontal drain hole, shallow or deep trench drains filled with coarse granular fill materials to drain the sub-surface water, vertical either small or large diameter boreholes with pumping, sub-horizontal (drilled from the slope surface) or sub-vertical boreholes, drainage tunnels and galleries and other measures can be taken as a remedy for landslides which related with the presence of sub-surface water. During the site visit, field investigation and minor excavation works the sub-surface water has observed along the majority section of the road. Especially JC/S/01, JC/S/02, JC/S/03, JC/S/05, JC/S/06, JC/S/07, JC/S/08, JC/S/10 and JC/S/11 has water at shallow depth and requires the sub-surface water management work as a remedial measure. The main means of sub-surface drainage is system is gravity flow and sometimes pumps are required to discharge water from the elevation holes or galleries.

c) Provision of river erosion protection

Uncontrolled riverbank erosion leads to the emergence of landslide by scouring the road foundation at the toe and widening the collapse toward the road prism. Landslides at various location of Jimma-Chida road section are directly related with inadequate provision of erosion protection works. Landslide JC/S/04 clearly elaborates the mentioned fact. Due to improper outlet protection and river training works the slide initiated from the downstream side and propagated toward the road corridor.

Provision of the river bank protection work can be implemented on different ways based on the intended purpose of the structures and the root cause of the river erosion. The main measures which has to be taken to protect the river from erosion can be classified as;

i. River bank erosion protection work

The river bank is highly susceptible for erosion unless proper protection works are conducted. Masonry or concrete retaining wall, gabion walls, stone pitching, block pitching, concrete pitching, concrete block walls and sheet piles are some of the widely used river bank erosion protection works. The road section under study are mainly crossed by streams and rivers which have various volume and velocity. The severity of river bank erosion mainly depends on the topography of the area, the property of the soil and the hydrological behavior of the stream. Overall, integrated river bank erosion protection works are required along the Jimma-Chida road section aiming to mitigate the existing and prevent the occurrence of additional landslide. Particularly, landslides along JC/S/01, JC/S/03, JC/S/04, JC/S/05 and JC/S/09 requires river bank protection works.

ii. River bed erosion protection work

Similar to the river bank erosion, the contribution of river bed erosion for the occurrence of prominent landslides cannot be overstated. The turbulent flow of streams mainly at the outlet cause bed erosion which could propagated towards the road unless appropriate measures are not taken properly. The widely used river bed erosion protection works are stone consolidation, gabion or concrete bed protection, check dams and spur dikes(Nippon Koei Co.Ltd & OYO International Corporation, 2007).Road sections which pass through the prominent streams and rivers require the provision of river bed protection works using either of the abovementioned methods.

Especially the landslide along JC/S/01, JC/S/03, JC/S/04, JC/S/05 and JC/S/09 are related with riverbed erosion which propagated towards the road prism and the remedial measure shall consist erosion protection works in combination with other measures under consideration.

iii. Relocation of stream channel

On some severe cases giving remedial for the existing problem by providing erosion protection works is not enough to mitigate the landslide and relocation of the stream channel away from the road corridor may find feasible. The problem related with river bank and bed erosion along JC/S/01 is found to be serious and providing erosion protection works seem to be difficult. For this particular case relocating the stream channel by channelization could be taken as a final solution to avoid initiation of additional landslide related with the stream at the toe of the road.

III. Provision of retaining structures

Different types of retaining structures have been used as a countermeasure to mitigate the occurrence of landslide. The core principle for the provision of retaining wall is the structure must be founded below the slip surface into the firm stratum to intercept and restrain the mobilized moving mass. All retaining structures are used to apply external forces to enhance the resistance of the mass against any movement and increase the overall stability of the retained slope. Most of the time the retaining structures are provide at the toe of the moving mass by employing different methods and types includes but not limited to; gravity retaining walls, crib-block walls, gabion walls, piles or piers, reinforced concrete walls, mechanically stabilized earth structures and so on(Popescu & Sasahara, 2005).

The main design principle of all retaining structures is identical which aims on ensuring both the external and internal stability of the structure. The external stability of the structure ascertain the stability against overturning, sliding and bearing capacity failure of the foundation(Kanungo et al., 2009).

Nearly all of the landslides encountered along the study road section has required the provision of retention structures as sole option or in combination with other remedial measures.

Particularly, JC/S/02, JC/S/05, JC/S/06, JC/S/07, JC/S/08, JC/S/10 and JC/S/11 are landslide sections which require retaining wall construction to support the slope as a remedial measure.

IV. Internal slope reinforcement

Internal slope reinforcement uses different approaches that employ various sort of soil and rock reinforcement sometimes in combination with conventional landslide remedial methods, such as, drainage, geometry modification and retaining structures(Gaurina-Medjimurec, 2014; Highland & Bobrowsky, 2008) .The core principle of all kinds of soil reinforcement works is the tensile resistance element is used in the soil mass to improve the shearing resistance behavior of the mass. The well-known and widely used internal slope reinforcement are mechanically stabilized earth(MSE), micro-piles, soil nailing, ground anchors, stone or lime/cement columns and vegetation planting to reinforce the soil (deep rooted plants)(Popescu & Sasahara, 2005).The provision of internal slope reinforcement by combining it with other remedial measure(structural and non-structural) can play big role on slope stabilization. For the case of the road section under study internal slope reinforcement can be taken as a viable remedial measure for existing landslide along JC/S/01, JC/S/03, JC/S/04, JC/S/05, JC/S/07 and JC/S/08 exclusively or in combination of other measures.

The dynamic and unpredictable nature of landslide requires an innovative and scientific approach to deal with the problem. Especially, providing the remedial measure for the existing landslide demand a comprehensive design and construction methodology. Considering all the above points, significant progress has made in formulating methods to provide the solutions for the prominent landslide problem. However, the landslide problem still causing a grave challenge on the infrastructure development sector. The same is true for the case of Jimma-Chida road section which has been frequently affected by landslides leading to social. financial and environmental problems. The general remedial measures proposed to be given for the landslide locations observed along the Jimma-Chida road section have presented in Table 4-4.

Table 4-4: Summary of general remedial measures for landslide sections along Jimma-Chida road.

S.No	Slide Section	Triggering factor	Proposed remedial measure
1	JC/S/01	Spoil mass at the crown of the slope, uncontrolled surface and sub-surface drainage and river bank and bed erosion by prominent stream traversing along the toe of the slope.	<ul style="list-style-type: none"> • Provision of surface and sub-surface drainage structures; • Removing the spoil mass at the head of the slope combined with slope flattening work; • River bank and bed erosion protection works; • Re-channelization of the eroding stream away from the road corridor.
2	JC/S/02	Steep back slope, loose material, surface water, lack of back slope drainage facilities that allows water to enter to the loose material and the presence of sub-surface water at shallow depth.	<ul style="list-style-type: none"> • An integrated surface and sub-surface drainage structure; • Construction of the retaining wall founded below the slip surface to support the moving back slope mass; • Back slope flattening work by excavating the mobilized mass and slope bench construction.
3	JC/S/03	Highly saturated, weak, thick residual soil affected by valleys, various gullies, presence of sub-surface water and steep slope topography of the area	<ul style="list-style-type: none"> • Subsurface drainage by providing deep drainage galleries to expel the subsurface water; • Remove the mobilized mass; • Proper stream channel protection works.
4	JC/S/04	Undercutting of the highly erodible silty clay soil by the stream water at the downstream side	<ul style="list-style-type: none"> • Provide proper river bank and bed protection work by construction gabion wall check dams with concrete bed protection.

S.No	Slide Section	Triggering factor	Proposed remedial measure
		propagates to the road embankment. In addition, uncontrolled surface and sub-surface water plays a vital role for the initiation of landslide.	<ul style="list-style-type: none"> • Subsurface water shall be intercepted by construction of trench drain on the right hand side of the road.
5	JC/S/05	Streams and sub-surface water along the road section contributes for a complex set of movements. In addition, the formation of wide erosion gullies by the crossing stream cause undercutting of the stream side slope and result failure of the drainage structure and propagating toward the road.	<ul style="list-style-type: none"> • Deep drainage galleries shall be provide to accommodate the subsurface water which is the main cause of landslide at this section; • Provide proper river bank protection work by masonry retaining wall and check dam construction.
6	JC/S/06	Saturation of slope material due to uncontrolled surface and sub-surface flow.	<ul style="list-style-type: none"> • Provide surface drainage by interconnecting furrow ditch and chute construction; • Provide deep trench gallery on the right side of the road (slope toe) to intercept the sub-surface water; • Construct masonry retaining wall to support the back slope mass.
7	JC/S/07	Weak and saturated residual soil due to uncontrolled surface and sub-surface water.	<ul style="list-style-type: none"> • Intercept the sub-surface water from the hill on the right side of the road by providing deep trench drain. • Combined with the above measure the left hand side slope shall be construct by mechanically stabilized earth(MSE) wall.

S.No	Slide Section	Triggering factor	Proposed remedial measure
			<ul style="list-style-type: none"> The surface water from the hill side shall be intercept at the head of the slope with furrow ditch and discharged into the side ditch using the cascaded chute.
8	JC/S/08	Saturated, weak residual soil slope with the presence of the sub-surface water and spring development.	<ul style="list-style-type: none"> The surface water shall be intercept at the head of the slope on right side of the hill by constructing the furrow ditch interconnected with chutes to discharge water into the side drainage. The sub-surface water shall be manage by providing either a sub-horizontal drains or deep trench drains.
9	JC/S/09	River bank and bed erosion leading to undercutting of natural and embankment slope material by the stream traverse across the road.	<ul style="list-style-type: none"> River bank and bed protection work by provision of cascaded check dams, masonry retaining wall and concrete bed protection works.
10	JC/S/10	Steepness of the slope combined with uncontrolled surface and sub-surface water.	<ul style="list-style-type: none"> Slope flattening of the steep back slope combined with surface drainage structures to protect the slope from erosion and saturation Shallow trench drains shall be provided at the toe of the back slope and relieved into the nearest cross drainage structures.
11	JC/S/11	Steep back slope , active infiltration of the surface water and erosion gully propagation on the slope.	<ul style="list-style-type: none"> Slope flattening work with management of surface water by provide furrow ditch at the head of the hill with chute to collect water into side ditch.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Jimma-Chida road is traverses through rolling and mountainous terrain which previously affected by an emergence of multiple landslides at different segments of the road which cause multiple damages ranging from blockage of the road for few days to costing human life.

In the present work landslide inventory and assessment were conducted throughout the road section by using satellite images, in-situ mapping, gathering information from local peoples and reviewing previous documents. From the landslide inventory and assessment works it is found that there are a total of eleven (11) landslides along the road corridor which occurred previously due to multiple triggering factors. The landslide assessment results indicate that:

- Most of the landslide locations are affected by the common triggering factor which is the uncontrolled surface and sub-surface water. As observed from the drainage map and site survey at the study road section, the route is characterized with the presence of numerous streams and development of sub surface waters. Water is the main underline cause of landslide and all remedial measures shall give sufficient attention to conduct water management work in the most effective manner. Moreover, development of erosion gullies at the stream bank and bed mentioned as causative factor for most of the existing landslides along the road section under study.
- The topography of the area is also another triggering factor which contribute for the initiation of landslide. Areas with the steep slope angle have more potential for the emergence of landslide comparing to the one with gentle slope.

From site survey and topographic map of the area, the terrain traversed by the road is dominantly rolling topography (5-25 degrees) while the remaining section consists of mountainous section. As indicated from the engineering geological maps and site observation most of the existing landslides are occurred on rolling to mountainous section of the road which support the general consensus discussed.

- Engineering, lithological and geological properties of the slope material is also the crucial factor for the occurrence of landslide. In case of the present study areas dominantly covered by a thick, loose, weak, highly saturated, highly erodible and low strength residual soil are affected by various severity of landslide.
- Rainfall is the well know influential factor which contributes significantly for landslides. The south-western corridor of Ethiopia is well known for its unique climatic condition that the rainfall season is extended throughout most months of the year. This climatic behavior makes the region highly susceptible for the frequent landslides. The same is true for the case of the study road section. The contribution of the rainfall is taken in to consideration while preparing the landslide susceptibility map of the area.
- Proper understanding of the landslide features is key to conduct proper assessment and to determine the type, extent as well as depth of the remedial measure. For most of the landslide sections the road is existed at the flexural zone (toe of rupture zone) with the surface of rupture zone (detachment zone) is located at the upslope side and the accumulation zone of the displaced mass is located at the downslope side of the road. Moreover, there are landslide sections with the toe type of failure and the slip surface is terminated at the toe of the slope before entering the road prism, a good example for this type of landslide is JC/S/06 where the slip surface is located at the boundary between the residual silty clay soil and decomposed basaltic rock and the former forms bulged concave lobate while the latter is nearly stable at vertical slope.

The Analytical Hierarchy Process(AHP) method which is a semi-quantitative multi-criterial decision making approach is used to prepare the landslide susceptibility map of Jimma-Chida road section. A total of nine landslide causative factors were selected and analyzed to produce the landslide susceptibility map of the road section.

The selected factors are slope angle, slope aspect, elevation, curvature, lithology, distance to stream, distance to road, land use/cover and rainfall of the road section under study. The comparative importance of the mentioned factors and factors classes for the activation of landslide and to predict the landslide susceptibility of the area is analysis based on the

pair-wise comparison matrix to generate the weight and check the consistency of the decision. The following are the observations from the landslide susceptibility analysis:

- Based on the analysis conducted, distance to the stream, distance to the road and rainfall are the most influencing factors to initiate the landslide and their weight is 0.203, 0.197 and 0.199, respectively. The other influential contributing factor is lithology which composed a weight of 0.167, followed by slope angle, aspect, elevation, curvature, land use/cover with the weight of 0.073, 0.023, 0.023 and 0.059, respectively.
- The areas highly susceptible for the landslide along Jimma-Chida road section are areas characterized by **(a)** slope angle 9° - 14° (26.20%) and 5° - 9° (25.77%) **(b)** slope aspect southeast (23.26%) and east (17.06%) **(c)** curvature flat (41.18%) and concave (40.55%) **(d)** elevation 2198-2388 (43.51%) and 1580-1802 (31.07%) **(e)** lithology of upper basalt flows (62.41%) and middle basalt flows (28.56%) **(f)** land use/cover of crops (50.26%) and built area (47.47%) **(g)** distance to road of 50 m (41.36%) and 150 m (23.20%) **(h)** distance to stream of 300 m (55.78%) and 600 m (25.94%) **(i)** rainfall of 1600-1675 mm (59.47%) and 1750-1815 mm (30.60%).
- The landslide susceptibility map generated using the AHP method has classified into five classes low (32.23%), moderate (62.87%), high (4.89%), and the very low and very high susceptibility zones are covered a very small and localized areas along the road section with composition of 0.01% and 0.0005% which considered as negligible comparing with the total extent of the studied area.

5.2. Recommendations

From this study it is recommended that additional researches shall be conducted to support the conclusion of this research. Recommendation for further research works are;

- The present study is tried to conduct the landslide assessment, produce the landslide susceptibility map and recommend preliminary remedial measure for Jimma-Chida road segment of the South-West road network of Ethiopia. In doing so, prominent factors which contribute for the occurrence of landslide were considered. However, other contributing factors for the landslide have to be incorporated to enhance the accuracy of the landslide susceptibility map.
- This research uses Analytical Hierarchy Process(AHP) approach to produce the landslide susceptibility map(LSM). Intensive studies regarding the landslide susceptibility analysis have to be conducted using other qualitative and quantitative methods.
- The influence of the rainfall on the occurrence of landslide, especially on the areas with intense and extended rainy season shall be studied further using all methods of landslide susceptibility analysis.
- Future road infrastructure design and construction works, especially on the rough terrain areas with long rainy season, shall consider the landslide as imminent hazard prior to commencing any permanent construction works;
- Detail studies on the features, failure mechanisms and practical remedial measures for landslides have to be conducted.
- Finally, all concerned stake holders shall take responsibility to take all necessary measures during pre and post construction phases of the road construction to minimize the probability of landslide occurrence.

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APPENDIX A
ANALYTIC HIERARCHY PROCESS(AHP) ANALYSIS

Analytic Hierarchy Process(AHP) Analysis for Landslide Contributing Factors and Classes

Pairwise comparison matrix

Factors		1	2	3	4	5	6	7	8	9
Slope Angle(Deg.)										
1	0-5	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9
2	5-9	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8
3	9-14	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7
4	14-20	4	3	2	1	1/2	1/3	1/4	1/5	1/6
5	20-27	5	4	3	2	1	1/2	1/3	1/4	1/5
6	27-32	6	5	4	3	2	1	1/2	1/3	1/4
7	32-39	7	6	5	4	3	2	1	1/2	1/3
8	39-48	8	7	6	5	4	3	2	1	1/2
9	48-75	9	8	7	6	5	4	3	2	1
Sum		45.0	36.5	28.8	22.1	16.3	11.5	7.6	4.7	2.8
CR		0.052								

Slope Aspect										
1	Flat	1	1/2	1/7	1/4	1/9	1/5	1/4	1/3	1/2
2	North	2	1	1/4	1/2	1/8	1/3	1/2	2	1
3	Northeast	7	4	1	3	1/3	2	4	4	7
4	East	4	2	1/3	1	1/4	1/2	1	2	3
5	Southeast	9	8	3	4	1	4	5	7	8
6	South	5	3	1/2	2	1/4	1	2	3	4
7	Southwest	4	2	1/4	1	1/5	1/2	1	2	3
8	West	3	1/2	1/4	1/2	1/7	1/3	1/2	1	2
9	Northwest	2	1	1/7	1/3	1/8	1/4	1/3	1/2	1
Sum		37.0	22.0	5.9	12.6	2.5	9.1	14.6	21.8	29.5
CR		0.034								

Elevation(m)								
1	1015-1300	1	1/2	1/3	1/4	1/5	1/6	1/8
2	1300-1580	2	1	1/2	1/3	1/4	1/5	1/7
3	1580-1802	3	2	1	1/2	1/3	1/4	1/6
4	1802-1998	4	3	2	1	1/2	1/3	1/5
5	1998-2198	5	4	3	2	1	1/2	1/4
6	2198-2388	6	5	4	3	2	1	1/3
7	2388-2732	8	7	6	5	4	3	1
Sum		29.0	22.5	16.8	12.1	8.3	5.5	2.2
CR		0.046						

Curvature				
1	Flat	1	1/5	1/3
2	Concave	5	1	3
3	Convex	3	1/3	1
Sum		9.0	1.5	4.3
CR		0.053		

Lithology						
1	Lower Trachyte Flow	1	1	3	2	1/8
2	Middle Basalt Flow	1	1	2	3	1/7
3	Middle Trachyte Flow	1/3	1/2	1	1	1/9
4	Quaternary Alluvial	1/2	1/3	1	1	1/9
5	Upper Basalt Flows	8	7	9	9	1
Sum		10.8	9.8	16.0	16.0	1.5
CR		0.051				

Distance to Stream(m)						
1	300	1	2	3	5	7
2	600	1/2	1	2	3	5
3	900	1/3	1/2	1	2	3
4	1200	1/5	1/3	1/2	1	3
5	>2000	1/7	1/5	1/3	1/3	1
Sum		2.2	4.0	6.8	11.3	19.0
CR		0.022				

Distance to Road(m)						
1	50	1	2	4	8	9
2	150	1/2	1	2	4	8
3	500	1/4	1/2	1	2	4
4	1000	1/8	1/4	1/2	1	4
5	>1000	1/9	1/8	1/4	1/4	1
Sum		2.0	3.9	7.8	15.3	26.0
CR		0.044				

Land use/cover								
1	Water	1	7	5	6	3	3	5
2	Trees	1/7	1	1/3	1	1/4	1/2	1/2
3	Flooded Veg.	1/5	3	1	2	1/4	1/2	1/2
4	Crops	1/6	1	1/2	1	1/4	1/2	1/2
5	Built Area	1/3	4	4	4	1	5	5
6	Bare Ground	1/3	2	2	2	1/5	1	1
7	Range Land	1/5	2	2	2	1/5	1	1
Sum		2.4	20.0	14.8	18.0	5.2	11.5	13.5
CR		0.064						

Rainfall(mm)					
1	1547-1600	1	1/3	1/5	1/7
2	1600-1675	3	1	1/3	1/5
3	1675-1750	5	3	1	1/3
4	1750-1815	7	5	3	1
Sum		16.0	9.3	4.5	1.7
CR		0.066			

		1	2	3	4	5	6	7	8	9
		Pair-wise comparison matrix								
		Slope	Aspect	Elevation	Curv.	Litho.	DTS	DTR	LULC	Rainfall
1	Slope	1	4	2	4	1/5	1/3	1/4	2	1/4
2	Aspect	1/4	1	1/3	1	1/6	1/6	1/8	1/4	1/6
3	Elevation	1/2	3	1	3	1/4	1/4	1/3	1/2	1/2
4	Curvature	1/4	1	1/3	1	1/5	1/7	1/9	1/3	1/8
5	Lithology	5	6	4	5	1	1/2	1/2	4	1
6	DTS	3	6	4	7	2	1	1	5	1
7	DTR	4	8	3	9	2	1	1	4	1/2
8	LULC	1/2	4	2	3	1/4	1/5	1/4	1	1/4
9	Rainfall	4	6	2	8	1	1	2	4	1
Sum		18.5	39.0	18.7	41.0	7.1	4.6	5.6	21.1	4.8
CR		0.056								

Analytic Hierarchy Process(AHP) Analysis for Landslide Contributing Factors and Classes

Normalized pairwise comparison matrix

Factors		1	2	3	4	5	6	7	8	9	Priority	Consistency	
Slope Angle(Degree)													
1	0-5	0.022	0.014	0.012	0.011	0.012	0.015	0.019	0.026	0.039	0.019	λ_{max}	9.604
2	5-9	0.044	0.027	0.017	0.015	0.015	0.017	0.022	0.030	0.044	0.026	n	9.000
3	9-14	0.067	0.055	0.035	0.023	0.020	0.022	0.026	0.035	0.050	0.037	λ_{max-n}	0.604
4	14-20	0.089	0.082	0.069	0.045	0.031	0.029	0.033	0.042	0.059	0.053	n-1	8.000
5	20-27	0.111	0.110	0.104	0.091	0.061	0.044	0.044	0.053	0.071	0.076	RI	1.450
6	27-32	0.133	0.137	0.139	0.136	0.123	0.087	0.066	0.071	0.088	0.109	CI	0.076
7	32-39	0.156	0.164	0.173	0.181	0.184	0.175	0.132	0.106	0.118	0.154	CR	0.052
8	39-48	0.178	0.192	0.208	0.226	0.246	0.262	0.263	0.212	0.177	0.218	Ok!!!	
9	48-75	0.200	0.219	0.243	0.272	0.307	0.349	0.395	0.424	0.353	0.307		
Sum											1.0		

Slope Aspect											Priority		
1	Flat	0.027	0.023	0.024	0.020	0.044	0.022	0.017	0.015	0.017	0.023	λ_{max}	9.398
2	North	0.054	0.045	0.043	0.040	0.049	0.037	0.034	0.092	0.034	0.047	n	9.000
3	Northeast	0.189	0.182	0.170	0.238	0.131	0.219	0.274	0.183	0.237	0.203	λ_{max-n}	0.398
4	East	0.108	0.091	0.057	0.079	0.099	0.055	0.069	0.092	0.102	0.083	n-1	8.000
5	Southeast	0.243	0.364	0.511	0.318	0.394	0.439	0.343	0.321	0.271	0.356	RI	1.450
6	South	0.135	0.136	0.085	0.159	0.099	0.110	0.137	0.137	0.136	0.126	CI	0.050
7	Southwest	0.108	0.091	0.043	0.079	0.079	0.055	0.069	0.092	0.102	0.080	CR	0.034 Ok!!!
		0.081	0.023	0.043	0.040	0.056	0.037	0.034	0.046	0.068	0.047		
		0.054	0.045	0.024	0.026	0.049	0.027	0.023	0.023	0.034	0.034		
Sum											1.0		

Elevation(m)											Priority
1	1015-1300	0.034	0.022	0.020	0.021	0.024	0.031	0.056	0.030	Consistency	
2	1300-1580	0.069	0.044	0.030	0.028	0.030	0.037	0.064	0.043	λ_{max}	7.374
3	1580-1802	0.103	0.089	0.059	0.041	0.040	0.046	0.075	0.065	n	7
4	1802-1998	0.138	0.133	0.119	0.083	0.060	0.061	0.090	0.098	λ_{max-n}	0.374
5	1998-2198	0.172	0.178	0.178	0.166	0.121	0.092	0.113	0.146	n-1	6
6	2198-2388	0.207	0.222	0.238	0.248	0.241	0.183	0.150	0.213	RI	1.35
7	2388-2732	0.276	0.311	0.356	0.414	0.483	0.550	0.451	0.406	CI	0.062
Sum										1.0	CR 0.046 Ok!!!

Curvature					Priority	Consistency			
1	Flat	0.111	0.130	0.077	0.106	λ_{max}	3.055	RI	0.52
2	Concave	0.556	0.652	0.692	0.633	n	3	CI	0.028
3	Convex	0.333	0.217	0.231	0.260	λ_{max-n}	0.055	CR	0.053
Sum					1.0	n-1	2		

Ok!!!

Lithology								Priority	Consistency			
1	Lower Trachyte Flow	0.092	0.102	0.188	0.125	0.08	0.118	λ_{max}	5.226	RI	1.11	
2	Middle Basalt Flow	0.092	0.102	0.125	0.188	0.10	0.120	n	5	CI	0.056	
3	Middle Trachyte Flow	0.031	0.051	0.063	0.063	0.07	0.056	λ_{max-n}	0.226	CR	0.051	
4	Quaternary Alluvial	0.046	0.034	0.063	0.063	0.07	0.056	n-1	4			
Sum								1.00				

Ok!!!

Distance to Stream(m)							Priority	Consistency			
1	50	0.460	0.496	0.439	0.441	0.368421053	0.441	λ_{max}	5.097	RI	1.11
2	100	0.230	0.248	0.293	0.265	0.263157895	0.260	n	5	CI	0.024
3	300	0.153	0.124	0.146	0.176	0.157894737	0.152	λ_{max-n}	0.097	CR	0.022
4	1000	0.092	0.083	0.073	0.088	0.157894737	0.099	n-1	4		
5	>1000	0.066	0.050	0.049	0.029	0.052631579	0.049				
Sum							1.0				

Ok!!!

Distance to Road(m)							Priority
1	50	0.503	0.516	0.516	0.525	0.346153846	0.481
2	150	0.252	0.258	0.258	0.262	0.307692308	0.268
3	500	0.126	0.129	0.129	0.131	0.153846154	0.134
4	1000	0.063	0.065	0.065	0.066	0.153846154	0.082
5	>1000	0.056	0.032	0.032	0.016	0.038461538	0.035

Consistency

λ_{max}	5.196	RI	1.11
n	5	CI	0.049
λ_{max-n}	0.196	CR	0.044
n-1	4		Ok!!!

Landuse/cover								Priority
Water	0.421	0.350	0.337	0.333	0.583	0.261	0.370	0.379
Trees	0.060	0.050	0.022	0.056	0.049	0.043	0.037	0.045
Flooded Vegetation	0.084	0.150	0.067	0.111	0.049	0.043	0.037	0.077
Crops	0.070	0.050	0.034	0.056	0.049	0.043	0.037	0.048
Built Area	0.140	0.200	0.270	0.222	0.194	0.435	0.370	0.262
Bare Ground	0.140	0.100	0.135	0.111	0.039	0.087	0.074	0.098
Range Land	0.084	0.100	0.135	0.111	0.039	0.087	0.074	0.090
Sum								1.0

Consistency

λ_{max}	7.515
n	7
λ_{max-n}	0.515
n-1	6
RI	1.35
CI	0.086
CR	0.064

Ok!!!

Annual Average Rainfall(mm)						Priority
1	1547-1600	0.063	0.036	0.044	0.085	0.057
2	1600-1675	0.188	0.107	0.074	0.119	0.122
3	1675-1750	0.313	0.321	0.221	0.199	0.263
4	1750-1815	0.438	0.536	0.662	0.597	0.558
Sum						1.0

Calculating Consistency

λ_{max}	4.177	RI	0.89
n	4	CI	0.059
λ_{max-n}	0.177	CR	0.066
n-1	3		Ok!!!

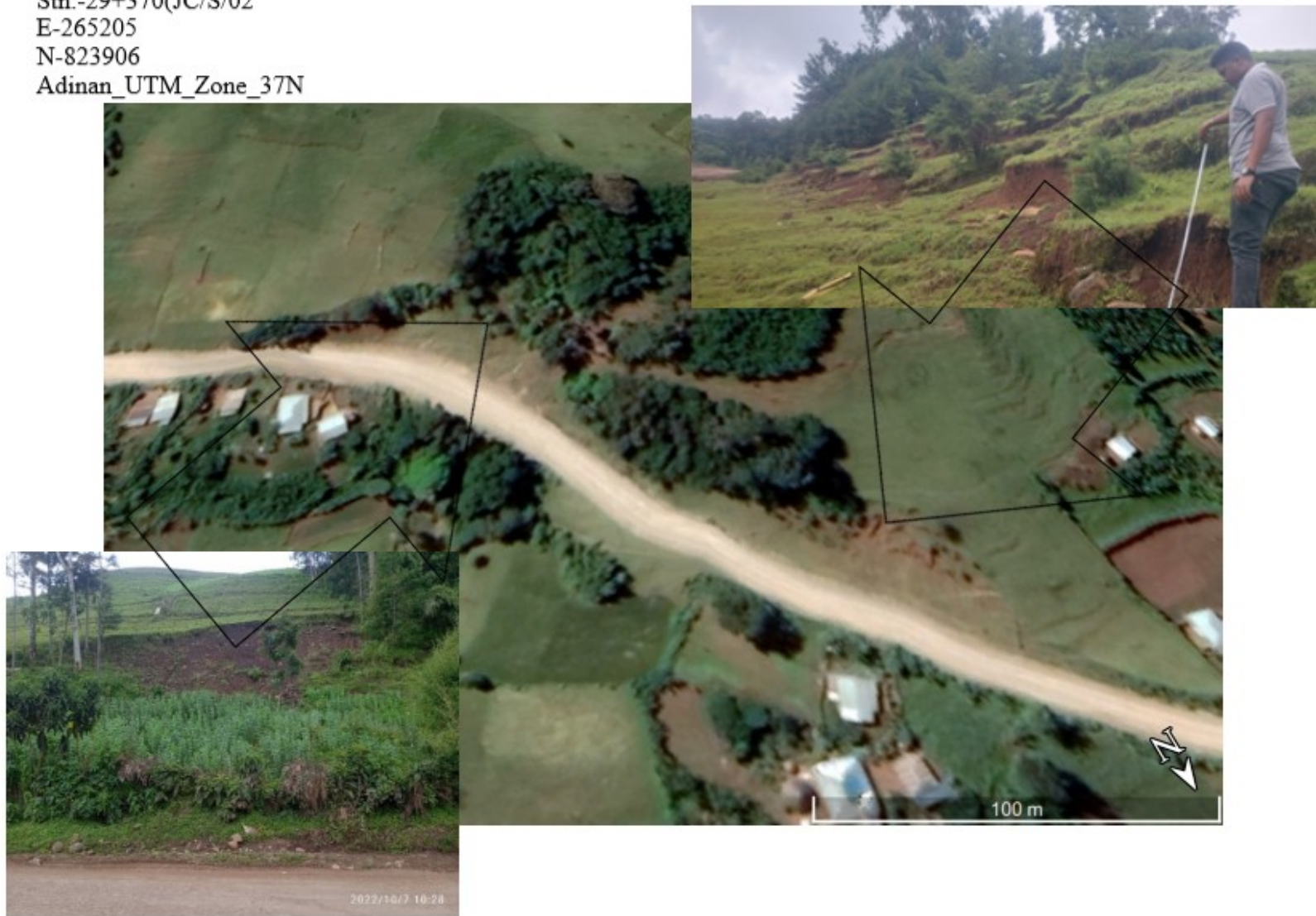
	Normalized pair-wise comparison matrix											Consistency
	Slope	Aspect	Elevation	Curva	Litho	DTS	DTR	LULC	Rainfall	Priority	%age	
Slope	0.054	0.103	0.107	0.098	0.028	0.073	0.045	0.095	0.052	0.073	7.3%	λ_{max} 9.644 n 9.000 λ_{max-n} 0.644 n-1 8.000 RI 1.450 CI 0.081 CR 0.056 Ok!!!
Aspect	0.014	0.026	0.018	0.024	0.024	0.036	0.022	0.012	0.035	0.023	2.3%	
Elevation	0.027	0.077	0.054	0.073	0.035	0.054	0.060	0.024	0.104	0.056	5.6%	
Curvature	0.014	0.026	0.018	0.024	0.028	0.031	0.020	0.016	0.026	0.023	2.3%	
Lithology	0.270	0.154	0.214	0.122	0.142	0.109	0.090	0.190	0.209	0.167	16.7%	
DTS	0.162	0.154	0.214	0.171	0.283	0.218	0.180	0.237	0.209	0.203	20.3%	
DTR	0.216	0.205	0.161	0.220	0.283	0.218	0.180	0.190	0.104	0.197	19.7%	
LULC	0.027	0.103	0.107	0.073	0.035	0.044	0.045	0.047	0.052	0.059	5.9%	
Rainfall	0.216	0.154	0.107	0.195	0.142	0.218	0.359	0.190	0.209	0.199	19.9%	
Sum	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.000	100%	

APPENDIX B
SATELLITE IMAGERIES AND SITE PICTURES

Stn.-23+200(JC/S/01)
E-265652
N-826874
Adindan_UTM_Zone_37N



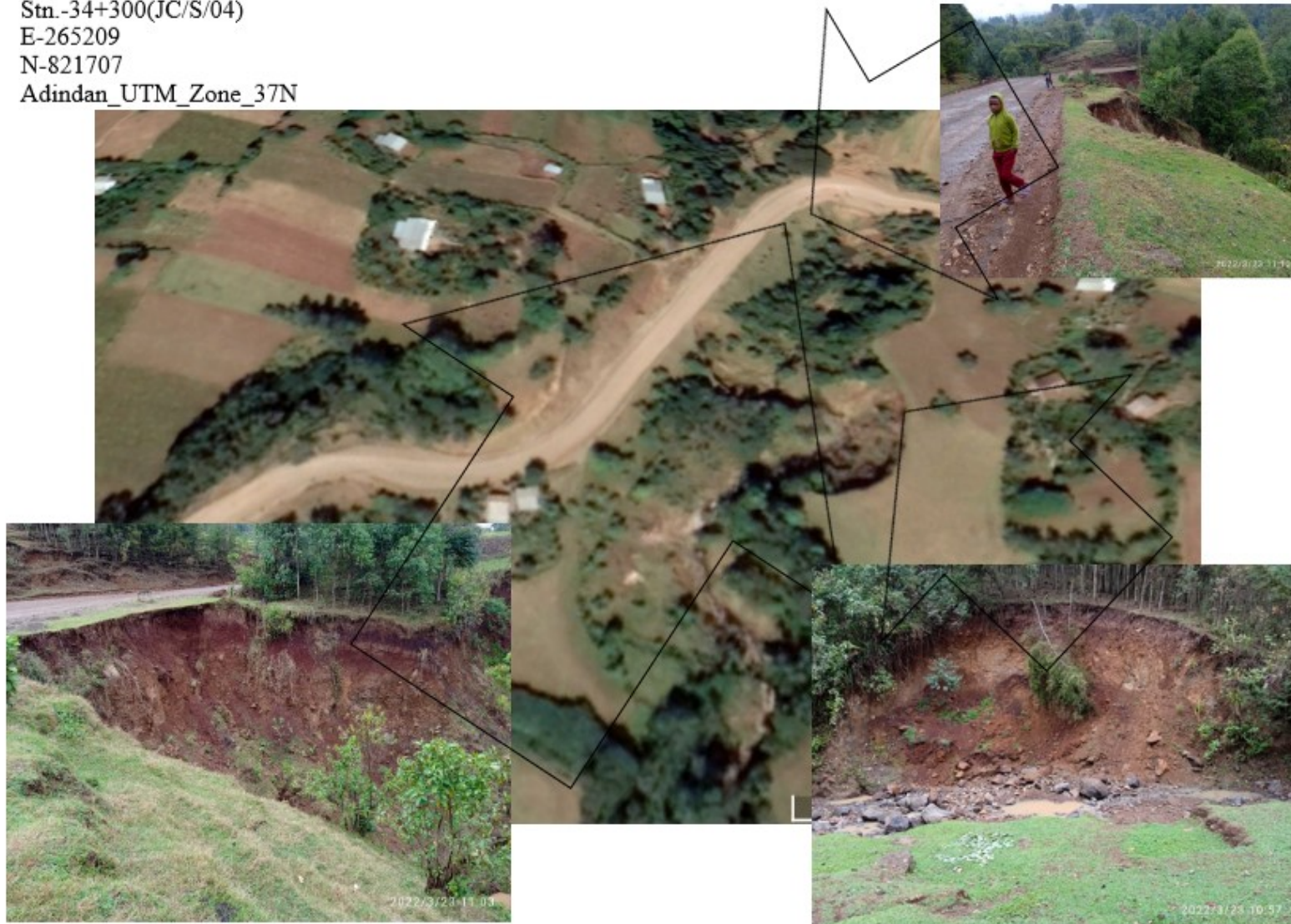
Stn.-29+370(JC/S/02
E-265205
N-823906
Adinan_UTM_Zone_37N



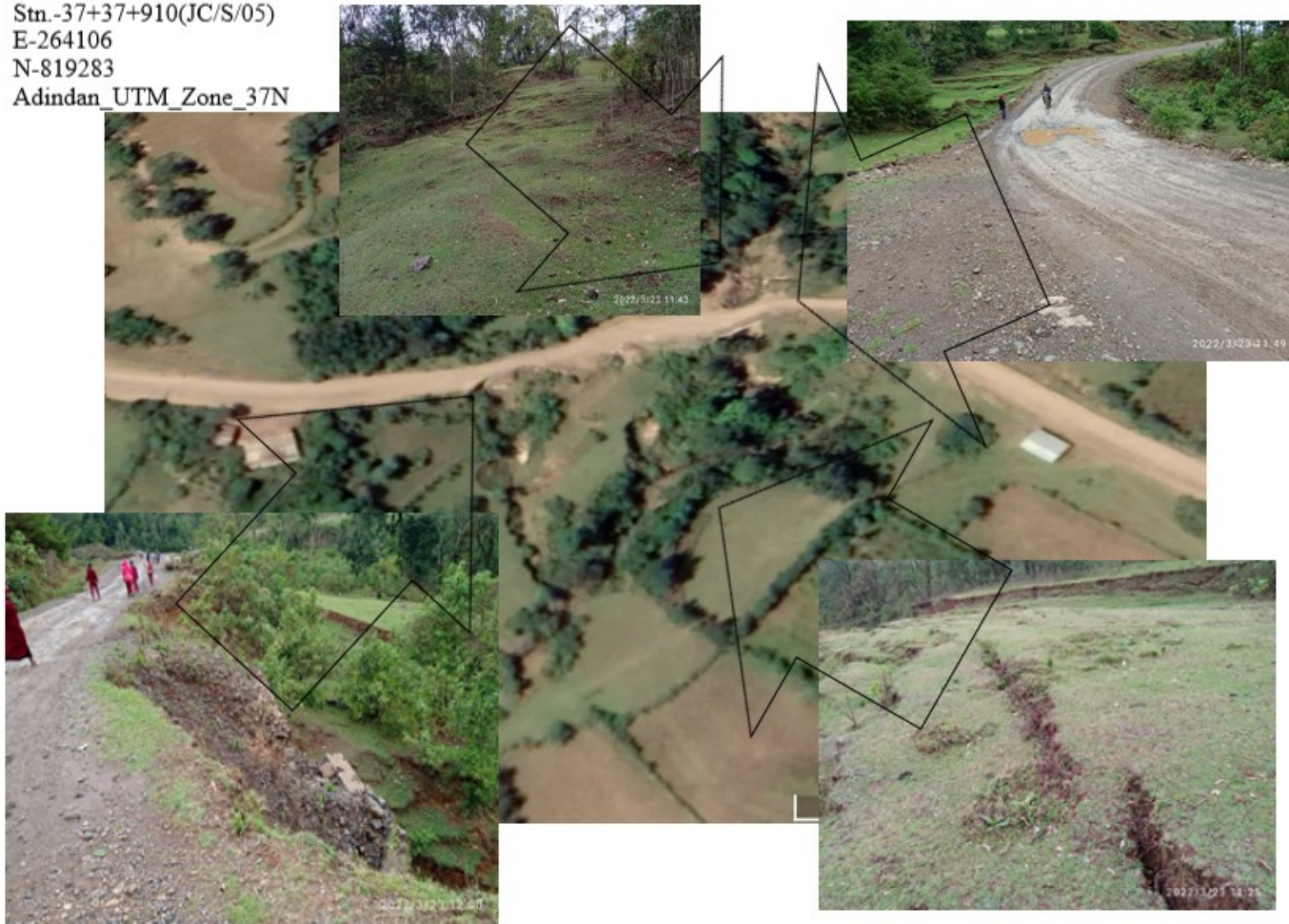
Stn.-30+600(JC/S/03)
E-265797
N-822920
Adindan_UTM_Zone_37N



Stn.-34+300(JC/S/04)
E-265209
N-821707
Adindan_UTM_Zone_37N



Stn.-37+37+910(JC/S/05)
E-264106
N-819283
Adindan_UTM_Zone_37N



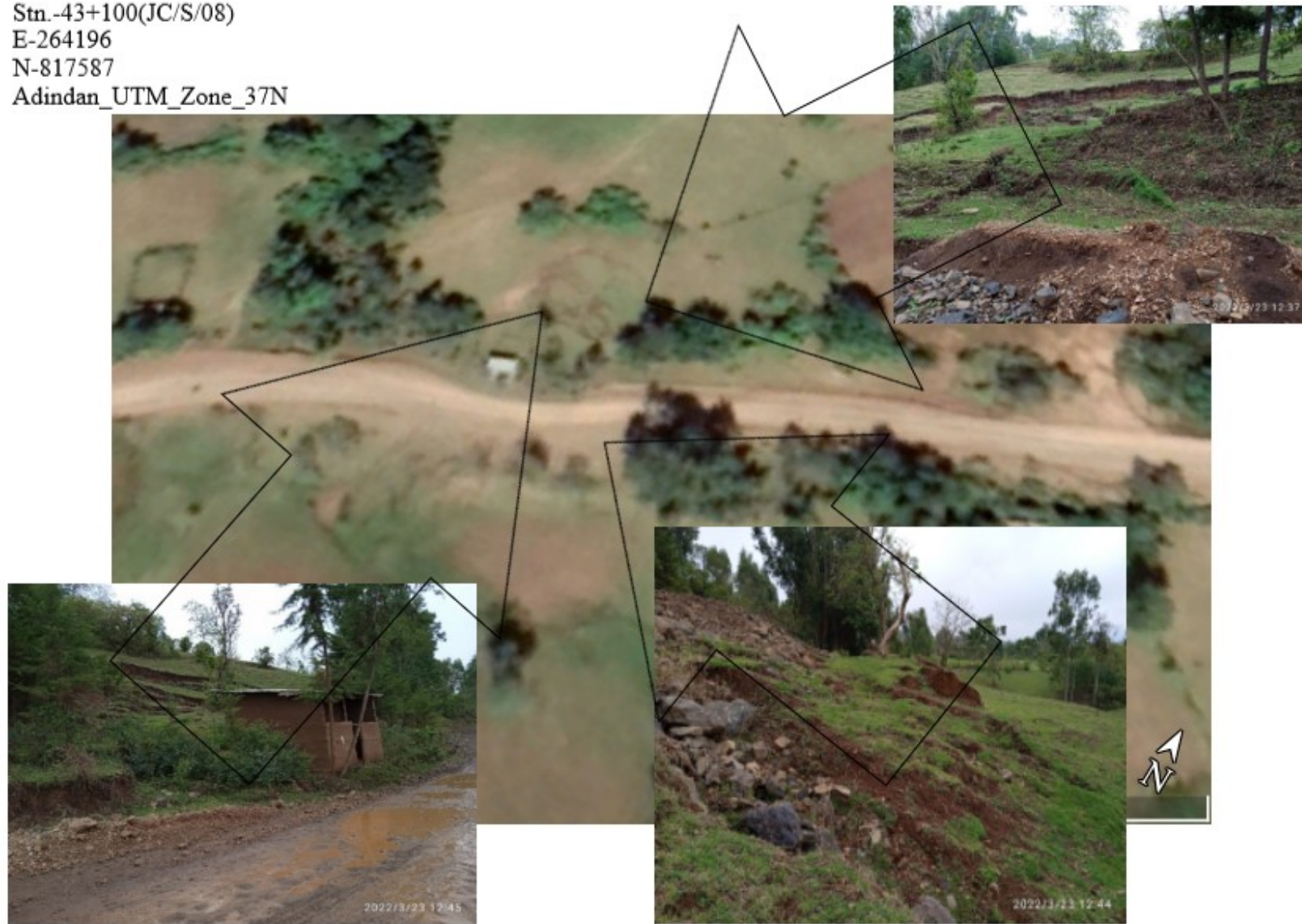
Stn.-39+170(JC/S/06)
E-264743
N-818330
Adindan UTM Zone 37N



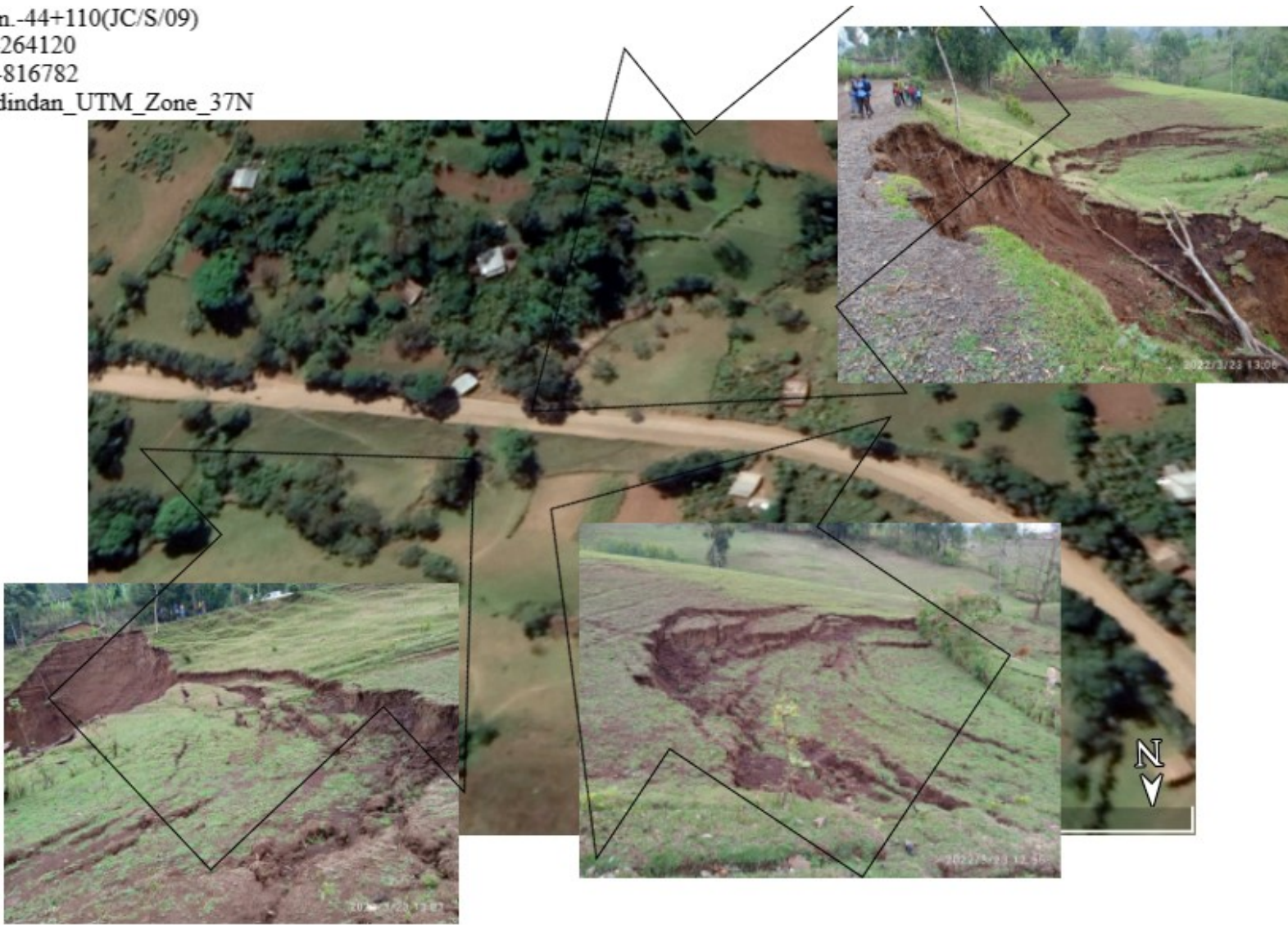
Stn.-42+300(JC/S/07)
E-264962
N-817740
Adindan_UTM_Zone_37N



Stn.-43+100(JC/S/08)
E-264196
N-817587
Adindan_UTM_Zone_37N



Stn.-44+110(JC/S/09)
E-264120
N-816782
Adindan_UTM_Zone_37N



Stn.-58+750(JC/S/10)
E-263066
N-807147
Adindan_UTM_Zone_37N



Stn.-79+350(JC/S/11)
E-256086
N-793553
Adindan_UTM_Zone_37N

