**ADDIS ABABA UNIVERSITY**

**COLLEGE OF TECHNOLOGY AND BUILT ENVIRONMENT**

**SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING**

# Landslide Inventory Mapping and Susceptibility Analysis for the Jimma-Metu-Gore Transportation Route.

A Thesis in Geotechnical Engineering

**By - Tibebu Tesfaye**

December, 2025.

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A Thesis in Geotechnical Engineering


By - Tibebu Tesfaye

Advisor – Tezera Firew Azmatch (Ph.D)


December, 2025.

Addis Ababa, Ethiopia.

The undersigned have examined the thesis entitled "Landslide Inventory Mapping and Susceptibility Analysis for the Jimma-Metu-Gore Transportation Route" presented by Tibebu Tesfaye Ayalkbet, a candidate for the degree of Master of Science and hereby certify that it complies with the regulations of the University and meets the accepted standards with respect to originality, content and quality.

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| External Examiner | Signature | Date |
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| Chairperson | Signature | Date |

# UNDERTAKING

I hereby declare that this thesis entitled **"Landslide Inventory Mapping and Susceptibility Analysis for the Jimma-Metu-Gore Transportation Route"** has been conducted by me under the advice and supervision of my advisor, Dr. Tezera Firew Azmatch.

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 has been used from any external sources it has been properly acknowledged.

____________________________

Tibebu Tesfaye Ayalkbet

# Abstract

In Ethiopia, the frequency and magnitude of landslides, followed by the subsequent damage, have been increased in recent years. The Jimma-Metu-Gore route is located in the southwestern part of Ethiopia which is characterized as one of a landslide prone route suffering from the repeated consequences of the hazard. This research ultimately aims identifying landslide prone zones along the route using a quantitative approach known as **CRITIC** (Criteria Importance Through Inter-criteria Correlation) method integrated with GIS techniques. Ten landslides are identified along the route and landslide assessment is conducted for each of the landslide stations. A detailed landslide inventory is first produced with the field investigations, satellite image interpretation and referring to existing records which served both as an input for factor analysis and as dataset for validation. Nine causative factors are carefully selected based on their relevance and data availability which are elevation, slope angle, slope aspect, curvature, rainfall, geology, use/land cover (LULC), proximity to streams, and proximity to lineaments. These thematic factors are extracted from high resolution datasets such as SRTM 30 m DEM, Landsat imagery, geological map and Ethiopian Meteorology Institute. Preparation of digitized layer maps of each of thematic factors are prepared employing ArcGIS tool and their weights are objectively determined using CRITIC method: Rainfall received the highest weight (0.159) among the nine factors followed by Proximity to streams (0.137), geology (0.127), Proximity to lineaments (0.124), elevation (0.071), slope angle (0.082), land use/land cover (0.109), curvature (0.095), and slope aspect (0.096). The final **Landslide Susceptibility Map (LSM)** is then developed and using Natural Breaks/Jenks method it is categorized into five susceptibility classes: Very Low Susceptibility (15.51%), Low Susceptibility (25.95), Moderate Susceptibility (29.39%), High Susceptibility (20.86%), and Very High Susceptibility (8.29%). Finally, based on the desk study, site investigation and landslide susceptibility analysis remedial measures such as construction reinforced retaining and installation of surface & subsurface drainage systems specifically tailored to each failure stations are proposed.

**Key words**: CRITIC, Landslide Susceptibility Map, DEM, Natural Breaks/Jenks

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# 1. INTRODUCTION

## 1.1 Background

Landslide has been defined in multiple ways by a number of scholars who have studied the phenomenon. According to Curden & Varnes (1996), a landslide is described as the downward movement of soil or rock along the earth's surface due to gravitational force. The phenomenon occurs in mountainous areas and escarpments where the terrain is rough. It can be triggered by external factors which affect the strength and stability of the slope material. Landslides cause reformation of landscapes since they are major mass wasting processes.

Landslides can be triggered by both human-induced developmental activities such as: construction, road cutting, mining, urbanization, usage of explosives for different purposes and natural causes including extended periods of rainfall, seismic activity and intense snowmelt (Aleotti & Chowdhury, 1999). They can be classified based on the physical characteristics of the sliding material and type of movement of the affected part of earth. Their classification can be listed as falls, topples, flows, spreads, slides, or any combination of these and the movement can be sudden or slow. The impact of such events may considerably differ based on specific conditions of the landslide. Among the major impacts, damage of infrastructure and the risk of human injuries and fatalities can be mentioned.

In Ethiopia, the frequency and magnitude of landslides, followed by the subsequent damage, have been increased in recent years (Azmeraw, 2021). Despite the localized nature of its impact, landslide causes catastrophic events leading to a significant loss of human lives and substantial property destruction. The area selected for this thesis is characterized as one of a landslide prone road alignment which suffers from the repeated consequences of the event.

The Jimma-Metu-Gore route is located in the southwestern part of Ethiopia. The area features a combination of highland and lowland terrains with significant elevation difference causing frequent landslide occurrence. The route crosses a range of landscapes including mountainous areas, which are highly exposed to landslides, especially during the rainy season.

The Jimma-Metu-Gore corridor is located in one of the high rainfall regions of southwestern Ethiopia, where the average annual precipitation commonly exceeds 1800-2200 mm. The area experiences a long rainy season with intense rainfall events that significantly increase soil saturation and pore water pressure. Such hydrological conditions reduce shear strength of slope materials and frequently act as a primary triggering factor for landslides in mountainous terrains. Numerous studies have indicated that prolonged and intense rainfall is one of the most critical factors initiating slope failures in tropical highland environments (Ayalew & Yamagishi, 2004).

The study route is dominated by volcanic formations associated with the Ethiopian volcanic plateau, mainly consisting of basalt, trachyte, and pyroclastic deposits formed during successive volcanic eruptions. These volcanic rocks have undergone varying degrees of weathering, producing thick residual soils and weak layers that can significantly influence slope stability (Abbate et al., 2015).

The selected route experiences periodic enhancements as a result of the road maintenance works of ERA (Ethiopian Road Administration). The recurring landslide problem has led to continuous property damage and loss of life over an extended period. This study aims to identify both the causative and triggering factors, and its primary objective is to provide solid landslide information by delineating distinct susceptible zones through the creation of susceptibility zone maps in the study area.

## 1.2 Statement of the problem

The Jimma-Metu-Gore route in Ethiopia has been consistently affected by landslides, resulting in property damage and loss of life for a long period of time. However, a comprehensive landslide study to identify causative and triggering factors and propose effective remedial measures has not been conducted which is tailored to the present study area. The unavailability of such studies made the region vulnerable to repeated landslide hazards which justifies the need for a detailed investigation and the development of landslide susceptibility maps to prevent the impact of landslides on both property and human lives. The assessments made previously, if any, are mainly focused on studying individual cases rather than analyzing the wider landslide triggering factors, such as geological, climatic and geomorphological conditions that control instability of slopes. It should be determined, which landslide factors impacts the slope instability considering the complex interaction between rainfall, geology and slope geometry in the area. Simultaneous application of field data with GIS-based spatial analysis enable the possibility to evaluate these factors objectively and generate a reliable landslide susceptibility map.

Therefore, this research ultimately aims to fill the existing knowledge gap by identifying landslide prone zones along the Jimma-Metu-Gore route using a quantitative approach named CRITIC method integrated with GIS techniques. The result will strongly support the works of decision makers in prioritizing vulnerable sections, improving slope management practices, and guiding what preventive engineering measures should be implemented.

## 1.3 Research Objective

### 1.3.1 General objective

The main objective of this research is to develop a landslide susceptibility map for the transportation route Jimma-Metu-Gore in Ethiopia, to bring clear information on the understanding of landslide susceptibility along the corridor and propose remedial measures for each of the landslide stations.

### 1.3.2 Specific Objective

- ✓ To conduct an assessment for each of the landslides along the study route
- ✓ To develop a comprehensive landslide inventory map through site investigation and using remote sensing.
- ✓ To identify and analyze the causative factors of the landslides.
- ✓ To develop landslide susceptibility map.
- ✓ To propose remedial measures tailored to each of the landslide sites.

## 1.4 Limitations

The scarcity of previous landslide records and systematic documentation leads to a challenge in constructing a strong landslide inventory, possibly limiting the ability to identify patterns and trends over an extended period. This limitation may influence the accuracy of the susceptibility assessment. The limited availability of detailed data sets, especially in less-accessible areas, may constrain the depth of the analysis and the precision of susceptibility mapping.

## 1.5 Scope of the study

The study concentrates on exploration of landslide susceptibility along the Jimma-Metu-Gore route in Ethiopia. Encompassing the entire transportation corridor, the research investigates the geological and topographic characteristics, analyzing the influence of slope features, rock types and other geological factors on landslide occurrences. Meteorological factors, particularly rainfall patterns and their correlation with landslides will be thoroughly examined. The study also involves compiling a detailed landslide inventory. Utilizing advanced remote sensing technologies and GIS techniques, high-resolution maps will be generated to enhance the accuracy of susceptibility mapping. The research will provide insights that are applicable not only to the specified transportation corridor but also to regions facing similar geological and climatic conditions.

# 2. LITERATURE REVIEW

## 2.1 Introduction

As Cruden defined Landslides, they are the mass movement of rock, debris or earth down a slope, results in a geomorphic transformation of the Earth's surface (Cruden, 1991). They indicate that there is a slope instability which can be described as the tendency for a slope to undergo morphologically and structurally disruptive landslide processes. The occurrence of landslides can be in combinations of various forms, including mud-flows, soil slips, rock falls, rockslides, rock avalanches and debris flow (Arbanas & Zeljko, 2015). If the slope failure is individual, it is generally not so huge or as costly as earthquakes, hurricanes, major floods or some other natural hazards. In comparison with any other geological hazards, landslides are more widespread, and gradually they may cause more damage to properties. The most common and major triggering factors of landslides can be listed as rugged topography, weakness of geological structure and variation in bedrock lithology (Varnes D. J., 1978).

The examination of landslides has gained global attention, primarily driven by the growing awareness of its socio-economic influences and the increasing impact of urbanization on mountainous environments (Aleotti & Chowdhury, 1999). As a result, conducting landslide susceptibility assessments becomes vital to spot susceptible threats. Moreover, strategic management projects can be formulated to prevent, avoid, or substantially mitigate this hazard causing phenomenon.

Slope failure occurrences depend up on a complex interaction between number of interconnected factors, requiring an extensive analysis of the relationship between terrain conditions and landslide phenomenon (Raghuvanshi T. K., 2016). Recognized as reasonably predictable susceptibility, slope failures offer an opportunity to significantly reduce damages compared to other geo-hazards. Regardless of their occurrence in both developed and developing nations, developing countries suffer more, while industrialized nations experience substantial economic losses due to landslides.

Landslide-induced hazards in Ethiopia have emerged as significant challenges for the public, as well as for planners and decision-makers across different government levels. Regardless of the increasing impact of these hazards on the population, there has been a limited initiative to reduce the associated losses. The ongoing movements of infrastructural and urbanization development, as well as the prevailing land management system indicates escalation in the frequency and magnitude of landslides, leading to increased losses unless proactive measures are implemented in Ethiopia (Woldearegay, 2013)

## 2.2 Types of Landslides

Among the steps of studying landslides, detailed classification of landslide is an important phase. It could be taken as the primary work when investigating the phenomena. While classifying landslides, number of variables have been employed by different researchers. However, the widely acknowledged classification of landslides is presented by (Varnes D. J., 1978), as he classified the event in to five primary movements: falls, topples, slides, flows, and spreads. He also classifies the material involved type into bedrock, debris, and earth. They are discussed as follows referring pictures from (USGS, 2004).

### 2.2.1 Rock Falls

Rock falls involve sudden movements of large rocks or boulders detached from their parent rock. Typically occurring along steep slopes or cliffs, these falls result from separation along discontinuities like fractures, joints, and bedding planes as shown in Figure 2-1. The movements manifest through free-fall, bouncing, and rolling. Rock falls are highly triggered by mechanical weathering and entrance of water in the fracture of rock masses. The phenomenon is common in jointed, fractured and weathered bedrock and steep slopes (Wachal & Hundak, 2000).

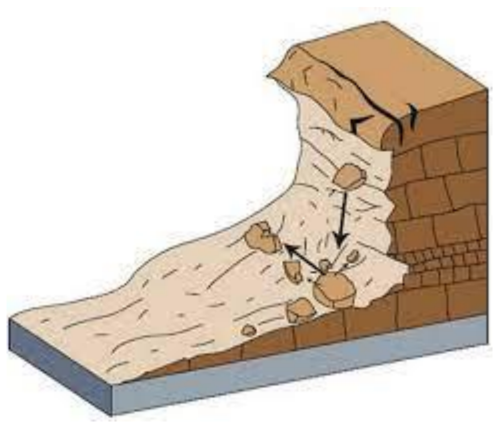


Figure 2-1: Rock Falls (USGS, 2004)

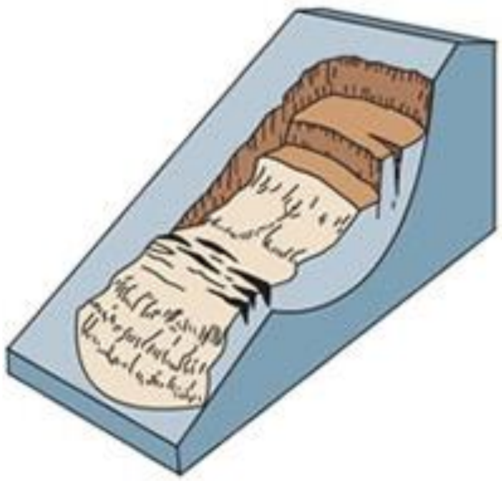
### 2.2.2 Topples

Topple refers to the forward rotation of a mass of slope materials such as huge masses of rock, debris and earth around a point or axis located below the center of gravity of the displaced mass (Varnes D. J., 1978). Unlike sliding, this form of failure occurs due to the overturning of blocks rather than simple sliding as shown in Figure 2-2. Cracks or fractures in bed rock are the main causes for this type of failure (Highland & Bobrowski, 2008)

Figure 2-2: Topples (USGS, 2004)

### 2.2.3 Slides

A slide is characterized by the downward movement of slope materials, primarily occurring on the surface of rupture or in relatively thin zones of high shear strain. In this type of land slide, materials move as coherent blocks or masses adjacent to the failure plane. Referring the US Geological Survey (USGS, 2004), there are two major types of slides. These are rotational and translational slides. Rotational slides, as shown in Figure 2-3 a), are characterized by a surface rupture that is curved concavely upward. The movement in these slides involves a roughly rotational motion around an axis parallel to the ground surface and transverse across the slide. And as the name indicates, translational slide (Figure b) is a type of landslide where the material moves along a roughly planar surface with minimal rotation or backward tilting (Lynn & Peter , 2008).

a) 

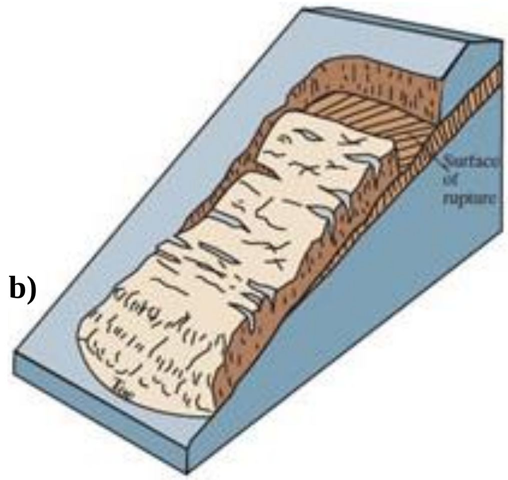
b) 


Figure 2-3: a) Rotational landslide b) Translational landslide, (USGS, 2004)

### 2.2.4 Flows

Flows encompass five distinct categories with fundamental differences. Namely, debris flow, debris avalanche, creeps, earth flow and mud flow.

The first type, debris flow, involves rapid downhill movement of loose earth material which is accompanied by water as shown in *Figure 2-4 a).* It is characterized by rapid mass movement where the mix of loose soil, rock, organic matter, air, and water flowing as a slurry. Less than 50% fines are included in debris flow. They are usually triggered by intense surface-water flow, as a result of heavy rainfall or quick snowmelt that erodes and moves loose soil or rock on steep slopes. Their source areas are often linked with steep gullies, and their deposits are usually identified by the existence of debris fans at the mouths of gullies. The second type, debris avalanche, have similarities with debris flow but shows a more accelerated flow as shown in Figure 2-4-b. It varies from rapid to extremely rapid debris flow.

The third type, creep (shown in Figure 2-4-c), known by its slower nature, which usually is the cause of slight bends in electric poles and roads. It is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. It is often triggered by heavy surface water flow, resulting from intense rainfall or rapid snowmelt, eroding and mobilizing loose soil or rock on mountainous areas which leads shear stress sufficient to produce permanent deformation, but too small to produce shear failure. It can also move large objects like houses downhill or fill structures with the rapid accumulation of organic matter or sediment, (Lynn & Peter , 2008). Creeps can be generally categorized in to three. The first one is seasonal, in which movement is along with the depth of soil affected by seasonal changes in soil moisture and soil temperature. The second is continuous, in which the shear stress continuously exceeds the strength of the material. The third one is progressive, in which the slopes are reaching the point of failure as other types of mass movements.

The fourth type, earthflow, exhibits washed away finer earth material, leaving a depression bowl at the head as shown in Figure 2-4-d. The slope material liquefies and runs out, forming a depression at the head (top). Fine-grained materials or clay-bearing rocks on moderate slopes and under saturated conditions are more exposed to this phenomenon. Despite the fact that earth flow usually happens in wet conditions with fine grained material, dry flows of granular material are also possible. The last type, mudflow, made of saturated silt, sand, and clay materials, flowing rapidly. It is an earthflow made of material that is sufficiently saturated to flow rapidly and that have a minimum of 50 percent sand, silt, and clay-sized particles.

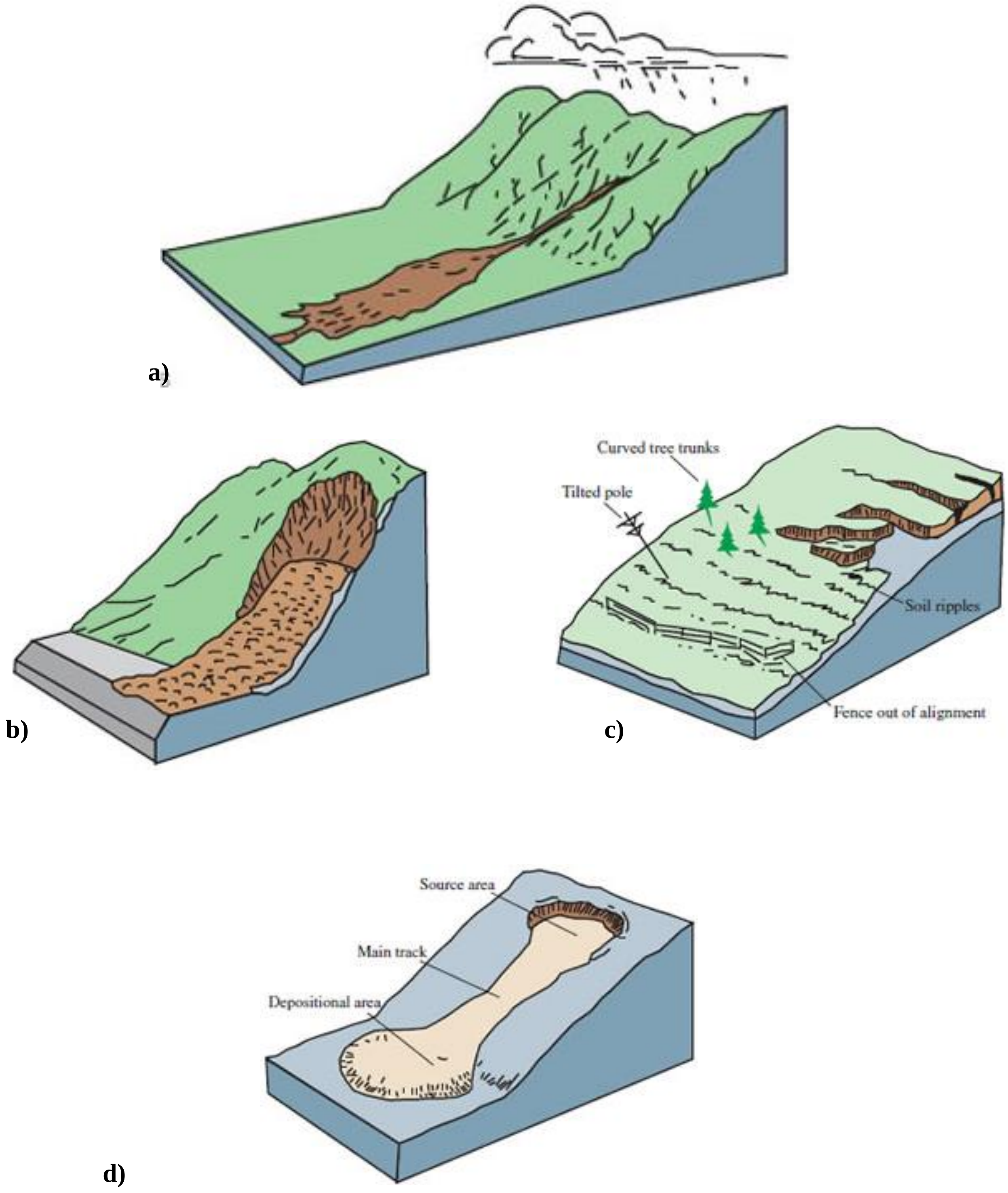



Figure 2-4: a) Debris Flow b) Debris Avalanche c) Creeps
d) Earth Flow and Mudflow (USGS, 2004)

### 2.2.5 Spreads

Spreads are unique type of landslide because they often occur on very gentle slopes or flat terrain. The most common mode of movement is lateral extension that go along with shear or tensile fractures. Liquefaction is the main cause of this type of failure which is the process whereby saturated, loose, cohesion less sediments (usually sands and silts) are transformed from a solid into a liquefied state. Spread in fine-grained materials on shallow slopes is usually progressive. It typically damages pipelines, utilities, bridges, and other structures with shallow foundations (Highland & Bobrowski, 2008).

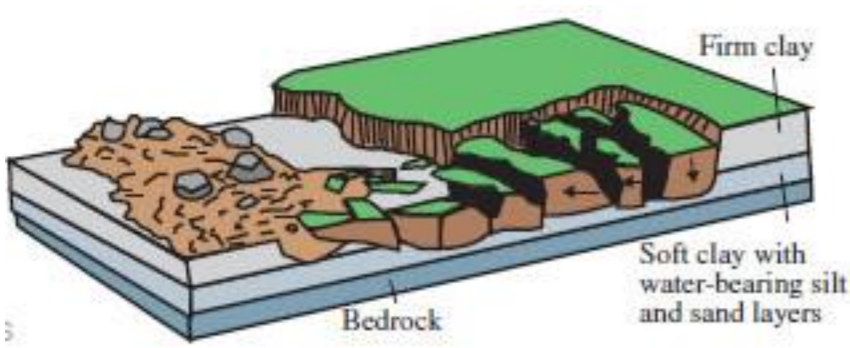



Figure 2-5: Spreads (USGS, 2004)

## 2.3 Factors influencing landslide

### 2.3.1 Intrinsic controlling factors

Intrinsic parameters are the internal controlling factors that determine the favorable or unfavorable condition within the slope (Raghuvanshi T. K., 2016). These include slope material, slope geometry, lithology and lineaments, land use/cover, and groundwater. The slope stability is highly affected by these factors. Therefore, mapping and understanding of their effect are crucial for slope stability analysis (Lynn & Peter , 2008).

#### 2.3.1.1 Slope material

The land surface may be covered with rocks, soils, or both. If the slope materials consist of rocks, the susceptibility to slope failure differs depending on the intact rock strength and the degree of weathering of rock. Rock strength and the extent of weathering are associated with the texture (grain size/shape), composition, and fabric of the rock. Moreover, physical properties of slope materials, like cohesion between grains, may contribute to a reduction in slope strength (Raghuvanshi T. K., 2016).

Slope materials can have rock and soil or both in its formation. The mineralogical arrangement of rock, characteristics and existence of binding materials texture, and other properties of slope material affects shear strength, permeability of materials and also defines the susceptibility of slope materials to physical as well as chemical weathering that can lead to landslide (Varnes D. , 1984)

In addition, Varnes D. (1984) mentioned that unconsolidated slope materials are more exposed to landslide compared to consolidate materials as a result of lower shear strength and rigidity and high infiltration rate. He showed the role of mineral composition on slope stability regarding to the abundance of clay minerals in the soil or rock. The relative abundance of clay minerals, clay mineralogy, presence and chemistry of water are dominant compositional factors which influences slope stability of slope materials in fine grained sedimentary rock. As the amount of water content increase in clay materials, its strength will decrease accordingly.

The shear strength of slope materials must be greater than the shear stress in order to keep a slope from failure. If the condition by in which shear strength of the soil or rock is less than the shear strength required for equilibrium happens, it will be the major cause for the slope failure. This condition can be occurred in two ways. It can be either through a decrease in the shear strength of soil or through an increase in shear stress required for equilibrium (Duncan & Wright, 2005). Various factors can lead to reduction in shear strength of soil. The following processes are particularly important regarding to slope stability. These are: increasing of pore water pressure, swelling, cracking, weathering, loading, whereas earthquake and surcharge load within the soil impose additional shear stress (Duncan & Wright, 2005).

#### 2.3.1.2 Slope geometry

Slope geometry encompasses both slope morphometry and relative relief. Relative relief denotes the disparity between the maximum and minimum elevations of individual slope facets (Hoek & Bray, 1981). Typically, higher relative relief indicates a greater susceptibility to failure. Conversely, slope morphometry refers to the steepness of the slope. A steeper slope results in an increased shear stress, rendering it more prone to failure compared to a gentler slope. The steepness of slope can be shown in slope morphometry. It defines slope classification based on frequency of occurrence of particular angles of slopes. The distribution of slope classification depends on the geomorphologic history of the area which the angle of slope of each unit is a reflection of a series of localized process and controls (Anbalagan, 1992). According to Varnes (1984) the occurrence of landslide has direct relationship with morphometry of slope, when the steepness of slope increases the possibility of landslide on the area will also increase.

#### 2.3.1.3 Lithology and Lineaments

This factor delineates the physical attributes of a rock unit and holds substantial influence in landslide occurrences. Lithological and structural variations play a pivotal role in altering the strength and permeability of rocks and soil (Ayalew & Yamagishi, 2004). Lineaments include fractures, faults, geomorphologic ridges, and other tectonic and topographic structures, introduce discontinuities in rocks and soil masses, thereby affecting slope stability. To assess the impact of lineaments on landslide occurrences, parameters such as distance to lineaments (faults) and the density of lineaments are commonly considered.

#### 2.3.1.4 Land Use/Cover

Land use and land cover play a vital role in slope stability. Areas with thick vegetation contribute to slope stability as the vegetation impedes excessive water seepage into the ground. Barren and sparsely vegetated lands are more prone to erosion, weathering, and slope failure. Vegetation cover significantly influences hydrological processes such as precipitation, soil moisture, and hydraulic conductivity. Additionally, cultivation and agricultural practices can impact the overall stability conditions of the slope (Anbalagan, 1992). In areas where there is a vegetation cover the stability of the slope on that area is enhanced as the roots of the plants increase the soil strength. According to Cruden and Varnes, rainfall-triggered landslide in mountainous terrain usually occurs as a result of degradation of vegetation (Curden & Varnes, 1996). The probability and susceptibility of slope failures can be significantly decreased by afforestation. The root of plants connects the soil particles together, prevents excessive seepage into the slope materials. In contrast, if the vegetation is removed the slope will exposed to weathering, erosion and surface runoff that tends to increase the probability of slope failure (Ayenew, 2004)

Land use or land cover is an indirect manifestation of the stable slopes. A deforested, barren and sparsely vegetated area shows a relatively high erosion and greater instability than thickly vegetated protected forest. A well-spread root system enhances the shearing resistance of slope materials. In general, vegetation cover smoothens the action of climatic agents on the slopes and defends them from the impacts of weathering and erosion (Anbalagan, 1992).

#### 2.3.1.5 Groundwater

Groundwater plays a crucial role in initiating landslides by diminishing the shear strength of the material and creating pore water pressure (Curden & Varnes, 1996). Rainfall, a major triggering parameter for landslides, is particularly significant in the Ethiopian highlands, where most occurrences happen during prolonged and heavy rainfall periods, notably between mid-July to mid-September (Woldearegay, 2013). In hilly terrain, groundwater is not uniformly distributed but is typically channeled along structural discontinuities. The infusion of water from rainfall onto slope material adds weight to the slope, escalating shear stress and potentially leading to slope failure or mass movement. When saturation happens due to the entry of groundwater into slope materials, reduction of the shear strength of materials occurs and this leads to the movements of rock and soil down ward under the influence of gravity (Highland & Bobrowski, 2008). Shear strength of materials significantly reduces due to presence of ground water. Under normal (dry) condition these slope materials remain stable, but if fluid pressure rises significantly, they can lose the force of friction. In this kind of cases the shear strength of sediments and rock is reduced to zero and this is where the slope materials will collapse.

### 2.3.2 External triggering factors

External triggering factors are dynamic factors, which may trigger slope movement by increasing driving force. These triggering factors include rainfall, seismicity and human action. Static and dynamic loads exerted on slopes modify the force distribution and may produce instability. Static loads include the load of structures or buildings on a slope or loads derived from fills, waste dumps, or heavy vehicles, and when these loads are exerted on the slope head, they create a further weight, which will contribute to the destabilizing forces. Dynamic loads are mainly due to natural or induced seismicity and vibrations caused by nearby blasting. These mainly affect jointed rock masses by opening up pre-existing discontinuities, reducing their shear strength, and displacing rock blocks, which can then fall.

#### 2.3.2.1 Rainfall

Rainfall stands as a critical external triggering factor, significantly impacting slope stability, with an increased risk of failure during rainy seasons in the hilly and mountainous terrain of Ethiopia, (Woldearegay, 2013). The intensity and duration of rainfall are pivotal, as they reduce the shear strength of slope materials and elevate pore water pressure. Rainfall serves as a catalyst for slope failure by lubricating discontinuity surfaces and inducing pore water pressure. The weight of slope material, particularly in soil-covered areas, is heightened by rainwater, contributing to slope failure. The effects of rainfall are intertwined with other influencing factors such as discontinuity orientation, slope morphometry, and the types of slope material. In areas covered by unconsolidated material, rainfall triggers slope failure by reducing the angle of repose (Raghuvanshi T. K., 2016).

#### 2.3.2.2 Seismicity

Earthquakes represent a significant triggering factor for landslides, posing a substantial hazard to both life and property. Landslides induced by earthquakes often manifest as rock falls and slides of rock fragments on steep slopes. The destabilizing impact of earthquakes is twofold, involving the imposition of shearing stress and a reduction in resistance to slope materials. Earthquake wave propagation has three principal effects (Crozier, 1986). The first is a reduction in inter-granular bonding due to sudden shock, regardless of the degree of saturation. Second, the direct mechanical effect of horizontal acceleration. And third cyclic loading, which weakens inter-particle bonding, leading to liquefaction. These effects contribute to the heightened risk of landslides during seismic events.

#### 2.3.2.3 Human Action

Slope instability can be triggered not only by natural parameters but also by human activities. Given the high population density in most Ethiopian highlands, these areas are particularly vulnerable to threats like deforestation, desertification, and other activities that intensify slope instability. These human-induced activities alter the natural slope, leading to increased soil moisture and steep slope cutting, both of which contribute to the triggering of slope instability. Some of human actions that trigger slope failures are: loading of slope or its crest, mining, deforestation, artificial vibration, construction of highway and railroads are some of the activities that may initiate landslide. Basically, undercutting of slopes while constructing highway and railway increases the average slope gradients and the extra weight on slope may widen the chance of slope failures (Long, 2008); (Kumar, 2009).

The rapid expansion of human activities, such as exhaustive agriculture, mining, highway construction, urbanization, etc. are also accountable for most of the slope failures (Ayalew, 1999)

## 2.4 Landslide inventory mapping

The simplest form of a landslide map is the one referred to as landslide inventory map (Guzzetti et al., 2005). It displays the density, frequency, size, activity, time, type, volume of displaced material, the intensity of damage, and spatial distribution of landslide. It is the base for future landslide susceptibility, hazard, and risk prediction by analysing the relation between landslide driving factors and the prevailing landslide event (Mohammad et al., 2012). Moreover, the accuracy and performance of the landslide susceptibility, hazard, and risk maps is frequently analysed and validated using landslide inventory map. It indicates the past and current landslide occurrences. Landslide inventory map can be prepared using a number of techniques such as field investigation, evaluation of archive data including GIS tools, the aerial photograph and Google Earth imagery. The selection of the techniques of preparation of inventory map is based on the goal, extent of the study area, size of the base map or aerial photograph, and hence the availability of data (Guzzetti et al., 2004).

## 2.5 Methods of Landslide Susceptibility Analysis

An area for a landslide study can be delineated using a variety of analysis approaches (Anbalagan, 1992). Both qualitative and quantitative approaches can be used for the landslide susceptibility mapping (Leori, 1997). A detailed explanation of each technique is covered below.

### 2.5.1 Qualitative (Expert Evaluation) Landslide susceptibility mapping approach

The expert evaluation method is a commonly used approach, but it relies on the expert's judgment and is more about describing the condition of a landslide using words rather than precise measurements. Qualitative methods depend on experts with field experience to assess and describe the situation (Dai & Lee, 2001). The major activities for qualitative landslide susceptibility mapping are field geomorphological analysis, landslide inventory analysis, and parameter assignment superimposition. The drawbacks of these methods are subjectivity and relying on the experience and professional background knowledge of experts. Landslide inventory mapping and heuristic method are included in this method.

**a) Landslide distribution (inventory) approach**

Landslide inventory is the simplest form of landslide that records landslide events in terms of location and dimension (Cruden, 1991). In this approach, inventory map are produced to display types of landslide movements, types of slide materials, spatial and temporal patterns of landslide distribution (Pardeshi et al., 2013). The major drawback with this approach is highly time taking. But a map which is developed based on this method can be used as a base for landslide susceptibility and hazard zonation (Kanungo et al., 2009). For example, landslide inventory maps were produced and compared for different parts of Italy (Galli et al., 2008). The result indicates that landslide inventory map provides highly predictive information for landslide susceptibility analysis.

**b) Heuristic method**

Heuristic method is a technique that is based on the experience and knowledge of the researcher. In this method, causative factor map (individual thematic map layer) is combined together to produce landslide susceptibility and hazard map (Dai & Lee, 2001)**.** The heuristic technique is based on the previous experience and knowledge of all causes and instability factors of landslide in the area under analysis. It is an indirect qualitative method that depends on how well and how much the expert comprehends the geomorphologic changes processing on the terrain (Guzzetti et al., 1999). Due to their highly subjective natures, heuristic approaches have been criticized time to time by several authors (Soeters & Van Western, 1996). Difficulty of determination of the weighting values to the input parameters is the main problem associated with this approach (Fell et al., 2008). Landslide hazard zonation map produced by different researchers on the same place employing the heuristic method are very different (Carrara et al., 1992). The hazard maps inconsistency reveals a high level of subjectivity in the decision making process.

### 2.5.2 Quantitative methods

Cangolu (2017) and Chen et al. (2019) state that there are three types of quantitative methods: statistical, physical-based, and machine learning/data mining.

#### 2.5.2.1 Statistical methods

Statistical methods are widely used to evaluate the relationship between landslide controlling variables and landslides using mathematical techniques (Chen & Wang , 2007). They are classified into multivariate and bivariate statistical methods. Reliable results are obtained using the statistical methods (Dai & Lee, 2001). Unlike the qualitative methods, the numerical methods produce results that are more dependable because they rely on the mathematical model, expression, and less on expert judgment. The statistical approach, which is one of the quantitative methodologies, is used to assess the slope instability based on the correlation between the landslide causative factors and the historical or current landslide (Carrara et al., 1992). An indirect technique known as a statistical method is used to create an objective landslide hazard/susceptibility map. It is created using an integrated GIS tool and statistical analysis based on the spatial link between the landslide and a set of landslide parameters. However, proper database development, model calibration, and iterative model validation methods are the most challenging aspects of this approach (Ercanoglu et al., 2004). This method calculates the contribution of each element and subcategory to the instability of the slope by mapping and overlaying them over historical and ongoing landslides (Girma et al., 2015). The statistical method's drawback is that it requires extensive and high-quality data on landslides and landslide factors, which can be time-consuming to gather across a wide area (Raghuvanshi et al., 2015). Where there hasn't been a landslide, the statistical approach is inapplicable. This is one of the drawbacks of using statistical techniques for risk, hazard, and landslide susceptibility mapping.

**a) Bivariate statistical analysis**

The bivariate statistical method can differentiate the effects of each sub factor class on the possibility of landslides, and it is simple to apply and update. The existence of landslides has been taken into account inside the bivariate statistical technique as they are the independent variable together with the parameters that increased the probability of landslides occurring (Shahabi & Khezri , 2013). In this method, the response of multiple factor classes to the occurrence of landslides is calculated by sub classifying each determinant map. A landslide distribution map and weighting values reflecting the landslide densities of each determinant class are frequently paired with the landslide factor classes. In order to generate the landslide susceptibility index map, the weighted raster map is precisely summed up using a raster calculator in Math algebra under the

GIS tool. In order to create the most accurate landslide susceptibility map, the hazard index map or landslide susceptibility map are frequently classed using different techniques, such as natural break under the GIS tool. Bivariate statistical approaches have the following advantages: they can give spatially distributed landslide information and its association with landslide factors; they can cover a large region at an effective cost; and they are easy to apply. However, the following is a shortcoming of the bivariate statistical methods. First, it is unable to differentiate between factors that have greater influence and those that have less. Second, unlike geotechnical methods (discussed in the following section), it is unable to provide information regarding the slope material's intrinsic conditions. Instead, it requires the occurrence of landslides in a particular area to forecast the region that is affected by a different environmental aspect. The most often used methods in bivariate statistical analysis are the load of evidence, information value, certainty factor, and frequency ratio.

**b) Multivariate statistical analysis**

Results from this approach are more accurate and realistic. Unlike bivariate statistical approaches, it additionally takes into account the mutual interaction among landslide factors. The corresponding contribution of each factor to the level of danger in a particular land unit is indicated by the weight of the causal factors. Unlike the bivariate statistical method, the multivariate statistical method assists in the performance of multivariate statistical analysis. One advantage of the multivariate approach is its ability to determine the relative influence of each landslide factor on the probability of landslides. The most often used techniques in this method are discriminant analysis, cluster analysis, and logistic regression.

#### 2.5.2.2 Physical based analysis (Geotechnical approach)

The geotechnical approach to landslide susceptibility mapping is based on the analysis of soil and rock mechanical properties that directly control slope stability. This approach relies on fundamental engineering principles, particularly the assessment of shear strength parameters such as cohesion (c), internal friction angle (φ), unit weight (γ), and pore water pressure conditions. These parameters are typically obtained through laboratory testing and field investigations, including standard penetration tests (SPT), triaxial tests, and direct shear tests. The stability of slopes is then evaluated using limit equilibrium methods (LEM), where the factor of safety (FS) is calculated to determine the likelihood of failure under given conditions (Duncan & Wright, 2005).

This approach provides a physically based and highly reliable assessment of slope stability, as it directly incorporates material behaviour and site specific conditions. However, its application at regional scale is often limited due to the requirement for detailed geotechnical data, which is costly and time consuming to obtain. Despite these limitations, integrating geotechnical parameters into spatial analysis frameworks significantly enhances the accuracy of landslide susceptibility mapping and provides valuable insights for engineering design and slope stabilization measures (Aleotti & Chowdhury, 1999).

### 2.5.3 Semi quantitative methods

Semi-quantitative methods determine the grade and weight of the effects of landslide causative factors on landslide phenomenon by combining qualitative and quantitative methods. These methods are usually applied when data is limited, uncertain, or when subjective elements need to be integrated in the decision making process. Even though some statistical concepts are applied in this method, it still depends on the expert's experience and the background of professional knowledge and some subjectivity remains. Weighted linear combination, analytical hierarchy process and expert knowledge/heuristic approaches are examples of semi-quantitative methods.

## 2.6 Previous Landslide Studies

There has been a restriction on expanding the practice toward landslide assessment and susceptibility analysis prior to the beginning of road project construction, despite the fact that numerous researchers have worked tirelessly to identify the nature, type, cause, and consequence of landslides in various parts of the country. There was a lack of detailed and methodical landslide assessment and susceptibility analysis on the majority of landslide-affected projects during the route selection and design stages. Landslides occur after construction is completed or during the roads service life, resulting in fatalities and serious damage to the road infrastructure. In general, a number of researchers thoroughly studied the landslides that happened around the whole country. The majority of research was done from a geological standpoint, and there was a lack of application of the findings to the development of appropriate engineering corrective actions.

Melese et al. (2022) and his colleagues mapped the susceptibility of the Dejen district, Ethiopia, using the Analytic Hierarchy Process (AHP), the Frequency Ratio (FR), and the Shannon Entropy (SE). A total of 87 landslides are included in the landslide inventory map produced by their study, and a total of 12 landslide factors are used to generate the landslide susceptibility map. In comparison to the other two ways, their study indicates that AHP is the most effective method.

Vařilová et al. (2014) investigated four specific Dessie town districts that were frequently damaged by landslides. They use the ArcGIS platform's digital elevation model and a high-resolution satellite picture to carry out landslide inventories. They outline the primary causes of landslides along the chosen section and come to the conclusion that, in order to prevent future landslides, engineering projects should prioritize adequate planning, the installation of suitable drainage structures, and close attention to landslide events during the design phase.

Zerihun (2016) conducted a study on the evaluation and zonation of landslide hazards in the Kindo Didayeworeda area of southwest Ethiopia. Two techniques were used in this work to zone the study region for landslide hazards: an information value model approach based on raters and an integrated slope stability susceptibility evaluation parameter. The results indicate that the most significant contributing factors for the occurrence of landslides in the studied area are human-caused slope deformation, agriculture, and modification, in addition to heavy rainfall and groundwater.

Manderso (2021) prepared the landslide hazard mapping and assessment surrounding Debre Markos town using a statistical methodology based on geographic information systems (GIS). He identified the following as controlling factors in his research: lithology, slope, aspect, elevation, curvature, land use/cover, distance to stream, and distance to fault. As per the model's outcome, the areas that fall into the very low, low, moderate, high, and very high susceptibility zones are 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) sectors, respectively.

The landslide hazard zonation of the Gilgel Gibe-II Hydroelectric Project area in South-Western Ethiopia has been examined (Mulatu et al., 2009). In particular, they investigated the newly constructed road alignment in southwest Ethiopia that connects Fofa town to the Gilgel Gibe-II powerhouse. They used the landslide hazard assessment factor rating scheme (LHEF) to evaluate this part of the road (Anbalagan, 1992). The investigation shows that 34% of the road portion is classified as moderately susceptible to landslides, 12% as lowly susceptible, and 54% of the road section as highly susceptible.

# 3. METHODOLOGY

## 3.1 Introduction

This research is mainly concerned with detailed investigation of landslide susceptibility within a specified study area, Jimma-Metu-Gore route, by using advanced techniques in both data collection and mapping. It will apply a multi-step methodology, including landslide inventory mapping, Google Earth imagery analysis, landslide factor evaluation, landslide factors thematic layer mapping, as well as landslide susceptibility mapping employing Geographic Information System (GIS). The study utilizes various datasets, including a Digital Elevation Model (DEM) with certain resolution, topographic maps, geological maps, and meteorological data, collected from reputable sources such as the Geological Survey of Ethiopia (GSE), Google Earth imagery from NASA, the Ethiopian National Meteorological Agency and for primary date field survey is executed.

In this study, the overall approach uses a combination of primary (field) and secondary data, GIS processing, factor selection and preparation, objective weight derivation using the Criteria Importance Through Inter-criteria Correlation (CRITIC) method, raster combination by Weighted Linear Combination (WLC) and model validation using overlay method. The approach is semi quantitative where factor maps are prepared and normalized quantitatively. The CRITIC method supplies objective weights derived from the factor data statistics, reducing potential expert bias while keeping the modeling transparent and reproducible.

## 3.2 Desk Study (Pre-field activity)

A detailed desk study was conducted prior to the onsite investigation and primary data collection for the Jimma-Metu-Gore route. This initial phase aimed to identify and characterize landslide-prone areas along the route and to provide a foundation for field verification. In order to reinforce the process, technical support was obtained from the regional district office of the Ethiopian Roads Authority (ERA). The collaboration facilitated access to critical background information, and ensured all significant landslides along the transportation corridor were addressed during the study.

Key components of the desk study included:

- Preparation of a landslide inventory using Google Earth imagery and historical records.
- Identification of specific locations where landslides have occurred.
- Classification of expected landslide types (e.g., rotational slide, debris flow, rock fall, etc.).
- Assessment of the possible causes of each landslide, such as heavy rainfall, slope angle, deforestation, or road cuts.
- Year of occurrence (where available), helping to understand temporal patterns or triggers.
- Land use/land cover mapping of hazard-prone areas to examine the role of human activities or vegetation cover in slope stability.

## 3.3 Data Collection (Field and Post Field Activities)

### 3.3.1 Primary Data Collection (Field Activity)

Onsite investigation and data collection were performed. The technical assistant (assigned senior engineer for the route) from ERA was also involved to help in locating the exact places of the LS hazards and in providing information on the history and remedial measures taken on each of the landslides.

Landslide inventory mapping proceeded by recording location (GPS coordinate in UTM Zone 37N), type (rotational, translational, lateral spread, etc.), material, slope position, age of the landslide (if known) and remedial measures that have been already taken. Each inventory point includes a unique ID and photographs showing images of failure surfaces. General visual material characterization proceeded by taking in situ notes on soil type (clay, loam, sand).

Data was collected by using Unstable Slope Management Program (USMP) slope rating form which is prepared by Alaska University transportation center. This field investigation and data collection was performed with the aim of gaining information about the current landslide activities and additionally to verify various thematic factor maps prepared following the field works.

### 3.3.2 Secondary Data Collection (Post Field Activity)

All secondary data were collected and organized from widely employed authorized sources and used as the inputs to GIS processing. The first one is Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) dataset, with a spatial resolution of 30 meters, provided by the United States Geological Survey (USGS). It is used to derive elevation, slope angle, slope aspect, curvature, and proximity to lineaments and streams maps.

Satellite imagery Landsat 8 OLI (30 m) was collected and used for supervised LULC classification and visual interpretation. National geological map prepared by GSE (Geological Survey of Ethiopia) was digitized for geological units. The 20 years rainfall data at three different stations on the study route (Jimma station, Bedele station and Gore station) is collected from Ethiopian Meteorology Institute. The data was digitized and interpolated to acquire areal rainfall data of the study area.

All thematic factor maps were resampled to a common 30 m cell size, projected to UTM Zone 37N, converted to floating point and normalized to the 0–1 range using min–max scaling. Categorical maps (geology, LULC) were reclassified into susceptibility scores (1-5) prior to normalization. Objective weights were obtained using the CRITIC method which combines standard deviation and inter-criteria correlation, (Diakoulaki et al., 1995). These weights were applied in a Weighted Linear Combination (WLC) to compute the Landslide Susceptibility Index (LSI). The continuous LSI was classified by Natural Breaks into five susceptibility zones and validated against the landslide inventory.

## 3.4 Criteria Importance Through Inter-criteria Correlation (CRITIC) Weighting Method

The CRITIC method was first proposed by Diakoulaki which is a statistical approach designed to identify objective weights of evaluation criteria by taking consideration of both the degree of contrast within each factor and the conflict that arises among criteria. CRITIC determines its weights, unlike purely subjective methods, straight from the structure of the decision matrix, hence minimizing bias invited by expert judgments.

The very first step involves constructing decision matrix and normalization of it, where each element represents the standardized value of alternative (landslide station) *i* under causative factor

$j$. Then vectors $r_{ij}$ are generated from this matrix with each vector having the normalized scores of all alternatives for factor $j$.

$$r_{ij} = \frac{x_{ij} - \min(x_j)}{max(x_j) - \min(x_j)} \quad [3\text{-}1]$$

Standard deviation $\sigma_j$ of each vector is then calculated, which measures the variability of factor $j$ across alternatives.

$$\sigma_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (r_{ij} - \bar{r}_j)^2} \quad [3\text{-}2]$$

Where $r_{ij}$: the normalized value of alternative i for factor j; $\bar{r}_j$: the mean of the normalized values for factor j; n: the total number of alternatives (landslide points). A greater value of $\sigma_j$ indicates that the factor have greater importance in the decision making process.

Moreover, CRITIC also takes the interdependence between criteria into consideration by calculating the linear correlation coefficient between every pair of criteria. A correlation matrix is constructed having symmetric nature, where the generic element $l_{jk}$ related to the correlation coefficient between factor $j$ and factor $k$.

$$l_{jk} = \frac{\sum_{i=1}^{n}(r_{ij} - \bar{r}_j)(r_{ik} - \bar{r}_k)}{\sqrt{\sum_{i=1}^{n}(r_{ij} - \bar{r}_j)^2}\sqrt{\sum_{i=1}^{n}(r_{ik} - \bar{r}_k)^2}} \quad [3\text{-}3]$$

The value of $l_{jk}$ indicates the extent of similarity between the two criteria. The closer the value of $l_{jk}$ is to 1, the higher the correlation, and the closer it is to 0, the lower the relationship. Therefore, regarding to weighting strongly correlated criteria give redundant information and should be assigned to relatively less weight.

The conflict or independence of factor $j$ with respect to the entire decision problem is quantified by the formula

$$C_j = \sigma_j \sum_{k=1}^{m}(1 - l_{jk}) \quad [3\text{-}4]$$

Where $C_j$: the information content of factor $j$; $\sigma_j$: standard deviation of factor j; $(1 - l_{jk})$: introduces the degree of conflict between factor $j$ and the other criteria. Thus, a factor will be more important if it has both a greater internal variability (large $\sigma_j$) and lesser redundancy with other criteria (low correlations).

Finally, the objective weights are obtained by normalizing the information content values across all criteria by the expression

$$w_j = \frac{C_j}{\sum_{j=1}^{m} C_j} \quad [3\text{-}5]$$

Where $w_j$: the weight of factor $j$, ensuring that the sum of all weights equals one.

Through this steps, the CRITIC method delivers weights in a completely data driven method, considering both the contrast of each factor and its independence from others. This makes it specifically suitable for Multi Criteria Decision Making (MCDM) problems such as landslide susceptibility mapping, where simultaneous evaluation is needed for multiple interrelated factors.

# 4. LANDSLIDE ASSESSMENT AND INVENTORY MAPPING

## 4.1 Description of the Study Area

### 4.1.1 Location of the Road Section

The Jimma-Metu-Gore route, which is approximately 278 km in length, passes through several woredas of Jimma and Illubabor Zones of the Oromia Regional State as shown in Figure 4-1. The road stretches from Jimma east through Limmu Kossa Woreda, cutting across various terrains and fertile agricultural land to Bedele, about 139 km from Jimma. It passes through intensive coffee plantation and other agricultural lands. It cuts through the rich agricultural parts of the Didessa River Basin. From Bedele, it proceeds southwest towards Metu and Gore via Chora, Dega, and Yayo Woredas. This road is important to connect the rural communities, markets, and agricultural hubs, but varying topography and climate present continuous engineering and maintenance challenges.

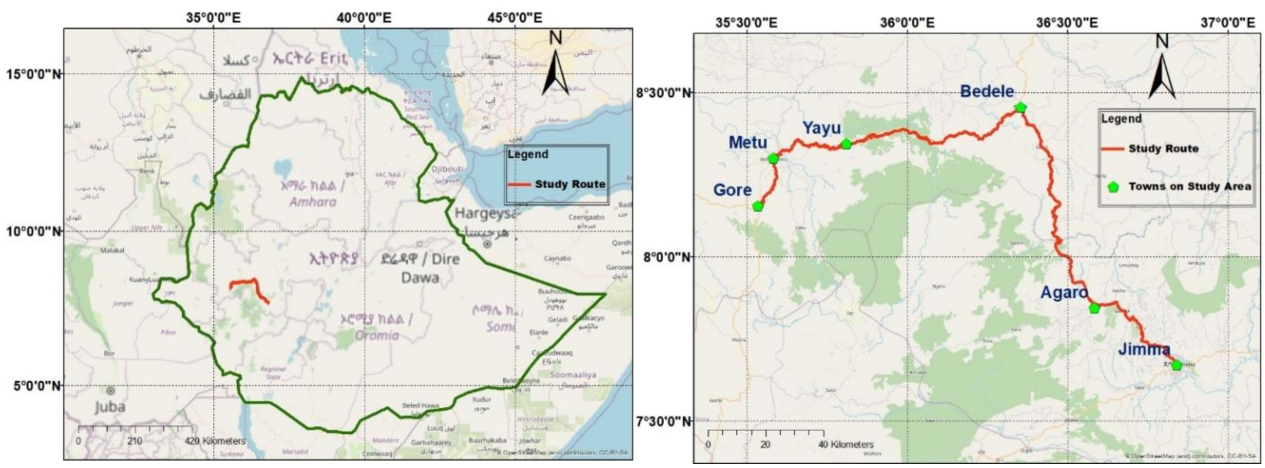



Figure 4-1: Location map of the Jimma-Metu-Gore route

### 4.1.2 Topography

The topography of the Jimma-Metu-Gore route is characterized by diverse and complex landscapes, typical of the south-western highlands of Ethiopia. The elevation along the route ranges from approximately 1213meters above mean sea level (a.m.s.l.) near Jimma and reaches 2481 meters a.m.s.l. in the more mountainous areas near Metu as shown in Figure 4-2.

Regarding to the slope exhibited by the route, it approximately ranges from 0 to 65 degrees as shown in Figure 4-3. As the journey starts from Jimma, the terrain is primarily composed of rolling hills in the lower elevations, with slopes ranging from 5 to 15 degrees, which gradually become steeper as the road ascends. As the road progresses, the topography becomes more rugged, with steep slopes ranging from 15 to 35 degrees, especially in forested areas near Yayo and Gore. These regions are characterized by undulating hills, dense forests, and deeply incised valleys, often influenced by the Baro and Didessa River Basins. The elevation fluctuations and steep slopes contribute to frequent soil erosion and landslide risks, particularly in the higher, densely forested areas. Overall, the varying topography along the route, from rolling hills to steep, forested highlands, presents significant challenges for road construction and maintenance, requiring careful consideration of slope stability and drainage systems.

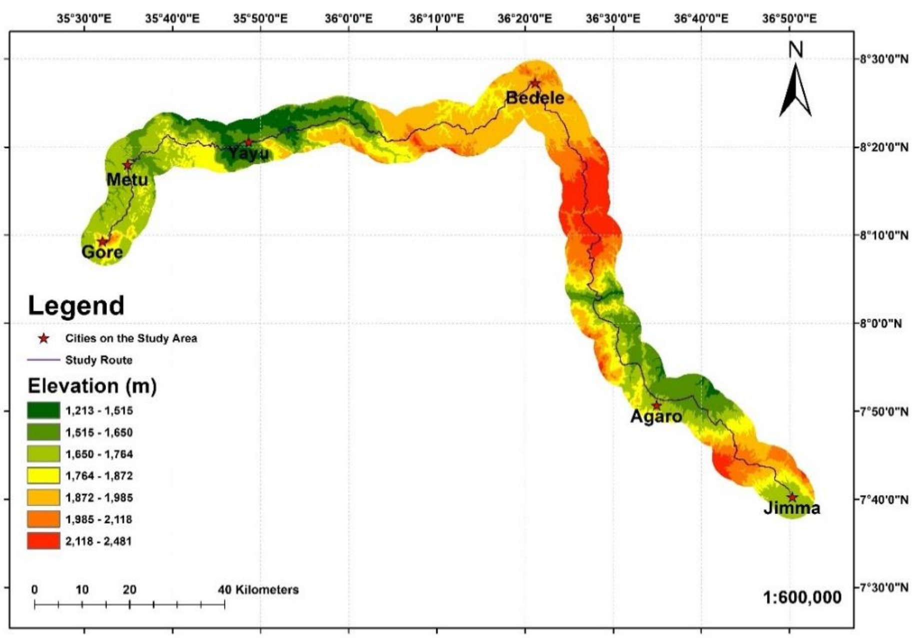



Figure 4-2: Elevation map of the study area

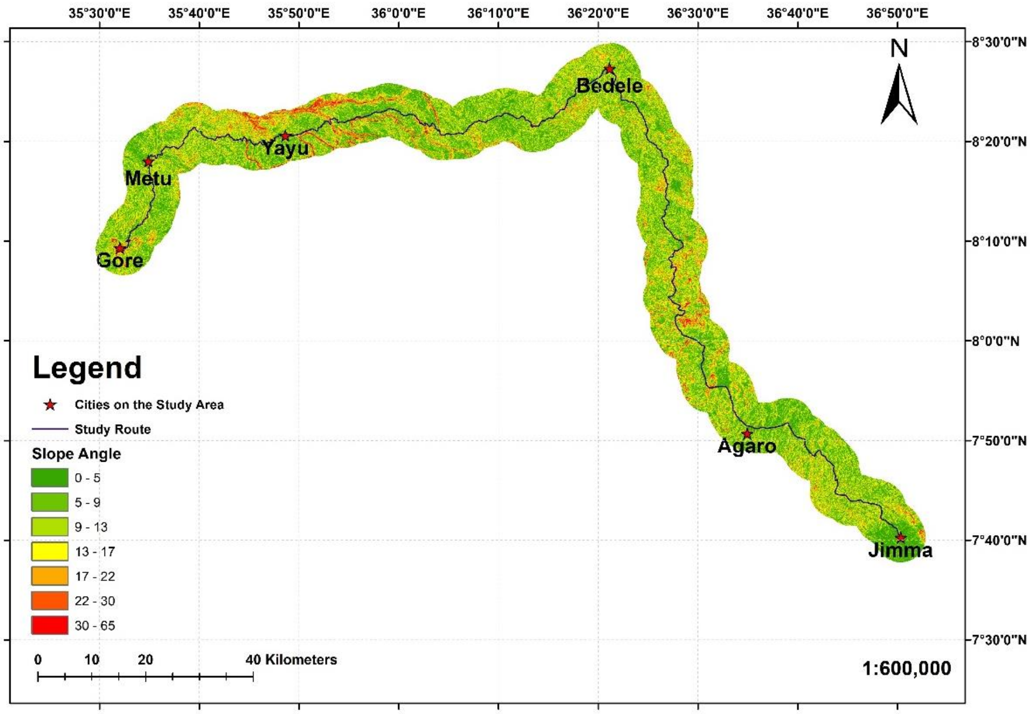



Figure 4-3: Slope map of the study area

### 4.1.3 Geomorphology

The Jimma-Metu-Gore road cuts through one of Ethiopia's most varying landscapes, shaped by ancient volcanic eruptions, tectonic movements, and the relentless forces of nature over long period of time. This region displays a fascinating mix of landforms that shows the earth's shifting crust and natural processes. Alluvial landforms along the Jimma-Metu-Gore route are evident in the low-lying river valleys, where sediment deposition occurs from tributaries. These areas can be identified by layers of fine sediment, such as sand, silt, and clay, deposited during periodic river flooding. Moreover, alluvial fans (a triangle shaped deposit of earth materials) are observed at the base of highland slopes, where materials transported from higher elevations spread out in fan-shaped deposits, particularly in valleys descending from the highlands. These alluvial features illustrate the role of fluvial processes in shaping the local landscape, contributing to soil fertility and influencing land use patterns along the route (Kazmin, 1972).

This route is formed over landscapes born from volcanic activity. Lava flows of basalt and trachyte shaped much of the rugged terrain. These volcanic ridges and highlands create the undulating landscape, especially as approached to Metu and Gore, where the rocky, elevated terrain is a direct result of these ancient eruptions. However, the land here isn't just shaped by volcanic activity. It's also been molded by the slow, powerful movements of the earth's crust. Even though this area lies just outside the Main Ethiopian Rift, tectonic forces have still played a major role. Passing through the region, particularly near Jimma, flatter valleys surrounded by hills can be seen. These are grabens, depressions formed by faults where the land has sunk between two cracks in the earth's crust. These structural features add to the variety of the landscape, giving way to both flat areas and hilly, undulating terrain as you move along the road (Abbate et al., 2015).

Moreover, wind, rain, and erosion have transformed the landscape into steep, rugged slopes, particularly near Metu. Here, the land has been worn down by constant weathering, leaving behind deep valleys and sharp ridges. This process of denudation, where rock and soil are stripped away, has created the dramatic scenery that makes this region so visually striking. These steep, well-drained slopes, shaped by the forces of erosion, offer spectacular views of the surrounding highlands. In some areas, especially as you near Gore, the landscape becomes dotted with rocky outcrops and small hills. These residual landforms are what's left after years of weathering have worn down softer materials, leaving behind harder rocks like basalt. These scattered features are reminders of the region's ancient geological history (Abbate et al., 2015).

### 4.1.4 Climate

As per the data collected from Ethiopian Meteorology Institute, the annual rainfall along the study route within 20 years (2003 GC to 2022 GC) is presented graphically at three locations (Jimma, Bedele and Gore) as shown in Figure 4-4. The average annual rainfall of Bedele is 1748.86 mm followed by Gore is 1640.76 mm. the average annual rainfall of Jimma which is 1518.87 mm displaying the least recording in comparison with the other two locations.

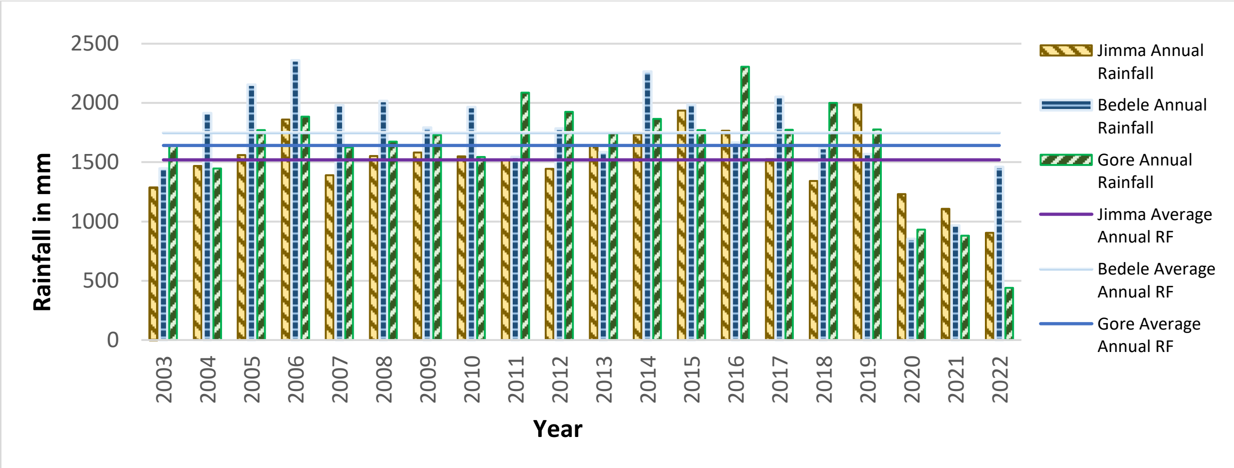
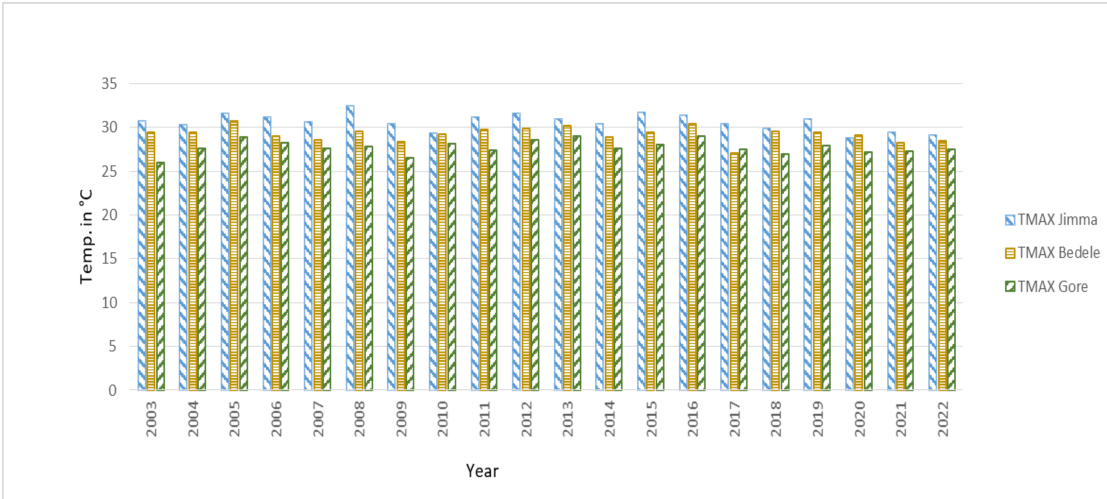



Figure 4-4: Annual rainfall of Jimma, Bedele and Gore (2003 - 2022G.C)

Based on the data collected by the Ethiopian Meteorology institute for consecutive 20 years, the maximum and minimum recorded temperature at three locations of the study route, (Jimma, Bedele and Gore), is presented graphically in Figure 4-5. It can be seen that the maximum temperature recorded at Jimma exceeds 32.5 °C whereas in Bedele and Gore the maximum temperature reach up to 30.7 °C and 29 °C respectively. The minimum temperature recorded at Jimma is 2.7 °C which makes it the lowest value among the cities that is 10.9 °C and 12.8 for Bedele and Gore is respectively.

a)




b)

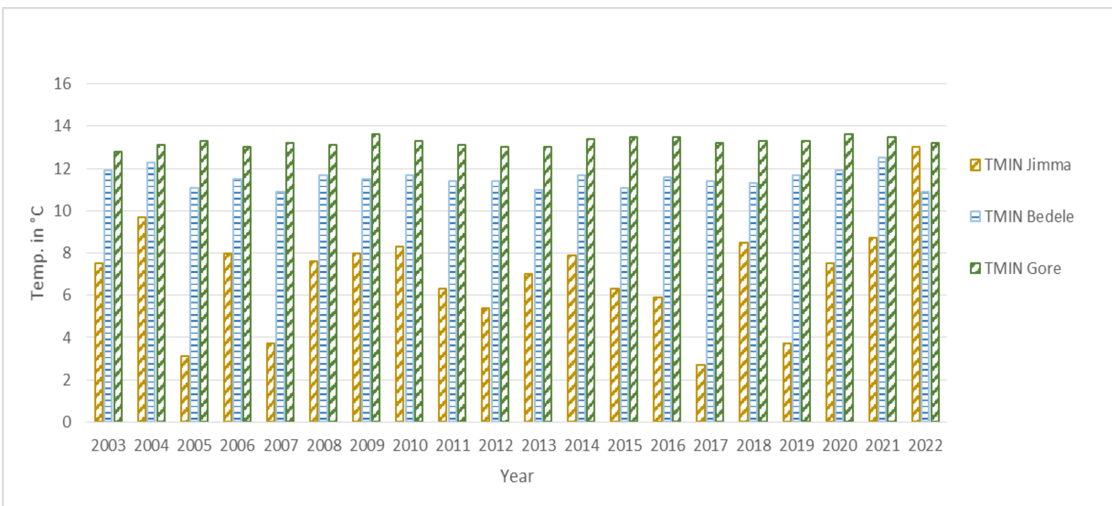



Figure 4-5: a) Maximum temperature recorded, and b) Minimum temperature recorded at Jimma, Bedele and Gore (2003 - 2022G.C)

## 4.2 Assessment of Landslides

The assessment of each the landslides located along the study route is presented as follows. Dedesa River is considered as the reference starting point (0+000) for the landslide stations.

### 4.2.1 Landslide at Station 36+720

*Coordinate: 8°16'43"N, 36°26'36"E*

*Local name of location: Gechi/ Bido Doma*

*Elevation: 2197 m*

**Description**

The landslide at this location occurred near the Gechi area, which exhibits a moderately steep slope of 35 degrees. The failure developed across the road alignment, with the crown positioned on the edge of the road, and the road way is partially damaged as shown in Figure 4-6. The type of landslide is rotational landslide extending across an estimated 75 meters in length along the road.

The event took place for extended period of time but the road was out of function during the 2018 - 2019 GC rainy seasons. Even though a detour path was developed as a remedial measure, the new alignment has also shown signs of instability. The area is predominantly red clay soil, which has low shear strength and high swelling and shrinking material property making it particularly vulnerable to saturation and failure during periods of intense rainfall.

Poor drainage and surface water accumulation are likely contributors to slope instability during wet seasons. The landslide exhibits a main scarp near the slope crest, with displaced materials moving downslope and minor scarps are also present.

A change of route with detour development was implemented to avoid the affected section as shown in Figure 4-7. While this measure temporarily solved the issue, the new path became completely out of service due to wet season. The old road way is currently giving service with twice a year maintenance at the landslide affected section.

Figure 4-6: Land slide at 36+720 (Gechi)


Figure 4-7: Existing and new detour roadways at 36+720 (Gechi) [Source – Satellite Image by Google Earth]

### 4.2.2 Landslide at Station - 44+000

*Coordinate - 8°21'31"N, 36°03'03"E*

*Local name of location: Hawa Yemobir/Sololo*

*Elevation - 1621 m*

**Description**

This landslide is located in the dense natural woods of Yayo Forest with a formation of gentle slope of approximately 20 degrees. The failure crosses the road alignment, with the main crown observed approximately 50 meters distance from the edge of the road. The landslide is very old and it has a translational sliding type of failure. The landslide affected about 450 meters of the road. The area is covered with natural forest and coffee cultivation. The site requires twice or more annual maintenance due to the active instability and repeated failure. The failed material consists of red clay, which has swelling and shrinkage characteristics depending on seasonal moisture fluctuation. These properties, combined with surface runoff, reduce the overall slope stability, and in the rainy seasons, there will be much water infiltration that weakens the clay rich material.

The landslide features a broad crown and scarp, with downslope movement. The ground is susceptible to seasonal reactivation, particularly during periods of high rainfall, making continuous maintenance necessary.

The primary cause is uncontrolled surface water runoff during the rainy season. To address ongoing movement, a gabion retaining system was installed, but this by itself is moving downslope with the failure material as shown in Figure 4-8 and Figure 4-9. The area still demands twice yearly maintenance, indicating that the current intervention only reduces the extent of failure.

Figure 4-8: Land slide at 44+000 (inside "Yayo Forest")

Figure 4-9: Landslide affected road section at 44+000 (inside "Yayo Forest") [Source – Satellite Image by Google Earth]

### 4.2.3 Landslide at Station - 44+800

*Coordinate:* 8°21'46"N, 36°02'45"E

Local name of location: Yembo

*Elevation:* 1570 m

**Description**

This landslide happened along the road section at Yembo as shown Figure 4-10, forming a moderately gentle slope of 20 degrees. The landslide is categorized as a translational slide which is occurring across the route. The land cover of the environment is dominated by natural forest and coffee cultivation.

This phenomenon has a long age, and is currently active with wide visible cracks on the pavement, and even damaging the whole cross section at some part of the failure zone, causing delays for travellers. Additionally, there is accumulated slide material beside the road and the failure affected route section reaches approximately 80 meters as shown in Figure 4-11, impacting accessibility and road safety.

The failure region is composed of clay loam soil which have material characteristics that tends to retain moisture and has moderate cohesion. Clay loam soil can become unstable when saturated which is contributing to the failure during seasonal fluctuations. The surface water management of the site is poor that aggravates the incidence of failure combined with nature of the natural material.

The damaged area has been repeatedly refilled with selected material as a treatment as well as the pavement is reconstructed. But the failure is being encountered redundantly and the site requires once up to two times annual maintenance, showing the continuous occurrence of the failure and partial effectiveness of the remedial measure.

Figure 4-10: Land slide at 44+800 (Yembo)


Figure 4-11: Landslide affected road section at 44+800 (Yembo) [Source – Satelite Image by Google Earth]

### 4.2.4 Landslide at Station - 46+920

*Coordinate: 8°21'47"N, 36°02'06"E*

*Local name of location: Yembo (Near Geba River)*

*Elevation: 1523 m*

**Description**

This landslide happened at the location named Yembo and it is one of the most severely damaging landslide along the study route due to the extreme steep slope formed by the failure which is nearly vertical orientation close to 90 degrees as shown in Figure 4-12. It can be categorized as a rotational landslide and it occurred across the route. The failure zone spans approximately 40 meters. The surrounding land is covered by natural forest and coffee cultivation.

The failure begins approximately 30 m above the edge of the road. The failure material is reddish brown loam with problematic property and underneath highly weathered rock combined with the slope steepness and saturation, becomes highly unstable. Heavy rainfall and existence of high discharge spring water upstream the route have contributed to internal erosion, weakening the slope material and triggering repeated failure events.

The landslide is very old and is still active. Even though the section has been treated repeatedly, the refilled material continues to fail bringing serious challenges to road safety and stability. To repair the damaged section of the road, various expensive remedial measures were taken. These are, large volume of selected fill material was applied at downstream side of the road as a construction of embankment to widen the passage way. The mountain above the roadway was also demolished to some extent for the same purpose as shown in Figure 4-13. Additionally, box culvert was built in order to give passage way for the upstream spring water. However, redundantly occurrence of the landslide indicates that the mitigation measures taken have only been partially effective, indicating that further investigation and improvement in stabilization techniques are still necessary.

Figure 4-12: Land slide at 46+920 (Yembo) before any remedial measure taken [Source – historical pictures of onsite investigation by ERA engineers]


a) Large volume of selected fill material application downstream of the roadway

b) The demolished mountain above the roadway to widen the passageway

Figure 4-13: Land slide at 46+920 (Yembo)


Figure 4-14: Landslide affected road section at 46+920 (Yembo) [Source – Satellite Image by Google Earth]

### 4.2.5 Landslide at Station – 48+800

*Coordinate: 8°22'41"N, 36°01'22"E*

*Local name of location: Achebo/Dawe*

*Elevation: 1536 m*

**Description**

This landslide is found at Achebo/Dawe, occurring along a section where the slope steepness is approximately 75 degrees within 5 to 10 meters downslope from the road edge as shown in Figure 4-15. The failure can be classified as a translational slide taking place below the route. The surrounding region is covered with natural forest and coffee cultivation.

The phenomenon at this location has long age and the failure extends over an estimated 160 meters beginning at the road's downslope edge as shown in Figure 4-16. The slope material consists of clay loam with non-plastic (NPL) characteristics, a composition that lacks cohesion when saturated and is particularly prone to movement during the rainy season. The steepness of the terrain and the weak moisture sensitive soil aggravates the landslide activity.

There are small streams on both sides of the failure zone which might indirectly contribute to continuous moisture infiltration elevating pore water pressure which maximize the opportunity of slope failure.

The only remedial measure taken so far has been localized treatment of the failed road section, which couldn't solve the redundantly occurring translational slide. The site has been investigated by a private geotechnical consulting firm and the solution provided was construction of pile foundation anchored to the bedrock. But the budgeting construction process is not started yet.

Figure 4-15: Land slide at 48+800 Achebo/Dawe

Figure 4-16: Landslide affected road section at 48+800 [Source – Satellite Image by Google Earth]

### 4.2.6 Landslide at Station - 49+000

*Coordinate: 8°22'44"N, 36°01'10"E*

*Local name of location: Achebo/Dawe*

*Elevation: 1566 m*

**Description**

This landslide is located at the same place of the preceding landslide named Achebo in less than 300 m difference. The failure occurred along a section of road where the slope reaches a steep angle of approximately 80 degrees as shown in Figure 4-17. The failure can be identified as a rotational landslide occurring across the route, in a landscape covered with dense bushes and natural forest, which makes it difficult for clear observation of the landslide features.

The hazard is very old and it repeatedly removed the entire pavement in the affected area. Even after maintenance reconstructions, the newly paved road surface is lost within a few months proving the persistent and aggressive nature of the failure. The total affected length is estimated to be around 250 meters which is highly compromising road functionality and accessibility as shown in Figure 4-18.

A river approximately 300 meters from the hazard site may have indirect impact to the failure by potentially influencing subsurface moisture conditions. The slope is composed of red clay that becomes unstable under saturation. The influence of rainfall in combination with the material properties highly contribute to the failure and continuous earth movement.

As a remedial measure, repeated pavement and roadbed reconstruction at the damaged section is executed. However, these efforts have not solved the core problem and the area continues to experience active failure proving that the need for a more permanent engineering intervention.

Figure 4-17: Land slide at 49+000 Achebo/Dawe

Figure 4-18: Landslide affected road section at 49+000 (Achebo/Dawe) [Source – Satellite Image by Google Earth]

### 4.2.7 Landslide at Station 65+000

*Coordinate: 8°22'12"N, 35°53'43"E*

*Local name of location: Witate*

*Elevation: 1357 m*

**Description**

This landslide is located at a place called Witate, occurring on the convex side of a curved section of the road as shown in Figure 4-19. The slope in this area is steep with an angle of approximately 60 degrees. The affected stretch of the road is approximately 120 meters in length. The failure can be categorized as a rotational landslide occurring across the route in a region covered by natural forest and coffee cultivation.

The slope material is loam soil, known for being sensitive to moisture fluctuation. The variable saturation and drying conditions weaken the soil structure triggering mass movement during wet seasons. A stream flowing at the toe of the slope may have indirect contribution for the slope saturation and instability aggravating the occurrence of failure.

The landslide developed between 2016 and 2018 G.C. and remains active. Huge bulging of the pavement surface is present, although difficult to clearly show in images, Figure 4-20. It can cause danger for the passengers using the route. It is obvious that it only needs time to completely affect (destroy) the path way. As it gets more time, the failed mass continuously pushes the pavement downslope, creating hazard to the road functionality.

Remedial measures applied so far include construction of a gabion retaining wall and refilling of damaged sections. Additionally, the pavement gets renewed time to time. Even though the remedial measure gives temporary solution for the roadway functionality, there should be major mitigation project to permanently solve the recurrent failure problem.

Figure 4-19: Land slide at 65+000 Witate

Figure 4-20: Landslide affected road section at 65+000 (Wutate) [Source – Satellite Image by Google Earth]

### 4.2.8 Landslide at Station - 66+100

*Coordinate: 8°22'12"N, 35°53'20"E*

*Local name of location: Witate*

*Elevation: 1352 m*

**Description**

This landslide occurred in Witate, along a curved section of the road on the convex side as shown in Figure 4-21. It has a moderately steep slope angle of approximately 45 degrees and the failure can be categorized as a rotational landslide. The affected length of the road extends for about 100 meters. The landslide crosses the entire width of the road and damages the pavement repeatedly creating hazardous conditions for passengers bringing delays and safety threats for very long age. Moreover, the failure is powerful enough to displace trees and even distance indicator concrete poles downslope.

The landslide composition material is brown coloured sandy loam soil, which has low cohesion and becomes unstable under high moisture content. The land cover is predominantly natural coffee plantation and natural forest and there are spring water and a river below the route as shown in Figure 4-22. Instability is aggravated during rainy seasons due to surface water infiltration and a rise in groundwater level which contributes to saturation and increased pore pressure within the soil mass.

Previous remedial efforts included backfilling the failed region and repairing the pavement, but the failure keeps coming redundantly. The site reportedly requires maintenance more than four times annually showing that it’s high recurrence rate and needs to be solved permanently with costly project.

Figure 4-21: Land slide at 66+100 Witate


Figure 4-22: Landslide affected road section at 66+100 (Wutate) [Source – Satellite Image by Google Earth]

### 4.2.9 Landslide at Station - 85+550

*Coordinate: 8°19'42"N, 35°45'35"E*

*Local name of location: Hurumu/Gaba*

*Elevation: 1514 m*

**Description**

This landslide is observed in the road section at Hurumu/Gaba along a terrain with a gentle slope angle of approximately 25 degrees as shown in Figure 4-23. It is categorized as an earth flow failure type of landslide that occurs across the road affecting both the pavement and its accessibility. The failure starts about 100 meters above from the road with approximately 140 meters of an affected part of the road as shown in Figure 4-24. The site has been experiencing failure since 2020 GC and the condition continued to current time due to uncontrolled surface water and poor drainage management in the area.

The failure zone is consisted with a material black cotton soil known for its high expansiveness and instability with seasonal moisture fluctuation. This type of soil tends to flow easily once it becomes wet contributing significantly to the landslide during rainfall seasons. Some part of the pavement even deteriorated due to collective factor of the localised material type and moisture fluctuation. The surrounding area is dominated by cultivated agricultural fields and animal grazing lands which may disturb the natural soil structure and facilitate erosion.

Remedial measures previously applied include removal of the deposited slide material on the road and the construction of a retaining structure. However, the redundant occurrence of the failure suggests that these measures only partially address the causes and that more effective and permanent solutions should be considered.

Figure 4-23: Land slide at 85+550 Hurumu/Gaba

Figure 4-24: Landslide affected road section at 85+550 Hurumu/Gaba [Source – Satellite Image by Google Earth]

### 4.2.10 Landslide at Station - 201+700

*Coordinate: 8°09'16"N, 35°32'36"E*

*Local name of location: Gore*

*Elevation: 1992 m*

**Description**

This landslide occurred at the entrance of Gore town forming a steep slope failure. Figure 4-25 and Figure 4-26 show the location and nature of this landslide. The failure zone lies below the road and its type can be categorized as rotational landslide. It cuts off of the carriage way and formed part of the pavement as its crown. The incident happened suddenly in 2020 G.C. destroying approximately half of the road width. This has left only a single lane open to traffic, resulting in serious risks and traffic delays. The road section affected by this failure extends about 120 meters in length.

The slope material consists of red clay soil which has poor strength characteristics. The surrounding land cover is dense with bushes and woods, and a river flows downstream from the failure zone, potentially increasing subsurface saturation and affects the stability of the slope.

No formal remedial measures have been taken so far leaving the road vulnerable to further damage. Due to the hazardous nature of the slope material type, and presence of uncontrolled surface and subsurface water, this site requires significant engineering intervention and budget to ensure long term stability and road safety.

Figure 4-25: Land slide at 201+700 (Gore)


Figure 4-26: Landslide affected road section at 201+700 (Gore) [Source – Satellite Image by Google Earth]

## 4.3 Summary of Primary Data Collection

The primary data collected during the site visit provide a clear overview of the spatial distribution, geometric characteristics, and types of slope failures along the study route. A total of ten landslide locations were identified between stations 36+720 and 201+700, with coordinates recorded for precise positioning. As summarized in Table 4-1, the observed failures vary in orientation, occurring either below, across, or above the roadway, indicating that both cut and fill slopes, as well as natural hillsides, contribute to instability. The length of the affected road sections ranges significantly from 40 m to 450 m. Slope angles also show wide variability, from gentle slopes of about 20° to extremely steep conditions, which strongly influence the failure mechanisms. In terms of landslide types, rotational and translational slides dominate the area, with occasional occurrences of translational slides and an earth flow, suggesting differences in soil composition, structure, and moisture conditions.

Table 4-1: Primary data collected during site investigation

| Station | Latitude | Longitude | Orientation | Length of Affected Road (m) | Slope angle (º) | Type |
|---|---|---|---|---|---|---|
| **36+720** | 8°16'43"N | 36°26'36"E | Below the road | 75 | 35 | Rotational |
| **44+000** | 8°21'31"N | 36°03'03"E | Across the road | 450 | 20 | Translational |
| **44+800** | 8°21'46"N | 36°02'45"E | Across the road | 80 | 20 | Translational |
| **46+920** | 8°21'47"N | 36°02'06"E | Across the road | 40 | nearly 90 | Rotational |
| **48+800** | 8°22'41"N | 36°01'22"E | Across the road | 160 | 75 | Translational |
| **49+000** | 8°22'44"N | 36°01'10"E | Across the road | 250 | 80 | Rotational |
| **65+000** | 8°22'12"N | 35°53'43"E | Across the road | 120 | 60 | Rotational |
| **66+100** | 8°22'12"N | 35°53'20"E | Across the road | 100 | 45 | Rotational |
| **85+550** | 8°19'42"N | 35°45'35"E | Above the road | 140 | 25 | Earth flow |
| **201+700** | 8°09'16"N | 35°32'36"E | Below the road | 120 | nearly 90 | Rotational |

## 4.4 Landslide Inventory Mapping

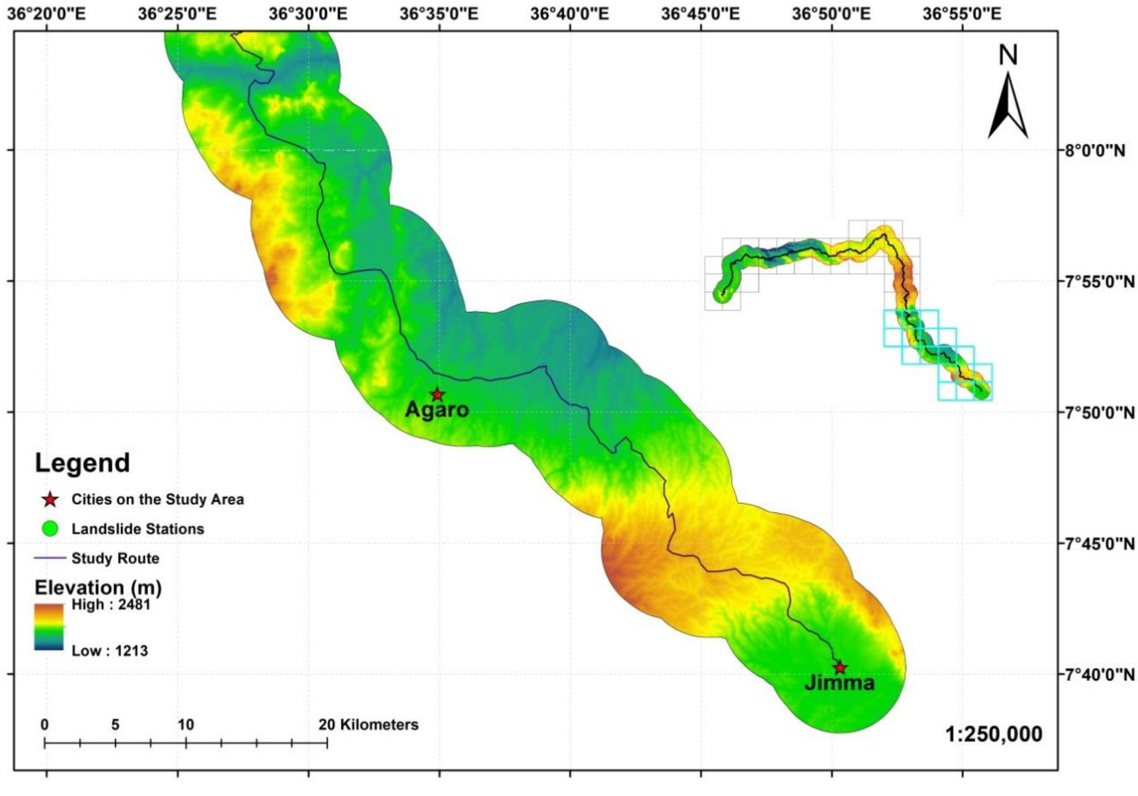
Landslide inventory mapping is a critical step in landslide susceptibility study since it provides the starting data needed to understand the spatial distribution of past and existing slope failures. Quality landslide inventory can be used as both a primary dataset for modelling and a reference data for validating the final susceptibility map. As explained by Guzzeti et al. (2012) and Rossi et al. (2010), the reliability of any susceptibility analysis highly depends on the quality and completeness of the inventory, as it shows the actual conditions that have led to slope instability in the past.

In this study, a brief landslide inventory was demonstrated to identify landslide occurrences along the Jimma-Metu-Gore transportation route covering different geological, geomorphological, and climatic conditions. The inventory was obtained by implementing a combination of primary and secondary data sources to achieve spatial precision and temporal comprehensiveness. Primary data were collected by extensive field surveys, during which active and dormant landslides were mapped. To obtain secondary data, interpretation of high resolution satellite imagery (Google Earth) as well as referencing road maintenance records was conducted.

GIS environment (ArcGIS software) was used to perform the mapping process, where individual landslide points were placed to identify their exact location. Each landslide point was georeferenced and attributed with key information such as elevation, ground material type, land use, and proximity to streams and springs.

In total, 10 landslides were identified and mapped along the Jimma-Metu-Gore corridor, covering an approximate cumulative area of 2306.48 $km^2$ as shown in Figure 4-27. These include a variety of failure types such as rotational slides, translation slides and earth flows. The landslides are unevenly distributed along the route with higher concentrations observed in weak lithology, high rainfall and poor surface drainage management.

The final landslide inventory provides the base for the susceptibility modelling by establishing the relationship between landslide occurrence and thematic factors. Additionally, it plays a vital role in validating the Landslide Susceptibility Index (LSI), enabling a direct comparison between high risk zone predictions and existing/historical failures.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Cities on the Study Area
Landslide Stations
Study Route
Elevation (m)
High : 2481
Low : 1213
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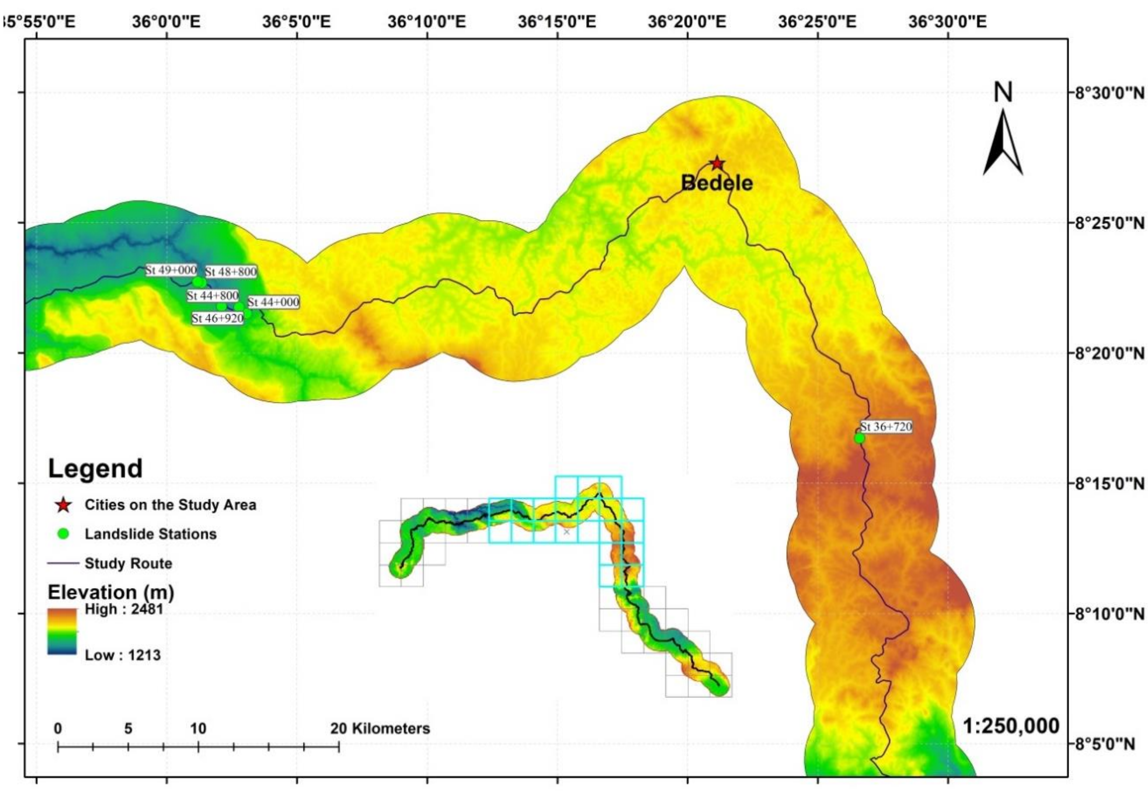
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Bedele
St 49+000
St 48+800
St 44+800
St 44+000
St 46+920
St 36+720
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Cities on the Study Area
Landslide Stations
Study Route
Elevation (m)
High : 2481
Low : 1213
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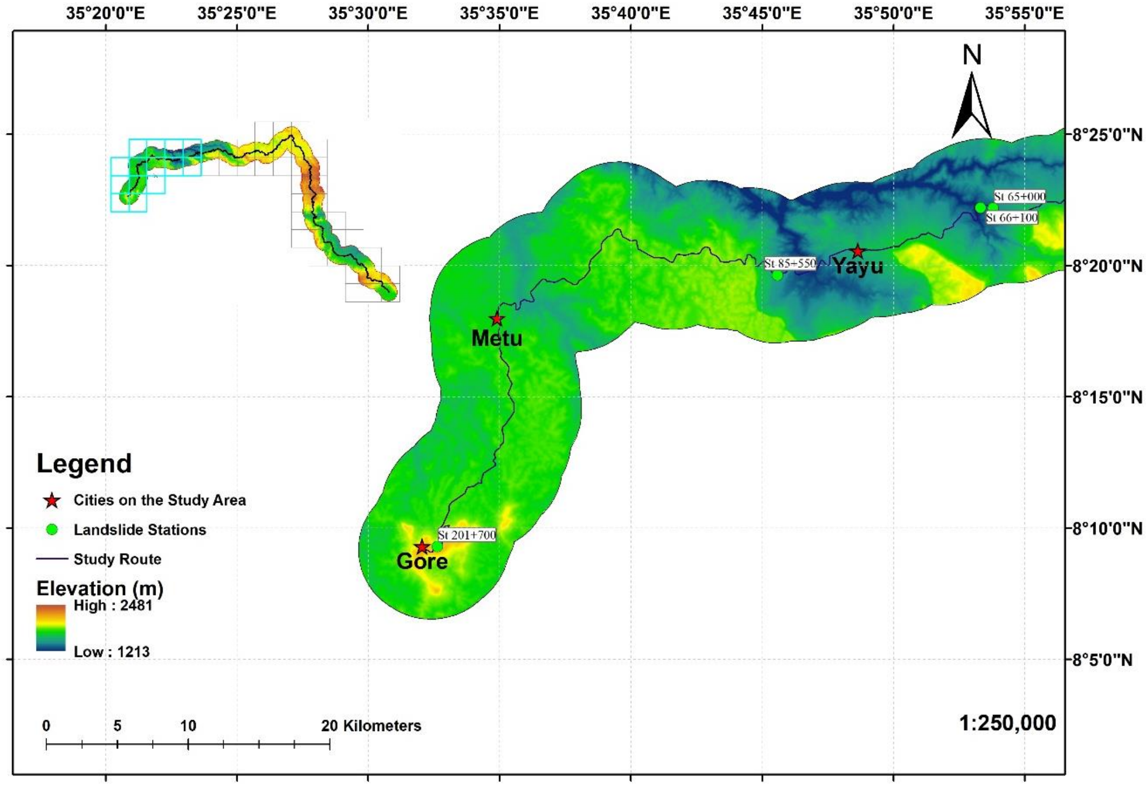



Figure 4-27: Landslide inventory map

# 5. PREPARATION OF THEMATIC FACTOR LAYER MAPS

## 5.1 Introduction

In order to ensure the accuracy of the final produced landslide susceptibility map, careful identification, selection and evaluation of causative factors is a crucial process. Even though a number of researchers selected and used various landslide causative factors for landslide susceptibility analysis, there is no specific standard or criteria for the selection (Raghuvanshi & Hamza, 2016). The main determinants that affect the selection of landslide causative factors are the geomorphological, geological, hydrological and human/manmade condition of the study area as well as the availability of data.

The selected factors for landslide susceptibility mapping are expected to be unique, measurable, complete, and practical, ensuring that they characterize the fundamental processes influencing slope instability (Melese et al., 2022). Based on these criteria, nine thematic factors are selected for this research: elevation, slope angle, slope aspect, geology, rainfall, land use/land cover, curvature, proximity to rivers and proximity to lineaments. These factors are commonly applied in landslide studies both in Ethiopia and globally and their usage is supported by previous researches demonstrating their significant role in influencing landslide processes.

Each thematic factor map was standardized to enable comparability across various datasets. The standardization included raster reclassification and normalization into common scales which enable integration in the multi criteria evaluation framework. The classification process of each of the factors was carried out based on both literature guidance and the data distribution of physical characteristics of the study area. The preparation process, therefore, provides a solid foundation for the proper weighting of factors and the final generation of the landslide susceptibility map.

## 5.2 Preparation of Thematic Factor Maps

### 5.2.1 Elevation

Elevation can be described as the vertical height of a location above mean sea level. It is one of the most widely used parameters in landslide susceptibility researches. Number of authors employed elevations as one of landslide causative factors in landslide susceptibility studies because of its strong indirect influence on slope processes (Catani et al., 2013). The relationship of elevation with landslide susceptibility can be stated as the higher the elevation the greater likelihood of landslide occurrences. Higher elevations are generally related with steeper slopes, increased rainfall intensity, and distinct vegetation patterns, all of which can enhance the likelihood of landslide occurrence.

In this study, elevation data for the Jimma-Metu-Gore corridor were extracted from a 30-meter resolution Digital Elevation Model (DEM) and processed in ArcGIS. This method aims to minimize variance within each class and maximize variance between classes. It automatically finds the best grouping of elevation values based on the data distribution, which can be useful for identifying natural breakpoints related to landslide susceptibility. The classed developed for the previously mentioned elevation range are (1,213 – 1,515), (1,515 - 1,650), (1,650 - 1,764), (1,764 - 1,872), (1,872 – 1,985), (1,985 – 2,118) and (2,118 – 2,481) as shown in the Figure 5-1.

Based on the map prepared from the 30m DEM, 40% of the landslides resides in 1,213 -1,515 elevation range, 40% of the landslides resides in 1515 - 1,650, and each of the 1872 - 1,985 & 2,118 - 2,481 elevation ranges contributes for 10% of LS occurrence. The graphical representation of this proportion is shown in Figure 5-2.

Even though higher elevations are generally more susceptible to landslides due to their correspondence with steeper slopes, higher rainfall, and problematic lithological conditions, the landslide inventory along the Jimma-Metu-Gore corridor shows more occurrences at lower elevations. This indicates that other factors may have played more significant role in causing landslides along this route

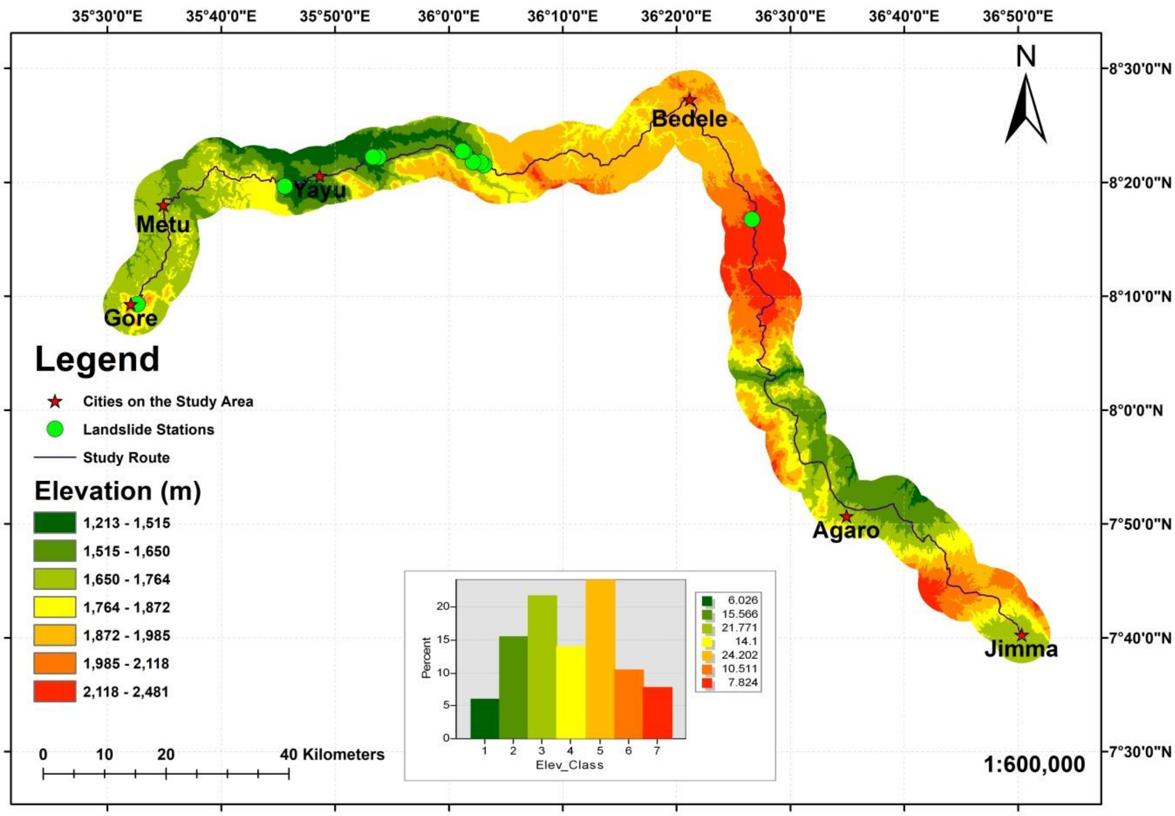



Figure 5-1: Elevation map

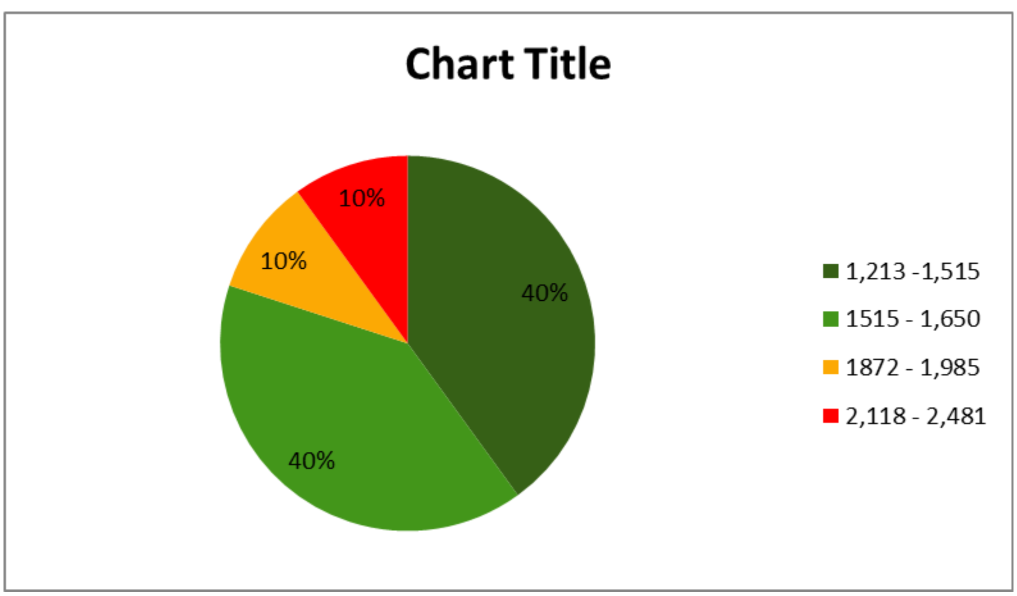



Figure 5-2: Distribution of existing landslides across elevation classes

### 5.2.2 Slope Angle

Slope angle is one of the major landslide causative factors and has been widely considered as a dominant causative factor in number of susceptibility mapping studies (Dai & Lee, 2001); (Guzzetti et al., 1999). Shear stress is highly affected by the slope angle. Shear stress acting on the soil or rock mass increases as slope inclination increases, while shear strength often decreases due to reduced root binding and soil depth.

For this study, slope angle was derived from a 30 m resolution DEM using ArcGIS slope tool as shown in Figure 5-3. The resulting slope gradient map was classified into seven categories using the Natural Breaks (Jenks) classification method. The classified slope ranges are 0°-5°, 5°-9°, 9°-13°, 13°-17 , 17°-22°, 22°-30° and 30-65°.

As shown in Figure 5-4, only 40% of the landslides were observed in 17°-22° slope range. 60% of the landslides occurred in 5°-9°, 9°-13°, 13°-17 slope ranges and these ranges are less expected to be landslide occurring zones. This highlights that, even though slope angle has great influence, there are more influential factors that affected the occurrence of landslides in the study area.

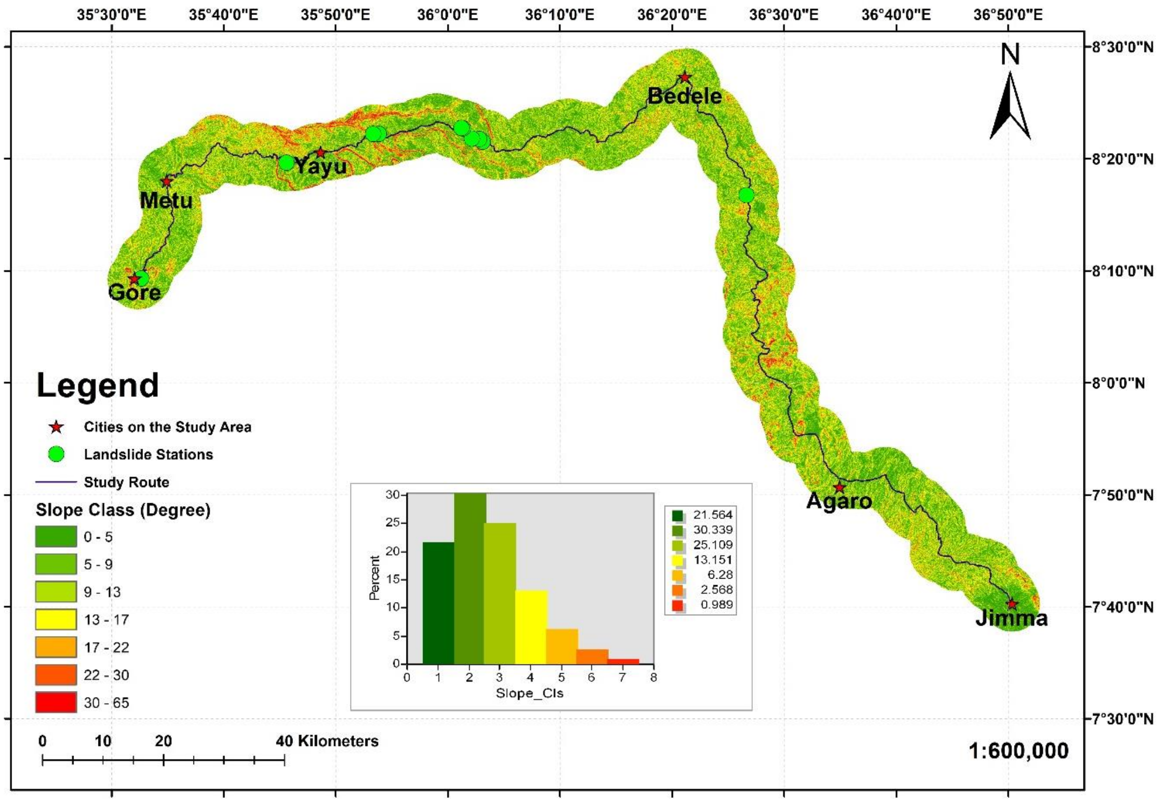



Figure 5-3: Slope Angle Map

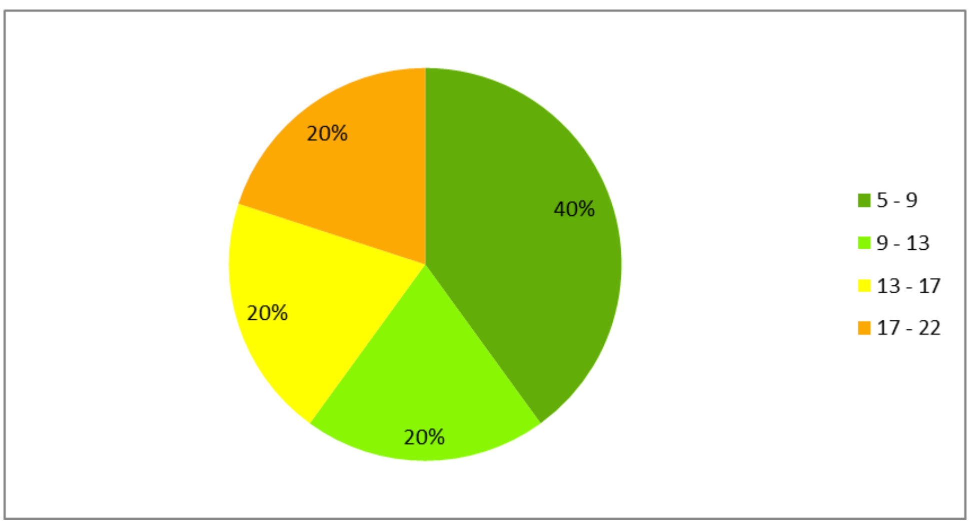



Figure 5-4: Distribution of existing landslides across slope angle classes

### 5.2.3 Slope Aspect

Slope aspect can be defined as the compass direction that a slope faces. It significantly affects landslide occurrence by varying climate conditions such as rainfall distribution, exposure to solar radiation, evapotranspiration, soil moisture, and type of vegetation cover, (Carrara A. et al., 1991); (Sidle & Ochiai, 2006). These changes result from differential weathering, soil development, and hydrological processes that directly impact slope stability. For example in humid tropical highlands like Ethiopia, aspects facing prevailing monsoon winds have the chance to be exposed for excess rainfall, which in turn maximize infiltration and pore water pressure and as a result aggravating landslide susceptibility (Ayalew & Yamagishi, 2004); (Woldearegay, 2013).

In this study, slope aspect was derived from the 30 m resolution DEM using ArcGIS's Aspect tool as shown in Figure 5-5. The raw aspect output (0°–360°) was classified into nine classes which are Flat, North (N). Northeast (NE), East (E), Southeast (SE), South (S), Southwest (SW), West (W), and Northwest (NW). North, Northeast, Northwest have high susceptibility as they receive more excessive rainfall and lower solar radiation, leading to prolonged soil saturation. East and west have moderate susceptibility as a result of having balanced exposure to sunlight and rainfall. South, Southeast and Southwest have low susceptibility (higher solar radiation maximize drying of soil, lowering instability potential) flat terrain very low susceptibility (minimal gravity caused processes), (Dai & Lee, 2002; Akgun & Turk, 2010). Specifically stated the influence of aspect in Ethiopian highlands, where north facing slopes are more exposed to failure due to higher rainfall concentration and weaker vegetation rooting compared to sun exposed southern slopes.

The derived slope aspect map as well as field observations along the Jimma-Metu-Gore corridor confirmed that most documented landslides occurred on north, northwest and northeast facing slopes. 60% of the landslides occurred in those classes whereas the remaining 40% occurred on the south and south west aspects as shown in Figure 5-6. This shows the importance of slope aspect in the susceptibility model.

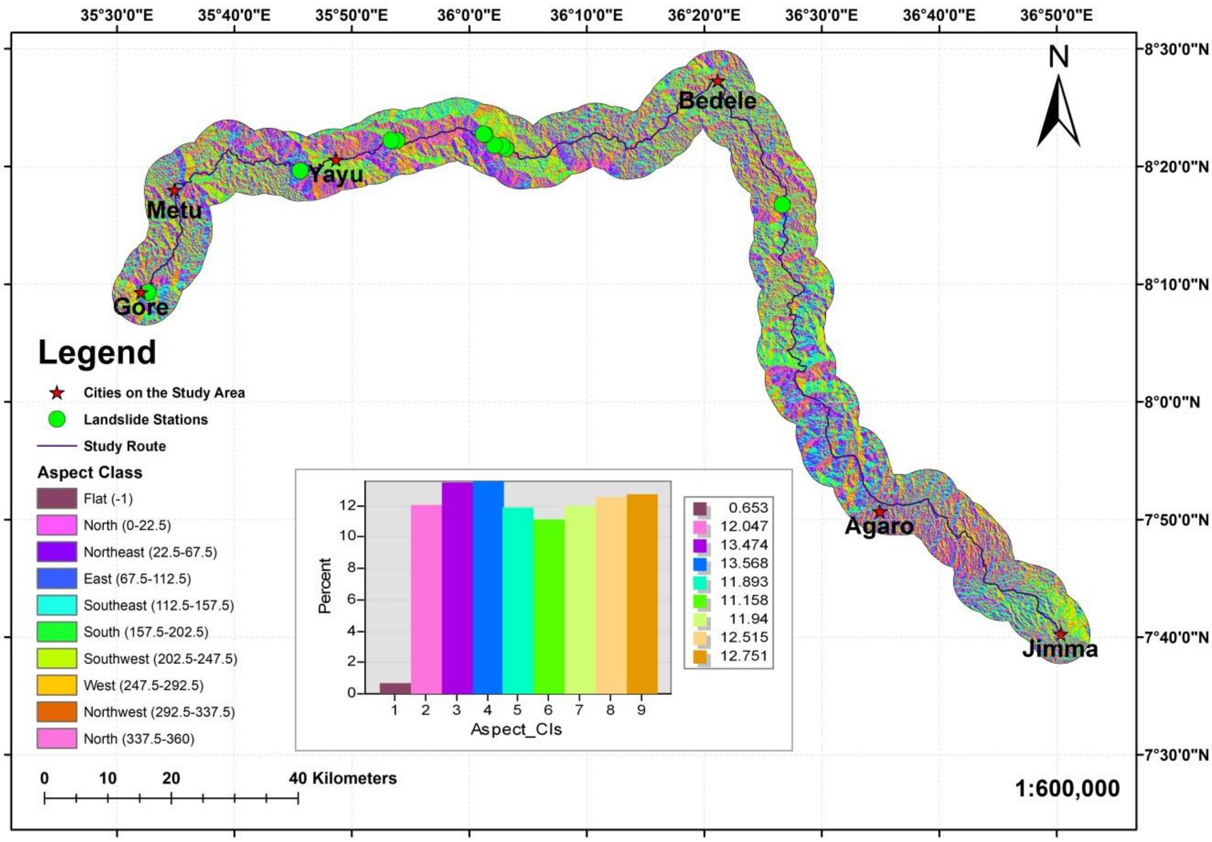



Figure 5-5: Slope aspect map

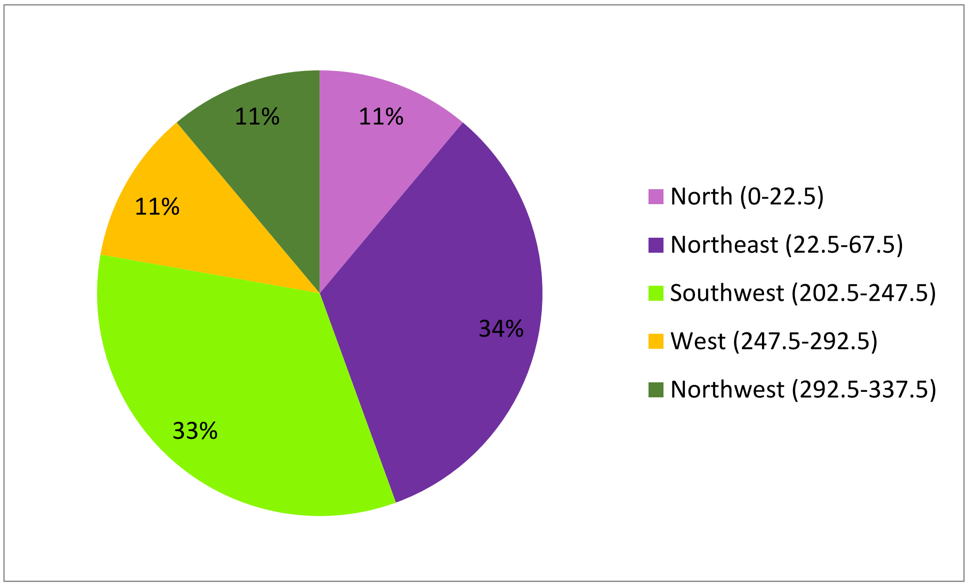



Figure 5-6: Distribution of existing landslides across slope aspect classes

### 5.2.4 Curvature

Curvature (vertical), the rate of change of slope along a surface, is one of the most important topographic parameter in landslide susceptibility studies. It provides information about how water flows and accumulates on the terrain, which directly plays vital role in affecting slope stability (Florinsky, 1998). Slope gradient only displays steepness whereas curvature distinguishes between convex (divergent or hill shaped), concave (convergent or valley shaped), and planar (flat) surfaces, each with different hydrological and geomorphological implications.

Concave slopes (negative curvature values) can potentially accumulate water and sediments maximizing pore water pressure and decreasing shear strength of slope materials. These areas are generally associated with high landslide susceptibility (Pike & Hengl, 1989). Convex slopes (positive curvature values) increases runoff and erosion usually causing removal of material and shallow failures. They have less exposure to deep seated slides. Flat slopes (curvature values near zero) have neutral flow conditions, generally showing low landslide susceptibility (Evans, 1980).

In this study, curvature was derived from the 30 m DEM using ArcGIS's Curvature tool as shown in Figure 5-7. The curvature values were classified into three categories, concave (less than –0.001 mapped with green color), near planar (–0.001 to +0.001 mapped with pink color), convex (greater than +0.001 mapped with yellow color). The output curvature map looked lemon color since the DEM used has 30m resolution and the curvature varies rapidly with small spatial difference mixing the green and yellow color. It can be seen that the actual colors can be visible as the map is zoomed.

Studies in different regions have shown the effectiveness of curvature in modeling landslide susceptibility. For instance, Ayalew & Yamagishi (2004) demonstrated that concave surface in Ethiopian highlands acquire higher landslide occurrence due to water accumulation. Based on the curvature map prepared from the 30m DEM, 70% the landslides on the Jimma-Metu-Gore corridor were located in concave slope positions, where runoff accumulation weakened slope materials. Conversely, convex ridges showed 30% of the total landslides, consistent with their lower susceptibility classification. The graphical representation of this proportion is shown in Figure 5-8.

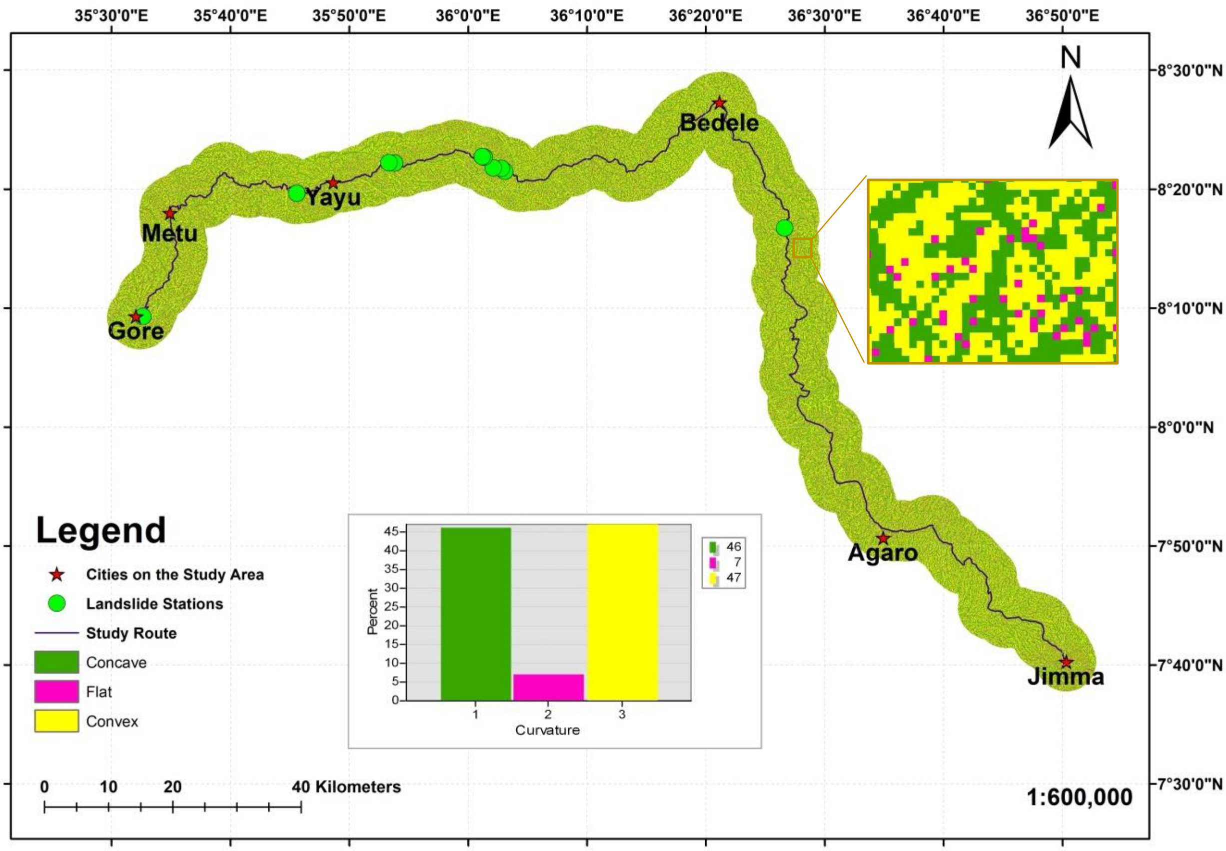



Figure 5-7: Curvature map

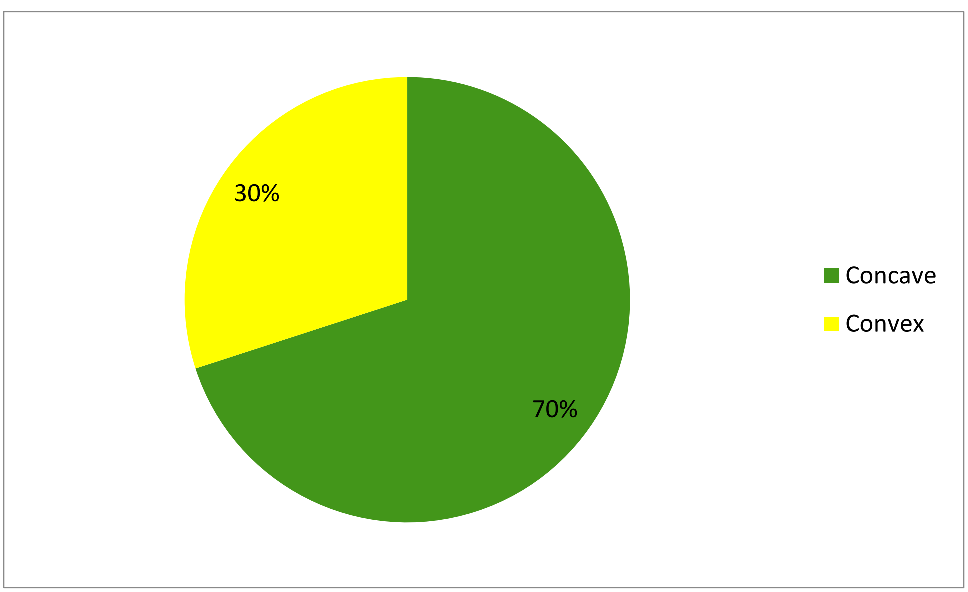



Figure 5-8: Distribution of existing landslides across curvature classes

### 5.2.5 Rainfall

Among all the thematic landslide factors, rainfall plays one of the significant roles for landslide occurrence, as it directly controls the hydrological conditions of slopes. Intense or prolonged rainfall enhances infiltration which directly increases pore water pressure within soils. As the pore water increases, it directly reduces effective stress and shear strength of the soil ultimately weakens triggering landslides (Crozier, 1986). In tropical and subtropical highlands such as Ethiopia, rainfall is widely recognized as the primary triggering factor for slope failure (Ayalew, 1999; Gessesse et al. 2010).

There are two major mechanisms that directly relate rainfall to landslide initiation. The first one is surface runoff and erosion where the activity is processed outside of the soil mass. Heavy rainfall produces rapid surface flow, which can erode slope toes and weakening the stability of upper slope materials. The second one is infiltration and pore pressure rise where the activity is processed inside of the soil mass. Rainwater infiltrates soils, increasing water content, decreasing matric suction of the unsaturated soil and leading to slope material saturation which potentially trigger slope failure (Rahardjo et al., 2007).

For this study, rainfall data were collected from meteorological stations along and near the Jimma-Metu-Gore route specifically located at Jimma, Bedele and Gore. Annual rainfall values found at the stations were spatially interpolated using the Inverse Distance Weighting (IDW) method in ArcGIS and the factor map was introduced as shown in Figure 5-9. This method was typically selected because the stations were relatively sparse but evenly distributed, making IDW appropriate for estimating continuous rainfall surfaces (Lu & Wong, 2008). The interpolated rainfall raster had a resolution of 30 m making it consistent with the other DEM derived factor maps.

The study area receives annual rainfall ranging from 1,646 mm to 1,950 mm, reflecting the moist subtropical climate of southwestern Ethiopia. Using Natural Breaks (Jenks), rainfall was classified into five categories, 1,646 - 1,708 mm (very low intensity), 1,708 - 1,768mm (low intensity), 1,768 - 1,829 mm (moderate intensity), 1,829 - 1,890 mm (high intensity) and 1,890 - 1,950mm (very high intensity).

This classification aligns with findings from previous research highlighting that the probability of landslide occurrence generally increases with maximized rainfall intensity and total annual precipitation. In Ethiopia, Ayalew & Yamagishi (2004) suggested that areas with greater than 1,800 mm annual rainfall are highly linked with landslide activity due to high surface erosion, deep weathering and persistent slope saturation.

Previous meteorology records, the field investigation and landslide inventory along the Jimma-Metu-Gore route confirmed this trend. All the documented landslides were concentrated in areas receiving more than 1,800 mm of annual rainfall. As shown in Figure 5-10, 40% of the recorded landslides are located at areas with annual rainfall ranging 1,829 - 1,890 mm (high intensity) and 60% of the recorded landslides are located at areas with annual rainfall ranging 1,890 - 1,950mm (very high intensity).

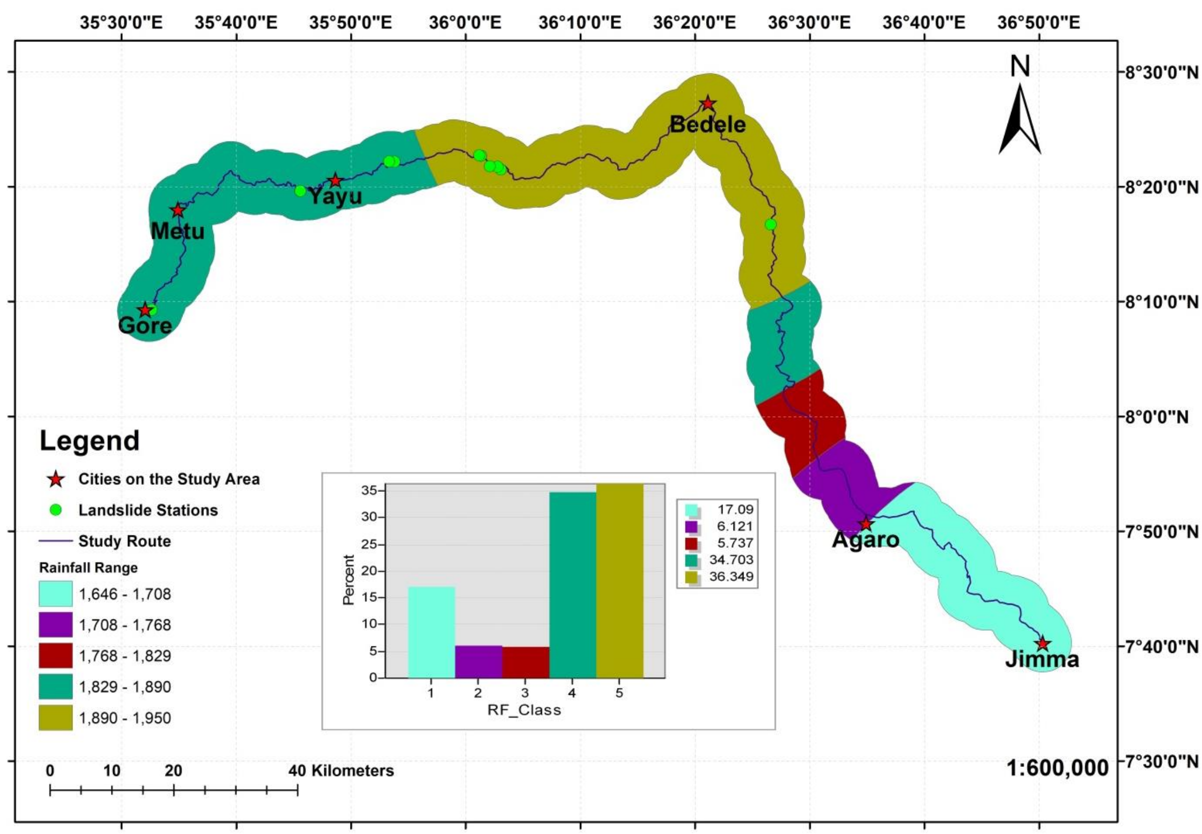



Figure 5-9: Rainfall map

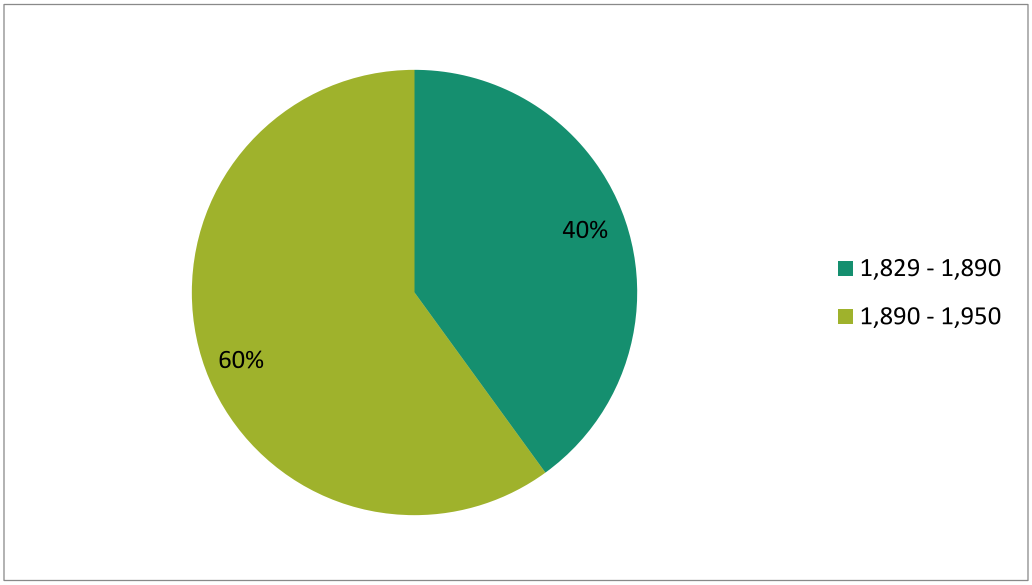



Figure 5-10: Distribution of existing landslides across rainfall classes

### 5.2.6 Geology

Geology is one of the crucial landslide causing factors highly affecting slope stability as the lithology and structural characteristics of rocks highly decides their strength, permeability, and exposure to weathering. Various rock types react differently to external triggers such as rainfall and seismic activity, depending on their mineral composition, degree of fracturing, and weathering state (Dai & Lee, 2001). In the case of Ethiopian Highlands, studies consistently demonstrated the vital role of geology in controlling landslide distribution especially in areas covered by highly weathered metamorphic formations (Ayalew & Yamagishi, 2004).

For this study, first, geological data were obtained from the map prepared by Geological Survey of Ethiopia (GSE) and the geological map for the study area was prepared using ArcGIS as shown in Figure 4-16. The major lithological units present along the Jimma-Metu-Gore route include Nm (Volcanic rocks, Magdala Group Upper Miocene), Pga (Trap Series, Ashangi Group, Alkali olivine basalt), and pE1 (Precambrian Lower Complex metamorphic rocks). These units were reclassified into susceptibility levels based on their lithological characteristics and evidence from previous studies (Abebe et al., 2010; Meten et al., 2015).

The Precambrian metamorphic rocks (pE1), mainly schist and weathered gneisses were categorized as highly susceptible. These materials are characterized by foliation and planes of weakness that facilitate sliding when saturated and the deep weathering in the Ethiopian Plateau has further downgraded their stability, aggravating slope failure (Abebe et al., 2010; Meten et al., 2015). The felsic volcanic rocks (Nm), including rhyolites and ignimbrites, were ranked as moderately susceptible. These materials are relatively brittle and prone to fracturing, which increases water infiltration and slope instability. Even though intact rhyolite is durable, weathered or faulted zones are vulnerable to slope instability. The basalts of the Ashangi Group (Pga) were also categorized as moderately susceptibility. Even though basalts are typically strong and massive that makes them resistant to weathering and slope failure, if they are highly fractured or overlain by weathered materials, the probability of localized landslide occurrence increases.

As it can be seen in Figure 5-12, 70 % of the existing landslides were located in the Precambrian metamorphic rocks (pE1) zone which were categorized as highly susceptible. The remaining 30% of the existing landslides were located in the basalts of the Ashangi Group (Pga) which were categorized as moderately susceptible.

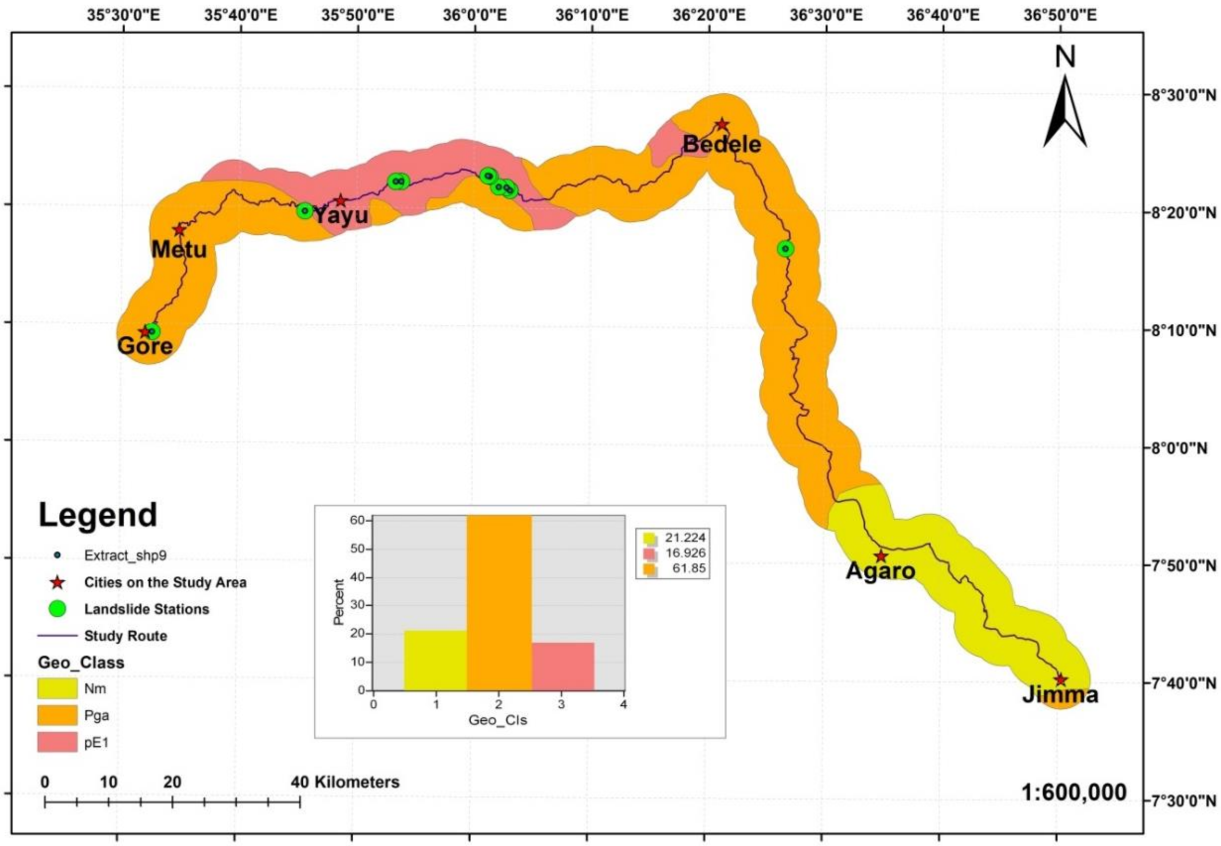



Figure 5-11: Geological map

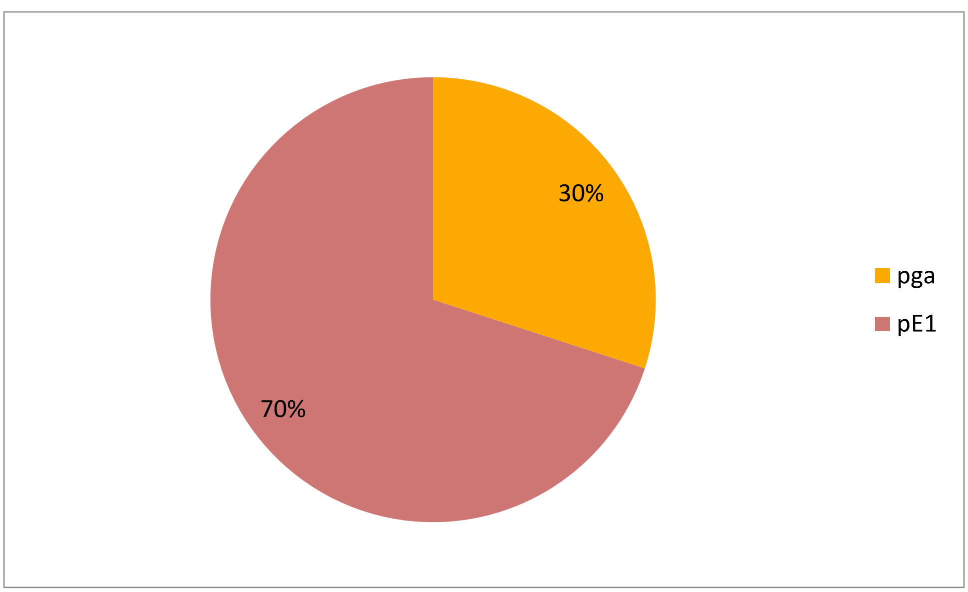



Figure 5-12: Distribution of existing landslides across geological classes

### 5.2.7 Land Use / Land Cover (LULC)

Land use and land cover (LULC) play an important role in evaluating slope stability and landslide susceptibility as they directly influence surface erosion patterns, soil reinforcement and hydrological processes. Vegetation cover, in particular, regulates infiltration, reduces runoff, and provides mechanical reinforcement through root systems. On the other hand human induced land use changes often increase slope instability.

In this study, LULC was extracted from Landsat 8 OLI imagery (30 m resolution) from United States Geological Survey (USGS) and employing ArcGIS tool. The LULC is classified into five major categories along the Jimma-Metu-Gore corridor which are dense forest, bush land, grassland, built up area, and bare land as shown in Figure 5-13. Each class was interpreted in relation to its contribution to landslide susceptibility.

Dense forest covered areas were found to be the least susceptible to landslides. The large root penetration into the ground provides strong reinforcement to the soil, enhance cohesion, and regulate subsurface hydrology and as a result reducing slope failure probability (Greenway, 1987). In contrast, bush land areas offer only moderate protection as their root do not go deep and wide enough to strongly reinforce the ground material making them less effective than dense forests, (Ayalew & Yamagishi, 2004).

Areas covered by grass are more susceptible compared to both dense forest and bush land. Even though grasses provide surface protection against erosion, their shallow roots are unable to act as the reinforcement needed to prevent slope failures particularly during prolonged rainfall. Studies in the Ethiopian highlands confirm the link between grass-covered slopes and frequent shallow slides, (Abebe et al., 2010). On the other hand built up areas have high susceptibility due to the direct influence of human activities such as road construction and slope cutting. In rural Ethiopian settlements, inadequate drainage systems usually cause slope saturation and initiates mass movements, (Woldearegay, 2013).

Bare land represents the most critical condition for landslide occurrence and classified as very high susceptible area. The absence of vegetation cover leads soils to direct erosion, aggravates runoff and leaves slopes highly exposed to failure. Such bare slopes in Ethiopia are commonly associated with landslide triggering processes, (Ayalew & Yamagishi, 2004).

Generally the LULC are classified in five categories which are dense forest (very low susceptibility), bush land (low susceptibility), grassland (moderate susceptibility), built up areas (high susceptibility), and bare land (very high susceptibility). This pattern highlights the preventive role of vegetation against slope failures and the influence of human induced or vegetation free landscapes.

As shown in the Figure 5-14, 70% of the existing landslide is recorded in the dense forest category (very low susceptibility). This highlights that other factors such as uncontrolled external drainage, the soil/rock type, excessive rainfall and others have great contribution on triggering landslide phenomenon. The remaining 30% of existing landslides occurred equally in bush land (low susceptibility), grassland (moderate susceptibility) and built up areas (high susceptibility) each of them taking 10%.

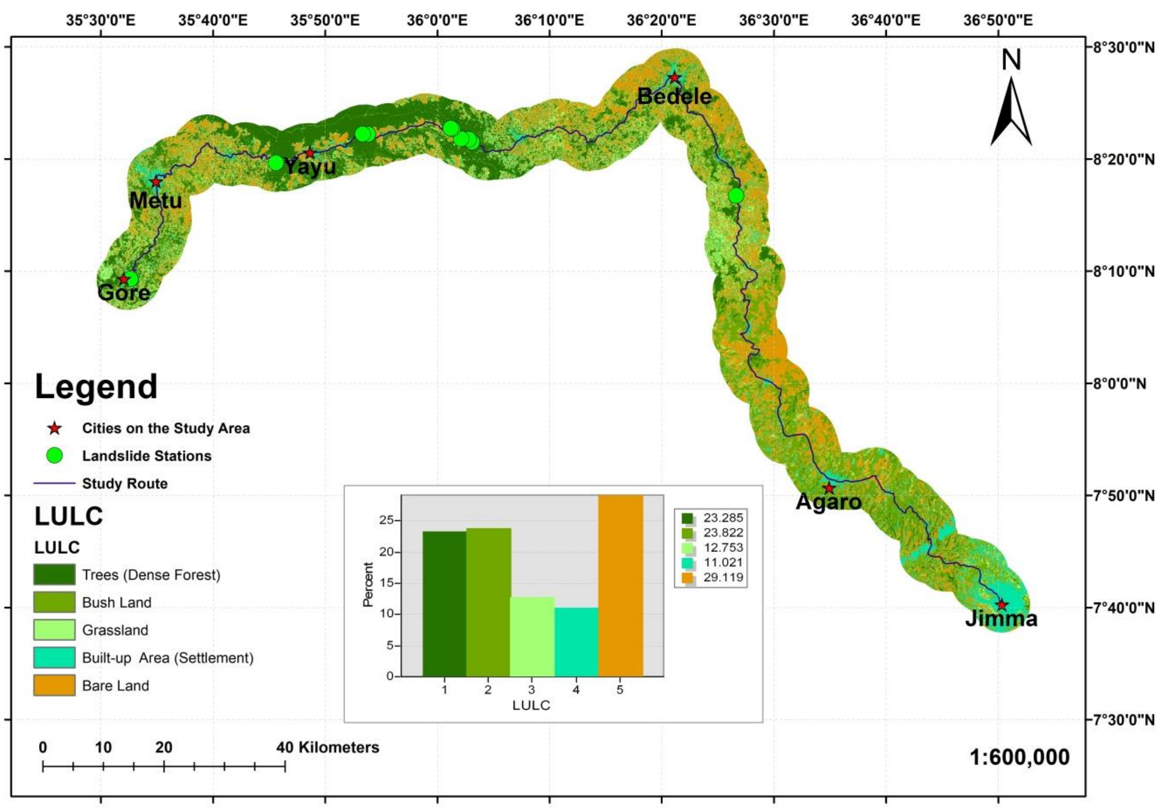



Figure 5-13: LULC map

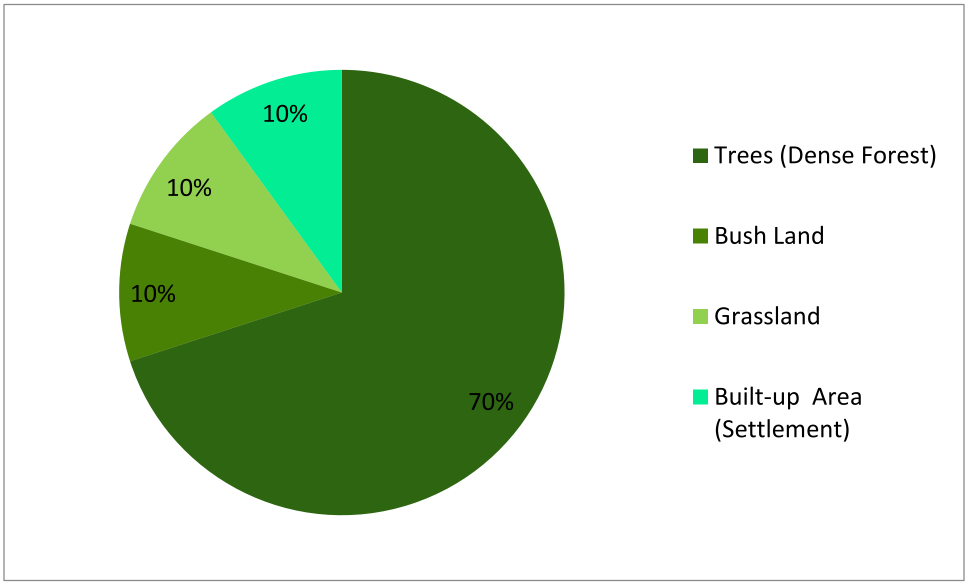



Figure 5-14: Distribution of existing landslides across LULC classes

### 5.2.8 Proximity to Streams

Proximity to streams is one of major factors having great influence on landslide susceptibility. Areas near drainage lines have wide exposure to toe erosion, undercutting, and maximized groundwater saturation. Streams reduce slope stability by eroding the base of hill slopes, weakening shear strength and increasing pore water pressure through infiltration (Crozier, 1986).

For this study, the stream network was extracted from the 30 m DEM using hydrological analysis in ArcGIS, and a buffer function was applied to generate a continuous raster of distance to streams as shown in Figure 5-15. The raster was classified into five distance zones using the Natural Breaks method. These are 0-100 m, 100-250 m, 250-500 m, 500-1000 m, and >1000 m. These classes were then reclassified based on their relative susceptibility to landslides.

Slopes in immediate proximity to streams are highly exposed to failure as a result of active toe erosion and saturation effects. As shown in Figure 5-16, 80% of the landslides happened in 200 - 1000 m ranges and only 20% of the existing landslides occurred in >1000 m range. This shows that the significance of consideration of proximity to streams in the study of landslide susceptibility of the route.

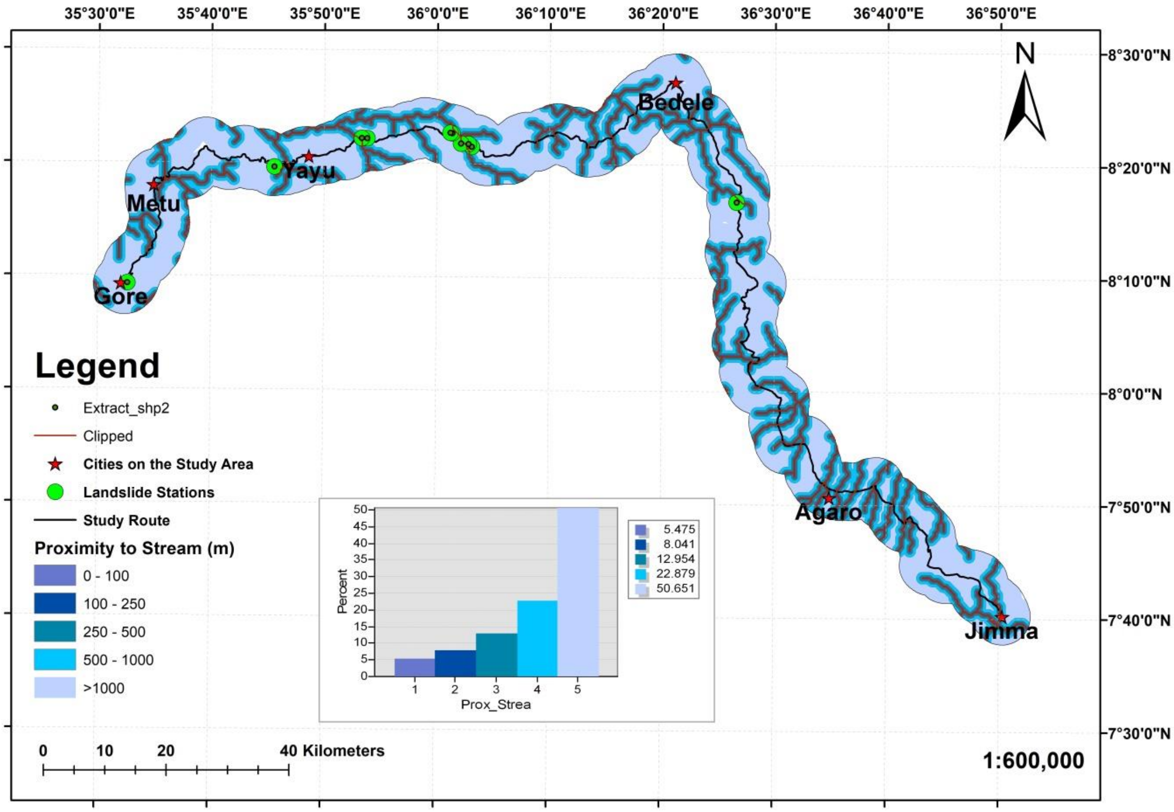



Figure 5-15: Proximity to streams map

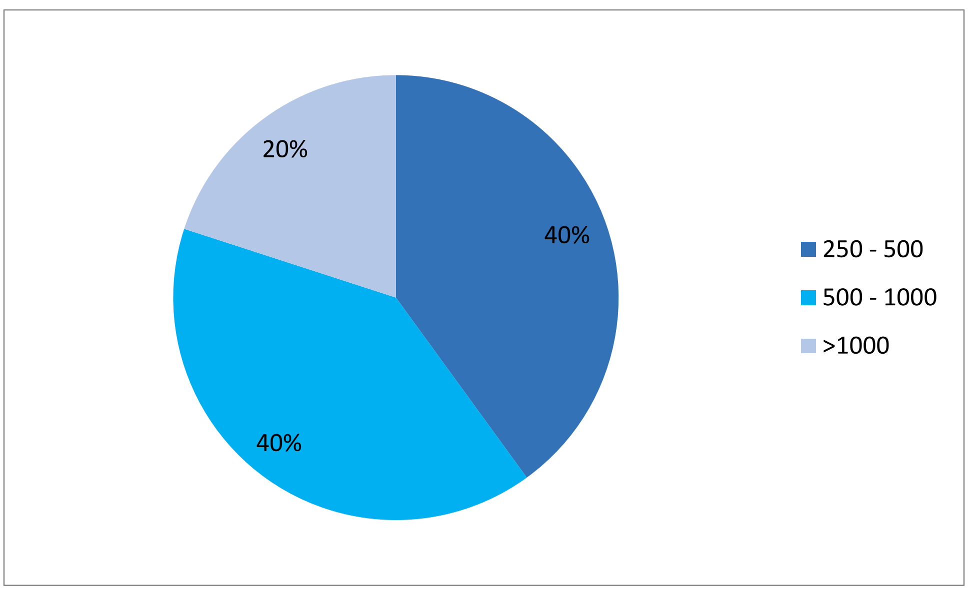



Figure 5-16: Distribution of existing landslides across proximity to streams classes

### 5.2.9 Proximity to Lineaments

Lineaments generally represent structural features such as faults, joints, and fractures. They play a vital role in slope instability as they create planes of weakness in rock masses and maximize water infiltration. These structural discontinuities weaken shear strength and pave the way for weathering and making slopes more exposed to failure near lineament zones (Guzzetti et al., 1999; Crosta et al., 2008). In Ethiopia, several studies have shown that landslides often occur close to geological lineaments, particularly in highland terrains where weathering and tectonic activity are intense, (Abebe et al., 2010; Meten et al., 2015).

For this study, lineaments were prepared by interpretation of hill shade images derived from DEMs with various azimuths. A buffer distance was generated in ArcGIS to prepare the distance ranges from the nearest lineament as shown in Figure 5-17. The raster was classified into five distance zones which are  0-100 m, 100-250 m, 250-500 m, 500-1000 m, and >1000 m.

Slopes near to lineaments are most unstable due to concentrated fracturing and maximized permeability. As shown in Figure 5-18, only 20 % of existing landslides resides in 100-250m zone, 10% of existing landslides resides in 250-500m zone. 40 % and 30% of existing landslides were observed in 500-1000 m and >1000 m zones which are expected to less likely be landslide occurring zones. This shows that the other causative factors have dominance over proximity to lineaments.

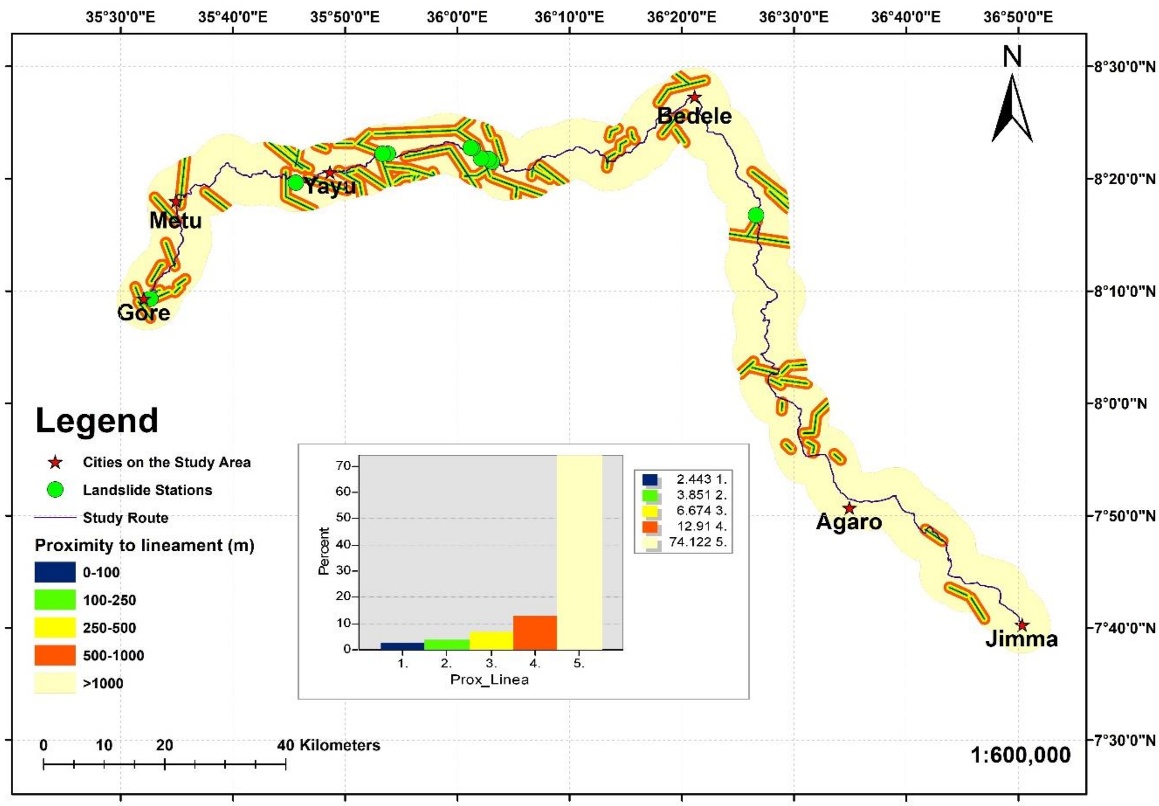



Figure 5-17: Proximity to lineament map

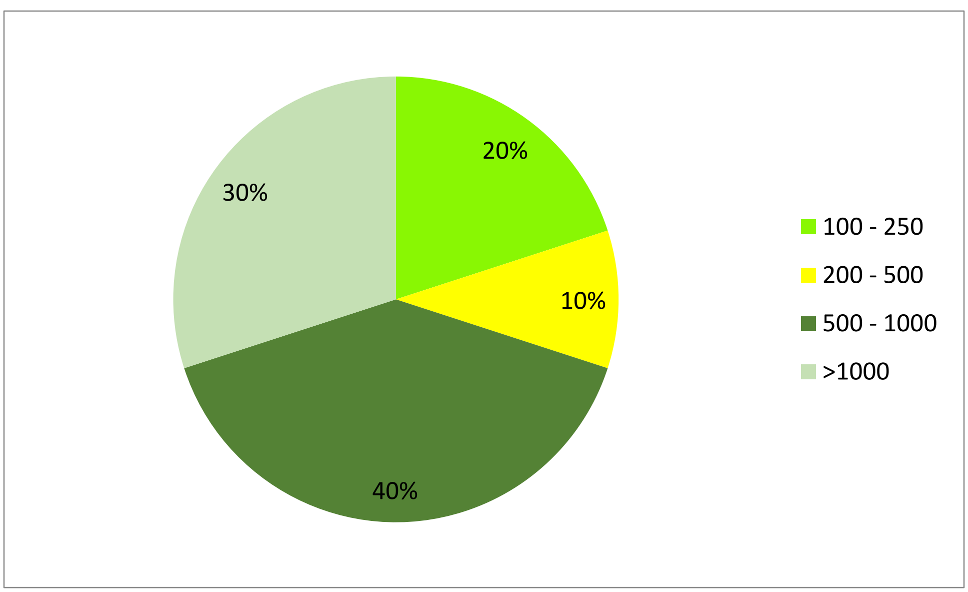



Figure 5-18: Distribution of existing landslides across proximity to lineaments classes

# 6. LANDSLIDE SUSCEPTIBILITY MAPPING, RESULTS AND DISCUSSION

## 6.1 Introduction

In this chapter, the fundamental results of the landslide susceptibility analysis carried out along the Jimma-Metu-Gore transportation corridor are presented. In the previous chapters, building on the data preparation, factor selection, and methodological framework were briefly described. This section integrates all thematic layers to generate a comprehensive Landslide Susceptibility Map (LSM) according to their respective weights. The LSM provides the spatial patterns of susceptibility and highlights their implications for slope stability. The main objective is to identify the spatial variation of landslide prone areas, briefly describe the controlling factors behind these variations, and providing insights that support risk management and mitigation projects in this main transport route of southwestern Ethiopia.

The preparation of the final LSM involves simultaneous application of multiple causative factors while accounting for their contrast intensity and conflict by using a CRITIC (Criteria Importance Through Inter-criteria Correlation) based Weighted Linear Combination (WLC) approach. The CRITIC method is first applied to determine the objective weights of each causative factor by determining their variability and interdependence. In order to ensure the most influential parameters exerted stronger control in the final model, causative factors with higher standard deviation and lower correlation with others were assigned larger weights. The resulting weights were then inserted into a WLC equation in order to obtain the Landslide Susceptibility Index (LSI) and produce a continuous susceptibility surface employing ArcGIS tool, where each pixel represents the layered effect of all causative factors.

## 6.2 CRITIC Derived Weights of Factors

Objective determination of weights is conducted based on both the variability of each factor by calculating the standard deviation ($\sigma_j$) and the degree of correlation among them through calculating inter-criteria correlation coefficients ($r_{jk}$), the relative importance of the selected causative factors was determined. Continuing this process, standard deviation ($\sigma_j$) of each factor was first calculated to measure its internal contrast or discriminating power and next the inter-criteria correlation coefficient ($r_{jk}$) is captured to identify the degree of redundancy between factors. Factors with greater variability and lesser correlation with others obtain greater weight, as they give the susceptibility model more independent and distinctive information. The step by step CRITIC method calculation and interpretation is presented as follows

**Step 1 Organization of the Decision Matrix**

Generation of the decision matrix comes on the first step. The matrix represents the relationship between all selected landslide contributing factors and the landslide locations. Each row represents to a landslide point and each column corresponds to a landslide factor, hence the cells contain the raw value of a causative factor recorded at a specific landslide point. The raw decision matrix is presented in Table 6-1.

Table 6-1: Raw decision matrix landslide stations with corresponding

| **Landslide Stations** | **Elevation** (m) | **Slope Angle** (deg) | **Slope Aspect** (deg) | **Curvature** (unitless value) | **Rainfall** (Class value) | **Geology** (Class value) | **LULC** (Class value) | **Proximity to Stream** (Class value) | **Proximity to Lineament** (Class value) |
|---|---|---|---|---|---|---|---|---|---|
| **36+720** | **2188** | **13.123** | **8.673** | **0.292969** | **5** | **5** | **2** | **2** | **4** |
| **44+000** | **1621** | **15.098** | **235.619** | **0.488281** | **5** | **3** | **1** | **3** | **4** |
| **44+800** | **1564** | **19.18** | **235.06** | **-1.1718** | **5** | **3** | **1** | **3** | **4** |
| **46+920** | **1505** | **11.24** | **45** | **-1.5625** | **5** | **3** | **1** | **3** | **2** |
| **48+800** | **1525** | **7.76** | **23.629** | **-0.78125** | **5** | **3** | **1** | **2** | **4** |
| **49+000** | **1548** | **9.909** | **349.695** | **-1.074219** | **5** | **3** | **1** | **2** | **5** |
| **65+000** | **1439** | **6.497** | **264.094** | **-0.390625** | **4** | **3** | **1** | **2** | **5** |
| **66+100** | **1354** | **8.687** | **237.529** | **0.195313** | **4** | **3** | **1** | **3** | **3** |
| **85+550** | **1514** | **5.29** | **27.646** | **-0.292969** | **4** | **5** | **3** | **1** | **5** |
| **201+700** | **1972** | **20.75** | **322.54** | **-0.195313** | **4** | **5** | **4** | **1** | **2** |

**Step 2 Normalization of the Matrix**

The raw data cannot be compared directly since each factor is measured in different units such as meters, degrees and class values. Normalization converts all values to a common and dimensionless scale (0 to 1) enabling the data to be comparable. The normalized values of each causative factor is presented in Table 6-2.

Table 6-2: Normalized values of the causative factors

| Landslide Stations | Elevation | Slope Angle | Slope Aspect | Curvature | Rainfall | Geology | LULC | Proximity to Stream | Proximity to Lineament |
|---|---|---|---|---|---|---|---|---|---|
| 36+720 | 1.000 | 0.507 | 0.000 | 0.905 | 1.000 | 1.000 | 0.333 | 0.500 | 0.667 |
| 44+000 | 0.320 | 0.634 | 0.665 | 1.000 | 1.000 | 0.000 | 0.000 | 1.000 | 0.667 |
| 44+800 | 0.252 | 0.898 | 0.664 | 0.191 | 1.000 | 0.000 | 0.000 | 1.000 | 0.667 |
| 46+920 | 0.181 | 0.385 | 0.107 | 0.000 | 1.000 | 0.000 | 0.000 | 1.000 | 0.000 |
| 48+800 | 0.205 | 0.160 | 0.044 | 0.381 | 1.000 | 0.000 | 0.000 | 0.500 | 0.667 |
| 49+000 | 0.233 | 0.299 | 1.000 | 0.238 | 1.000 | 0.000 | 0.000 | 0.500 | 1.000 |
| 65+000 | 0.102 | 0.078 | 0.749 | 0.571 | 0.000 | 0.000 | 0.000 | 0.500 | 1.000 |
| 66+100 | 0.000 | 0.220 | 0.671 | 0.857 | 0.000 | 0.000 | 0.000 | 1.000 | 0.333 |
| 85+550 | 0.192 | 0.000 | 0.056 | 0.619 | 0.000 | 1.000 | 0.667 | 0.000 | 1.000 |
| 201+700 | 0.741 | 1.000 | 0.920 | 0.667 | 0.000 | 1.000 | 1.000 | 0.000 | 0.000 |

**Step 3 Standard Deviation ($\sigma_j$) Calculation**

This step determines the contrast intensity of each factor by computing the standard deviation of its normalized values. Standard deviation ($\sigma_j$) reflects how much a causative factor differs across all landslide locations. Higher variation refers to the causative factor has stronger discriminating power in identifying stable and unstable zones. The standard deviation of each causative factor is presented in Table 6-3.

Table 6-3: Standard deviation values of the causative factors

| Landslide Stations | Elevation | Slope Angle | Slope Aspect | Curvature | Rainfall | Geology | LULC | Proximity to Stream | Proximity to Lineament |
|---|---|---|---|---|---|---|---|---|---|
| Standard Deviation (σ) | 0.307 | 0.339 | 0.392 | 0.333 | 0.516 | 0.483 | 0.358 | 0.394 | 0.378 |

**Step 4: Construction of the Correlation Matrix ($l_{jk}$)**

In addition to evaluating individual variability, CRITIC also accounts for the interdependence between factors. For each pair of factors j and k, the correlation coefficient $l_{jk}$ is calculated. It measures the degree to which two factors give overlapping or redundant information.

A value close to 1 indicates strong positive correlation (high redundancy) and value close to **0** indicates small correlation (great independence). The correlation coefficient matrix is presented in Table 6-4.

Table 6-4: Correlation coefficient matrix

| Landslide Stations | Elevation | Slope Angle | Slope Aspect | Curvature | Rainfall | Geology | LULC | Proximity to Stream | Proximity to Lineament |
|---|---|---|---|---|---|---|---|---|---|
| Elevation | 1.000 | 0.542 | -0.150 | 0.354 | 0.179 | 0.722 | 0.562 | -0.378 | -0.214 |
| Slope Angle | 0.542 | 1.000 | 0.379 | 0.026 | 0.238 | 0.171 | 0.304 | 0.125 | -0.512 |
| Slope Aspect | -0.150 | 0.379 | 1.000 | 0.044 | -0.245 | -0.286 | -0.014 | 0.056 | 0.014 |
| Curvature | 0.354 | 0.026 | 0.044 | 1.000 | -0.351 | 0.388 | 0.275 | -0.137 | 0.095 |
| Rainfall | 0.179 | 0.238 | -0.245 | -0.351 | 1.000 | -0.356 | -0.520 | 0.491 | 0.038 |
| Geology | 0.722 | 0.171 | -0.286 | 0.388 | -0.356 | 1.000 | 0.899 | -0.758 | -0.081 |
| LULC | 0.562 | 0.304 | -0.014 | 0.275 | -0.520 | 0.899 | 1.000 | -0.812 | -0.255 |
| Proximity to Stream | -0.378 | 0.125 | 0.056 | -0.137 | 0.491 | -0.758 | -0.812 | 1.000 | -0.199 |
| Proximity to Lineament | -0.214 | -0.512 | 0.014 | 0.095 | 0.038 | -0.081 | -0.255 | -0.199 | 1.000 |

**Step 5: Calculation of Information Content ($C_j$)**

CRITIC combines the variability of each factor with its independence from other factors to determine its total information contribution. This enables to capture both the contrast intensity and the uniqueness of each factor.

Higher $C_j$ value shows a factor with high variability and low correlation with other factors and hence it provides significant and unique information to the model. The information content of each causative factor is presented in Table 6-5.

Table 6-5: The information content of each causative factor

| Landslide Stations | Elevation | Slope Angle | Slope Aspect | Curvature | Rainfall | Geology | LULC | Proximity to Stream | Proximity to Lineament | $\sum(1-l_{ij})$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Elevation | 0.000 | 0.458 | 1.150 | 0.646 | 0.821 | 0.278 | 0.438 | 1.378 | 1.214 | 6.383 |
| Slope Angle | 0.458 | 0.000 | 0.621 | 0.974 | 0.762 | 0.829 | 0.696 | 0.875 | 1.512 | 6.728 |
| Slope Aspect | 1.150 | 0.621 | 0.000 | 0.956 | 1.245 | 1.286 | 1.014 | 0.944 | 0.986 | 8.202 |
| Curvature | 0.646 | 0.974 | 0.956 | 0.000 | 1.351 | 0.612 | 0.725 | 1.137 | 0.905 | 7.306 |
| Rainfall | 0.821 | 0.762 | 1.245 | 1.351 | 0.000 | 1.356 | 1.520 | 0.509 | 0.962 | 8.527 |
| Geology | 0.278 | 0.829 | 1.286 | 0.612 | 1.356 | 0.000 | 0.101 | 1.758 | 1.081 | 7.301 |
| LULC | 0.438 | 0.696 | 1.014 | 0.725 | 1.520 | 0.101 | 0.000 | 1.812 | 1.255 | 7.562 |
| Proximity to Stream | 1.378 | 0.875 | 0.944 | 1.137 | 0.509 | 1.758 | 1.812 | 0.000 | 1.199 | 9.612 |
| Proximity to Lineament | 1.214 | 1.512 | 0.986 | 0.905 | 0.962 | 1.081 | 1.255 | 1.199 | 0.000 | 9.114 |

| Landslide Stations | $\sum(1-I_{ij})$ | σ | $C_j=\sigma*(\sum(1-I_{ij}))$ |
|---|---|---|---|
| Elevation | 6.383 | 0.307 | 1.963 |
| Slope Angle | 6.728 | 0.339 | 2.283 |
| Slope Aspect | 8.202 | 0.392 | 3.213 |
| Curvature | 7.306 | 0.333 | 2.434 |
| Rainfall | 8.527 | 0.516 | 4.403 |
| Geology | 7.301 | 0.483 | 3.527 |
| LULC | 7.562 | 0.358 | 2.710 |
| Proximity to Stream | 9.612 | 0.394 | 3.791 |
| Proximity to Lineament | 9.114 | 0.378 | 3.449 |
| | | Total ($\sum C_j$) | 27.772 |

**Step 6 Derivation of CRITIC Weight ($W_j$)**

The information content is then divided by the total information content to obtain the final weights of each factor which express the relative importance of each factor in controlling landslide susceptibility. The final critic weights of the causative factors is presented in Table 6-6.

Table 6-6: Final critic weights of the causative factors

| Landslide Stations | $W_j = Cj/\sum C_j$ |
|---|---|
| Elevation | 0.071 |
| Slope Angle | 0.082 |
| Slope Aspect | 0.116 |
| Curvature | 0.088 |
| Rainfall | 0.159 |
| Geology | 0.127 |
| LULC | 0.098 |
| Proximity to Stream | 0.137 |
| Proximity to Lineament | 0.124 |

## 6.3 Landslide Susceptibility Mapping

The final susceptibility score for each raster cell is computed by applying the Weighted Linear Combination (WLC) of all factors to produce the Landslide Susceptibility Index (LSI). LSI is a continuous index representing the extent of landslide susceptibility across the study area.

$$LSI = \sum_{j=1}^{m}(w_j * r_j) \quad [6\text{-}1]$$

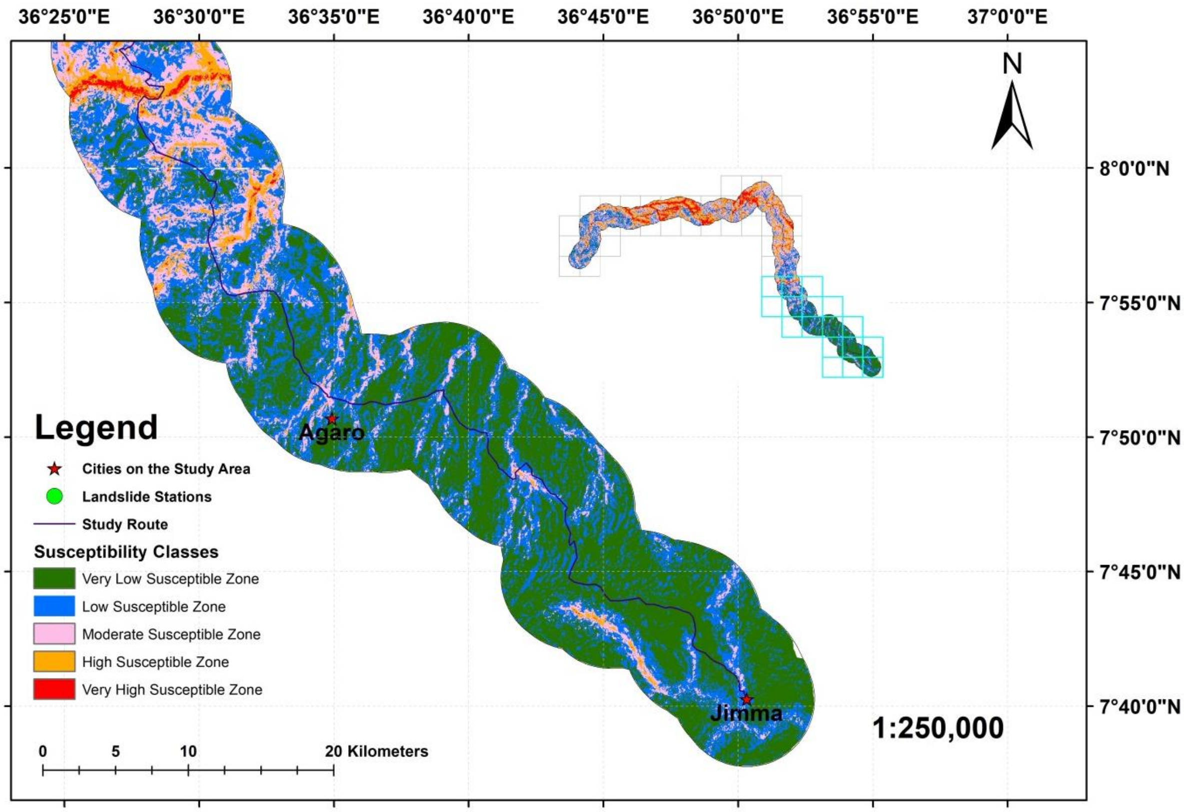
Where, $r_j$ is normalized raster value of LS causative factor j; m is number of LS causative factors

LSI= 0.071*Elevation + 0.082*Slope Angle + 0.116*Slope Aspect + 0.088*Curvature + 0.159*Rainfall + 0.127*Geology+0.098*LULC + 0.137*Proximity to Stream + 0.124*Proximity to Lineament

With the causative factor weights derived from the CRITIC method, the final LSM was produced by combining all the weighted thematic factor layers using the Weighted Linear Combination (WLC) technique as shown in Figure 6-1. Every raster layer representing a causative factor has been first standardized to a common scale and then multiplied by its respective CRITIC generated weight. The weighted layers were summed in ArcGIS to generate the continuous raster which is the final LSM representing the spatial probability of landslide occurrence across the Jimma-Metu-Gore corridor.

The output LSM values were then categorized into five susceptibility class: Very Low Susceptibility (VLS), Low Susceptibility (LS), Moderate Susceptibility (MS), High Susceptibility (HS), and Very High Susceptibility (VHS). Natural Breaks (Jenks) classification method is used due to its ability to lower internal variance within each class as well as increase variance between classes, hence highlighting natural groupings in the data. The area and percent of coverage of the landslide susceptibility classes are presented in Table 6-7.

The final map illustrates the spatial distribution of these susceptibility classes enabling a clear visualization of areas with varying degrees of landslide hazard potential. This spatial differentiation provides a critical tool for understanding slope instability and determining priority areas for further investigation, mitigation planning, and infrastructure management.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37°0'0"E
8°0'0"N
7°55'0"N
7°50'0"N
7°45'0"N
7°40'0"N
N
Agaro
Jimma
Legend
Cities on the Study Area
Landslide Stations
Study Route
Susceptibility Classes
Very Low Susceptible Zone
Low Susceptible Zone
Moderate Susceptible Zone
High Susceptible Zone
Very High Susceptible Zone
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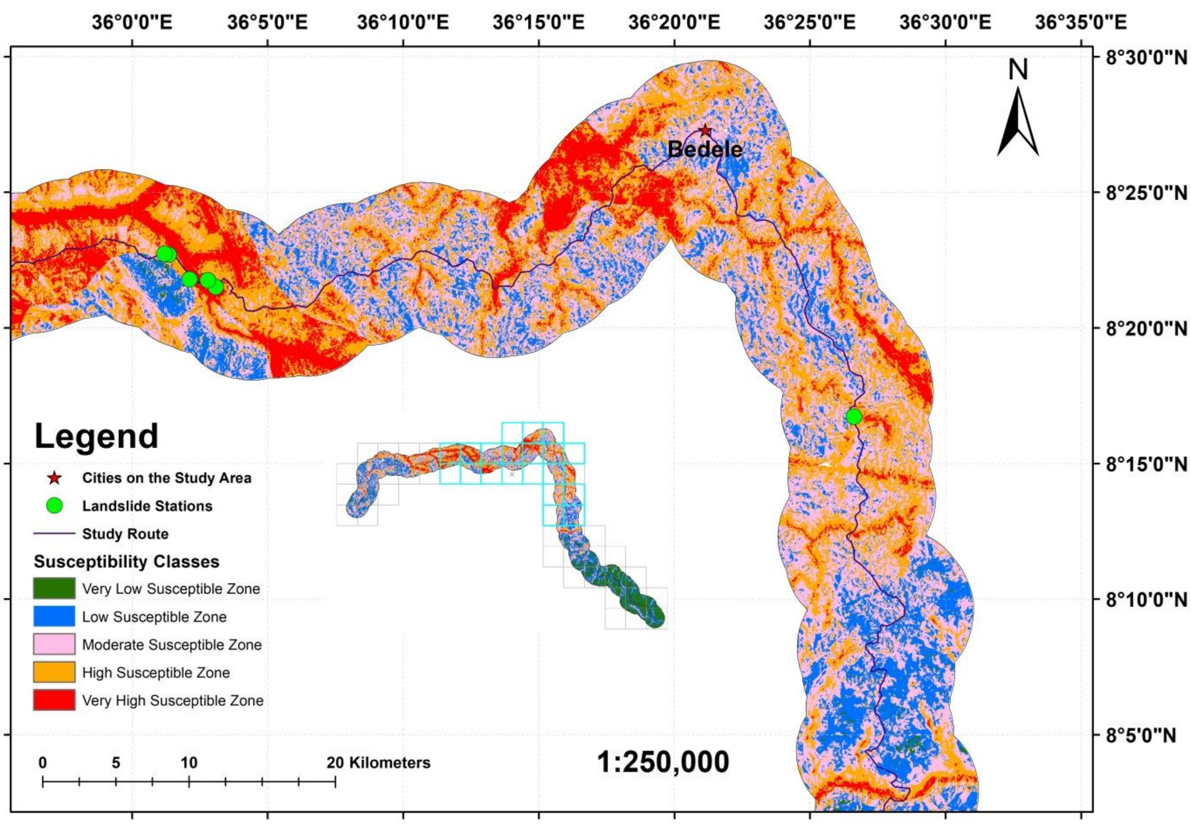
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Bedele
Legend
Cities on the Study Area
Landslide Stations
Study Route
Susceptibility Classes
Very Low Susceptible Zone
Low Susceptible Zone
Moderate Susceptible Zone
High Susceptible Zone
Very High Susceptible Zone
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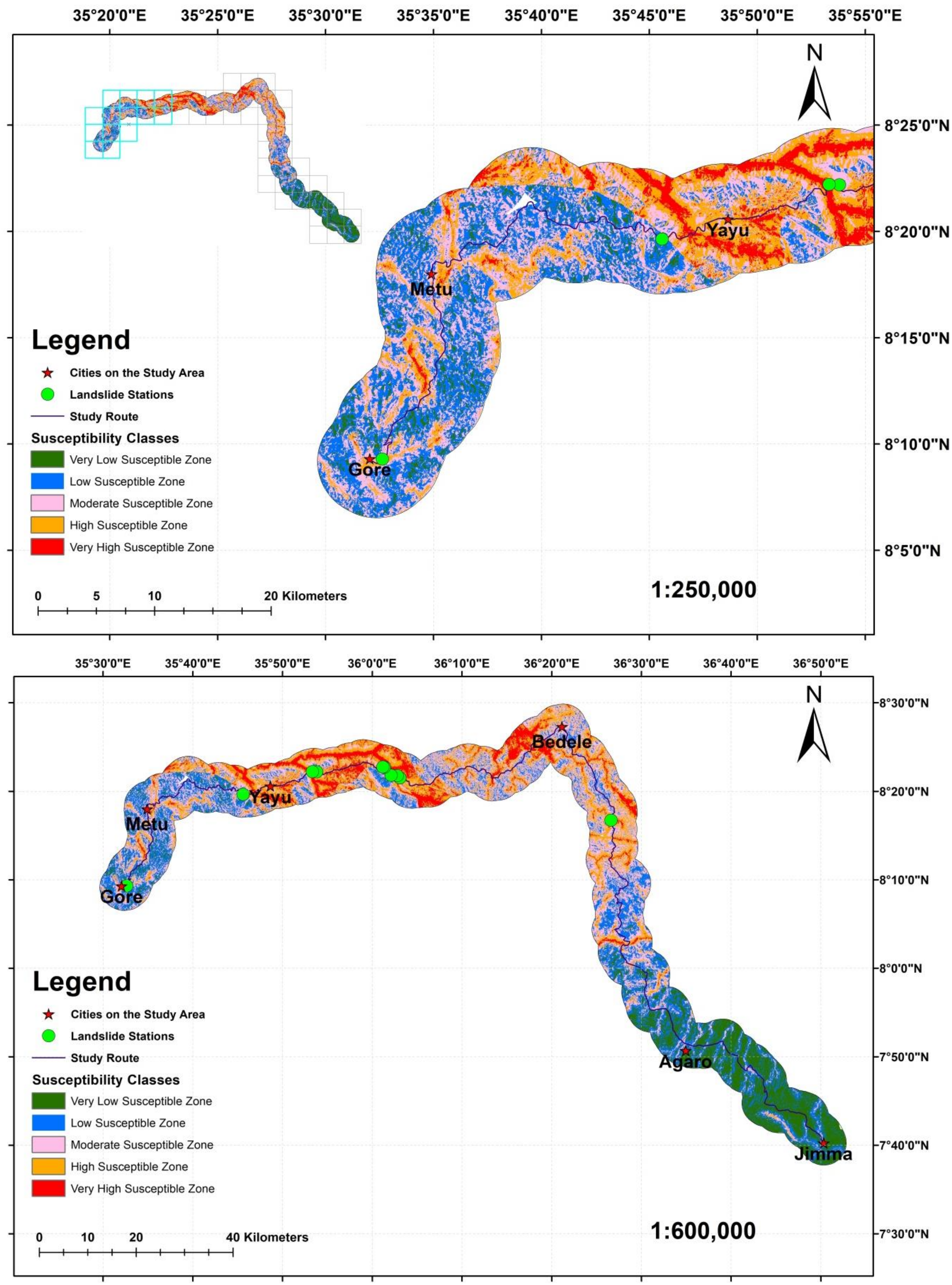


Figure 6-1: Landslide Susceptiblity Map of Jimma-Metu-Gore Route

Table 6-7: Area and percent of coverage of the landslide susceptibility classes

| LSM Class | Area Km2 | Percent of Coverage |
|---|---|---|
| **VLS** | 357.76 | 15.51 |
| **LS** | 598.53 | 25.95 |
| **MS** | 677.86 | 29.39 |
| **HS** | 481.21 | 20.86 |
| **VHS** | 191.12 | 8.29 |

## 6.4 Validation of the Susceptibility Map

It is essential to validate the final Landslide Susceptibility Map (LSM) to assess its reliability and predictive performance. In this study, validation was carried out by comparing the spatial distribution of known landslide occurrences with the susceptibility classes derived from the model, known as overlay validation technique. As the name indicates, validation process involved overlaying the landslide inventory points on the classified LSM within the ArcGIS environment.

The location of the existing landslides within each susceptibility class: Very Low Susceptibility (VLS), Low Susceptibility (LS), Moderate Susceptibility (MS), High Susceptibility (HS), and Very High Susceptibility (VHS) is extracted as shown in Table 6-8.

Table 6-8: Existing landslides location within LS susceptibility classes

| Landslide Stations | Susceptibility zone |
|---|---|
| **36+720** | MS |
| **44+000** | VHS |
| **44+800** | VHS |
| **46+920** | VHS |
| **48+800** | HS |
| **49+000** | VHS |
| **65+000** | HS |
| **66+100** | VHS |
| **85+550** | LS |
| **27+000** | HS |

Then the percentage of the existing landslides located within each susceptibility class was calculated and used to evaluate the predictive performance of the model.

Table 6-9: Percent of existing landslides within susceptibility classes

| LSM Class | Percent of Coverage (%) |
|---|---|
| VLS | 0 |
| LS | 10 |
| MS | 10 |
| HS | 30 |
| VHS | 50 |

A reliable susceptibility map is expected to show a higher concentration of recorded landslides in the VHS and HS zones and a minimal proportion in the LS and VLS zones. This precondition is fulfilled by the produced LSM as the calculated percentage of the existing landslides located within each susceptibility class shown in Table 6-9.  A total of 80% of the existing landslides located in HS and VHS zones. This result indicates strong predictive accuracy of the LSM, confirming that the CRITIC based WLC model effectively determined the spatial relationships between landslide occurrences and the selected causative factors. The validation result thus provides confidence in the practical applicability of the LSI map as a decision-support tool for hazard mitigation, infrastructure planning, and risk management along the Jimma-Metu-Gore transportation corridor.

## 6.5 Discussion

The aim of this analysis was to determine the spatial patterns of landslide susceptible zones for the Jimma-Metu-Gore transportation corridor by collectively using a set of thematic factors derived from various sources of data. With the integration of CRITIC method and WLC approach, the landslide susceptibility analysis was conducted for the study route. The CRITIC method overcomes the subjectivity associated with expert based methods such as AHP by providing an objective means of thematic factors weighting by considering both the internal contrast of each variable and the degree of correlation among variables.

Rainfall received the highest weight (0.159) among the nine factors considered, indicating that precipitation puts the strongest influence on landslide occurrence of the route. This result is goes perfectly with the climatic conditions of the southwestern Ethiopian highlands, where heavy and prolonged rainfall trigger slope failures. Similar findings have been reported in other Ethiopian corridors such as the Debremarkos Bahirdar road, (Melese et al., 2022).

Proximity to streams (0.137) was found to be the second most influential factor which facilitates lateral erosion in destabilizing slopes, particularly along river valleys where undercutting of the toe promotes mass movement. The presence of perennial and seasonal rivers along the Jimma-Metu-Gore route facilitates continuous removal of support material, which, combined with high rainfall, accelerates slope failure. The strong weight acquired by geology (0.127) also supports the observation that lithological composition is a critical determinant of slope stability. Various studies also demonstrated that slope failures often occur in weathered volcanic rocks (rhyolites, ignimbrites) and in areas where basaltic units are highly fractured or overlain by thick residual soils, confirming the susceptibility of weak, altered lithology to mass movement.

Proximity to lineaments (0.124) was also found to be a key factor. Lineaments are fractures, faults or any other structural discontinuities that enables groundwater infiltration, leading to increased pore pressure and progressive weakening of the rock mass. The greater weight of this factor suggests that, even though the route is located outside the main Ethiopian rift, consideration of structural control is mandatory in the study area. Guzzeti et al., (2012) demonstrated that fractured zones are usually have great influence on triggering landslide in volcanic and metamorphic terrains which is consistent with the observation of this study.

On the other hand, elevation (0.071) and slope angle (0.082) were assigned with relatively lesser weights in comparison with the previously stated factors. However, this does not mean topography is not an important factor rather it reflects the fact that in the study route, without the combined influence of the other causative factors, steep slope just by itself is insufficient to trigger landslides. The rest of the thematic factors such as land use/land cover (0.109), curvature (0.095), and slope aspect (0.096) have found intermediate positions.

The final Landslide Susceptibility Map (LSM) generated with the application of CRITIC method was categorized into five susceptibility classes that are Very Low Susceptibility (VLS), Low Susceptibility (LS), Moderate Susceptibility (MS), High Susceptibility (HS), and Very High Susceptibility (VHS). The spatial distribution of these classes shows a varying pattern of susceptibility across the study route.

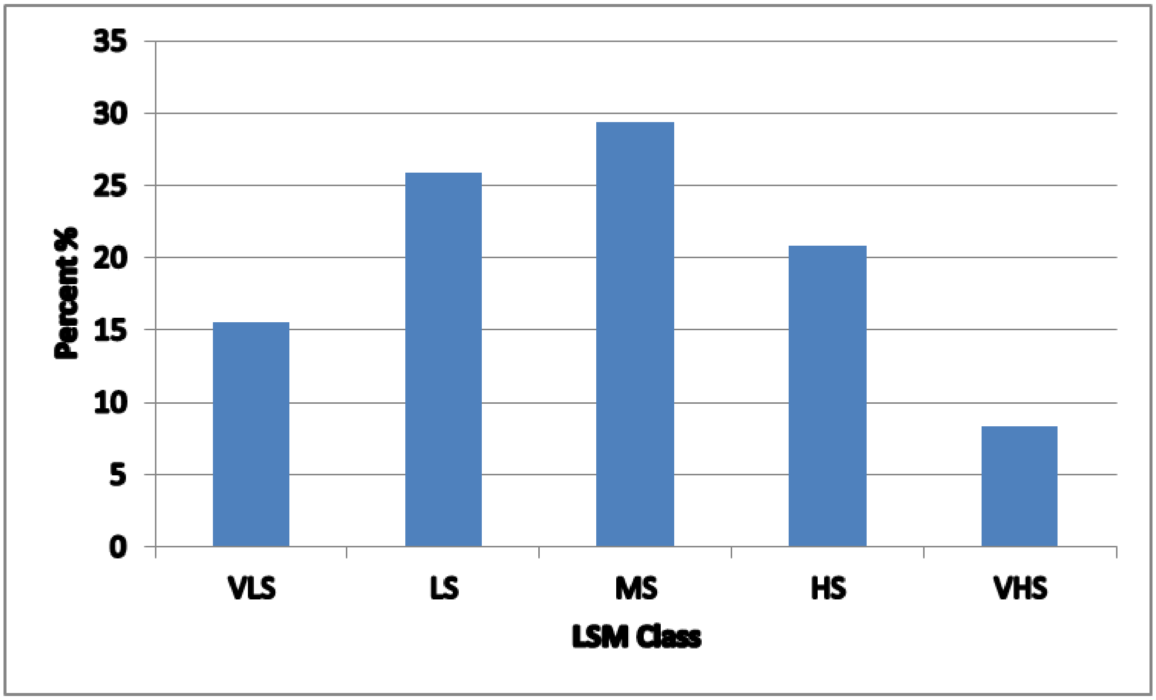


Figure 6-2: Landslide susceptibility classes' coverage in percent

Figure 6-2, MS covers the largest portion of the study area which is 29.39%, showing that most part of the route is subject to intermediate levels of instability. LS take 25.95% of the study area, typically referring to areas of gentle terrain, well drained slopes and stable geology. HS covers 20.86%, while VHS zones occupy only 8.29% of the total area. The rest part which is 15.51% of the route is covered by the VLS class.

Rainfall, proximity to streams, and geological factors were dominant as observed in this study which is consistent with demonstrations from other Ethiopian routes such as the Addis Ababa Debremarkos road, (Melese et al., 2022). Despite this, the relatively low weight acquired by slope angle contrasts with results from tectonically active mountain belts, where steep gradient is the primary cause to trigger slope instability, (Guzzeti et al., 2012). This difference highlights the unique geomorphological setting of the Jimma-Metu-Gore corridor, where lithological weathering and hydrological triggers are more critical than the gradient.

On the other hand, while the literature usually correlates higher elevations with maximized landslide redundancy due to increased rainfall and weathering, the landslide inventory in this study shows that many failures occurred in lower elevation zones, (Catani et al., 2013). This apparent discrepancy may be explained by the concentration of road cuts and human activity in lower valleys, where road construction, drainage alterations, and river undercutting locally increase instability despite lower overall elevation.

In order to understand the influence of causative factors on the occurrence of landslides along the study route, zonal statistical analysis between the causative factor maps and the final landslide susceptibility classes is executed. Regarding to elevation, even though higher elevation should exhibit strong relationship with higher landslide susceptibility, the low elevated regions took a bit larger portion of highly susceptible zones, (Figure 6-3). For example, 67.32% of low elevated regions ranging between 1,213 - 1,515 m located in highly susceptible areas, while high elevated areas ranging 2,118 - 2,481 m covers only 33.03% of the highly susceptible zones. This highlights that a single factor cannot be considered as the only factor influencing the occurrence of landslide which means the other causative factors have significant impact.

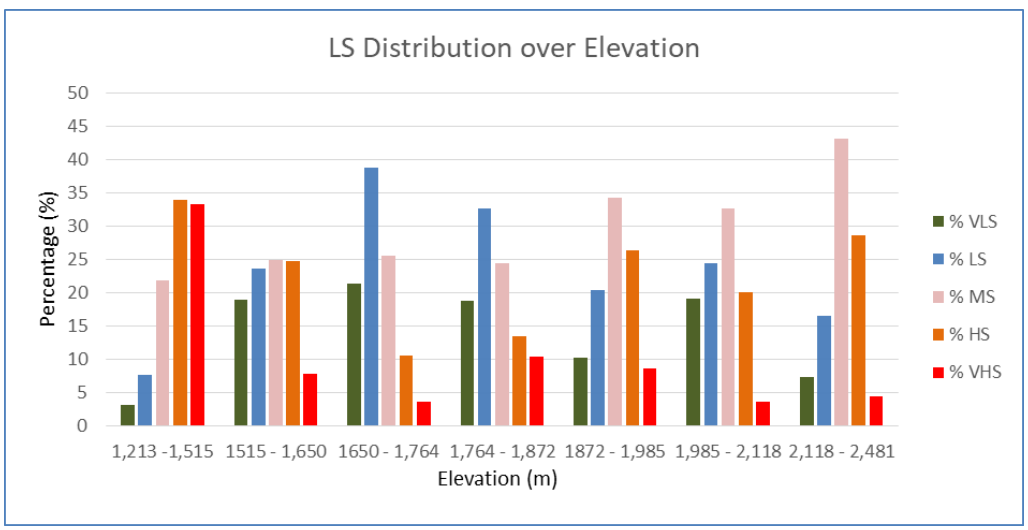


Figure 6-3: Distribution of landslide susceptibility classes across elevation classes

On the other hand, slope angle exhibits one of the strongest controls on landslide susceptibility as the steeper slopes ranging 30 - 65 are predominantly associated with higher susceptibility. 63.21% of the area in the stated slope ranges are found to be high and very high susceptibility classes,

(Figure 6-4). In contrast, gentle slope classes are found to be in less landslide prone zones. For instance 74.61% of the gentle slope regions ranging 0-5 degree are between moderate susceptibility to very low susceptibility categories. This proves the fundamental role of slope gradient in increasing shear stress and gravitational driving forces acting on slope materials causing failure.

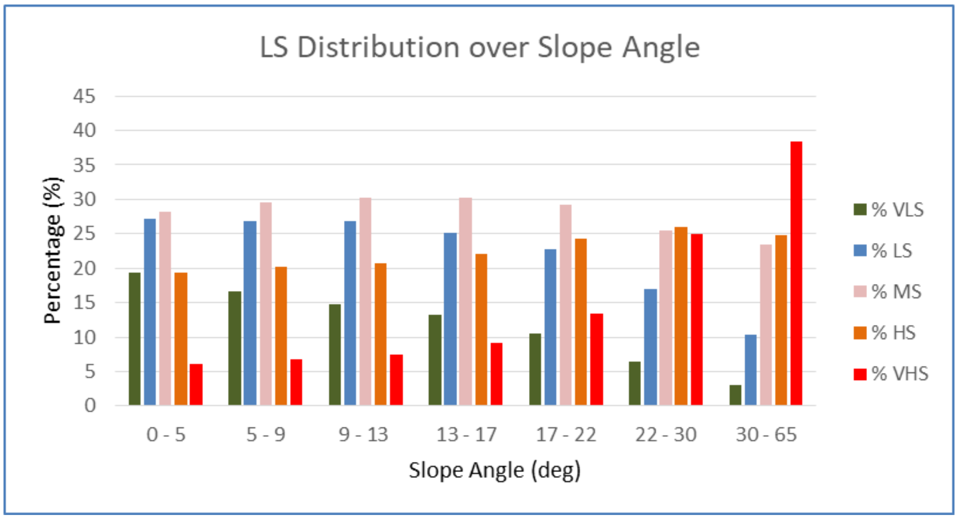


Figure 6-4 Distribution of landslide susceptibility classes across slope angle classes

Regarding to slope aspect, NW, W and SW facing slopes account for 41.86%, 39.75% and 39.25% of high and very high susceptibility zones respectively, (Figure 6-5). These results are relatively higher from the other aspects percent coverage on high and very high susceptibility classes. It prove that NW, W and SW are subjected to higher solar radiation which can accelerate weathering and reduce slope stability. Additionally, curvature analysis shown that concave and convex slope sections have almost equal proportion coverage in every susceptibility class, (Figure 6-6). And flat areas exhibits significant contributions to moderate susceptibility classes covering 29% of the area.

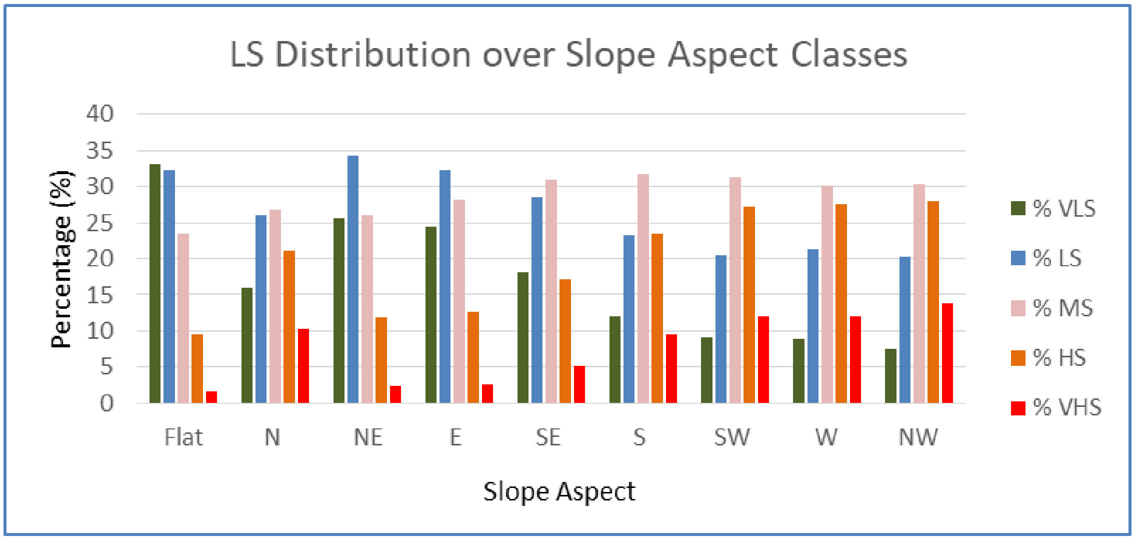


Figure 6-5: Distribution of landslide susceptibility classes across slope aspect classes

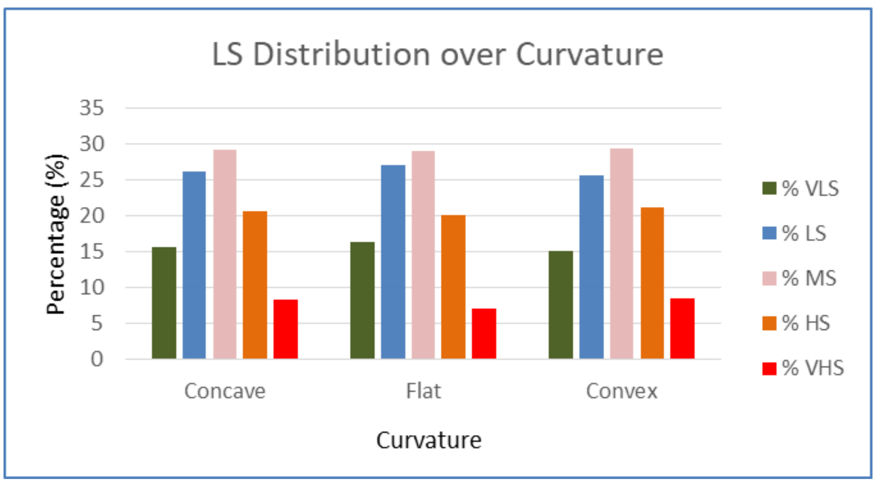


Figure 6-6: Distribution of landslide susceptibility classes across curvature classes

Rainfall is identified to be the most influential landslide causative factor as the data clearly highlights, higher rainfall exposed regions most likely falls into high and very high susceptibility classes, (Figure 6-7). For example rainfall class ranging 1,890 - 1,950 mm covers 50.98% of the high and very high susceptibility classes while rainfall class ranging 1,646 - 1,708 mm covers 63.50% of the very low susceptibility classes. This is proves that heavy rainfall produces rapid surface flow, which can erode slope toes and weakening the stability of upper slope materials.

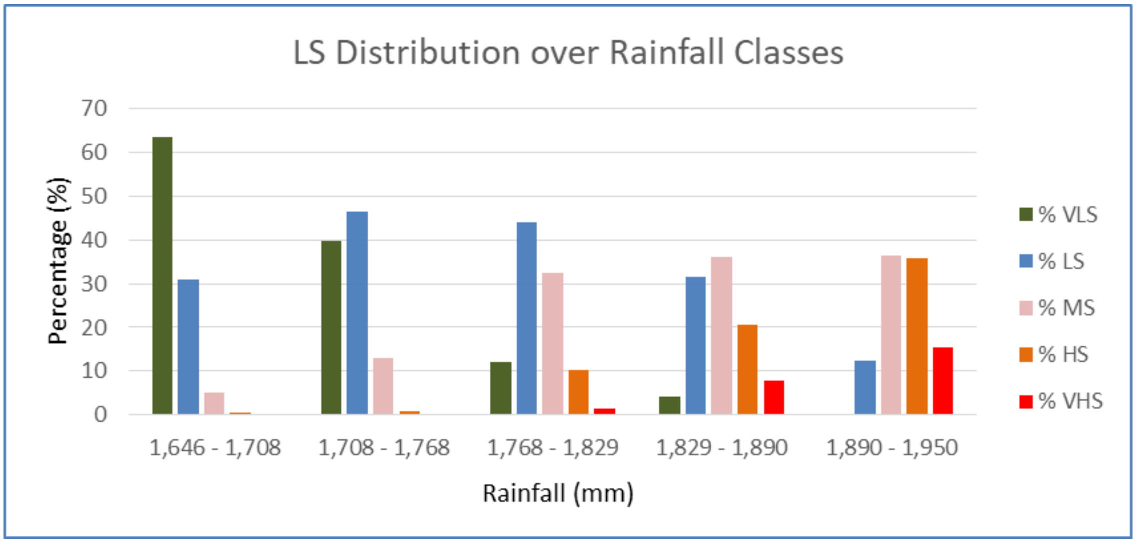


Figure 6-7: Distribution of landslide susceptibility classes across rainfall classes

Among the highly influential landslide causative factors, geology is proven to be one of them as areas underlain by Precambrian metamorphic rocks (pE1) contribute for a large proportion of high and very high susceptibility classes exceeding 78.28% of the total area, (Figure 6-8). The material is known by its formation of planes of weakness that facilitate sliding when saturated and the deep weathering. It can be observed aggravating the occurrence of landslide in combination with high rainfall intensity and poor surface drainage system. The Ashangi (Pga) and felsic volcanic rocks (Nm) mostly lay on the low and moderate susceptibility.

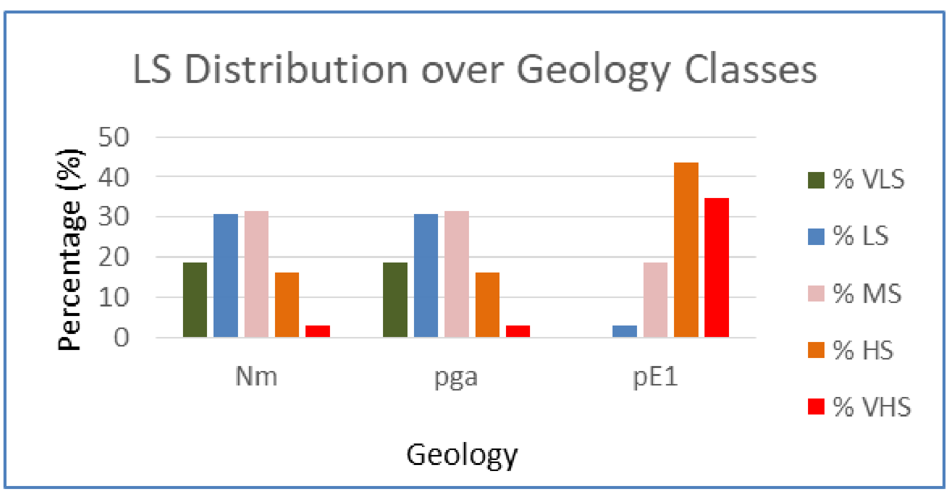

Figure 6-8: Distribution of landslide susceptibility classes across geology classes

The landslide occurrence along the study route is significantly affected by Land use and land cover (LULC) as bare land areas account for a relatively greater percentage of the high and very high susceptibility class which is 42.46%, (Figure 6-9). This reflects the absence of root reinforcement leads to increased erosion and hence slope instability. On the other hand, dense forest and coffee cultivation areas also contribute considerably to moderate and high susceptibility classes especially where steep slopes and high rainfall dominate. Built-up areas show moderate susceptibility contributions while 68.15% of bush land is found to be very low and low susceptibility classes.

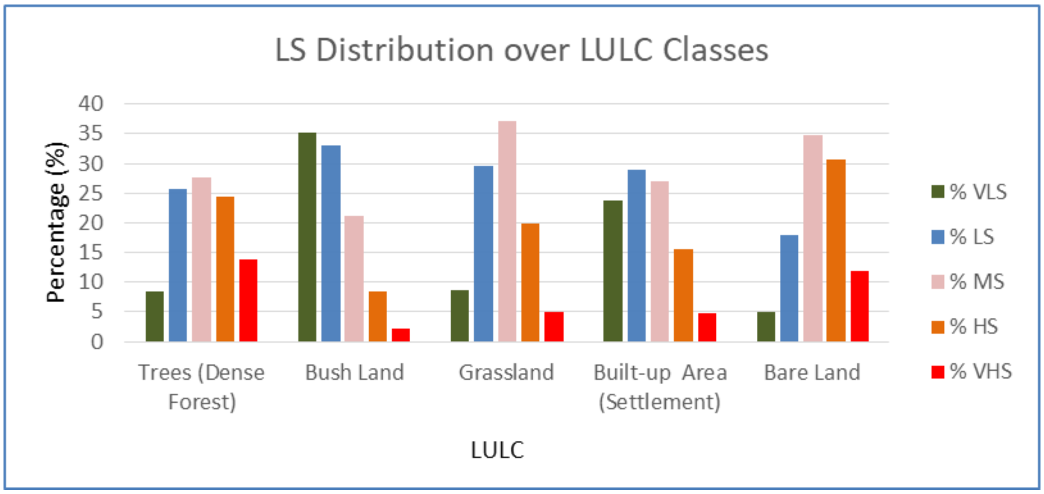


Figure 6-9: Distribution of landslide susceptibility classes across LULC classes

The data obtained regarding to proximity to streams shows a direct relationship with distance. For instance, 62.6% of areas within 0 - 100 m from streams are found to be low and moderate susceptibility zones while 64.96% of areas with in >1000m away from streams lay on high and very high susceptibility zones, (Figure 6-10). This emphasizes the role of other factors such as higher steepness of head of slops contribute more significantly for slope failure as streams are located at toe of slopes with gentle steepness.

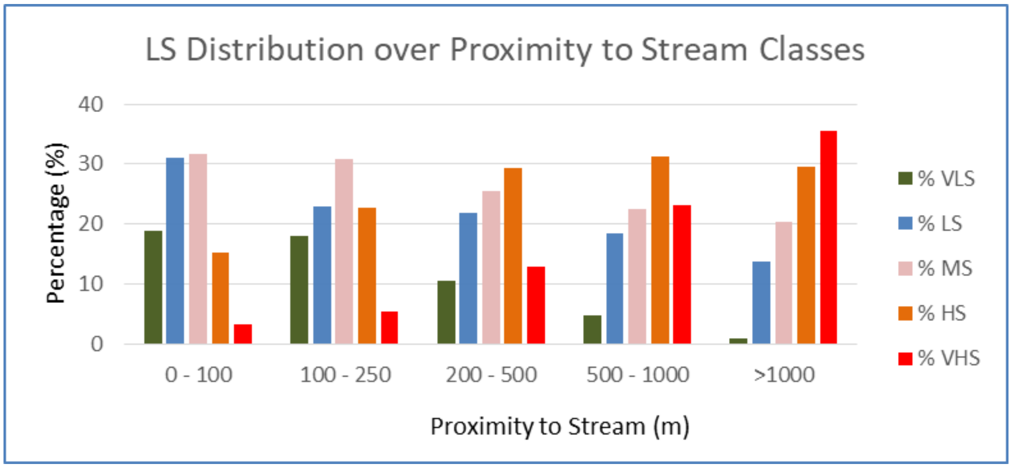


Figure 6-10: Distribution of landslide susceptibility classes across proximity to stream classes

In similar fashion proximity to lineaments shows a direct relationship with distance as 83.28% of areas within >1000m away from streams lay on high and very high susceptibility zones while 60.55% of areas within 0 - 100 m from lineaments are found to be low and moderate susceptibility zones, (Figure 6-11). This highlights the strong contribution of other landslide causative factors for the redundant occurrence of landslide phenomenon.

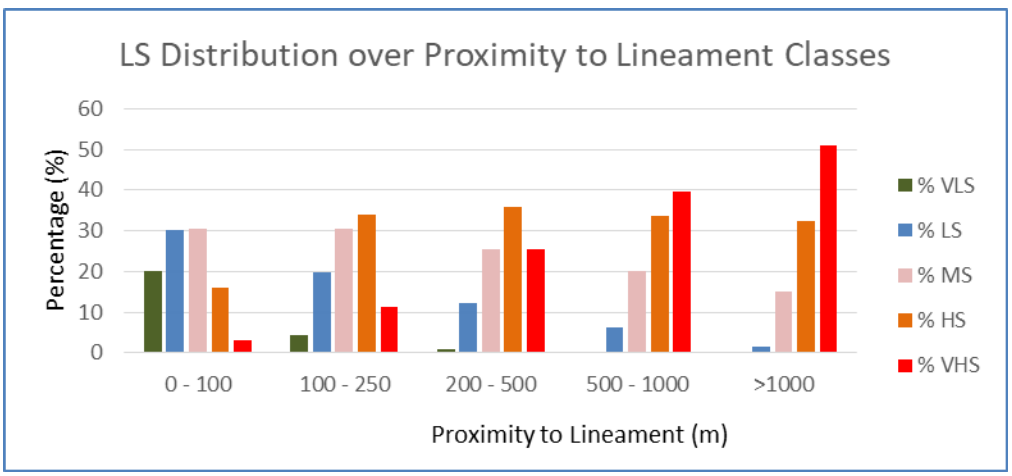


Figure 6-11: Distribution of landslide susceptibility classes across proximity to lineaments classes

Generally the analysis confirms that landslide susceptibility along the study route is mainly controlled by the combined effects of heavy rainfall, unfavorable geological conditions, steepness of slopes and poor land cover characteristics. The percentage based relationships observed across these factor classes are found to be consistent with established landslide susceptibility studies highlighting the effectiveness of the CRITIC based WLC approach applied in this research. The results of this study have direct implications for infrastructure planning and disaster risk reduction providing priority areas for engineering interventions, such as improved drainage systems, slope reinforcement, and regular monitoring. The strong role of rainfall underscores the need for early warning systems and seasonal maintenance schedules during the rainy season. Additionally, the influence of geological and structural factors highlights the importance of detailed geotechnical investigations when designing new road segments or upgrading existing ones.

## 6.6 Proposed Remedial Measures for Landslides along the Study Route

The Jimma-Metu-Gore route faces a hard challenge for daily operation caused by frequent landslide. Based on the desk study, site investigation and landslide susceptibility analysis first level remedial measures specifically tailored to each failure stations are recommended as follows, Table 6-10. However, detailed geotechnical investigation is required before making final decisions and implementing any of the remedial measures.

Table 6-10: Proposed Remedial Measures for Landslides along the Study Route

| Landslide Station | First Level Remedial Measures |
|---|---|
| **36+720** ***(Gechi)*** | ❖ Immediate traffic safety measures, including lane restriction, warning signs, and temporary barriers.<br>❖ Construction reinforced retaining wall to stabilize the road edge.<br>❖ Installation of subsurface drainage systems to reduce pore water pressure.<br>❖ Provision of a proper surface drainage network for diverting runoff away from the crown area.<br>❖ If stabilization proves uneconomical, realignment of the road to a more stable alignment should be considered. |
| **44+000** ***(Hawa Yemobir/Sololo)*** | ❖ Construction of a continuous drainage system along the affected stretch.<br>❖ Stabilization using gabion retaining structures.<br>❖ Improvement of pavement support by strengthening the subgrade and base layers.<br>❖ Establishment of a routine maintenance schedule, particularly before and after the rainy season. |
| **44+800** ***(Yembo)*** | ❖ Installation of subsurface drainage trenches to lower groundwater levels.<br>❖ Replacement of highly deformable clay loam soil with mechanically stabilized material.<br>❖ Regular sealing of pavement cracks to prevent water infiltration.<br>❖ Consideration of partial realignment if deformation persists despite repeated treatment |

| | |
|---|---|
| **46+920** ***(Achebo)*** | ❖ Capture and diversion of spring water using intercepting drains and pipe culverts.<br>❖ Construction of a retaining structure at the road edge.<br>❖ Installation of deep subsurface drains to control internal erosion.<br>❖ Avoidance of repeated refilling without addressing drainage, as this has proven ineffective.<br>❖ Detailed geotechnical investigation before implementing permanent stabilization works. |
| **48+800** ***(Achebo/Dawe)*** | ❖ Implementation of the previously proposed deep foundation system (pile foundation) anchored into bedrock, as recommended by geotechnical consultants.<br>❖ Construction of adequate surface and subsurface drainage to control runoff and seepage.<br>❖ Temporary stabilization using toe support and erosion control until permanent measures are implemented.<br>❖ Strict control of water flow from adjacent streams on both sides of the failure zone. |
| **49+000** ***(Achebo)*** | ❖ Comprehensive slope stabilization design, including retaining structures and ground improvement.<br>❖ Drainage improvement to manage rainfall infiltration and subsurface water.<br>❖ Evaluation of road relocation as a long-term solution due to persistent reactivation. |
| **65+000** ***(Witate)*** | ❖ Strengthening of the existing gabion retaining wall.<br>❖ Installation of additional drainage outlets to relieve water pressure.<br>❖ Reinforcement of the pavement structure using geosynthetics.<br>❖ Continuous monitoring, as the landslide shows progressive deformation. |

| | |
|---|---|
| **66+100**<br>***(Witate)*** | ❖ Construction of a reinforced retaining system combined with toe protection.<br>❖ Installation of efficient surface and subsurface drainage systems.<br>❖ Replacement of failed loam material with stable engineered fill.<br>❖ Establishment of a permanent maintenance and inspection plan, as frequent reactivation has been observed. |
| **85+550**<br>**(*Hurumu/Gaba)*** | ❖ Drainage management should be prioritized, as uncontrolled surface and subsurface water is the dominant triggering factor along the route.<br>❖ Regular maintenance of side drains, culverts, and cross-drainage structures to prevent blockage.<br>❖ Incorporation of slope stabilization measures (retaining walls and gabions) during road upgrading projects.<br>❖ Establishment of a routine monitoring and early warning system, particularly during the rainy season. |
| **201+700**<br>***(Gore)*** | ❖ Immediate traffic safety measures, including lane restriction, warning signs, and temporary barriers.<br>❖ Construction of a reinforced retaining structure to stabilize the road edge.<br>❖ Installation of subsurface drainage systems (horizontal drains or weep holes) to reduce pore water pressure.<br>❖ Provision of a proper surface drainage network to divert runoff away from the crown area.<br>❖ Long-term monitoring of slope movement using visual inspection and simple deformation markers. |

# 7. Conclusions and Recommendations

## 7.1 Conclusions

The Jimma-Metu-Gore route passes through one of Ethiopia's most geological and geomorphological complex terrain connecting major economically significant locations of southwestern Ethiopia. It is characterized by variation of highlands and valleys with intense seasonal rainfall combined with human activities such as poor drainage management. After completing landslide study along the study route, the following conclusions were made.

- ✓ Rainfall received the highest weight (0.159) among the nine factors considered followed by proximity to streams and geology were the second and third coming factors dominating the others with 0.137 and 0.127 respective weights. This indicate that precipitation puts the strongest influence on landslide occurrence of the route. This result is goes perfectly with the climatic conditions of the southwestern Ethiopian highlands, where heavy and prolonged rainfall trigger slope failures.

- ✓ Among the susceptibility classes, the highly susceptible zones (HS and VHS) are characterized by the following factor classes; i) Elevation: 1,213 -1,515m with 34.04% HS and 33.28% VHS zones, ii) Slope Angle: (22-30) degree 26.01% HS Zone and (30 - 65) degree with 38.45% VHS zone, iii) Slope Aspect: NW 28.02% HS and 13.83% VHS zones, iv) Curvature: Convex 21.16% HS and 8.50% VHS zones, v) Rainfall: 1,890 - 1,950mm 35.69% HS and 15.29%VHS zones, vi) Geology: pE1 43.45% HS and 34.83% VHS zones, vii) LULC Bare Land: 30.59% HS zone and Trees (Dense Forest) 13.85% VHS zone, viii) Proximity to Stream: (500 – 1000)m 31.16% HS zone and >1000m 35.47 VHS zone, ix) Proximity to Lineament: (200 – 500)m 35.97% HS zone and >1000m 50.88%VHS zone.

- ✓ Moderate Susceptibility (MS) covers the largest portion of the study area which is 29.39% followed by Low Susceptibility (LS) take 25.95% of the study area, typically referring to areas of gentle terrain, well drained slopes and stable geology. High Susceptibility (HS) covers 20.86%, while Very High Susceptibility (VHS) zones occupy only 8.29% of the total area. The rest part which is 15.51% of the route is covered by the Very Low Susceptibility (VLS) zone.

## 7.2 Recommendations

The findings of this research have important implications for infrastructure planning, hazard mitigation, and sustainable land management along the Jimma-Metu-Gore corridor. Based on the findings during the research progress and the final results obtained, the following recommendations are developed.

- A quantitative approach known as Criteria Importance Through Inter-Criteria Correlation (CRITIC) technique was applied in this research with a limited amount of data collected only along the route with certain cross sectional span. A full scale areal study with intensive site investigation and collection of adequate inventory data have to be conducted in order to address the regional slope failure problem.

- Drainage conditions are recognized as a critical factor influencing slope stability, particularly in road corridors where inadequate surface and subsurface water management can significantly accelerate landslide occurrence. Poorly designed or maintained drainage systems, including blocked side ditches, undersized culverts, and uncontrolled discharge, can lead to water accumulation, increased pore water pressure, and erosion of slope materials. Future studies should include engineering drainage conditions as a key factor in landslide susceptibility assessment. Integrating such data into GIS based models would improve the accuracy of susceptibility mapping by capturing the influence of hydrological disturbances.

- As the major landslide triggering factor identified was seasonal heavy rainfall, the route zones mapped as high and very high susceptibility areas shall be given priority for the design and implementation of engineering counter measures mainly installation of surface and subsurface drainage systems. This measure can prevent number of hazards occurring on the study route that repeatedly causing sudden accidents, traffic flow difficulty and damage of properties.

- Repeated remedial measure for most of landslide damaged areas were applied. However, the failure at those road sections reoccur once or twice a year. Therefore, further detailed and deep study tailored to each of the landslide stations should be conducted in order to understand their failure mechanism and permanently solve the stubborn redundant landslide hazards.

- The bare lands taking significant failure zone percentages which are formed by human activities for developmental and cultivation purpose shall be reforested with larger plants so that their routes reinforce the steep slope subjected to failure.

- Future studies should incorporate time element and develop a landslide hazard map predicting when where failures can occur, their frequency and how intense landslides might occur. This enables strategic selection and application of landslide mitigation measures.

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