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Landslide Threat Evaluation and Zoning in Birbir Mariam District, Gamo Highlands, Ethiopia Great Rift Valley Escarpment

Yonas Oyda[1*], Gebremedhin Berhane[*2], Hailu Regasa[*1]

[1]Department of Geology, Arba Minch University, College of Natural Sciences, Arba Minch, Ethiopia
[2]Department of Earth Sciences, Mekelle University, College of Natural and Computational Sciences, Mekelle city, Ethiopia
*Corresponding author:yonasoyda777@gmail.com

ABSTRACT

The current research focuses on landslide assessment and hazard zonation in the Birbir Mariam district of the Gamo Highlands. The study examined landslide causative factors and used the slope susceptibility evaluation parameter to create a landslide hazard zonation covering an area of 110 square kilometers. The landslide hazard zonation was classified using facet-wise observation. As a result, the intrinsic and external causal parameters of score schemes have been held responsible for slope instability. Inherent causative elements consist of slope geometry, slope material (rock or soil), structural discontinuities, land use or land cover, and groundwater conditions. Rainfall and human interest have seemed like external elements. The intrinsic and external triggering elements for every facet (a total of 106) were rated for their contribution to slope instability. Finally, an evaluated landslide hazard value was calculated and classified into three landslide hazard classes. According to the findings, the area has a high hazard zone of 18.87 percent (20.76 km^2), a moderate hazard zone of 54.72 percent (60.19 km^2), and a low hazard zone of 26.41 percent (29.05 km^2). The methodology employed in this investigation, as well as the resulting landslip susceptibility zonation map, were both reliable and applicable to other places with similar geology and topographic circumstances.

Keywords: Landslide evaluation, Slope stability, Landslide, Hazard zonation, Ethiopia

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1. INTRODUCTION

Landslides are a series of events in which a mass of rocks, soil, or debris slides down a slope due to gravitational pull. The mechanisms include sliding, falling, or flowing material down a slope (Woldearegay, 2013). Landslides are one of the most common geological hazards in the world, with a high incidence, a wide range of distribution, and catastrophic severity, resulting in numerous fatalities each year (van Western *et al*., 2008; Abbate *et al*., 2015; Bernat *et al*., 2019).

Landslides are caused by inherent causative parameters that define the unfavorable stability conditions within the slope, such as slope geometry, slope material, structural discontinuities, land use, land cover, and groundwater conditions (Erener and Duzgun, 2012; Santangelo *et al.*,2015; Kannan *et al*., 2015). External causative factors, such as rainfall, volcanism, seismic motion, and human activities, are also relatively variable or dynamic, temporary, and forced by upcoming events (Santangelo *et al*., 2015; Raghuvanshi *et al*., 2014; Silalahi *et al*., 2019). The slope is prone to instability when the slope characterization is steep, and the possibility of a landslide increases as the slope steepness increases (Raghuvanshi *et al*., 2014). Landslides such as rockfall, toppling, and rockslides/avalanches are common in the area because the slope material has been covered by highly fractured bedrock such as basalt and ignimbrite (Ayalew and Yamagish, 2004; Lee and Pradhan, 2007). Discontinuities in the slope, such as bedding, joints, and faults are potentially weak planes that affect slope stability (Ayalew and Yamagishi, 2004; Dahal *et al*., 2012). As a result, the strength of fractured rocks is typically less than that of intact rocks. They are the most vulnerable component of slope geology and critical to understanding their orientation, spacing, continuity, roughness, separation, and type of filling material with slope angle, slope direction, and strength along such potential weak planes (Raghuvanshi *et al*., 2014; Santangelo *et al*., 2015). Land use and land cover affect slope stability, and groundwater conditions on the slope reduce the material's shear strength.

It creates pore water pressure, both of which are important in slope stability conditions (Mulatu *et al*., 2011). Landslides are one of the most common natural disasters in Ethiopia, which includes the current study area of Birbir Miriam district. Slope conditions, slope angle, lithology, soil type, and hydrologic conditions are all factors that can influence slope stability (Silalahi *et al*., 2019).

Human activities such as deforestation, changes caused by the construction of engineering structures on the slope, undercutting the toe of the slope for road construction, and so on all contribute to potential factors. Human fluctuations on the hill can cause the slope to become less stable (Anbalagan, 1992; Ayalew and Yamagishi, 2004; Woldearegay, 2013). The negative impact of landslides is the destruction of infrastructure (houses, roads, buildings, irrigation, canals, etc.), geological and environmental damage, and severe injuries and loss of human and animal life due to landslide events. In the meantime, an organized landslide hazard zonation is critical to minimizing damage to infrastructure, houses, cultivated lands, and loss of life. This significance will be evident when decision-makers employ these landslide zonation maps in regional land use planning, landslide prevention, and mitigation measures (Ayalew and Yamagishi, 2005; Das *et al*., 2012).

The focus of landslide investigation is to assess the nature of susceptibility and the damages to human life, land, roads, buildings, and other properties (Azeze, 2020). As a result, identifying landslide-prone areas is critical to ensuring human life safety and avoiding adverse effects on regional and national economies (Kundu *et al*., 2013; Shahabi and Hashim, 2015). Landslides are common in the Birbir Mariam district along riverbanks, slope toes, and slope faces. Landslides are responsible for any losses and also affect much of the farmland and farmers' income. Moreover, landslides in the study area cause significant damage to properties and massive destruction, particularly in Zala Gutisha and Waro localities, among the height-prone areas.

2. Materials and Methods

2.1 Study area

The current study area is in the Birbir Mariam district of Ethiopia's Gamo Highlands, in the rift valley escarpments. It is approximately 450 kilometers from Addis Abeba's capital city and 47 kilometers from the Zonal capital of Arba Minch town. It has a total area of 110 km^2 and is geographically bounded (UTM Zone 37N) by latitudes ranging from 692000 mN to 702000 mN and longitudes ranging from 342000 mE to 360000 mE. The area can be reached from Arba Minch town via the Chencha-Ezo main road and the Birbir Mariam gravel road (Figure 1). The geological setting has a significant impact on the occurrence of landslides in the study area. Volcanism has affected the southern part of the Main Ethiopian Rift (MER), which includes the Ganjuli graben (Lake Abaya), and the western side of Lake Abaya, which consists of the plateau and the Chenecha escarpment, since the Oligocene (Ebinger *et al*., 1993; Bonini *et al*., 2005; Abbate *et al*., 2015). Pre-rift and post-rift deposits dominate the geology of the study area, and the stratigraphy (Bonini *et al*., 2005) has the following significant units in the Galena and north Abaya basins: Pyroclastic, early flood basalts, alkaline basalt intermediate flows, pyroclastic rocks, Pleistocene basalt, trachyte, and rhyolites Field investigations can be used to map the geology of the study area. Basalt, tuff, and Igeniberite are among the geologic units found in the study area (rock units). The measurement's rock units can be present along rivers, road cuts, and natural hillsides. Overall, the dominance of destructive materials, basalt, and ignimbrite is a crucial feature of the lithologies of this region (Figure 2).

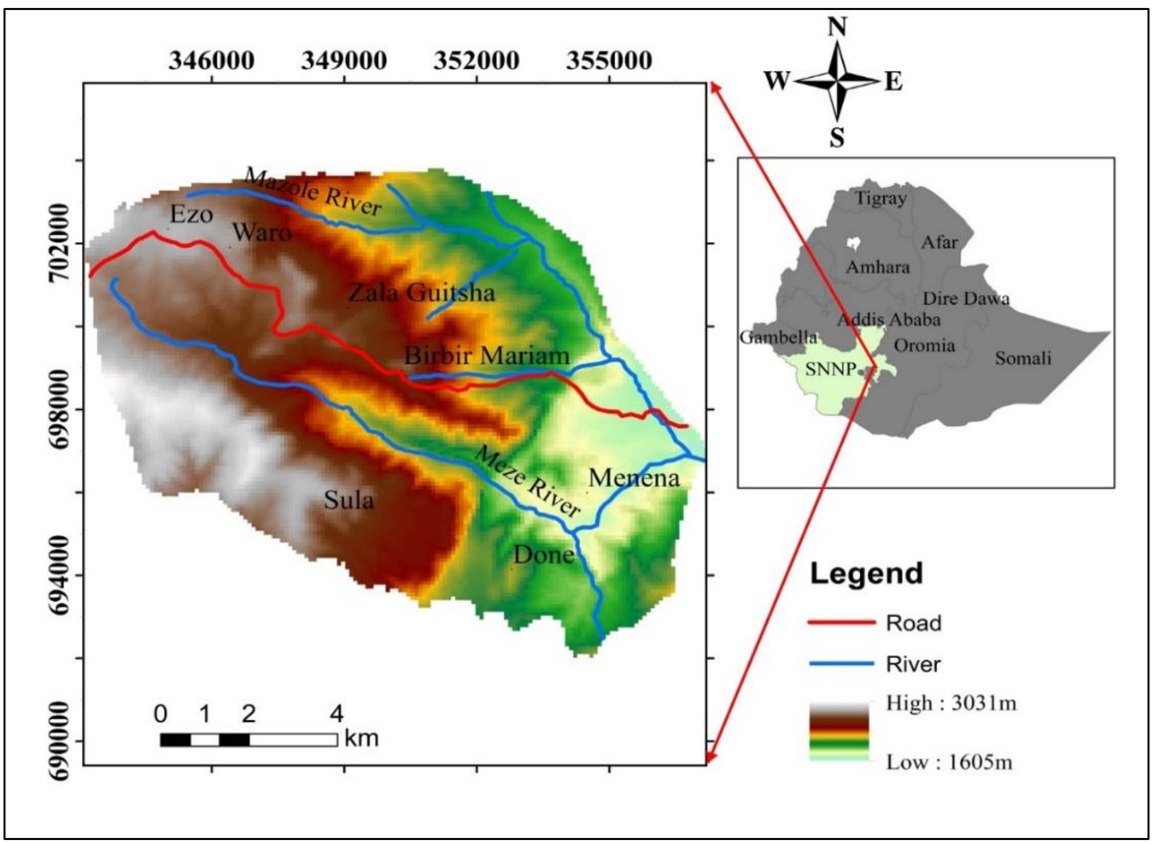

Figure 1 Location map of Birbir Mariam district

2.2 Materials

The datasets used in the current study, including the Ethiopia Mapping Agency's topo-sheet number (0637 D1) at a scale of 1:50,000, were used to delineate the study area and land facet. DEM (Digital Elevation Model) with a spatial resolution of 12.5 m has been downloaded from the Alaska Satellite Facility site. It was used to extract the slope morphometry and relative relief map. The cloud-free optical satellite data acquired by Landsat-8 Operational Land Imager (OLI) with path-row numbers 170-051 obtained on 10 January-2019 was also inputted in the following portal (http://earthexplorer.usgs.gov/), exact and was used to develop a land use /land cover/ map of the current study area.

2.3 Methods

The entire study area was initially divided into 106 slope facets (Figure 3). Facets are land units with more or less uniform slope geometry in slope inclination and direction (Azeze, 2020). Topographical maps were used to delineate the slope facets for this purpose. Significant and minor hill ridges, primary and secondary streams, and other topographical undulations defined facet boundaries (Bonini *et al*., 2005; Azeze, 2020). The prepared facet map was then used as a base map to collect data on the various causative factors. Relative relief, land use, land cover, groundwater conditions, rain-induced manifestations, and human activities are all factors that contribute to slope instability (Ayalew, 1999; Santangelo *et al*., 2015). As a result, the susceptibility evaluation parameter rating was assigned for each causative factor to evaluate the landslide hazard

Table 1 Rating methods for both intrinsic and external causative factors (Anbalagan, 1992; Raghuvanishi et al., 2014, 2015).

Code	Susceptibility evaluation parameter (SEP) Parameters		Maximum rate assigned (R)	Landslide hazard zone	Landslide hazard class	Evaluated landslide hazard
	Intrinsic parameters			High hazard zone	IV	12-8
R1	Slope Geometry	Relative relief	1.0	Moderate hazard zone	III	7.9-5
R2		Slope morphometry	2.0	Low hazard zone	II	4.9-2
R3	Slope geo–material		1.0	Very low hazard zone	I	<2
R4	Structural discontinuity		2.5			
R5	Land use land cover		1.5			
R6	Groundwater condition		2.0			
	External parameters					
R7	Seismicity		2.0			
R8	Rainfall		1.5			
R9	Man-made activity		1.5			
	Total parameters		15.00			

The total maximum susceptibility evaluation parameter rating for the various causative factors is 15. The maximum value was accounted for for slope morphometry, groundwater condition, and seismicity 2.0. Land use, land cover, rainfall-induced surface manifestation, and human activity contributed to a maximum susceptibility evaluation parameter rate of 1.5. Furthermore, relative relief and slope geomaterial each contribute at a rate of 1.0. Structured discontinuity, on the other hand, contributes a maximum susceptibility evaluation parameter rate of 2.50 (Table 1). The evaluated landslide hazard is the total sum of susceptibility evaluation parameter ratings for all causative factors; therefore, the greater the value of the susceptibility evaluation parameter, the greater the degree of hazard.

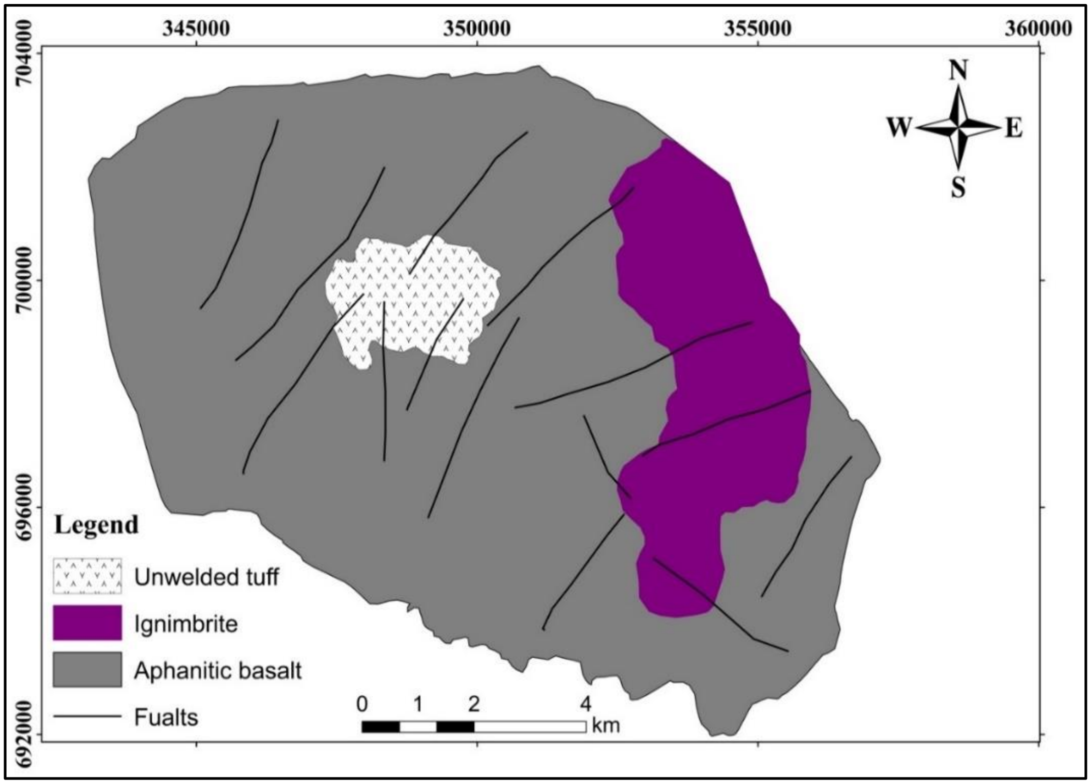

Figure 2 Geological map of the study area

The slope susceptibility evaluation parameter was developed by Raghuvanshi et al. (2014) through taking intrinsic (inherent) and external landslide causative parameters such as slope geometry, geo-material, discontinuity, land use, land cover, groundwater condition, rainfall, and artificial activity. Furthermore, the total likelihood of instability was established by assessing landslide hazards, and it was determined face-to-facet for which observations and investigations were made during the fieldwork. As a result, ratings from Table 1 have been assigned and evaluated. The landslide hazard is the total sum of the susceptibility evaluation parameter ratings for the various causative factors for each facet. Each causative parameter was assigned a rate based on subjective judgments acquired from past research on intrinsic and external causing factors and their relative contribution to slope instability. Field and literature review data on intrinsic and extrinsic causative parameters were incorporated. Finally, each causative parameter was rated on a facet-by-facet basis (Figure 3).

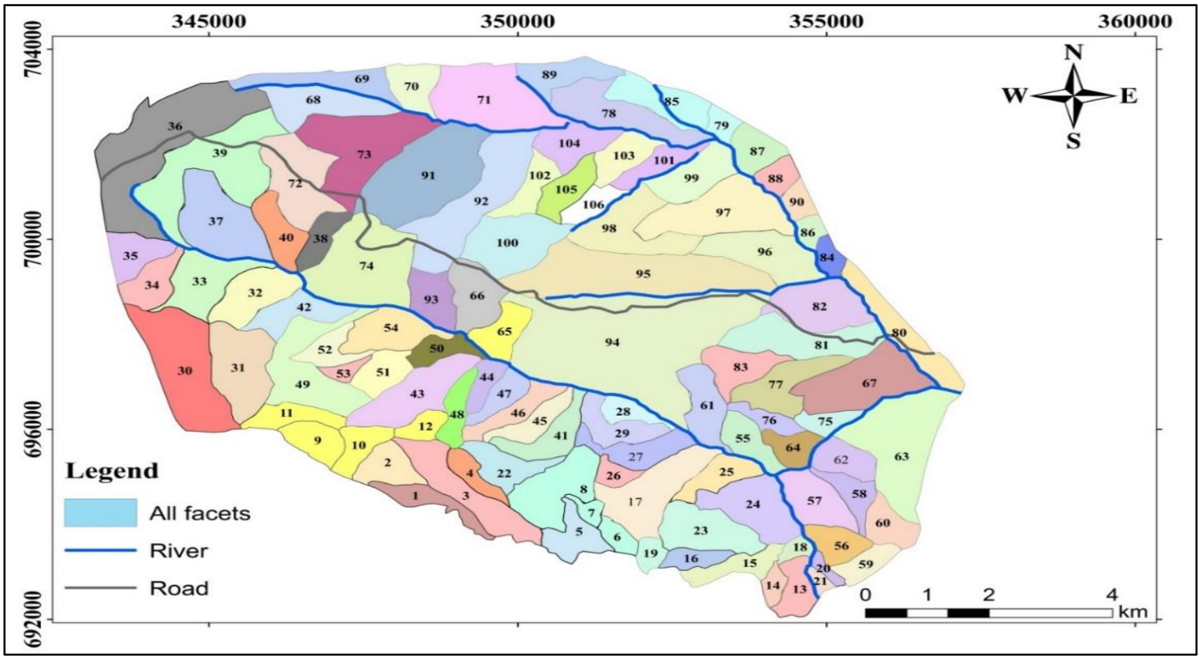

Figure 3 Land facet map of the study area

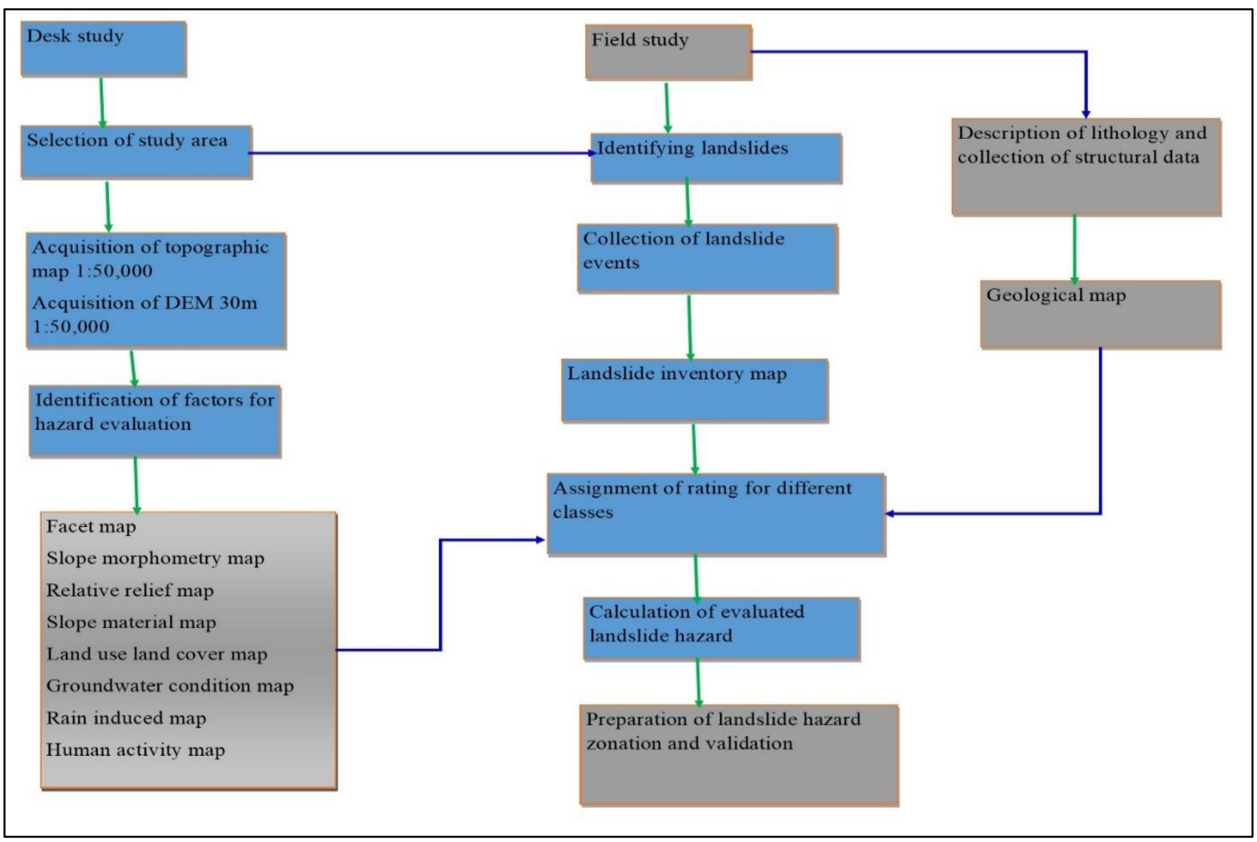

Figure 4 General methodology flow chart for the study

3. RESULTS AND DISCUSSION

3.1 Landslide inventory: Landslide inventions serve as the foundation for classifying landslide hazards (Raghuvanishi et al., 2014, 2015; Silalahi et al., 2019). A thorough understanding of landslide conditions and a more detailed assessment of the area's risks are required for a systematic landslide inventory. Field investigations and previously identified landslide events have been compiled regarding their locations and the conditions of the existing landslide damages. These routine activities are required to proceed with slope stability analysis (Anbalagan, 1992). The landslide inventory map depicts the location and characteristics of past and present landslides. The map does not show the failure mechanisms or the triggering factors. The site's geologic, topographic, and climatic conditions indicate previous slope failures' causes and triggering mechanisms. As a result, landslide inventory mapping provides valuable information about the likelihood of future landslide occurrences. The landslide inventory on sliding processes is based on relevant literature, historical sources, and traditional field survey and mapping. The inventory includes 46 past and present-day mass movements of various types distributed throughout the area. The landslide inventories (Figure 4) were gathered using the direct field survey method. The density of landslides is very high in the central part of the area, which is covered by highly weathered aphanitic basalt.

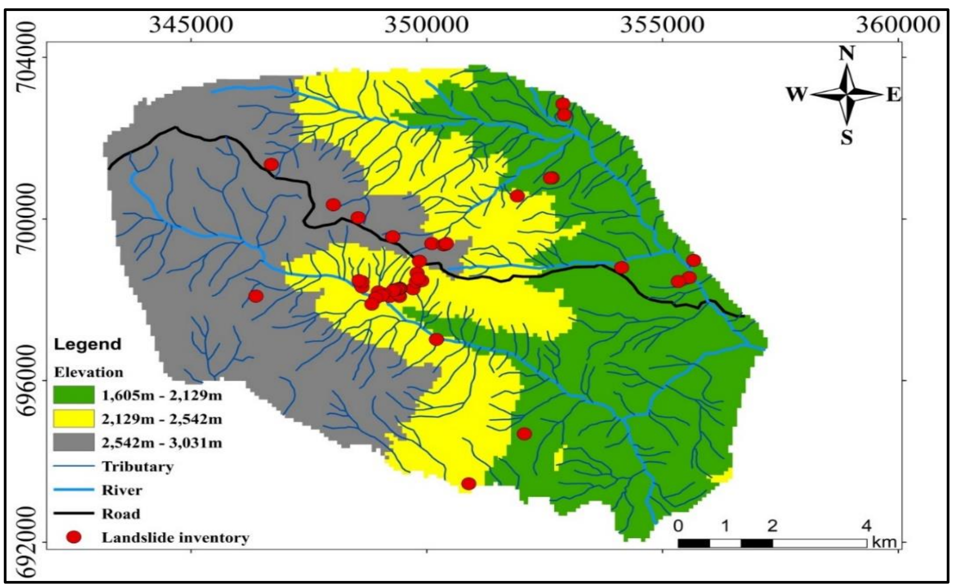

Figure 5 Landslide inventory map of Birbir Mariam district

3.2 Landslide causative parameters

Intrinsic parameters are the inherent or static causative parameters that define whether the slope is stable or unstable (Bonini *et al*., 2005; Azeze, 2020). The main landslide causative factors selected for the Birbir Mariam area are summarized in Table 1, and brief descriptions are provided below. Groundwater condition: Groundwater has a significant impact on slope stability. Groundwater in hilly terrain does not follow a consistent pattern and is generally channeled along structural discontinuities in rocks. The assessment of groundwater behavior in hilly terrain over large areas is difficult and time-consuming. So, for a quick assessment, groundwater behavior was assessed based on surface indications of groundwater, which may provide valuable information on the stability of hill slopes for hazard mapping purposes (Bonini *et al*., 2005; Sarkar *et al*., 2013). Surface indications of groundwater (Figure 6a), such as damp, wet, dripping, and flowing, provide valuable information on the stability of hill slopes and are helpful in rating Chauhan *et al*., 2010; Dahal *et al*., 2012;). Land use and land cover: Land use is also a significant factor responsible for landslide occurrences (Raghuvanshi *et al*., 2014; Jeong *et al*., 2018). Thereby, vegetation covers play an essential role in slope stabilization through a different mechanism. The study area's land use cover is divided into agricultural land, bare land, sparsely vegetated land, and moderately vegetated land categories (Figure 6b). Slope instability can also be described by land cover. Sparsely vegetated and barren areas cause more erosion and thus greater instability than reserves or protected forests, which are densely vegetated and less susceptible to mass wasting processes (Figure 6b).

Slope morphometry: Slope morphometry is the steepness of the slope (Anbalagan, 1992; Guzzetti *et al*., 2012). Slope morphology significantly affects the types of landslides that occur and the severity of the resulting damage to life and property. It is divided into five categories (Figure 6c): escarpment/cliff (> 45°), steep slope (36°–45°), moderately steep slope (26°–35°), gentle slope (16°–25°), and very gentle slope 15° (Erener and Duzgun , 2012).

Relative relief: relative relief is the difference between the maximum and minimum elevation within a given facet. The relative relief map (Figure 6d) depicts the maximum height difference between the ridge top and the valley floor within an individual facet. Based on the slope geometry classification system, this relative relief is classified as very high, high, medium, and moderate in the area. The very high-class value ranges from elevations more significant than 300m, high 201 m–300 m, medium 101 m–200 m, and moderate 51 m–100 m. As a result, a high relative relief area is more vulnerable to slope failures than a low relative relief area (Das *et al*., 2012; Kannan *et al*., 2015;).

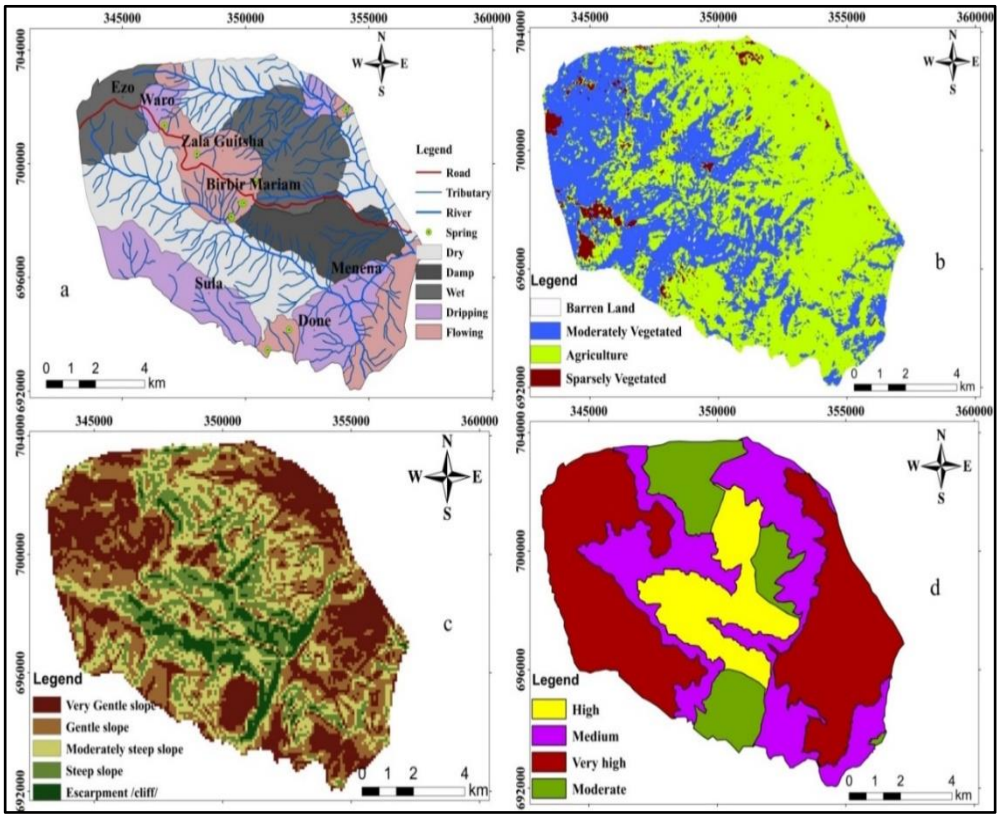

Figure 6 Landslide causative factor maps, a. Groundwater condition manifestation, b. land use land cover, c. slope morphometry, d. relative relief Lithology

Landslides in the study area are primarily caused by lithologies, with the dominant lithological units being highly weathered basalts, ignimbrite, and residual soils overlying the bedrock. Rocks like basalt and ignimbrites, for example, are complex, massive, and resistant to erosion, resulting in steep slopes. Soft rocks, on the other hand, such as tuff, are less resistant to weathering and more prone to erosion and slope instability (Figure 7).

Structural discontinuities: In bedding planes, joints, and faults, there are primary and secondary discontinuities. The preferred orientations of these discontinuities about slope inclination have a significant impact on slope instabilities. Data on the orientation of structural discontinuities were collected facet by facet from the exposed rock mass, and their relationship to slope inclinations was determined. Based on field observations and preliminary analysis, joints and faults were identified as the primary geologic structures for further hazard/susceptibility evaluations. Facet-by-facet, structural data were collected, and ratings were assigned based on the proposed slope susceptibility evaluation parameter and weight (Table 1).

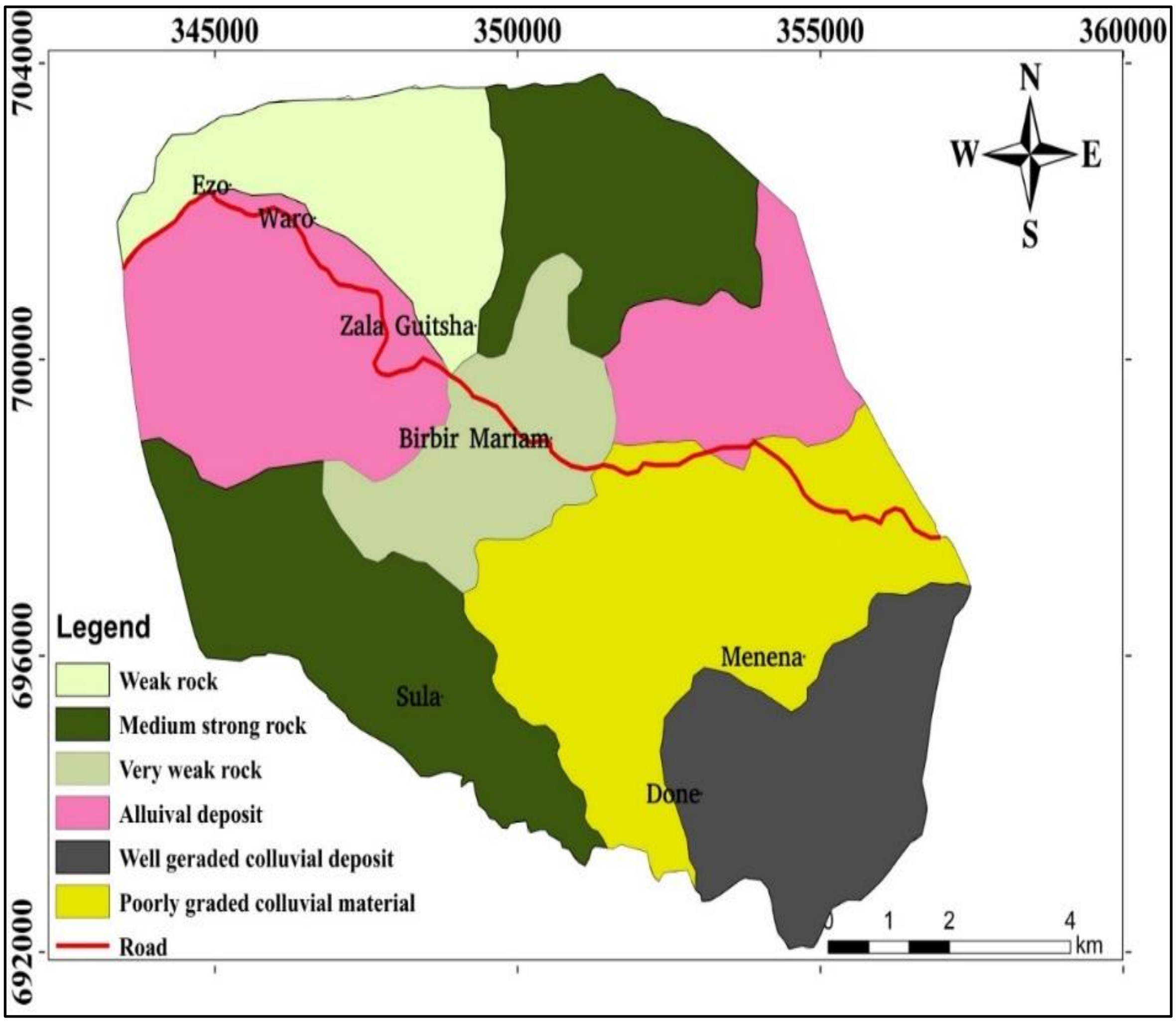

Figure 7 Slope geo-material map of Birbir Mariam district

Rainfall manifestation: The average annual rainfall in the study area is 1372.8 mm. Rain has a significant impact on the slope stability condition (Ayalew, 1999; Meten et al., 2015;). However, due to the nature of the materials exposed on the slopes and the drainage characteristics of the slopes, this is not always the case. As a result, rainfall-induced features are critical indicators for assessing the role of rainfall on slope instabilities. The rainfall-induced manifestations on slopes (e.g., gully formation, toe erosion, stream bank erosion) were considered when assigning the rainfall rating.

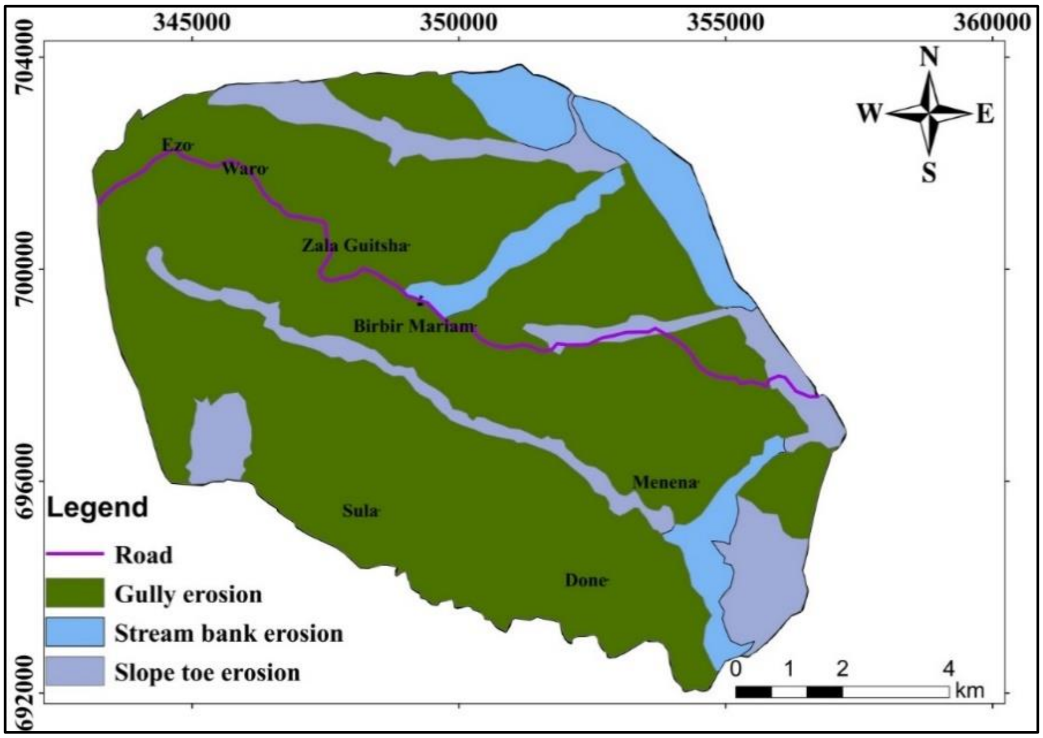

Figure 8 Rainfall induced surface manifestation map

In addition to naturally causing parameters, Man-made activities are also increasing the potential instability (Kanungo et al., 2009). Developmental activities such as road construction and cultivation have a negative impact on slope stability conditions. Such anthropogenic activities increased the moisture content of soil or rock masses and decreased slope stability.

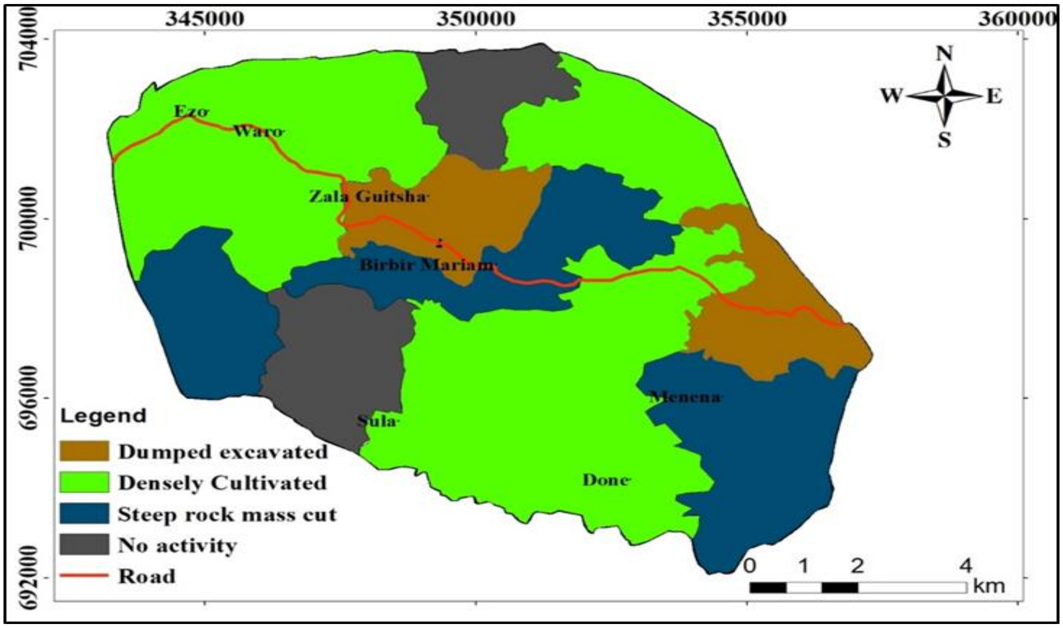

Figure 9 Anthropogenic developmental activities affecting slope stability

3.3 Landslide hazard zonation

The study area's slopes were divided into individual land facets for landslide hazard zonation. A total of 106 slope land facets were delineated (Figure 3). Individual slope facets were given class ratings based on their relative relief. From a total area of 110 km2, 60.5 km2 (55%) is in very high relative relief (> 300 meters), 24.2 km2 (22%) is in high relative relief (201-300 meters), 14.3 km2 (13%) is in medium relative relief (101-200 meters), and 11 km2 (10%) is in moderate relative relief (51-100 meters) (Figure 6d). The steepness of the slopes is determined by slope morphometry. Around 18.87 percent of slopes in the study area are classified as escarpments or cliffs (> 45°), and 29.25 percent are classified as steps (36°–45°). Moderately steep slope (26°–35°), gentle slope (16°–25°), and very gentle slope (15°) account for 30.19 percent, 15.09 percent, and 6.60 percent of the remaining slope, respectively (Figure 6c). The slope geomaterial of the study area is characterized by highly weathered and disintegrated rock masses due to the geological setting of the area. The study area's most dominant lithological units are highly weathered basalt. Chemical and physical weathering is very common in these rock types, and it was found in the northwest and central parts of the area. The dominant geological structures affecting the slope material are faults and joints. The most common slope materials are residual soils and alluvial and colluvial deposits (Chauhan *et al*., 2010; Guzzetti *et al*., 2012). The degree of weathering may impact the relative strength of the rocks, which was considered when assigning ratings to the different rock types. Fresh, slightly weathered, moderately weathered, extremely weathered, and residual soil are all terms used to describe the degree of weathering (Lee and Pradhan, 2007; Das *et al*., 2012).

Using the topographic map as a base map, a slope material map of the study area was created based on field observations. According to the map, soil mass covers 58.11 percent of the total area, disintegrated rock mass covers 28.3 percent, and medium-strong rock mass covers 18.87 percent (Figure 7). Residual soils are more consolidated and have a higher shear strength than alluvial or recently deposited soils (Anbalagan, 1992). Data related to the orientation of structural discontinuities were collected facet-wise from the rock mass outcrops, and their relation to slope inclinations was evaluated. The rock mass condition concerning structural discontinuities was also observed. Accordingly, ratings were assigned for structural discontinuities based on the standard table of slope susceptibility evaluation parameters.

A significant portion of the slopes is covered by agricultural land, according to land use land cover (43.4 percent). Furthermore, moderately vegetated, sparsely vegetated, and barren land cover 27.34 percent, 18.87 percent, and 10.39 percent of the total land area, respectively (Fig. 6b). Surface indicators such as damp, wet, dripping, and flowing water were considered for each facet. Watermarks, algal growth, and other anomalies were also noted. As a result, each land facet was given a rating (Figure 6a). According to a rainfall record, the study area received more rain from April to June and July to October. Rain-induced slope manifestations such as gully, toe, and stream bank erosion were also considered. Slope toe erosion, stream bank erosion, and gully erosion accounted for 24.53 percent, 20.75 percent, and 54.72 percent of total erosion (Figure 8).

Cultivation, road construction, and unsafe material dumping are examples of artificial activities that affect the slope stability of the study area. Field data showed that intensive cultivation activity accounted for 43.4 percent of the total, steep rock cuts for road construction accounted for 26.4 percent, and hazardous dumped materials accounted for 22.6 percent. Approximately 7.6% of the total area is unaffected by human activity (Figure 9). The study area's landslide hazard zonation was determined facet-by-face using the evaluated landslide hazard, which indicated the net probability of instability. The area was divided into three zones based on the assessed landslide hazard values: high hazard zone, moderate hazard zone, and low hazard zone (Figure 10a).

The high-hazard zones are mostly concentrated in the central and northeast parts of the current study area. These areas are primarily agricultural lands that have been subjected to a variety of anthropogenic activities. Most of the main roads that cross the area fall within the high-hazard zone areas. Along the main road, it is common to observe slope failures in the form of rock falls. Such failures mainly occurred following heavy rains. It was also reported that in the past, the main road had frequent failures and maintenance. The issue persists due to a lack of proper understanding of the causes and mechanisms of failures in the area. The area's southern and northeastern parts are in the moderate hazard zone, while the west and northwestern parts are in the low hazard zone (Figure 10a). The study area's landslide hazard map shows that 18.87 percent (20.76km2) are in the high hazard zone, 54.72 percent (60.19km2) are in the moderate hazard zone, and 26.41 percent (29.05km2) are in the low hazard zone.

3.5 Validation of susceptibility evaluation rating scheme

The prepared landslide hazard zonation map for the current study area was validated by comparing it to existing landslide inventory data. These landslide activities were primarily concentrated along the road section and river banks. The landslide inventories were superimposed on a landslide hazard map created for the area. Based on the validation (by overlying), 37 (80.43 percent) of the 46 landslide inventory data fall under the high hazard zone, 9 (19.57 percent) fall under the moderate hazard zone, and no landslide occurred in the low hazard zone. As a result, the landslide hazard zonation map produced by the slope susceptibility rating scheme is reliable and comparable to actual ground conditions (Figure 10b).

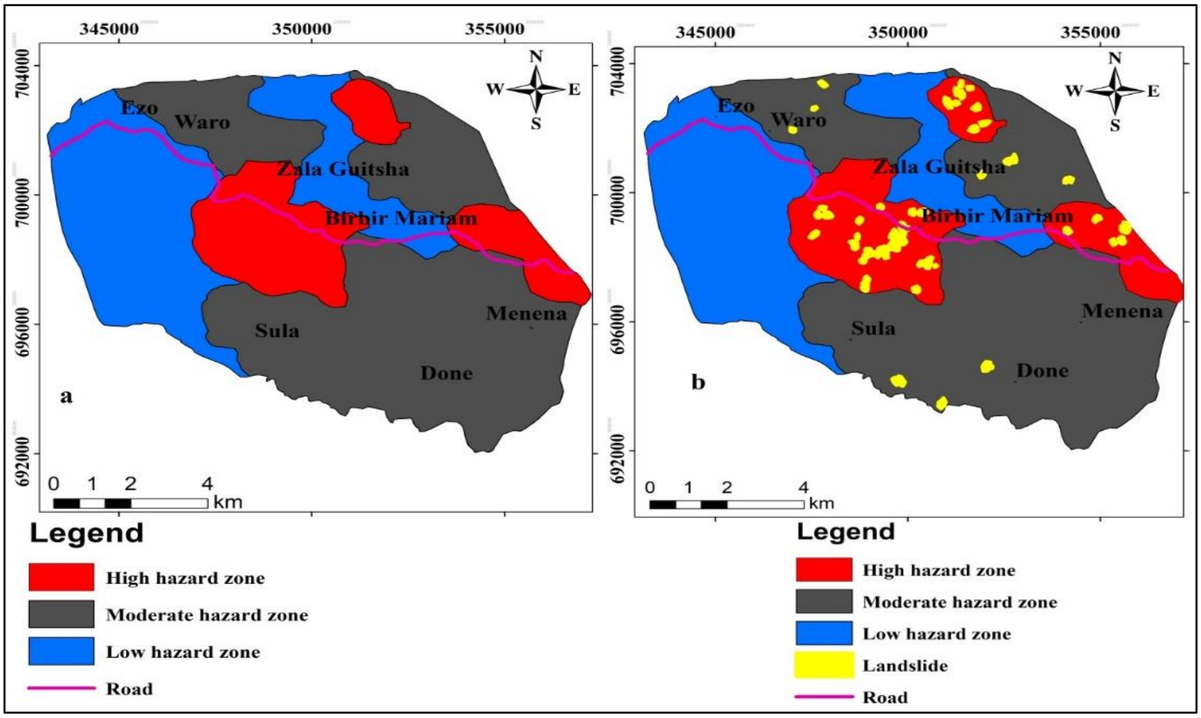

Figure 10 a. Landslide hazard zonation map of Birbir Mariam and b. Validation of present landslide hazard zonation map of Birbir Mariam

CONCLUSIONS

Landslide hazards and susceptibility zonation are critical for land use planning and development activities in highland and mountain terrain. A landslide hazard zonation was created using the susceptibility evaluation parameter rating. Based on their role and contribution to slope instability, this method considers intrinsic and external causative parameters used in the Birbir Mariam district. According to the findings, 18.87 percent of the total area (20.76 km^2) is in the high hazard zone, 54.72 % (60.19 km^2) is in the moderate hazard zone, and 26.41 percent (29.05 km^2) is in the low hazard zone. The generated landslide susceptibility zonation map was compared to actual past landslide activity data to ensure accuracy. According to the comparison, 37 (80.43 percent) of the 46 landslide inventory data fall into the high hazard zone, 9 (19.57 percent) fall into the moderate hazard zone, and none fall into the low hazard zone. As a result, the method used in this study and the resulting landslide susceptibility zonation map were reliable and could be used in other areas with similar geologic and topographic conditions.

Conflict of interest

No potential conflicts of interest are reported by the authors.

REFERENCES

Anbalagan R (1992). Landslide hazard evaluation and zonation mapping in mountainous terrain. *Eng Geol*.32(4): 269–77.

Abbate E, Bruni P, Sagri M (2015). Geology of Ethiopia: A Review and Geomorphological Perspectives.–65.

Ayalew L, Yamagishi H (2004). Slope failures in the Blue Nile basin, as seen from landscape evolution perspective. Geomorphology, 57(1–2):95–116.

Bernat Gazibara S, Krkač M, Mihalić Arbanas S (2019). Landslide inventory mapping using LiDAR data in the City of Zagreb (Croatia). *J Maps*, 15(2):773–9.

Calligaris C, Poretti G, Tariq S, Melis MT (2017). First steps towards a landslide inventory map of the Central Karakoram National Park First steps towards a landslide inventory map of the 7254.

Erener A, Düzgün HSB (2012). Landslide susceptibility assessment: What are the effects of mapping unit and mapping method? *Environ Earth Sci.*, 66(3):859–77.

Binh Thai Pham, Dieu Tien Bui, Prakash Indra, Dholakia M B (2015). Landslide Susceptibility Assessment at a Part of Uttarakhand Himalaya, India using GIS – based Statistical Approach of Frequency Ratio Method. *Int J Eng Res*.V4(11):338–44.

Raghuvanshi TK, Ibrahim J, Ayalew D (2014). Slope stability susceptibility evaluation parameter (SSEP) rating scheme - An approach for landslide hazard zonation. *J African Earth Sci [Internet]*,. 99(PA2):595–612.

Raghuvanshi TK, Negassa L, Kala PM (2015). GIS based Grid overlay method versus modeling approach - A comparative study for landslide hazard zonation (LHZ) in Meta Robi District of West Showa Zone in Ethiopia. *Egypt J Remote Sens Sp Sci*. [Internet];18(2):235–50.

Mulatu E, Raghuvanshi TK, Abebe B (2011). Landslide hazard zonation around Gilgel Gibe-II Hydroelectric project, Southwestern Ethiopia. SINET Ethiop J Sci. 32(1):9–20.

Lee, S., Pradhan, B (2007). Landslide hazard mapping at Selangor, Malaysia using frequency ratio and logistic regression models. Landslides **4**, 33–41. https://doi.org/10.1007/s10346-006-0047-y

Dahal RK, Hasegawa S, Bhandary NP, Poudel PP, Nonomurac A, Yatabe Y (2012). A replication of landslide hazard mapping at catchment scale. Geomat Nat Hazards Risk.

Silalahi FES, Pamela, Arifianti Y, Hidayat F (2019). Landslide susceptibility assessment using frequency ratio model in Bogor, West Java, Indonesia. Geosci Lett [Internet].6(1).

Woldearegay K (2013). Review of the occurrences and influencing factors of landslides in the highlands of Ethiopia: With implications for infrastructural development. Momona Ethiop J Sci., 2013;5(1):3.

Meten M, Bhandary NP, Yatabe R (2015). GIS-based frequency ratio and logistic regression modelling for landslide susceptibility mapping of Debre Sina area in central Ethiopia. J Mt Sci. 12(6):1355–72.

Ayalew L, Yamagishi H (2005). The application of GIS based logistic regression for landslide susceptibility mapping in the Kakuda–Yahiko Mountains. Cent Japan Geomorphol [Internet].;65.

Guzzetti F, Mondini AC, Cardinali M, Fiorucci F, Santangelo M, Chang KT (2012). Landslide inventory maps: New tools for an old problem. Earth-Science Rev [Internet]. 112(1–2):42–66.

Azeze AW (2020). Modeling of Landslide susceptibility in a part of Abay Basin , northwestern Ethiopia.(March).

Chauhan S, Sharma M, Arora MK, Gupta NK (2010). Landslide susceptibility zonation through ratings derived from Artificial Neural Network. Int J Appl Earth Obs Geoinf [Internet]. 12.

Jeong S, Kassim A, Hong M, Saadatkhah N (2018). Susceptibility assessments of landslides in Hulu Kelang area using a geographic information system-based prediction model. Sustain., 10(8).

Santangelo M, Gioia D, Cardinali M, Guzzetti F, Schiattarella M (2015). Landslide inventory map of the upper Sinni River valley, Southern Italy. J Maps [Internet]. 11(3):444–53.

Kannan M, Saranathan E, Anbalagan R (2015). Comparative analysis in GIS-based landslide hazard zonation—a case study in Bodi-Bodimettu Ghat section, Theni District, Tamil Nadu, India. Arab J Geosci. 8(2):691.

Sarkar S, Roy AK, Martha TR (2013). Landslide susceptibility assessment using Information Value Method in parts of the Darjeeling Himalayas. J Geol Soc India, 82(4):351–62.

Shahabi, H., Hashim, M (2015). Landslide susceptibility mapping using GIS-based statistical models and Remote sensing data in tropical environment. Science Rep **5**, 98-99. https://doi.org/10.1038/srep09899

Mezughi TH, Akhir JM, Rafek AG, Abdullah I (2011). Landslide susceptibility mapping using the statistical index method and factor effect analysis along the E- W highway (Gerik - Jeli), Malaysia. Aust J Basic Appl Sci.;5(6):847–57.

Legorreta Paulín G, Bursik M, Hubp JL, Mejía LMP, Aceves Quesada F. (2014). A GIS method for landslide inventory and susceptibility mapping in the Río El Estado watershed, Pico de Orizaba volcano, México. Nat Hazards.;71(1):229–41.

Kundu S, Saha AK, Sharma DC, Pant CC (2013). Remote Sensing and GIS Based Landslide Susceptibility Assessment using Binary Logistic Regression Model: A Case Study in the Ganeshganga Watershed, Himalayas. J Indian Soc Rem Sens [Internet].41. Available from: https://doi.org/10.1007/s12524-012-0255-y.

Ebinger C, Yemane T, Woldegabriel G, Aronson J (1993). Late Eocene-Recent volcanism and faulting in the southern Main Ethiopian Rift Late Eocene-Recent volcanism and faulting in the southern main Ethiopian rift. Journal of the Geological Society, 150: 99 - 108. https://doi.org/10.1144/gsjgs.150.1.0099.

Abbate E, Bruni P, Sagri M (2015). Geology of Ethiopia: A Review and Geomorphological Perspectives.–65.

Bonini M, Corti G, Innocenti F, Manetti P, Mazzarini F, Abebe T (2005). Evolution of the Main Ethiopian Rift in the frame of Afar and Kenya rifts propagation Evolution of the Main Ethiopian Rift in the frame of Afar and Kenya rifts propagation. Tectonics, Vol. 24, Tc1007, Doi:10.1029/2004tc001680, 2005

Ayalew L (1999). The effect of seasonal rainfall on landslides in the highlands of Ethiopia. Bull Eng Geol Environ. 58(1):9–19.

Kanungo DP, Arora MK, Sarkar S, Gupta RP (2009). A fuzzy set based approach for integration of thematic maps for landslide susceptibility zonation. Georisk, 3.

Das I, Stein A, Kerle N, Dadhwal (2012). Landslide susceptibility mapping along road corridors in the Indian Himalayas using Bayesian logistic regression models. Geomorphology [Internet].179. Available from: https://doi.org/10.1016/j.geomorph.2012.08.004.

van Westen CJ, Castellanos E, Kuriakose SL (2008). Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview. Eng Geol.102(3–4):112–31.