ORIGINAL PAPER

Application and Validation of the Evaluation Using Slope Stability Susceptibility Evaluation Parameter Rating System to Debre Werk Area (Northwest Ethiopia)

Dawit Asmare ⬤ · Chalachew Tesfa

Abstract The present research was conducted in the town of Debre Werk, East Gojjam, North West Ethiopia. This study aimed to apply and validate Slope Stability Susceptibility Evaluation Parameter (SSEP) rating system and produce a landslide hazard zonation (LHZ) map of the area. This rating system was done by considering the parameters of intrinsic and external triggering factors that cause landslides. Systematic and detailed fieldwork had been undertaken as a justification. Secondary data, on the other hand, were required to define the general conditions of the area and to gain a thorough understanding of the field of study. Ratings for intrinsic parameters in the SSEP system include slope morphometry, relative relief, slope content, geological structures/discontinuities, land use land cover, groundwater, and external parameters include erosion, seismicity, and manmade activities. Individual facet-wise ratings for intrinsic causative factors and external triggering factors ratings are summarized to evaluate the landslide hazard zonation of an environment. The sum of all causative parameter ratings will give evaluated landslide hazards. Therefore, the research was carried out by dividing the study area into 70 facets. A landslide inventory including 85 landslide activities was prepared. Thus, 23, 39, and 23 landslide activities were identified as active landslide, past landslides, and signs of landslide, respectively. The delineated 70 facets were categorized into three landslide hazard zones. There are about 73.3 km^2 (27.2%) of the study area within the low hazard zone, 140.8 km^2 (52.1%) within the moderate hazard zone, and the remaining 55.9 km^2 (20.7%) within the high hazard zone. Based on the findings of SSEP, it can be deduced that the present research area is highly susceptible to landslides and requires special attention during rainy seasons. Finally, the validity of the prepared LHZ map was checked by overlaying the inventory map over the produced LHZ map. The results were compared with the actual active landslide activity data in the area. The overlay analysis reveals that out of a total of 23 active landslide locations, 19 (82.6%) fall within the 'high hazard zone,' whereas the remaining 4 (17.4%) fall within the 'moderate hazard zone.' The validation of the prepared LHZ map suggests that the applications of the SSEP rating system provide a good basis to produce produced LHZ maps.

D. Asmare (✉) · C. Tesfa
Debre Markos Institute of Technology, Debre Markos University, P.O. Box 269, Debre Markos, Ethiopia
e-mail: dawitasmare55@gmail.com

C. Tesfa
e-mail: chalachewtesfa@gmail.com

1 Introduction

Landslides are a frequent natural occurrence in Ethiopia, particularly in hilly and mountainous terrains. It is the product of a combination of several processes that include meteorological, earthquakes, precipitation, geological, and human influences (Kumar and Anbalagan 2015; Jamalullail et al. 2021; Nowicki et al. 2018). Further, the interaction of soil, vegetation, and atmosphere can cause significant pore pressure variations in the soil, which can lead to slope instabilities (Pedone et al. 2021). Landslide is responsible for immediate economic harm, damages to property and repair costs, accidents, or loss of life (Dai and Lee 2001; Asmare and Hailemariam 2021). The Ethiopian highlands are defined by complex geological conditions, poor soil cover, high rainfall, geomorphological settings, and uncertain hydrogeological and hydrological conditions (Ayalew and Yamagishi 2005; Hamza and Raghuvanshi 2017; Raghuvanshi et al. 2014). These conditions are usually responsible for massive to small landslides. Landslide is mostly originated in muddy areas, road cuts, stream cuts, or valleys. The soil type and physiographic conditions of the area are susceptible to landslides. Besides, landslide during the rainy season is a common concern of the area (Elia et al. 2020; Jamalullail et al. 2021). Therefore, landslide hazard zoning and evaluation are perhaps the most critical components of any development and settlement in the area. In detail, the present research area is in the Ethiopian highlands.

Landslide Hazard Zonation is a process of ranking different parts of an area based on the degrees of actual or potential hazard from landslides (Varnes 1984). Landslide hazard zoning (LHZ) was carried out according to various approaches. Such approaches can be divided into three main classes; statistical methods, expert evaluation methods, and deterministic methods (Fall et al. 2006; Dai and Lee 2001; Du et al. 2017; Van Westen et al. 2003; Cotecchia et al. 2016; Jamalullail et al. 2021). However, there is no agreement on the methods used for the production of landslide hazard zoning (LHZ) as several qualitative and quantitative methods have been proposed for landslide susceptibility evaluation. Selection of approaches for landslide hazard zoning depends on the size of the analysis to be performed, the total coverage area, expertise, and skill set of evaluators,

the geological or geomorphic parameters or methods used to produce parameter data (Fall et al. 2006; Ermias et al. 2017). For the present study, the slope stability susceptibility evaluation parameter (SSEP) rating system was followed. This system is preferred due to the ease of its application and considers both intrinsic (causative) factors and external (triggering) parameters that are responsible for slope instability. Besides, it is more practical and provides much more realistic field data well supported by the experience of an expert.

This study applies and validates the performance of the slope stability susceptibility evaluation parameter (SSEP) rating system by producing a landslide hazard zonation (LHZ) map of the study area. The validation was performed by overlaying the past landslide inventory map of the study area on the produced landslide hazard zonation (LHZ) map.

2 Study Area

Landslide hazard zonation (LHZ) mapping has been carried out in an area of 270 km² in the Northwestern Ethiopian Plateau (NWP), in the Amhara regional state. The Abay River Gorge to the east and Choke Mountain to the west define its boundaries (Fig. 1). Generally, the topographical setting of the study area exhibits a highly rugged nature. The climate condition of the area is characterized by mean sea level 2300–3300 m and mean annual temperature between 10 and 15 °C. Generally, the area receives rainfall twice a year. These are heavy precipitation from June to September and light to moderate precipitation from mid-February to mid-March. However, there are also unseasonal or unexpected rainfalls in the area. The study area was selected considering the drainage networks, lineaments, ridges, and past landslide events.

3 Geology

The research area is located in the Northwestern Plateau, which is defined by the geology of the Abay basin. The basin composes of Precambrian basement, Mesozoic sedimentary rocks, Palaeozoic and Tertiary to Quaternary volcanic rocks, and Quaternary deposits (Assefa 1991; Gani et al. 2008; Mogessie et al. 2002;
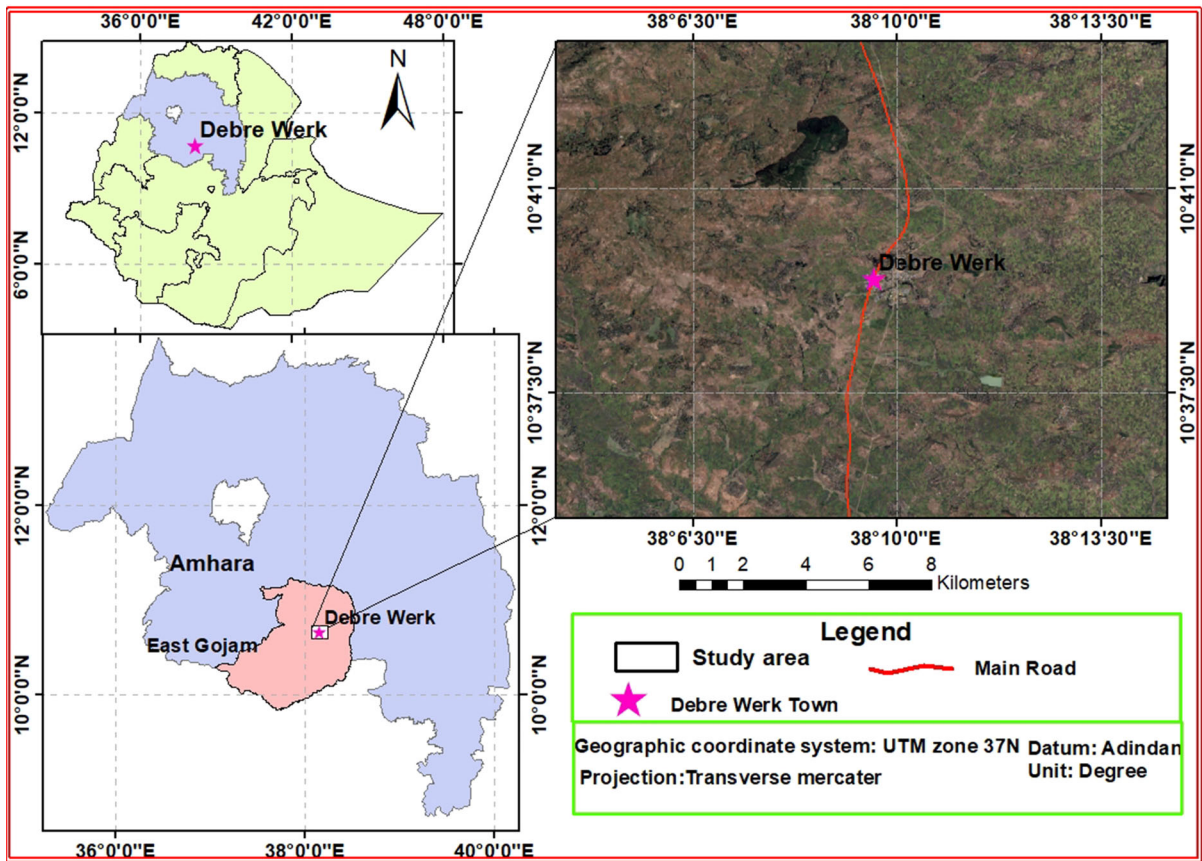
Fig. 1 Study area

Lebenie and Bussert 2009; Ahmed 2008, 2009; Gani and Abdelsalam 2006).

According to the regional map prepared by Tefera et al. (1996), the study area consists of different geological formations including Tarmaber Gussa, quaternary sediments, Ashange formation, Ambaradom formation, Antalo formation, Abay formation, basalt flow, spatter cones, and hyaloclastites, Alkaline basalts, Shield volcano of the Ethiopian plateau, other major volcanic edifices. Alkaline to transitional basalts, frequently forming shield volcanoes with small trachyte and phonolite flows, and Late Proterozoic Ultramafic rock, consisting of serpentinite, peridotite, dunite, and talc schists, define the Tarmaber Gussa formation. The Quaternary sediments are the youngest sediments that are composed of alluvial, colluvial, and lacustrine deposits (Mogessie et al. 2002; Poppe et al. 2013). Ashangi formation is characterized by extremely weathered Alkaline and transitional basalt flows with unusual tuff intercalation, frequently tilted (contains Akobo basalts of SW Ethiopia). Ambaradom formation consists of sandstone, conglomerate, and shale. Antalo formation consists of limestone formation and Abay formation consists of middle Jurassic limestone, shale, and gypsum (Fig. SM1).

Slope colluvium is mixed with alluvial and colluvial deposits formed by fluvial processes (Poppe et al. 2013). Quaternary lacustrine, fluvial-colluvial, and superficial deposits cover the basement and fill river channels on an irregular basis (Kebede et al. 2005). Colluvial is material that moves downslope primarily under the influence of gravity. These materials consist of rock fragments and soil which is accumulated on the slopes.

4 Data Preparation

To map the landslide susceptibility of the study area, the spatial database was designed and developed. This

database contained three primary parts: (1) the land-slide inventory dataset, (2) the facet map dataset, and (3) the datasets of landslide controlling factors.

4.1 Preparation of Landslide Inventory

Landslide inventory is used to document the location and dimensions of landslides. It is a basic and essential component for landslide susceptibility mapping processes (Du et al. 2017). Landslide inventory map determines the type, behavior, and spatial variability of each landslide (Soeters, and Van Westen 1996). Landslide inventory is essential to investigate the relationship between the conditioning factors and the distribution of landslides.

The inventory mapping of the present study was carried out through field surveys, historic data, satellite imagery, and aerial photo interpretation. Accordingly, a recent landslide has occurred in the area along with the valley and river cuts such as Zunjit, Teza, and Zeya River and its tributaries. It covers an extensive area and this slide is still progressing headward. Generally, in the present study, a landslide database inventory with 85 landslide activities was identified and mapped. Thus, 23, 39, and 23 landslide activities were identified as active landslide, past landslides, and signs of landslide, respectively.

4.2 Facet Map Preparation

A facet map is a piece of land with generally uniform slope geometry in terms of slope inclination and slope direction (Raghuvanshi et al. 2014; Anbalagan 1992). Initially, the topography of the study area to be mapped was extensively studied, and then the area was divided into several facets. The facet boundaries were demarcated following hill ridges (can be major or minor), streams (main and tributary), and different topographical features.

Accordingly, the present study area to be covered was divided into several slope facets. This is performed by using Google Earth Pro, Global mapper 20 software, and DEM 30 m data obtained from USGS data sources. Finally, the area was divided into 70 slope facets (Fig. 2). The prepared facet map was later used as a base map for several predisposing factor maps.

4.3 Landslide Causative Factors

Landslide is the product of a broad range of processes influenced by geological, meteorological, and geomorphological factors (Chingkhei et al. 2013; Ermias 2017; Anbalagan 1992). Some of the major cause of slope failure includes intrinsic parameters (slope geometry (relative relief, slope morphometry), slope material (rock and soil nature), structural discontinuity conditions, groundwater conditions), and external causative parameters (rainfall, manmade activities, and seismicity) (Varnes 1984; Anbalagan 1992; Ermias 2017).

According to Raghuvanshi et al. (2014) discussion, most of the slope instability observed in the present research area is the result of the combined effect of all of the above-mentioned causative and triggering factors. In this study, the ratings for all causative factors were assigned and classified based on the presentation provided by Raghuvanshi et al. (2014).

4.3.1 Slope Geometry

In landslide zonation, the most important geomorphological feature to be recognized is the existence of past landslides (Varnes 1984). The slope geometry of the area is also a very important factor that needs consideration in landslide hazard zonation. Slope geometry is defined by the slope's relative relief and slope morphometry.

4.3.1.1 Relative Relief A relative relief map of the research area was produced using topographic maps and DEM. Maximum and minimum elevations were noted for each slope facet, and the variation in the two elevations was used to classify the facet into several relative relief categories. Consequently, the relative relief map of the research area was developed.

The relative relief of the study area was classified into five groups; low (< 50 m), moderate (51–100 m), medium (101–200 m), high (201–300 m), and very high (> 301 m) (Table SM2). Accordingly, as presented in Table SM2 (see the supplementary material), 29.5 km^2 (10.9%) of the study area showed moderate relief, 160.5 km^2 (59.5%) is medium relief, 51.2 km^2 (19.0%) is high relief and 28.8 km^2 (10.6%) is very high relief zones. As presented in Figure SM3, the majority of the research area is defined by a medium relief zone (101–200 m) and thus contributes to slope
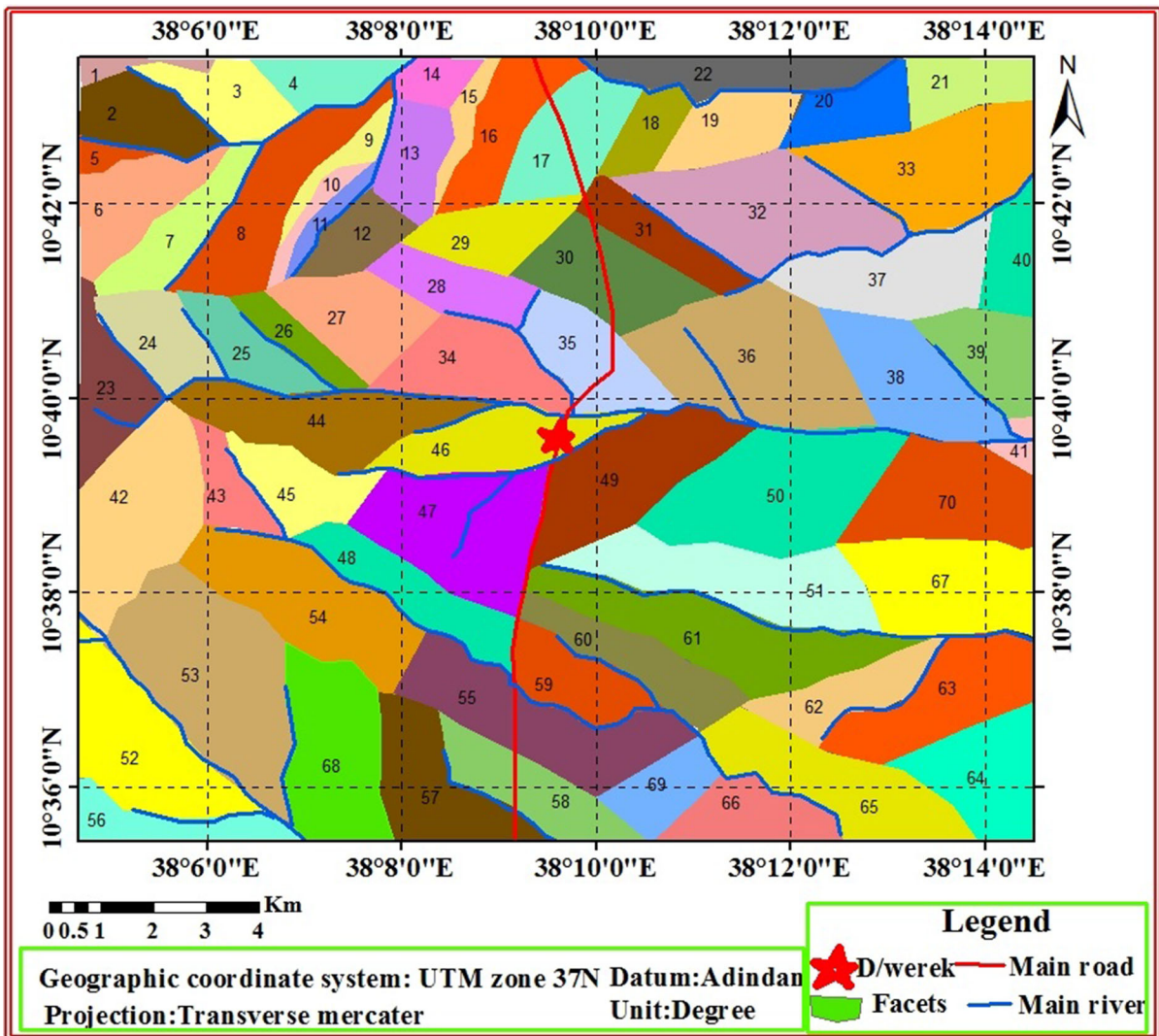
Fig. 2 Facet map of the research area

instability in the area. Despite this, when the relative relief is high, the slope is more vulnerable to instability (Hoek and Bray 1981). Slope Stability Susceptibility Parameter (SSEP) ratings for each facet were assigned accordingly.

4.3.1.2 Slope Morphometry The slope morphometry defines its steepness. The slope inclination is often grouped into ranges of degrees or percentages to be used to produce the slope morphometry map *(*Varnes 1984*). Anyway, for the estimation of the slope angle, a method proposed by* Anbalagan (1992) was adopted (Table SM3a).

Consequently, the slope morphometric categories are escarpment/cliff (> 45°), steep slope (36–45°), moderately steep slope (26–35°), gentle slope (16–25°), and very gentle slope (15°). The slope morphometry ratings for each subclass are shown in (Table SM3b). The steepness of the slope concerning the strength of the lithology and type of slope material (rock and soil nature) is given special attention in landslide hazard zonation. To generate the slope morphometry map, slope sections in the general slope direction within the individual slope facet are developed, and the slope angle is determined. Accordingly, the slope map of the research area was

produced by dividing the larger topographical map into smaller units (Fig. SM4).

In the present research area (Fig.ure SM4), very gentle, gentle, moderately steep, steep and escarpment cliff slope covers 232 km², 26 km², 6 km², 4 km² and 2 km² respectively. This indicates that about 85.9% of the study area is very gentle, 9.6%—gentle slope, 2.2%—moderate slope, 1.5%—steep slope, and 0.8% of the area falls under the Escarpment cliff. Based on the slope class, ratings were assigned to individual facets depending on the SSEP system.

4.3.2 Slope Material

According to Raghuvanshi et al. (2014) presentation, slopes can include soils, rock mass, or a combination of the two. The requirements for assigning ratings to rock type subclasses are dependent on intact rock intensity and weathering degree (Raghuvanshi et al. 2014). The response of rocks to erosion depends on the strength of the rock types. High-strength rocks are generally more resistant to erosion. The rock subclasses are obtained from the rock mass classification depending on Uniaxial Compressive Strength (UCS) suggested by Hoek and Brown (1997). Therefore, very weak rock (1–5 Mpa), weak rock (5–25 Mpa), medium-strong rock (25–50 Mpa), strong rock (50–100 Mpa), very strong rock (100–250 Mpa), an extremely strong rock (> 250 Mpa) are the different classes (Table SM4).

Accordingly, in the research area, the classes observed are strong rock (50–100 MPa), medium-strong rock (25–50 MPa), and weak rock (5–25 MPa). Moreover, about 68% of the study area is covered with residual expansive soil deposits, 20.4% of the area is covered by strong rock, 7.5% of the area is covered by medium-strong rock, and the remaining 4.1% of the research area is covered by weak rock (Table SM4). The thickness of soil deposits varies across the research area.

Moreover, the degree of weathering has an impact on the relative strength of the rocks so it has to be considered when giving ratings to the rock types. The degree of weathering was classified as fresh, slightly weathered, moderately weathered, highly weathered, and rock as soil (Raghuvanshi et al. 2014) (Table SM4).

4.3.3 Structural Discontinuities Conditions

Structural discontinuities (geological structures) play a significant role in determining rock slope stability conditions (Hoek and Bray 1981; Asmare and Hailemariam 2021). The orientation, spacing, surface properties, separation of the discontinuity surface, continuity, and thickness, and nature of the filling material inside the discontinuity surfaces are important structural discontinuity plane factors that affect the stability of the rock mass (Asmare and Hailemariam 2021; Hack 2002; Li and Xu 2015; Karaman et al. 2013; Karaman et al. 2013). Therefore, when assigning a rating for structural discontinuities, their interrelationship and their extent of parallelism to slope and the depth of the soil cover for the soil slopes were considered (Table SM5).

In this study, the characteristics of discontinuities were observed facet-wise from the rock mass, as with other parameters, and their relationship to slope inclinations was determined. These include the spacing, continuity, and surface characteristics, separation of the discontinuity surface and thickness, and the composition of the filling material between the discontinuity surfaces. Besides, assigning the ratings for the characteristics of discontinuities, their interconnection and their extent of parallelism to slope have been considered. All SSEP assigned ratings were discussed facet-wise.

4.3.4 Land Use and Land Cover

Land use and land cover natures were indirect indication factors influencing landslide activity (Anbalagan 1992). The stability condition of a hill slope to a large extent is influenced by land use and land cover. A thick vegetation cover over a slope is an indication of stable condition as the vegetation cover prevents excess seepage of water into the slope (Raghuvanshi et al. 2014). Barren slopes are more susceptible to landslide activity than forested or vegetated areas (Raghuvanshi et al. 2014; Wang and Niu 2009). Cultivation is the main land use activity that is performed on the hill slopes. The climatic factors, such as the rainfall rate, the net solar radiation, the relative humidity, the wind speed, and the air temperature, determine soil–vegetation–atmosphere interaction, which is responsible for slope instability processes (Cotecchia et al. 2019).

Land use land cover map of the study area was produced by integrating satellite images such as Landsat 8 images obtained from USGS data sources and visual field observation (Fig. SM5). Later, to assign SSEP ratings for the individual facet and facet-wise percentage area coverage of land use, the land cover was generated by geoprocessing in the GIS environment (Arc GIS 10.5). A single facet can have two or more land use land cover types. To assign a rating to a single facet, the percentage area coverage of each LULC nature was first determined. These percentage coverages were then multiplied by their ratings and divided by 100. The results were later summed and used as the rating value for a single facet.

As shown in Fig. SM5, 225.3 km^2 (83.4%) of the study area is cultivated land, 12.4 km^2 (4.6%) is a thickly vegetated area, 12.4 km^2 (4.6%) is sparsely vegetated, 10.4 km^2 (3.9%) is a barren land and 9.5 km^2 (3.5%) is moderately vegetated, and ratings were assigned for each facet. As a result, the above points were taken into account when assigning a rating for land use land cover (Table SM6).

4.3.5 Groundwater

Groundwater is the one that is highly responsible for slope instability (Hoek and Bray 1981). However, direct measurements of groundwater activity within slopes are difficult to obtain, while to determine the impact of groundwater in causing slope instability, indirect measures can be used. Groundwater-surface manifestations such as dampness, wetness, pouring, and streamings are examples of indirect interventions (Anbalagan 1992). When assigning ratings, several traces of the surface including algal growth and watermarks must be considered (Table SM7), as these surface traces provide some indication of the slope's saturation for an extended time. It may be possible that at the time of field investigation, the slope demonstrates dry condition only without any traces of water. Thus, while assigning ratings, all these points were considered.

In the present research area, groundwater conditions were assessed using surface manifestations like wet, damp, dripping, and flowing. Besides, watermarks, moss, algal growth, etc., were investigated (Fig. 3). Accordingly, in assigning ratings for individual facets, the presence of these springs and hand pumps was also considered and ratings were given based on their location and density within the individual facet. For instance, the presence of springs around the top part of the slope of the facet is assigned a higher rating than those located around the toe of the slope. As a result, ratings for groundwater were assigned.

4.3.6 Rainfall

Rainfall is the primary inducing factor for landslide activity (Ahmed et al. 2016; Suradi and Fourie 2014). Rainfall recharging increases the pore water pressure inside the rocks and fractures and weakens the rock strength parameters as well as increases the weight of the slope (Suradi and Fourie 2014; Chen et al. 2008, 2004; Ahmadi and Eslami 2011; Ahmed et al. 2016; Hack 2002). These excess pore water pressures are certainly the triggering factor for the largest slope instability (Jaboyedoff et al. 2004; Dai and Lee 2001; Pedone, et al. 2021). This is evident as the slope's inability rises mostly during the rainy season (Elia et al. 2020). The occurrence of landslides is usually an outcome of oversaturation of soil with rainwater and that initiates slope failure (Elia et al. 2020). The mean annual rainfall was considered to be a way of assigning ratings to integrate its influence in the SSEP rating system (Oberoi and Thakur 2004).

According to information obtained from locals, heavy rainfall was the main cause of the previous landslides. Most of the landslides happen during rainy seasons. During the field investigation, the various manifestations of landslide activities such as active and past landslide events, as well as different signs or surface manifestations of landslide features, were observed. Accordingly, the corresponding SSEP rating was assigned for mean annual rainfall. When assigning rainfall ratings, rain-induced slope indicators like toe erosion, stream bank erosion, gully formation, etc., were also considered. The long-term average annual precipitation in the research is 1130 mm/year. This indicates that the mean annual rainfall in the study area lies within the high class (i.e., 1101–1500 mm). Accordingly, ratings were assigned to each element (Table SM8).

4.3.7 Manmade Activities

Manmade activities contribute to the inherent failure of the slopes (Wang and Niu 2009). Deforestation for
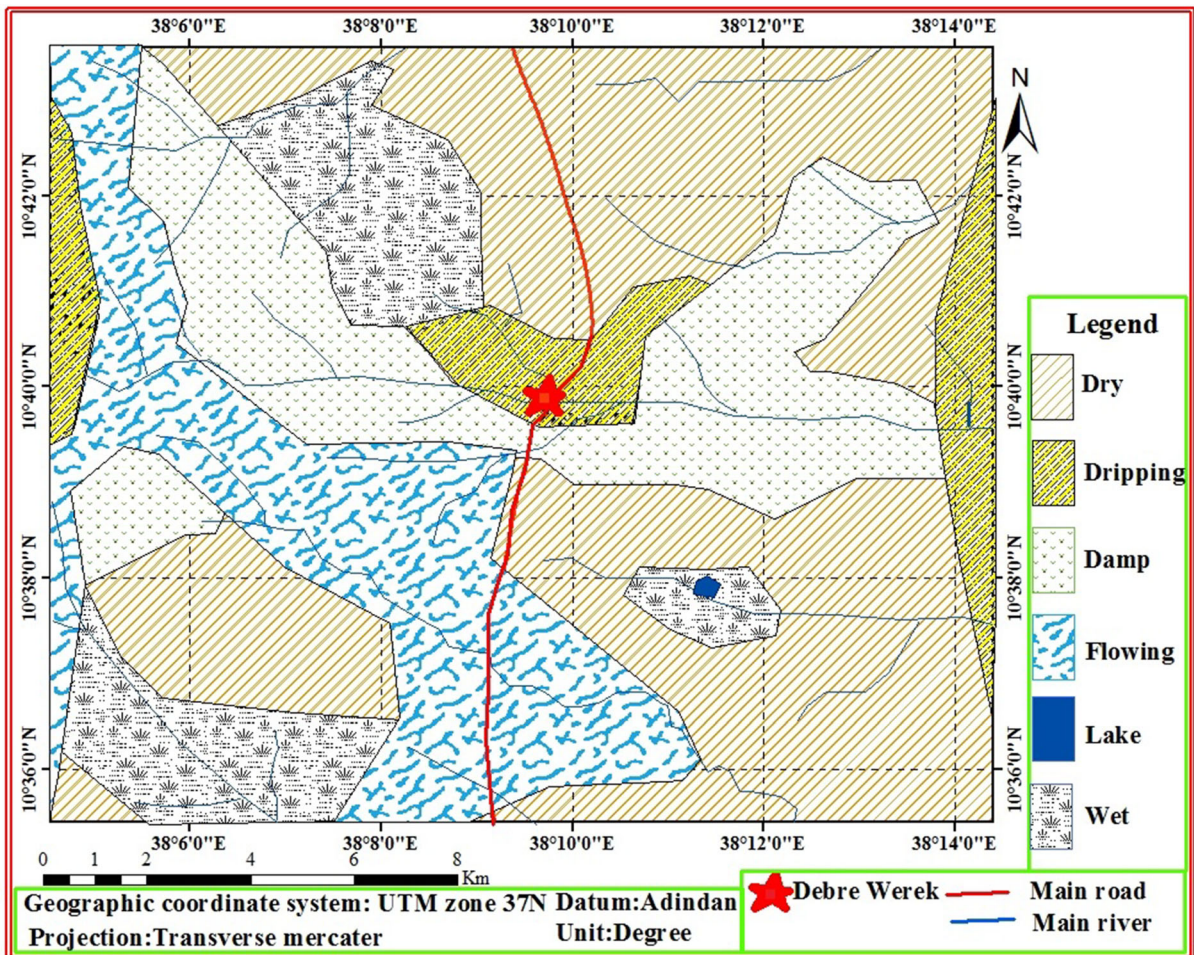
Fig. 3 Groundwater-surface trace map

the sake of settlement or timber harvesting especially in mountainous areas such as valleys and hills is highly responsible for loose soil shear strength, and it will be susceptible to erosion and sliding. Manmade activities are economic tasks such as road-building and agriculture. All these events change the slope morphometry. Also, the material excavated from the slope is deposited always in an unplanned way on the down slopes. These loose dumped content fails when flooded with rainwater.

Slope cultivation often increases instability due to increased soil mass moisture due to irrigation. Besides, several surface drainage ditches constructed slopes in an unplanned manner. However, these ditches were constructed in the wrong ways that drain toward unstable slope material. Furthermore, poor irrigation practices can result in an excessive

infiltration of rainfall, which may cause slope failure (Raghuvanshi et al. 2014). Thus, the above factors were considered when assigning SSEP ratings (Table SM9).

4.3.8 Seismicity

Seismicity causes instability in the ground resulting in slope instability (Parise and Jibson 2000). Hill slopes show different properties under static loads and dynamic loads caused by seismic activity (Hoek and Bray 1981). When rock slopes characterized by significant structural discontinuities are exposed to ground acceleration, the structural discontinuities expand or open. As a result, shear strength and structural discontinuity decrease, and slope failure increases. Under seismic loading, slopes consisting of

surficial deposits or unconsolidated soft sediments with steep slopes, high groundwater levels, and sparse vegetation are often vulnerable to landslide.

The strength of the seismic activity may be related to the source, stratigraphic and topographic effects (Akkar et al. 2014; Bouchon 1973; Bouckovalas and Papadimitriou 2005; Falcone et al. 2021; Galli et al. 2020; Galli and Peronace 2014; Peronace et al. 2018; Zhang et al. 2018; Del Gaudio et al. 2012; Mori et al. 2020; Nowicki et al. 2018). Moreover, the seismic activity may be quantified in terms of ground acceleration. Furthermore, depending on the Modified Mercalli intensity scale, Hays (1980) proposes a relationship between earthquake intensity and ground acceleration. Bearing in mind that an advanced evaluation of seismic motion is out of the scope of this work, the relationship between earthquake intensity and ground acceleration, as provided by Hays (1980), was adopted. This provides g-value indications; ground motion is described in terms of gravitational accelerations that are acceptable for engineering computations (Johnson and DeGraff 1991). According to Asfaw's (1986) presentation, the seismic risk map of Ethiopia for a hundred-year return duration and 0.99 probability shows that the current research area falls within 7 M.M scales.

The earthquake intensity can be obtained from the seismic maps of the research area. Thus, seismicity ratings are assigned based on the relationship between ground acceleration and earthquake intensity (Modified Mercalli intensity scale) (Table SM10). Accordingly, based on Figs. SM6 and SM7, the present study area lies in a Modified Mercalli intensity scale of VII and the estimated horizontal earthquake acceleration comes out to be 0.05–0.1 g, with an average value of 0.075 g.

5 Methodology

5.1 Slope Stability Susceptibility Evaluation Parameter (SSEP) Rating System

The slope stability susceptibility evaluation parameter (SSEP) rating method was proposed by Raghuvanshi et al. (2014) to demarcate different parts of an area based on the degrees of hazards. This rating system was developed by considering several governing factors including slope geometry, structural discontinuities, slope material, land use, land cover, groundwater, and rainfall, seismicity, and manmade activities. The system assigns numerical ratings based on logical judgments formed from studies of several factors and their possible influence on slope failure. The distribution of maximum SSEP ratings given to each factor is based on their relative contribution for slope instabilities as presented by Raghuvanshi et al. (2014).

6 Landslide Hazard Zonation and Evaluation

6.1 Landslide Evaluation

Individual facet ratings for predisposing factors ratings were summarized to determine LHZ in an area. The evaluated landslide hazards are defined using Eq. 1 as follows, and then, the ELH was classified into five categories, as shown in Table 1. The result indicates that the whole research area falls into three landslide hazard classes, typically, landslide hazard classes II, III, and IV. The minimum ELH value obtained is 3.9 which shows landslide hazard class of II and low hazard zone, whereas the maximum evaluated landslide hazard value obtained is 9.9, which indicates landslide hazard class of IV and high hazard zone.

ELH = Sum of ratings of intrinsic causative factors
(relative relief + slope morphometry + slope material
+structural discontinuity + Groundwater
+Land use land cover)
Sum of ratings of External causative factors
(Rainfall + Seismicity + Manmade activities)

(1)

6.2 Landslide Hazard Zonation

The ELH for a single facet was computed by summing the ratings of individual intrinsic causative factors and external triggering factors from the SSEP rating system. The research area was divided into categories of hazard zones as per the SSEP rating system after collecting primary data for the rating values facet-wise and evaluating them, and the landslide hazard zonation map of the research area was produced in a GIS

Table 1 Evaluated landslide hazards (Raghuvanshi et al. 2014)

Landslide hazard zone	Landslide hazard class	Evaluated landslide hazard
Very high hazard zone (VHHZ)	V	> 12
High hazard zone (HHZ)	IV	12–8
Moderate hazard zone (MHZ)	III	7.9–5
Low hazard zone (LHZ)	II	4.9–2
Very low hazard zone (VLHZ)	I	< 2

environment. Figure 4 shows the produced LHZ map. It can be seen that about 73.3 km^2 (27.2%) of the study area is found within the Low Hazard Zone, 140.8 km^2 (52.1%) found within Moderate Hazard Zone, and the remaining 55.9 km^2 (20.7%) falls into High Hazard Zone.

This confirms that the area is extremely vulnerable to landslides. Therefore, the research area needs a landslide protection system, especially during the rainy season. Field observation during the present study confirms that no place in the study area is free of slope instability problems.

6.2.1 High Hazard Zones

The present research covers about 270 km^2. About 20.7% of the area is found within the high hazard zone that is about 55.9 km^2 of the area. The high hazard zones in the research area are generally defined by moderate steep and significant groundwater-surface traces such as flowing and wet areas. The slope material covering in this zone is mainly soil slope deposits and disintegrated rock.

The rock was moderate to highly weathered, and the characteristics of structural discontinuities play a significant role in slope instabilities. Field
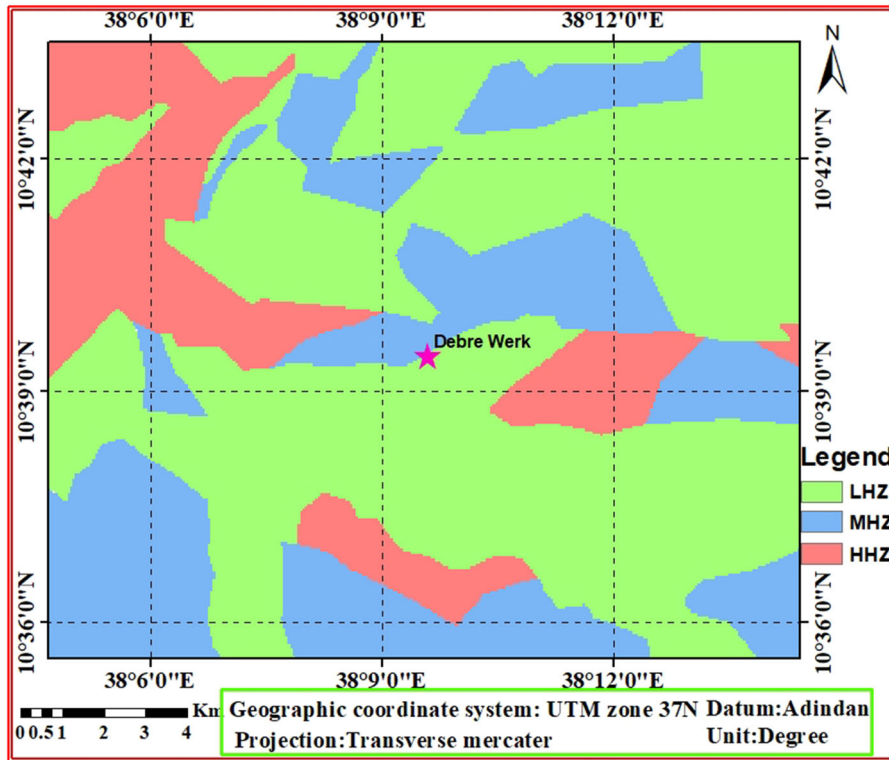
Fig. 4 Landslide Hazard Zonation map of the study area

investigation, data analysis, and the results of the present research indicate that this zone is highly susceptible to landslide hazards, and hence, proper care and concern have to be taken during the design and planning of future developmental activities and irrigation practices.

6.2.2 Moderate Hazard Zone

About 52.1% of the present research area falls into the moderate hazard zone which is about 140.75 km^2. This shows that the majority of the research area is in the moderate hazard zone. The moderate hazard zones in the research area are generally defined by relatively gentler slopes with dry to low groundwater-surface traces. Moreover, some areas are characterized by wet and flowing. The slope materials in this zone are residual soil deposit and blocky disturbed (mainly) and disintegrated rock mass. The degree of weathering is high to moderately weathered and the effect of structural discontinuities is relatively insignificant.

6.2.3 Low Hazard Zone

The remaining 27.2% of the present study area falls into the low hazard zone which is about 73.3 km^2. The low hazard zones in the research area are generally defined by relatively gentler to very gentler slopes with dry to low groundwater-surface traces. Moreover, some areas are characterized by wet and damps. The slope materials in this zone are residual soil deposits and strong to very weak rock mass. The degree of weathering is characterized by slightly weathered to moderately weathered, and the effect of structural discontinuities is relatively insignificant.

7 Validation of LHZ Map

In this research, a total of 85 landslide events were identified and a landslide inventory map was produced (Fig. SM2). Considering both intrinsic and extrinsic landslide triggering factors, a landslide hazard zonation map of the study area was developed (Fig. 4). To validate the LHZ map produced by using the SSEP rating scheme, an overlay analysis was performed between the LHZ map and landslide inventory map of the study area (Fig. 5). The results were compared with the actual active landslide activity data in the

area. The overlay analysis reveals that out of a total of 23 active landslide locations, 19(82.6%) fall within the 'high hazard zone,' whereas the remaining 4(17.4%) fall within the 'moderate hazard zone.' Thus, the LHZ map prepared by using the SSEP rating technique validates with the active landslide activities in the area. Thus, it can safely be concluded that the prepared LHZ map has satisfactorily delineated various zones of potential landslide hazard in the study area. Generally, the SSEP technique looks to be more accurate in terms of the performance of landslide hazard zonation mapping and may serve as a useful tool for planning developmental activities.

8 Conclusion

The present study area is characterized by rugged terrain, and the majority of the area is covered with residual expansive soils. As a result, it is highly susceptible to landslide activities during rainy seasons. Poor agricultural practice and constructions at the toe or on the top of slopes are triggering some landslides in the area and raise the need for landslide hazard zonation and evaluation in the area for urban planning and infrastructure development.

The major aim of the present study was to apply and validate the Slope Stability Susceptibility Evaluation Parameter (SSEP) rating system and produce a landslide hazard zonation (LHZ) map of the study area, by considering several intrinsic and triggering parameters.

During the field investigation, the study area was divided into 70 facets and 85 landslide activities were identified. Thus, 23, 39, and 23 landslide activities were identified as active landslide, past landslides, and signs of landslide, respectively. Extensive field works were conducted to investigate and select possible SSEP parameters, and ratings were assigned accordingly facet-wise for each factor. These possible parameters selected during fieldwork include slope geometry, relative relief, slope morphometry, slope material, structural discontinuities, land use and land cover, groundwater seismicity, rainfall, and manmade activities. Furthermore, different characteristics of structural discontinuities and corresponding adjusting factors were assigned for each facet. The final result indicates that the research area is categorized into a high hazard zone, moderate hazard zone, and low
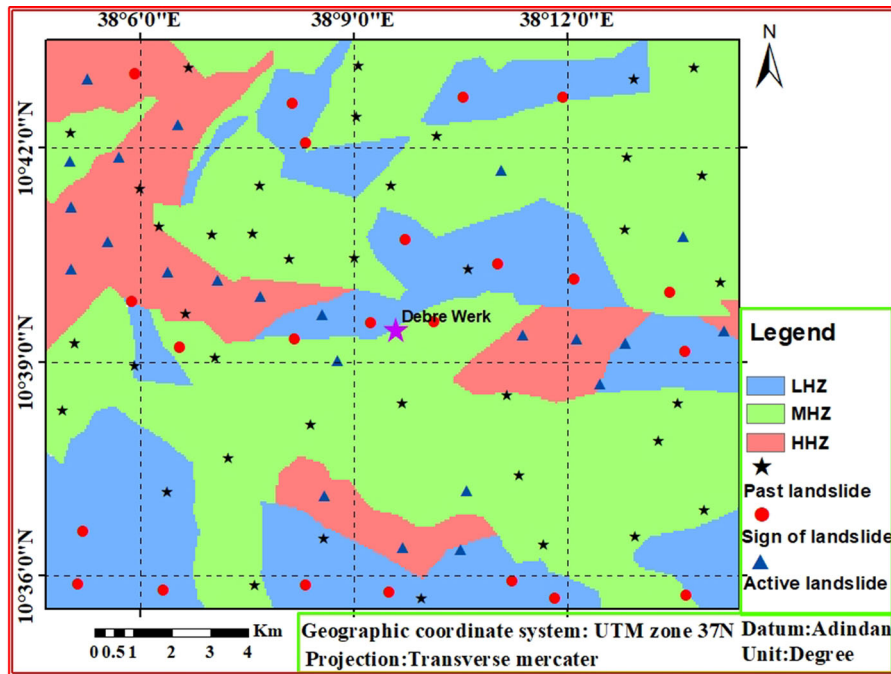
Fig. 5 Map showing past landslide events overlaid on LHZ map of the study area

hazard zone. These showed that the study area is highly exposed to landslide risks.

Thus, validation of the LHZ map prepared by using the SSEP rating technique was performed. This is done by comparing the result with the active landslide activities. Accordingly, out of a total of 23 active landslide locations, 82.6% fall within the high hazard zone, whereas the remaining 17.4% fall within the moderate hazard zone. Accordingly, a high percentage of active landslide activities have occurred in the high hazard zone. Thus, it reasonably confirms the rationality of the adopted methodology, considered intrinsic and triggering parameters, and their evaluation in producing an LHZ map for the present study area.

References

Ahmadi M, Eslami M (2011) A new approach to plane failure of rock slope stability based on the water flow velocity in discontinuities for the Latian dam reservoir landslide. J Mt Sci 8:124–130. https://doi.org/10.1007/s11629-011-2088-5

Ahmed W (2008) Sedimentation of The Triassic–Jurassic Adigrat sandstone formation, Blue Nile (Abay) Basin, Ethiopia. J Afr Earth Sci 52:30–42

Ahmed W (2009) Sedimentation and depositional environments of the Barremian-Cenomanian debre libanose sandstone, Blue Nile (Abay) basin. Ethiopia Cretaceous Resarch 30(5):1133–1145. https://doi.org/10.1016/j.cretres.2009.04.002

Ahmed MF, Kang X, Khan MS (2016) Impact of rainwater infiltration on the stability of Earth slopes. Int J Econ Environ Geol 7(2):20–25. https://doi.org/10.46660/ijeeg.Vol0.Iss0.0.84

Akkar S, Sandıkkaya MA, Bommer JJ (2014) Empirical ground-motion models for point- and extended-source crustal earthquake scenarios in Europe and the Middle East. Bull Earthq Eng 12:359–387. https://doi.org/10.1007/s10518-013-9461-4

Anbalagan R (1992) Landslide hazard evaluation and zonation mapping in mountainous terrain. Eng Geol 32:269–277. https://doi.org/10.1016/0013-7952(92)90053-2

Assefa G (1991) Lithostratigraphy and environment of deposition of the late Jurassic early Cretaceous sequence of the central part of Northwestern Plateau. Ethiopia. N J Geol

Palaont Abh 182(3):255–284. https://doi.org/10.1127/NJGPA/182/1991/255

Asfaw LM (1986) Catalogue of Ethiopian earthquakes, earthquake parameters, strain release and seismic risk, geophysical observatory, Faculty of Science, Addis Ababa University

Ayalew L, Yamagishi H (2005) The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda-Yahiko Mountains. Central Japan 65:15–31. https://doi.org/10.1016/j.geomorph.2004.06.010

Bouchon M (1973) Effect of topography on surface motion. Bull Seismol Soc Am 63:615–632

Bouckovalas GD, Papadimitriou AG (2005) Numerical evaluation of slope topography effects on seismic ground motion. Soil Dyn Earthq Eng 25:547–558. https://doi.org/10.1016/j.soildyn.2004.11.008

Chen H, Lee CF, Law KT (2004) Causative mechanisms of rainfall-induced fill slope failures. J Geotech Geoenviron Eng 130:593–602. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:6(593)

Chen X, Guo H, Song E (2008) Analysis method for slope stability under rainfall action. Landslides Eng Slopes 1507–1515

Chingkhei RK, Shiroyleima A, Robert Singh L, Kumar A (2013) Landslide hazard zonation in NH-1A in Kashmir Himalaya, India. Int J Geosci. https://doi.org/10.4236/ijg.2013.410147

Cotecchia F, Santaloia F, Lollino P, Vitone C, Pedone G, Bottiglieri O (2016) From a phenomenological to a geomechanical approach to landslide hazard analysis. Eur J Environ Civ Eng 20:1004–1031. https://doi.org/10.1080/19648189.2014.968744

Cotecchia F, Tagarelli V, Pedone G, Ruggieri G, Guglielmi S, Santaloia F (2019) Analysis of climate-driven processes in clayey slopes for early warning system design. Proc Inst Civ Eng Geotech Eng 172:465–480. https://doi.org/10.1680/jgeen.18.00217

Dai FC, Lee CF (2001) Terrain-based mapping of landslide susceptibility using a geographical information system: a case study. Canadian Geot J 38(5):911–923. https://doi.org/10.1139/t01-021

Dawit Asmare and Trufat Hailemariam (2021) Assessment of rock slope stability using slope stability probability classification (SSPC) system, around AlemKetema. Sci African 12:e00730. https://doi.org/10.1016/j.sciaf.2021.e00730

Del Gaudio V, Pierri P, Calcagnile G (2012) Analysis of seismic hazard in landslide-prone regions: criteria and example for an area of Daunia (southern Italy). Nat Hazards 61:203–215. https://doi.org/10.1007/s11069-011-9886-5

Du G, Zhang Y, Iqbal J, Yang Z, Yao X (2017) Landslide susceptibility mapping using an integrated model of information value method and logistic regression in the Bailongjiang watershed, Gansu Province, China. J Mountain Sci 14(2):249–268. https://doi.org/10.1007/s11629-016-4126-9

Elia G, Falcone G, Cotecchia F, Rouainia M (2020) Analysis of the effects of seasonal pore pressure variations on the slope stability through advanced numerical modelling. In: Lecture notes in civil engineering. Springer, pp. 184–194. https://doi.org/10.1007/978-3-030-21359-6_20

Ermias B, Raghuvanshi TK, Abebe B (2017) Landslide hazard zonation (LHZ) around Alemketema town, North Showa Zone, Central Ethiopia: a GIS-based expert evaluation approach. Int J Earth Sci Eng 10(1):33–44. https://doi.org/10.21276/ijese/2017.10.01.06

Falcone G, Acunzo G, Mendicelli A, Mori F, Naso G, Peronace E, Porchia A, Romagnoli G, Tarquini E, Moscatelli M (2021) Seismic amplification maps of Italy based on site-specific microzonation dataset and one-dimensional numerical SE approach. Eng Geol 289:106170. https://doi.org/10.1016/j.enggeo.2021.106170

Fall M, Azzam R, Noubactep C (2006) A multi-method approach to study the stability of natural slopes and landslide susceptibility mapping. Eng Geol 82:241–263. https://doi.org/10.1016/j.enggeo.2005.11.007

Galli P, Peronace E (2014) New paleoseismic data from the Irpinia Fault: a different seismogenic perspective for southern Apennines (Italy). Earth Sci Rev 136:175–201. https://doi.org/10.1016/J.EARSCIREV.2014.05.013

Galli P, Galderisi A, Marinelli R, Messina P, Peronace E, Polpetta F (2020) A reappraisal of the 1599 earthquake in Cascia (Italian Central Apennines): hypothesis on the seismogenic source. Tectonophysics 774:228287. https://doi.org/10.1016/J.TECTO.2019.228287

Gani ND, Abdelsalam MG (2006) Remote sensing analysis of the gorge of the Nile, Ethiopia with emphasis on Dejen–Gohatsion region. J Afr Earth Sci 44:135–150. https://doi.org/10.1016/j.jafrearsci.2005.10.007

Gani ND, Abdelsalam MG, Gani MR (2008) Stratigraphic and structural evolution of the Blue Nile Basin, Northwestern Ethiopian Plateau. Geo J 44:30–56. https://doi.org/10.1002/GJ.1127

Hack R (2002) An evaluation of slope stability classification. ISRM EUROCK'2002, Portugal Madeira Funchal. Lisboa, Portugal, pp 3–32

Hamza T, Raghuvanshi TK (2017) GIS based landslide hazard evaluation and zonation: a case from Jeldu District, Central Ethiopia. J k s Univ Sci 29:151–165. https://doi.org/10.1016/j.jksus.2016.05.002

Hays WW (1980) Procedures for estimating earthquake ground motion. U.S. Geol. Surv. Prof. Paper. 1114, 77pp. https://doi.org/10.3133/pp1114

Hoek E, Bray JW (1981) Rock slope engineering (revised third ed.). Ins. Of Mining and Metallurgy, London, 358Pp

Hoek E, Brown ET (1997) Practical estimates of rock mass strength. Int J Rock Mech Mining Sci 34:1165–1186

Jaboyedoff M, Baillifard F, Bardou E, Girod F (2004) The effect of weathering on Alpine rock instability. Quarterly J Eng Geo and Hydrogeo 37:95–103. https://doi.org/10.1144/1470-9236/03-046

Jamalullail SNR, Sahari S, Shah AA, Batmanathan N (2021) Preliminary analysis of landslide hazard in Brunei Darussalam. SE Asia Environ Earth Sci 80:1–16. https://doi.org/10.1007/S12665-021-09815-Z

Johnson RB, Degraff JV (1991) Principles of engineering geology. John Willy and Sons, New York, p 497

Karaman K, Ercikdi B, Kesimal A (2013) The assessment of slope stability and rock excavatability in a limestone quarry. Earth Sci Res Sj 17(2):169–181

Kebede S, Travi Y, Alemayehu T, Ayenew T (2005) Groundwater recharge, circulation, and geochemical evolution in

the source region of the Blue Nile River. Ethiopia App Geoch 20:1658–1676. https://doi.org/10.1016/j.apgeochem.2005.04.016

Kumar R, Anbalagan R (2015) Landslide susceptibility zonation in part of Tehri reservoir region using frequency ratio, fuzzy logic, and GIS. J Earth Syst Sci 124(2):431–448. https://doi.org/10.1007/s12040-015-0536-2

Laike Mariam Asfaw (1996) Environmental hazard from fissures in the Main Ethiopian Rift. J Affr Earth Sci 27(3/4):481–490. https://doi.org/10.1016/s0899-5362(98)00074-8

Lebenie D, Bussert R (2009) Stratigraphy and facies architecture of Adigrat sandstone, Blue Nile Basin, Central Ethiopia. Zentral Blatt Geol Paläont 1(34):217–232. https://doi.org/10.14279/DEPOSITONCE-2607

Li XZ, Xu Q (2015) Application of the sspc method in the stability assessment of highway rock slopes in the Yunnan province of China. Bull Eng Geol Env 75(2):551–562. https://doi.org/10.1007/s10064-015-0792-z

Mogessie A, Krenn K, Schaflechner J, Koch U, Egger T, Goritchnig B, Bauernfeind D (2002) A geological excursion to the Mesozoic sediments of the Abay Basin (Blue Nile), recent volcanic of the Ethiopian Main Rift, and basement rocks of the Adola Rea. Ethiopia Mitt Österr Miner Ges 147:43–74

Mori F, Gena A, Mendicelli A, Naso G, Spina D (2020) Seismic emergency system evaluation: the role of seismic hazard and local effects. Eng Geol 270:105587. https://doi.org/10.1016/j.enggeo.2020.105587

Nowicki Jessee MA, Hamburger MW, Allstadt K, Wald DJ, Robeson SM, Tanyas H, Hearne M, Thompson EM (2018) A global empirical model for near-real-time assessment of seismically induced landslides. J Geophys Res Earth Surf 123:1835–1859. https://doi.org/10.1029/2017JF004494

Oberoi SV, Thakur NK (2004) Safety assessment of existing road in the Himalayas using Geographic information system and Satellite imagery. In: Third international symposium on new technologies for urban safety of mega cities in Asia, organized by IIT Kanpur and International Center for Urban Safety Engineering (ICUS), University of Tokyo, Agra, India, October 18–19, pp. 11–20

Parise M, Jibson RW (2000) A seismic landslide susceptibility rating of geological units based on analysis of characteristics of landslides triggered by the 17 January 1994 Northridge, California Earthquake. Eng Geol 58:251–270. https://doi.org/10.1016/S0013-7952(00)00038-7

Pedone DG, Tsiampousi DA, Cotecchia PF, Zdravkovic DL (2021) Coupled hydro-mechanical modelling of soil-vegetation-atmosphere interaction in natural clay slopes. Canadian Geotech J. https://doi.org/10.1139/CGJ-2020-0479

Peronace E, Seta MD, Troiani F, Galli P, Giaccio B, Messina P, Fredi P (2018) Testing geomorphic signal of active normal faulting: The case of the Cittanova Fault (Calabria, southern Italy). Earth Surf Process Landforms 43:2256–2270. https://doi.org/10.1002/ESP.4384

Poppe L, Frankl A, Poesen J, Teshageradmasu A, Dessie M, Adgo E, Nyssen J (2013) Geomorphology of the lake Tana Basin. Ethiopia J Maps 9(3):431–437. https://doi.org/10.1080/17445647.2013.801000

Raghuvanshi TK, Ibrahim J, Ayalew D (2014) Slope stability susceptibility evaluation parameter (SSEP) rating scheme: an approach for landslide hazard zonation. J Afr Earth Sci 99:595–612. https://doi.org/10.1016/j.jafrearsci.2014.05.004

Soeters R, Van Westen CJ (1996) Slope instability recognition analysis and zonation. In: Turner KT, Schuster RL (eds) Landslides: investigation and mitigation special report no. 247. Transportation research board national research council, Washington Dc., pp 129–177

Suradi M, Fourie A (2014) The effect of rainfall patterns on the mechanisms of shallow slope failure. Aceh Int J Sci Technology 3(1):1–18. https://doi.org/10.13170/AIJST.0301.01

Tefera M, Chernet T, Haro W (1996) Geological map of Ethiopia (1:2,000,000), 2nd edn. Inst. Geo. Surv. Ethiopia, Addis Ababa, Ethiopia

Terzaghi K (1950) Mechanisms of landslides. In: Paige S (ed) Application of geology to engineering practice. Berkley Volume, American Geological Society, pp 83–124

Van Westen CJ, Rengers N, Soeters R (2003) Use of geomorphological information in indirect landslide susceptibility assessment. Nat Hazards 30:330–419. https://doi.org/10.1023/B:NHAZ.0000007097.42735.9e

Varnes DJ (1984) And the international association of engineering geology commission on landslide and other mass movements on slopes. Landslide hazard zonation: a review of principles and practice (ISBN 92–3–101895–7) (UNESCO), 7 places de Fontenoy, 75700 Paris, France, 60 pp

Wang X, Niu R (2009) Spatial forecast of landslides in three gorges based on spatial data mining. Sensors 9:2035–2061. https://doi.org/10.3390/s90302035

Zhang Z, Fleurisson JA, Pellet FL (2018) A case study of site effects on seismic ground motions at Xishan Park ridge in Zigong, Sichuan, China. Eng Geol 243:308–319. https://doi.org/10.1016/j.enggeo.2018.07.004