Landslide Hazard Zonation and Evaluation around Debre Werk Town, North West Ethiopia

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Research

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Abstract

The present research was conducted in the town of Debre Werk, East Gojjam, North West Ethiopia, with the ultimate aim of conducting a Landslide Hazard Zonation and Evaluation. To reach this aim, the Slope Stability Susceptibility Evaluation Parameter (SSEP) rating system was adopted to zone and evaluate the landslide status 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, was 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 (ELH). Therefore, the research was carried out by dividing the study area into 70 facets. Then 85 landslide incidents in the study area were investigated. From 85 landslides, 39 districts showed past landslides, 23 showed active landslides and the remaining 23 districts showed signs of landslides. The delineated 70 facets were categorized into 3 landslide hazard zones. There are about 73.3km² (27.2%) of the study area within the low hazard zone, 140.8km² (52.1%) within the moderate hazard zone, and the remaining 55.9km² (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 landslide 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 overlap map shows that 17 districts showing active landslides, 2 districts showing signs of landslides, and 5 districts showing past landslide activities fall into high hazard zones. Likewise, 5 districts showing active landslides, 3 districts showing signs of landslides, and 28 districts showing past landslides fall into moderate hazard zones. The remaining 1 district showing active landslides, 18 districts showing signs of landslides, and 6 districts showing past landslide activities fall into moderate hazard zones.

Introduction

landslides are a frequent natural occurrence in Ethiopia's hilly and mountainous terrains. It is the product of a combination of geo-environmental processes that include meteorological, geological, and human influences (*Kumar and Anbalagan, 2015*). Landslide is responsible for immediate economic harm, damages to property and repair costs, accidents, or loss of life (*Dai and Lee, 2011; Wang et al., 2015; Ermias et al., 2017; 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*).

The present research area is in the Ethiopian highlands, which are defined by rugged, complex geological settings and poor soil cover. 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. Therefore, landslide hazard zoning and evaluation are perhaps the most critical components of any development and settlement in the area.

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; Westen et al., 2003*). 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*).

Study Area

The present research area is in the North-Western Ethiopian Plateau (NWP), in the Amhara Regional State's East Gojjam district. The Abay River Gorge to the east and Choke Mountain to the west define its boundaries (Figure 1). The area covers an area around 270km². The study area can be accessed via Addis Ababa to Debre Werek main Asphalt road which is about 300 Km. The area is generally not easily accessible by vehicles, and there are no standard routes to reach throughout the whole research area. The type of soil and its landscape is difficult to go through various parts of the research area.

Geology

Since 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; Mogessie et al., 2002; Lebenie and Bussert, 2009; Gani et al, 2008; Ahmed, 2008, 2009; Gani and Abdelsalam, 2006*).

According to the regional map prepared by *Mengesha Tefera et al. (1996)*, the research 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 (Figure 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.

General Methodology

General methodology

Raghuvanshi et al. (2014) proposed a new Slope Stability Susceptibility Evaluation Parameter (SSEP) rating method for landslide hazard zonation. The SSEP rating system was created by taking into account both intrinsic causative factors and external triggering factors that affect slope stability conditions (Raghuvanshi et al., 2014). SSEP approach considers internal causative and external triggering factors to evaluate an area's landslide hazard zonation. Slope geometry, structural discontinuities, slope material, land use, land cover, and groundwater are parameters intrinsic parameters. Additionally, external triggering parameters have been considered including rainfall, seismicity, and manmade activities.

Therefore, numerical ratings were assigned every one of the intrinsic causative factors and external triggering factors based on their influence on the instability of slope. The SSEP technique assigns numerical ratings based on logical judgments formed from studies of intrinsic causative factor and external triggering factors and their possible influence on slope failure (Raghuvanshi et al., 2014). The distribution of maximum SSEP ratings given to each intrinsic causative factor and external triggering factor based on their relative significance in causing slope instability (Table SM1).

Landslide hazard zonation and evaluation

The present study's Landslide Hazard Zonation was conducted using the evaluated landslide hazard (ELH). This represents the net probability of instability and was computed facets by facets. (*Raghuvanshi et al., 2014; Anbalagan, 1992*). The ELH for a specific facet was attained by summing up the ratings of individual intrinsic factors and external triggering parameters attained from the SSEP rating system. The rating values of each parameter were assigned facet-wise and evaluating them. The area was then divided into groups of hazard zones according to the SSEP rating system, and a Landslide hazard zonation map of the area was created. Moreover, the validity of the produced LHZ map was done by overlaying the inventory map on the prepared landslide hazard zonation (LHZ) map.

Individual facet-wise ratings for intrinsic causative factors and external trigger factors ratings were summarized to determine landslide hazard zoning in an area (*Raghuvanshi et al., 2014; Anbalagan,*

1992). The summation of all ratings for intrinsic causative factors and external triggering factors was represented as an evaluated landslide hazard (ELH) (*Raghuvanshi et al., 2014*).

Landslide inventory mapping

Landslide inventory mapping is a technique for recording the location and dimensions of landslides. The basic and essential component for landslide susceptibility mapping is landslide inventory (*Du et al., 2017*). A consistent landslide inventory map specifying the type and behavior of each landslide, and spatial variability of landslides, is needed before any study of the occurrence of landslides and their contribution to environmental conditions is undertaken (*Soeters and Westen, 1996*).

The detection and mapping of all landslide manifestations, or the preparation of a landslide inventory map, is the first phase in any landslide hazard assessment. The inventory map shows all landslides in the area through field surveys, historic data, satellite imagery, and aerial photo interpretation. Furthermore, it is important to investigate the relationship between the conditioning factors and the distribution of landslides.

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 research, a total of 85 slope instability processes were identified and mapped during fieldwork (Figure SM2).

Past landslide distribution

In the research area, a total of 85 landslide activity districts have been investigated during the inventory map preparation. As can be seen from the inventory map, most of the landslides are concentrated in Zunjit, Teza, and Zeya rivers including their tributaries. Besides, there are also a significant number of landslides in other rivers and valleys. The presence of landslides is linked with the existence of causative and triggering factors in these rivers and valleys.

Possible causative factors

Some of the major cause of slope failure is intrinsic in the soil or rock, in its composition or structure; such as the inclination of undisturbed slopes, are relatively constant and some complex, such as groundwater levels; some are temporary (seismic vibration) and some are triggered by new incidents, such as infrastructure construction (*Varnes, 1984; Ermias, 2014*).

According to *Raghuvanshi et al. (2014)* discussion, the major causes and mechanisms for landslides and slope failure problems observed in this study area can be classified into two internal causative factors and external triggering factors. The crucial intrinsic causes are slope material (lithology or soil type), slope geometry, structural discontinuities, land use, land cover, and groundwater, while seismicity, erosion, and manmade activities are the responsible external triggering parameters.

Most of the slope instability observed in the present research area is the result of the combined effect of all of these causatives and triggering factors as described above. However, groundwater and manmade effects are frequently investigated in the area. The effect of groundwater (as an internal causative factor) contributes to slope instability in residual soil deposit (as an internal causative factor). There are also man-made activities that lead to slope failures, such as slope cuts for road work, deforestation, and irrigation activities.

Facet map of the study area

A facet map is a piece of land with generally uniform slope geometry in terms of slope inclination and slope direction (*Anbalagan, 1992*). Initially, the topography of the area to be covered by landslide hazard zonation mapping is studied extensively, and the area is divided into several facets generally bounded by ridges, gullies, spurs, and rivers (*Anbalagan, 1992*). For landslide hazard mapping, the area of the to-be-mapped slopes must be divided into different slope facets (*Raghuvanshi et al., 2014*).

In the present research, the facet map was done by using Global mapper software and DEM data. Accordingly, the research area to be covered was divided into several slope facets. As a result, the slope facets were demarcated using DEM with 30 m. The facet boundaries were demarcated following hill ridges (can be major or minor), streams (main and tributary), and different topographical features (*Raghuvanshi et al., 2014*). The prepared facet map was later used as a base map for several intrinsic causative factors and external triggering factor maps. The facet map of the area prepared during the present research is given below in Figure 2.

Landslide hazard triggering parameters and their distribution

Landslide is the product of a broad range of processes influenced by geological, and meteorological, geomorphological factors (*Chingkhai et al. , 2013; Ermias, 2014*). In this research, the spatial distribution of landslides reflects internal causative factors; particularly slope geometry, lithology and type of slope material, and structural discontinuities. LHZ map of the research area was produced by considering various causative and triggering factors.

Intrinsic parameters

The causative parameters are intrinsic parameters that define whether slope stability conditions are favorable or unfavorable. These include lithology and type of slope material (rock and soil nature), slope geometry, structural discontinuities, land use landcover, and groundwater conditions (*Anbalagan, 1992*). The slope stability condition can be influenced depending on the conditions defined for each of these intrinsic parameters.

I. Slope geometry

In landslide zonation, the most important geomorphological feature to be recognized is the presence or absence 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.

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 of 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 slope would be more vulnerable to instability if the relative relief is more significant (*Hoek and Bray, 1981*)

According to Raghuvanshi et al. (2014), relative relief of the research 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 below, 29.5km² (10.9%) of the study area is showed moderate relief, 160.5km² (59.5%) is medium relief, 51.2 km² (19.0 %) is high relief and 28.8km² (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 (101-200m), and thus contributes to slope 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.

Slope morphometry

The slope morphometry defines its steepness. The slope morphometric categories are like those used in Anbalagan's (1992) LHEF rating system: 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. The slope inclination is often grouped into ranges of degrees or percentages to be used to produce the slope morphometry map (*Varnes, 1984*).

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 (Figure SM4). For the estimation of the slope angle, a method proposed by *Anbalagan (1992)* was adopted (Table SM3a).

In the present research area Figure SM4, very gentle slope covers about 232km², gentle slope cover 26km², moderately steep slope cover 6km², Steep and escarpment cliff slope covers 4km² and 2km² areas, 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.

II. 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 covered by strong rock, 7.5% of the area 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).

III. Structural discontinuities

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*).

Discontinuity spacing also influences the rock mass's stability condition. If the discontinuities are spaced tightly, the rock mass is more vulnerable to instability (*Asmare and Hailemariam, 2021; Hack, 2002; Li and Xu, 2015; Karaman et al., 2013*). According to *Raghuvanshi et al.(2014)*, the continuity of discontinuity planes affects the stability of the rock mass given the discontinuity orientation is kinematically important. If the continuity of the discontinuity planes is larger, the rock slope will reveal more unstable compared to the case where there is less continuity, and intact rock bridges are in between.

According to *Hack (2002)*, These discontinuity surface characteristics are also important for the assessment of the rock mass stability condition. Therefore, when assigning rating characteristics of structural discontinuities their interrelationship and their extent of parallelism to slope were considered (Table SM5). Moreover, the depth of the soil cover is considered for the soil slopes and ratings are assigned accordingly (Table SM5).

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 has been considered. All SSEP assigned ratings were discussed facet-wise.

VI. Land Use and Land Cover

Land use land cover (LULC) in Ethiopia varies significantly from year to year. The majority of these changes were caused by human activity and were from forest land to agricultural land (*Gebreslassie, 2014*). Land use and land cover natures were indirect indication factors influencing landslide activity (*Anbalagan, 1992*). Barren slopes are more susceptible to landslide activity than forested or vegetated areas (*Raghuvanshi et al., 2014; Wang and Niu, 2009*). As a result, the above points were taken into account when assigning a rating for land use land cover (Table SM6).

In the present research area, some localities are free from population settlement and are sparsely settled peoples. In the field, scarcely covered by Eucalyptus and short bushes have been observed. Valley sides are sparsely vegetated and mainly comprise bushes and grasses. Most of the present research area is covered by sparsely and barren land and used for extensive agricultural practice. Very gentle slope areas covered by various crop kinds are Teff, Maize, Pea, Chickpea, Vetch, Legume, barley, and Vegetables (Figure SM5).

The research area's land use land cover map was produced based on secondary data and satellite image interpretation. Then, the map was modified and updated based on visual field observation and the final map was produced (Figure SM5). Later, to assign SSEP ratings for the individual facet, facet wise percentage area coverage of land use - the land cover was generated by geoprocessing in the GIS environment. As shown in Figure SM5, 225.3km² (83.4 %) of the study area is cultivated land, 12.4km² (4.6%) is a thickly vegetated area, 12.4km² (4.6%) is sparsely vegetated, 10.4km² (3.9%) is a barren land and 9.5km² (3.5%) is moderately vegetated, and ratings were assigned for each facet.

V. Groundwater

Groundwater the one which 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 like dampness, wetness, pouring, and streaming is 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 could be true that the slope shows dry conditions even without any signs of water during field investigation. And all of these points were considered when assigning ratings.

In the present research area, groundwater conditions were assessed using surface manifestations like; wet, damp, dripping, and flowing were investigated facet-wise. Besides, watermarks, moss, algal growth, etc. were investigated (Figure 3). Accordingly, in assigning ratings for individual facets, the presence of these springs and hand pumps were 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.

External causative parameters

The most essential external causative factors that can induce slope instability are rainfall, seismicity, and man-made activities.

I. Rainfall

Rainfall is the primary inducing factor for landslide activity. The frequency and severity of rainfall events, as well as other variables such as lithology, morphology, and land cover, all, have a major impact on the occurrence of landslides. Hydraulic properties, infiltration patterns and amount of rainfall infiltrate have a vital influence on the slope instability (*Ahmed et al., 2016; Suradi and Fourie, 2014*). The amount of rainwater that infiltrates into the slope determines the effect of rainfall on slope failure mechanisms (*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 (*Chen et al., 2008; Ahmadi and Eslami, 2011; Chen et al., 2004; 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*).

The amount of rainfall magnifies slope stability problems (*Dai and Lee, 2001*). This is evident as the slope's inability rises mostly during the rainy season. Groundwater within discontinuities in rock mass raises water pressure, resulting in a decrease in shear strength across the discontinuity surface (*Hoek and Bray, 1981*). Furthermore, the groundwater lubricates the discontinuity surfaces, promoting the rock sliding. In soil slopes, the weight of soil mass increases after rain-fed saturation and thus contributes to the soil mass instability. Moreover, groundwater contributes to the formation of pore water pressure within the soil mass, intensifying soil slope failure (*Arora, 1997*).

The mean annual rainfall was considered to be a way of assigning ratings to integrate its influence in the SSEP rating system (*Obero and Thakur, 2004*). Slope morphometry has been used to determine the influence of rainfall on slope failure causatives such as slope content and discontinuity orientation relative to the slope (Table SM8). It is simple and logical to infer that slope instability is more prevalent in areas that have higher mean annual rainfall. However, this does not imply that all slopes in the area defined by higher mean annual rainfall would be unstable, as other intrinsic causative factors together decide the slope instability conditions. Furthermore, when assigning rainfall ratings, the manifestations

caused by rain on a slope such as a gully formation, toe erosion, and stream bank erosion were taken into consideration.

According to information obtained from locals, heavy rainfall was the main cause of the previous landslides. Most of the landslides happened 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 research area lies within the high class (i.e.1101-1500 mm). Accordingly, ratings were assigned to each element.

II. Manmade Activities

Manmade activities contribute to the inherent failure of the slopes (*Wang & Niu, 2009*). Deforestation for the sake of settlement or timber harvesting especially in a mountainous area 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. For example, road or building construction frequently requires the uncontrolled cutting or explosion of slope material. Cutting of slope toe is the result of removing slope supports. Moreover, blasting activities during road construction disturb the slope material and new structural discontinuities may develop. This leads to soil or rock mass overhangs that are prone to failure.

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 were constructed slopes in an unplanned manner. However, these ditches were constructed in the wrong ways that drain towards 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).

III. Seismicity

Seismicity causes instability in the ground resulting in slope instability (*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 increase. 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 ground acceleration. Depending on the Modified Mercalli intensity scale, *Hays (1980)* proposes a relationship between earthquake intensity and ground acceleration. This provides g-value indications; ground motion is described in terms of gravitational accelerations that are acceptable for engineering computations (*Johnson & 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 Figure SM6 and Figure 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 - 0.1g, with an average value of 0.075g.

Landslide Evaluation

Individual facet ratings for causative intrinsic factors and external trigger factors ratings were summarized to determine landslide hazard zonation in an area. The evaluated landslide hazards are described as the sum of all ratings for intrinsic causative factors and external triggering factors (ELH) (*Raghuvanshi et al., 2014*). (eq.1).

ELH = Sum of ratings of intrinsic causative factors (relative relief + slope material + slope morphometry + structural discontinuity + Ground water+ Land use land cover) Sum of ratings of External causative factors (Rainfall + Seismicity + Manmade activities).....eq. 1.

The ELH was classified into five categories, as shown in Table 1. The SSEP rating system allows an area to be evaluated for landslide hazard zonation under current and/or predictable difficult conditions. The predicted difficult conditions to which the research area can be exposed may be described when heavy rains occur or when complex loading of the slopes is triggered by seismic activity or both.

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

Accordingly, the present research area was evaluated. The result indicates that the whole research area falls into three landslide hazard classes, typically, landslide hazard classes II, III, and IV. The minimum Evaluated Landslide Hazard value resulted 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 that indicates Landslide Hazard Class of IV and High Hazard Zone.

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 environment. The produced LHZ map is illustrated in Figure 4 below. It can be seen that about 73.3km² (27.2 %) of the study area is found within the Low Hazard Zone, 140.8km² (52.1%) found within Moderate Hazard Zone, and the remaining 55.9km² (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 resulted in landslide confirms that no place in the study area is free of slope instability problems.

I. High Hazard Zones

The present research covers about 270km². About 20.7 % of the area is found within the High Hazard Zone that is about 55.9 km² 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 weather and the characteristics of structural discontinuities play a significant role in slope instabilities. Field 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.

II. Moderate Hazard Zone

About 52.1 % of the present research area falls into Moderate Hazard Zone which is about 140.75 km². 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.

III. Low Hazard Zone

The remaining 27.2 % of the present study area falls into Low Hazard Zone which is about 73.3 km². 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 damp. 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.

Validation of LHZ Map

In this research, a total of 85 landslide events and a landslide inventory map were produced. Considering both intrinsic and extrinsic landslide triggering factors, landslide hazards in the study area were validated and a landslide hazard zonation map of the study area was developed. To check the validity of the produced map, the Landslide Inventory map of the research area (Figure SM2) was overlaid on the Landslide Hazard Zonation map (Figure 4) of the research area as shown in Figure 5.

The overall results of landslide events investigated during field observation (landslide inventory map) and SSEP assessment are presented in Figure 5. Accordingly, the landslide inventory map was validated by comparing it to the SSEP map.

As presented in the previous section, the research area is categorized into a high hazard zone, a moderate hazard zone, and a low hazard zone. Similarly, during field investigation, three different landslide activities were mapped in different parts of the study area. These include active landslide districts, districts showing signs of a landslide, and past landslide activities are observed.

The overlap map of the SSEP landslide hazard zonation map and landslide inventory map showed that 17 districts showing active landslides, 2 districts showing signs of landslides, and 5 districts showing past landslide activities fall into high hazard zones. Similarly, 5 districts showing active landslides, 3 districts showing signs of landslides, and 28 districts showing past landslide activities fall into moderate hazard zones. The remaining 1 district showing active landslides, 18 districts showing signs of landslides, and 6 districts showing past landslide activities fall into moderate hazard zones. The comparison of the stability assessment results obtained by the SSEP and landslide inventory map showed that both assessment techniques provide more or less related results.

Generally, both results showed that most areas are characterized by a moderate hazard zone. This implies that the study area is moderately influenced by landslide activities. These results were also verified using visual field observation and most of the landslide events were observed following the rivers as well as valleys. Besides that, areas covered by black cotton soils with shallow groundwater depth are highly susceptible to landslide activities. Moreover, areas linked with the Abay river gorge are also highly exposed to landslide rock slope failure problems.

Declarations

Availability of data and materials

Not applicable

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors' contributions

All persons who meet authorship criteria are listed as authors. All authors approved the final version of the manuscript and agree to be held accountable for the content therein. All authors certify that they have participated sufficiently in the work including participation in the concept, data collection, mapping, data interpretation, analysis, writing, or revision of the manuscript. Moreover, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the Geoenvironmental Disasters.

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Figures

Figure 1

Study area

Figure 2

Facet map of the research area

Figure 3

Groundwater surface trace map

Figure 4

Landslide Hazard Zonation map of the study area

Figure 5

Map showing past landslide events overlaid on LHZ map of the study area

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