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Landslide Hazard Assessment and Zonation by using Slope Susceptibility Evaluation Parameter (SSEP) Rating Scheme- a Case from Debre Sina, Northern Ethiopia

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Landslide Hazard Zonation;

Slope Susceptibility;

Debre Sina;

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ABSTRACT

Rainfall-induced landslides of different types and sizes frequently affect the hilly and mountainous terrains of the highlands of Ethiopia. The principal aim of the proposed research work was intended to prepare a landslide hazard zonation map of the area, particularly for hazardous zones. In this study, the Slope Susceptibility Evaluation Parameter rating scheme has been implemented as a relevant approach to map the landslide hazard of the Debresina area, which has experienced slope failure problems for a long period of time. The geology of the area includes quaternary sediments, ignimbrite, rhyolite, different kinds of basalts, and tuff deposits, which are highly weathered and changed into unconsolidated sediments at some localities. Locally observed geological structures such as joints, dykes, and other discontinuities have a considerable role in the initiation of landslide hazard. As a general methodology, a facet map was prepared from a topographic map (1:50,000) and rating values were assigned to each causative parameter (both intrinsic and external) based on its severity in triggering landslide hazard. The study area was classified in to three hazard classes, of which 25 % of the slopes fall in to a moderate hazard zone, while 58 % and 17 %were found to be high and very high hazard zones, respectively. Authentication of the landslide hazard zonation map with past landslide activities suggests the rationality of the considered leading parameters, the adopted technique, tools, and procedures in developing the study area's landslide hazard map. Furthermore, in order to validate the landslide hazard map prepared during the present study, active landslide activities and potential instability areas, delineated through inventory mapping, were overlaid on it, which yielded promising results.

INTRODUCTION

The earth's surface is always in a dynamic change. These changes are more pronounced in mountainous terrains as a result of different mass wasting processes. One of these mass-wasting processes is landslides (Hansen, 1984). According to Mohammad *et al*. (2012), landslide is a slow to rapid downward motion of unbalanced rock and debris masses because of gravity, whereas Baeza and Corominas (2001), identified landslides occur at a very slow rate, particularly in areas that are very dry and areas that receive sufficient rainfall such that vegetation has stabilized the surface. They may also occur at very high speed, such as in rock slides or landslides, with disastrous consequences, both immediate and delayed, e.g.,

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resulting from the formation of landslide dams (Saro and Biswajeet, 2006). Depending on techniques applied, activities involved, data analysis, scale of study, and data availability, various landslide hazard-mapping approaches were introduced. Barredo *et al*. (2000) divided these methods into inventory, heuristic, statistical, and deterministic approaches. Performing deterministic slope stability analyses demands a considerable amount of time and a deep understanding of both geological and geotechnical factors, coupled with a clear grasp of potential slope failure mechanisms. Besides, such analysis techniques may be suitably applied to small areas, at the scale of a single slope only (Clerici, 2002; Casagli *et al*., 2004; Raghuvanshi *et al*, 2014). McClelland *et al*. (1997) emphasized the heuristic or expert-driven approach, as a method in which a geomorphological expert decides on the type and degree of hazard for each area, using either a direct mapping or indirect mapping approach. This approach is a time consuming and it depends on a large degree on the expertise of the geomorphologist (Barredo *et al*, 2000). The statistical approach compares the spatial distribution of existing landslides in relation to different causative factors (Aleotti and Chowdhury, 1999). These methods are good for assessing the spatial probability but there are problems in evaluating either temporal probability or the effects of future environmental changes (Van Westen *et al*., 2006). The Landslide Hazard Evaluation Factor **(**LHEF) technique has been utilized successfully over the years by many researchers but as proposed by Raghuvanshi *et al*. (2014), its major drawback is that it does not account for external causative factors. Further, it does not predict for anticipated adverse conditions during construction and performance stage rather it offers stability condition for the slopes only for the existing situations prevailed at the slopes during the time of investigation.

In the current study effort is made to overcome the shortcomings of above approaches and thus, a slope susceptibility evaluation parameter (SSEP) rating technique, which encompasses both intrinsic and external parameters, has been implemented. Landslide problem has been causing lots of casualties, economic and social problems to societies especially to those who are living in the mountainous areas. According to Kifle Woldearegay (2013), the hilly and mountainous terrains of the highlands of Ethiopia are frequently affected by rainfall-induced landslides of different types and sizes. According to Gebreslassie (2011), the widespread occurrence of landslides in Ethiopia is largely due to a combination of predisposing factors, including rugged morphology, high topography, and the characteristics of outcropping rocks. The triggering factors are essentially connected with the rainfall regime and to a minor extent with seismicity (Gebreslassie, 2011). According to Asmelash Abay and Barbieri (2012), Debre Sina is located along the southwestern Afar rift margin, and it was frequently affected by landslides in the past few years. It is bounded by different mountains because of which it has experienced rainfall triggered landslides which endangered the life of people and destroyed public and private properties including various infrastructures.

MATERIALS AND METHODS

Description of the study area

Location and climate

The study area, Debre Sina, is situated in Amhara Regional State at a distance of 200 Km toward NNE of Addis Ababa, the capital city of Ethiopia. Geographically, it is bounded between UTM coordinates of 582000-593000 mE; 1080000-1100000 mN (Fig.1). The prevailing climatic condition of the area is "Dega" with mean annual rainfall of 1736 mm/year and temperature varying between 10°C to15°C.

Physiography and the drainage pattern

Physiographically, the study area is located in the Showan highlands, the smallest highlands of the Ethiopian northwestern highlands, which also includes the Tigrean north central massif, South Western highlands of Gojam and Gondar (Leta Alemayehu, 2007). The Showan plateau is bounded by the Ethiopian rift on the eastern and south eastern sides while Abay gorge border it on the north western side. The study area generally is characterized by highly variable topographical features which are a reflection of the past geological and erosion processes. The landscape includes plateaus, steep hill slopes, deeply incised valleys and gorges. The elevation of the study area ranges from 1500 m in the Southern sector to 3100 m in the Northern section.

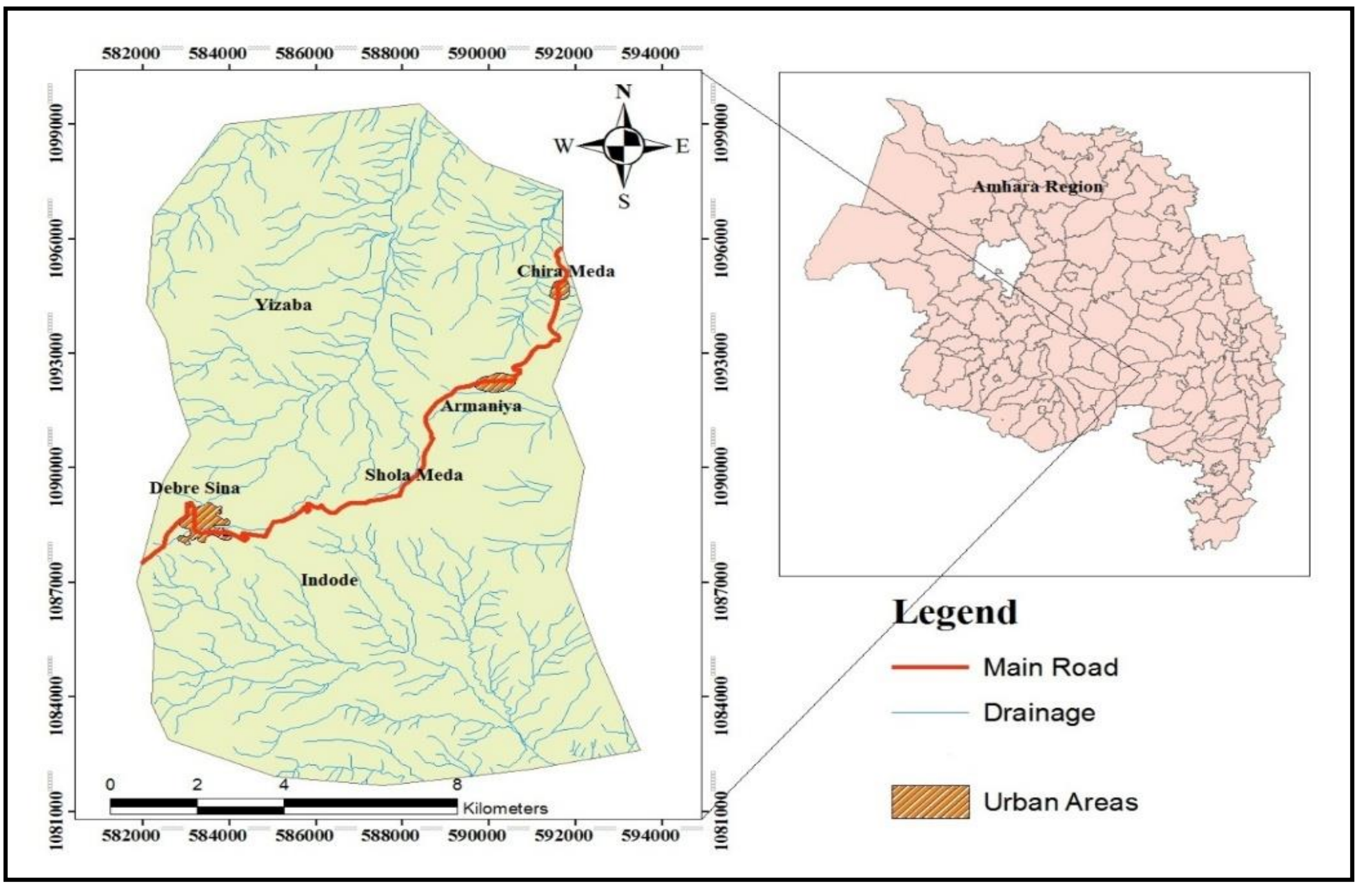

Figure 1. Location map of the study area.

The drainage system of the area includes many small tributaries feeding the main rivers. Most of the tributaries were dry during the present field visit. Majority of them, especially small tributaries, arise from high mountains and join the main rivers at the valley floor. The general drainage pattern of the study area is dendritic type as portrayed in (fig.1).

Geology

The Paleozoic–Mesozoic sediments associated with transgression regression of the sea and Cenozoic volcanic rocks which is directly overlying the Precambrian metamorphic and Mesozoic sedimentary rocks in Ethiopia (Kazmin, 1973). Among these rock units, the geology of the study area and its surroundings can be grouped in to the Cenozoic volcanic rocks (fig.2).According to Astis *et al*. (1997), the Ethiopian volcanics can be related to two main magmatic stages. The first is the Oligocene – Pliocene large fissure eruptions of basalts which build up abundant flood lava sequence known as Ashange and Aiba Basaltic Formations associated with late ignimbrite sheet (AlajiRhyolitic Formations).

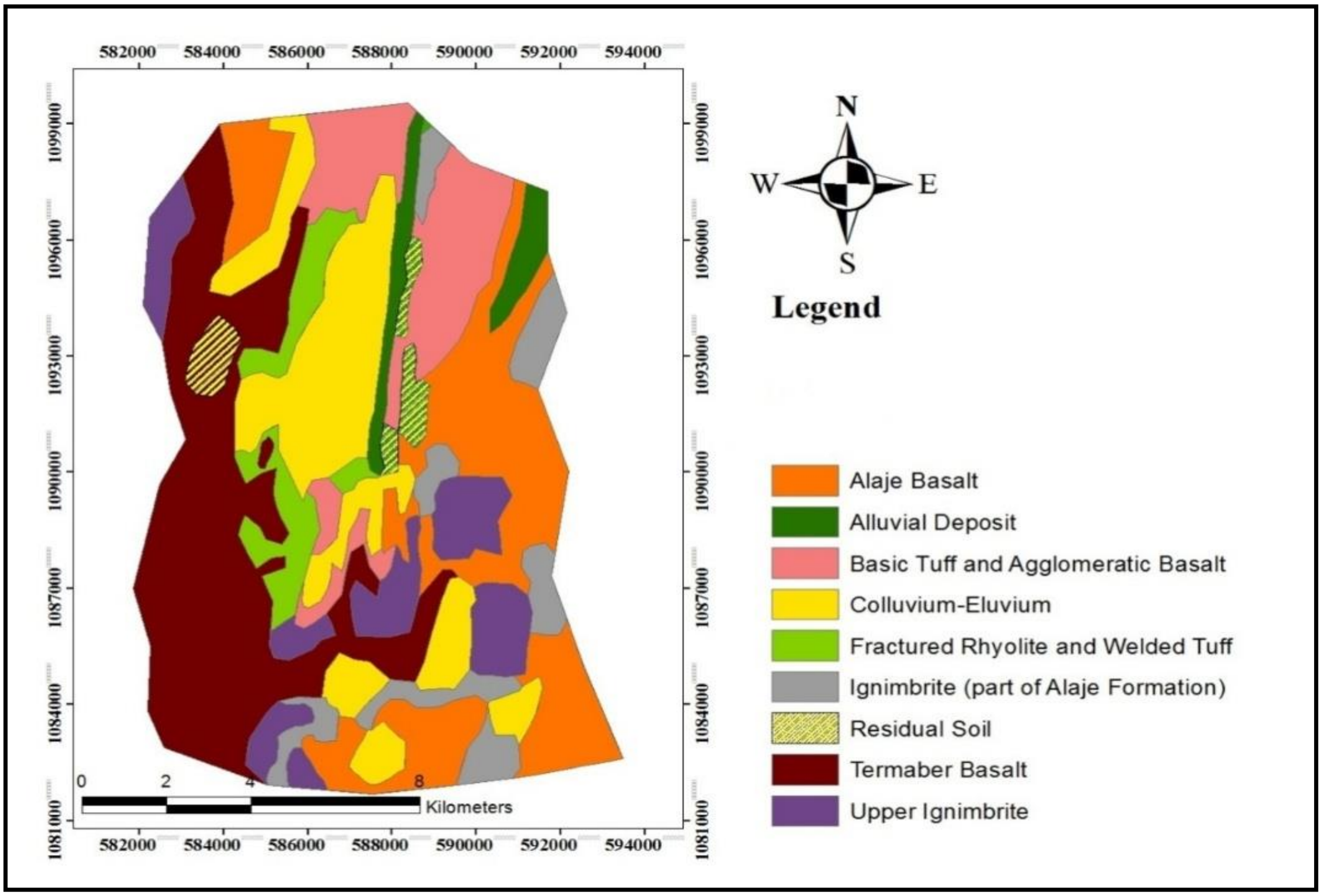

Figure 2. Geological map of the study area.

This magmatic stage ended with the development of large basaltic shield volcanoes, known as the Tarmaber Formation. However in the recent studies about the continental flood basalts of north-western part of Ethiopia, the whole formations were considered as a single unit (Hofman *et al.,* 1997; Pik*et al.,* 1998. Recent classification for continental flood basalt of North western part of Ethiopia was followed as Lower Formation, Upper Formation and the Shield Volcano. Both the Lower and Upper Formation of the continental flood basalt was emplaced 30 my ago within short period of time, less than 1My (Hofmann *et al*., 1997).

The central Ethiopian highlands exhibit a geological structure consisting of Tertiary volcanic rocks capping Mesozoic sedimentary rocks, which are visible only in the deep valleys carved by major rivers. Examples include: Abay Gorge, Jimma Gorge, and Mugher Gorge. According to Mohr and Zenitttin (1988), the Ashangie Formation has been defined by three characteristics: it has experienced a marked dip into the flow sequence of up to 40^{o}; flow thickness averages only about 5m; and individual flows are rarely traceable for more than a few kilometers along strike. Mohr and Zenitttin (1988), highlighted that the Aiba Formation is typically composed entirely of massive flood basaltic flows, with or without intervening agglomerate beds. According to GezahegnYirgu (1997), two major phases of magmatic activity took place, which produced different formations. A first phase was responsible for the eruption of lavas that built thick succession, up to nearly two kilometers, of fissural basalts (known as Ashange and Aiba Basaltic Formation) and later emplacement of a thick series, up to 500 meters, of silicic lavas mainly in the form of ignimbrite sheets (Alaji Rhyolite Formation). The building up of huge shield-like volcanic complexes followed this fissural magmatic stage from central vents with the predominance of basalts over evolved volcanics (Termaber Basalt Formation).

Methodology

Most of the landslide hazard zonation methods are based on the basic assumptions that mass movements are caused by the geological, geomorphic, human induced, etc. factors that can be described through physical parameters, and that the knowledge about these conditions enables drawing conclusions on future landslides (Lang *et al*., 1999). According to Anbalagan (1992), Landslide susceptibility maps can be constructed by using the relation between each landslide and causative factors. Different landslide hazard mapping methodologies in relation to types and scales are portrayed in Table 1.

Table 1. Methods of landslide susceptibility mapping in relation to types and scales.

Types	Techniques	Activities	Characteristics				Scale		
			Direct	**Indirect**	**Qualitative**	**Quantitative**	**1:100,000**	**1:25,000**	**1:10,000**
Heuristic	Geomorphologic analysis	Use field-expert opinion in zonation	X	X	X		X	X	X
	Qualitative map combination	Use expert-based weight values of parameter maps		X	X	X	X	X	
Statistical	Bivariate statistical analysis	Calculate importance of contributing factor combination		X		X		X	
	Multivariate statistical analysis	Calculate prediction formula from data matrix		X		X		X	
	Probabilistic analysis	Calculate prediction from inventory and time period		X		X	X	X	
Deterministic	Safety factor analysis	Apply hydrological and slope stability models		X		X			X
Inventory	Remote sensing and field investigations	Show locations and characteristics of past landslides	X	X	X			X	

Landslide Hazard Evaluation Factor (LHEF) Rating Scheme

The weight rating system is usually designed in many different ways on the basis of studying the impact of each selected factor, for their importance in inducing the instability. Anbalagan (1992), has suggested a landslide hazard evaluation factor (LHEF) rating system that incorporates all the causative factors as listed in Table 2. The LHEF rating scheme may be more relevant as it is based on an empirical approach using important natural contributing factors of slope instability such as; lithology, structure, slope morphometry, land use and land cover, relative relief and hydro-geological conditions. In this scheme, the external factors including rainfall and seismicity have not been included. The maximum weight for individual factor has further been sub-divided into a number of categories to form a detailed LHEF rating scheme. This scheme can then be used for calculating total estimated hazard (TEHD) for individual facets. The total estimated hazard (TEHD) value indicates the net probability of instability of a slope facet. It is calculated slope facet-wise, because adjoining slope facets may have completely different stability situations. The TEHD value of an individual slope facet is obtained by summing up the ratings of each causative factor, obtained from the LHEF rating scheme for that slope facet. Thus, TEHD value is equal to the sum of ratings of categories of all causative factors. As depicted in Table 2, TEHD values are then arbitrarily categorized into different landslide hazard zones.

Table 2. Maximum LHEF rating for causative factors for macro-zonation.

S.No	Causative Factors	Maximum LHEF Rating
1	Lithology	2
2	Relationship of structural discontinuities with slope	2
3	Slope morphometry	2
4	Relative relief	1
5	Land use and land cover	2
6	Hydrogeological condition	1
	Total	10

The LHEF rating scheme employs an empirical method to evaluate slope instability by considering the individual and combined influences of inherent causative factors. These inherent factors then form the basis for Landslide Hazard Zonation. (LHZ) mapping on macro-zonation approach. Maximum values of rating for each parameter is awarded keeping in mind its estimated significance in resulting slope failure and also to denote overall field circumstances (Table 3).

Table 3. LHZ classes on the basis of Total Estimated Hazard (TEHD)

S.No	TEHD Value	Hazard Class
1	<3.5	Very Low Hazard (VLH)
2	3.5-5.0	Low Hazard (LH)
3	5.1-6.0	Moderate Hazard (MH)
4	6.1-7.5	High Hazard (HH)
5	>7.5	Very High Hazard (VHH)

Slope Stability Susceptibility Evaluation Parameter (SSEP) Rating Scheme

This landslide hazard zonation mapping methodology is a modified technique which is developed by Raghuvanshi *et al.* (2014) and is applicable in large areas demanding rapid slope stability assessment. It mainly relies on field data and produces landslide hazard zonation map by combining both intrinsic and external slope instability triggering parameters. It was developed in order to overcome the shortcomings of Anbalagan (1992) LHEF rating scheme and is found to be suitable to be applied in present study. The SSEP rating technique involves both internal and external activating parameters accountable for slope instability. The slope stability is mainly governed by intrinsic parameters such as; slope geometry, slope material (lithology or soil type), structural discontinuities, land use and land cover and groundwater (Wang and Niu, 2009). In addition to the factors mentioned, both natural and human-induced external parameters that contribute to slope instability are also taken into account. The primary natural factors identified as triggers for slope instability include seismic activity (Keefer, 2000) and rainfall (Collison *et al*., 2000; Dahal *et al*., 2006). Other natural influences that can lead to slope instability, such as snow and avalanches, wind erosion, permafrost conditions, shoreline processes, and volcanic activity, are not considered in the SSEP for landslide hazard assessments. Manmade activities mainly include constructions and cultivation practices on slopes (Wang and Niu, 2009). Slope Facet is defined as a land unit, which is characterized by uniform slope geometry in terms of slope inclination and slope direction (Anbalagan, 1992). To demarcate the slope facets, topographic maps were utilized. Facet boundaries were delineated using prominent and minor hill ridges, as well as primary and secondary streams, along with other topographical features. For the present study, Debre Sina topo map of 1:50,000 was utilized to delineate slope facets of the study area. Rating values was assigned for each intrinsic and external causative factor based on its severity in landslide initiation and the summation of all causative factors will provide Evaluated Landslide Hazard (ELH). Finally landslide hazard zonation (LHZ) map was prepared based on the facet-wise distribution of ELH values. Table 4 portrays distribution of higher SSEP ratings assigned to each causal factor.

Table 4. Distribution of maximum SSEP ratings assigned to different intrinsic and external factors (Source: Raghuvanshi *et al.*, 2014)

Triggering Parameters			Maximum Rating
Intrinsic Parameters			
	1. Slope Geometry	Relative Relief	1
		Slope Morphometry	2
	2. Slope Material		1
	3. Structural Discontinuities		2.5
	4. Land use Land cover		1.5
	5. Groundwater		2
External Parameters			
	1. Seismicity		2
	2. Rain Fall		1.5
	3. Man-made Activities		1.5
Total			**15**

ELH= Summation of ratings of intrinsic parameters (relative relief + slope morphometry + slope material + structural discontinuity + land use and land cover + groundwater) + Summation of ratings of external parameters (rainfall + seismicity + man-made activities)

RESULTS & DISCUSSION

Preparation of facet map

For convenience and ease assessment of landslide hazard, the study area has been divided into different slope facets which were defined by major or minor hill ridges, primary and secondary streams, and other topographic waves. According to Anbalagan (1992), slope facets are characterized by more or less uniform slope inclination and slope direction. These slope facets were prepared from topographic map of scale 1:50,000 and verified in the field. Slope facet was used as base map to award rating values for landslide hazard triggering parameters (Table 5). The slope facets were usually delimited by ridges breaks in slope, streams, spurs, gullies and rivers etc. The facet maps form the basis for the preparation of thematic maps in general and SSEP mapping in particular and individual facet is the smallest mappable unit. In all 60 facets have been delineated in the study area on the basis of visual interpretation of topographic maps fig. 3a.

Landslide Hazard Triggering Parameters

For landslide hazard zonation, numerical ratings have been assigned to each of the internal and external activating parameters on the basis of their impact towards instability of slope, based on standard SSEP rating table.

Intrinsic Parameters

Intrinsic parameters are considered in hazard mapping because they play a great role in the stability conditions of the slope. These intrinsic parameters are relative relief, slope morphometry, slope material, structural discontinuities, land use and land cover and groundwater (Anbalagan, 1992; Wang and Niu, 2009). Based upon the given conditions for each of these internal parameters they may have an effect over the stability condition of the slope.

Relative Relief

Relative relief is one of the important causative factors which may cause slope instability. It affects the instability condition by increasing the gravitational energy which pulls the slope material down the slope. The relative relief map represents the local relief of maximum height between the ridge top and the valley floor within an individual facet (Anbalagan, 1992). Relative relief map of the study area has been prepared by taking the altitude difference between hill top and valley bottom within each slope facet which was later processed by ArcGIS-10.8 software. In the study area 57% of the facets fall in very high relative relief whereas 22% fall in high relief. The remaining facets (21%) fall in medium and moderate relative relief (fig.3d). This implies that more than half of the study area possesses very high relative relief which renders it susceptible to landslide.

Slope Morphometry

Slope morphometry map of the study area has been designed by calculating the slope angles from topographic map. The ratio of height difference between two points in a given facet to horizontal distance gives decimal value of the slope. By taking the inverse tangent of this value slopes in degrees have been manipulated. These slopes fall in to different slope classes as escarpment/cliff (> 45°), steep slope (36°-45°), moderately steep slope (26°-35°), gentle slope (16°-25°) and very gentle slope (< 15°). Later, slope morphometry map of the study area has been prepared by using ArcGIS-10.8 software. Accordingly, 42% of the facets experience moderately steep slope (26°-35°) while 33% fall under gentle slopes. The remaining facets possess steep slopes, escarpment and very gentle slope which account for about 10%, 8% and 7%, respectively. Generally, most of the facets have moderately steep slope ranging from 26° to 35°(fig 3e).

Slope Material

The rock sub classes in SSEP rating system are adopted from classification of rocks based on field estimates of strength by observation which is proposed by (Hoek and Bray, 1997). Thus, slope material is classified as 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) and extremely strong rock (>250 MPa). Slope material map of the study area has been prepared from field observation using l:50,000 scale topographic map as base map (fig. 3f). Slope material of the study area is well described by highly weathered and fragmented rock mass that made it difficult to distinguish some rocks from soil during field visit. Ignimbrite, Alaje Basalt and fractured rhyolite are some of the lithologies on which intense weathering was observed. Generally, 38% of the study area is covered by medium strength rocks while colluvium materials cover about 27% of it. Highly weathered materials and weak rocks each comprise 22% and 13%, respectively.

Land Use Land Cover

Land use and land cover pattern is one of the important parameters governing slope stability. Vegetation has major role to resist slope movements, particularly for failures with shallow rupture surfaces. A well spreaded network of root system rises the shearing resistance of the slope material because of natural anchoring of slope materials, particularly for soil slopes. Moreover, a thick vegetation or grass cover reduces the action of weathering and erosion, hence adds to stability of the slopes. On the other hand, barren or sparsely vegetated slopes are usually exposed to weathering and erosion action, thus rendering it vulnerable to failure (Wang and Niu, 2009). Slope instability is also induced because of anthropogenic activities, i.e., urbanization, particularly on higher slope angles ($>30^0$). It not only removes vegetation cover but also adds to the natural weight of the slope as surcharge due to the weight of civil structures. In a hill slope with higher slope angle, buildings are usually located by constructing local cut slopes and flat terraces. With this concept urbanization is broadly classified into three categories (Zubair *et al*., 2012). A sparsely urbanization slope is where construction terraces are located far apart (more than 15 m of horizontal spacing) providing a considerable distance between two terraces along the slope. When we see the areal coverage of land covers in the present study area, bushes and shrubs alone cover 29 % of the study area whereas bare land comprises 23 %. On the other hand heterogeneous agricultural areas, arable land and forest encompass 20 %, 17 % and 11 % of the study area, respectively as shown on fig. 3c. The LULC map of the study area was prepared from ERDAS 9.2 softer and later verified during field visit.

Groundwater conditions of the study area

The susceptibility of rock/ soil to failure is majorly determined by groundwater of an area. Hydrological characteristics of an area include underground water conditions, saturation state of rock/soil, presence of streams, rivers, and drainage pattern of the area. Water bodies displaced because of presence of interruptions and shallow water-table environments in hilly terrains along with torrential rainfall make the slopes susceptible to instability. According to Murck *et al*. (1996) during the prolonged monsoon phases, increased pore-water pressure creates favorable conditions for deep-seated landslides. In the present study area, groundwater is not uniformly distributed over all facets. Therefore, groundwater investigation has been conducted facet wise. Some facets have small flowing streams whereas others display wet to dry conditions. As fig. 3b depicts, surface terraces of groundwater of the study area portrays dry slopes (28 %), wet (22%), flowing (18 %), damp (18 %) and dripping (14 %), respectively.

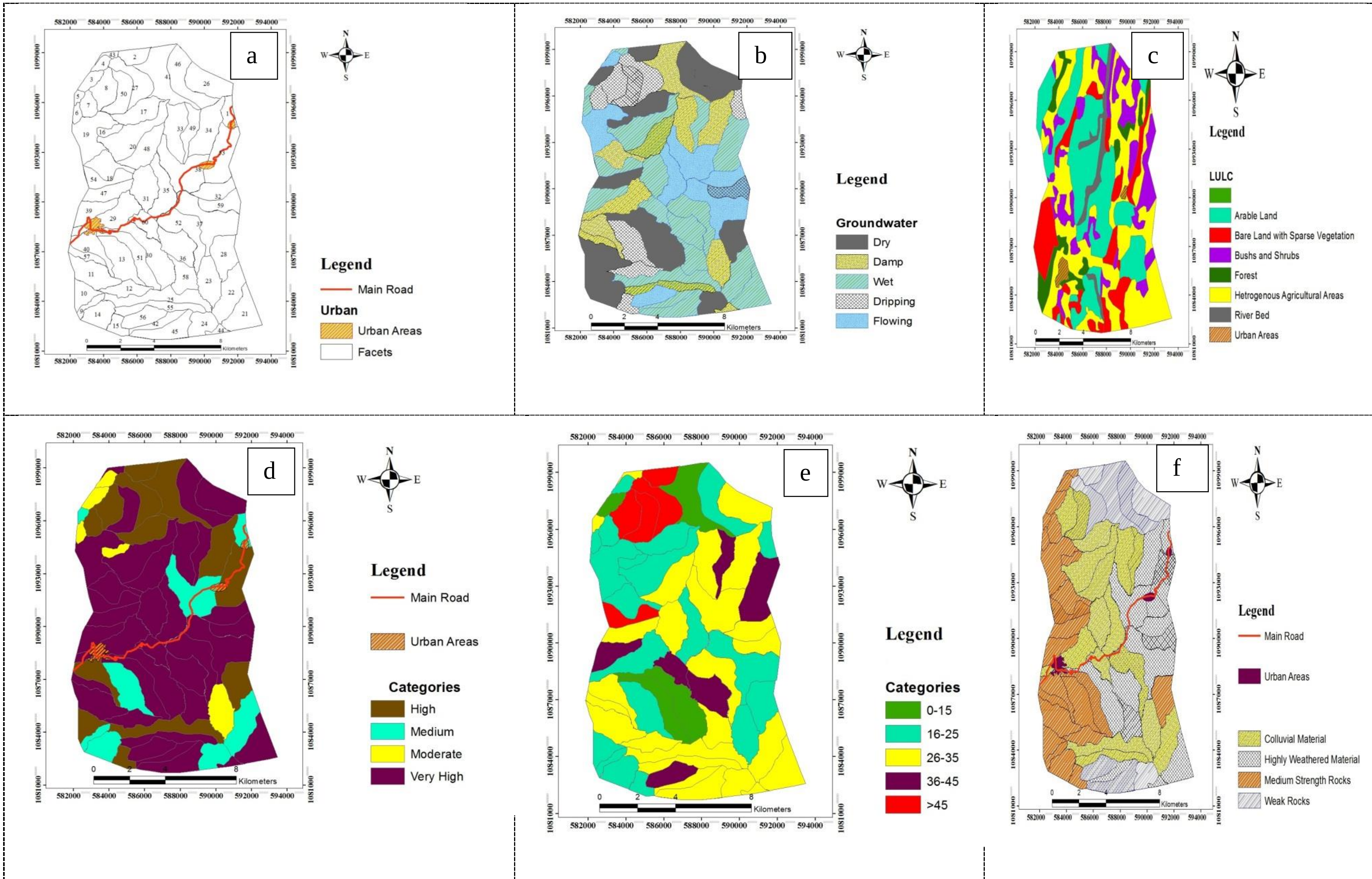

Figure 3. Maps showing slope facets and intrinsic landslide triggering parameters of the study area. (a)Slope facet;(b) groundwater;(c)land use land cover;(d) relative relief;(e) slope morphometry; (f) slope material.

External Landslide Hazard Triggering Parameters

Rain Fall

To assess and see the effect of rainfall to the landslide occurrences of the area, rain fall data for 35 years (1981-2013) was collected from National Meteorology Agency of Ethiopia. It indicates that the maximum, minimum and mean annual rainfall in the study area is 3592.7 mm, 683.6 mm and 1,735.591 mm, respectively. The maximum annual rainfall was recorded in the year 1997, while the minimum in the year 2012. The monthly maximum rainfall is always in the months of July and August for all the recorded data. The study area is one of the areas receiving a high rainfall in the country having a bimodal rainfall nature which possesses alternating dry and rainy seasons. It receives exceptionally peak precipitation in the months of July and August. These two months alone contribute 43% of annual precipitation, which maximizes landslide occurrences. On the other hand months such as; March, April, May and September experience moderate amount of monthly precipitation. Low amount of mean monthly precipitation is recorded in the months of October and November whereas December, January and February are generally regarded as dry months as they receive very low amount of monthly precipitation (fig. 4b)

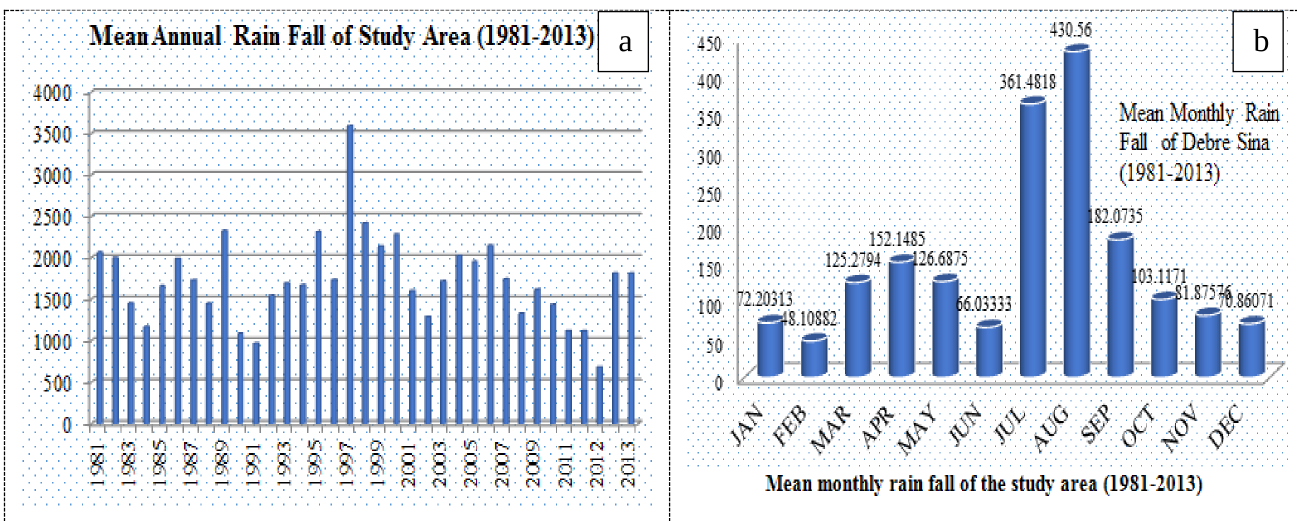

Figure 4. Mean annual and mean monthly rainfall of the study area (1981-2013).

Most of the landslides recorded in the study area happened when the annual rain fall exceeds the long term average rainfall. However, there were lower occurrences of major landslides between the years of 1983 to 1994 where the amounts of annual rainfalls were lower than the long term average except for 1986 and 1989.

Seismicity

The earthquake shocks may be responsible for triggering new landslides and reactivating old landslides. The vibrations due to earthquake may induce instability, particularly in loose and unconsolidated material on steep slopes. The Afar rift margin, where the study area is situated, is known for its earthquake occurrences. Most of the earthquake ranges from small to medium level (Atalay Ayele, 2007). Although not registered, the occurrences of landslide in association with Afar earthquake in the area are common as evidenced by local dwellers. For example, as obtained from local information, there was a landslide occurrence around the Nibamba Gebriel and Sina Aregawi contemporaneous with the 1961 Kara-Kore earthquake.

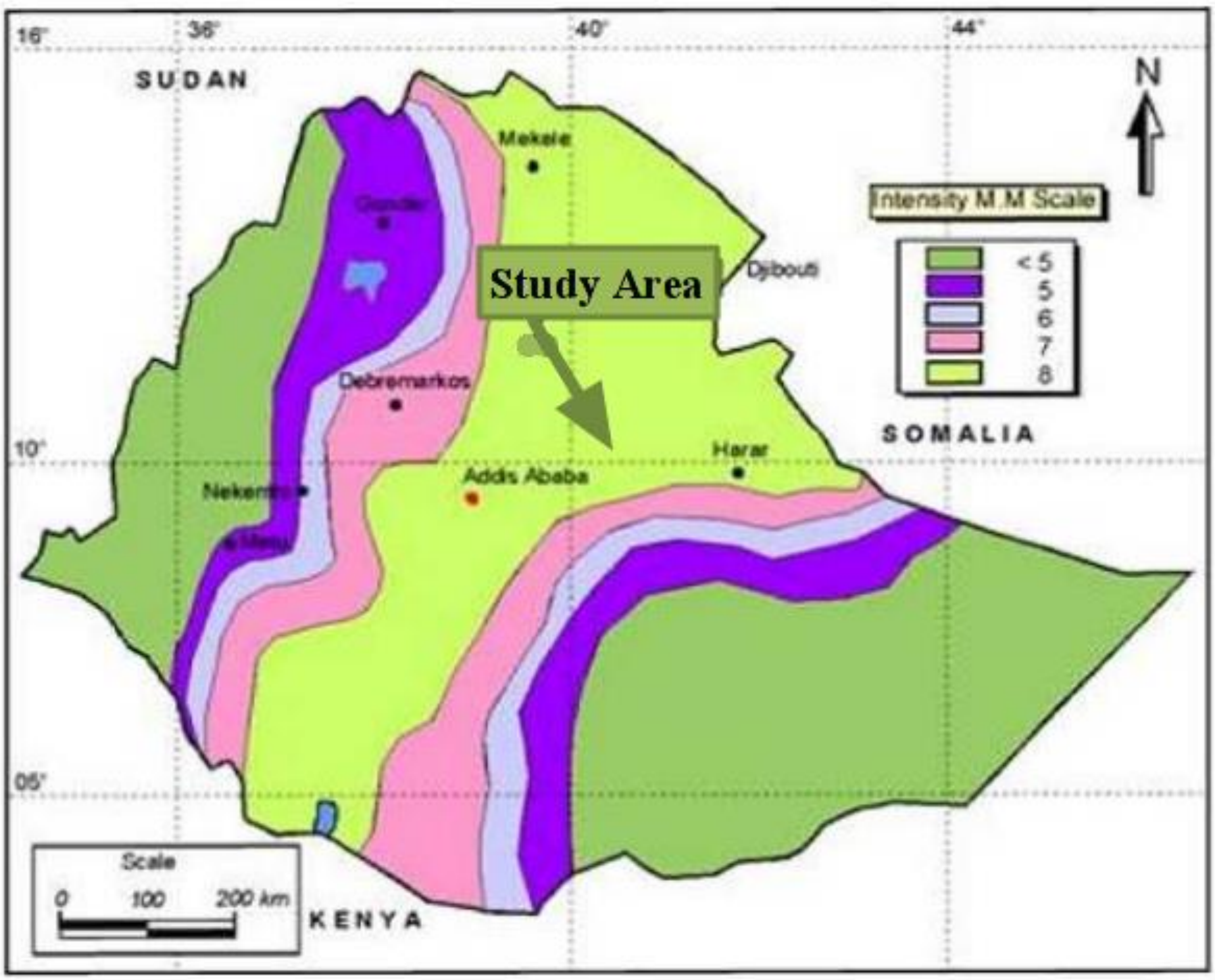

Figure 5. Seismic risk map of Ethiopia (Source: Laike Mariam Asfaw, 1986).

As portrayed above in figure 5, the present study area falls in seismic zone which has an intensity of 8, this zone has a ground acceleration of 0.1- 0.5g. Thus, the rating for ground acceleration of 0.1-0.5g, as per the standard SSEP table is estimated to be 1.5. Accordingly, this rating value has been distributed to all 60 slope facets in order to generate landslide hazard zonation map of the study area. Earthquake induced landslide is so frequent in most parts of Ethiopia that it needs intensive analysis of causative factors for any landslide including seismic factor.

Table 5.Rating values assigned to each causative parameter in all slope facets

Facets	Relative Relief	Slope Morphometry	Structures	Groundwater	LULC	Slope Material	Man-made Activities	Seismicity	Rain Fall
1	0.6	0.6	1.66	0.6	0.4	0.5	1	1.5	0.75
2	0.8	2	1.86	0	0.4	0.8	1.25	1.5	0.75
3	0.2	0.3	2.31	0	0.75	0.8	1	1.5	0.75
4	0.2	0.6	2.49	2	0.4	0.3	1	1.5	0.75
5	0.6	1	1.82	1	1.5	0.4	0.75	1.5	0.75
6	0.2	0.6	2.5	1	1.5	1	0.75	1.5	0.75
7	0.8	0.6	2.38	1.5	1.2	0.5	0.1	1.5	0.75
8	0.8	2	1.84	1.5	1.5	0.4	0.1	1.5	0.75
9	0.6	0.6	1.58	0	0.4	0.4	0.1	1.5	0.75
10	0.8	0.6	1.88	0	0.75	0.5	0.15	1.5	0.75
11	1	1	2.49	0	1.5	0.4	1.25	1.5	0.75
12	1	1	2.23	1.5	1.5	0.1	1	1.5	0.75
13	0.6	0.6	2	1.5	0.4	0.4	1	1.5	0.75
14	0.6	0.6	1.86	0	0.75	0.8	1	1.5	0.75
15	0.8	1.7	2.5	1.5	1.5	1	1	1.5	0.75
16	0.2	0.6	2.43	2	1.5	1	1.25	1.5	0.75
17	0.8	0.6	1.86	0	0.4	0.3	1	1.5	0.75
18	1	0.6	2.24	0.6	1.2	0.3	0.5	1.5	0.75
19	1	1.7	2.32	2	1.5	1	1	1.5	0.75
20	1	0.6	1.81	0	0.4	1	0.1	1.5	0.75
21	1	1.7	2.5	2	1.5	1	1.25	1.5	0.75
22	0.6	1	1.6	1	0.4	1	0.75	1.5	0.75
23	0.2	0.6	2.11	0.6	1.2	0.8	0.15	1.5	0.75
24	0.6	1	2.13	0	0.4	0.8	0.1	1.5	0.75
25	0.8	1	2.38	1	0.4	0.25	0.75	1.5	0.75
26	1	1	2.5	0	0.4	0.5	0.75	1.5	0.75
27	0.8	2	1.71	2	1.5	1	1	1.5	0.75
28	0.8	0.6	1.94	0	0.4	0.5	0.1	1.5	0.75
29	1	0.6	2.39	0.6	0.75	1	1	1.5	0.75
30	1	0.3	1.78	0	1.5	1	0.1	1.5	0.75

….Continuation of Table 5

Facets	Relative Relief	Slope Morphometry	Structures	Groundwater	LULC	Slope Material	Man-made Activities	Seismicity	Rain Fall
31	1	2	2.32	1	1.5	1	1.25	1.5	0.75
32	1	1	2.16	2	0.4	1	1.25	1.5	0.75
33	1	1	1.6	0.6	0.75	0.5	1	1.5	0.75
34	0.8	1	2.45	0.6	1.2	0.8	0.75	1.5	0.75
35	1	0.6	1.62	2	0.4	0.1	1.25	1.5	0.75
36	1	1.7	2.46	2	1.5	0.4	1	1.5	0.75
37	1	0.6	2.17	2	1.5	0.8	0.75	1.5	0.75
38	0.6	1	2.5	2	1.5	1	1.25	1.5	0.75
39	1	1.7	1.69	1	0.4	0.8	0.1	1.5	0.75
40	0.8	1	2.22	0	0.4	0.8	0.1	1.5	0.75
41	0.8	0.3	2.48	0.6	0.75	0.8	0.75	1.5	0.75
42	1	1	2.03	1	0.4	1	0.15	1.5	0.75
43	1	1	1.94	1	1.5	0.5	1	1.5	0.75
44	1	1.7	2.48	1.5	1.5	1	1.25	1.5	0.75
45	1	1	1.55	0.6	0.4	0.8	0.1	1.5	0.75
46	1	0.6	1.7	0	1.2	0.5	1	1.5	0.75
47	1	1	1.64	0	0.75	1	0.1	1.5	0.75
48	1	1	1.83	0.6	1.2	0.5	0.75	1.5	0.75
49	1	1.7	2	1	1.2	1	0.1	1.5	0.75
50	1	2	2.48	1.5	0.75	0.8	1.25	1.5	0.75
51	1	0.3	2.24	0	0.75	1	1	1.5	0.75
52	1	1	2.5	1	1.2	1	1	1.5	0.75
53	0.8	1.7	1.98	1	1.5	0.5	0.75	1.5	0.75
54	1	2	2.33	1	1.5	0.5	0.75	1.5	0.75
55	1	1	1.84	0.6	1.2	0.8	1	1.5	0.75
56	1	1.7	2.4	2	1.5	1	1	1.5	0.75
57	1	1	2.39	0.6	1.5	0.4	1.25	1.5	0.75
58	1	1	1.98	0	1.2	0.4	0.1	1.5	0.75
59	1	1	2.08	1.5	0.75	1	1	1.5	0.75
60	1	1.7	2.08	1	1.2	0.4	1	1.5	0.75

Estimation of Evaluated Landslide Hazard (ELH)

The evaluated landslide hazard indicates the net likelihood of instability and has been calculated facet-wise. The ELH of an individual facet was obtained by adding the ratings of the individual causative factors obtained from the SSEP rating scheme. Evaluated Landslide Hazard is estimated as summation of ratings of intrinsic and external parameters. On the basis of evaluated landslide hazard (ELH), three categories of landslide hazard zones have been identified for the present study area (fig.6) viz., moderate hazard (MH), high hazard (HH) and very high hazard (VHH). These zones are distributed in accordance with the geology and geomorphology of the area. Areal coverage of moderate hazard is 25 % whereas those of high hazard and very high hazard are 58 % and 17 %, respectively. These figures indicate that 75 % of the study area is very susceptible to landslide hazard

Moderate Hazard Zone

Moderate hazard zone represents relatively safe areas for construction and various infrastructural activities. It covers 25 % of the study area and out of 60 slope facets 15 fall in moderate hazard zone. Moderate hazard zones are commonly distributed in Northern, Central and Southern parts of the study area. Chira Meda area falls in this zone. Even if this zone is not totally suitable, it should not be avoided because it has less probability of landslide occurrence as compared to others.

High Hazard Zone

The maximum area of the study area is covered by high hazard zone which accounts about 58 % of the study area. This zone represents high susceptibility to landslide hazard as compared to moderate hazard zone. Some of the inventoried landslides are known to occur in this zone. High hazard zone is mostly dispersed in Northern, Eastern and Southern parts of the study area. Out of 60 slope facets, 35 are categorized under this zone. Part of the town Debre Sina and Armania also fall in High hazard zone. Those slopes falling in this zone should be partially avoided or detailed study on larger scale (1:1000) should be done to evaluate the status of stability of these slopes. Suitable control measures should also be identified before taking up constructions in order to minimize related geo-environmental hazards.

Very High Hazard Zone

This zone represents totally unsuitable areas for constructions and settlement as well as agricultural activities. It covers the least area coverage and accounts 17 % of the study area. Because of very high susceptibility of landslide occurrence in very high hazard zone, it is not advisable and should be totally avoided. About 10 facets of the study area have been identified to be very susceptible to landslide hazard. Among these, very high hazard zones are located in North-Western, Central and South-Eastern part of the study area. Part of town Armania also falls in this zone.

Validation of SSEP Results

The results obtained in present study correlated with the past landslide events recorded in the study area. Thus, the final Landslide Hazard Zonation map has been checked against the inventoried landslides of the study area for its validity. Landslide inventory map of the study area has been prepared by integrating field observation and GPS data collection with some ideas obtained by interviewing local people living around the study area. Most of the inventory landslides are concentrated in high and very high hazard zones. Out of 36 landslide inventories prepared during the field visit, 22 (61 %) of them fall in high hazard zone while the remaining 14 (39 %) fall in very high hazard zone. The methodology followed during the present study relates intrinsic and external landslide triggering parameters to landslide occurrences. It has produced the results that match to past landslides. Thus, Slope Stability Evaluation Parameter (SSEP) rating scheme is found to be suitable methodology in landslide hazard zonation as it validated with the past landslide hazard events.

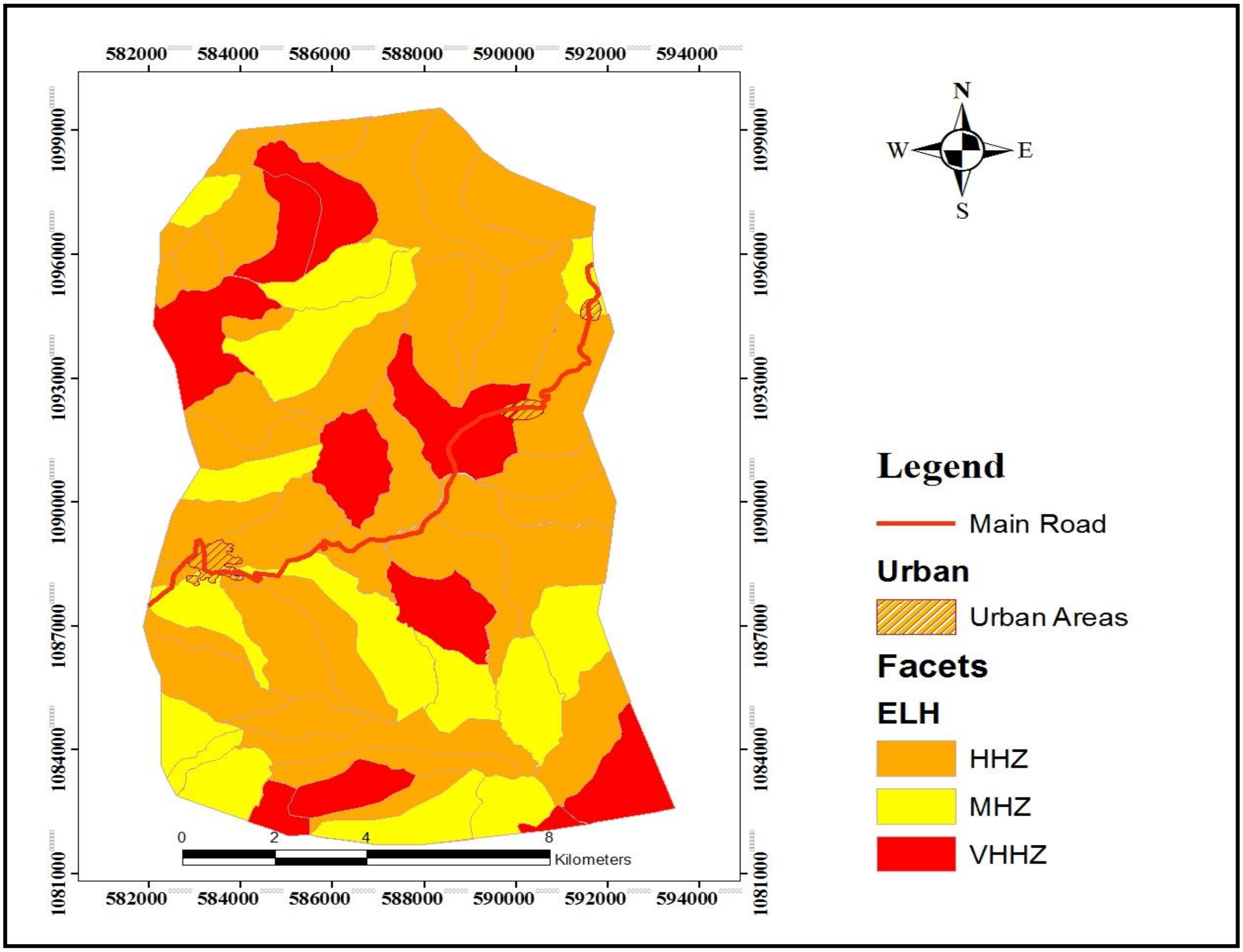

Figure 6. A map showing Evaluated landslide hazard of the study area.

CONCLUSIONS

The present study area has been affected by landslide hazard which devastated both public as well as private properties including infrastructures. It also threatened the life of people and animals living around the study area. Landslide hazard and fatalities have been reported in the study area for a long period of time. Several landslide hazard assessment approaches are available based on the kind of data input, study area size, data availability, kind of topography, etc., each of these approaches has its own benefits and shortcomings. Concerning slope susceptibility in the present study area, areas covered with bare land, shrub and urban classes are more vulnerable to landslides, as compared to vegetation cover and forest classes which disfavor landslides. North, Northeast and West facing slopes are favorable to landslides, whereas South, Southwest and West orientation disfavor slope failure. Moreover, slopes inclined at greater than 25° angle have strong susceptibility to landslides. Distance to streams also has strong relations with landslide occurrence because areas close to streams prove to be highly prone to slope instability suggesting that slope undercutting by stream is an important process. Most of the recent landslides observed during field visit and delineated through inventory mapping fall into high and very high hazard classes suggesting the reliability of the SSEP rating scheme in delineating landslide prone areas of mountainous terrains. This approach is found to be more effective as it heavily depends on realistic field data andhelps to map landslides in large areas in a short period.

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