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Landslide hazard zonation in Ada Berga district, central Ethiopia – A GIS based statistical approach

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Abstract: The present study is focusing on evaluating the landslide hazard in Ada Berga district in the central Blue Nile (Abay) basin in central Ethiopia. Forty five landslides have been identified through field investigation and GIS-based inventory in the study area. Details of inventory of each landslide and its governing factors such as lithology, soil type, slope, aspect, curvature, elevation, land use/ land cover and groundwater conditions was compiled. These data sets were prepared as layered spatial GIS database which were later utilized for the purpose of generating landslide hazard zonation map. Slope, aspect, curvature and elevation were calculated from the Digital Elevation Model (DEM) of the area, which was obtained from the ASTER satellite. Lithology was extracted from the geological map of Ethiopia (scale 1:2,000,000) while the soil and land use/ land cover maps were prepared from Landsat + ETM satellite data using digital image processing techniques. Springs were also mapped through field surveys and further analyzed with respect to the proximity of landslides. These factors were analyzed to find the statistical relationship with the landslide occurrence in the area.

GIS based statistical and probabilistic approach was used to rate the governing parameters, which were used for preparation of the landslide hazard (LHZ) map. The resulting LHZ map revealed that 24% (36.72 km^2) of the study area falls under no hazard, 32% (48.96 km^2) as low hazard, 17% (26.01 km^2) as moderate hazard, 25% (38.25 km^2) as high hazard and the rest 2% (3.06 km^2) as very high hazard zones. Further, the LHZ map prepared in this study is validated using the landslide inventory data compiled in this study. Out of forty five landslides in the study region, 89% of them fall either in the high or very high hazard zones, while 9% fall in medium and only 2% falls under low hazard zones. Thus, the satisfactory agreement confirms the success of adopted methodology. Such an approach will play important role in future infrastructural development in Ethiopia where landslide hazard is very common in the rugged mountainous incised valleys of major river basins.

Keywords: Blue Nile, Digital elevation model, Landslide, Landslide hazard mapping

1. Introduction

In natural system, landslides are recognized as one of the most significant "natural hazards" in many areas throughout the world (Crozier and Glade, 2005; Varnes, 1996). The damage caused by these landslides accounts for millions of dollars and hundreds of thousands of casualties and injuries every year (Pan et al., 2008; Kanungo et al., 2006; Dai et al., 2002). In order to minimize the threat of landslide hazard it is necessary that the areas which have a potential for such landslides should be identified and mapped. Such delineation of landslide hazardous zones may help in recommending proper mitigation measures for stabilization of landslides or such hazardous areas may be avoided to minimize the threat of damage to the people and developmental activities (Pan et al., 2008; Anbalagan, 1992).

Landslides have been a frequent problem in Ethiopia especially in highlands in most parts of the north, south and western regions of the country and parts of the Rift valley escarpments (Ayele et al., 2014). Ayalew (1999) reported that the Ethiopian plateau has demonstrated significant instability in both the superficial materials and the bedrock. The Blue Nile basin has shown slope failures both in the form of landslides and rock falls. Almost all common types of landslides in the region have been reported, these include deep-seated rotational slumps, massive translational slides, progressive creep movements, rock fall and debris and mudflows. As indicated by the studies in the region, the effects of landslides and rock falls are known to be severe in many localities and it needs an integrated study (Ayalew and Yamagishi, 2003).

Few decades ago the land was highly forested. Due to deforestation, soil erosion and the runoff process has increased significantly. This has aggravated the landslide process. The main anthropogenic activity in the present study area is the cultivation activity. Significant numbers of past landslides were observed within cultivated land. Since the area covers significant cultivated land area, the alluvo-colluvial material gets disintegrated and facilitates percolation of rain water during rainy season. This makes the area susceptible to landslides.

The study area is highly susceptible to landslide problems, with number of active landslides in the last few years. The landslides are extensively damaging agriculture and houses in the study area. The magnitude of the problem in the area is alarming and the vulnerability of the lives and property of the people

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by landslides needs immediate attention. Thus, in this study an attempt has been made to prepare landslide hazard zonation (LHZ) map of the region so that due attention may be given by the planners to minimize the problem.

2. Review on LHZ techniques

For the purpose of delineation of an area susceptible for landslide activity various LHZ techniques can be employed (Van Den Eeckhaut et al., 2009; Anbalagan, 1992). For this the degree of potential hazard is estimated based on qualitative or semi-qualitative measures of different instability inducing factors (Varnes, 1984). The LHZ techniques are broadly classified into landslide inventory mapping, heuristic approach, statistical methods and deterministic approaches (Leroi, 1997; Fall et al., 2006).

Landslide inventory mapping is identification of landsides and compilation of details of each landslides i.e. location, dimension, causative factors, frequency of occurrence etc. (Dai and Lee, 2001; Dai et al., 2002; Fall et al., 2006). It is believed that "the past and the present are the keys to the future", as the landslides, most likely, occur under similar conditions which has prevailed during the past or the present times (Van Den Eeckhaut et al., 2009). The landslide inventory forms the basis for most of the susceptibility mapping techniques (Dai and Lee, 2002).

The heuristic techniques are the expert evaluation techniques where expert decides on the type and degree of hazard for each area, using either a direct mapping or indirect mapping approach. The landslide hazard is determined based on quasi-static variables (Dai and Lee, 2001; Fall et al., 2006). Several expert evaluation techniques were developed in the last three decades (Raghuvanshi et al., 2014a, Ayenew and Barbieri, 2005, Guzzetti et al., 1999, Turrini and Visintainer 1998, Sarkar et al., 1995, Anbalagan, 1992, Pachauri and Pant, 1992). However, these techniques are considered to be subjective (Fall et al., 2006; Kanungo et al., 2006, Casagli et al., 2004). However, the merit of these techniques is that they are simple in application and utilizes much field data well supported by experience of an expert (Raghuvanshi et al., 2014a and b).

In statistical methods, various causative factors responsible for instability are analyzed by univariate and multivariate statistical methods (Fall et al., 2006; Dai and Lee, 2001). Based on the analysis for the interrelationship of causative factors and the past activities, quantitative or semi-quantitative estimates are made for those areas where similar conditions prevailed. The major shortcoming of the statistical techniques is related to the collection of the data on landslide distribution and causative factors over large area for considerable prolonged periods. Another drawback of these methods is that the results are dependent on quality of data and details of the landslide frequency data (Fall et al., 2006).

Deterministic approach involves hazard determination in terms of factor of safety or the probability of failure by considering various intrinsic and external triggering factors (Go´mez and Kavzoglu, 2004). The deterministic approach is physically sound and provides absolute value for instability of slope in terms of safety factor (Fall et al., 2006; Westen Van et al., 1997). These techniques are useful for mapping hazard at large scale for construction sites. Further, these techniques require good knowledge on geological and geotechnical aspects with proper understanding on potential mode of slope failure. Besides, these techniques are time consuming and can be applied to small areas, at the scale of a single slope only (Casagli et al., 2004; Clerici, 2002).

3. Objective and methodology of the study

The main objective of the study was to prepare LHZ map of Ada Berga district in the central Blue Nile (Abay) basin in central, Ethiopia.

First, landslide inventory mapping was carried out and later statistical hazard model based on the various causative factors and their interrelation with past landslides was developed in a GIS environment. Finally, LHZ map was prepared based on relative influence of various causative factors.

4. Study area

The present study area, Ada Berga district, lies in the Oromiya National Regional State in West Showa Zone of central Ethiopia (Fig.1). The study area is about 88 km west of the capital city, Addis Ababa and covers a total surface area of 153 km^2.

In the study area the elevation ranges from 1375 m to 2565 m and the area falls in tropical (800 -1500 m), subtropical (1500-2300 m) to temperate (2300 – 3300 m) climatic zones. The long term average annual precipitation of the area is 1790 mm (period from 1997 to 2006). The highest monthly average precipitation recorded was 365 mm in the month of July 2006. There is one rainy season from June to August. In other words the area is characterized by unimodal rainfall pattern. Landslides are quite common during the rainy season indicating the role of surface and sub-surface water flow / hydrology in triggering landslides.

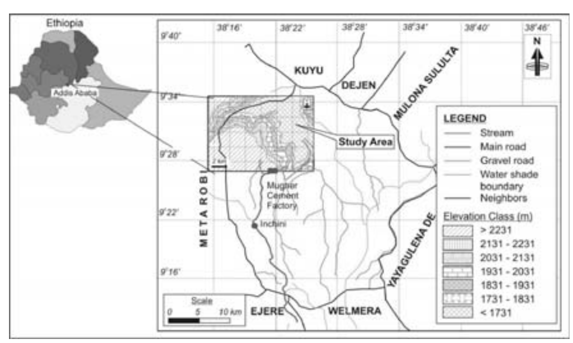

Figure 1: Location map of the study region

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4.1 Geomorphology

The geomorphology of the area is related to tectonic events followed by erosion. The northern part of the area is located on the eastern margin of the Abay (Blue Nile) basin and is typically characterized by deep cut gorges with sharp escarpments, flat top hills, gently sloping and undulating plains; whereas the southern part is associated with the development of the Main Ethiopian Rift system and recent erosion and sedimentation processes related to river development. The rift margins are defined by deep-seated, structurally controlled deformations (Asrat et al., 1997; Abebe et al., 2010). However, the study area is mostly affected by recent erosion and sedimentation processes related to river development.

There is a high variation in altitude within the study area ranging from 1375 – 2565 m a.s.l. It is characterized by the development of deep gorges with steep slopes and escarpments of Mugher river. The lowest altitude of this zone is recorded inside the river gorge in the northwestern part of the area which is less than 1400 m a.s.l. This zone is composed of a Mesozoic sediments and Tertiary volcanic rocks in which especially basalt with columnar joints form steep escarpments and cliffs. In the Muger River gorge, Mesozoic limestone also forms steep escarpment and cliffs. The drainage system is dendritic with a perennial and number of intermittent streams.

4.2 Geology

The regional characteristics were described by Kazmin (1972). The description of the lithological units is mainly taken from the geological map of the area at a scale of 1:50,000 prepared by the Geological Survey of Ethiopia (GSE) (Fig. 2).

4.2.1 Mesozoic sedimentary formations

4.2.1.1 Mesozoic sandstone: This sandstone (Lower sandstone) unit is exposed in Mugher river gorges below the volcanic rocks but mainly below the Mesozoic limestone. It has a maximum thickness of 1131 m (Ilfious, 2008). The succession mostly consists of sandstone with very thin intercalations of siltstone, mudstone and some paleosoils. In the top part it is conglomeratic and fine to medium grained, reddish brown to light gray in color. The degree of weathering and fracturing is high in the top part.

4.2.1.2 Limestone: Limestone (Antalo limestone) is exposed in the northern, northeastern, central and western parts of the area. It mainly outcrops in the Mugher river valley. The contact with the underlying mudstone formation is gradational which is marked by siltstone and gypsum layers followed by calcareous siltstone, silty limestone and gradually to limestone. There are intercalations of yellow limestone at the base and shale towards the top (Getahun, 2006). There are also shale intercalations which are frequent towards the bottom. Structures such as karst openings, chert nodules and stylelites are observed at the bottom of the limestone.

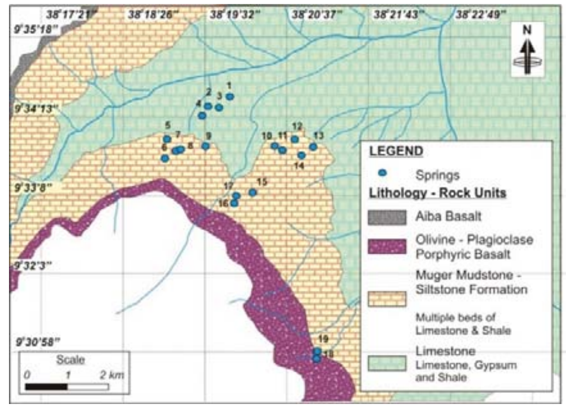

Figure 2: Lithological map of the study region

4.2.1.3 Muger mudstone–siltstone formation: This formation is exposed in the southern, central, and northern eastern parts of the area. The dominant types of rocks in this formation are mudstone, siltstone and shale. However, there are multiple beds of different intercalations of limestone (Getahun, 2006). The main structures are laminations, cross laminations, ripple mark and sand bedding. It has a sharp and unconformable contact with the overlying basalt.

4.2.2 Tertiary volcanic rocks

Tertiary volcanic rocks are the main constituent of the Ethiopian plateau. They are found in a wide variety from liquid basalt rocks to highly viscose acidic rhyolite representing a fissured and central type of volcanism.

4.2.2.1 Aiba basalt: This unit is exposed in northern and central parts of the map area in river valleys and canyons. The contact with the underlying limestone is characterized by an abrupt nature. In this unit there is vertical compositional variation. The top part is composed of vesicular basalt. In the middle, coarse grained basalt is noticed. The bottom of this unit is made up of columnar jointed, cliff forming and relatively fresh aphanitic basalt. These columnar joints are characterized by well-developed hexagonal faces (Meten, 2007).

4.2.2.2 Olivine – plagioclase porphyric basalt: This basalt (Tarmaber-Megzeze basalt) is present in north western parts of the map area. Its origin is from fissure eruption. The basalt overlies non-conformably over the mudstone. Intense fracturing, columnar jointing and spheroidal weathering are very common features. Meten (2007) classified this unit into porphyritic aphanitic and very coarse grained porphyritic basalt.

4.2.3 Quaternary superficial deposits

This unit comprises mainly the colluvial soil and alluvial deposit. The colluvial soil is deposited in the central part of the area (Fig.3). It is dark grey, dark brown and black in colour, its thickness ranges from 1–5 m (Meten, 2007).

The alluvial sediments are deposited in northern, northeastern and western parts of the study area along

Muger River valley. Its texture varies from sand to silt in size. The basalt, limestone and quartz grain fragment association indicate the probable parent rocks from which this alluvial is derived (Getahun, 2006).

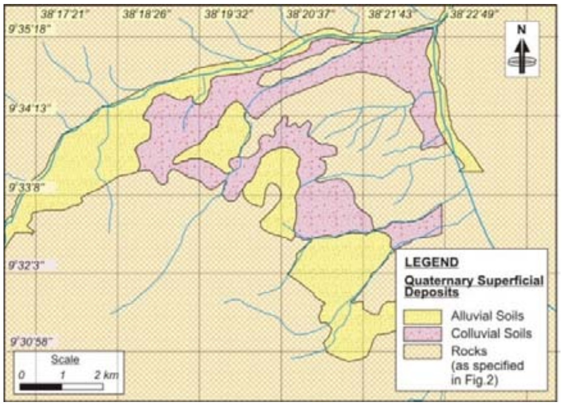

Figure 3: Soil map of the study region

5. Inventory mapping

Landslide inventory mapping forms the basis for most of the susceptibility mapping techniques and is considered as the initial tool for landslide hazard evaluation (Dai and Lee, 2002). Thus, for the present study landslide inventory data was collected through filed investigations. The data includes; location of landslides, possible mechanisms by which it failed, land use/ land cover, geometry of each slide, location and type of springs present and nature of deposits on the slope involved in the failure. Accordingly, 45 landslides (sites) of varied dimensions and types were mapped, affecting a total of 75 km^2 of the area (Fig.4).

Based on the failure mechanisms the landslides are grouped into five classes namely; rotational slides, complex, flow, toppling and rock/ soil fall mode of failure. Out of the total 45 landslide activities 53% of the landslides were failed with the rotational mode of failure and 29% with complex mode of failure. The remaining 18% of the landslides fall in debris flow, rock/soil fall and toppling mode of failures.

Further, pre-structured questionnaire were also used to collect information from the local respondents on landslide process, mechanism involved and triggering factors. The analysis of the data revealed that the main triggering factor for the landslides was heavy rainfall. No systematic records on the exact date, time and duration is available for these landslide events. Moreover, analyzed respondents data indicated that most of these landslide activities occurred around mid of July. The precipitation for the month of July, as compared with the preceding 10 years rainfall records, was the highest, which affirms the possible cause of landslide activities.

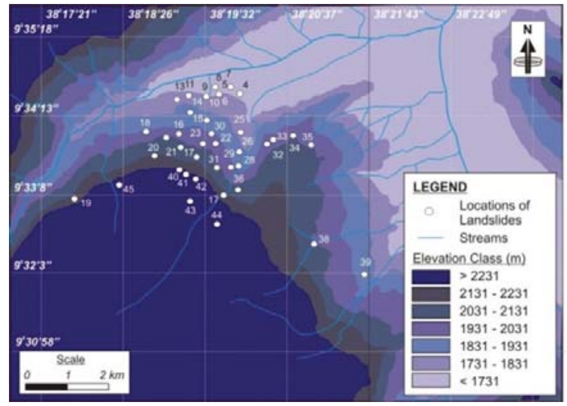

Figure 4: Landslide inventory map of the region

6. Relation of causative factors with landslide distribution

The causative factors are the intrinsic parameters which dictate the stability condition of a slope. Depending upon the given conditions for each of these causative factors they may have an influence over the stability condition of the slope (Raghuvanshi et al., 2014a; Anbalagan, 1992; Wang and Niu, 2009; Ayalew et al., 2004).

The causative factors considered during the present study are; geological (lithology of rocks and soil deposit), slope, aspect, elevation, slope curvature, land use/ land cover and groundwater.

6.1 Geology

Landslide activity is greatly influenced by the nature and type of the regolith material (Thomson, 1971). The various mechanical properties influencing the stability of slopes such as; shear strength, unit weight and the water-related forces are entirely dependent on the rock formations and the type of soil that constitutes the slopes (Raghuvanshi et al., 2014a).

For the present study lithology of rocks and type of soil deposits were considered as basic contributing factors. The rocks in the study area, with limited exposures (Outcrops), are mainly; limestone, gypsum with shale and limestone with shale intercalations and overlying basalts (Fig. 2). Most of the landslides were observed/ located within the lower limestone and shale lithological unit. The Quaternary deposit consists of colluvial material mainly with limestone fragments and alluvial deposits of volcanic and sedimentary origin. In the Quaternary deposits landslides were observed mainly within the colluvial deposit (Fig. 3).

The results, as determined from the raster maps overlay analysis shows that 97% of the landslides occurred in the lower limestone and gypsum with shale and the remaining 3% were recorded within limestone and shale intercalation units which underlies the upper mostly cliff forming basalts of the area. No landslide occurred in the cliff forming basalt and the soil deposit which forms the topmost flat portions in the study area. In Quaternary deposits 78% of the landslide occurred within the colluvial deposit and 22% occurred in the alluvial deposits. Residual soils are almost non-existent in the valley and slopes (Fig. 4).

Majority of the present study area is covered by thick colluvial and alluvial type of soils (Fig. 3). The rocks are only exposed in the upper reaches (Elevation >2231 m). Further, it was observed through landslide inventory that out of 45 past landslides 39 occurred in colluvial and alluvial type of soils. Moreover, no linear pattern was observed in the past landslides which imply that they are not structurally controlled (Fig. 4). However, this fact may require further sub-surface investigations to know the structural setup of the area which is covered by thick surfacial soils and to evaluate possible correlation of structures on landslides in the present study area. Further, no structural lineaments, major or minor, are reported to be present in and around the study area.

6.2 Elevation

The influence of elevation may be attributed in terms of degree of weathering, variation in humidity, rate of hydrate reaction, erosion process and depth of weathering. Higher the elevation higher will be the intensity of erosion and weathering. Thus, it is quite reasonable to consider elevation as one of the causative factor for controlling landslide process (Ahmed, 2009).

The digital elevation model (DEM), of the study area, at a resolution of 30m which was obtained from the ASTER data, scenes of the study from November 2008 was used to prepare the DEM. The STER scene Level 1 B scene with nadir (3n) and aft-viewing (3b) orientations of 15m resolution were obtained from the Land Processes DAAC at EROS Data Center.

The images were then processed to extract a DEM using automated stereo auto-correlation procedures using eight ground control points (GCP), which were digitized from the topographic maps and field GPS reading at river crossings, spot elevations and road intersections and identified on images. The resulting ASTER derived DEM had 30 m post spacing and its raster image was further used for topographical parameter derivations and raster calculations.

For this purpose, a suitable operation was applied in ArcMap-GIS with the help of interpolation tools using spline to obtain a smoothened output (Fig. 4).

For landslide hazard analysis, the elevation of the study area was categorized into seven classes; (<1730m), (1731-1830 m), (1831-1930 m), (1931-2030m), (2031-2130), (2131-2230m) and (≥2230 m). From the results, obtained from raster data calculation; 37% of the landslide occurred in the elevation class of (2131-2230 m) followed by 38% within (1931-2130 m) class. However, 2% of the landslides occurred within the elevation class of 1630-1730m. When the elevation decreases the landslide distribution in the study area also decrease particularly for class (1831-1930) m to (1630-1730) m the landslide distribution is from 10% to 2%, respectively. The elevation greater than 2480 m also shows the lower distribution of landslides as the area becomes flat above this elevation which is a part of the flat central Ethiopian Plateau.

6.3 Slope

The slope is an important factor which influences the landslide process (Ayalew and Yamagishi, 2003). If the slope is steep, there will be an increment in shear stress and the tangential component of the weight of the mass will increase while the perpendicular component of weight will decrease. Therefore, when the shear stress increases more than the resisting forces the slope mass will acquire tendency to slide down the slope (Ahmed, 2009). Thus, more steeper the slope, tendency for failure will be more provided other instability contributing factors also favor sliding (Raghuvanshi et al., 2014a).

The slope factor for the study area was extracted from the DEM using ArcMap-GIS tool (Fig. 5). The minimum slope angle as deduced was 0° along the flat sections while the maximum slope of 62.86° was observed for the vertical cliffs. For the present study slope was categorized into five classes; (0-5°), (5-12°), (12-30°), (30-45°) and (>45°). The raster computation results indicate that 63% of the landslides occurred in the slope class of 12°-30°. As observed, lower the slope angle, lower is the frequency of the landslides and the same was true when the slope angle gets greater than 30°. The reason for this is that when the slope is steeper the thickness of the colluvial material decreases. The percentage of the landslide distribution with respect to slope indicates that 63% of the landslides occurred in the slope class of (12°-30°). This shows a strong correlation between slope class (12°-30°) and landslide distribution in the area. Further, almost 74% of the landslide occurred within a slope angle range of 5^o to 30^o and the remaining 26% were either below 5^o or above 30^o.

6.4 Aspect

The aspect of slopes in the study area was derived from the DEM. The aspect map was prepared by classifying aspect into 10 classes; Flat (-1°), North (0°-22.5°), North east (22.5°-67.5°), East (67.5°-112.5°), South east (112.5°-157.5°), South (157.5°-202.5°), South west (202.5°-247.5°), West (247.5°-292.5°), North west (292.5°-337.5°) and North (337.5°-360°).
The results indicate that 32% of the landslide occurred along the north facing slopes and 23% were towards northeast facing slopes (Fig. 6).

The landslide which occurred along Eastern, South-Eastern and North-Western facing slopes account to 13%, 9% and 8%, respectively. No landslides were observed in South and South-West facing slopes. Only 1% of landslides occurred in South-East facing slopes. The low frequency of landslides towards South, South-West or South-East directions seems to be correlated with the groundwater flow direction in the area, as almost all the springs which are present in the area are located on the North or North-Easting facing slopes.

Groundwater plays important role in aggravating landslides in many places in Ethiopia. Landslide processes study made in the volcanic terrain of Northern Ethiopia displayed strong correlation of ground water flow and landslide occurrences (Ayenew and Barbieri, 2005).

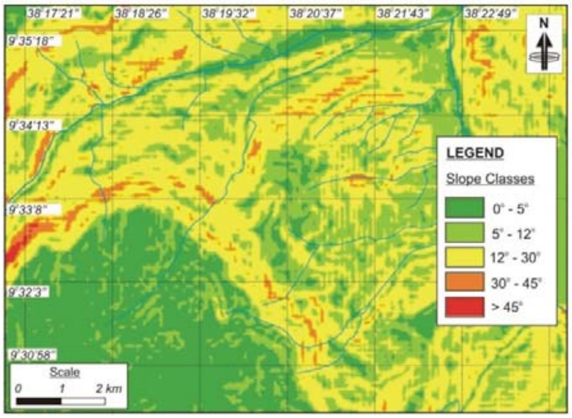

Figure 5: Slope map of study region

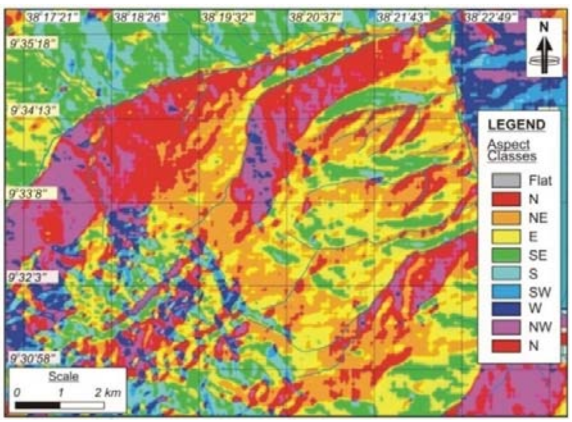

Figure 6: Aspect map of the study region

6.5 Land use/ land cover

Land use is also one of the key factors responsible for landslides. The barren and sparsely vegetated lands are prone to erosion, weathering and slope failures (Turrini and Visintainer, 1998; Wang and Niu, 2009; Anbalagan, 1992). In landslide hazard studies land use/ land cover is generally considered as a static factor however, few researchers have treated it as a constantly changing factor (Van Beek and Van Asch, 2004). The vegetation cover has an influence on the hydrological process of relatively shallow potential landsliding mass. Vegetation cover may intercept the precipitation, soil moisture reduction and may check hydraulic conductivity (Van Beek, 2002).

For the present study area, land use/land cover map was prepared from Landsat + ETM satellite image by supervised classification using ERDAS IMAGINE. A combination of bands 5, 3 and 2 of Red, Blue and Green, respectively were used and the training pixels were controlled with Google Earth image (Fig. 7).

The result indicates that 48% of the land is covered by bush land, 24% by cultivation, 13% by villages, 9% by water body and remaining 6% is a bare land. The landslide distribution with respect to land use/ land cover indicates that 48% of landslides occurred in bush land and 24% were observed in cultivated land.

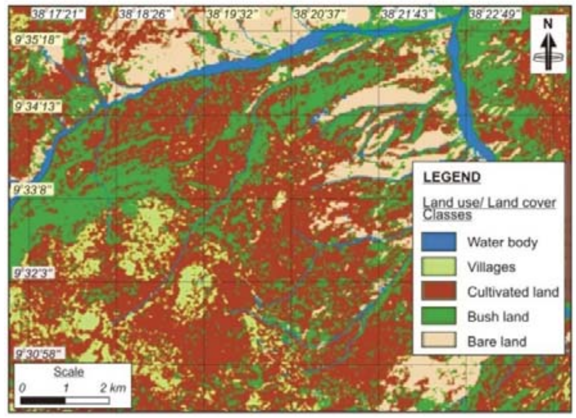

Figure 7: Land use/ land cover map of the study region

6.6 Curvature

The morphology of the topography can be defined by curvature values. If the surface is upward concave at that raster cell the curvature is negative whereas if the surface is upward convex at that cell the curvature is positive. If the surface is flat the curvature value will be zero. The chances of landslide activity increase with increasing negative value of curvature. According to topographic type, the value is higher in the hilly and mountainous areas, and low in flat areas (Lee and Min, 2001).

For the present study, the curvature of the area was classified in to three general classes; (i) negative value (ii) zero value and (iii) positive value. The 36%, 29% and 35% of the raster pixel of landslide occurred in area with negative, zero and positive curvatures values, as calculated from the raster maps, respectively (Fig. 8). This relation shows that the negative and the positive values have equal proportion.

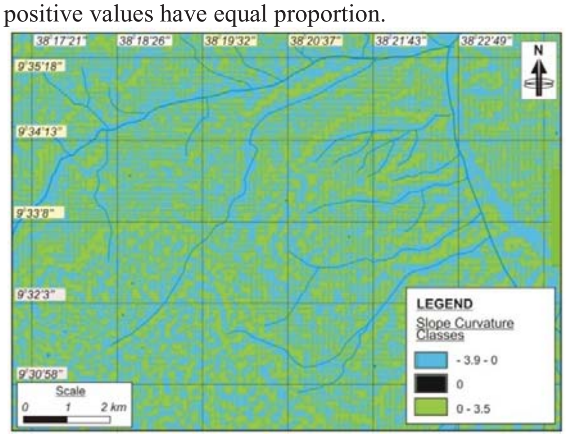

Figure 8: Curvature map of the study region

6.7 Groundwater

Hydrology plays an important role in landslide initiation. Some of the most significant hydrologic processes in this respect are precipitation (spatial and temporal distribution of rainfall), water recharge into soil (and the potential for overland flow), lateral and vertical movement within the regolith, evapo-transpiration and interception (Thanhn, 2008).

For the present study, the locations of 19 springs were mapped and they were correlated with the distribution of the landslides (Fig. 2). Later the relation of the springs and the landslides was analyzed. The result of the analysis shows that 19% of the landslides were concentrated with elevation class of 1931-2030 m and the 37% of the landslides were concentrated in elevation class of 2131-2230m. However, the distribution of springs in the study area decreases as the elevation increases. In addition to that 95% of the springs were observed in the area below the elevation of 1931-2030m. That means the groundwater level concentrates at the elevation lower than the highest percentage landslide occurred locations. In the case of landslide occurrence 37% of the landslide occurred within 2131-2230m and 19% of the landslide occurred within 1931-2030m elevation. Generally, the elevations of the springs in the study area were highly correlated with the elevation of the landslide occurrence. As reported by the locals, many of the springs were emerged after the landslide and some of the springs were also disappeared after the landslide in the area. That means springs had the contribution for landslide to occur and the landslides itself had the effect to generate new springs in the study area.

7. Landsilide hazard zonation

Among all the techniques statistical approaches are the most popular techniques for the landslide hazard assessment and zonation. The effectiveness of these techniques is defined in terms of its low cost, large coverage area in relatively short period of time and quantitative assessment of relations between causative factors and landslides. To make the approach more reliable it is desirable to combine field investigations and satellite image interpretation in building the landslide database.

The core of statistical analysis is mainly upon the relationship between past landslides and causative factors (Dai and Lee, 2001). Thus, it is necessary to understand and asses the causative factors which probably resulted independently or in combination to the past landslide activity in an area. Therefore, one has to understand that how the past landslide has triggered. Such assessment of mechanism facilitates in assigning weight to the causative factors. Later, the general quantitative prediction is developed to rate the causative factors which might have resulted in probable failure of slopes with similar conditions.

For the present study, factors were considered to be responsible which might be significant in inducing slope instability in the area. These causative factors are; lithology, soil deposit, slope, aspect, elevation, curvature and land use/ land cover.

In bivariate statistical approaches, the objective is to know the densities of landslide occurrences within each causative factor map and its parameter map classes, and to derive data driven weights based on the class distribution and the landslide density (Süzen and Doyuran, 2004). With these weights causative factor maps can be put together to obtain a landslide hazard map. For a bivariate statistical approach, medium scale maps are suitable in the range of 1:250,000 to 1:50,000 (Westen Van et al., 1997), because this technique is not detailed to be applied on a larger scale.

The area investigated for the present study was 153 km^2 therefore, the medium scale was adopted and the relationship between the landslide and contributing factors were statistically analyzed. An expert opinion about the weight and ratio of factors were applied to assess the hazard. Later, the causative factors were compared separately and the importance of each factor was determined independently over the other factors. The technique is based on the assumption that the important causative factors leading to landslide can be quantified by calculating landslides for each variable class by counting the grid cell. The hazard index value was then calculated by ratio of landslide 'did' occurred with landslide 'did not' occur. As per these hazard index value comparison of each causative factors were analyzed and weight were assigned with respect to the hazard index value.

By neglecting the effect of curvature (which does not correlate strongly with landslide in the present study) and with all other weight equal to '1' have been assigned. Random trial combinations of all the six layers have been made and the best combination was considered for the LHZ map preparation.

A map of landslide boundaries was produced for the present study area which was later utilized for analysis in the GIS environment. A vector to raster conversion was undertaken to provide a raster data of landslides with 15 X 15m pixels. To apply the statistical method, a spatial database that considered landslide related factors such as; lithology, soil deposit, slope, aspect, elevation, curvature land use/ land cover were designed and prepared with Arc Map. The data layers used for analysis are shown in Table 1.

For evaluation of topography, data was obtained from DEM which involved categorizing the slope, aspect, elevation and curvature. Also, the digital data of the lithology, soil deposit and land use/ land cover for different classes was prepared.

Table 1: Data layers used for analysis

Classification	Sub class	GIS data type	Scale
Geological Hazard	Landslide	Polygon Coverage	1:50,000
Basic Maps	Lithological map	Polygon Coverage	1:50,000
	Soill deposit map	Polygon Coverage	1:50,000
	Slope map	Grid	30X30m
	Aspect map	Grid	30X30m
	Elevation map	Grid	30X30m
	Curvature map	Grid	30X30m
	Land use/cover map	Grid	30X30m
Image data	Satellite image of +ETM	Grid	30X30m

All 7 causative factors were considered during calculation of the probability. The factors were extracted from the prepared spatial database. Using the DEM, the slope, aspect, elevation and curvature were calculated. The lithology map, obtained from the geological map of Ethiopia at the scale of 1:2,000,000 with some modification as per the field survey data, was prepared. A satellite image was utilized to digitize the modification in the lithologic map. The soil deposit map and land use/land cover were prepared by utilizing Satellite image in ERDAS and ArcMap software.

7.1 Hazard analysis using probability method

It is common to assume that landslide occurrence is determined by landslide-related factors, and that future landslides will occur under the same conditions as the past landslides. Using this assumption, the relationship between landslides occurrence in an area and the landslide-related factors can be distinguished from the relationship between landslides not occurring in an area and the landslide-related factors. It can be expressed as a frequency ratio that represents the quantitative relationship between landslide occurrences and different causative parameters (Lee and Min, 2001).

The frequency ratio is defined as follow;

$$W_{ij} = f_{ij} / \overline{f_{ij}} \qquad \text{………. eq. 1}$$

where;

W_{ij} is the frequency ratio of class 'i' of parameter 'j'.

f_{ij} is the frequency of observed landslides in class 'i' of parameter 'j'.

$\overline{f_{ij}}$ is the frequency of non-observed landslides in class 'i' of parameter 'j'.

Greater the ratio above unity, the stronger the relationship between landslide occurrence and the given factor's attribute, and the lower the ratio below unity, the lesser the relationship between landslide occurrence and the given factor's attribute. Hence, probabilistic approaches are based on the observed relationship between each factor and the distribution of observed landslides. The probability method uses the frequency ratio to rate the relationship between landslides and each factor's type (Lee and Min, 2001).

Topographic, lithological, soil deposit, land use/ land cover data for the present study area were prepared/ extracted/ digitized and processed to be used in GIS environment. Later, rating layers for the different causative factors were prepared based on the obtained frequency ratios. These spatial data were evaluated using probability method to reveal the correlation between landslide location and the factors in the study area. The calculated frequency ratios for various causative factors and corresponding classes are given in Table 2. Rating layers for the different causative factors were prepared based on the obtained frequency ratios. As discussed above the probabilistic and statistical approaches are based on the observed relationships between each factor and the distribution of landslides.

7.1.1 Hazard index for various causative factors

7.1.1.1 **Lithology and soil:** The probability of occurrence of landslide within limestone, gypsum and shale is higher as the hazard index value is 3.49 (Table 2). For limestone with shale intercalation the hazard index value is 0.51, thus the probability of occurrence of landslide is low. Similarly, probability of occurrence of landslide in basalt and top soil deposit is almost nil.

In case of colluvial material the hazard index value is 8.11 (Table 2) which shows a strong correlation with landslides. In the study area the colluvial material is mainly composed of unconsolidated fragments of limestone and highly weathered shales. The highly disintegrated and unconsolidated loose material is readily affected by the surface and subsurface water which probably induce instability in colluvial slopes. For this reason only a high hazard index value has been observed in the colluvial material. Similarly, in case of alluvial deposits hazard index value of 2.16 has been computed, again which shows a high probability of landslide occurrence in this unit. However, a very low hazard index value for hard rock shows a least probability of landslide occurrence in the area.

7.1.1.2 Slope: The probability of occurrence of landslide is high in slope class 12^o-30^o as the hazard index value is 3.16 (Table 2). Thus, the slopes in the study area which have an inclination 12^o-30^o are most susceptible for landslides. Further, the slopes below 5^0 shows a hazard index value of 0.1 and for slope class 5^0-12^0 the hazard index value is 0.45, lower than 1, indicating a low probability. Also, for slope class 30^o-45^o the hazard index value is 0.45 which again indicates a low probability of landslide to occur.

In the study area it was observed that, even though the slope is steep, especially in the case of slopes which have limestone with shale and the basalt, the slopes were in general, stable except for some cases where minor toppling and rock fall was observed. Thus, in spite of the fact that the slope is steep it is not always true that it will have a higher degree of landslide hazard as in such cases the stability might be controlled by other factors such as; slope deposit type, discontinuity orientation and shear strength.

7.1.1.3 Aspect: In the study area the probability of occurrence of landslide on North and North-Eastern facing slopes is higher as the hazard index value is 2.23 and 1.75, respectively (Table 2). Thus, slopes facing towards North and North-East wards are highly susceptible to landslides. The frequency of past landslides is lowest on South and South-West facing hill slopes thus, the probability of occurrence of landslides on South and South-West facing hill slopes is least.

7.1.1.4 Elevation: In the study area the highest probability of landslide to occur was observed in the slopes falling in elevation range of 2131-2230 m as the hazard index value for this elevation class was computed as 3.71. Also, the elevation classes 1931-2030 m and 2031-2130 m shows an index value of 1.9 and 1.88, respectively which again implies a probability of landslide to occur within these elevation classes. Thus, from the hazard index results for elevation it may be said that the higher the elevation the higher is the probability of landslide to occur. However, for the elevation > 2230 m the probability of the landslide is lower as it shows the hazard index value of 0.76. The reason for this is that in the study area after the elevation 2230 m the topography becomes flatter.

7.1.1.5 Curvature: In the study area the curvature values were categorized in to three major class of negative, zero and positive curvature value. From the results both the negative and the positive curvature value have the same probability of landslide hazard, as both shows a hazard index value of 1.1. The zero value which is flat shows a lower probability of landslide occurrence.

7.1.1.6 Land use/ land cover: The probability of landslide occurrence is higher in bush land with hazard index value of 1.88. The bush land covers 48% of the slopes and majority of it is constituted by colluvial or alluvial deposits which is highly susceptible for landslide occurrence. The remaining land use classes show low probability of landslide occurrence as the hazard index value is < 1 for all other classes.

7.1.2 Estimation of landslide hazard

Using probability method, the spatial relationship between landslide occurrence location and each landslide related factors was driven. The factors are slopes, aspect, elevation and curvature derived from the DEM; lithology and the type of soil deposit; was derived from the geology database; and land use/land cover was prepared from satellite images. The factor maps were converted to a 15x15m grid so that they can be used conveniently in statistical package. The total number of cells computed for the entire study area was 6,80,418 whereas the area covered by landslides has cell numbers equal to 3,329.

Later, the correlation ratings were calculated from relation analysis between landslides and the relevant factors. Therefore, the rating of each factor's type or ranges was assigned to the relationship between landslide and each factor's type or ranges, that is, ratio of the number of the cells where landslides does not occurred to the number of cells where landslides occurred (Table 2).

The hazard is the ratio of the area where landslides occurred to the total area, therefore a value of '1' means an average value. It implies that, if the value of hazard is greater than '1' higher probability of landslide occurrence exists. In the present study, all causative factor raster maps were normalized with respect to its maximum value such that the maximum possible value of the Hazard Index (Hji) for each layer is scaled to '1' as shown in Table 4. The 20% of the total index is classified equally for the two extreme hazard classes of no hazard and very high hazard and the remaining 80% was classified into three equal class of low, medium and high hazard (Table 3).

The hazard map of the study area was prepared by using eq. 2 and eq. 3

$$\text{Hazard}(x) = F(x) \sum_{j=1}^{7}((\text{WjHji})x)/\sum_{j=1}^{7}(\text{Wj}) \qquad \text{………… eq. 2}$$

where F(x) is a filter function defined by

$$F(x) = 0 \text{ if } \theta < 15^0 \text{ and Hj25} = 0$$
$$= 1 \text{ otherwise} \qquad \text{………… eq. 3}$$

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Table 2: The hazard index for various causative factors

Causative Factors and Corresponding Classes	Landslide Did Not Occurred		Landslide Occurred		Hazard Index (b/a)	Percent
	Count	Ratio (%) (a)	Count	Ratio (%) (b)		
(a) Lithology						
Limestone, gypsum with shale	148819	22	2552	77	3.49	97
Limestone with shale	307035	45	776	23	0.51	3
Basalt	44111	7	1	0	0	0
Top Soil Deposit	177124	26	0	0	0	0
Total	**677089**	**100**	**3329**	**100**		**100**
Soil Deposit						
Alluvial deposit	82046	12	862	26	2.16	22
Colluvial deposit	63571	9	2429	73	8.11	78
Hard rock	531471	79	39	1	0.01	0
Total	**677089**	**100**	**3329**	**100**		**100**
(b) Aspect						
(Flat Area)	199425	29	972	29	1.0	14
N	117007	17	1279	38	2.23	32
NE	27885	4	219	7	1.75	23
E	130908	19	565	17	0.89	13
SE	25243	4	8	0	0.07	1
S	77998	12	7	0	0.02	0
SW	10239	2	0	0	0	0
W	68317	10	220	7	0.7	9
NW	20067	3	58	2	0.67	8
Total	**677089**	**100**	**3329**	**100**		**100**
(c) Slope (degree)						
0-5	271127	40	127	4	0.1	2
5-12	132908	20	289	9	0.45	9
12-30	174356	25	2654	79	3.16	63
30-45	72368	11	171	5	0.45	10
>45	26331	4	87	3	0.75	16
Total	**677089**	**100**	**3329**	**100**		**100**
(d) Elevation (m)						
1630-1730	179833	27	145	4	0.15	2
1731-1830	73165	11	153	5	0.45	5
1831-1930	72892	11	347	10	0.90	10
1931-2030	69659	10	629	19	1.9	19
2031-2130	65281	9	566	17	1.88	19
2131-2230	49887	7	862	26	3.71	37
>2230	166373	25	626	19	0.76	8
Total	**677089**	**100**	**3329**	**100**		**100**
(e) Curvature						
-3.9 - 0	234216	34	1243	37	1.1	36
0	208647	31	876	26	0.83	29
0 - 3.5	234226	35	1211	37	1.1	35
Total	**677089**	**100**	**3329**	**100**		**100**
(f) Land use/Land cover						
Cultivated land	331583	49	1498	45	0.92	24
water Body	18917	3	14	1	0.33	9
Villages	58621	9	138	4	0.44	13
Bush land	173393	25	1570	47	1.88	48
Bare land	94575	14	110	3	0.21	6
Total	**677089**	**100**	**3329**	**100**		**100**

Since the value on the right-hand side of eq. 2 is scaled with respect to the sum of the weightings, the maximum value of hazard (x) at any pixel must be $\leq$ 1. The hazard map was prepared based upon eq. 2 and eq. 3 using ‘‘raster calculator’’ available in ArcGIS 9.2.

Table 3: Hazard classification

Hazard Class	Hazard Classification	Hazard Class Name
1	0-0.1	No Hazard
2	0.11- 0.38	Low Hazard
3	0.38-0.64	Medium Hazard
4	0.64-0.91	High Hazard
5	0.91-1.0	Very high Hazard

Table 4: Weightings and hazard indices for various factor classes

Class No.(i)	Layer(j)	Class (Ci)	Weighting (Wj)	Hazard Index (Hji)	Hazard Class
1	Lithology	Limestone, gypsum with shale	1.0	1	5
2		Limestone with shale		0.15	2
3		Basalt		0.08	1
4		Soil deposit		0	1
5	Soil Deposit	Alluvial	1.0	0.3	2
6		Colluvial		1	5
7		Hard rock		0.0	1
8	Aspect	(Flat Area)	1.0	0.4	2
9		N		1.0	5
10		NE		0.8	4
11		E		0.4	3
12		SE		0.0	1
13		S		0.0	1
14		SW		0.0	1
15		W		0.3	2
16		NW		0.3	2
17	Slope (degree)	0-5	1.0	0.03	1
18		5-12		0.13	2
19		12-30		1.00	5
20		30-45		0.16	2
21		>45		0.22	2
22	Elevation (m)	<1730	1.0	0.0	1
23		1731-1830		0.1	1
24		1831-1930		0.2	2
25		1931-2030		0.5	3
26		2031-2130		0.5	3
27		2131-2230		1.0	5
28		>2230		0.2	2
29	Curvature	-3.5 - 0	0	1	5
30		0		0.8	4
31		0-3.9		1	5
32	Landuse/ Landcover	Cultivated	1.0	0.5	3
33		Water Body		0	1
34		Villages		0.25	2
35		Bush land		1	5
36		Bare land		0.12	2

Random trial combination of 7 layers has been made and the best combination was considered to produce the landslide hazard map of the study area (Fig.9). The combination of the causative factor maps were carried out following different order of importance of causative factors for which many trials were made. Finally, combination of layers with the following order; land use/ land cover, lithology, aspect, elevation, soil deposit and slope was attempted. The perusal of LHZ map (Fig. 9) revealed that 24% (36.72 km^2) of the study area falls under no hazard, 33% (48.96 km^2) as low hazard, 17% (26.01 km^2) as moderate hazard, 25% (38.25 km^2) as high hazard and the rest 2% (3.06 km^2) as very high hazard. In this model, 89% of the past landslide inventory data agrees with the landslide hazard. As compared with others, this model was found to be the best model for the present study area. In spite of the fact that the same weight were given to the causative factors except for curvature, different outputs were obtained from different combination of layers of these factors. That means each causative factors have different degree of effect with different combination of factors and thus, the result depicted different hazard zones.

7.1.3 Verification of landslide hazard

The verification was performed by comparison of existing landslide data (inventory data) with the prepared landslide hazard zone map. From the inventory data only 2% of the failed slopes falls on the low hazard class and 9% of the landslide falls in the moderate hazard class. It means only 11% of the total inventory landslide shows deviation from Hazard map prepared during the present study. The 73% of the inventory landslide location falls in high hazard zone and 16% in very high hazard zone. Thus, 89% of the existing landslide location shows satisfactory agreement with the present landslide hazard map (Fig. 9).

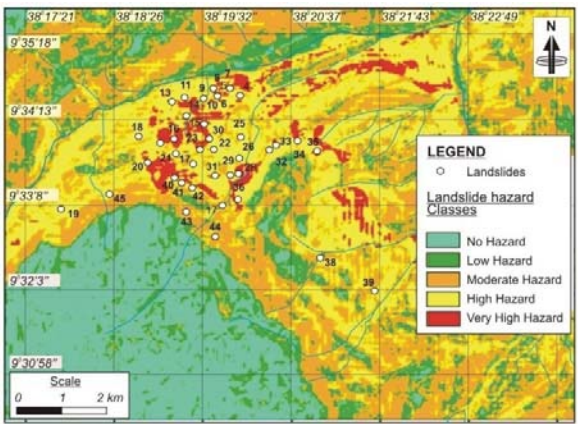

Figure 9: Landslide hazard zonation (LHZ) map of the study region

The marginal variation in the validation of this model to real landslide events may be on account of various other factors which are not considered during the present study due to limitation of methodology i.e. the study was conducted at medium scale (1:50,000).

The factors which were not considered for medium scale study are; characteristics of discontinuity surfaces such as; scale of roughness of the surface, infilling of material within discontinuities, shear strength mobilized along discontinuity surfaces, interrelationships of discontinuities, pore water pressure in soil mass; reducing strength of soil mass, water forces acting within the discontinuity surfaces reducing the effective normal stresses, shape factor of particles in colluvial material resulting in interlocking and giving more strength to material. All these factors contribute for stability condition of slopes. However, these factors can only be taken into account on detailed scale (>5,000) studies. Therefore, it may be concluded that the LHZ map prepared during the present study has reasonably identified areas which have potential for varied degree of landslide hazard.

8. Summary and conclusion

The main objective of the present study was to evaluate the landslide hazard in the area and to prepare the hazard zonation map by following integrated GIS based statistical approach in the Mesozoic Sedimentary sequence overlaid by thick tertiary volcanic rocks in Ada Berga district of central Ethiopia. By using probability method, the spatial relationship between landslide occurrence location and each landslide related causative factors was driven. The causative factors considered for the analyses are; lithology, soil deposit, slope, aspect, elevation, curvature, land use/ land cover and groundwater. The factor maps were converted to a 15x15m. The correlation ratio was calculated from relation analysis between landslides and the relevant factors. All causative factor raster maps were normalized with respect to its maximum value such that the maximum possible value of the Hazard Index for each layer is scaled to '1'. Later customized raster calculation was done to develop the landslide hazard (LHZ) map.

The resulting LHZ map revealed that 24% (36.72 km^2) of the study area falls under no hazard, 32% (48.96 km^2) as low hazard, 17% (26.01 km^2) as moderate hazard, 25% (38.25 km^2) as high hazard and the rest 2% (3.06 km^2) as very high hazard. Further, the 45 past landslides in the area were considered to validate the landslide hazard map. Out of 45 past landslides, 89% fall either in high or very high hazard zones, while 9% fall in medium and only 2% falls under low hazard zones. This reasonably validates the prepared LHZ map.

The general finding suggests that the most susceptible material for the occurrence of the landslide in the study area is loose unconsolidated colluvial deposits on a moderately steep topography. Most of the landslides were surficial and involved in deposits of alluvial and colluvial material of basaltic and limestone origin. Some old landslide show current signs of reactivation especially immediately below the cliff forming limestone. The major causes of the landslide in the study area are hydrological and hydrogeological conditions associated with gravity movements favored by typical geological and geomorphological conditions of the area. Most of the landslides occur during the wet season indicating the importance of water as the most important triggering factor. Future multi-temporal monitoring of landslides occurrences and groundwater level mapping with test well drilling and installation of inclinometers may provide very good picture of the landslide process in the rugged deeply incised terrain of the area and the Blue Nile Gorge at the large.

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References

Abebe, B., F. Dramis, G. Fubelli, M. Umer and A. Asrat (2010). Landslides in the Ethiopian highlands and the rift margins. Journal of African Earth Sciences, 56(4-5):131-138.

Ahmed, S. (2009). Slope stability analysis using GIS and numerical modeling techniques. Unpublished MSc Thesis, Vrije Universiteit, Brussel.

Anbalagan, R. (1992). Landslide hazard evaluation and zonation mapping in mountainous terrain. Journal of Engineering Geology, 32, 269–277.

Asrat, A., O. Berakhi, L. Branccaccio, F. Dramis and M. Umer (1997). Gravitational slope phenomena along the eastern escarpment of Wollo (Ethiopia). In: Federici PR (ed.), 4th International Conference on Geomorphology -Abstracts. Geographia Fisica e Dinamica Quaternaria, Supplement 3, Vol. T1, 59p.

Ayalew, L., H. Yamagishi and N. Ugawa (2004). Landslide susceptibility mapping using GIS-based weighted linear combination, the case in Tsugawa area of Agano river, Niigata Prefecture. Japan, Journal of Landslides, 1, 73–81.

Ayalew, L. and H. Yamagishi (2003). Slope failures in the Blue Nile basin, as seen from landscape evolution perspective. Journal of Geomorphology, 61, 1 –22.

Ayalew, L. (1999). The effect of seasonal rainfall on landslides in the highlands of Ethiopia. Bulletin of Engineering Geology and Environment, 58, 9-19.

Ayele, S., T.K. Raghuvanshi and P.M. Kala (2014). Application of remote sensing and GIS for landslide disaster management - A case from Abay Gorge, Gohatsion – Dejen Section, Ethiopia. Landscape Ecology and Water Management, Proceedings of International Geographical Union (IGU) Rohtak Conference, Advances in Geographical and Environmental Sciences (M.Singh, R.B.Singh and M.I.Hassan: Editors), Springer Japan. Vol-2, pp.15 – 32

Ayenew, T. and G. Barbieri (2005). Inventory of landslides and susceptibility mapping in the Dessie area, Northern Ethiopia. Journal of Engineering Geology, 77,1–15.

Casagli, N., F. Catani, C. Puglisi, G. Delmonaco, L. Ermini and C. Margottini (2004). An inventory-based approach to landslide susceptibility assessment and its application to the Virginio river basin, Italy. Journal of Environmental & Engineering Geoscience, 10 (3), 203–216.

Clerici, A. (2002). A GRASS GIS based shell script for landslide susceptibility zonation by the conditional analysis method. Proceedings of the Open source GIS - GRASS Users Conference 2002 - Trento, Italy, September 11-13, 2002, pp. 1-17.

Crozier, M.J. and T. Glade (2005). Landslide hazard and risk: Issues, concepts and approach. (T. Glade, M. Anderson. and M. Crozier: Editors): Landslide hazard and risk. Wiley, Chichester, pp. 1-40.

Dai, F.C., C.F. Lee and Y.Y.Ngai (2002). Landslide risk assessment and management: An overview. Journal of Engineering Geology, 64, 65–87.

Dai, F.C. and C. F. Lee (2002). Landslide characteristics and slope instability modeling using GIS, Lantau Island, Hong Kong. Journal of Geomorphology, 42, 213– 228.

Dai, F.C. and C.F Lee. (2001). Terrain-based mapping of landslide susceptibility using a geographical information system: A case study. Canadian Geotechnical Journal, 38, 911 – 923.

Fall, M, R. Azzam and C. Noubactep (2006). A multi-method approach to study the stability of natural slopes and landslide susceptibility mapping. Journal of Engineering Geology, 82, 241– 263.

Getahun. A. (2006). Geology of Addis Ababa city (NC 37-10/ X and Y and NC 47-6/ E and F Subsheets). Unpublished Report, Geological Survey of Ethiopia. Addis Ababa, Ethiopia.

Go´mez, H. and T. Kavzoglu (2004). Assessment of shallow landslide susceptibility using artificial neural networks in Jabonosa River Basin, Venezuela. Journal of Engineering Geology,78, 11 – 27.

Guzzetti, F., A. Carrara, M. Cardinali and P. Reichenbach (1999). Landslide hazard evaluation: A review of current techniques and their application in a multi-scale study, central Italy. Journal of Geomorphology, 31 (1–4), 181– 216.

Ilfious,W. (2008). Geology of Kewo, Dedu, Hormat, Hamus Gebeya and Chercher of Addis Ababa map sheet (NC37-10). Unpublished Report, Addis Ababa.

Kazmin, V. (1972). Geological map of Ethiopia. Unpublished, Geological Survey of Ethiopia, Addis Ababa, Ethiopia.

Kanungo, D.P., M.K. Arora, S. Sarkar and R.P. Gupta (2006). A comparative study of conventional, ANN black box, fuzzy and combined neural and fuzzy weighting procedures for landslide susceptibility zonation in Darjeeling Himalayas. Journal of Engineering Geology, 85, 347–366.

Lee, S. and K. Min (2001). Statistical analysis of landslide susceptibility at Yongin, Korea. Journal of Environmental Geology, 40,1095-1113.

Leroi, E. (1997). Landslide risk mapping: problems, limitation and developments. (F.Cruden: Editor), Proceedings Landslide Risk Assessment, Balkema, Rotterdam, pp. 239–250.

Meten, M. (2007). Geology of chancho(s) subsheet of Addis Ababa sheet. Unpublished, Geological Survey of Ethiopia, Addis Ababa, Ethiopia.

Pachauri, A.K. and M. Pant (1992). Landslide hazard mapping based on geological attributes. Journal of Engineering Geology, 32, 81–100.

Pan, X., H. Nakamura, T. Nozaki and X. Huang (2008). A GIS-based landslide hazard assessment by multivariate analysis. Landslides – Journal of the Japan Landslide Society, 45 (3), 187-195.

Raghuvanshi, T.K., J. Ibrahim and D. Ayalew (2014a). Slope stability susceptibility evaluation parameter (SSEP) rating scheme – An approach for landslide hazard zonation. Journal of African Earth Sciences, 99, 595–612.

Raghuvanshi, T.K, P.M. Kala and M. Singh (2014b). Landslide disaster management and reduction- An approach through remote sensing and GIS. **In:** Landscape Ecology and Water Management, Proceedings of International Geographical Union (IGU) Rohtak Conference, Advances in Geographical and Environmental Sciences (M.Singh, R.B.Singh and M.I.Hassan: Editors), Springer Japan. Vol-2, pp. 33 - 40.

Sarkar, S., D.P. Kanungo and G.S. Mehrotra (1995). Landslide hazard zonation: A case study in Garhwal Himalaya. Journal of India Mountain Research Development, 15 (4), 301–309.

Süzen, M.L. and V. Doyuran (2004). A comparison of the GIS based landslide susceptibility assessment methods: multivariate versus bivariate. Journal of Environmental Geology, 45, 665–679.

Thanhn, N.L. (2008). Landslide susceptibility mapping of the mountainous area in a Loui district, Thua Thien Hue Province, Vietnham. PhD. Thesis, Vrije Universiteit Brussel.

Thomson, S. (1971). Analysis of a failed slope. Canadian Geotechnical Journal, 8, 596-599.

Turrini, C. T. and P. Visintainer (1998). Proposal of a method to define areas of landslide hazard and application to an area of the Dolomites, Italy. Journal of Engineering Geology, 50, 255–265.

Van Den Eeckhaut M., P. Reichenbach, F. Guzzetti, M. Rossi and J. Poesen (2009). Combined landslide inventory and susceptibility assessment based on different mapping units: An example from the Flemish Ardennes, Belgium. Journal of Natural Hazards Earth System Science, 9, 507–521.

Van Beek, L.P. and Th. W. Van Asch (2004). Regional assessment of the effects of land-use change on landslide hazard by means of physically based modeling. Journal of Natural Hazard, 31, 289- 304.

Van Beek, L.P. (2002). Assessment of the influence of changes in climate and land use on landslide activity in a Mediterranean environment. Neth. Geogr. Stud 294, Utrecht, KNAG/Faculty of Geographical Sciences.

Varnes, D.J. (1996). Landslide types and processes, Landslides: Investigation and mitigation (A.K.Turner and R.L. Schuster: Editors), Transportation Research Board Special Report 247, National Research Council, Washington, D.C. National Academy Press.

Varnes, D.J. (1984). Landslide hazard zonation: A review of principles and practice. UNESCO, Paris, pp. 1–63.

Wang, X. and R. Niu (2009). Spatial forecast of landslides in three gorges based on spatial data mining. Journal of Sensors, 9, 2035-2061.

Westen Van, C.J., N. Rengers, M.T.J. Terlien and R. Soeters (1997). Prediction of the occurrence of slope instability phenomena through GIS-based hazard zonation. Geologische Rundschau, 86(2), 404-414.