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Landslide Susceptibility and Causative Factors Evaluation of the Landslide Area of Debresina, in the Southwestern Afar Escarpment, Ethiopia

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Abstract: Remote sensing and GIS based mapping and evaluation of landslide is carried out at the Debresina area, located in the SW Afar Margin of Ethiopia. The purposes of the study were (1) to evaluate the landslide susceptibility of the area; (2) to evaluate the contribution of the various causative and triggering factors such as lithology, geological structure, land use, drainage, slope gradient, slope aspect, elevation, rainfall and earthquake to the occurrences of the landslides. Remote sensing and detailed field survey are applied to map the distribution of existing landslides and the factors that affect the landslide occurrences. Field measurements on joint characteristics (orientation, dip angle, spacing, opening, and roughness), degree and depth of weathering of the different lithologies are done. While, GIS is used for digitizing, data processing and analysis, map overlay techniques and overall data base construction. The FR (frequency ratio) model is adopted to evaluate and to correlate the various causative factors to the occurrences of landslide, and as well to delineate the landslide susceptible area. A kinematic slope stability method is also applied to see the controlling effect of the rift margin faults to the occurrences of landslides. Finally, landslide susceptibility zonation has identified four classes/zones, namely as very high (0.7%), high (22.7%), moderate (65.0%) and low (11.6%) zones. The results of the kinematic analysis show that the major part of the September 2005 landslide is a large wedge failure controlled by the NNE-SSW, NNW-SSE trending rift margin faults.

Key words: Landslide susceptibility, FR (frequency ratio), GIS, Debresina, Afar Rift Margin, Ethiopia.

1. Introduction

Landslides are one of the major destructive natural hazards in mountainous and rift margins of Ethiopia, resulting in loss of human life and property and severe damage to agricultural lands.

Many researchers [1-5] depicted that landslides have affected human lives, infrastructures, agricultural lands and natural environment in the highlands and rift margins of Ethiopia. In the years 1990-1998 alone, landslides or landslide-generated hazards have claimed about 300 human lives, damaged over 100 km asphalt road, demolished more than 200 dwelling houses and devastated in excess of 500 hectares of land in different areas of the highlands of Ethiopia [1]. According to the press reports of Walta information Centre of 2000, 2002, 2003a, 2003b, 2003c, 2003d as cited in Ref. [5], 135 human lives have been lost, about 3500 people were displaced and an estimated 1.5 million US Dollar worth property has been damaged in the highlands of Ethiopia in the years 1998-2003.

The Debresina area is one of the most landslide prone areas located in the Afar Rift Margin of Ethiopia. In this area a large scale and complex landslide is started in September 13-14, 2005. According to the aid reports of ACT (Action by Churches) released in 2006 and the information of the local authorities, this event caused losses of over 900 hectares of arable lands, displacement of more than

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4,049 peoples, destruction of more than 1,200 dwelling local houses and over 75% crop harvesting failure specifically in the localities named Izaba andShotel Amba. The prevalence of landslide hazards in such terrains could certainly have major role in aggravating the food insecurity problem of the country as most people living here are farmers who are dependent on subsistent agriculture.

Thus, the aim of this study mainly includes: (1) mapping of the landslide occurrences and the various causative factors; (2) correlating and evaluating the contribution of these various factors to slope failures; (3) assessing and mapping potential hazard, as applied to the Debresina area, to be used by the local decision makers and communities in their planning stage. Remote sensing and GIS based mapping with help of intensive field surveys are used in preparing the landslide causative factors and inventory map. FR (frequency ratio) with help of GIS is used for the correlation between landslide locations and the chosen causative factors in the study area.

The study area lies in the SW Afar Rift Margin, between UTM coordinates 580,000 to 593,500 m E and 1,085,000 to 1,103,800 m N, at about 190 km NE of Addis Ababa (Fig. 1). The total study area covers an area of 218 km^2.

It is one of the areas located in the high seismic zone, with relatively high annual rainfall (1,947 mm). It is characterized by gentle to steep slope gradients, dense drainage system & deep river cut and gully erosion, with elevation range of 1,368 to 3,100 m above the sea level. The middle and lower parts are densely populated and intensely cultivated. East facing steps of flat terraces and cliffs are commonly attributed to the rift margin faults. Geologically, the study area is covered by Alaje formation (basalts, rhyolitic/trachytic ignimbrites, tuffs, and agglomerates), Tarmaber formation (basalts) and Quaternary sediments (alluvial, colluvial-eluvial deposits, fine residual soils) (Fig. 2). Several springs, which appear at the interface where fractured rock overlays the weathered part or where there is paleosol between the various lava flows, are common. The area has suffered severely from mass movement

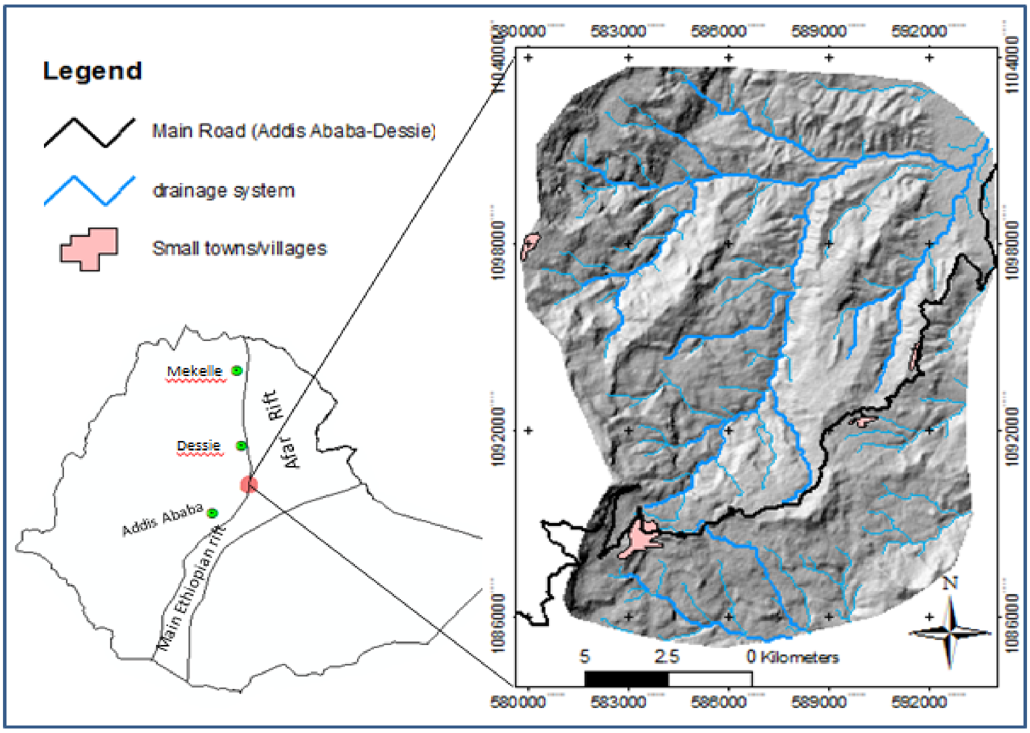


Fig. 1 Location map of the study area.

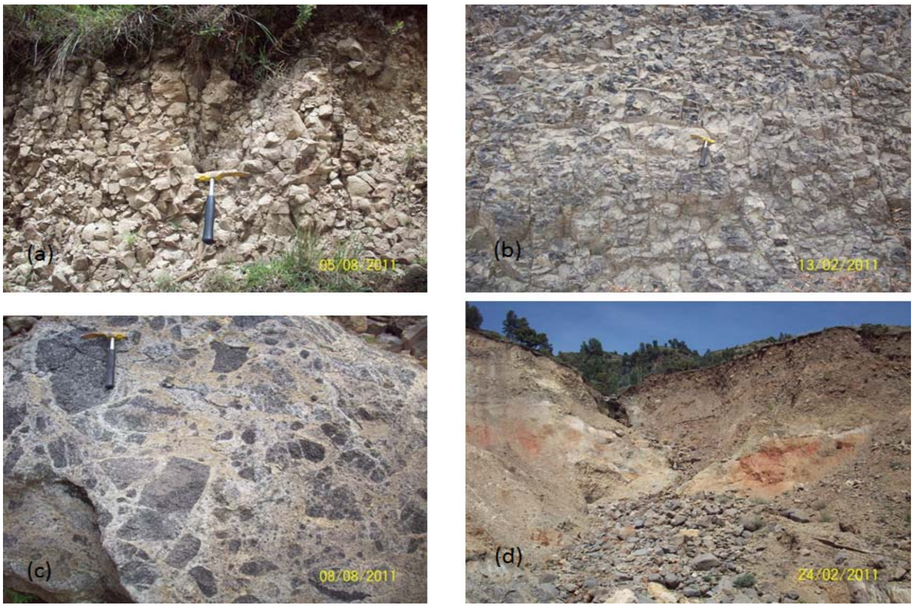


Fig. 2 Photos showing some of the lithologies in the study area: (a) fractured rhyolitic ignimbrite; (b) fractured Alaje basalt; (c) agglomerate; (d) colluvium-eluvium deposit.

problems. Available field evidences of old landslide scars, and oral local information are witnesses for the occurrences of the landslides in the study area. Landslide inventory carried out by this study depicts that more than 140 large and small occurrences are mapped in the study area. However, it is very difficult to find the historical time records of the occurrences. Nevertheless, as mentioned in the introduction, the event of September 2005 has relatively better information. It is the largest known landslide event in Ethiopia so far. It has an average length of 3 km from crown to toe, and a width of 5-6 km, covering more than 15 km^2 (Fig. 3). It is a very complex and composite type of failure consisting of bedrocks, debris

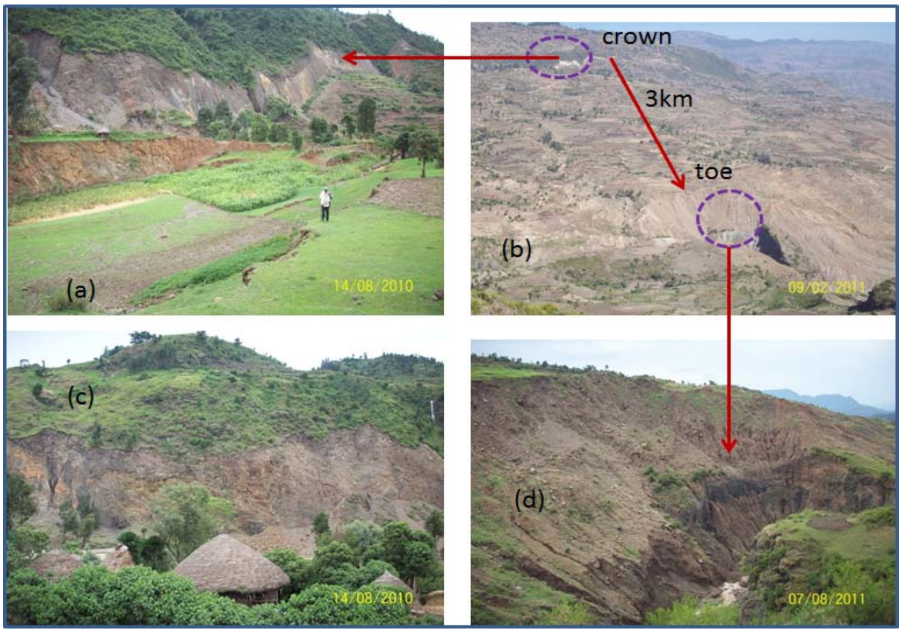


Fig. 3 Photos showing some of the characteristics of the landslide of September 2005: (a) zoomed photo at the crown part; (b) photo showing the distance from crown to toe of the landslide; (c) newly constructed house at the foot of the slide scar; (d) zoomed photo at the toe of the landslide.

and earth materials and has a rotational, translational and combined type of movement.

2. Methodology and Data Preparation

There are various methods to study and evaluate the landslide phenomena and its causative and triggering factors. The elements that affect slope stability and landslides are numerous and varied, and interact in complex ways [6]. In this study, seven causative factors that are lithology, proximity to fault, land use, slope steepness, aspect, elevation and proximity to drainage have been chosen as inputs for the landslide hazard evaluation based on the site condition. Data were extracted and collected using remote sensing and field based surveys to first prepare the preliminary lithological, structural, land use, landslide inventory maps from the interpretation of Aster image (Level-1B) of various years, Lands at images of 2001 and Google Earth, supported by the existing regional geological and topographic maps. The images have been interpreted using ENVI4.5 by applying different enhancing and band composition techniques to visualize various features and digitize them using ArcGIS9.3. The topographic factors, like elevation, slope steepness and slope aspect have been prepared from the 30m DEM (digital elevation model). Then, detailed field surveys have been conducted and the preliminary input maps have been crosschecked and updated into more detailed maps (Fig. 4).

FR (frequency ratio) model using ArcGIS and kinematic slope stability methods have been adopted to correlate the various causative factors and the landslide locations. The FR model is a popular quantitative method which has been recently applied with satisfactory results in several works intending to create landslide susceptibility maps [7]. It is the ratio of occurrence probability to non-occurrence probability, for specific attributes [8].

The spatial data base and the input maps have been constructed using GIS techniques, and the FR method has been applied to quantitatively describe the relationship between the landslide causative factors and the past landslide occurrences, as well as to prepare the landslide susceptibility map of the study area. The FR index of each landslide causative factor has been calculated with the help of spatial analyst techniques of ArcGIS. The weighted sums of FR values of all classes have been used to produce a landslide susceptibility map.

The collected structural field data have been also treated with the conventional kinematic method and plotted using the Dip software to visualize their effect on the major landslide event of September 13-14, 2005.

2.1 Landslide Inventory Mapping

The delineation of landslide occurrences is vital for the prediction of future patterns of instability directly from the past distribution of landslide occurrences. With this consideration, the landslide distribution of the study area is determined through image interpretation (Aster of various years, Landsat images, and Google Earth) and direct field survey, and then digitized directly into inventory map using GIS. Rock/debris/earth slides and rock falls are most common types of landslides in the area. The landslide inventory map is overlapped and crossed with the various causative factor maps to visualize their relationship with the factors.

2.2 Lithology

Lithology is considered as one of the main cause for slope instability. Thus, the lithological map of the study area has been prepared from the interpretation of Aster image (Level-1B) of various years, Landsat images of 2001, and Google Earth, supported by the existing regional geological and topographic maps and intensive field surveys. The main lithological units of the study area can be grouped as Alaje formation (basalts, rhyolitic/trachytic ignimbrites, tuffs, and

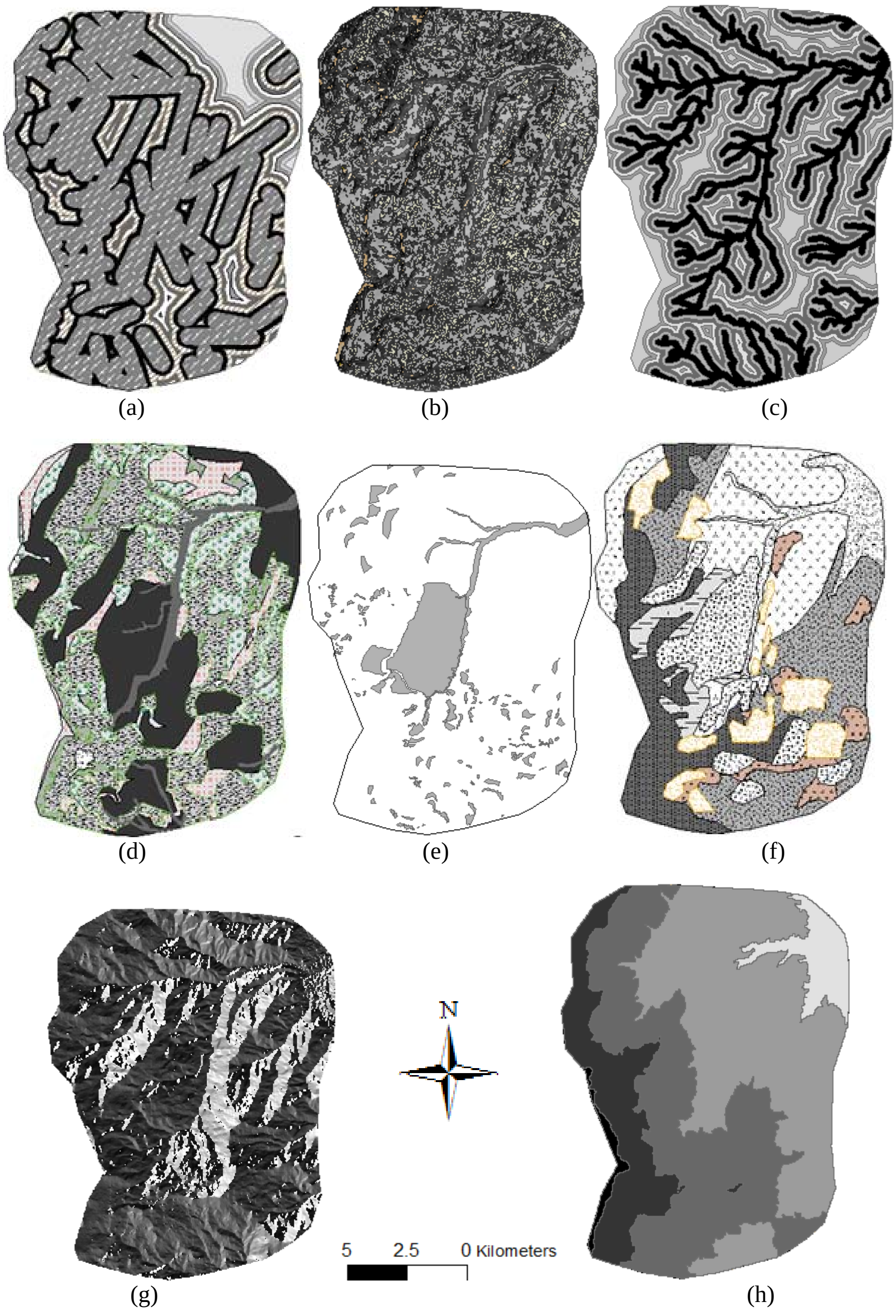


Fig. 4 Input maps: (a) proximity to fault; (b) slope steepness; (c) proximity to drainage; (d) land use; (e) landslide inventory; (f) lithology; (g) aspect; (h) elevation.

agglomerates), Tarmaber formation (basalts), Quaternary sediments (alluvial, colluvial-eluvial deposits, fine residual soils) (Fig. 4f and Table 1). The Alaje formation especially the ignimbrites and the tuffs are highly altered and weathered. Alaje basalts, basic tuffs and agglomerates and Tarmaber basalts cover 24.4%, 22.2% and 19.7% of the whole area respectively while the remaining 33.7% is covered by other lithologies (Table 1). However, about 50% of the landslide has occurred in the colluvium-eluvium sediments. The physico-mechanical parameters, such as degree and depth of weathering, orientation and spacing of discontinues, unconfined compressive strength, hydraulic nature, compaction of each

Table 1 FR of landslide occurrences.

Classes	% X (total area)	% Y (landslide area)	FR (%Y/%X)
Lithology			
Ignimbrite (upper)	4.7	0.9	0.2
Fractured Rhy/Trach. Welded tuff	3.9	6.8	1.7
Alaje basalt	24.4	9.3	0.4
Alluvial/debris	5.6	10.6	1.9
Basic tuff &agglomerate	22.2	6.8	0.3
Colluvium-eluvium deposit	6.6	49.8	7.6
Ignimbrite (part of Alaje)	4.9	1.3	0.3
Residual soil (clay & silt dominant)	8.1	5.1	0.7
T.basalt	19.7	9.3	0.5
Proximity to fault (m)			
0-400	56.0	65.7	1.2
400-600	17.3	17.0	1.0
600-800	9.6	10.1	1.1
800-1000	5.6	4.0	0.7
1000-1200	3.3	1.1	0.3
1200-1400	2.0	0.9	0.4
1400-1600	1.5	0.4	0.3
> 1600	4.8	0.9	0.2
Proximity to drainage (m)			
0-150	30.9	42.4	1.4
150-300	21.8	27.3	1.3
300-450	17.2	15.9	0.9
450-600	13.7	8.3	0.6
600-750	9.0	4.1	0.5
> 750	9.2	2.0	0.2
Slope steepness (degree)			
0-5	25.4	18.1	0.7
5-10	47.3	45.1	1.0
10-25	8.9	16.7	1.9
25-40	12.6	16.3	1.3
40-55	5.2	3.6	0.7
> 55	0.6	0.2	0.3
Elevation (m)			
1368-1500	5.5	6.2	1.1
1500-2000	44.5	38.8	0.9
2000-2500	32.5	47.4	1.5
2500-3000	16.1	7.5	0.5
> 3000	1.4	0.2	0.2
Land use			
Forest	4.1	1.1	0.3
Bushes & shrubs	15.8	6.0	0.4
Bare land/sparse vegetation	9.5	5.3	0.6
Arable land	27.8	54.2	2.0
Heterogeneous agricultural areas	40.0	18.8	0.5
Urban/semiurban areas	0.7	0.0	0.0
River bed	2.1	14.6	6.8
Aspect (degree)			
NE(40°)	12.7	12.6	1.0
E(89°)	18.0	26.8	1.5
SE(134°)	23.9	31.6	1.3
S(180°)	15.0	13.0	0.9
SW(224°)	6.8	3.6	0.5
W(270°)	4.5	1.4	0.3
NW(315°)	7.8	3.3	0.4
N(360°)	11.3	7.7	0.7

lithologies, have been described and measured in 183-GPS points during the field work. The depth of weathering has been measured from gully and ridge exposure using the meter tape, while Schmidt hammer, compass and GPS have been used to measure the compressive strength, joint characteristics and locations respectively.

2.3 Proximity to Faults

Fault map of the study area was prepared and compiled from various images (Aster and Landsat images) and previous works. The images have been interpreted using ENVI4.5 by applying different enhancing and band composition techniques, identifying the various features and digitizing them using ArcGIS9.3. The Afar rift margin is worldwide known for its extensional tectonic movement and characterized by normal faults. Thus, faults are very important factor for the landslide evaluation of the study area. This is due to the fact that they are not only weak zones, but also mostly characterized with: (a) deeper weathering, resulting in greater thickness of soil masses; (b) higher potential for concentrated groundwater flow, which can act as lubricant and also can produce water pressures causing landslides. With this in mind, the fault proximity maps are produced to evaluate its contribution to the landslide (Fig. 4a).

2.4 Land Use

Land-use is another causative factor considered in the landslide evaluation of the area. Similarly, Aster and Landsat image, Google Earth, topographic maps of 1:50,000 and field surveys have been used in preparing the land use map (Fig. 4d). The major land use pattern in the area comprises heterogeneous agricultural areas, arable land, bushes & shrubs, bare land/sparse vegetation, forest, river bed and Urban/semi-urban areas. Lower regions (up to slopes less than 30 degrees) have comparatively higher human influence. People in this region are still actively involved in agriculture, moving into steep slopes and cultivating without constructing proper terraces. This has created major hazards and disasters like landslide and soil erosion in the area.

2.5 Slope Steepness

This is an important factor with regard to landslide initiation. In most studies of landslides, the slope steepness is taken into account as the major causative factor of landslide. With this consideration, slope of the study area has been prepared from the 30 m DEM using the ArCGIS9.3.

2.6 Slope Aspect

The slope aspect map of the study area was derived from the DEM of the study area. During mapping, the slope aspect was grouped into eight main directions (Table 1). Slopes facing to the SE(134°), E(89°), NE(40°), S(180°) have more relationship with landslides, while slopes facing to W(270°), NW(315°), SW(224°) and N(360°) have less impact for the slope failure of the area.

2.7 Elevation

Elevation is another factor that can cause landslides. The elevation map of the area of interest has been prepared from the 30 m DEM using the spatial analyst of ArcGIS9.3 and categorized into 5-class ranges (Fig. 4h). The minimum elevation is 1,368 m, while the maximum is 3,200 m. Elevation classes in the range of 1,500-2,000 m and 2,000-2,500 m covers 44.5% and 32.5% of the total area respectively, while the elevation class with greater than 3,000 m covers the smallest area (Table 1). About 86% of the landslides initiated at elevation between 1,500 and 2,500 m.

2.8 Proximity to Drainage

The drainage map has been prepared from the 30 m DEM, using the Arc hydro9.3 and digitized from the topographic map of 1:50,000 scale for comparison. Most drainage system of the area is created following the geological structures. The tectonic morphology of the study area is greatly modified by stream incisions, which finally could influence slope stability through over steepening the lower sections of the slopes and removal of materials that provided support at the toe. For this reason the drainage proximity is considered as one causative factor in the landslide susceptibility study. About 52.7% of the study area is found within 300 m distance from the drainage and about 70% of the landslides occur in these areas.

3. Results and Discussion

3.1 Correlations between Landslides and Causative Factors Using FR-Probability Model

The areal coverage of landslide occurrences in each class of causative factors is calculated by crossing with the inventory map using the ArcGIS. Then, the FR is determined by the ratio of landslidearea in each class (Y in %) and total area occupation of each class (X in %) and its value is used for the correlation of each of the various factors and the landslide occurrences. The FR values of the seven chosen landslide causative parameters are demonstrated in Table 1. When $FR < 1$, it means that it has less correlation than average, $FR > 1$, it means that it has higher correlation than average and $FR = 1$ means comparable to average [9]. The ratios of each factor's type were summed to calculate the LSI (landslide susceptibility index) using the equation below:

$$LSI = \sum FR \quad (1)$$

where LSI = landslide susceptibility index;

FR = frequency ratio of each causative factor of the classes.

(1) Lithology and landslide occurrences

The colluvium-eluvium, alluvial/debris, and fractured rhyolitic tuffs are sensitive to the landslide activity as they have $FR > 1$ (Table 1), while the fine residual soils are marginally prone and the rest is less prone to landslide activity. This result is consistent with field observations.

(2) Land use and landslide occurrences

Considering the land use factor, only the river courses and arable lands are more prone to landslide ($FR > 1$). The bare rock is marginally prone to landslide. The rest has low FR value and is with less contribution to sliding.

(3) Proximity-based factors and landslide occurrences

The fault and drainage proximities show a strong correlation with landslide occurrences with in distance ranges of 0-800 m and 0-300 m respectively, while the rest ranges are less sensitive to landslide occurrences.

(4) Topographic-based factors and landslide occurrences

Three main topographic factors such as slope, aspect and elevation are evaluated in correlation to the landslide occurrences. Hence, the slope angle of 10°-25° and 25°-40°, the aspect of East(89°) and SE(134°) and the elevation range of 2,000-2,500 m and 1,368-1,500 m have more than 1 of the FR value indicating that they are vulnerable areas to landslide in the study area.

Finally, the landslide susceptibility map was produced (Fig. 5) from the obtained LSI values given by Eq. (1), where the weighted sum is done by map overlay and raster calculation techniques of the ArcGIS. Based on the LSI values, the study area is divided into four susceptibility classes (or zones), namely very high (0.7%), high (22.7%), moderate (65.0%) and low (11.6%) susceptibility zones. The classified landslide susceptibility map depicts that most parts of the area are having moderate to high susceptible levels to landslide activity.

3.2 Kinematic Method

The impact of geological structures to the September 2005 landslide is evaluated using the kinematic approach (daylightingplanes). The collected structural field data and slope face are plotted on the equal area lower hemisphere using the Dip software. Results show that the major part of the September 2005 landslide is a large slope failure controlled by the NNE-SSW, NNW-SSE trending rift margin faults (Fig. 6).

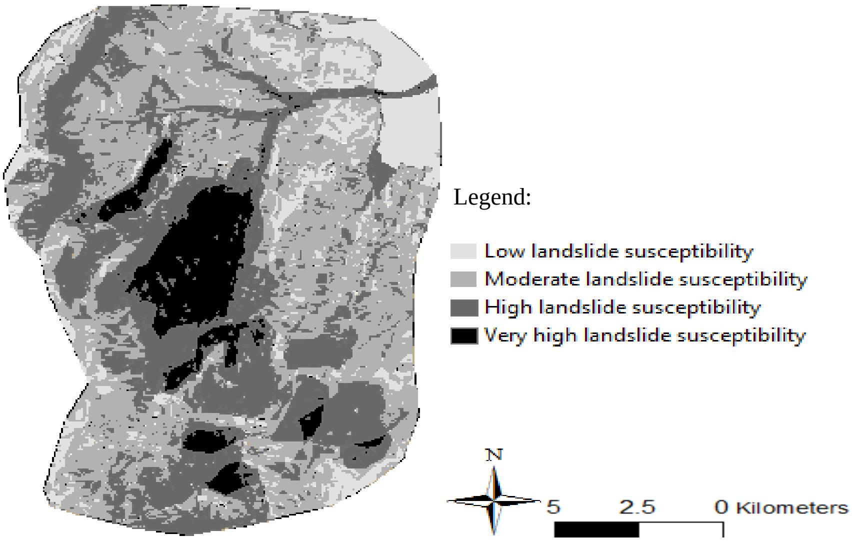
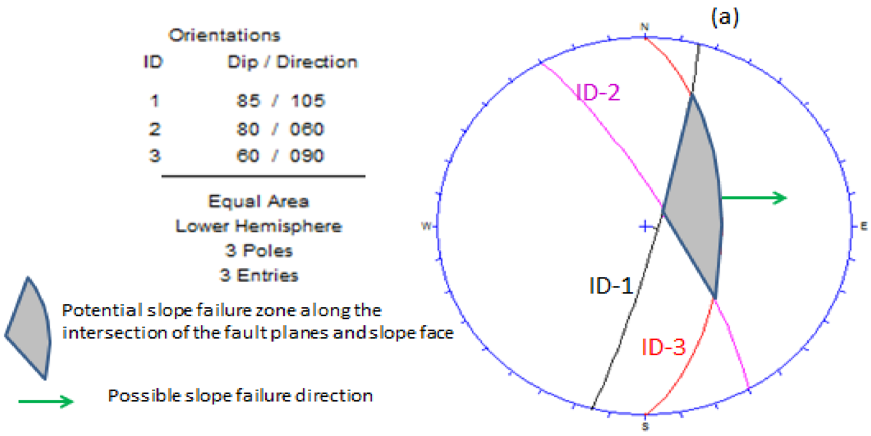


Fig. 5 Landslide susceptibility zonation of Debresina area based on the index-based approach.



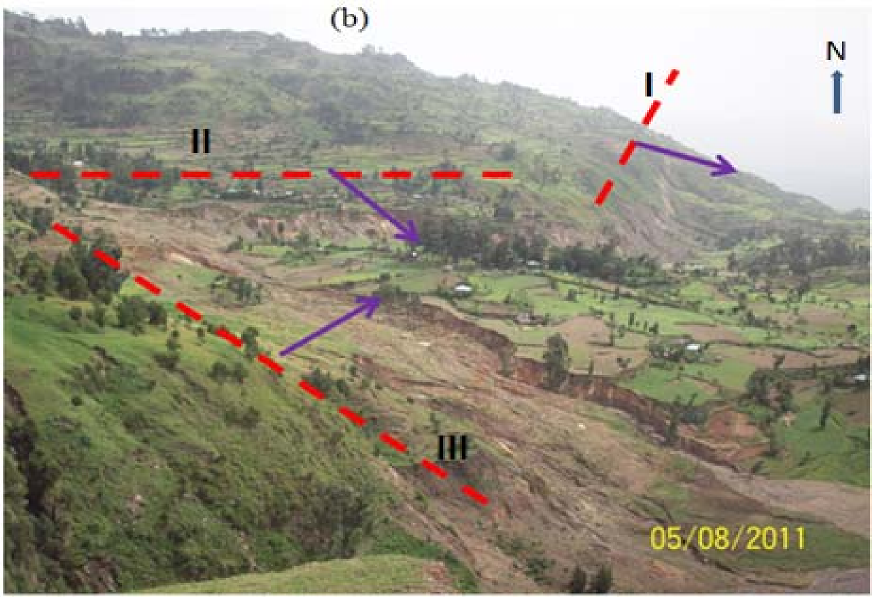


Fig. 6 (a) Stereographic plots of faults and slope face for kinematic slope stability analysis; (b) Photograph showing the landslide scars following the trends of (I) NNE-SSW; (II) E-W and (III) NNW-SSE trending rift margin faults.

3.3 Relationships between Landslides and Triggering Factors

Rainfall and earthquakes are the major landslide triggering factors in the world. Their relationship to the occurrence of landslides can be well addressed when there is a long time records series of the events. However, there are no historical records of the landslide events in the study area. Thus, these factors are treated here in relation to the landslide event of the September 2005, which has relatively better information on its date of occurrence.

Rainfall (from National Meteorology Agency of Ethiopia) and earthquakes (from the United States Geological Survey and Geo-observatory of Addis Ababa University) data were collected to assess their triggering effect on the September 2005 landslide.

(1) RF (rainfall)

The maximum, minimum and average annual rainfall in the study area is 3,409 mm, 1,165 mm and 1,948 mm respectively. The maximum annual rainfall is recorded in the year 1997, while the minimum in the year 1983. The monthly maximum rainfall is always in the months of July and August for all the recorded data. The daily maximum RF of the year 2005 is recorded on August 8, but the landslide is occurred on September 13-14, 2005. Hence, the RF shows weak correlation to that landslide occurrence as compared with the yearly, monthly and daily rainfalls (Figs. 7 and 8).

(2) EQ (earthquakes)

Records of collected earthquake data show that there had been 169 occurrences (Fig. 9) in an area located between latitude 11.72°-12.75°N and longitude 40.2°-40.7°E from June to October 2005. This area is found at about 160 to 300 km NE of the study area. Several researchers, such as Wright et al. [10-14] also reported that a major diking episode occurred in various localities of Afar depression in September 2005, causing a number of associated earthquakes of magnitude greater of 3.5 mb. Interviews with local people also confirmed that the then volcanic explosion and earthquake shake was felt around the study area. Thus, the most probable triggering factor for the September 2005 largescale landslide is the earthquake associated to the dike episode of the region.

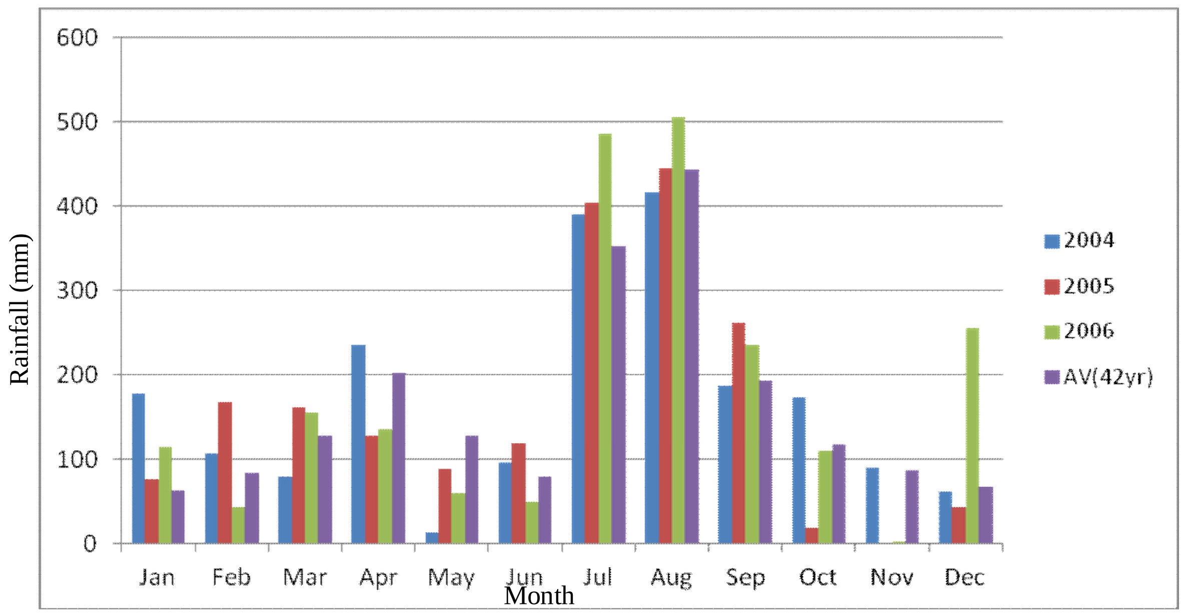


Fig. 7 Comparison of the monthly rainfall of 2004, 2005 and 2006 and the average monthly rainfall for 42 years (Debresina station).

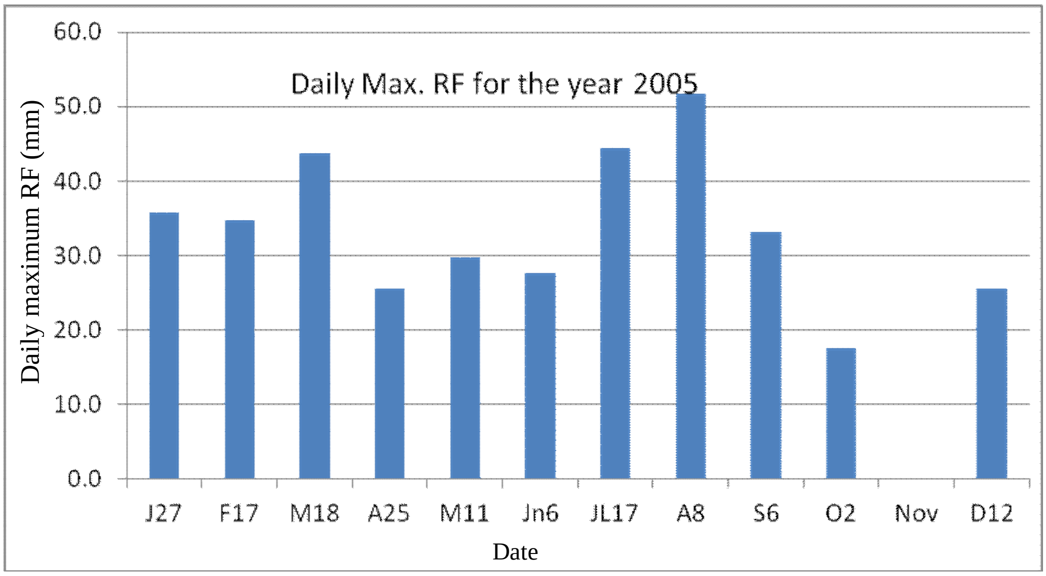


Fig. 8 Daily maximum RF (mm) for 2005 (J27 = January 27; F17 = February 17; M18 = March 18; A25 = April 25; M11 = May 11; Jn6 = June 6; Jl17 = July 17; A8 = August 8; S6 = September 6; O2 = October 2; Nov = November with no rainfall; D12 = December 12).

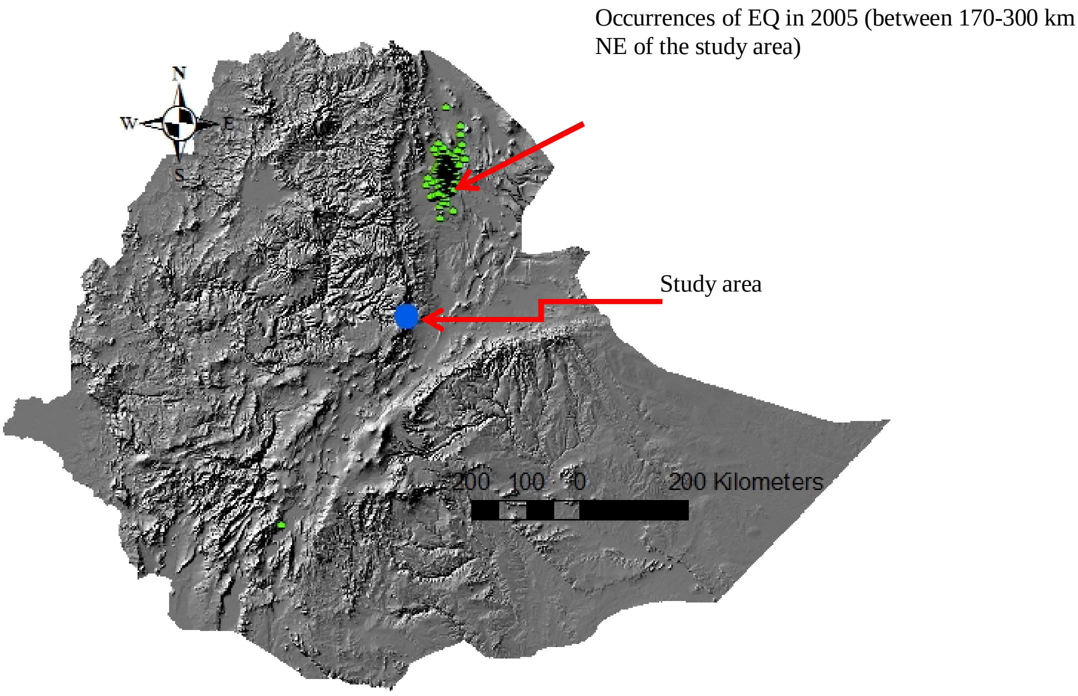


Fig. 9 Location of EQ epicenters on September 2005 in relation to the study area.

4. Conclusions

The conclusion of this research work is summarized as follows:

Ÿ Results show that the areas covered by colluvium-eluvium, various tuffs, clay soils, with slope range of 10°-40°, with arable type of land use, with distance of 0-400 m from fault and 0-300 m from drainage, with elevation of 2,000-2,500 m, with aspect to East and SE are highly prone to landslide;

Ÿ The kinematic slope stability analysis indicated that the major landslide of September 13-14, 2005 is structurally controlled, especially by the NNE-SSW, NNW-SSE trending rift margin faults;

- The landslide susceptibility zonation has identified four zones, namely as very high (0.7%), high (22.7%), moderate (65.0%) and low (11.6%) zones;
- The EQ occurrences in September 2005 within the Afar rift and its margins seem to be the main triggering factor for the September 13-14, 2005 large scale landslide.

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