Review of the occurrences and influencing factors of landslides in the highlands of Ethiopia: With implications for infrastructural development

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ABSTRACT

The hilly and mountainous terrains of the highlands of Ethiopia are frequently affected by rainfall-induced landslides of different types and sizes. The major types of landslides reported to have been triggered by heavy rainfalls include debris/earth slides, debris/earth flows and, and medium to large-scale rockslides. Though rockfalls are common in the Ethiopian highlands no association is made with rainfalls. Review of the previous studies revealed that landslide hazards have been causing: loss of human lives, failure of engineering structures, damage on agricultural lands and on the natural environment. Medium to large-scale rockslides were reported in areas underlain by Paleozoic glacial sediments and volcanic rocks. Evaluation of the relationship between landslides and various influencing factors show that the debris/earth slides/flows have prevailed in: (a) areas which are underlain by Paleozoic glacial sediments, shales, and basalt flows, (b) hillslopes characterized by slope angles in the range 15-45 degrees, (c) terrains represented by concave shapes with some on planar surfaces, (d) areas affected by active gully erosion/artificial excavations, and (e) places represented by sparse or no vegetation cover with deeper roots. With regard to the triggering mechanisms, most of the rainfall-induced landslides have taken place in the late periods of the rainy seasons (late August to early September) following heavy rainfalls indicating that process is related to raise in groundwater level coupled with a certain intensity of rainfall event. Ethiopia is currently involved in massive infrastructural development (including roads and railways), urban development and extensive natural resources management. In this whole socio-economic development, landslides and landslide-generated ground failures need to be given due attention in order to reduce losses from such hazards and create safe geo-environment.

Key words: Review, Landslides, Highlands, Ethiopia.

1. INTRODUCTION

Landslides and landslide-generated ground failures are among the common geo-environmental hazards in many of the hilly and mountainous terrains of both the developed and developing world. As defined by Brunsden (1979), landslide is the downslope movement of soil and rock under the influence of gravity without the primary assistance of a fluid transporting agent.

Various authors (e.g. Schuster and Fleming, 1986; Schuster, 1995; Glade, 1998) indicated that in many countries the economic losses and casualties due to slope failures are greater than commonly recognized. According to Terlien (1996), although a small percentage of individual landslides are catastrophic, it is essentially the high number which makes the total economic loss due to slope instability (direct damage to agricultural land and infrastructure and indirect damage to economic activity) to be higher than due to other hazardous natural phenomena.

Slope failures are generally considered as fairly well predictable hazards and economic losses due to such hazards can be reduced significantly (Hansen, 1984). Especially in recent years, there have been advances in better understanding of the initiations of landslides and in techniques of slope instability hazard assessments, prediction and mitigation (Hansen, 1984). In spite of such advancements, landslides continue to prevail in both the developed and developing countries, with larger casualties in developing nations but with severe economic losses in the industrialized world (Guzzetti et al., 1999). According to Schuster (1995), world-wide landslide activities are expected to continue in the 21st century for the following reasons: (a) increased urbanization and development in landslide-prone areas, (b) continued deforestation of landslide-prone areas, and (c) increased precipitation caused by changing climatic conditions.

The hilly and mountainous terrains of the highlands of Ethiopia which are characterized by variable topographical, geological, hydrological (surface and groundwater) and land-use conditions, are frequently affected by rainfall-triggered slope failures. Earthquake triggered landslides are little reported in Ethiopia.

In Ethiopia, landslide-generated hazards are becoming serious concerns to the general public and to the planners and decision-makers at various levels of the government. However, so far, little efforts have been made to reduce losses from such hazards.

With the on-going infrastructural development, urbanization, rural development, and with the present land management system, it is foreseeable that the frequency and magnitude of landslides and losses due to such hazards would continue to increase unless appropriate actions are taken in the Ethiopia. In order to bring the issue of landslides and associated geohazards into the attention of the academia, decision makers, and concerned organizations this review paper was made.

2. THE HIGHLANDS OF ETHIOPIA

Broadly, the Ethiopian landmass is divided into highlands and lowlands. According to FAO (1986), the Ethiopian highlands (which include areas with altitude over 1500m a.m.s.l) cover about 44% of the Ethiopian landmass. These highlands represent the most densely populated areas; with over 60% of the population living in these areas.

2.1. Topography

The highlands of Ethiopia are generally characterized by highly variable topography which is a reflection of the past geological and erosion process. The landscape includes plateaus, steep hillslopes, and deeply incised valleys and gorges. Much of the elevation of the highlands ranges from about 1500 to 3500m: with some of the gorges within the highlands having elevations upto 1000m while some mountains rising over 4600m above sea level. Many of the hillslopes are steep enough to reach the limit equilibrium state, whereby external factors such as rainfall infiltration and/or excavations (artificial or natural) could trigger slope failures.

2.2. Climate

The Ethiopian highland is characterized by variable climatic conditions. The fact that the region is located in the tropics combined with the existing high range of altitude and air pressure difference determines the variation in climate that prevails in different areas (Chernet, 1993). Atmospheric temperature, of the highlands, varies from about 30^0C to -5^0C during the seasons October to January.

As reported by several authors (e.g. Mesfin, 1970; Chernet, 1993; Ayalew, 1999), the highlands of Ethiopia are associated with high rainfall variability. The mean annual rainfall varies from about 500mm to 2000mm, with major precipitation in the months of June to September, and with minor rainfall in the months of February to May. Many rivers originate in these highland terrains and flow through deep gorges, draining extensive areas of the region.

2.3. Land Use

As indicated by FAO (1986), the highlands of Ethiopia are the most densely populated and intensively cultivated areas in the country. These areas are threatened by desertification and deforestations (Virgo and Munro, 1978; FAO, 1986; Oldeman et al., 1991; Hurni and Perich, 1992; Billi and Dramis, 2003).

Ethiopia's forest resources are reported to have been depleting at alarming rate. A century ago, forests covered about 40% of the total land area (Worku, 1995; Bekalo and Bangay, 2002). This proportion has been reduced to 16% in the early 1950's and to 3.6% in the 1990's (Worku, 1995). The rate of deforestation, according to Bekalo and Bangay (2002), is estimated roughly at 6% of natural forest per year. In its 2011 annual performance report, the MoARD (2011) has indicated a general increase in forest cover in Ethiopia which is attributed to the on-going nation-wide efforts in natural resources management and afforestation programs. Deforestation is believed to have an influence on shallow landslides in Ethiopia.

2.4. Erosion Processes

It is well known that land degradation and associated gully erosion has been a major problem in Ethiopia. Various authors (e.g. Hurni and Perich, 1992; Beraki and Brancaccio, 1993; Beraki et al., 1997; Bull, 1997; Nyssen et al, 2004; Billi and Dramis, 2003) have reported on the prevalence of stream/river incisions and gully erosion in the highlands of Ethiopia. According to Billi and Dramis (2003), two main types of gully erosion are common in the highlands of Ethiopia: (a) discontinuous gullys which generally develop on low slope gradients, and (2) stream gullys which are formed by deep erosion processes typically migrating up-slopes. The existence of deep gorges with active geomorphological processes like stream/river incisions and gullying indicate that the landmass is still active in surface processes which could have influence on landslide evolutions.

2.5. Rock and soil types in the highlands of Ethiopia

The major rock types in the highlands of Ethiopia include: (1) Metamorphic rocks (mainly metasediments and metavolcanics) and associated intrusive rocks (Mohr 1983; Tadesse et al. 2003), (2) Paleozoic sediments which include glacial tillites and post-glacial sediments (siltstone/sandstone units) (Mohr 1962, 1967, 1983; Kazmin 1972), (3) Mesozoic sediments which include sandstone, shale and limestone units (Assefa 1981, 1991; Russo et al., 1999), (4) Cenozoic volcanics (basalt flows of the trap series) which are often associated with pyroclastic and lacustrine deposits (Mohr and Zanettin 1988), and (5) Trachytes and Intrusive rocks (like dolerites) (Mohr 1962). These rock formations are often affected by different geological structures. The main soil types found in the highlands of Ethiopia are unconsolidated recent sediments which include colluvial/debris materials, residual soils and alluvial deposits.

With regard to the influence of rock types on landslides, Gezahegn (1998) and Ayalew (1999) have indicated the presence of soft and low permeability nature of materials (shales) in the Abay Gorge as factors controlling landslides in the area. Ayenew and Barbieri (2005) have reported the presence of loose unconsolidated deposits which overlie the highly weathered basalt as a factors influencing landslides in the Dessie town. Woldearegay (2005) have also reported on the influence of rock types in controlling landslides in areas underlain by Paleozoic glacial tillites (in Feresmay area, northern Ethiopia) and on shale hillslopes (Mekelle area). According to the same author the presence of soft and low permeability sediments (glacial tillites and shales) which underlie the unconsolidated deposits influence debris/earth slides in northern Ethiopia.

3. RECORDS OF LANDSLIDES IN THE HIGHLANDS OF ETHIOPIA

Because of its complex geomorphological, hydrological, and geological setting, the hilly terrains of the Ethiopian landmass has been frequently affected by first time as well as reactivated old landslides. Except for some efforts made by the Ethiopian Geological Survey and Ethiopian Roads Authority, so far no comprehensive inventory of landslides and their significance (economic, social and environmental) is made in Ethiopia. However, despite multi-facet challenges in landslide research in the country, several authors have reported on slope instability problems in different parts of country (Figure 1). A summary of the major slope failures reported so far in the country is given below.

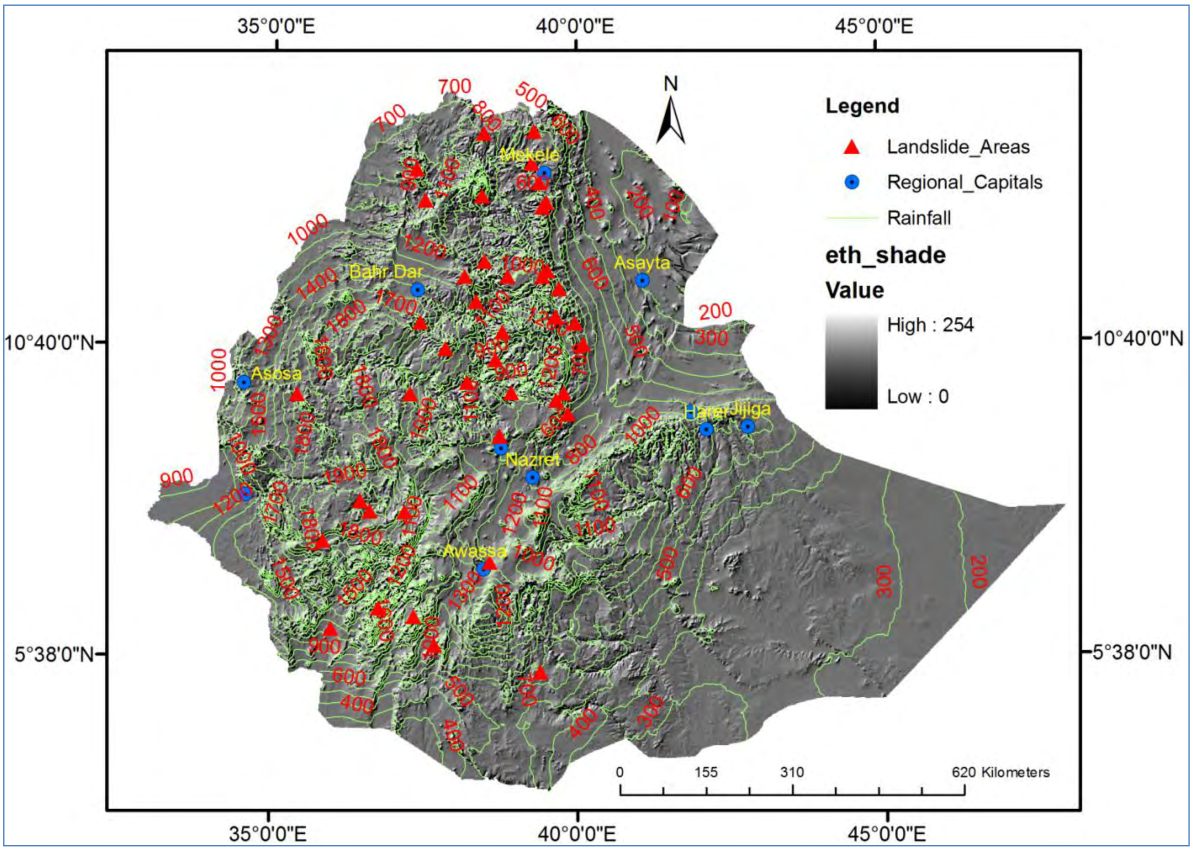

Figure 1. Locations of landslide affected areas in the highlands of Ethiopia. Modified after the works of the various researchers acknowledged in the text; mainly from the maps produced by Ayalew (1999), Woldearegay et al. (2005), and Woldearegay (2005).

3.1. Landslides in Dessie town, northern highlands of Ethiopia

Several authors (e.g. Eshete, 1982; Hailemariam, 1995; Tsehayu and Gezahegn, 1995; MoURD, 1995; Ayalew, 1999; Terefe, 2001; Ayenew, 2002; Ayenew and Barebieri, 2005) have reported on the prevalence of landslides in Dessie town, central highlands of Ethiopia. According to these authors, failure mainly involved unconsolidated materials which overlie the trap volcanics. To mitigate the landslide problems in the town a number of mitigation measures have been implemented. Despite these efforts, however, landslides still remain major challenges for the development of Dessie town.

3.2. Landslides in Abay Gorge, central highlands of Ethiopia

One of the areas with major slope stability problem in Ethiopia is the Gohatsion-Dejen highway route (called the Abay gorge); this route is one of the critical road corridors in Ethiopia which connects Addis Ababa to Bahir Dar. A number of studies have been carried out in this area. The geology of the area has been studied by different researchers (e.g. Assefa, 1979, 1980, 1981, 1991; Assefa and Atnafu, 1994). Landslides in the Abay Gorge were reported by different organizations (e.g. EIGS, 1987, 1994, 1995; TCDSE, 2003; AAU through MSc research works). In recent years, in collaboration with Ethiopian Geological Survey the Ethiopian Roads Authority have involved in the monitoring and design of remedial measures for the landslides in the Abay Gorge.

Several researchers from the industry and academia have also studied the slope stability problems in the Abay Gorge (e.g. Gezahegn and Dessie, 1994; Tadesse et al., 1994; Wubshet et al., 1994; Ayalew and Temesgen, 1995; Gezahegn, 1996, 1998, 1999; Ayalew 2000; Ayalew and Yamagishi, 2003, 2004). All these studies have indicated the complex nature of landslide problems in the Abay Gore. As part of the on-going road rehabilitation work, the Ethiopian government is undertaking efforts to mitigate the landslide problems in the area. Recent studies on the landslide issues in the Abay Gorge (e.g. Ayalew et al., 2009; Gonai et al., 2013; Kuwano et al., 2013; Yamada et al., 2013) mentioned the challenges on the on-going road rehabilitation work in the area. In addition to the above studies, MSc research works which deal with application of GIS and RS for landslide hazard zonation has been done in the Abay Gorge (e.g. Ayele, 2009; Endalamaw, 2010).

3.3. Landslides in Jemma basin, central highlands of Ethiopia

The Jemma basin which is a tributary of the Blue Nile river is reported to have been affected by landslides of different types and sizes. As part of the development cooperation program among Ethiopian Geological Survey, Aquatest, and Czech Republic Development Cooperation, a comprehensive study on the Water Resources Management and Environmental Protection Studies was made for the Jemma basin. Part of this project output, Sima et al. (2009), and Zvelebi et al (2010) have reported on the prevalence of geohazards (like landslides) in the Jemma basin.

3.4. Landslides in Goffa, Gilgel Gibe-II, and Sodo-Shone areas, Southern Ethiopia

Landslides were reported in southern highlands of Ethiopia: Asrat et al (1996) and Lemessa et al. (2000) have studied slope failures in the Goffa area. According to these authors the slope instability in these areas mainly involved earth/debris materials. Mulatu et al (2009) have tried to use GIS for landslide hazard zoning in Gilgel Gibe II, southern Ethiopia. Teferi (2005) also tried apply GIS for evaluating landslides in Sodo-Shone area, Southern Ethiopia.

3.5. Landslides in the Rift Margin

Several authors (e.g. Abebe et al. 2010; Asrat et al., 1997; Ayalew 1999; Ayalew and Yamagishi, 2002; Ayenew and Barbierie, 2005; Woldearegay et al., 2011) have reported on the complex nature of landslides and associated slope deformation in different regions of the Ethiopian rift margins and associated highlands.

3.6. Landslides on shale hillslopes, northern Ethiopia

Landslides are also common on shale hillslopes of northern Ethiopia. Woldearegay (2005), Woldearegay et al. (2006), Assay (2008), and Amare et al. (2011) studied landslides in Adishu area (Tigray). Nyssen et al. (2002) reported on mass movements in Hagereselam area, Tigray. All these studies indicate that landslides are dominantly controlled by the presence of soft and low permeability materials (shale) which underlie the unconsolidated deposits.

3.7. Landslides on Paleozoic glacial and post-glacial terrains, northern Ethiopia

The terrains which are underlain Paleozoic glacial sediments, in Tigray, northern Ethiopia, are reported to have frequent landslide problems. Woldearegay (2004); and Woldearegay et al. (2005, 2006) have reported on the causes and failure mechanisms of landslides in these terrains. According to these authors, the most common types of landslides are shallow debris/earth slides (with limited medium to large-scale rockslides). Slope failures in these terrains are mainly controlled by the presence of soft and low permeability Paleozoic glacial tillites and post glacial sediments.

3.8. Landslides in Tarmaber and surrounding areas

Landslides in Tarmaber area, central highlands of Ethiopia was reported by Atsbeha (2008), Woldearegay (2008) and Schneider et al (2008). As indicated by these authors, the localities "Yizaba Wein" and "Shotel Amba" areas, with an estimated total area of 35 square kilometer, were completely affected by a single major deep-seated landslide which took place in September 12, 2006. As a result of this landslide: more than 3000 people were displaced; 1250 dwelling houses were demolished; and 4 Churches, 4 Mills, and one elementary school were destroyed. The landslide also devastated about 1500 hectare of agricultural land and caused damage to the natural environment.

3.9. Landslides in different areas of Wollo, northern Ethiopia.

Slope instability problems are reported in different areas of Wollo, northern Ethiopia: Ayalew (1993, 1999) reported on the landslide problem in Wudemen area, while Ibrahim (2011) studied the slope instability issues in Mersa and Wurgessa areas.

3.10. Landslides in Wondogenet area, Southern Ethiopia

The Wondogenet area, southern Ethiopia, is reported to have been affected by rainfall-triggered landslides (e.g. Temesgen et al., 1999, 2001). According to these authors, landslide took place dominantly on unconsolidated deposits which are underlain by volcanic rocks.

3.11. Landslides in Tekeze hydropower project, northern Ethiopia

Hailemariam and Schmeider (2009) have reported on the slope stability condition of the reservoir sides of the Tekeze hydropower project, northern Ethiopia.

4. TYPES, SIZES AND TRAVEL DISTANCE THE RAINFALL-TRIGGERED LANDSLIDES

As indicated by Cruden and Varnes (1992), the mechanisms of slope failures range from creep type of slow movements (less than 0.15mm per year) to instantaneous and catastrophic slides (1.5m per second). Varnes (1978) defined the major types of slope failures into creep, slide, fall/topple, flow, and spread.

Though rockfalls are common slope failures in the highlands of Ethiopia, so far, little is reported on the association of rockfalls with rainfalls. From the previous studies, the major types of landslides triggered by rainfalls in the highlands of Ethiopia include: debris/earth slides, debris/earth flows, and rockslides.

The size of the failed masses varied from shallow debris/earth slides/flows (Figure 2) to large-scale rockslides (5Km*6Km*8Km) (Figure 3). The depths of the failure of the unconsolidated deposits was reported to be variable which ranges from about 0.5m to over 30m, with the majority of failures not exceeding 10m depth. The modes of failures of the debris/earth slides varied from translational types in areas with shallow soil cover to quasi-rotational failures in areas where greater thickness of unconsolidated deposits prevail.

The medium to large-scale rockslides in Feresmay area have depths that varied from about 40m to 80m (Woldearegay, 2005) (Figure 4). In the case of the large-scale rockslide in Tarmaber area, the depth of failure is estimated to be over 100m (Woldearegay 2008). In both cases, the large-scale rockslides have quasi-rotational modes of instabilities. The run-out (excess travel distance) of the debris/earth slides, debris/earth flows, and medium to large-scale rockslides varied from about 10m to 250m, with greater run-out for debris/earth flows.

Figure 2. Typical characteristics of a rainfall-triggered landslide on shale hillslopes (affecting farm land), Adishu area, northern Ethiopia.

Figure 3. Large-scale rockslide and associated debris/earth slides/flows on volcanic terrains, Tarmaber area, central highlands of Ethiopia.

Figure 4. A view of large-scale rockslide and associated debris/earth slides in Feresmay area, northern Ethiopia. Underlying the basalt flows and sandstone is the Paleozoic glacial tilles and post glacial sediments which control the slope deformation (Woldearegay et al., 2004).

5. Effects of landslides in the highlands of Ethiopia

All the studies on landslides carried out in the highlands of Ethiopia indicated that such hazards have economic, social and environmental significance. To mention some:

- According to Ayalew (1999), from 1993 to 1998, landslides or landslide-generated problems have claimed about 300 lives, damaged over 100 km asphalt road, demolished more than 200 dwelling houses and devastated in excess of 500 ha of land in Ethiopia.
- Woldearegay (2005) compiled different landslide reports from Ethiopian press headlines (WIC, 2000, 2002, 2003a, 2003b, 2003c, 2003d). According to this author, in the years 1998 to 2003, 135 human lives have been lost, about 3500 people were displaced and an estimated 1.5Million US Dollar worth property has been damaged in the highlands of Ethiopia.
- Ayenew and Barbieri (2005) indicated that landslides in Dessie town have been affecting roads, buildings, pipe-lines, and other infrastructures in the town.
- Various authors (Woldeaegay, 2008; Atsbeha, 2008; Schmeider et al., 2008) mentioned that as a result of a single large-scale landslide in the Tarmaber area: more than 3000 people were displaced; 1250 dwelling houses were demolished; 4 Churches, 4 Mills, and one elementary school were destroyed; over 1500 hectar of farm land was devastated.
- As a result of landslides, Ayalew (1999) and Woldearegay (2005) mentioned the spread of malaria in different parts of the highlands of Ethiopia due to ponding of water in low altitude areas.
- Woldearegay (2005) mentioned aggravation of sedimentation/siltation of reservoirs due to landslides in the watershed of several micro-dams in Tigray, northern Ethiopia.

It should be noted that the so far reported landslides in the highlands were recognized either because of their location (being along major economic routes) or because the people affected by the landslides needed critical support from the government. Otherwise, the issue of landslides and landslide-generated ground failures remain far above what is actually reported. Landslides still are affecting infrastructures like roads (e.g. Figure 5a, b) and agricultural lands (Figure 6) in different parts of the country.

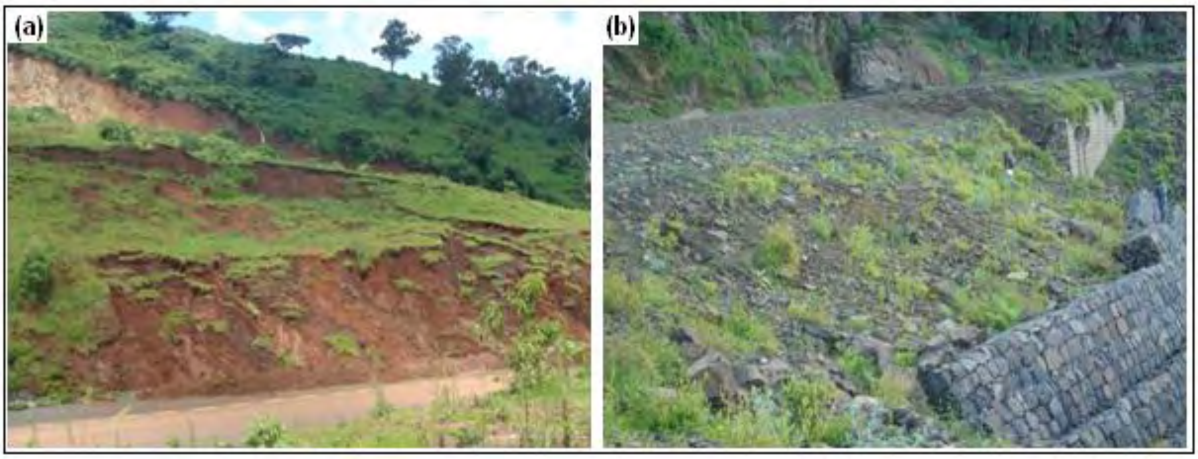

Figure 5. a) Earthslide affecting an asphalt road in Jimma area, southern Ethiopia, b) .Debris/earth slide which involved colluvial/debris deposits that are underlain by basalt flows on the Jemma basin, central highlands of Ethiopia. Note that the landslide is affecting the road; it caused failure of retaining structures (gabion).

Figure 6. Shallow earth/debris slides on unconsolidated deposits underlain by volcanic rocks (mainly volcanic ash/lacustrine deposits) in Mush area (Debreberhan), central highlands of Ethiopia.

6. HYDROLOGICAL TRIGGERING MECHANISMS OF LANDSLIDES

As reported by several authors in different parts of the world (e.g. Lumb, 1975; Wieczorek, 1987; Wilson and Wieczorek, 1995) both antecedent rainfall and a critical intensity of rainfall are important factors in triggering landslides. Review of the previous studies on landslides in the highlands of Ethiopia revealed that most of the reported rainfall-induced landslides have occurred during prolonged and heavy rainfalls; dominantly at the end of the rainy seasons (mainly in the period mid August to mid September). The so far reported extensive landslide which has taken place in the month of June is the Wondogenet landslide; it occurred after 17 hours continuous rainfall of 61mm (Temesgen et al., 1999).

Ayalew (1999) have developed relationship between rainfall and landslides taking into consideration historical records of landslides in different parts the country. Woldearegay (2004) also made an evaluation of the hydrological triggering mechanism of a large-scale landslide in Feresmay area, northern Ethiopia. Moreover, various authors (e.g. Ayenew and Barbieri, 2005; Gezahegn, 2009) have associated landslides with water pressure development within the slopes.

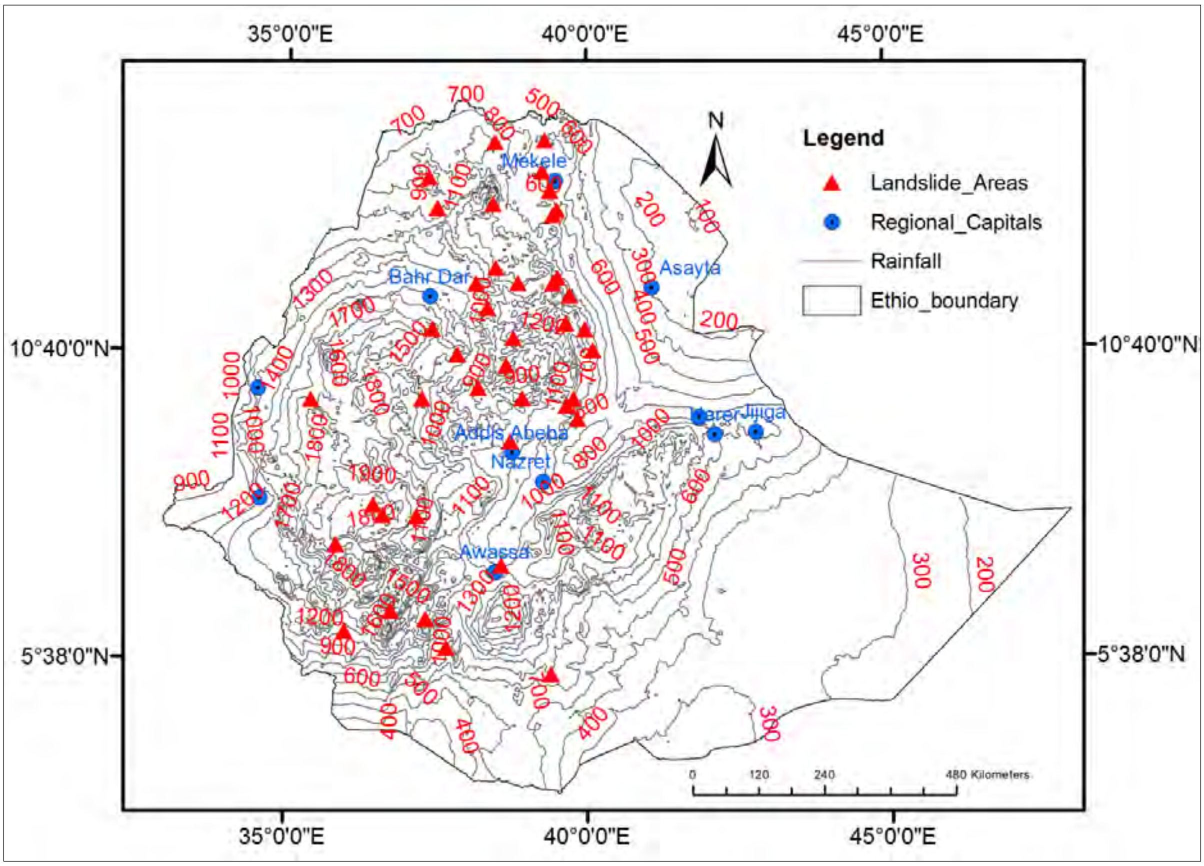

Figure 7. Locations of landslide-affected areas in relation to the rainfall distribution (mean annual rainfall in mm) in Ethiopia.

As can be noted from Figure 7, most of the so far reported landslides have occurred in the northern and south western parts of Ethiopia. Only few landslides were recorded in the western part of Ethiopia despite the high rainfall distribution in these areas. Though it requires further evaluation, the low prevalence of landslides in the high rainfall regions of western Ethiopia could be related to topographic, vegetation, human and other factors which favour stabilization of slopes.

The major rainfall-induced landslides in the highlands of Ethiopia are, therefore, believed to have occurred as a result of a combination of: (a) shear strength reduction due to saturation in the upper part of the soil profile, and (b) the build up of positive pore water pressures in the lower parts of the slopes which were on the verge of failures. Establishing a relationship between landslide events and rainfall has important implication for landslide monitoring and forecasting in the region in the future.

7. LANDSLIDE CONTROLLING FACTORS IN THE HIGHLANDS OF ETHIOPIA

Landslide controlling/influencing factors are those factors which make the slope susceptible to movements without actually initiating it and thereby tending to place the slope in a marginally stable sate. The factor that initiates the movement of slope which was on the verge of failure is the triggering factor. According to several authors (e.g. Terzaghi, 1950; Varnes, 1978, 1984; Hutchinson, 1988; Selby, 1993; Abramson et al, 1996; Guzzetti et al, 1999), the processes and factors that influence slope stability are numerous and varied and they interact in complex ways.

Review of the previous studies on rainfall-triggered landslides in the highlands of Ethiopia revealed that most of the slope failures prevailed in areas with certain geological (lithological and structural) settings, slope shapes, slope gradients, drainage lines (stream incisions/gullying) and artificial excavations (cuts), and vegetation cover.

7.1. Influence of geological (lithological and structural) settings

Factors inherent in the nature of the materials and discontinuities may have an influence on engineering characteristics of slopes, as it causes a marked anisotropy in the permeability, strength and deformation characteristics of soil/rock masses (Abramson et al., 1996).Though the highlands of Ethiopia is represented by different rock types, most of the reported landslides took place in areas which are underlain by: (a) incompetent rocks (Paleozoic glacial tillites, post-glacial sediments, and Shales), and (b) competent rocks (basalt flows) which are associated with volcanic ash/lacustrine deposits.

According to Woldearegay (2005), the prevalence of landslides in areas underlain by Paleozoic glacial tillites, Post-glacial sediments, and shale (in northern Ethiopia) is attributed to the fact that these slope masses are associated with: (a) low shear strength behaviours, (b) low permeability characteristics which enhance the development of seepage forces within the overlying slope masses, and (c) high susceptibility to weathering, erosion, and lubrication (softening). Similar observation was reported by several authors (e.g. Gezahegn, 1998, 1999; Ayalew, 1999; Ayalew and Yamagishi, 2004) on the landslide problems in the Abay gorge (central highlands of Ethiopia); the authors indicated that shale materials, overlain by loose soil masses and/or intercalated within more resistant rocks, are important factors affecting slope stability.

Various authors (e.g. Gezahegn, 1999; Ayalew, 1999; Ayenew and Barbieri, 2005; Woldearegay, 2005) have studied the occurrences of rainfall-triggered landslides on terrains underlain by basalt flows in the highlands of Ethiopia. Based on these studies, the prevalence of landslides in volcanic terrains could be attributed to: (a) the intrinsic behaviours of these rocks that resulted in horizontal flows which enhance lateral flow of water and recharge the unconsolidated deposits at the lower sections of the slopes, (b) the presence of volcanic ash and lacustrine deposits of low shear strength, and low permeability that enhance water pressure build-up within the soil mass, and (c) the presence of unconsolidated soils with high susceptibility to weathering, erosion, and lubrication (softening).

As stated by different researchers (e.g. Asrat et al., 1997; Abebe et al., 2010; Schneider et al., 2008), the landslides in the rift margins of the highlands of Ethiopia are associated with deep-seated, structurally controlled deformations which require comprehensive understanding of the geological and structural settings in order to clearly define the failure mechanisms and mitigation options.

7.2. Influence of slope gradients on landslides

It is known that the common force tending to generate movements on slopes is gravity. Review of the previous studies show that most of the reported debris/earth slides/flows and rockslides have taken place in areas with slope angles between 15 to 45 degrees. As indicated by different researchers (e.g. Ayalew and Yamagish, 2004; Ayenew and Barbieri, 2005; Woldearegay, 2005), the low probability of occurrence of landslides in low slope gradients is likely to be due to the corresponding increase in the factor of safety and thus a higher water table will be required to initiate failure. On the other hand, absence of major debris/earth slides and debris/earth flows on terrains with slope gradients greater than about 50 degrees is related to the insignificant thickness or even absence of unconsolidated deposits on such terrains because most of the steep slopes are dominated by slightly to moderately weathered rocks. The moderately steep terrains are often covered by unconsolidated deposits, which are more vulnerable to rainfall-triggered slope failures.

7.3. Influence of slope shapes on landslides

Slope shapes influence the susceptibility of a slope to landslides by governing the distribution of water (surface/subsurface) within a slope (Anderson and Burt, 1978; Reneau and Dietrich, 1987; Sitar et al., 1992). Positive plan curvature values (convex) indicate divergence and negative plan curvature values (concave) indicate concentration of flow. Concave plan terrains promote concentrated flow of water, while convex plan terrains cause divergence of flow (Anderson and Burt, 1978). Plan curvature therefore regulates converging/diverging flow and soil-water content.

Though no systematic comparison of slope shapes and landslides was made for all the reported landslides in Ethiopia, many of the authors (e.g. Gezahegn, 1998; Ayalew, 1999; Ayalew and Yamagishi, 2004; Woldearegay, 2005) have indicated that many of the landslides have taken place on concave areas, with some on planar terrains. According to these authors, the high susceptibility of concave areas to rainfall-triggered landslides is related to the fact that such terrains are associated with: (a) convergent water flows (surface and subsurface) which leads to water pressure build-up, (b) high susceptibility to subsurface erosion (piping), due to concentrated subsurface water flow along pervious layers, and (c) greater thickness of unconsolidated deposits, since such areas are generally zones of material accumulation.

7.4. Influence of slope modification on landslides

Several authors (Varnes, 1978; Greenway, 1987; Selby, 1993; Bell, 1999) indicated that modification of slope geometry through natural or artificial processes could influence the stability of slopes. As indicated by different researchers (e.g. Asrat et al., 1997; Gezahegn, 1999; Ayalew, 1999; Ayenew and Barbieri, 2005; Woldearegay, 2005), the majority of the rainfall-triggered landslides in the highlands of Ethiopia have taken place in areas close to streams/topographic breaks or where there is active gully erosion. The association of landslides with drainage lines which are affected by stream/river incisions and gullying indicates the effects of land degradation and associated erosional processes to the initiation of slope failures in the highlands of Ethiopia.

Some landslides have taken place along road cuts. The association of landslides with road cuts was reported by different authors (e.g. NEDECO 1997; Ayalew, 2000; Ayenew and Barbieri, 2005; Woldearegay, 2005). This implies that there is a need for proper site investigation and design of road cuts in order to mitigation landslides.

7.5. Influence of vegetation cover on landslides

Vegetation influences slope stability by affecting the hydrology and/or mechanical properties of soil slope masses (Greenway, 1987). As suggested by different authors (e.g. Prandini et al., 1977; Greenway, 1987), vegetation cover with deeper and wider roots have positive influence on shallow debris/earth slides, by improving the strength of soils through reinforcement of root networks and buttressing the slope masses by roots anchoring into the underlying bedrock. Prandini et al. (1977) made a review of the behaviour of vegetation on slope stability and concluded that forest reduces the action of the climatic agents on the natural mass, in a manner favourable to slope stability.

Vegetation change could have a very important influence on slope stability in areas where forests are being removed from hillslopes (Selby, 1993). Deforestation of slopes are reported to have been followed by severe shallow landsliding in areas such as New Zealand, Alaska, British Columbia, the Himalayan foothills, and Japan.

In relation to vegetation cover, most of the reported landslides in the highlands of Ethiopia prevailed in areas with sparse or no vegetation with deeper roots. Most of the authors have indicated deforestation and land degradation as a contributing factor to the initiation of landslides in Ethiopia. Temesgen et al. (1999) indicated human intervention on steep slopes for irrigated agriculture and cultivation of shallow rooted permanent crops as factors influencing landslides in Wondogenet area, Ethiopia. Similar observations were reported by NEDECO (1997) and Gezahegn (1998) where the authors mentioned deforestation as one of the factors causing landslides in the Abay Gorge of Ethiopia.

Vegetation cover is believed to have little effect on the shear strength of slope masses with deeper failure surfaces because such instability conditions have depths of failures greater than the general root penetrations of vegetations. However, it could have a positive role on slope stability by influencing the hillslope hydrological processes, as is stated by Prandini et al. (1977), even for failure surfaces deeper than the general depths of penetrations.

With regard to the effects of soil/water conservation on landslide initiations, Nyssen et al. (2002) reported the increase in slope movements in the early stages of vegetation growth. This is due to the fact that infiltration of rainwater could be enhanced. With the on-going nation-wide natural resources management (which involves construction of deep-trenches, terraces and associated afforestation work), groundwater recharge is expected to increase on hillslopes which aggravate slope instability.

8. IMPLICATIONS FOR FURTHER RESEARCH AND DEVELOPMENT IN ETHIOPIA

In Ethiopia individual landslides usually affect certain local areas and individual landowners, and, so far, no comprehensive inventory of losses due to such hazards has been made to justify their economic, social and environmental significance. As a result, damage resulting from landslide hazards has not generally been recognized as a problem of national importance. In order to address landslide issues in the country, there is strong need for further research and development work in Ethiopia.

8.1. Implications for further research

Considering the scale of the landslide problems and the socio-economic development in the country, the on-going research on landslides is very negligible. There is a strong need to initiate research on: (a) landslide hazard mapping and loss assessment, (b) landslide hazard forecasting and monitoring, and (c) cost-effective landslide mitigation (remedial) measures.

The following recommendations can be given for further landslide research in Ethiopia:

Rainfall is the main triggering factor of landslides in the highlands of Ethiopia. There is, therefore, a need for: (a) establishing landslide-groundwater and landslide-rainfall relationships, and (b) evaluation of the soil/rock-water interactions. These are essential for proper hazard mappings and predictions as well as for developing early warnings of landslide hazards (at regional and national levels).

For better understanding of landslide initiations and hence improving the quality of landslide hazard mapping and predictions, all recent landslides, which have occurred in a specified period of time, have to be mapped. Furthermore, the failure circumstances of each new landslide should be studied as this will improve our knowledge on the triggering mechanisms and controlling parameters of landslides.

Evaluation of the failure mechanisms of the so far reported medium to large-scale rockslides were based on the distributions of slope masses and field observations of features indicative of failure mechanisms. Our understanding of the initiations of failures of such rockslides could be improved through further research which includes field monitoring and numerical modeling.

Most of the recorded landslides were found to be associated with deforestation and gully developments. This process is expected to be aggravated by climate change. It is, therefore, advisable to consider landslide mitigation as part of land management in the country.

Landslides are geological in nature. As a result, proper understanding of the geological setting (lithological and structural), terrain characteristics, hydrological condition (surface and groundwater), land use/vegetation status, and other geomoprhological processes is crucial for understanding the failure mechanisms as well as for designing appropriate mitigation measures of landslides.

With the assumption that there exists a direct relationship between the occurrence of landslides and the characteristics of rainfall (such as intensity, duration and antecedent rainfall), it is necessary to develop nationwide landslide predictions through establishing rainfall-landslide relationships.

8.2. Implications for development works

There are a number of landslide-related issues that need to be addressed by the industry:

The hilly terrains of the highlands of Ethiopia remain highly fragile environments in terms of slope stability whereby any external factors such as heavy rainfall and/or excavations could trigger landslides. It is, therefore, advisable to undertake proper landslide hazard assessment and risk analysis prior to development planning and constructions.

Landslide hazards are affecting many of the roads in the country and different organizations (e.g. Ethiopian Geological Surveys and Ethiopian Road Authority) are involved in the investigation and design of mitigation measures. Though this effort is encouraging, landslide investigations and design of mitigation measures require clear understanding of the processes and factors leading to slope failures based on multi-disciplinary approach.

For a successful landslide risk management program, there need to be policies, legislation and guidelines related to, among others: (a) building codes on excavation, construction and grading, and (b) land-use regulations and management of landslide-prone areas.

Ethiopia is embarking massive road construction which links the different Kebeles in the country. Many of these road pass through potentially unstable areas. There is, therefore, a strong need to evaluate the landslide condition of these roads.

The planned railway routes in Ethiopia pass through the hilly and mountainous terrains of the highlands of Ethiopia. It is therefore, critical, to make comprehensive evaluation of potential shallow as well as deep-seated slope deformation along these routes.

As part of the on-going massive natural resources management effort in the country, soil and water conservation practice is being implemented in Ethiopia. Such practice was being implemented in Tigray (northern Ethiopia) and this has resulted in groundwater recharge. However, such practice in Tigray has induced landslides though in limited areas. Soil and water conservation in volcanic terrains of the highlands of Ethiopia is expected to have more effect on groundwater recharge (due to the high amount of rainfall in the central, southern and western parts of the country). This could lead to initiations of landslides in the highlands of Ethiopia. Though soil and water conservation practice need to be promoted, it should be well planned. As a mitigation measure, there is a need to integrate soil and water conservation works with water harvesting (drainage) for multi-purpose use, as stated by Woldearegay (2005).

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