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LANDSLIDE HAZARD ZONATION USING EXPERT EVALUATION TECHNIQUE: A CASE STUDY OF THE AREA BETWEEN GOHATSION TOWN AND THE ABAY (BLUE NILE) RIVER, CENTRAL ETHIOPIA

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ABSTRACT: The area between Gohatsion town and the Abay River in Central Ethiopia is witnessing severe problems of landslides during rainy seasons. These landslides in the area affect the safe functioning of the road, which is an essential link between Addis Ababa and the northwestern part of the country. In the present study, an attempt is made to delineate the area into landslide hazard zones (LHZ). The landslide hazard zonation was carried out by "Landslide Hazard Evaluation Factor" (LHEF) rating scheme. The LHEF is an expert evaluation technique that is based on the observational past experience gained over causative factors and their contribution for instability of slopes in the area. The causative factors responsible for landslide activity, which were considered during the present study, are: relative relief, slope morphometry, geology, groundwater and land use/ land cover. The information pertaining to these causative factors was collected from the field and analyzed as per the LHEF scheme. The evaluated LHZ revealed that most of the study area falls within the moderate and high hazard zones. The existing road that links Addis Ababa with the northwestern part of the country mostly passes through high hazard zones and some of it passes through moderate hazard zones. This seems to be the main reason for frequent landslides along the road during the rainy season. Thus, it is imperative to conduct detailed investigations to suggest proper remedial measures for slope stabilization along the road section or to realign the road section to avoid such critical slope sections.

Key words/phrases: Hazard evaluation, hazard zonation, landslide, landslide causative factors, slope stability

INTRODUCTION

Landslides are significant natural hazards in mountainous terrain all around the world. Such landslides cause hundreds of millions of dollars in damage, and hundreds of thousands of death and injuries each year (Dai *et al.*, 2002; Kanungo *et al.*, 2006; Pan *et al.*, 2008). The incidents of landslides and other types of mass movements have accounted not only for the loss of life of people and animals but have also damaged or destroyed residence and industrial areas in addition to agricultural and forest land (Turner and Schuster, 1996). Therefore, it is mandatory to identify such areas, which may have a potential for landslide before implementing any developmental activity in mountainous terrain. Such delineation of hazardous zones may facilitate in evolving proper mitigation measures for critical unstable areas or such hazardous areas may be avoided to minimize the threat of damage or destruction to the developmental activities (Anbalagan, 1992; Pan *et al.*, 2008).

Landslides of various forms are common in northern, western and southern highlands of Ethiopia (Engdawork Mulatu *et al.*, 2009). The Abay River Basin in Ethiopia witnesses a wave of landslides both small and large scale during the rainy season. Such landslides and rock falls have been identified starting from some 150 km downstream of Lake Tana up to the Sudan border (Lulseged Ayalew and Yamagishi, 2004). The present study area, which includes the main road from Gohatsion Town to the Abay River Bridge, manifests problems of landslides and rock fall every year during the main rainy season. Such landslides and rock falls in the said area have resulted into damage of infrastructure. These landslide activities in the area also disrupt the safe functioning of the existing road, which is

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an important link between the capital city (Addis Ababa) and the northern part of the country. Various types of slope stability problems have been reported in this area. These include, deep-seated rotational slumps, massive translational slides, progressive creep movements, debris and mud flows and rock falls/slides all along the natural valley slopes and road cuts (Lulseged Ayalew and Yamagishi, 2004; Jemal Saed, 2005; Henok Woldegiorgis, 2008; Mulugeta Beyene, 2013; Shiferaw Ayele *et al.*, 2014).

In order to assess landslide hazard several government and research institutions worldwide have spent substantial resources. This effort perhaps is an attempt to investigate and delineate spatial distribution of such landslide hazards (Guzzetti *et al.*, 1999). Several techniques have been developed worldwide to demarcate and investigate landslide hazard zones. One such technique is expert evaluation approach, which can further be classified, into landslide inventory mapping and heuristic approaches (Fall *et al.*, 2006). In landslide inventory approach, various past landslide events are recorded for their location and dimensions (Dai and Lee, 2001; Dai *et al*., 2002; Fall *et al*., 2006). The limitation of this method is that it provides susceptibility for those areas where past landslide activities were recorded but it cannot provide any information for future potential areas for landslide activity (Casagli *et al*., 2004). The heuristic expert evaluation techniques are based on judgment of a geoscientist where he assigns numerical ratings to various causative factors which have an influence on the landslide occurrence (Dai and Lee, 2001; Fall *et al*., 2006; Raghuvanshi *et al.*, 2014). There are several expert evaluation techniques available for landslide hazard zonation. These include techniques proposed by Anbalagan (1992), Pachauri and Pant (1992), Sarkar *et al*. (1995), Turrini and Visintainer (1998), Guzzetti *et al*. (1999). Expert evaluation techniques are most versatile for landslide hazard zonation (Turrini and Visintainer, 1998; Fall *et al*., 2006). These expert evaluation techniques are more practical, simple in application and provide much more realistic results, which are well supported by experience of an expert (Raghuvanshi *et al*., 2014).

The main objective of the present study is to investigate the study area and delineate the various zones of landslide susceptibility and to prepare a landslide hazard zonation map.

MATERIALS AND METHODS

Previous studies

In order to investigate slope stability in the present study area many studies have been carried out in the past by individual researchers and institutions. According to Jemal Saed (2005), the Ethiopian Road Authority (ERA) in 1967 investigated the area between Fliklik village and Washa Mikael church. The study mainly concentrated on the slope stability condition of the road where failure of the viaduct occurred. Realignment of the road avoiding the problematic slope section along the viaduct was suggested by these works.

Mesfin Wubshet *et al.* (1994) by using geophysical methods explained material characteristics along the proposed new road alignment section. The Ethiopian Institute of Geological Survey, (EIGS, 1994) carried out a detailed Engineering Geological investigation by utilizing an integrated approach between Gohatsion and Dejen towns. Almaz Gezahegn and Tadesse Dessie (1994) classify slope instabilities in the Abay Gorge and its tributaries in to four types. These are (i) continuously moving granular deposits from the slopes of basalt escarpments, (ii) rotational failure of colluvial soil, (iii) gully erosion and (iv) rock fall and toppling. Based on their investigation they proposed a road realignment, which relatively avoided the landslide hazard zone. Further, as cited in Jemal Saed (2005), the Transport Construction Design Share Company (TCDSCo) carried out detailed geotechnical investigation project along the Gohatsion-Dejen-Debre Markos road in 2003 (TCDSCo, 2003). This study revealed that thick unconsolidated colluvial soil mass was responsible for the damage of the northern parts of the road. Lulseged Ayalew and Yamagishi (2004) described slope failures in the Abay Gorge from the point of view of landscape evolution. In their study, they attempted to relate topographical characteristics with the process of landslide and rock fall. They concluded that slope instability was a part of the mega-forces that shaped the entire Abay River basin and that it also contributed to general landscape evolution. In addition, Jemal Saed (2005) presented an inventory of landslides mainly along the road alignment between Gohatsion and Dejen towns. This inventory on landslides showed 17 critical slope sections. He further attempted a detailed slope stability evaluation on critical slope sections to suggest suitable remedial measures. Oriental/ Japan Engineering Consultants (2008) conducted investigations for the immediate counter measures against landslides and a confirmatory survey on the trunk road project. This study described the landslides that have occurred around Fliklik village, which is located between the Abay River and Gohatsion town. The recommendations made based on the results of this study included proper drainage mechanisms (like open ditches and conduits) and removal of soil material in those sections where there has been overloading. Further, Mulugeta Beyene (2013) conducted research on assessment of slope stability using combined probabilistic and deterministic approach for selected sections along Gohatsion – Dejen route. He assessed stability condition for existing and anticipated worst conditions defined with varied water saturation conditions. The study suggests stability conditions in terms of probability of failure and safety factor. Based on research findings he suggests remedial measures for critical slope sections in the area. Recently, Shiferaw Ayele *et al.* (2014) delineated landslide hazard zones in the Gohatsion - Dejen section by utilizing Remote Sensing and GIS approach. For the study the causative factors, which were considered, were: slope, structures, aspect, geology, groundwater condition, drainage, and land use/ land cover. The landslide hazard zone map prepared was validated with the past landslide activities in the study area and it was found that 67% of the past landslide locations lie within the maximum hazard zone delineated by this study.

The study area

The present study area falls between Gohatsion town and the Abay River in Central Ethiopia. The area forms a part of the Abay River basin and is geographically defined by co-ordinates 38°9′ E – 38°17′E to 10°00′N – 10°06′N. The study area is located 185kms north of Addis Ababa on the main road that connects Addis Ababa to Bahir Dar town through Debre Markos and covers a total surface area of 89 km^2 (Fig. 1).

The study area receives an annual rainfall in the range of 1400–2000 mm and the temperature varies between 14°C to 20°C (recording period 1997 to 2006) Oriental/Japan Engineering Consultants, 2008). The study area is located within the Abay gorge and has a rugged topography. The maximum elevation is 2542 m.a.s.l (around Gohatsion town) and the minimum elevation is 1023 m.a.s.l. at the Abay River Bridge. The drainage pattern is of dendritic type (Fig. 1) that mainly follows the weakness zones of the valley. Further, the 'Seismic Risk Map' produced by Laike Mariam Asfaw (1986) for a hundred year return period and 0.99 probability shows that the study area falls within 7 MM scale. Since the present study area falls on the main Ethiopian Rift margin and has been placed in 7 MM intensity scale, it is seismically an active area. The study area is sparsely vegetated with grass growth at places. The grasslands are mainly found on the plateau part of the study area. Similarly, grass covered with random growth of thorny *acacia* trees is specific to steep areas.

Geology of the study area

The stratigraphic succession in the study area is dominated by sedimentary formations formed for the most part within the Mesozoic Era (Getaneh Assefa, 1981; Russo *et. al.*, 1994). Beyond these, at the extreme base, exposed near the riverbed, Late Paleozoic clastic sediments do occur (Jepson and Athearn, 1964; Enkurie Dawit and Bussert, 2009) while at the top the Mesozoic sedimentary succession is covered by Tertiary volcanic rocks. A succession of about 1200 m thickness with a nearly horizontal stratification is well exposed in the study area (Figs 2 and 3).

Close to the Abay river a thick sequence of sandstones known as the Lower Sandstone Unit (Adigrat Sandstone Unit) unconformably overlies Paleozoic sediments. In the study area, the former is about 300 m thick. This unit is made up of sub-horizontal layers of fine-grained sandstone intercalated with reddish mudstones and siltstones in its lower part. In the upper reaches, the layer thickness increases up to 1m and is characterized by angular to sub angular medium to coarse grained sandstones with planar cross bedding. The upper most part (about 40m thick) is constituted of horizontal layers of greenish clays and fine siltstones, with 10–20 cm thick beds, alternating with low-angle cross-bedded siltstones (Russo *et al.*, 1994). Structurally the unit has three well-developed joint sets, the bedding plane that is nearly horizontal and other two sets trending NW and NE, respectively.

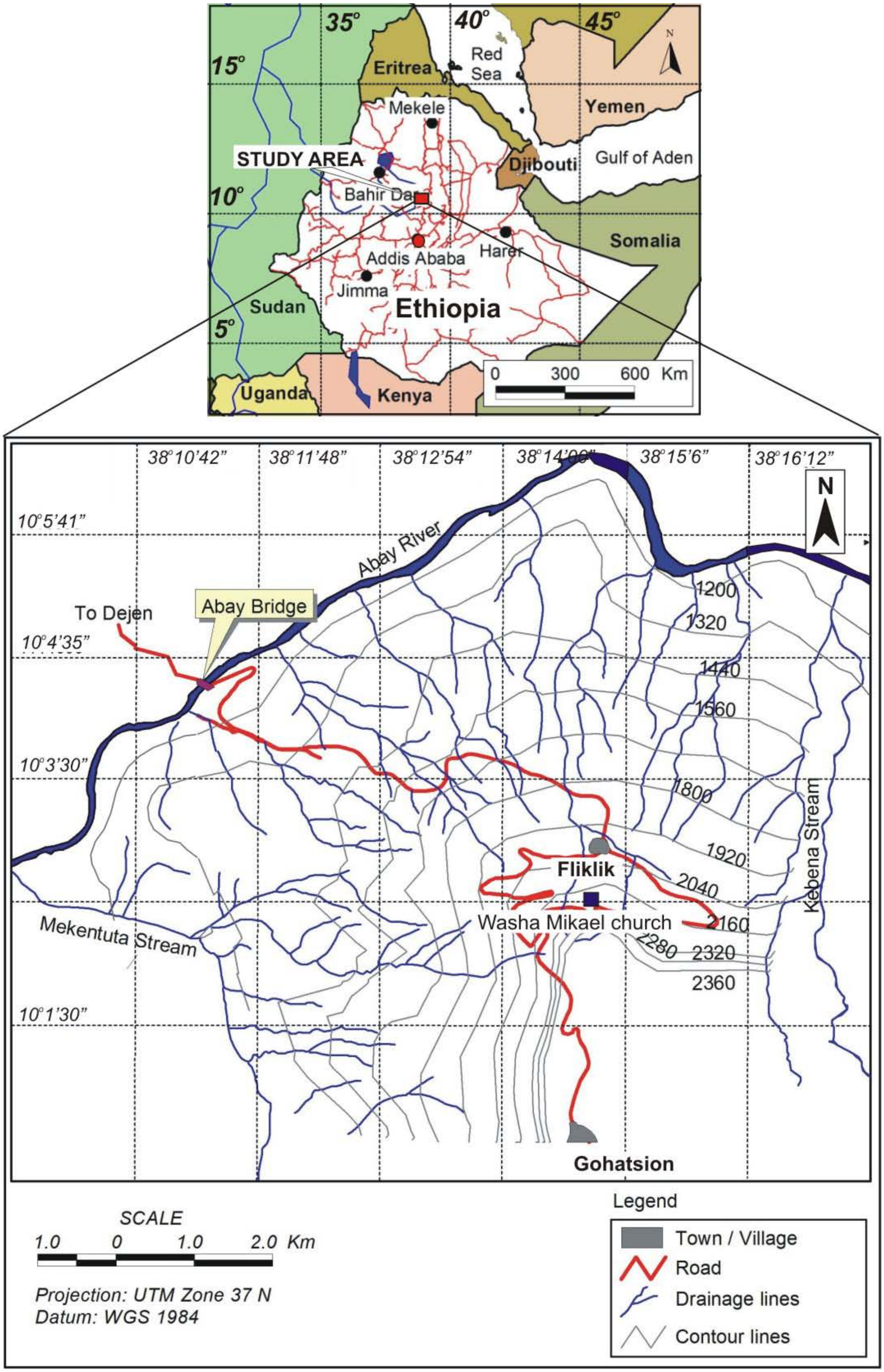

Figure1. Location map of the study area.

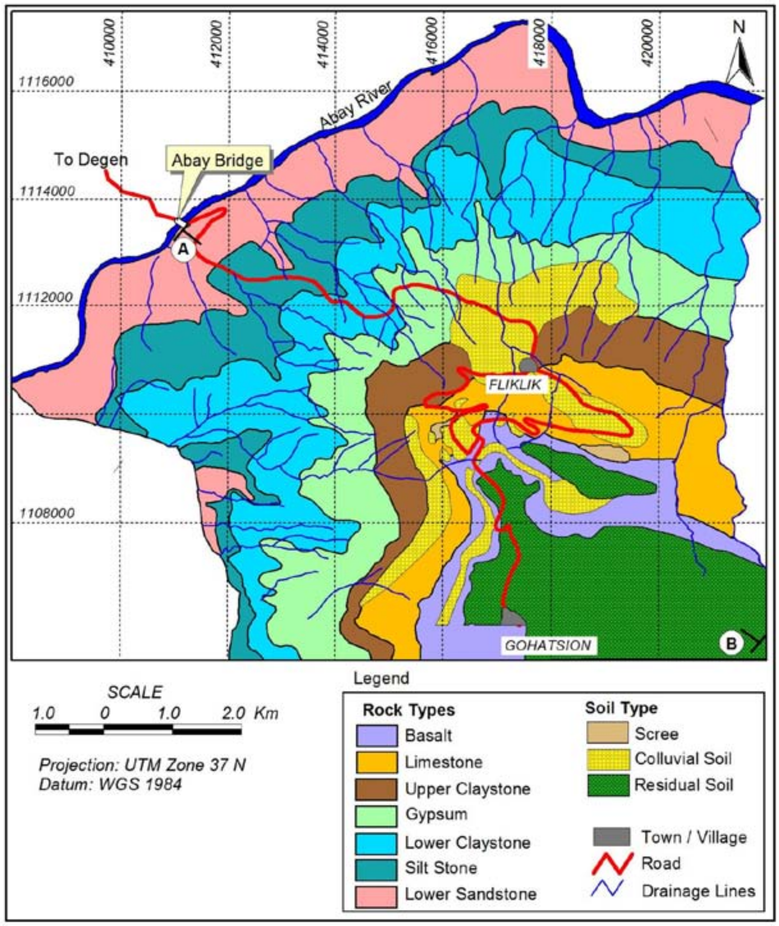

Figure 2. Rock and soil types in the study area.

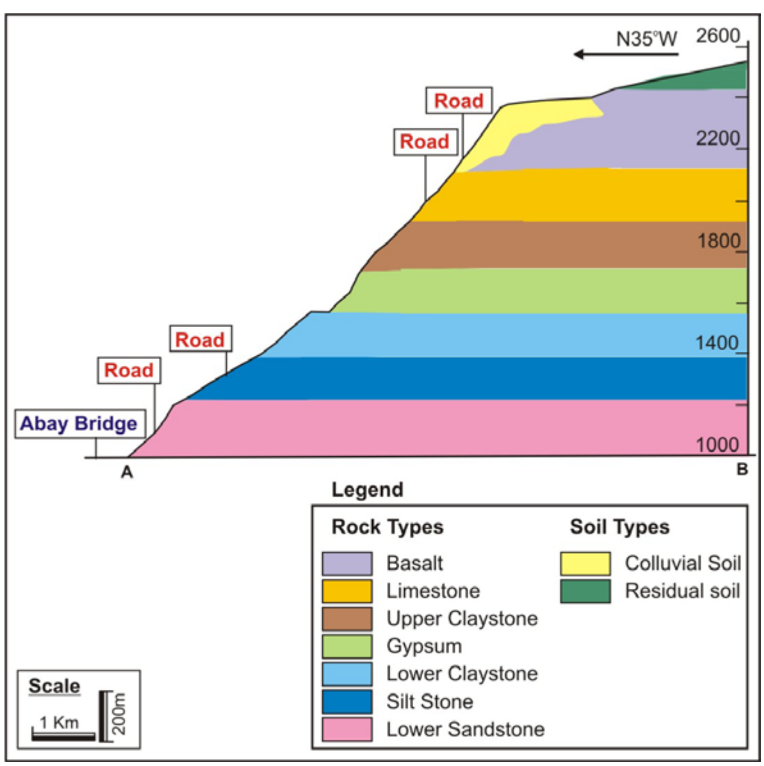

Figure 3. Geological cross section along A-B in Figure 2.

The Lower Sandstone Unit is overlain by what has been formally defined as the Gohatsion Formation (Getaneh Assefa, 1981). The Formation is more than 440 m thick and is made up of argillaceous, gypsiferous and calcareous sediments. The Formation is divided into four informal members, namely: the Mudstone Member, the Lower Claystone Member, the Gypsum Member and the Upper Claystone Member (Getaneh Assefa, 1981). The mudstone member in addition to the common mudstones has siltstones. The mudstone is mostly yellowish green to brownish grey in colour. The siltstones are is well indurated, with alternating, thickly laminated and cross-laminated beds. The Member is generally horizontally bedded, resting on sandstones with closely spaced minor vertical joints. The siltstones mineralogically consist of orthoclase, quartz, illite, kaolinite and iron oxides (Getaneh Assefa, 1979; Almaz Gezahegn and Tadesse Dessie, 1994).

This argillaceous clastic sedimentary rock, found in between the underlying siltstone and overlying gypsum, is the Lower Claystone Member (Getaneh Assefa, 1981). The unit is 120 m thick and varies in colour from grey, black, red, green to purple. Intercalations of shales are observed within this lithological unit. The presence of soft, weak, and decomposed shales underlying relatively dense limestone and gypsum creates instability of slopes because the shale is very thin and it cannot accommodate the overlying load exerted by both limestone and gypsum.

The Lower Claystone Member is overlain by the 200 m thick Gypsum Member (Getaneh Assefa, 1981). It has a gradational contact with the underlying clay stone unit and is overlain by the Upper Claystone Member. The gypsum rocks are generally white but vary in colour through gray, bluish gray, reddish to black. The variation in colour is due to some ferruginous minerals and organic impurities (Almaz Gezahegn and Tadesse Dessie, 1994). This unit is comprised of two well-developed joint sets trending N30°W and N70°E, respectively. The gypsum is intercalated with thinly bedded shale and dolostones. Weathering in gypsum results in change of colour on the surface and along joint planes whereas, the weathering of shale totally changes it to clay.

The Upper Claystone Member is poorly exposed and is about 100m thick. It is made up of greenish and reddish clay stones sometimes becoming variegated in colour. Rare intercalations of carbonates are also observed within this unit.

The major transgressive deposit in the Abay basin is characterized by marine carbonate rocks, which overlie the Upper Claystone Member of the Gohatsion Formation. These marine carbonates are predominantly made up of limestones while marls also form a significant proportion (Balemwal Atnafu, 2003). The Limestone Unit is about 400 m thick, is generally horizontally bedded and is topped by the Trap series basalts. Highly resistant, limestone dominated cliffs and less resistant marl-dominated gentle slope forming parts can be grossly identified within this carbonate unit. Microfacies investigations on the limestones have indicated quite a variety of carbonate facies ranging from micritic limestones through fossiliferous limestones to oolitic grainstones. (Balemwal Atnafu, 2003). Bedding thickness varies from thin beds (5–30 cm) in the marl-dominated parts to thick beds (0.50–2 m) in the limestone dominated uppermost parts of the unit. The limestone consists of three well-developed joint sets; the bedding plane, which is nearly horizontal, and two other joint systems, one trending NW and the other NE, respectively.

The basalt unit with a total thickness of 300 m unconformably overlies the limestone unit. Oxidation reactions at the surface of the basalt flows have commonly resulted in reddish colourings at the surface. Columnar jointing (with 20–30cm thick columns) is common within the flows at the top of this unit whereas at the bottom the flows are massive with huge blocks being observed in the field.

Methods

For the present study, a systematic methodology was followed. Pre-field work included data collection on topographical and geological maps; meteorological data and other relevant previous study reports from the area were also collected.

For the present study Landslide Hazard Evaluation Factor (LHEF), rating scheme proposed by Anbalagan (1992) has been followed. The LHEF is an empirical expert evaluation rating technique that is based on the observational past experience gained from the study of causative factors and their contribution for instability with conditions anticipated in the study area. The LHEF technique is simple in its application and cost- effective over extensive areas with quite satisfactory results (Turrini and Visintainer, 1998; Raghuvanshi *et al*., 2014). Therefore, this technique has been utilized successfully over the past years by many researchers; such as the works of Gupta *et al*. (1993), Gupta and Anbalagan (1995;

1997), Srivastava *et al.* (2001), Engdawork Mulatu *et al.* (2009) and others.

The LHEF technique considers inherent slope instability causative factors such as slope morphometry, geology, relative relief, groundwater and land use/land cover. The total maximum LHEF rating assigned for various causative factors is 10 out of which lithology, relationship of structural discontinuities with slope, slope morphometry and land use and land cover contributes maximum LHEF rating as 2.0 each whereas, relative relief and groundwater conditions contributes maximum LHEF rating as 1.0 each. The maximum LHEF rating for each inherent causative factor has been further subdivided according to various anticipated conditions. These ratings have been assigned based on the significance and relative contribution of each causative factor on stability condition. The sum total of LHEF ratings for all causative factors gives the total estimated hazard (TEHD). The larger the TEHD value the higher will be the degree of hazard. Thus, based on the TEHD values the study area was divided into zones of various landslide hazards. Later, a Landslide Hazard Zonation (LHZ) map of an area was prepared.

LHZ is a macro zonation technique in which maps are prepared at 1:25000 to 1:50000 scales. LHZ mapping is carried out in two stages; desk study and field investigation. Pre field maps such as lithological, structural, slope morphometry, relative relief, rock outcrop, soil cover and land use land cover maps are prepared during desk study for which aerial photographs or satellite imageries, topographical maps and pre existing geological maps are used. These maps are later utilized/ verified or modified during field investigation as per the actual field observations/ investigations. The observations on various causative factors are made slope facet wise. Slope facet is the land unit, which has more or less similar characteristics of slope showing consistent slope direction and inclination (Anbalagan, 1992; Sharma, 2006). Thus, during the present study, the field investigations were carried out and later the data analysis was made to evolve the landslide hazard in the study area. Later, validation of the LHZ map was carried out with the help of observed past landslides in the area.

Field investigations and data analysis

As a general methodology for LHEF technique, the area of slopes to be covered was divided into individual slope facets (Anbalagan, 1992). For this, purpose a topographic map at a scale of 1:50,000 was utilized. Slope facet boundaries were delineated by major or minor hill ridges, primary and secondary streams and other topographic undulations. In total 139 slope facets were delineated for the present study area (Fig. 4). Later, this slope facet map was used to serve as a base map for the preparation of various intrinsic causative factor maps.

The key causative factors that are relevant for the landslide hazard zonation mapping of a given terrain are geology, slope morphometry, relative relief, lands use and land cover and ground water conditions (Anbalagan, 1992; Lulseged Ayalew *et al*., 2004; Wang and Niu, 2009). These key parameters form the basis of the proposed zonation for spatial categorization of the terrain in terms of landslide vulnerability of varying intensity. For the present study, data/ information pertaining to these causative factors were collected from the field. Later, this data was analyzed slope facet wise and numerical ratings from the standard LHEF table were assigned. The following paragraphs presents elaborate description on the various causative factors as observed/ investigated in the field.

Lithology

The geological map (Fig. 2) represents the distribution of the various rock types and structural setting in the study area. A detailed description of the study area has already been presented under the section Geology section.

Lithology is one of the important causative factors taken into consideration for estimating the total hazard for a given slope facet. According to Anbalagan (1992), rocks that are massive, hard and resistant to erosion such as basalts, granite, quartzite and limestones generally form steep slopes whereas terrigenous sedimentary rocks usually erode easily and thus, are more vulnerable to instability. Thus, the potential of rocks to weathering and erosion processes form the basis of assigning ratings to various sub categories of lithology in LHEF rating scheme. Accordingly, higher ratings are awarded to softer rocks and lower ratings are assigned for hard rocks. In order to account for degree of weathering correction factors has also been provided in LHEF scheme.

The dominant rock types that are present in the study area are basalt, limestone, clay stone, gypsum, siltstone and sandstone. The basalt, siltstone and sandstone types are resistant to erosion and form relatively steep slopes; however, clay stone, gypsum and limestone weather relatively quickly and are prone to instability.

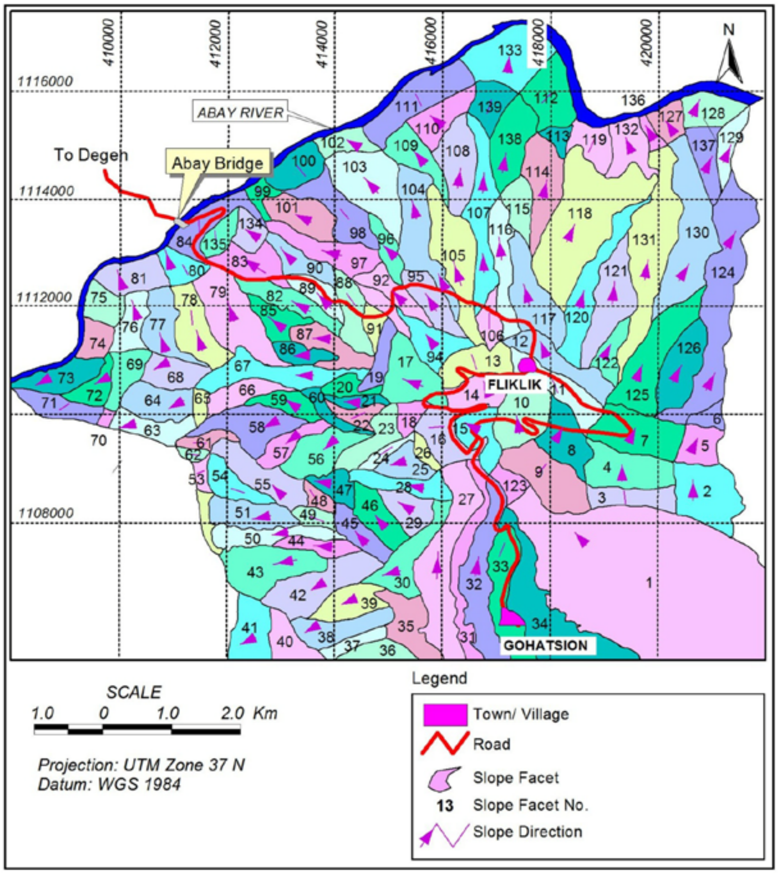

Figure 4. Slope facet map.

In the study area, mainly sedimentary rock formations are exposed, except in the northern part where basalts are exposed. Very strong rocks (100–250 MPa), mainly basalts covers about 5% of the study area whereas, strong rocks (50-100 MPa) comprising Lower sandstone unit and limestone are exposed over 20% of the study area. A large portion, about 40% of the study area is covered by medium strength rocks (25–50 MPa) which comprise mainly siltstone and clay stones. Gypsum constitutes the weak rocks (5–25 MPa) which are exposed over nearly 14% of the study area (Fig. 2). While assigning the ratings for various rock types weathering grade was also considered (Table 1). Soils of various origins are present in the central and northern parts of the study area. Residual soils cover about 11% of the slopes whereas 10% of the slopes are covered by poorly graded colluvial material. A very small portion (<1%) of the study area is covered by collapsible soils (Fig. 2). While assigning ratings for soils, soil depth was also considered (Table 1).

Geological structures

Structural discontinuities mainly include joints and faults. The relationship of slope inclination with orientation of structural discontinuities is an important controlling factor for slope stability (Hoek and Bray, 1981; Anbalagan, 1992). The following relations between slope inclination and structural discontinuity orientation are important in defining slope stability condition (Anbalagan, 1992):

(i) The degree of parallelism between the directions of the discontinuities, or the line of intersection of two discontinuities and the slope.
(ii) The steepness of the plane of the discontinuity, or the plunge of the line of intersection of two discontinuities.
(iii) The difference in the dip of the discontinuity, or the plunge of the line of intersection of the two discontinuities to the inclination of the slope.

When the parallelism between the slope inclination and the dip direction of the discontinuities or the line of intersection of two discontinuities is high, chances for slope failure will increase. Similarly, the greater dip of discontinuities or plunge of the line of intersection of two discontinuities, the higher will be the risk of failure. In addition, the chances of failure will be more when the dip of the discontinuity plane or the plunge of the line of intersection is less than the slope inclination and more than the angle of friction along the discontinuity plane (Hoek and Bray, 1981; Johnson and De Graff, 1991; Anbalagan, 1992; Yoon *et al*., 2002). Thus, these interrelationships between structural discontinuities and slope were considered in LHEF rating scheme and accordingly ratings were mainly awarded based on Romana's (1985) Slope Mass Rating System approach (Anbalagan, 1992).

For the present study the structural discontinuity data, mainly joints and bedding planes were collected from each facet where rock was exposed. Later, this structural data along with slope inclination was analyzed facet wise and respective ratings were awarded from the standard LHEF table. The processed ratings for interrelationships between structural discontinuities and slope as deduced for the present study area are presented in Table 1.

Slope morphometry

Slope morphometry in general represents the inclination of slope. This is an important causative factor, which has much influence on the stability condition of the slope. According to Anbalagan (1992), the category of slope class more or less is controlled by the geomorphological history of the area, whereas slope angle within a given facet is controlled by sequence of localized processes to which the slope facet has been subjected. In LHEF rating system, slope morphometry has been categorized into very gentle slope (<15°), gentle slope (15°–25°), moderately steep slope (26°–35°) and steep slope (36°–40°).

For the present study, slope morphometry was deduced from topographic map at 1:50,000 scale. The slope morphometric map thus produced is presented in Figure 5. The perusal of Figure 5 clearly indicates that the valley slopes adjoining to Abay River and Kebena and Mekentuta streams are steep to very steep at a number of locations. The basaltic cliffs at the southern part of the study area also show steep to very steep morphology. Most of the study area is covered with moderately steep slopes. Gentle to very gentle slopes are seen mainly in the southern and central part of the study area where agricultural activities are widely practiced.

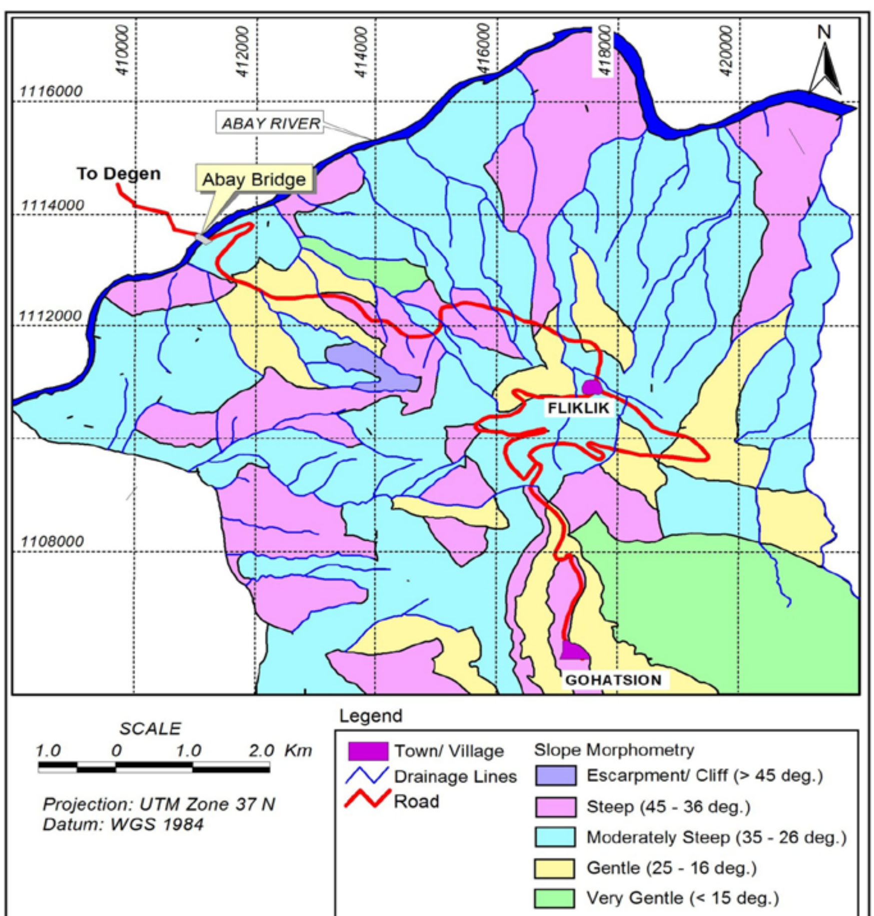

Figure 5. Slope morphometry map of the study area.

In the study area about 50% of the slopes fall under the category of moderately steep (26°–35°) and 25% are steep (36°–45°). The remaining slopes fall under gentle (15°–25°), very gentle (<15°) and escarpment (>45°) categories which account for 14.6%, 9.6% and 0.8%, respectively. The ratings were assigned from the standard LHEF table and the processed results, facet wise, are presented in Table 1.

Relative relief

The elevation difference between the bottom and top of the slope facet defines the relative relief. According to Anbalagan (1992), for LHEF slopes are categorized into low (<100 m), medium (101–300 m) and high (>300 m). Studies have shown that height of the slope has a great influence over the instability of the slope. As the height increases the instability in slope also increases, provided other causative factors are contributing towards instability of slope (Hoek and Bray, 1981; Sharma *et al*., 1995; Raghuvanshi and Nehemia Solomon, 2005).

In the present study area, all the three categories of relative relief are found to be well distributed. A perusal of Figure 6 clearly shows that more than 55% of the area is covered with moderate relief whereas more than 36% is of high relief. Thus, this distribution of relative relief explains by itself that much of the study area is susceptible for slope instability as far as relative relief is concerned. However, as already discussed earlier, instability in slope depends upon various causative factors and it is the collective effect of all causative factors that induces slope failure. The ratings were assigned from the standard LHEF table and the processed results, facet-wise, are presented in Table 1.

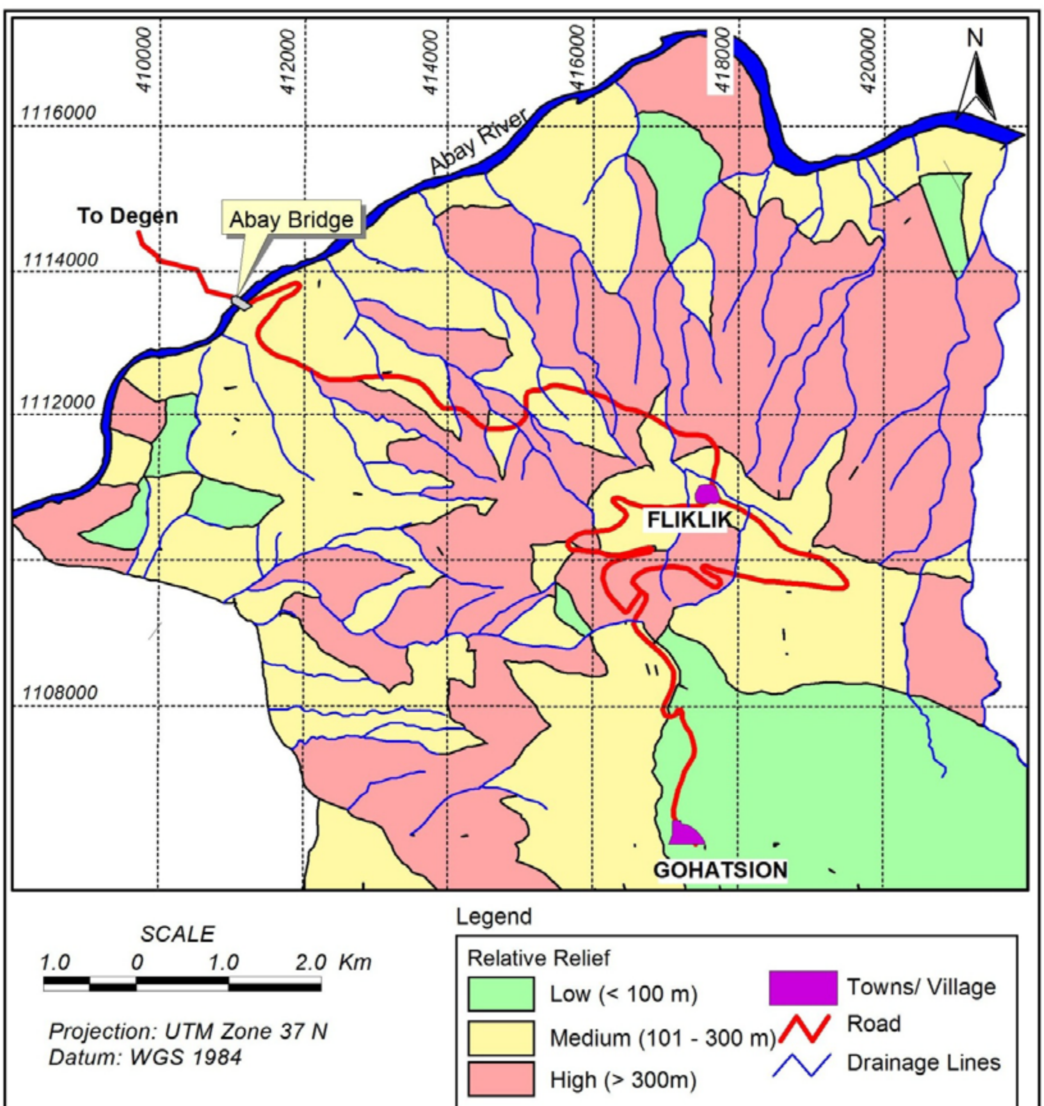

Figure 6. Relative relief map of the study area.

Table1. TEHD **ratings, facet wise, for the study area.**

Facet No.	Geology	Structure	GW Condition	Relief Rating	Land use	Slope morphometry	Summation	TEHD*	Facet No.	Geology	Structure	GW Condition	Relief Rating	Land use	Slope morphometry	Summation	TEHD*
1	1	0.85	0.2	0.3	0.65	0.5	3.5	LH	71	1	1.3	0.2	1	1.5	1.2	6.2	HH
2	1	0.85	0.2	1	1.2	0.8	5.05	LH	72	1	1.3	0	0.3	1.5	1.2	5.3	MH
3	1	0.65	0	0.6	1.2	1.2	4.65	LH	73	1	1.3	0	1	1.5	1.2	6	MH
4	1.2	0.65	0	0.6	2	1.2	5.65	MH	74	1	1.3	0	0.6	1.5	1.2	5.6	MH
5	0.2	0.65	0	1	1.2	1.2	4.25	LH	75	1	1.3	0	1	1.5	1.2	6	MH
6	0.2	0.65	0	0.6	1.5	1.2	4.15	LH	76	1	1.3	0	0.3	1.5	1.2	5.3	MH
7	1	0.85	0	0.6	0.65	0.8	3.9	LH	77	1	1.3	0	0.6	1.5	1.2	5.6	MH
8	1.2	1.3	0.5	0.6	1.2	0.8	5.6	MH	78	1	1.3	0	0.6	1.5	1.2	5.6	MH
9	1.2	1.5	0.2	0.6	2	1.7	7.2	HH	79	1.8	0.85	0	0.6	1.5	0.8	5.55	MH
10	1.2	1.3	0.5	1	1.2	1.2	6.4	HH	80	1.3	0.65	0	0.6	1.5	1.7	5.75	MH
11	1.2	1.2	0	0.6	0.65	1.2	4.85	MH	81	1.3	0.85	0	0.6	1.5	1.7	5.95	MH
12	1.2	1.3	0	0.6	1.2	1.2	5.5	MH	82	1.3	1.2	0	1	1.2	0.8	5.5	MH
13	1.3	1.3	0	0.6	0.65	0.8	4.65	LH	83	1.3	1.2	0	0.6	0.65	0.8	4.55	LH
14	0.2	1.3	0	0.6	1.5	1.2	4.8	LH	84	1.3	1.2	0	0.6	1.5	1.2	5.8	MH
15	1.2	1.3	1	1	1.2	1.2	6.9	HH	85	1.8	0.65	0	0.6	1.5	1.2	5.75	MH
16	1.2	1.3	0.5	1	1.5	1.2	6.7	HH	86	1.8	0.65	0	0.6	1.5	1.2	5.75	MH
17	1.8	1.3	0	1	1.5	1.2	6.8	HH	87	0.3	1.2	0	1	2	2	6.5	HH
18	0.31	0.85	0.5	0.6	2	1.7	5.96	MH	88	0.5	1.2	1	1	1.5	1.7	6.9	HH
19	1.8	1.3	0	1	1.5	1.7	7.3	HH	89	0.5	1.2	0	0.6	1.5	1.7	5.5	MH
20	1.3	1.3	0	1	1.5	1.2	6.3	HH	90	1.8	1.2	0.5	0.6	1.2	0.8	6.1	HH
21	1.3	0.65	0	1	1.5	1.2	5.65	MH	91	1.6	1.3	0.2	0.6	2	1.7	7.4	HH
22	1.3	0.85	0.2	1	1.5	1.2	6.05	MH	92	0.6	1.3	0.2	1	1.5	1.2	5.8	MH
23	1.3	0.85	0.2	1	1.5	1.2	6.05	MH	93	0.6	1.3	1	0.6	1.5	1.7	6.7	HH
24	1.3	1.3	0.2	1	1.5	1.2	6.5	HH	94	1.8	1.3	0	1	2	1.2	7.3	HH
25	1.3	0.3	0.5	0.6	1.5	1.7	5.9	MH	95	1	1.3	0	0.6	1.5	1.7	6.1	HH
26	0.2	2	0.2	0.3	1.5	1.7	5.9	MH	96	1.3	0.65	0	0.6	1.2	1.2	4.95	LH
27	0.2	1.3	0.8	0.6	1.5	1.2	5.6	MH	97	1	1.3	0	1	1.2	0.5	5	LH
28	0.2	1.3	0.5	1	1.5	0.8	5.3	MH	98	1.3	0.85	0	0.6	1.2	1.2	5.15	MH
29	0.2	1.3	0.5	0.6	1.5	1.7	5.8	MH	99	1.3	0.65	0	0.6	1.5	1.7	5.75	MH
30	1.8	0.65	1	0.6	1.2	1.2	6.45	HH	100	1.3	0.65	0	0.6	1.5	1.7	5.75	MH
31	0.5	1.3	0	0.6	1.5	1.7	5.6	MH	101	1.3	0.85	0	0.6	1.2	1.2	5.15	MH
32	1.2	1.3	0.5	0.6	2	0.8	6.4	HH	102	1.3	0.85	0	0.6	1.5	1.2	5.45	MH
33	1	1.3	0.5	0.3	1.5	1.7	6.3	HH	103	1.3	0.65	0	1	1.5	1.2	5.65	MH
34	1	1.3	0.5	0.3	0.65	0.8	4.55	LH	104	1.8	1.3	0.2	1	1.2	1.2	6.7	HH
35	1.2	0.85	0	0.6	1.5	0.8	4.95	LH	105	1.8	1.3	0.5	1	1.5	1.2	7.3	HH
36	1.2	1.3	0.5	1	1.5	1.7	7.2	HH	106	1.8	1.3	0	0.6	1.5	0.8	6	MH
37	1.2	2	0	1	1.5	1.7	7.4	HH	107	1.8	1.3	0	1	1.5	1.7	7.3	HH
38	1.2	0.85	0	1	1.5	1.7	6.25	HH	108	1.8	1.3	0	0.6	1.2	1.7	6.6	HH
39	0.2	0.65	0	1	1.5	0.8	4.15	LH	109	1.3	1.3	0	0.6	1.5	1.2	5.9	MH
40	1.8	0.65	0	0.6	1.5	1.2	5.75	MH	110	1.3	1.3	0	0.6	2	1.2	6.4	HH
41	1.8	0.65	0	0.6	1.5	1.2	5.75	MH	111	1.3	0.65	0	0.6	2	1.2	5.75	MH
42	1.8	0.65	0	1	1.5	1.2	6.15	HH	112	0.2	1.3	0	1	1.2	1.7	5.4	MH
43	1.8	0.65	0.2	1	1.5	1.7	6.85	HH	113	1.4	0.85	0	0.6	1.5	1.2	5.55	MH
44	1.8	1.3	0.2	0.6	1.5	1.2	6.6	HH	114	1.4	0.65	0	1	1.2	1.2	5.45	MH
45	1.8	1.3	0.5	1	1.5	1.2	7.3	HH	115	1.4	1.3	0	0.6	1.5	1.2	6	MH
46	1.2	0.85	0	1	2	1.2	6.25	HH	116	1.4	1.3	0	1	1.2	1.2	6.1	HH
47	1.2	1.3	0	0.6	2	1.2	6.3	HH	117	1.4	1.3	0	1	0.65	0.8	5.15	MH
48	1.2	1.3	0	0.6	2	1.2	6.3	HH	118	1.4	1.3	0	1	1.2	1.2	6.1	HH
49	0.2	0.65	0.5	0.6	2	1.7	5.65	MH	119	1.3	0.85	0	0.6	1.2	1.2	5.15	MH
50	1.3	1.3	0	0.6	1.5	1.2	5.9	MH	120	1.8	0.85	0	1	1.2	1.2	6.05	MH
51	1.3	1.3	0	0.6	1.5	1.7	6.4	HH	121	1.8	0.65	0	1	1.5	1.2	6.15	HH
52	1.3	1.3	0	0.6	1.2	1.7	6.1	HH	122	1.2	0.85	0	0.6	1.5	1.2	5.35	MH
53	1.3	1.3	0	0.6	1.5	1.7	6.4	HH	123	1.2	1.3	0.5	0.3	1.5	1.7	6.5	HH
54	1.3	1.3	0	0.6	1.5	1.7	6.4	HH	124	1.8	0.85	0	1	1.5	1.2	6.35	HH
55	1.3	0.85	0	1	1.5	1.7	6.35	HH	125	0.8	0.85	0.5	1	0.65	0.8	4.6	LH
56	1.2	1.3	0.2	1	1.5	1.2	6.4	HH	126	1.8	0.85	0.2	1	1.5	1.2	6.55	HH
57	1.2	1.3	0.5	0.6	1.5	1.2	6.3	HH	127	1.3	0.85	0	0.6	1.5	1.7	5.95	MH
58	1.2	1.3	0.2	1	1.5	1.2	6.4	HH	128	1.3	0.85	0	0.6	1.5	1.7	5.95	MH
59	1.8	0.65	0	0.6	1.2	1.7	5.95	MH	129	1.3	0.65	0	0.6	1.5	1.7	5.75	MH
60	0.2	0.85	0	1	1.5	1.2	4.75	LH	130	1.8	0.65	0	1	1.5	1.7	6.65	HH
61	0.2	0.85	0	0.6	1.5	1.2	4.35	LH	131	1.8	0.65	0	1	1.2	1.2	5.85	MH
62	0.2	0.85	0	0.6	1.5	1.2	4.35	LH	132	1.3	0.65	0	0.6	1.2	1.2	4.95	LH
63	0.2	0.85	0	0.6	1.5	1.2	4.35	LH	133	1.3	0.65	0	1	1.5	1.7	6.15	HH
64	1	1.3	0	0.6	1.5	1.7	6.1	HH	134	1.3	0.65	0	0.6	1.5	1.2	5.25	MH
65	1	1.3	0	0.6	1.5	1.7	6.1	HH	135	1.5	0.85	0.2	0.6	2	1.2	6.35	HH
66	1	1.3	0	0.6	1.5	1.7	6.1	HH	136	1.3	0.85	0	0.6	1.5	1.2	5.45	MH
67	1	1.3	0.5	0.6	1.5	1.7	6.6	HH	137	1.3	0.65	0	0.3	1.5	1.7	5.45	MH
68	1	1.3	0.2	0.3	1.5	1.2	5.5	MH	138	0.2	1.3	0	0.3	1.2	1.7	4.7	LH
69	1	1.3	0.2	0.6	1.5	1.2	5.8	MH	139	1.3	1.3	0	0.3	1.5	1.7	6.1	HH
70	1	1.3	0.2	0.6	1.5	1.2	5.8	MH									

* HH – High Hazard Zone, MH – Moderate Hazard Zone, LH – Low Hazard Zone

Land use and land cover

The type of land use/ land cover to a greater extent controls the stability of a slope: as the areas that are barren are more prone to erosion and weathering (Turrini and Visintainer, 1998). Barren and sparsely vegetated lands are more prone to soil erosion and slope failures (Anbalagan, 1992; Wang and Niu, 2009). Cultivation is the main land use activity, which is performed on the hill slopes. For cultivation purposes, land is generally made flat which is considered to be stable.

In the present study area more than 63% of the area is sparsely vegetated and about 20% area is moderately vegetated (Fig. 7). Thus, from this it is reasonable to deduce that much of the study area is susceptible to landslide events as far as land use/ land cover is concerned. Thus, based on the land use/ land cover type, facet-wise ratings were assigned from the standard LHEF table (Table 1).

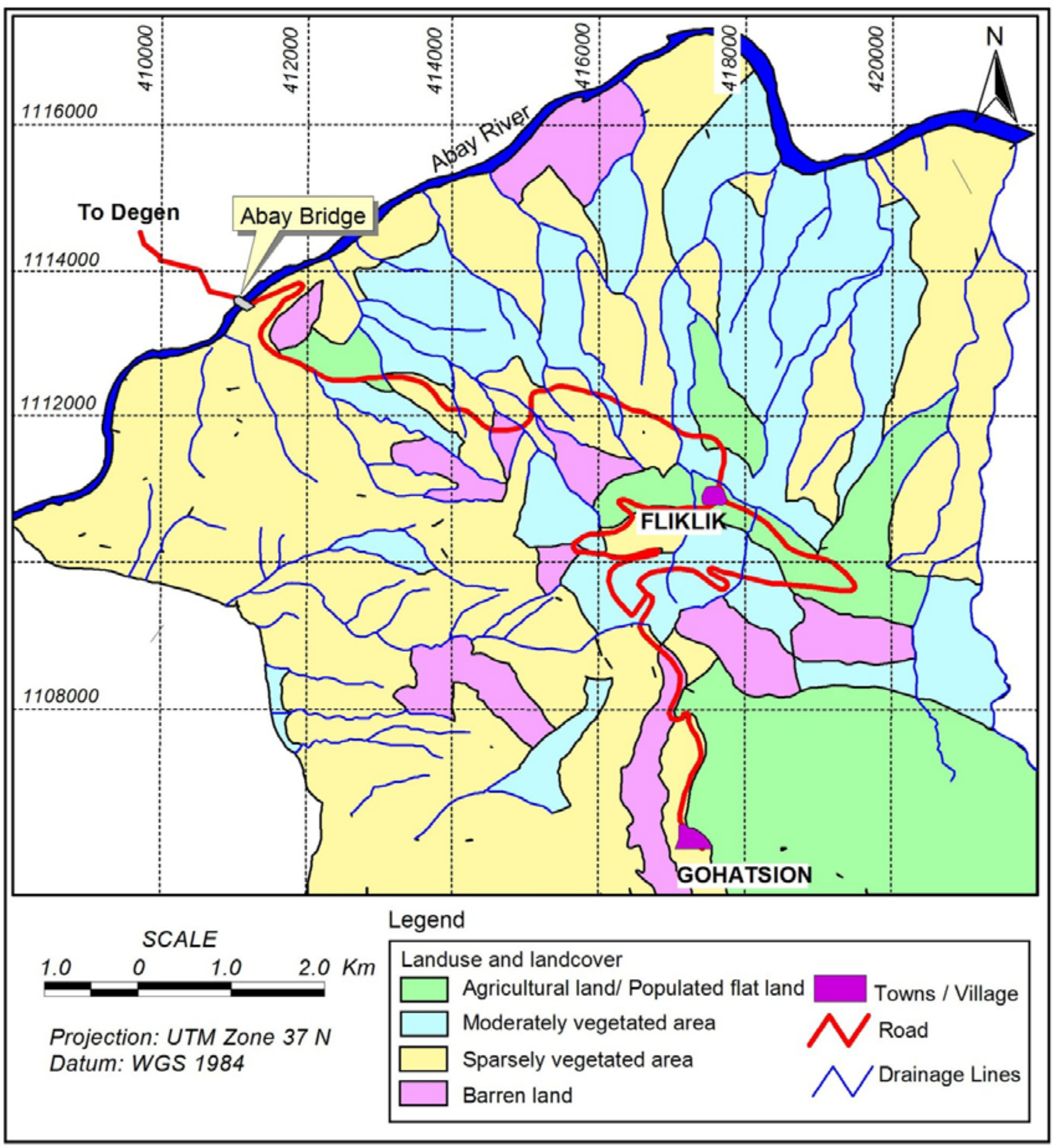

Figure 7. Land use and land cover map of the study area.

Shallow Groundwater conditions

One of the important causative intrinsic parameter for slope stability is groundwater (Hoek and Bray, 1981). It is difficult to have direct observations of groundwater behaviour within slopes when landslide hazard zonation/ mapping is carried over extensive areas. Therefore, for rapid assessment, surface traces of groundwater like water flowing, dripping, wet and damp are useful in understanding the role of groundwater towards slope instability (Anbalagan, 1992).

For the present study, the groundwater traces as mentioned above were observed facet-wise. Besides looking for surface traces such as; flowing, dripping, wet and damp surfaces other water marks like algal growth were also observed on the slopes. These surface traces give some idea about the degree of saturation of slope for prolonged periods of time. It may be possible that at the time of field investigation the slope demonstrates dry condition only, without any traces of water. Thus, while assigning ratings all these points were considered (Table 1). The study area dominantly shows dry and damp conditions (Fig. 8). The damp conditions were generally observed in vegetated areas where as the flowing, wet and dripping conditions were observed at relatively fewer places.

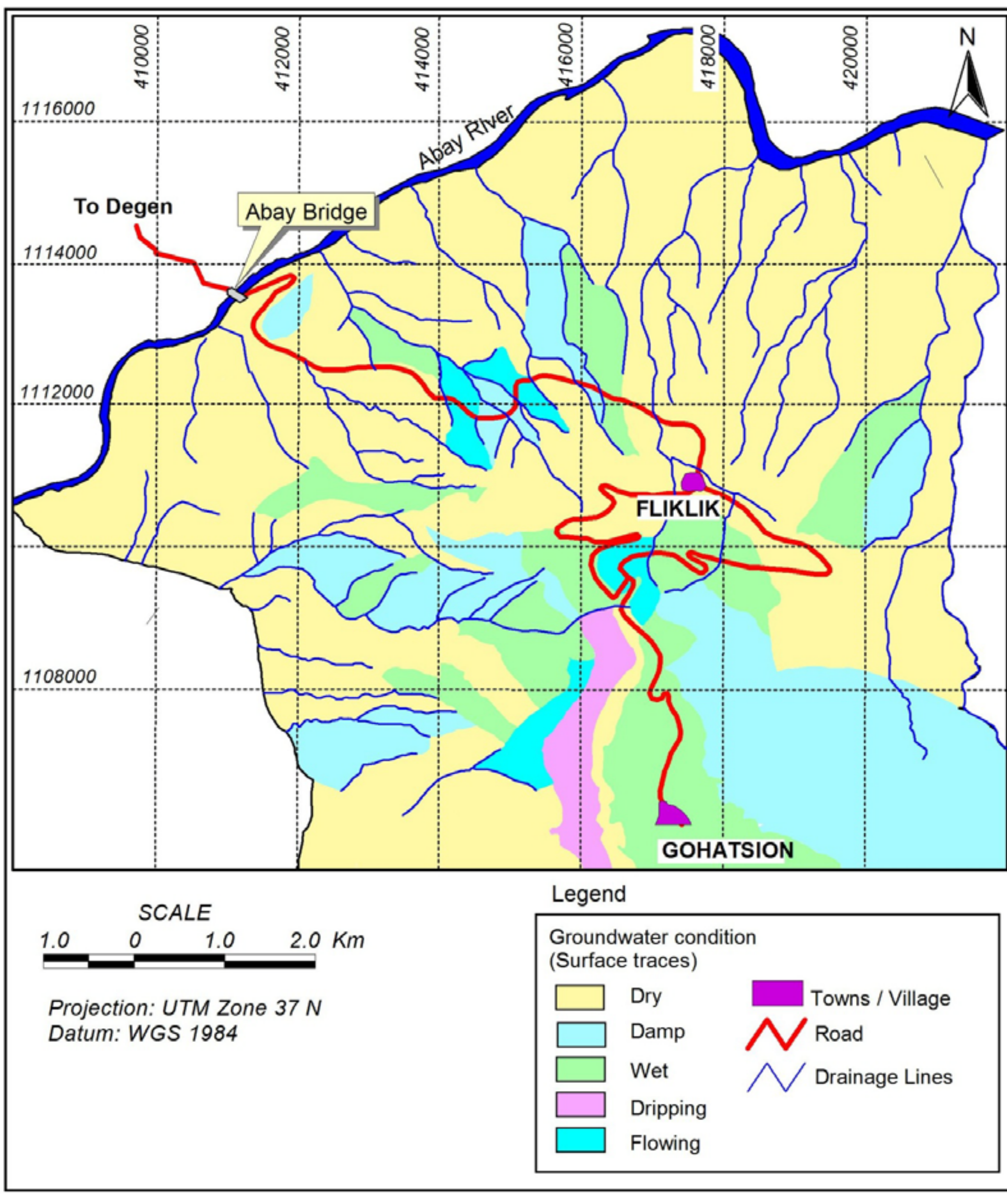

Figure 8. Groundwater conditions (surface traces) map of the study area.

RESULTS AND DISCUSSION

According to Anbalagan (1992) the net probability of instability within a given slope facet is determined through total estimated hazard (TEHD). The TEHD for each individual facet will be the sum total of ratings for all causative factors. Therefore, each individual slope facet, based on its computed TEHD value, was categorized into five landslide hazard zones, namely; very high hazard (VHH), high hazard (HH), moderate hazard (MH), low hazard (LH) and very low hazard (VLH).

Landslide hazard evaluation

For the present study observation/ data was collected for all causative factors and TEHD was computed for each individual slope facet (Table 1). The entire study area falls into three hazard zones - low hazard (LH), moderate hazard (MH) and high hazard (HH) where as very low hazard (VLH) and very high hazard (VHH) zones were not at all observed in the present study area (Fig. 9).

The low hazard (LH) zones are mainly located in southern part of the study area where there is populated land and farmlands are present. The central and southeastern part of the area also falls in this hazard zone. There are wide presence of farmland and populated land. Besides, at some distributed places also this hazard zone is depicted in the study area. Thus, out of 139 slope facets only 20 facets fall in low hazard (LH) zone covering 14.4% of the total study area. These areas are relatively flat or low relief, mainly used for the purpose of agriculture and dwelling.

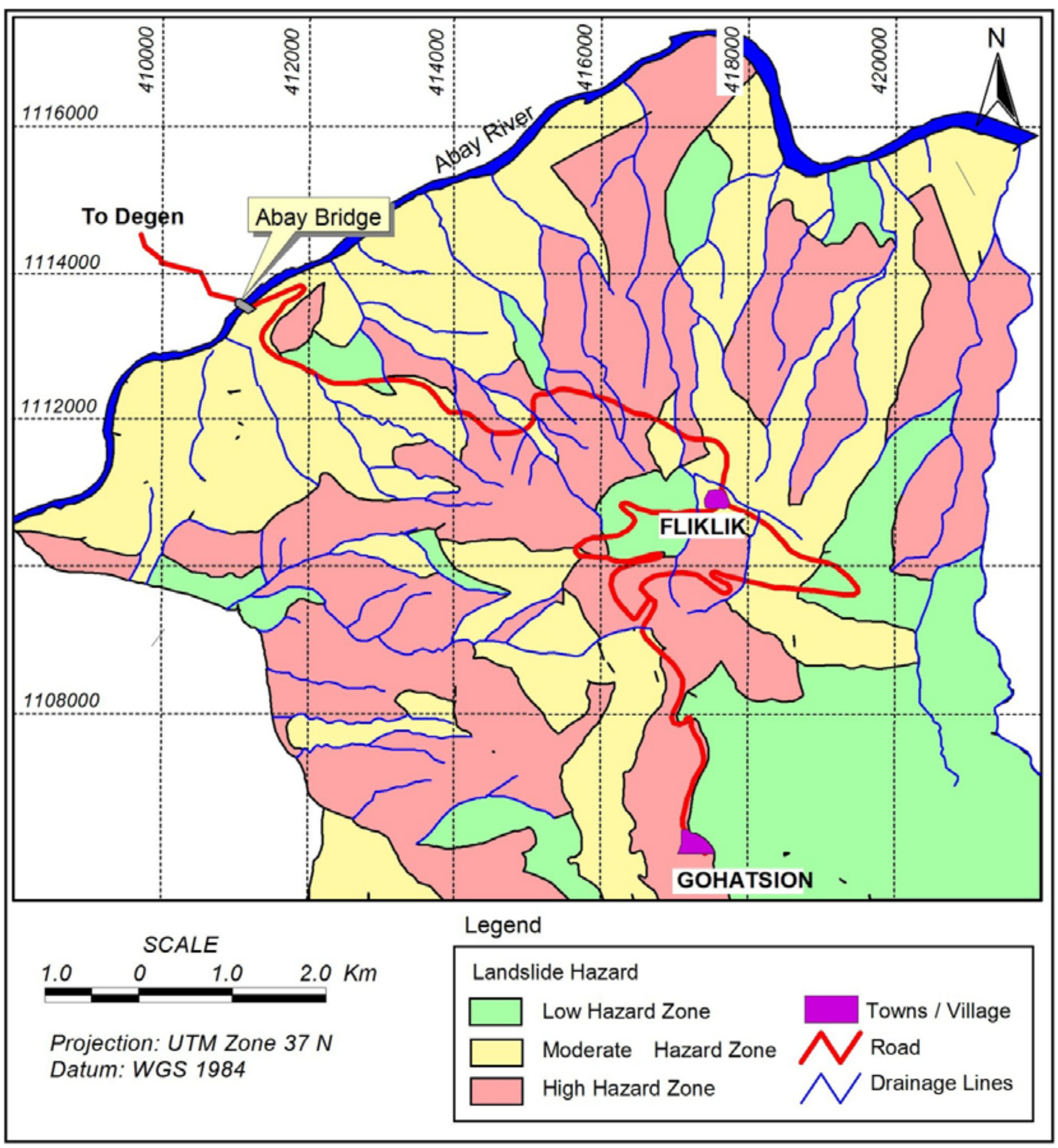

Figure 9. Landslide hazard zonation of the study area.

Moderate hazard (MH) zones are found in abundance and well distributed in the study area. The north and northwestern parts of the study area mainly fall in this hazard zone. This hazard zone is also found evenly distributed on the southwestern part of the study area. In total, out of 139 slope facets, 63 of them fall in this zone. In terms of proportion, this would be 45.3% of the total study area. From this, it is clear that almost half of the study area has a moderate potential for landslide activities.

The high hazard (HH) zones are mainly located in the central and western parts of the study area. Out of 139 facets, 56 of them are in this hazard zone that comprises 40.3% of the total area (Fig. 9). A large portion of the main road in the study area, that links Addis Ababa with the northern part of the country, falls within the high hazard (HH) zone and some of it passes through moderate hazard zone. This is one of the main reasons for the frequent failures of the road sections at various places. On the main road, it is common to find slope failures and rock falls especially after heavy rains (Lulseged Ayalew and Yamagishi, 2004; Jemal Saed, 2005; Henok Woldegiorgis, 2008; Shiferaw Ayele *et al*, 2014). However, a given slope fails if the sum of all driving forces exceeds the resisting forces. On rock slopes the orientation of discontinuities favour sliding, either on single discontinuity or on a wedge formed by two intersecting discontinuities (Hoek and Bray, 1981). Further, even if a slope is potentially unstable, it does not mean that it is actually going to fail, until or unless there are some driving forces that trigger sliding. Triggering factors such as, rainfall that results in heavy water saturation, earthquake loading and any man-made activities near the slope could result in the failure of the slopes (Keefer, 1984; 2000; Bommer and Rodriguez., 2002; Dai *et al.*, 2002; Malamud *et al.*, 2004; Dahal *et al.*, 2006). Therefore, it is necessary to carry out further detailed slope stability studies, particularly on slope sections where the main road passes and which fall within High hazard (HH) zone. Further, proper remedial measures for slope stabilization along the said road section could be implemented. Alternatively, the road may be realigned so that the critical slope sections, which have high susceptibility for landslide activities, may be avoided.

Validation of landslide hazard zonation

In the study area a total of 12 critical slope sections having past landslide activity or having potential for instability have been reported by Jemal Saed (2005) and Henok Woldegiorgis (2008). A description of these critical slope sections is given in Table 2. These critical slope sections are mainly located along the main road. Figure 10 shows that most of these critical slope sections fall within high hazard zone while a few fall within moderate hazard zone, as delineated during the present study. Out of these 12 critical slope sections 10 (83.3%) fall within high hazard (HH) zone and 2 (16.7%) fall within moderate hazard (MH) zone. Thus, the landslide hazard zonation (LHZ) map prepared by utilizing LHEF rating scheme during the present study validates the critical slope sections having past landslide activity or having potential for instability. Further, a field visit was later undertaken to validate the landslide hazard map, the results of which are shown in Table 3. Both Table 3 and Figure 10 clearly indicate that out of 16 potential sites for slope instability, 14 (87.5%) fall within high hazard zone and remaining 2 sites fall within moderate hazard zone as depicted from LHEF scheme during the present study. Thus, the LHZ map prepared during the present study is in close agreement with the actual sites, which have potential instability problems. Further, it can be concluded that those areas, which are delineated under high hazard zone, may pose problems of instability in the future. Therefore, it is strongly recommended that more detailed investigations must be carried out in these areas for the safe functioning of the existing road.

Table 2. Inventory data for critical slope sections having past landslide activity or having potential for instability. (Jemal Saed (2005) and Henok Woldegiorgis (2008)**).**

Critical Slope No.	Location (*Projection: UTM – Zone 37N; Datum: WGS 1984*)		Description	Landslide Hazard Zone as per present Study
	Northing	Easting		
1	1109091	416525	Vertical cliff formed of highly fractured columnar basaltic rock. Top of the cliff is covered by colluvial material. Gully erosion observed in colluvial material. Debris flow and rock fall reported in past.	Moderate Hazard (MHZ)
2	1109972	417571	Mainly comprises of colluvial soil containing gravel to very big size basaltic rock fragments in clayey fine matrix overlying highly weathered limestone. The slope is highly disturbed due to gradual soil mass movement. The actual landslide occurred on August 17th 2000. At present the area is very rugged as big basaltic boulders are displaced by rolling down. At places the underlying decomposed limestone is exposed.	High Hazard (HHZ)
3	1110064	416525	This slope section comprises colluvial soil, which contain clay and gravel to boulder size sub angular to rounded basaltic rock fragments. Vertical displacement up to 3m has been reported. This slope section stretches greater than 500m along the road section. Gully erosion and massive colluvial soil movement is the major problem of this section	High Hazard (HHZ)
4	1110247	415772	The slope is approximately 75m high and inclined at 50^{o} towards N35^{o}W. The large portion of the slope is covered with fine silt to boulder size limestone rock fragments. Debris flow and gully erosion has been reported.	High Hazard (HHZ)
5	1110009	415534	The slope is formed of vertically jointed columnar basalt overlying the horizontally bedded limestone. The limestone is fractured and disintegrated. Rock blocks fallen on the slope face.	High Hazard (HHZ)
6	1109954	415919	Vertical cliff of about 50 m height formed of horizontal bedded limestone. Rock fall has occurred in past. The section extends for about 100m along the road section.	High Hazard (HHZ)
7	1111954	415130	This slope section mainly comprises of whitish to greyish, slightly weathered and fractured Gypsum with interbedded pinkish moderately to highly weathered friable clay stone. The slope is moderately steep and extends for about 200m along the road. Rock fall and debris flow reported.	High Hazard (HHZ)/ Moderate Hazard (MHZ)
8	1111752	414212	The rock exposed on this section is horizontally bedded gypsum with intercalations of clay stone. Rock fall has been reported in this section.	High Hazard (HHZ)/ Moderate Hazard (MHZ)
9	1112762	411845	Along this slope section reddish to yellowish horizontally bedded massive sandstone is exposed. Rock fall may detach from the top of the cliff.	Moderate Hazard Zone (MHZ)
10	1112908	411514	The slope is formed of yellowish red to pinkish, slightly weathered and widely jointed sandstone. The cliff is vertical and beddings are almost horizontal. The slope extends about 120m along the road section. Big blocks of rock fall has been reported.	High Hazard (HHZ)
11	1113184	411423	The slope section comprises of reddish sandstone. Rock fall has been reported and it has a potential for further rock fall as wide-open vertical joints were observed near to the top portion of the slope section.	High Hazard (HHZ)
12	1113441	411643	At this slope section, the rock is reddish to yellowish red, fresh to slightly weathered jointed sandstone. Rock fall reported in this slope section.	High Hazard (HHZ)

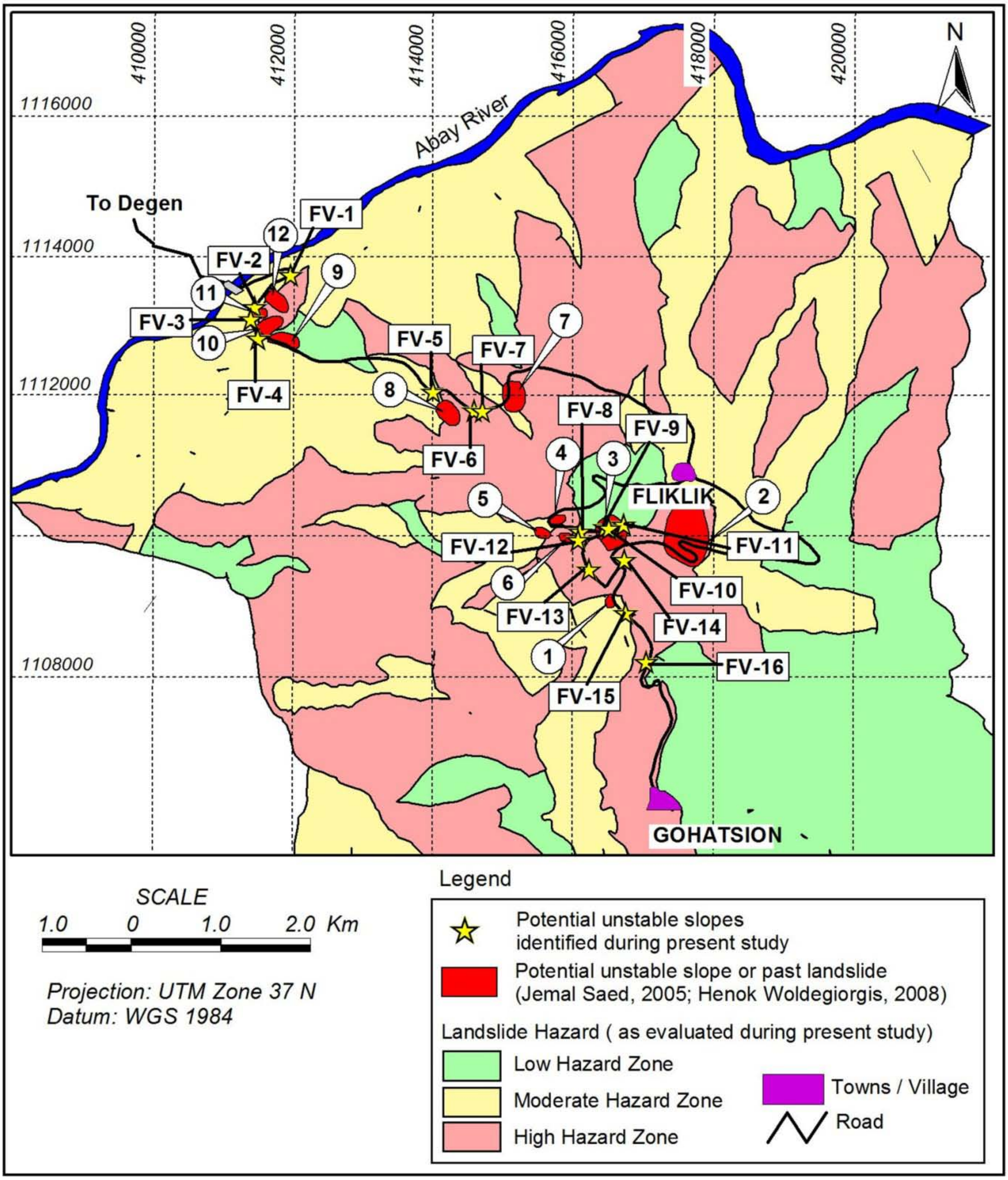

Figure 10. Relative position of critical slopes (having past landslide activities or having potential for instability) with respect to landslide hazard zonation.

Table 3. Field validation of the landslide hazard map.

Critical Slope No. *	Location (*Projection: UTM – Zone 37N; Datum: WGS 1984*)		Description	Landslide Hazard Zone as per Present Study
	Northing	Easting		
FV-1	1113728	411961	Potential site for rock fall. Moderately steep slope. Rock blocks of sandstone of varied dimensions can be observed along the roadside.	High Hazard (HHZ)
FV-2	1113267	411450	Potential site for rock fall. Moderately steep slope. Rock blocks of sandstone of varied dimensions can be observed along the roadside.	High Hazard (HHZ)
FV-3	1113096	411396	Potential site for rock fall. Moderately steep slope. Rock blocks of sandstone of varied dimensions can be observed along the roadside.	High Hazard (HHZ)
FV-4	1112817	411492	Potential site for rock fall. Moderately steep slope. Rock blocks of sandstone of varied dimensions can be observed along the roadside.	High Hazard (HHZ)
FV-5	1112058	413997	The rock exposed is horizontally bedded gypsum with intercalations of clay stone. Potential site for Rock fall.	Moderate Hazard Zone (MHZ)
FV-6	1111789	414577	Whitish to greyish slightly weathered and fractured Gypsum with interbedded pinkish moderately to highly weathered friable clay stone. The slope is moderately steep and extends for about 200m along the road. Surface traces of groundwater present. Potential for rock fall and slide along highly weathered friable clay stone.	High Hazard (HHZ)
FV-7	1111783	414695	Whitish to greyish slightly weathered and fractured Gypsum with interbedded pinkish moderately to highly weathered friable clay stone. The slope is moderately steep and extends for about 200m along the road. Surface traces of groundwater present. Potential for rock fall and slide along highly weathered friable clay stone.	High Hazard (HHZ)
FV-8	1110058	416094	Vertically jointed columnar basalt overlying the horizontally bedded limestone. The limestone is fractured and disintegrated. Rock blocks fallen on the slope face and sides of the roadbed. Potential site for rock fall and toppling of basalt blocks.	High Hazard (HHZ)
FV-9	1110127	416446	Potential site for rock fall and toppling of basalt blocks. Jointed columnar basalt overlying the horizontally bedded limestone.	High Hazard (HHZ)
FV-10	1110162	416711	Slope comprises colluvial soil containing clay and gravel to boulder size sub angular to rounded basaltic rock fragments. This slope section stretches greater than 500m along the road section. Potential for gully erosion and massive colluvial soil movement.	High Hazard (HHZ)
FV-11	1110103	416502	Potential site for basaltic block failures. Failed blocks of varied dimension can be seen on the sides of the slope.	High Hazard (HHZ)
FV-12	1109939	416063	Potential site for basaltic block toppling.	High Hazard (HHZ)
FV-13	1109518	416217	Potential site for basaltic columnar joint block failure.	High Hazard (HHZ)
FV-14	1109659	416720	Potential site for basaltic block failure.	High Hazard (HHZ)
FV-15	1108903	416737	Potential site for basaltic block toppling.	High Hazard (HHZ)/ Moderate Hazard (MHZ)
FV-16	1108206	417038	Active slide zone comprising colluvial material. Road subsided along this zone. Further potential for massive failure of slope. Road may be further damaged partially or fully.	High Hazard (HHZ)

* For critical slope number, please refer to Figure 10.

CONCLUSION

The landslide hazard zonation of the study area carried out through the LHEF rating scheme indicates that 45.3% of the slopes fall in the moderate hazard zone, while 40.3% and 14.4% fall in the high hazard and low hazard zones, respectively. In essence it is easy to understand that most of the study area falls within the moderate and high hazard zones. From this premise it can be concluded that the probability of slope failures in most of the study area is high. A comparative analysis of various causative factors revealed that slope morphometry, geology and land use and land cover are the most important factors in inducing instability to the slope, particularly within the high hazard zone. The landslide hazard zonation (LHZ) map prepared during the present study validates the presently identified critical slope sections. In fact about 83% of the slope sections having past landslide activity or having potential for instability fall within the high hazard zone. Much of the main road passes through the high hazard zone. This is one of the main reasons for the frequent failures of the road sections at various places. More detailed slope stability studies are required along the road section which fall within the high hazard zone so that proper remedial measures can be worked out.

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