Chapter 2
Application of Remote Sensing and GIS for Landslide Disaster Management: A Case from Abay Gorge, Gohatsion–Dejen Section, Ethiopia

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Abstract The Abay Gorge, along Gohatsion–Dejen road, in Ethiopia witness frequent landslides during the rainy season. The natural stability of slopes has been disturbed due to the road construction, the fragile geological conditions, groundwater and uncontrolled surface run-off which favor landsliding during rainy season. Such landslide hazard has resulted into frequent disruption in traffic movement and endangered the people life and their property in the area. Rock fall, toppling, debris slide and rotational failure of colluvial material are some of the common land instability manifestations observed in the area. Mitigating landslide risk disaster is of prime concern and through the present study attempts are made to delineate the landslide hazard prone zones in the study area. For this purpose Landslide Hazard Zonation (LHZ) mapping using integrated Remote Sensing and GIS technique was carried out so as to classify the land surface into zones of varying degree of hazard. Thus, the landslide hazard zonation mapping produced through present study will be useful to the planners and engineers to know the zones which are prone for landslide disaster and they may evolve suitable remedial measures for disaster risk reduction and management.

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For the present study, "Weighted Linear Combination (WLC)" technique was used to prepare the Landslide hazard zonation map. In WMC technique, each factor was multiplied by its derived weight and later the results were added to produce the landslide hazard map.

WLC helps to handle the problem of integration of different data layers with heterogeneity and certain degree of uncertainty. The method used is very useful to integrate single factor maps with each other and thus to produce a multi-thematic map. This model requires multi spatial data on a target area and then can be extrapolated in to a larger area as required. For landslide hazard zonation the major event controlling parameters which were considered are; geology, groundwater conditions, drainage, slope, geologic structure, aspect, and land use/land cover.

For landslide hazard zonation five relative classes, namely Very Low Hazard (VLH), Low Hazard (LH), Moderately Hazard (MH), High Hazard (HH) and Very High Hazard (VHH) were considered. The result has shown that out of 21 past slope failures, seven (33.33 %) occurs in very high, seven (33.33 %) in high, five (23.81 %) in moderate and two (9.52 %) in low hazard zones, respectively. The comparison shows satisfactory results as 67 % of the past landslides lie within the maximum hazard zone, and the remaining within the moderate and low hazards zones. No landslide event was observed in the very low hazard zone. Thus, the satisfactory agreement confirmed the rationality of the considered governing parameters, their influential weight, the adopted methodology, tools and procedures in developing the landslide hazard map of the study area.

Keywords DEM • GIS • Landslide hazard zonation • Multi-criteria evaluation • Remote sensing • Weighted linear combination

2.1 Introduction

The Abay Gorge, along Gohatsion–Dejen road, is one of the common areas in the country where most slope instabilities are frequently observed. It is very common to see slope failure events that hinder traffic movements during the rainy season (Woldegiorgis 2008). Rock fall, toppling, debris slide and rotational failure of colluvial material are some of the common land instability manifestation (Ayalew 2000; Woldegiorgis 2008; Saed 2005; Ayalew and Yamagishi 2003). Huge columnar jointed basalt, groundwater, uncontrolled surface run off, joints of rocks, and the presence of marl and shale within hard rocks are the main causes of slope instability. During the past years, landslides and rock falls had damaged the road sections, bridges and farmlands.

The study area is a part of economically important main Addis Ababa-Debremarkos—Bahardar—Gondar—Metema—Sudan root and Gondar—Tigray road that connects north central and north western part of the country with the capital of Addis Ababa and port of Sudan. The study area is situated in the central

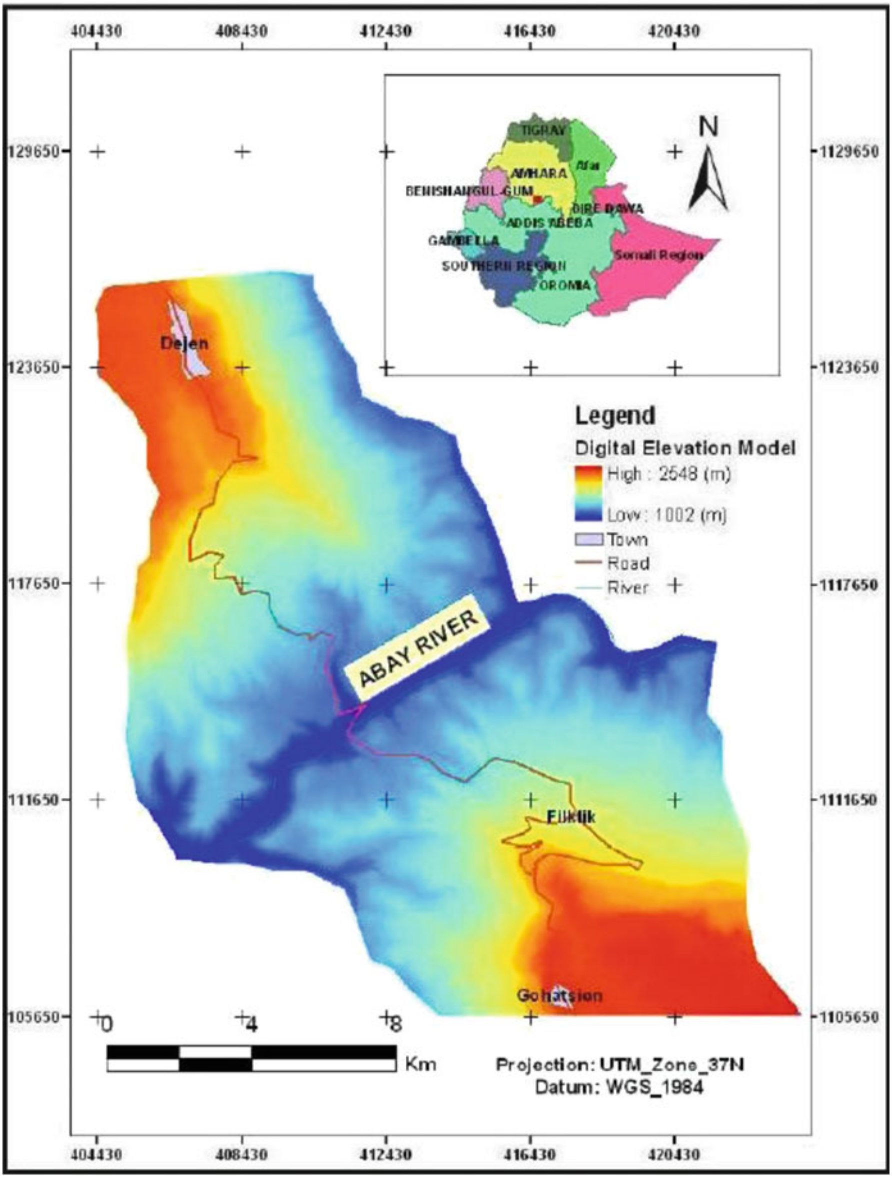


Fig. 2.1 The study area

plateau of Ethiopia and bounded by 38°07′38″ E and 38°18′18″ E longitudes, and 10°00′ N and 10°10′11″ N latitudes (Fig. 2.1), covering an area of about 235.1 km^2.

The present research study was aimed at application of Remote Sensing and GIS for landslide disaster Management—A case from Abay Gorge, Gohatsion–Dejen

Section, Ethiopia. The main objectives of the study were: (1) to examine and demonstrate the usefulness of integrated RS and GIS approaches for landslide hazard mapping in the study area, (2) to produce landslide hazard map of the study area, (3) to delineate the different critical as well as unstable areas in the area in terms of the land hazard risks and (4) to propose possible remedial measures to the problem.

2.2 Geomorphology

The study area is characterized by its 1,400–1,500 m deep gorge, which is made of stratified sedimentary rocks capped by basaltic plateau. The present physiographical setting of the study area is a result of various processes. Uplifting which is believed to be responsible for the formation of the deep canyon, erosional leveling, weathering and mass wasting have played a major role in creating the present landform (Gezahegn and Dessie 1994).

The main landforms of the study area, based on their origin, are Volcanic/ Denudational, Denudational, Fluvial/Denudational and Fluvial Land Forms.

2.3 Geology of the Study Area

The sedimentary history of the Mesozoic succession is related to the formation of basins around the borders of the mega continent, especially along the eastern African margin. These basins are the results of the break-up of Gondwanaland during Paleozoic-Jurassic times. The basins is largely fault-controlled and with limited marine access, are filled with a thick succession of Karoo sediments known also as the Gumburo Formation in Ethiopia (Assefa 1991).

The sedimentary rocks in Abay Gorge are formed within Mesozoic time and the volcanic rocks within Cenozoic times, respectively. The nature of lithology fossils dispersion and sedimentary structures are due to a complex of depositional environments, such as coastal fluvial lacustrine, partially arid lagoon. However, the basalt is from fissural flow of Magma (Gezahegn and Dessie 1994).

The Mesozoic sedimentary rocks are exposed in the Abay river valley, between the towns Gohatsion and Dejen, along Addis Ababa to Debre Markos road. A succession about 1,200 m thick is well exposed on the left side of the above mentioned valley, with a nearly horizontal stratification. The major transgression deposit is characterized by restricted marine evaporate sediments lagoonal, Sabkha sediments and continental sandstones in Abay River (Atnafu 2003).

The Geological units of the study area are Paleozoic and Mesozoic Sedimentary Rocks, and Tertiary Volcanic Rocks and Quaternary Superficial Deposits (Fig. 2.2).

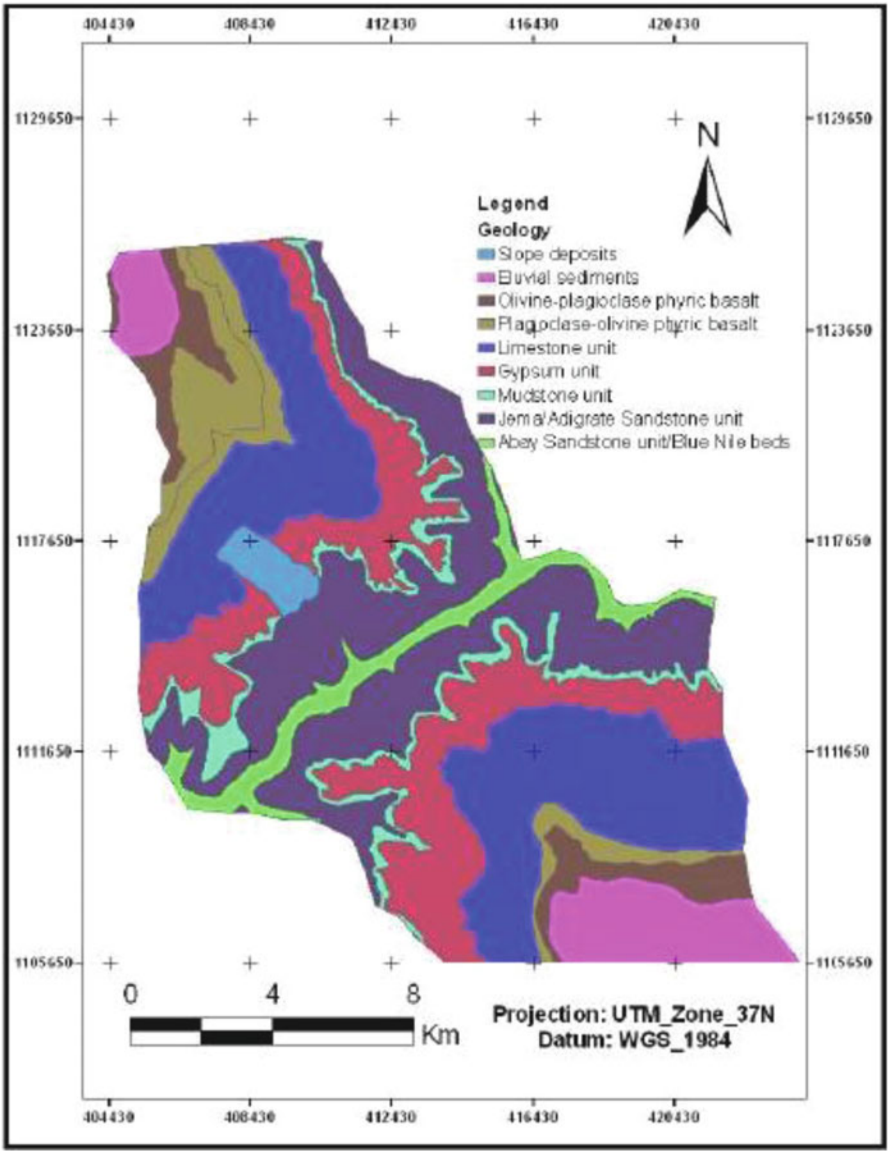


Fig. 2.2 Geological map of the study area

The Paleozoic sedimentary rocks are: Abay Sandstone Unit or Abay Beds (Pssm)—The sandstone at its top part alternates with siltstone and/or shale and mudstone; the siltstone and/or shale and mudstone sediments occupy the top most part while the sandstone occupies the lower part.

The Mesozoic sedimentary rocks from the oldest to the youngest are: Jema Sandstone or Adigrat Sandstone Unit (Mst), Mudstone Unit (Mms), Gypsum Unit

(Mgb) and Limestone Unit (Mls). The Tertiary basalt lava flows from the oldest to the youngest are: Migira basalt (Tv3), Hacho basalt (Tv4), Olivine Plagioclase phyric basalt (Selelkula basalt) and Basalt (Tv6). The Quaternary superficial sediments are Quaternary Eluvial Sediments (Qe) and Quaternary slope sediments (Qs).

2.4 Materials and Methodology

The data that was used for the present study includes; topographic map, geological, structural and engineering geological maps, soil maps, Landsat 7 ETM + Enhanced Thematic (Mapper Plus), Shuttle Radar Topographic Mission (SRTM). ERDAS Imagine 8.6 was used for image processing of landsat ETM + image in lineanament analysis and landuse/landcover classification, MapInfo for digitizing structures and landuse/landcover, respectively, ArcGIS 9.1, IDRISI 32 and Global Mapper were used for data acquisition, analysis and presentation of the final research results.

Several methods have been employed by several authors to assess landslide hazard and to map hazard zone in different parts of the world. These methods can be classified into three groups; expert evaluation, statistical methods and deterministic method (Leroi 1997; Guzzetti et al. 1999; Casagli et al. 2004; Fall et al. 2006; Kanungo et al. 2006).

Expert evaluation method further can be classified into two; landslide inventory mapping and heuristic method (Fall et al. 2006). Landslide inventory mapping is the simple method in which the landslide events are recorded for their location and dimension (Dai and Lee 2001; Dai et al. 2002; Fall et al. 2006).

The heuristic method includes opinion in classifying the landslide hazard which is based on quasi-static variables only (Dai and Lee 2001; Fall et al. 2006). Different maps of causative factors, which may have influence on the landslide occurrence are prepared and combined to prepare the hazard map (Dai and Lee 2002). The numerical ratings are assigned to various causative factors responsible for instability of slope which is based on logical judgments of Geoscientist acquired from experience of studies of causative factors and their relative impact on instability of slopes (Anbalagan 1992). Higher the numerical value of rating, greater will be its influence on the occurrence of landslide (Kanungo et al. 2006). There are several Expert evaluation techniques available these includes techniques proposed by Anbalagan 1992; Pachauri and Pant 1992; Sarkar et al. 1995; Turrini and Visintainer 1998; Guzzetti et al. 1999, etc.

The statistical methods are indirect and landslide hazard assessment is made based on the rules evolved statistically with the relative contribution of instability factors on past landslides. The statistical methods are used to evaluate spatial landslide instability based on relationship in between the past landslide activities and the instability causative factors (Carrara et al. 1992). Statistical analysis approach includes bivariate and multivariate methods. In bivariate method for landslide susceptibility assessments the weights are assigned to various factors based upon statistical relationships between past landslides and various factor (Van Westen 1994). Individual factor maps are overlaid on past landslide map to workout relative contribution for each factor and subclass in inducing landslide. From this data, weights are developed to be applied to each factor subclass so that landslide hazard can be deduced. The multivariate model uses an equation in which independent variables are the geo-environmental factors with coefficients maximizing the predictive capability of the model, and the independent variable is the presence/absence of landslides.

Deterministic approach provides hazard in absolute values in the form of factor of safety, or the probability. In these methods various forces responsible for instability and the forces responsible for stability are evaluated in quantitative terms. The deterministic approach provides the quantitative results for landslide hazard that can be directly used in the engineering design. The deterministic approach requires detailed geotechnical data and can be applied at large scales only (Barredo et al. 2000).

The successful use of one method over other strongly depends on many factors such as; scale of the study area, the accuracy of the expected results, the availability of data, parameters considered etc. (Fall et al. 2006).

In the present study, a "Weighted Linear Combination method" (WLC) to delineate the landslide hazard zones was employed. The method includes three main stages; pre-field work (data preparation), field work (data verification) and post field work (analysis and interpretation) (Ayalew et al. 2004).

The first stage includes data collection from different sources and map preparations. In this stage, lineament/structural and landslide inventory maps were prepared by the interpretation of aerial photographs, satellite image interpretation and digitizing from previous works; bedrock geology of the study was imported; DEM, slope, slope aspect and drainage maps were prepared from SRTM data; land use/land cover map was prepared from Landsat ETM + image interpretation. The study area boundary has been set, (UTM) Zone 37 N & WGS84 datum was chosen.

The second stage of the methodology was ground truthing. It is done with the help of Global positioning System (GPS) and field compass. All other necessary data/information was collected for ground truthing and maps were prepared, verified and modified whenever it was felt necessary.

Finally, the susceptibility maps produced from the weighted linear combination method was produced and subsequently evaluated using field data/ground truthing. Figure 2.3 shows the general methodology followed for the landslide hazard zonation mapping of the study area.

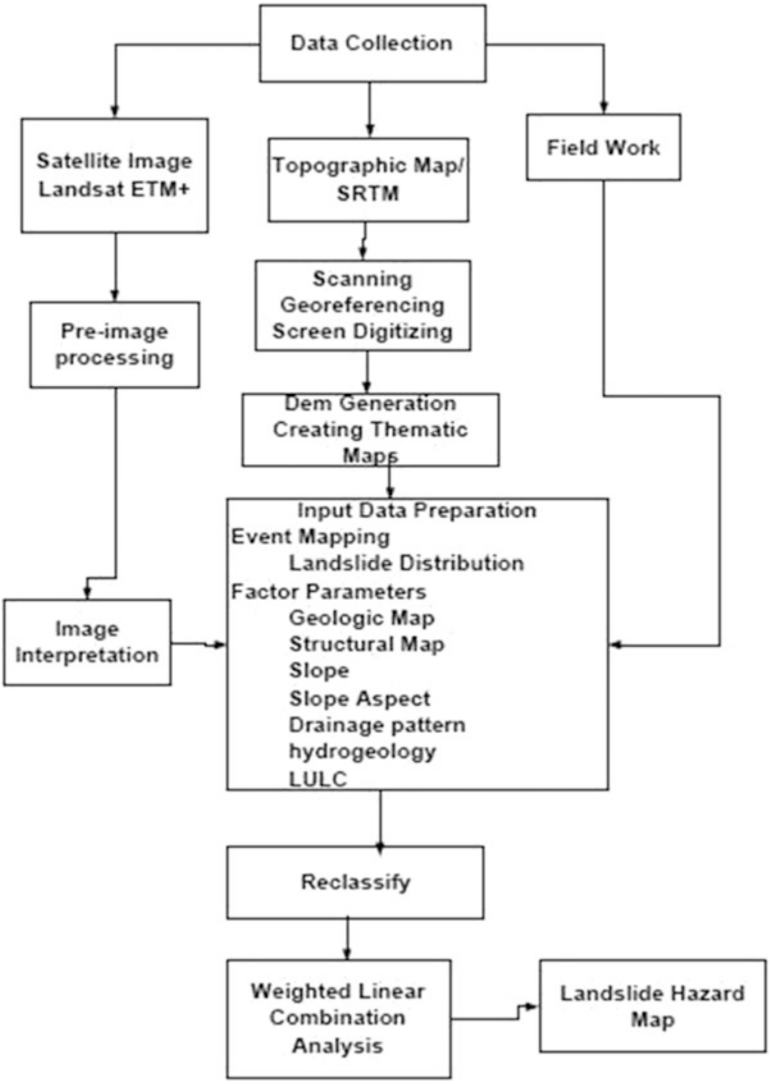


Fig. 2.3 Conceptual workflow the methodology

2.5 Results and Discussion

2.5.1 Factor Maps Preparation

A field survey was carried out to identify and establish priority based on the number of landslide occurrences for the causative factors that might have triggered the mass movement in the area. Accordingly, the location of landslides, type of landuse/

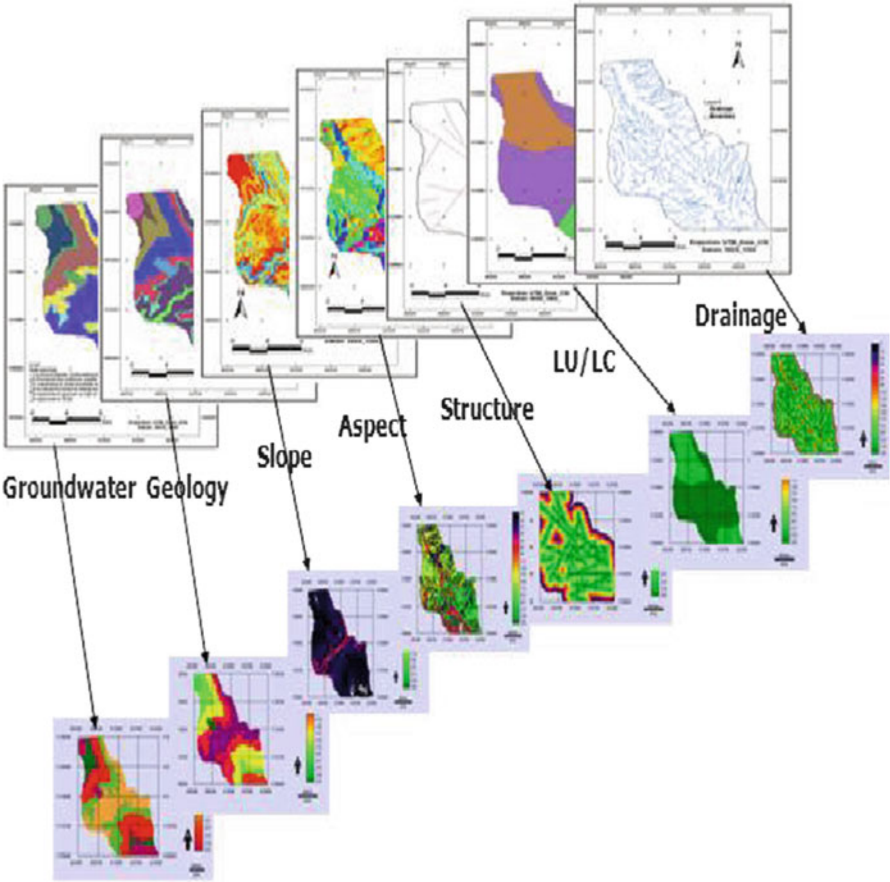


Fig. 2.4 Reclassified factor maps

landcover, slope angle, lithology, geological structures, drainage pattern & hydrogeology/groundwater conditions, degree of weathering and soil types were identified.

Two types of reclassification were applied to reclassify factor maps. The first type is the Fuzzy module in IDRISI 32 software used for the reclassification of different data layers of drainage and geological structures, and slope data layer to avoid distinct boundary where continues scaling values ranging from 0 to 255 was assigned. The second type of reclassification, the STANDARD RECLASS module in IDRISI 32 software, uses each class and has a distinctive rating value that makes it more suitable as compared to the other classes where distinct boundary is assigned.

Based on the landslide event mapping and field observations, each factor was reclassified into different classes (Fig. 2.4 and Table 2.1).

Table 2.1 Input parameters and their relative rating

S.No.	Major factors	Sub factors	Landslide occurrence	Rating
1	Slope angle	As the slope angle increases the impact is also expected to increase	As the slope angle increases the landside occurrences assumed to be increase	0–255 (fuzzy boundary) High value means high impact and vise versa
2	Slope aspect	North (0–22.5, 337.5–360)	9	200
		East (67.5–112.5)	1	20
		South (157.5–202.5)	6	150
		West(247.5–292.5)	7	175
		Northeast (22.5–67.5)	1	20
		Southeast (112.5–157.5)	4	100
		Southwest (202.5–247.5)	2	50
		Northwest (292.5–337.5)	14	255
		Flat (−1)	0	0
3	Landuse/ landcover	Intensively cultivated	14	238
		Bareland/woodland/bush	15	255
		Less dense bush land	14	255
4	Drainage	The drainage impact is expected to decreases further away from the drainage line	Away from the drainages the landslide occurrences assumed to decrease	0–255 (fuzzy boundary) High value means high impact and vise versa
5	Geological structure	The impact of geological structures is expected to decreases further away from the structure lines	Away from the geological structures the landslide occurrence assumed to decrease	0–255(fuzzy boundary) High value means high impact and vise versa
6	Lithology	Colluvial soil	3	255
		Residual soil	1	200
		Basalt overlain by colluvim	14	180
		Limestone with intercalated with friable material	12	50
		Gypsum	4	72
		Shale	1	90
		Fractured Sandstone	9	50

7	Groundwater	Loose materials (colluvial/Residual/basalt) yield up to 1 L/s	15	255
		Fractured discontinuous aquifer in basalt, with Q up to 0.2 L/s	3	200
		Limestone and shale localized aquifer along fracture, Q up to 1 L/s	12	180
		Localized fractured & intergranular aquifer (SST) Q up to 0.4 L/s	9	100
		Aquiclude in gypsum except at some fractures	5	40
		Aquiclude in shale	0	40

Table 2.2 Pair wise comparison matrix

Parameters	Geology	Groundwater	Drainage	Slope	Structure	LULC	Aspect
Geology	1						
Groundwater	1	1					
Drainage	5/7	5/7	1				
Slope	5/7	5/7	1	1			
Structure	3/7	3/7	3/5	3/5	1		
LULC	1/7	1/7	1/5	1/5	1/3	1	
Aspect	1/7	1/7	1/5	1/5	1/3	1	1

Each factor map was reclassified into classes in order to make the same output scaling of 0–255. This Byte (0–255 range) is mainly used with modules such as MCE that require byte data format. This scaling is assigned based on the number of landslides and parameter estimation during field survey. Accordingly, the classes of each factor that had the maximum number of landslide events were given the maximum value of 255 or close to 255, whereas classes in which none or a few number of landslides occurred were assigned with a minimum value of 0 or close to 0.

For slope monotonically increasing module was used because as slope increases landslide effect also increases. This reclassification is applied to avoid distinct boundary where continues scaling values ranging from 0 to 255 is assigned. The second type of reclassification classification is the Standard Reclass module in IDRISI 32 software, in which each class has a distinctive rating value that makes it more suitable as compared to the other classes where distinct boundary is assigned.

2.5.2 *Weighting Factor Maps*

After the standardization to common scale of each controlling factor, weight is given for each layer based on pair-wise comparison of two data layers at the same time, using pair-wise comparison of 9-point continuous rating scale in IDRISI 32 (Table 2.2). WEIGHT Module is used to develop a set of relative weights for a group of factors in a multi-criteria evaluation.

The weights were developed by providing a series of pairwise comparisons of the relative importance of factors to the suitability of pixels for the activity being evaluated. These pairwise comparisons are then analyzed to produce a set of weights that sum to one. The larger the weight means the more influencing is the factor. The factors and their resulting weights can be used as input for the MCE module for weighted linear combination or for other MCE modules. The weights developed to each factor are given based on the analytical hierarchy process proposed by Saaty (1994) by means of providing a series of pair-wise comparisons of the relative importance of factors.

Table 2.3 The eigenvector of weights

Factors	Weight
Geology	0.2414
Groundwater	0.2414
Drainage	0.1724
Slope	0.1724
Structure	0.1034
LULC	0.0345
Aspect	0.0345

Note: Consistency ratio = 0.00
Consistency is acceptable

The rating assigned during the pair-wise comparison is a subjective term based on the knowledge of the problem with its causing factors obtained during the field. In each cell of the matrix the relative importance of the row variable to its corresponding column variable was considered and the appropriate rating was given (Table 2.2). All the diagonal cells in the matrix contain a one since it represents the comparison of each variable with itself. Only the lower-left triangular half will actually be evaluated since the upper right is symmetrically identical and values are equal to the reciprocal of the lower-left.

After the pair-wise comparison matrix, individual factor weights were calculated (Table 2.3) using the WEIGHT module of IDRISI 32. The resulting consistency ratio of the above pair-wise comparison matrix is 0.00 that indicate acceptable consistency range because the acceptable consistency ratio of the pairwise comparision matrix is below 0:10). This consistency ratio value indicates the probability that the ratings were randomly assigned. The weights calculated indicate the relative significance of the factors in accomplishing the mass movement.

Based on field observations, the geology and groundwater, drainage and slope in the area have a great contribution in aggravating the mass movement. Thus, the highest weight has been given to geology and groundwater. The next highest weight has been given to drainage and slope.

The Dejen–Gohatsion section of the Abay Gorge is not intensively tectonized. However, structural systems in the area can be generalized into three systems of faults and joints of variable magnitude, extent and minor to significant orientation variations. These are the NW system which varies from N20°W to N50°W, the NE system which varies between N60°E to N85°E and the NS system which swings by about 10° in either side. There are some EW fractures at some places although they are not considered as major dislocations in the area. The N42°W faulting and associated jointing system seems the dominant structure in the gorge. The joint sets that affect the rocks especially the top basalt are both structure related and/or cooling joints.

These faults are significant factors in controlling the development of landslides and rock fall. Generally, rock masses near the faults and fractures are highly weathered and severely fractured. Therefore, reasonable weight is assigned for the structure. Finally, less weight has been given to landuse/land cover and aspect as compare to others although they play a reasonable contribution to the existing mass movements in the study area.

Table 2.4 Landslide hazard zonation on the basis of total estimated hazard (TEHD)

Zone	TEHD value	Description of zone
I	<93	Very Low Hazard (VLH) Zone
II	93–118	Low Hazard (LH) Zone
III	118–143	Moderate Hazard (MH) Zone
IV	143–168	High Hazard (HH) Zone
V	>168	Very High Hazard (VHH) Zone

Through a Multi-Criteria Evaluation, these criteria images (the reclassified geology, groundwater, drainage, slope, structure, aspect and landuse image maps) representing are combined to form a single suitability map. To combine the spatial layers to assess landslide hazard, algebraic combination techniques have been used (Wang and Unwin 1992). The integration is done through the application of WLC procedure. Each factor was multiplied by its derived weight and then the results added to produce the landslide hazard map (Fig. 5.15) using the following formula:

$$LHZ = w1\ X1 + w2\ X2 + w3\ X3 + w4\ X4 + w5\ X5 + w6\ X6 + w7\ X7$$

Where; LHZ = Landslide Hazard Zonation

w1 . . . w7 = weights for each factor and

X1 . . . X7 = the seven factors used in the analysis based on the degree to which factor weights influence the final result (i.e. X1 is the most influencing factor, where as X7 the least influencing factor the seven factors used in the analysis.

The produced hazard map was reclassified into very low hazard, low hazard, moderate hazard, high hazard and very high landslide hazard zone using ARCGIS Spatial analyst module (Table 2.4 and Fig. 2.5).

Accordingly, the five categories correspond to five relative scales of landslide hazard zones, namely Very Low Hazard (VLH) (1), Low Hazard (LH) (2), Moderately Hazard (MH) (3), High Hazard (HH) (4) and Very High Hazard (VHH) (5). This is depicted in Fig. 2.6.

2.6 Conclusion

Landslides and rock falls are the major frequently occurring problems identified from previous work in the Abay (Blue Nile) Gorge along and near by Gohatsion–Dejen road. Nearly all slope failures occur during rainy season. The frequently occurring landslides have damaged the road sections, bridges and farmlands. The main causes of slope instability identified during the present study were mainly due to the presence of huge columnar jointed basalt, uncontrolled surface run off, preferred orientations of the discontinuities within the rock mass and the presence of soft rocks such as; marl and shale confined within the hard rocks.

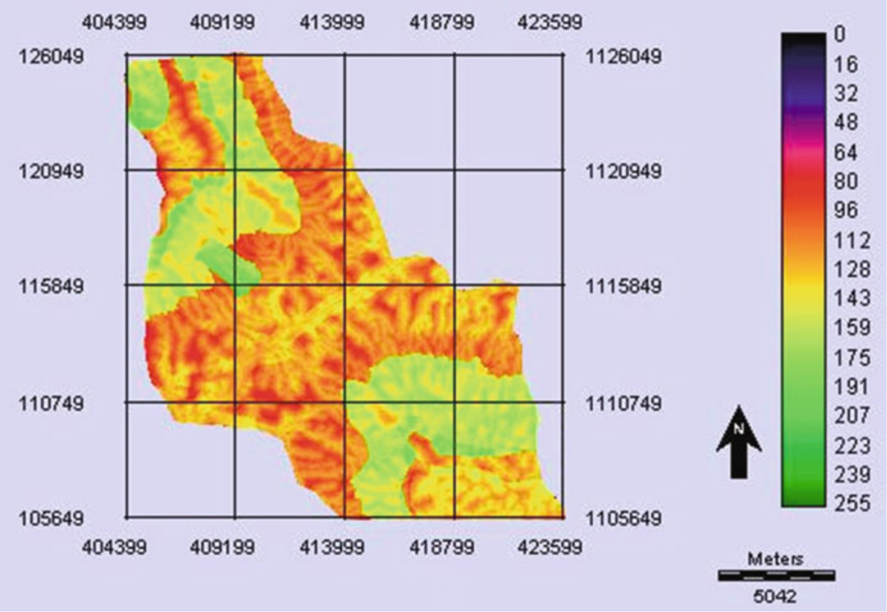
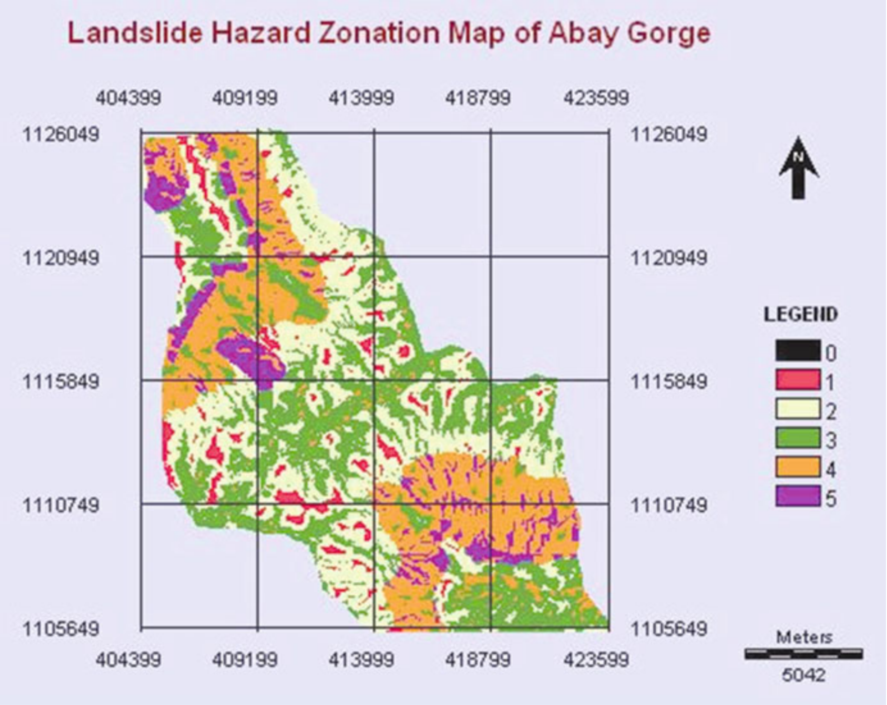


Fig. 2.5 landslide hazard map of Abay Gorge



***Note*: Nos. 1 to 5 marked in the legend indicate: 1, Very Low Hazard (VLH); 2, Low Hazard (LH); 3, Moderately Hazard (MH); 4, High Hazard (HH); 5, Very High Hazard (VHH)**

Fig. 2.6 Landslide hazard zonation map of Abay Gorge

The structural systems of the study area can be generalized into three systems of faults and joints of variable magnitude, extent and minor to significant orientation variations. These are the NW system which varies from N200W to N500W, the NE system which varies between N600E to N850E and the NS system which swings by about 100 in either side. There are some EW fractures at some places although they are not considered as major dislocations in the area. The N420W faulting and associated jointing system seems the dominant structure in the gorge.

Colluvial soils are also the most susceptible soils for the sliding process in the study area. This is because when these colluvial soils are oversaturated during the rainy season, they will be subjected to swelling this ultimately results into landsliding process. Furthermore, when these soils get dried there will be shrinkage which will result into change in the volume of the soil mass, thus the rock fragments of varied dimensions will be subjected to movement.

In this study, seven landslide-controlling parameters, namely lithology, groundwater, drainage, slope geologic structure, aspect and landuse/Landcover were identified. A Weighted Linear combination method to delineate the landslide hazard zones was employed.

The results of the entire analyses and evaluation of MLC method allowed dividing the study area into five zones of susceptibility, namely very low, low, moderate, high and very high using ARCGIS Spatial analyst module. Out of 21 critical slope failures, seven (33.33 %) has occurred in very high, seven (33.33 %) in high, five (23.81 %) in moderate and two (9.52 %) in low hazard zones, respectively.

According to this method landslide hazard was caused by the collective effect of the event controlling parameters. The method used is very useful to integrate single maps with each other and thus produce a multi-thematic map. The comparison of the landslide hazard map with the actual landslide activity distribution map has shown 67 % of the landslides lie within the maximum hazard zone, and the remaining with the moderate and low hazard zones.

Based on the present study following recommendations are forwarded;

The effects of landslides on people and structures can be minimized by total avoidance of landslide hazard areas or by restricting, prohibiting, or imposing conditions on hazard-zone activity.

In area which have intense gully erosions on both down and up slope of the road cut side retaining wall construction is required after clearing the rocks and debris fallen on the road, besides, proper drainage on the upper slope sections must be provided.

Develop appropriate policies in consultation with the local people and encourage their participation is an alternative mitigation strategy.

For the future development and strengthening of this model additional factor such as; characteristics of discontinuity surfaces, interrelationships of discontinuities, pore water pressure in soil mass, water forces acting within the discontinuity surfaces, shape factor of particles in coluvial material may be considered.

Effects of triggering factors such as; rainfall, seismicity, constructional activities and cultivation practices may also be considered.

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