

# Landslide hazard evaluation and zonation in and around Gimbi town, western Ethiopia—a GIS-based statistical approach

Gemechis Chimidi<sup>1</sup> · Tarun Kumar Raghuvanshi<sup>1</sup> · K. V. Suryabhagavan<sup>1</sup>

Received: 13 March 2017 / Accepted: 11 September 2017 / Published online: 24 September 2017  
© Società Italiana di Fotogrammetria e Topografia (SIFET) 2017

**Abstract** The main purpose of the present study was to carry out landslide evaluation and zonation in and around Gimbi town in western Ethiopia, located about 440 km from Addis Ababa. This study was conducted following GIS-based statistical method. For hazard evaluation and zonation, nine causative factors viz., slope material, elevation, slope, aspect, curvature, groundwater surface traces, distance to roads, and distance to streams were considered. Data on these causative factors were obtained from secondary maps, digital elevation model, topographical sheets, and through field mapping. Fifty past landslides in the study area were also identified and mapped through field survey and image interpretation. Statistical correlations between each of the causative factors and the past landslides were established in GIS environment to rate the relative contribution of individual factor classes. Thus, by considering ratings for each causative factor subclasses and by assigning suitable weights to each factor, random trial combinations were attempted to produce the landslide hazard zonation map. The results showed that 12.2% of the study area falls in very high hazard, 30.7% in high hazard, 24.3% in moderate hazard, 23.3% in low hazard, and the remaining 9.5% in no hazard zones. Validation of landslide hazard zonation map with past landslides showed that 75% of the past landslides fall within very high and high hazard zones. Thus, the hazard zones depicted can be considered for future planning and development of the study area.

**Keywords** Landslide hazard evaluation · Hazard index · Landslide hazard zonation

## Introduction

The highlands in Ethiopia are characterized by complex geology, unstable soil cover, typical geomorphological conditions, high rainfall, and uncertain hydrologic and hydrogeological conditions. These characteristics along with the increased man-made activities in the recent past, such as road and other construction activities, have resulted in increased landslides in Ethiopian highlands (Ayalew 1999; Ayalew and Yamagishi 2004; Ayenew and Barbieri 2005; Woldaregay 2013; Raghuvanshi et al. 2014; Woldegiorgis et al. 2014; Girma et al. 2015; Raghuvanshi et al. 2015; Hamza and Raghuvanshi 2016). The present study area forms part of the western Ethiopian highland, located in the Oromia National Regional State in the western part of Gimbi district. Just like other areas in Ethiopian highlands, the present study area is also severely affected by landslide incidence. Thus, it needs attention to evaluate and carry out systematic study on landslide so that people and property in the area can be protected and the adverse effects of landslides can be minimized. For proper strategic planning, it is required to evaluate and delineate landslide hazard prone areas, using landslide hazard zonation (LHZ) techniques (Anbalagan 1992; Girma et al. 2015; Raghuvanshi et al. 2015; Hamza and Raghuvanshi 2016).

In order to carry out LHZ, different methods such as inventory, expert evaluation, statistical, and deterministic approaches are available (Leroi 1997; Guzzetti et al. 1999; Casagli et al. 2004; Fall et al. 2006; Kanungo et al. 2006; Raghuvanshi et al. 2015; Hamza and Raghuvanshi 2016). Each of these methods requires data on past landslides, inherent causative factors, and external triggering factors. The

---

✉ K. V. Suryabhagavan  
drsuryabhagavan@gmail.com

<sup>1</sup> School of Earth Sciences, College of Natural Sciences, Addis Ababa University, P.O. Box 1176, Addis Ababa, Ethiopia

inherent causative factors considered are geometry of the slope elevation, slope inclination, aspect, curvature, geologic factors-lithology or soil type, discontinuity characteristics, hydrogeology and land-use/land-cover (Hoek and Bray 1981; Ayalew et al. 2004; Wang and Niu 2009; Raghuvanshi et al. 2014). Among the external triggering factors, rainfall (Collison et al. 2000; Dai and Lee 2001; Ayalew et al. 2004; Dahal et al. 2006), seismicity (Keefer 2000; Parise and Jibson 2000; Bommer and Rodríguez 2002), and man-made activities (Wang and Niu 2009; Raghuvanshi et al. 2014) are considered. The LHZ techniques may be applied at different scales, and selection of a technique is often decided on the basis of scale at which the LHZ map can be prepared (Carrara et al. 1995; Leroi 1997; Guzzetti et al. 1999; Casagli et al. 2004; Fall et al. 2006; Kanungo et al. 2006; Raghuvanshi et al. 2014). The main objective of the present study was to evaluate landslide hazard and to prepare a LHZ map of the study area.

## Study area

The present study area is located in the Oromia National Regional State of Ethiopia, West Wellega Zone in the western part of Gimbi district, western Ethiopia. This area is about 440 km from Addis Ababa, the capital city of Ethiopia. The study area is bounded by coordinates 35° 42' 00" E–36° 9' 00" E longitude and 8° 57' 00" N–9° 16' 30" N latitude and covers a total area of 94.5 km<sup>2</sup> (Fig. 1) in the subtropical climate zone (Daniel, 1977). The topography of the area is rugged with altitudes ranging from 1688 to 2172 m. This area has dendritic drainage pattern and has small intermittent streams, Gefere and Sariti rivers joining. The study area falls in the subtropical climatic zone (Daniel 1977). The highest mean annual rainfall in the area recorded was 2191 mm in the year 2006 and a minimum of 1500 mm rainfall in the year 2011, respectively. The rainfall pattern in the study area is characterized as unimodal with one distinct rainy season from May to August. The lowest mean and height annual temperature in the study area were from 17 to 23 °C, respectively.

## Geology

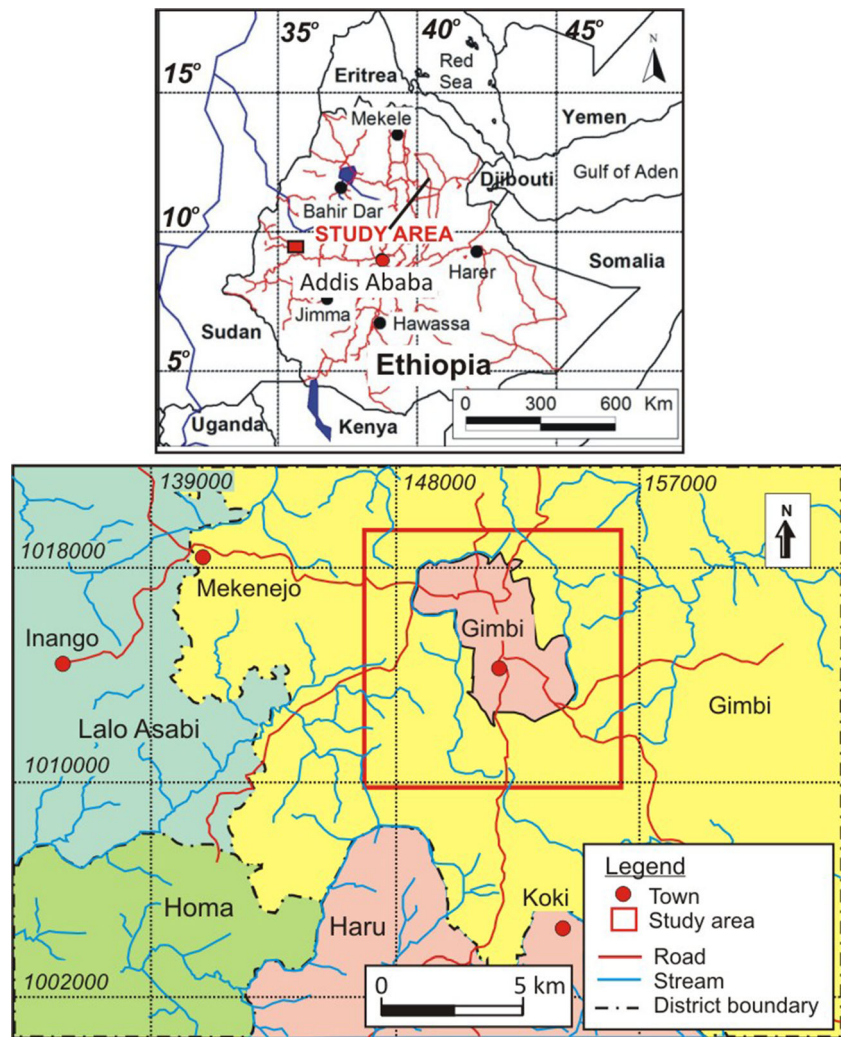
Rocks present in the study area belong to western basement rock types of Ethiopia, which age from Archean to upper Proterozoic and mainly comprise of high-grade gneiss and extensive low-grade volcano-sedimentary sequences (Kazmin 1973; Tefera 1991). The study area consists of five lithotectonic units: granitoid orthogneiss, gabbro, granite, granite-granodiorite, and metagabbro amphibolite (Fig. 2). Rocks belonging to granitoid orthogneiss unit mainly consist of granitic gneiss with subordinate granodiorite tonalite and

diorite gneiss. This lithology is grouped into Precambrian lithotectonic unit (GES 2005). The rocks belonging to this unit are mostly present in the western, northwestern, and southern parts of the study area. Gabbro unit is late-to-post-tectonic intrusive lithologic unit and is massive, medium to coarse grained, and have olivine gabbro, gabbro, and olivine diabase (GSE 2005). Rocks belonging to this unit are mostly present in the eastern and the southern parts of the study area. Granite is intrusive Precambrian rocks of late-to-post-tectonic times, which are massive, medium to coarse grained, and comprise alkali amphiboles and pyroxenes. These rocks are mainly present in the south and southwestern parts of the study area. Granite-granodiorite unit is present in the western parts of the study area, and it forms dominant part of the tectonic intrusive body with elliptical, circular, and subcircular outline. In general, the rocks are foliated, sheared, and are medium grained. Metagabbro amphibolite unit has elongated masses and has shear contact with the meta-ultramafic rocks. This unit is dominantly present in the central, northern, and southern areas. Metagabbro is the predominant rock type belonging to this unit, which is massive, dark green to greenish in color, and coarse to medium grained (GSE 2005). Quaternary superficial deposits: Residual, alluvial, and colluvial soils constitute the superficial deposits in the area. Majority of the study area is covered by the colluvial soil deposit, followed by the residual soil type. Residual soils are mainly present in the southern, central, and southwestern parts of the study area. The colluvial soils are present in the northern, central, and northeastern parts. Alluvial soils are present in the central portion of the study area. Most of the study area is covered by superficial soil deposits.

## Methodology

For landslide hazard zonation, probabilistic statistical method was followed. This method can provide functional relationships between various instability causative factors and the past and present distribution of landslides (Carrara 1983). For statistical methods, it is assumed that the past and the present are the keys to the future (Varnes 1984; Carrara et al. 1991). Thus, it is believed that the conditions led by various factors, which have resulted in past landslides, if re-occur in the area, landslides may re-occur (Aleotti and Chowdhury 1999; Dai et al. 2002; Lan et al. 2004; Girma et al. 2015; Raghuvanshi et al. 2015; Hamza and Raghuvanshi 2016). In order to rate the various causative factors likely to be responsible for re-occurrence of landslides with similar conditions in the area, quantitative prediction was developed based on the density ratio of the past landslides with respect to respective factor classes (Lee et al. 2004; Su'zen and Doyuran 2004; Girma et al. 2015). Later, with the derived ratings for various

Fig. 1 The study area



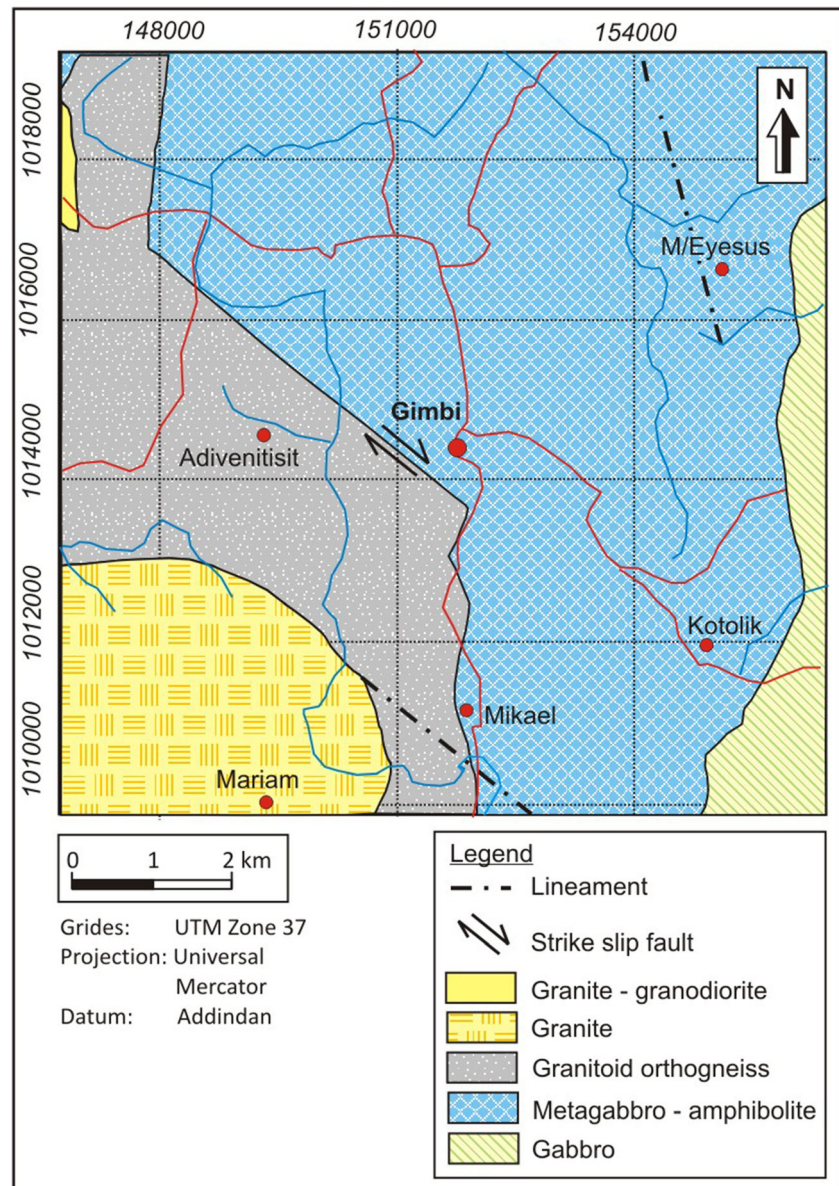
causative factors, each of the factor maps were analyzed and combined in GIS environment to produce LHZ map.

Nine factors were considered for the LHZ map preparation, viz., slope material, elevation, slope, aspect, curvature, land-use/land-cover, groundwater, distance to road, and distance to stream. These are the significant causative factors (Anbalagan 1992; Wang and Niu 2009; Raghuvanshi et al. 2014), which might have resulted in the occurrence of past landslides in the area. All these factors were individually evaluated in GIS environment to know the respective densities of the past landslides within each of the factor classes. Using the tool raster calculator in ArcGIS, total pixels occupied by each factor class and the total pixels covered by the landslides within the respective factor classes were assessed. Later, statistical hazard index, which is a ratio between percent of landslide occurrence to percent coverage of each factor, was derived for every factor subclasses (Lee and Min 2001). Further, based on these hazard index values and by assigning suitable weights to each factor, random trial combinations were attempted to

produce the LHZ map. Finally, the prepared LHZ map was validated with the past landslides in the area (Fig. 3).

### Data collection and landslide inventory analysis

Data pertaining to the factors related to landslides were collected from both secondary and primary sources. Secondary data included topographical maps, geological maps, satellite images, digital elevation model (DEM), and meteorological data (Table 1). Primary data were collected in the field, which included landslide inventory and mapping and verification and updating of causative factor maps prepared prior to the field work. To understand the landslide mechanism and the likely triggering factors that might have resulted into landslides, informal discussions were held with local respondents. Landslide inventory data are very important for landslide hazard evaluation and zonation, as it is presumed that the topographical, geological, hydrogeological, and climatic

**Fig. 2** Geology of the study area

conditions that have led to the past landslides in the area, may provide useful information for potential locations for the future landslides in an area (Dai et al. 2002; Lan et al. 2004; Raghuvanshi et al. 2015). Systematic observations, necessary for landslide hazard evaluation, were made in the field. Data on location, dimension, type of the material involved, type of failure, likely cause of failure, and damages it has caused in the area were recorded. Along the past landslide periphery, geographical coordinates were recorded with the help of handheld GPS. Later, with the help of GPS point data collected in the field during the inventory mapping and the Google Earth (2014), polygon data on 50 past landslides were created and mapped. Landslides were mostly observed in the eastern, central, and northeastern parts of the study area (Fig. 4).

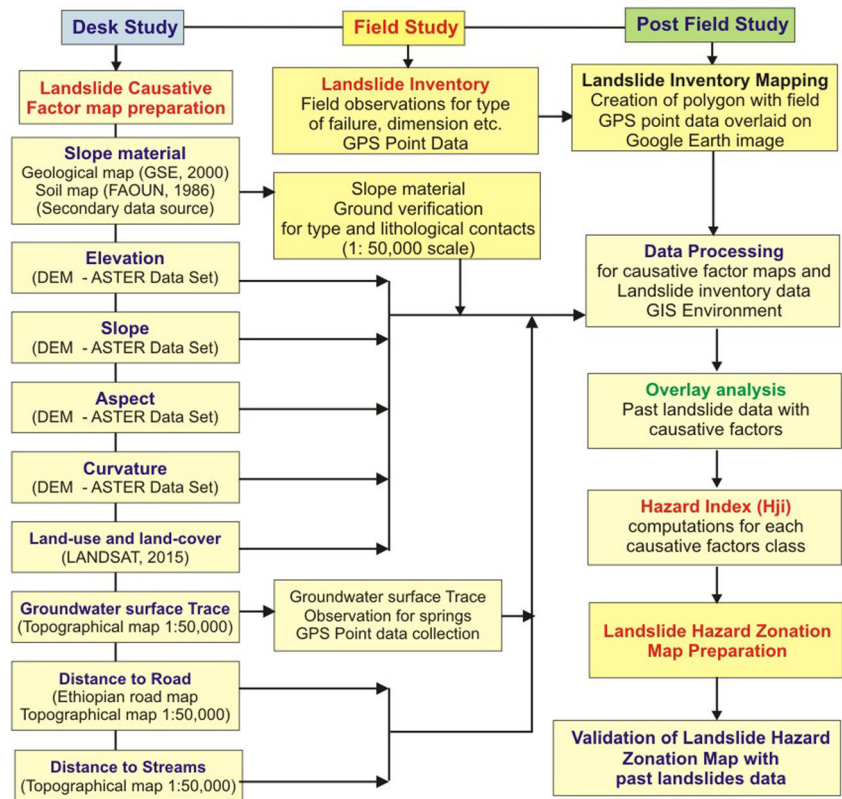
### Governing factors and distribution

For the present study, nine factors were considered for landslide hazard evaluation. These factors were slope material, elevation, slope, aspect, curvature, land-use/land-cover, groundwater surface traces, distance to road, and distance to streams. It was realized that possibly, a combination of these factors has resulted into landslide in the area.

### Slope material

Slope material map for the present study area was prepared at a scale of 1:50,000 by combining the lithological and soil

**Fig. 3** General methodology followed for the present study



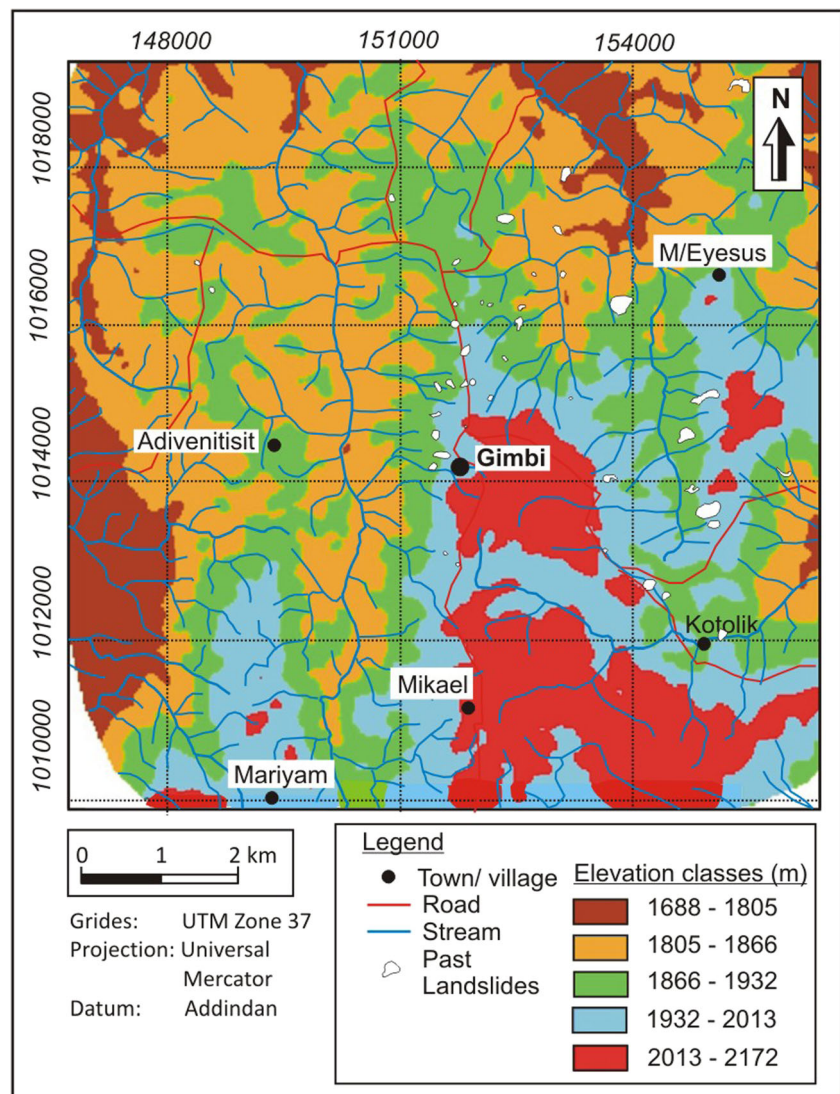
maps of the area. Lithological map was extracted from the geological map, prepared by the Geological Survey of Ethiopia (GSE 2000), and the soil map was prepared from the soil map of Ethiopia, prepared by Food and Agriculture Organization (FAOUN 1986). Later, through field survey and

image interpretation, this map was modified and updated. In the present study area, three types of soils viz., colluvial, residual, and alluvial soils are present (Fig. 5a). Colluvial soils are mostly present in the northern, western, and eastern parts of the study area and constitute about 48% of the area

**Table 1** Data layers for causative factors used in GIS analysis

No.	Particulars	GIS data type	Scale	Data source
1	Landslide inventory	Polygon coverage	1:50,000	Field observation GPS point data, Google Earth image (2014)
2	Slope material	Polygon coverage	1:50,000	Geological map prepared by Geological Survey of Ethiopia (GSE, 2000), soil map of Ethiopia prepared by Food and Agriculture Organization of United Nations (FAOUN, 1986), and field traverse observations and mapping
3	Elevation	Grid	90 m × 90 m	DEM Aster data set
4	Slope	Grid	90 m × 90 m	
5	Aspect	Grid	90 m × 90 m	
6	Curvature	Grid	90 m × 90 m	
7	Land-use/land-cover	Grid	0.5 m × 0.5 m	Landsat (2015)
8	Groundwater surface trace	Polygon coverage	1:50,000	Field observations—GPS point data
9	Distance to road	Grid	1:50,000	Ethiopian road map (1:2,250,000) topographical map (1:50,000)
10	Distance to streams	Grid	1:50,000	Topographical map (1:50,000)

**Fig. 4** Landslide inventory map of the study area



coverage, whereas residual soils are present in the southern, central, and southwestern parts of the study area and covers about 38% of the study area. The alluvial soils are mainly present in the central portion of the study area and covers only 13% of the study area.

### Elevation, slope, aspect, and curvature

Elevation, slope, aspect, and curvature of the present study area were prepared from the DEM at 90 m resolution, which was obtained from the ASTER data set (Table 1). Elevation was divided into five classes as shown in Fig. 4. The north, northwestern, and western parts of the study area is dominated by elevation class 1805–1866 m with area coverage of 32.9%. The elevation class 1866–1932 m covers about 25% of the study area and is distributed mainly in the central and

southwestern parts of the study area. The elevation class 1932–2013 m is distributed in the central, eastern, and southern parts of the study area and covers about 19.3% of the study area. The remaining elevation classes 1688–1805 m and 2013–2172 m covers 11.9 and 10.9% of the study area, respectively. The slope was categorized into five classes as shown in (Fig. 5b). The north, northwestern, and western parts of the study area are dominated by gentle slope classes ( $0^{\circ}$ – $5^{\circ}$ ,  $5^{\circ}$ – $10^{\circ}$ ,  $10^{\circ}$ – $25^{\circ}$ ) whereas moderate to steep slopes are mostly present in the central, eastern, and southeastern parts of the study area. Most of the study area is covered by viz.,  $10^{\circ}$  to  $25^{\circ}$  (47%),  $5^{\circ}$  to  $10^{\circ}$  (37%), and  $0^{\circ}$  to  $5^{\circ}$  (15%) slope classes. The slope aspect in the study area was characterized into 10 classes (Fig. 5c). These are in no particular dominant aspect classes and are evenly distributed throughout the study area. The slope curvature in the study area was classified into negative curvature ( $-4.4$ – $0$ ), flat ( $0$ ), and positive curvature ( $0$ –

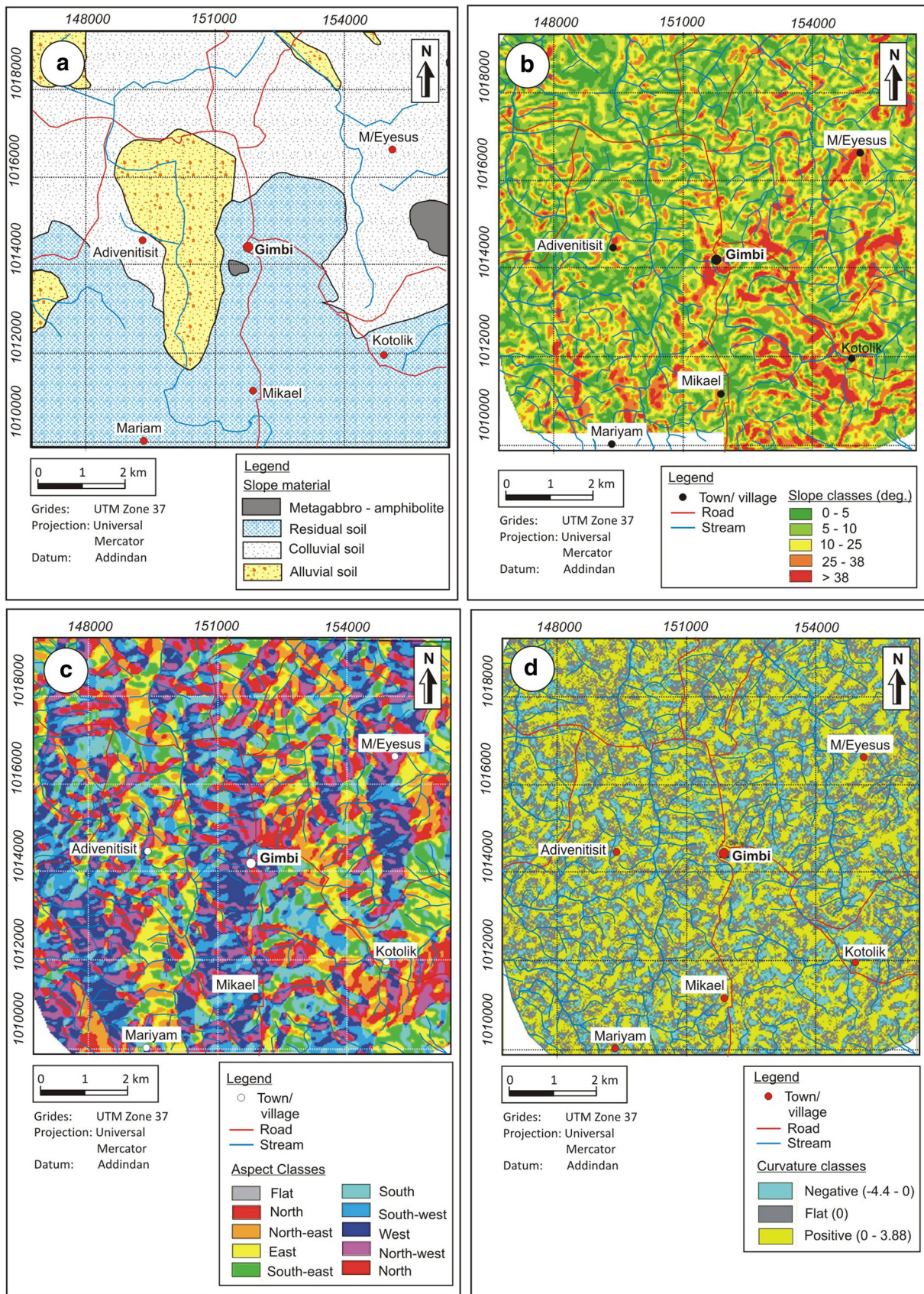


Fig. 5 Causative factor maps. a Slope material map. b Slope. c Aspect. d Curvature

3.88) (Fig. 5d). About 44% of the study area falls into negative curvature class, 13.4% into flat, and remaining 42.6% into positive curvature, respectively.

### Land-use/land-cover

The land-use/land-cover map was prepared from LANDSAT data through supervised classification using ERDAS Imagine. The delineated land-use/land-cover classes are shown in Fig. 6a. The cultivated land is mostly dominated (8.5%) in the eastern and southeastern parts of the study area. The higher elevation (above 2000 m) is mostly covered by dense forest (14.7%) and is distributed in the southern and southeastern parts of the study area (Fig. 6a). Densely vegetated areas are present in the southwestern, western, and northwestern parts and covers about 20.4% of the study area. Bare land is mostly present in the southeastern, eastern, and northeastern parts and cover about 19% of the study area. Bush land, sparsely vegetated, irrigated wetland, and built-up area cover 0.5, 15.7, 7.4, and 3.6% of the study area, respectively.

### Groundwater homogeneous zones

In order to incorporate the groundwater effect in hazard evaluation, indirect surface manifestations of groundwater such as springs were considered (Anbalagan 1992). It is believed that spring location over a slope may indicate groundwater proximity and relative saturation of the slope mass. Also, it has been observed that spring location and landslides have direct correlation (Girma et al. 2015; Raghuvanshi et al. 2015). Inventory was made to locate springs in the study area and 70 springs were located and mapped. Later, with the relative density of these springs within certain elevation range, hydrogeological homogeneous zones were delineated. Three such zones were identified as shown in Fig. 6b. In terms of area coverage, HGH-Zone-I covers 40.8% of the study area, whereas HGH-Zone-II and HGH-Zone-III cover 36.6 and 22.6% of the study area, respectively (Fig. 6b).

### Distance to roads and streams

In order to incorporate the effect of roads on slope stability, a buffer zone of 50 m on either side from the center line of existing roads was prepared. Later, proximity of roads to slopes was determined using Euclidean distance function in ArcGIS 10.2. The distance to road from the slopes was classified into four classes (Fig. 6c). Further analysis revealed that 38.2% of the slopes in the study area are less than 0.6 km from the existing roads, 30.3% of the slopes are within 0.6–1 km, 20.2% of slopes are within 1 to 2 km, and the remaining

11.3% of slopes are more than 2 km away from the existing road. In order to incorporate effect of streams in landslide evaluation process, proximity of stream to slopes was determined using Euclidean distance function in ArcGIS 10.2. Distance to streams was classified into five classes (Fig. 5d). In the study area, 31% slopes are 100 to 200 m away from streams, 28% in less than 50 m away, and 25% in 50 to 100 m away from the streams.

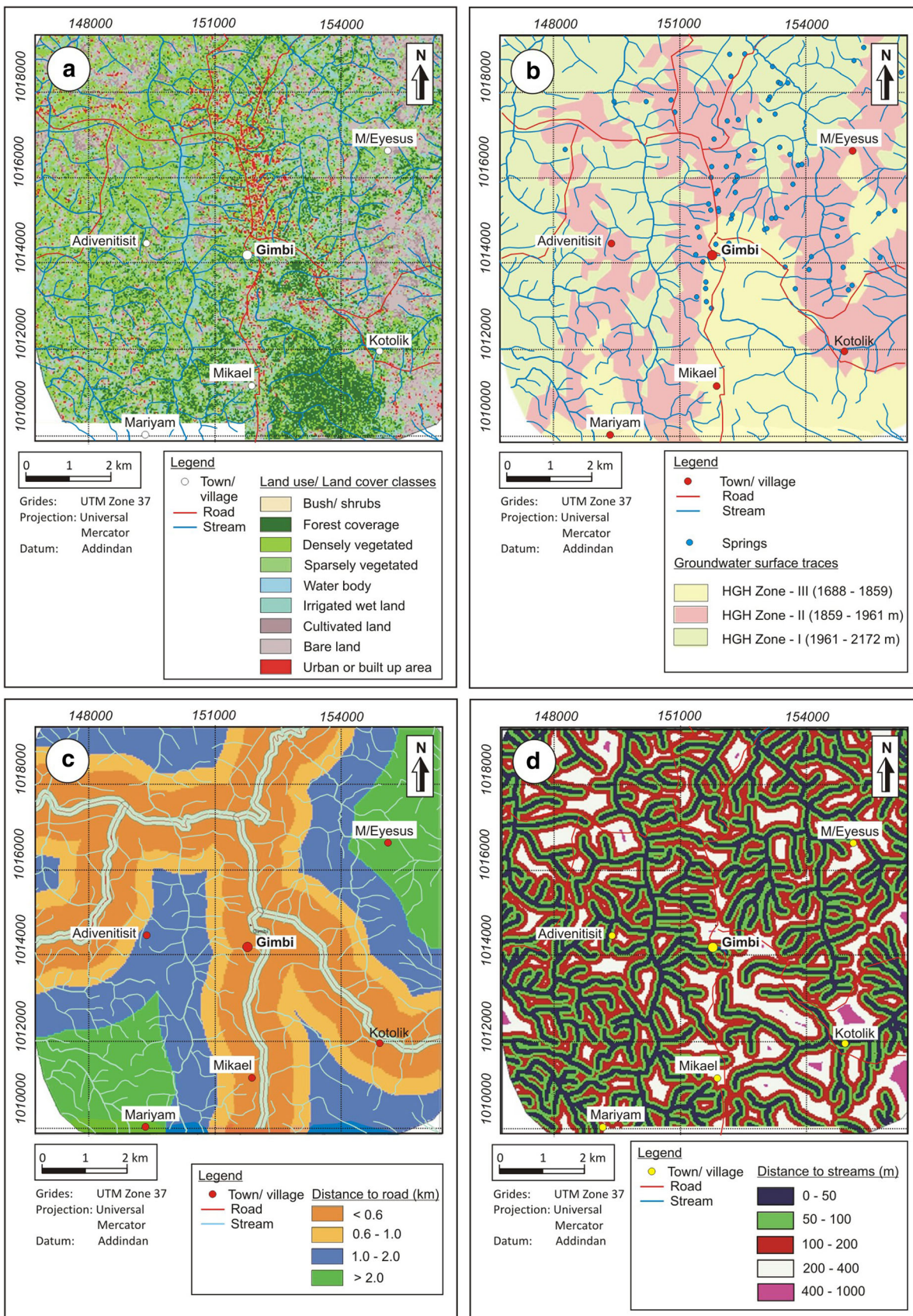
### Landslide hazard evaluation

Probabilistic statistical method was followed, and a density relationship between various factor classes and past landslides was established to work out the ratings for various factor classes and later in GIS environment, these ratings were combined to derive the LHZ map of the study area (Guzzettie et al. 1999; Dai and Lee, 2001; Su'zen and Doyuran 2004). Such statistical hazard model is basically based on an assumption that the conditions, which were responsible for the past landslides in the area, may form the basis to predict landslides in other areas (Varnes 1984; Carrara et al. 1992).

### Data preparation and GIS computations

In order to evaluate landslide hazard, a spatial database using all causative factors was prepared. The data layers and the respective sources of various causative factors used are presented in Table 1. The slope material map for the study area was prepared from secondary maps (Table 1) and was verified and updated during the field survey. Further, elevation, slope, aspect, and curvature were extracted from DEM. The land-use/land-cover patterns were prepared from Landsat data through supervised classification using ERDAS Imagine 2014. In order to prepare, “distance to stream” topographical map (1:50,000) was used and later, proximity of slopes to stream was determined using Euclidean distance function in ArcGIS 10.2. Similarly, for “distance to road” map, Ethiopian road map (1:2,250,000) and topographical map (1:50,000) were used. By taking a buffer zone of 50 m on either side from the center line of existing roads in the study area, proximity of slopes to roads was determined using Euclidean distance function in ArcGIS 10.2. The landslide inventory map was prepared through field investigation where all existing landslides were identified and GPS reading were taken along the periphery, later, with the help of Google Earth image (2014), polygon data for all observed past landslides in the study area was prepared. This landslide inventory map was further processed, and a vector to raster conversion was made to obtain 30 × 30 m pixels raster data set. For “groundwater homogeneous zones,” GPS point data at all observed springs in the area was collected and later, with the help of elevation





**Fig. 6** Causative factor maps. **a** Land-use and land-cover map. **b** Groundwater surface trace. **c** Distance to road. **d** Distance to stream

map, groundwater homogeneous zones were extracted. For all causative factor maps, suitable processing was carried out in GIS environment, to be later use in statistical analysis.

### Landslide hazard zonation

For landslide hazard evaluation, probabilistic statistical approach was followed. The core of this approach was to find out a quantitative relationship between various factor classes and past landslides in the area. In order to understand the quantitative relationship, all factor maps and landslide inventory map were processed in GIS environment, and the total pixel count for each factor class where landslide occurred and landslide did not occur were deduced (Tables 2 and 3). The pixel count for the total area where landslide did not occur is 98,839, whereas the area where landslide occurred had 320 pixels. In order to deduce the relative significance of each individual factor class of respective causative factors having potential for landslide, hazard index was calculated (Lee and Min 2001) as a ratio between landslide occurred to landslide did not occur within a given factor class. If the hazard index for a given factor class is less than 1, it shows less probability of that factor class for landslide whereas if this value is greater than 1, it shows more probability in contributing for landslide. The hazard index for various causative factor classes is presented in Tables 2 and 3.

For landslide hazard zonation, all nine factor maps were processed in GIS environment, and the maximum hazard index values ( $H_{ji}$ ) for each factor map were normalized and scaled to 1 (Table 4). The normalized hazard index values ( $H_{ji}$ ) (scaled to 1) are the ratio between corresponding hazard index value ( $H_{ji}$ ) for a causative factor class ( $i$ ) and the maximum hazard index value ( $H_{ji}$ ) within that causative factor ( $j$ ). Thus, a hazard index value of 1 represents most significant factor class ( $i$ ) for a respective causative factor ( $j$ ) that may contribute most to the landslide occurrence. In order to incorporate the relative contribution of individual factor, suitable weightings were also assigned. In the present case, equal weight ( $W_j$ ) of 1 was assigned to each causative factor (Table 4). The reason for assigning equal weight to all the factors was based on the fact that relative contribution of individual parameter in inducing instability to slopes cannot be quantified and it was assumed that each of these factors may have relative contribution for instability. Using these ratings, LHZ map was prepared using ArcGIS 10.2. The landslide hazard was evaluated by using Eq. (1)

$$x = F(x) \sum_{j=1}^9 ((W_j \cdot H_{ji})x) / \sum_{j=1}^9 (W_j) \quad (1)$$

where “ $x$ ” is the estimated hazard, “ $H_{ji}$ ” is the hazard index for class “ $i$ ” of causative factor “ $j$ ,” “ $W_j$ ” is a weighting assigned to causative factor “ $j$ ,” and  $F(x)$  is a filter function varying between 0 and 1.

Based on the estimated hazard values, landslide hazard classes were defined as no hazard, low hazard, medium hazard, high hazard, and very high hazard. In order to obtain the most suitable distribution of estimated hazard values for various landslide hazard classes, trial attempts were made. Later, for each trial efforts, overlay analysis between prepared LHZ map and the past landslide inventory map was made. The best validation was obtained for the hazard value distribution as presented in Table 5.

## Results and Discussion

### Landslide inventory

The landslides in the study area have caused widespread damage in Gimbi town and surrounding areas. The landslide inventory in the present study area showed 50 prominent landslides characterized as translational, rotational, and flow type of slides. The past landslides were dominated in the central, eastern, and northeastern parts of the study area. Majority of these slides occurred in colluvial type of soils. Most of the past landslides occurred in gentle slopes along the gullies and stream banks. As reported, these landslides were mainly triggered by long-duration rainfall. The slope stability in the area is influenced by the unstable unconsolidated slope material, rugged topography, and complex hydrological conditions.

### Governing factor influence and hazard potential

#### *Slope material*

Landslide inventory data showed that 78.9% of past landslides occurred within colluvial soils, 19.9% within residual soils, and only 1.2% landslides occurred in alluvial soils (Fig. 7). No landslides were observed in the rocky area. Table 2 shows that potential for landslides in slopes having colluvial soils is very high as the hazard index is 1.7. In contrast, the probability of landslide occurrence in alluvial, residual, and metagabbro amphibolites is low as the hazard index values were 0.03, 0.4, and 0, respectively. Getting high hazard index value for colluvial soils is reasonable as colluvial soils are unstable and readily destabilized when get saturated (Raghuvanshi et al. 2014; Hamza and Raghuvanshi 2016).

#### *Elevation, slope and aspect*

It was found that about 44.6% of past landslides occurred in 1932–2013 m elevation class, followed by 32.6% in 1866–

**Table 2** Hazard index for various classes of inherent causative factors

Causative factors and corresponding factor class	Landslide did not occur		Landslide occurred		Hazard index (Hij) (b/a)	Past landslide occurrence (%)
	Count	Ratio (a) (%)	Count	Ratio (b) (%)		
<b>(a) Slope material</b>						
Alluvial	13,087	13.2	1	0.3	0.03	1.2
Colluvial	47,467	48.0	266	83.1	1.7	78.9
Residual	38,186	38.7	53	16.6	0.4	19.9
Metagabbro amphibolite	99	0.1	0	0	0	0
Total	98,839	100	320	100	–	100
<b>(b) Elevation (m)</b>						
1688–1805	11,860	12	13	4	0.3	7.5
1805–1866	32,617	33	72	22.5	0.7	15.3
1866–1932	24,710	25	115	36	1.4	32.6
1932–2013	18,779	19	120	37.5	1.9	44.6
2013–2172	10,873	11	0	0	0	0
Total	98,839	100	320	100	–	100
<b>(c) Slope (degree)</b>						
0–5	15,351	15.5	19	5.9	0.4	11.7
5–10	36,597	37	90	28.1	0.7	23.5
10–25	46,022	46.6	209	65.3	1.4	43.2
25–38	869	0.9	2	0.6	0.7	21.6
> 38	0	0	0	0	0	0
Total	98,839	100	320	100	–	100
<b>(d) Aspect</b>						
Flat	10,254	10.4	33	10.3	0.9	10.2
N	10,635	10.8	28	8.8	0.8	8
NE	9068	9.2	20	6.3	0.7	7
E	8687	8.8	12	3.7	0.4	4
SE	7960	8.0	14	4.4	0.5	5.8
S	8192	8.3	21	6.6	0.8	8
SW	9935	10.0	70	21.9	2.1	22.2
W	11,038	11.2	42	13.1	1.2	12.3
NW	10,922	11.0	52	16.2	1.4	15.2
NNW	12,148	12.3	28	8.7	0.7	7.3
Total	98,839	100	320	100	–	100
<b>(e) Curvature</b>						
Negative (– 4.4–0)	43,584	44.1	180	56.2	1.3	42
Flat (0)	13,251	13.4	46	14.4	1.1	35.5
Positive (0–3.88)	42,004	42.5	94	29.4	0.7	22.5
Total	98,839	100	320	100	–	100
<b>(f) Land-use and land-cover</b>						
Bush land	504	0.5	2	0.6	1.2	12.4
Forest land	14,564	14.8	44	13.8	0.9	9.3
Densely vegetated land	20,200	20.4	40	12.5	0.6	6.2
Sparsely vegetated	15,489	15.7	57	17.8	1.1	11.7
Water body/springs	9847	9.9	39	12.2	1.2	12.4
Irrigated wetland	7342	7.4	25	7.8	1.0	11.3

**Table 2** (continued)

Causative factors and corresponding factor class	Landslide did not occur		Landslide occurred		Hazard index (Hij) (b/a)	Past landslide occurrence (%)
	Count	Ratio (a) (%)	Count	Ratio (b) (%)		
Cultivated land	8477	8.6	41	12.8	1.5	15.5
Bare land	18,880	19.1	60	18.8	0.9	10.2
Urban/build-up area	3536	3.6	12	3.7	1.0	11
Total	98,839	100	320	100	–	100
(g) Groundwater surface traces						
HGH-Zone-I (1688–1859 m)	40,404	40.9	70	21.9	0.5	18
HGH-Zone-II (1859–1961 m)	36,063	36.5	197	61.5	1.7	57
HGH-Zone-III (1961–2172 m)	22,372	22.6	53	16.6	0.7	25
Total	98,839	100	320	100	–	100

1932 m elevation class (Fig. 7). The remaining landslides occurred in elevation classes 1805–1866 m (15.3%) and 1688–1805 m (7.5%). No landslides were observed in elevation class 2013–2172 m. Potential for landslide in elevation class 1932–2013 m and 1866–1932 m is very high as the hazard index values are 1.9 and 1.4, respectively (Table 2). However, other elevation classes show less probability for landslides as hazard index is less than 1. The reason for getting high hazard values for elevation class 1932–2013 m and 1866–1932 m may be related to the fact that in these elevations, mostly colluvial and residual soils are present. Residual soils are under the influence of surface flows, results into gully erosion (Raghuvanshi et al. 2014).

Past landslide data revealed that 43.2% landslides occurred in slope class 10°–25°, whereas 23.5 and 21.6% occurred in slope class 5°–10° and 25°–38°, respectively (Fig. 7). Further, 11.7% landslide was recorded in slope class 0°–5°, and no landslide was observed in slope class > 38°. High concentration of landslides was observed in gentle slopes (5°–25°), which account for about 67%. The density analysis revealed that most susceptible slopes in the present study area fall under gentle slope category of 10°–25° range. The hazard index value for this class was computed to be 1.4. Other slope classes in the study area show low probability for slope instability as the hazard index values are much < 1 (Table 2). Gentle slopes in the study area are formed by the colluvial and residual soils, which are susceptible for instability (Hamza and Raghuvanshi 2016). Much of the gentle slopes in the study area are used for cultivation, which induces instability due to slope alterations and enhanced soil moisture due to periodic irrigation (Raghuvanshi et al. 2014).

Past landslides in the study area revealed that 22.2% occurred in slopes facing towards southwest, 15.2% in northwest, and 12.3% in slopes facing towards west direction, respectively (Fig. 7). Other landslides occurred in slopes facing towards north (8%), south (8%), north-northwest (7.3%), northeast (7%), southeast (5.8%), and east (4%), respectively. This shows that concentration of landslides (49.7%) was in slopes facing towards southwest, northwest, and west. Slopes oriented towards southwest, west, and northwest show high probability for landslide occurrence (Table 2). The probability of slope failure in other aspect classes is low as the hazard index values are less than 1. The high hazard index values for slopes oriented towards southwest, west, and northwest may possibly be correlated with the distance of groundwater flow. As observed during the field work, majority of the springs in the area are on slopes oriented towards northwest and southwest directions.

#### Curvature

About 42% of the past landslides fell within negative curvature class, 35.5% in flat, and the remaining 22.5% in positive

**Table 3** Hazard index for various classes of external causative factors

Causative factors and corresponding factor class	Landslide did not occur		Landslide occurred		Hazard index (b/a)	Percent landslide occurrence
	Count	Ratio (a) (%)	Count	Ratio (b) (%)		
<b>(a) Distance to road (km)</b>						
< 0.6	37,774	38.2	107	33.4	0.8	22
0.6–1.0	29,998	30.4	83	25.9	0.8	21
1.0–2.0	19,967	20.2	101	31.6	1.5	38
> 2.0	11,100	11.2	29	9.1	0.8	19
Total	98,839	100	320	100	–	100
<b>(b) Distance to streams (m)</b>						
0–50	27,823	28.2	69	21.6	0.7	20.5
50–100	25,040	25.3	86	26.9	1.1	28
100–200	31,070	31.4	143	44.6	1.4	38.5
200–400	13,847	14.0	22	6.9	0.5	13
400–1000	1059	1.1	0	0	0	0
Total	98,839	100	320	100	–	100

curvature class, respectively (Fig. 7). Relatively higher concentration (42%) in negative curvature class justifies the susceptibility of negative curvature slopes (Lee and Min 2001). Slopes having negative and flat curvature in the study area show high probability for landslides as the hazard index values are 1.3 and 1.1, respectively (Table 2). The high hazard index value for negative curvature slopes is justified, as negative curvature is more susceptible for instability (Lee and Min 2001). However, high hazard index value in flat curvature slopes in the study area indicates dominance of other causative factors over curvature.

#### Land-use/land-cover

Past landslide data (Fig. 7) indicates that 15.5% of landslides occurred within cultivated land, 12.4% both in bush land and along water bodies/springs, 11.7% in sparsely vegetated area, 11.3% in irrigated wetland, and 11% in urban/built-up area. The remaining 38.1% of landslides occurred in forest land, densely vegetated land and barren land. From the landslide distribution, it can be seen that landslides are more or less distributed in every class and do not show relative dominance in a particular class, except for cultivated land (15.5%). The probability of landslides in most of the land-use/land-cover classes is high as the index values are > 1 except for the forest land, densely vegetated land, and bare land classes where the hazard index values are < 1. In general, relatively cultivated land shows high probability for landslide occurrence as the hazard index value is 1.5 (Table 2). Cultivated lands in the study area are mostly on gentle slopes, which are composed of colluvial and residual soils. Gentle slopes (10° to 25°) have

high probability for landslides in the study area. Also, colluvial and residual soils are susceptible for instability. Further, cultivation practices on such soils make them unstable due to increase in saturation by frequent irrigation and alteration in slope geometry to make these slopes cultivable (Raghuvanshi et al. 2014).

#### Groundwater surface traces

Based on the evaluation of the past landslide data, 57% of the landslides occurred within HGH-Zone-II, followed by HGH-Zone-III (25%), and remaining 18% in HGH-Zone-I (Fig. 7). The dominance of past landslides within HGH-Zone-II (1859 to 1961 m) and equally high density of springs within the elevation class 1859 to 1961 m clearly shows a good correlation between springs and landslides. HGH-Zone-II on elevation range 1859 to 1961 m was more susceptible for landslides as the hazard index value was 1.7. The other two zones, HGH-Zone-I and HGH-Zone-III showed low probability for landslide (Table 2). The HGH-Zone-II is more susceptible for instability because most of the springs in the study area fall within this zone. The presence of springs on slopes suggests proximity to groundwater and relative saturation of slope material which in turn increases susceptibility of slopes for instability (Raghuvanshi et al. 2015).

#### Distance to roads and streams

The overlay analysis revealed that 38% of past landslides occurred in class 1–2 km, 22% in class < 6 km, 21% in 6–1 km, and the remaining 19% in class > 2 km, respectively (Fig. 7).

**Table 4** Hazard index and weightings for various causative factors

Causative factors (j)	Causative factor class (i)	Weightings (W <sub>j</sub> )	Hazard index (H <sub>ji</sub> )	Hazard index scaled to 1 (H <sub>ji</sub> )
Slope material	Alluvial	1	0.03	0.02
	Colluvial		1.7	1
	Residual		0.4	0.23
	Metagabbro amphibolite		0	0
Elevation (m)	1688–1805	1	0.3	0.16
	1805–1866		0.7	0.36
	1866–1932		1.4	0.73
	1932–2013		1.9	1
	2013–2172		0	0
Slope (degree)	0–5	1	0.4	0.28
	5–10		0.7	0.5
	10–25		1.4	1
	25–38		0.7	0.5
	> 38		0	0
Aspect	Flat	1	0.9	0.42
	N		0.8	0.38
	NE		0.7	0.33
	E		0.4	0.19
	SE		0.5	0.24
	S		0.8	0.36
	SW		2.1	1
	W		1.2	0.57
	NW		1.4	0.67
	NNW		0.7	0.33
Curvature	Negative (– 4.4–0)	1	1.3	1
	Flat (0)		1.1	0.84
	Positive (0–3.88)		0.7	0.54
Land-use and land-cover	Bush land	1	1.2	0.8
	Forest land		0.9	0.6
	Densely vegetated land		0.6	0.4
	Sparsely vegetated		1.1	0.73
	Water body/springs		1.2	0.8
	Irrigated wetland		1.0	0.7
	Cultivated land		1.5	1
	Bare land		0.9	0.6
	Urban/build-up area		1.0	0.7
	HGH-Zone-I (1688–1859 m)		1	0.5
HGH-Zone-II (1859–1961 m)	1.7	1		
HGH-Zone-III (1961–2172 m)	0.7	0.41		
Distance to road (km)	< 0.6	1	0.8	0.53
	0.6–1.0		0.8	0.53
	1.0–2.0		1.5	1
	> 2.0		0.8	0.53
Distance to streams (m)	0–50	1	0.7	0.50
	50–100		1.1	0.78
	100–200		1.4	1
	200–400		0.5	0.35
	400–1000		0	0

Thus, about 43% landslides occurred within slopes, which are at a distance < 1 km from roads. It was expected that slopes in close proximity to roads may have higher probability for instability. However, density analysis showed that slopes, which are 1 to 2 km away from the roads, have higher probability for landslides, as the hazard index value for this range is 1.5 (Table 3). This shows more dominance of other factors in inducing instability than proximity to roads.

Overlay analysis between distance to stream and past landslides in the area has revealed that 38.5% landslides occurred in slopes, which were 100–200 m away from the streams, 28% between 50 and 100 m, and 20.5% between 0 and 50 m classes, respectively (Fig. 7). Thus, about 87% of past landslides occurred in slopes, which were 0 to 200 m away from the streams. The analysis showed fair correlation between distance to stream and past landslides. Here, it is important to

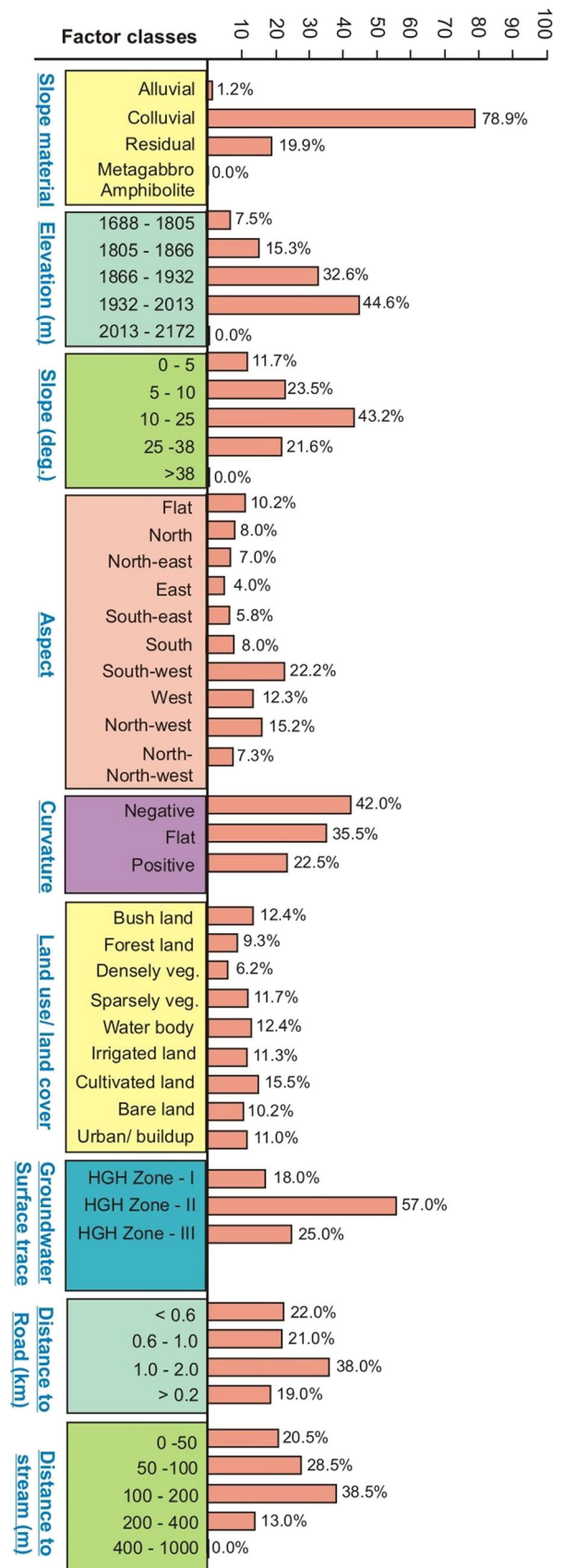
**Table 5** Hazard classification

Landslide hazard class	Landslide hazard classification	Estimated landslide hazard ( $x$ )
1	No hazard (NH)	0–0.1
2	Low hazard (LH)	0.1–0.37
3	Medium hazard (MH)	0.37–0.64
4	High hazard (HH)	0.64–0.9
5	Very high hazard (VHH)	0.9–1.0

understand that landslide is a complex geo-process, which depends on several factors (Anbalagan 1992; Ayalew et al. 2004; Wang and Niu 2009; Raghuvanshi et al. 2014; Raghuvanshi et al. 2015) and no single factor can provide full evaluation. However, understanding significance of individual factors and their correlation with the past landslides may provide a useful guide for landslide hazard evaluation in a given area (Varnes 1984; Carrara et al. 1991; Girma et al. 2015). The slopes in the study area, which are 50 to 200 m away from the streams, have higher probability for landslides as the hazard index value is > 1 (Table 3). In the study area, it was observed that streams have resulted in to erosion, stream bank erosion, and gully erosion at several locations. All such features induce instability to slopes (Raghuvanshi et al. 2014).

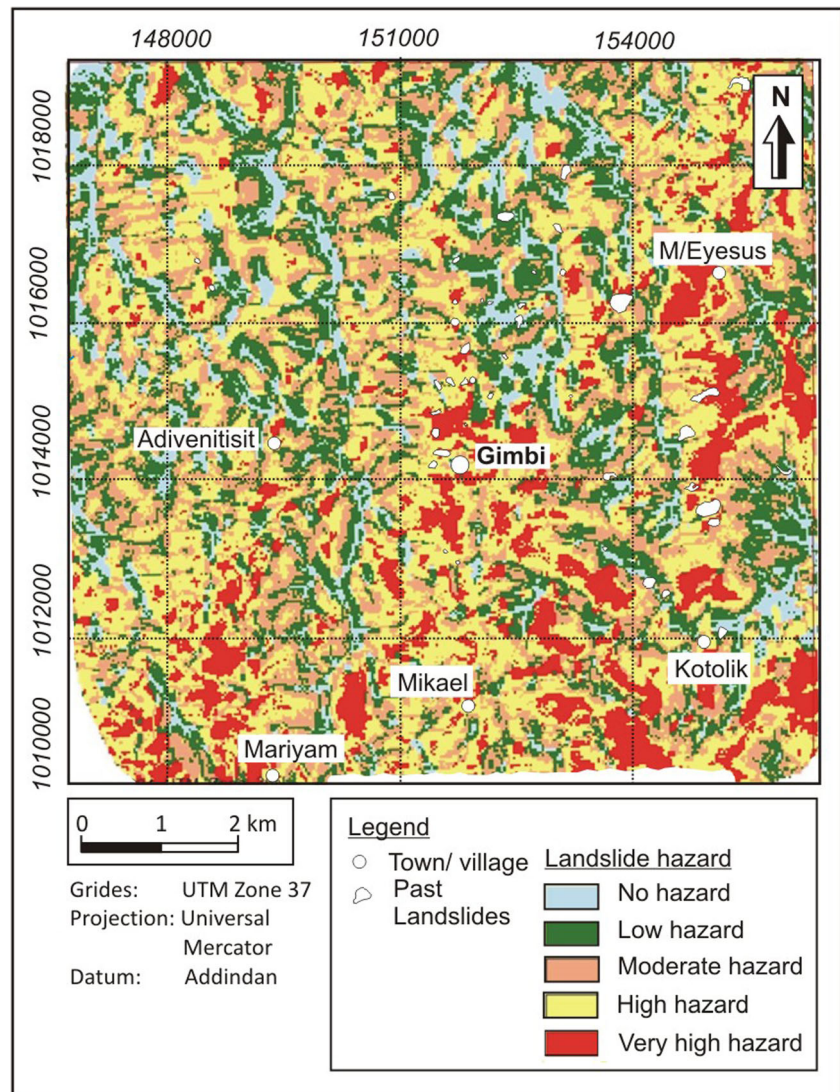
*Landslide hazard zonation and distribution*

The landslide hazard zonation of the study area revealed that 12.2% (11.5 km<sup>2</sup>) of the study area falls into very high hazard (VHH), 30.7% (29 km<sup>2</sup>) in high hazard (HH), 24.3% (23 km<sup>2</sup>) in moderate hazard (MH), 23.3% (22 km<sup>2</sup>) in low hazard (LH), and remaining 9.5% (9 km<sup>2</sup>) in no hazard (NH) zones. Figure 8 indicates that very high hazard zones are mainly concentrated in southern and eastern parts of the study area and have scattered distribution in the central and northern parts. In very high hazard zones, the slope is mainly composed of residual soils in higher elevations and colluvial soils in lower elevations. High hazard zones are evenly distributed throughout the study area with relatively more concentration towards southern and eastern parts of the study area. This zone is also found in slopes, which are mainly composed of residual and colluvial soils. Further, high hazard zones in the study area are characterized by high variations in elevation. Many springs in the area fall in this zone. Moderate hazard zones are concentrated in the central and eastern parts and have scattered distribution throughout the study area. Low hazard zones are mainly distributed in the eastern, western, and northern parts of the study area. They are mostly found in flat areas within the colluvial soils. No hazard zone is distributed in the northern and northwestern parts. This zone is characterized mostly



**Fig. 7** Governing factors influence on past landslides

**Fig. 8** Landslide hazard zonation map of the study area



by flat area and found along the banks of the stream. Some scattered areas with low hazard also fall within the highly elevated areas. In general, landslide hazard zonation does not show dominance of any factor or factors among particular hazard zone. However, concentration of VHH and HH in the south, southeastern, and eastern parts may be related to the presence of colluvial and residual soils, moderate to steep slopes, higher elevation, and to some extent to hydrogeological factors.

#### Validation of LHZ map

It was revealed that 25% of the past landslides fell within VHH zone, 37% fell within HH zone, 13% within MH zone, 16% in LH zone, and remaining 9% within NH zone (Fig. 8). From the landslide distribution within various hazard zones, it can be noted that about 62% of past landslides within the very

high hazard and high hazard zones and 13% within medium hazard zone that also have probability of landslide occurrence. With this distribution, about 75% of the past landslides validates with the prepared LHZ map. The remaining 25% landslides, which do not validate and fell within low hazard and no hazard zones, may possibly be on account of limitations of the methodology that was followed during the present study. Statistical approach followed during the present study was applied at a medium scale (1:50,000) and certain factors, which may be responsible for instability, cannot be considered at this scale (Ayele et al. 2014). Factors such as shear strength of slope material, water forces within soil and rock mass, and characteristics of discontinuities are responsible in defining stability condition of a slope. However, these factors can only be considered when deterministic approach at detailed scales (> 5000) is followed on individual slope basis (Hamza and Raghuvanshi 2016).



## Conclusion

The Gimbi town and the surrounding areas are severely affected by the landslides and related slope instability problems. Villages Kotolik in southeastern part, M/Eyesus in northeastern part, and Mariyam in southern part of the study area also fall within the high hazard and very high hazard zones. Thus, it is clear that much of the populated sites in the present study area are at risk of landslides. Hence, it is essential to initiate measures to mitigate landslide problems in the area. More detailed slope stability studies are required, particularly in the high hazard and very high hazard zones to develop stability measures. Hazard zones delineated as low hazard or no hazard in LHZ map may be utilized for future planning and implementation of new developmental activities, if essential.

**Acknowledgements** We are thankful to the head of School of Earth Sciences, College of Natural and Computational Sciences, Addis Ababa University, for all kinds of support during the present study. We also thank the anonymous reviewers for their valuable comments to the manuscript.

## References

- Aleotti P, Chowdhury R (1999) Landslide hazard assessment: summary review and new perspectives. *Bull Eng Geol Environ* 58:21–44
- Anbalagan R (1992) Landslide hazard evaluation and zonation mapping in mountainous terrain. *Eng Geol* 32:269–277
- Ayalew L (1999) The effect of seasonal rainfall on landslides in the highlands of Ethiopia. *Bull Eng Geol Environ* 58:9–19
- Ayalew L, Yamagishi H (2004) Slope failures in the Blue Nile basin, as seen from landscape evolution perspective. *Geomorphology* 61:1–22
- Ayalew L, Yamagishi H, Ugawa N (2004) Landslide susceptibility mapping using GIS-based weighted linear combination, the case in Tsugawa area of Agano River, Niigata Prefecture, Japan. *Landslides* 1:73–81
- Ayele S, Raghuvanshi TK, Kala PM (2014) Application of remote sensing and GIS for landslide disaster management—a case from Abay Gorge, Gohatsion–Dejen section, Ethiopia. In: Singh, M., Singh, R.B., Hassan, M.I. (Eds.), *Landscape ecology and water management, proceedings of International Geographical Union (IGU) Rohtak Conference, Adv. Geogr. Environ. Sci.* Springer, Japan, pp 15–32
- Ayeneu T, Barbieri G (2005) Inventory of landslides and susceptibility mapping in the Dessie area, Northern Ethiopia. *Eng Geol* 77:1–15
- Bommer JJ, Rodriguez CE (2002) Earthquake-induced landslides in Central America. *Eng Geol* 63:189–220
- Carrara A (1983) Multivariate methods for landslide hazard evaluation. *Math Geol* 15:403–426
- Carrara A, Cardinali M, Detti R, Guzzetti F, Pasqui V, Reichenbach P (1991) GIS techniques and statistical models in evaluating landslide hazard. *Earth Surf Process Landf* 6:427–445
- Carrara A, Cardinali M, Guzzetti F (1992) Uncertainty in assessing landslide hazard and risk. *ITC J* 2:172–183
- Carrara A, Cardinali M, Guzzetti F, Reichenbach P (1995) GIS technology in mapping landslide hazard. In: Carrara A, Guzzetti F (eds) *In: geographical information system in assessing natural hazard.* Kluwer Academic Publisher, Netherlands, pp 135–175
- Casagli N, Catani F, Puglisi C, Delmonaco G, Ermini L, Margottini C (2004) An inventory-based approach to landslide susceptibility assessment and its application to the Virginio River Basin. *Italy Environ Eng Geosci* 3:203–216
- Collison A, Wade S, Griffiths J, Dehn M (2000) Modelling the impact of predicted climate change on landslide frequency and magnitude in SE England. *Eng Geol* 55:205–218
- Dahal RK, Hasegawa S, Masuda T, Yamanaka M (2006) Roadside slope failures in Nepal during torrential rainfall and their mitigation. *Disaster Mitigation of Debris Flows, Slope Failures and Landslides*, pp 503–514
- Dai FC, Lee CF (2001) Terrain-based mapping of landslide susceptibility using a geographical information system: a case study. *Can Geotech J* 38:911–923
- Dai FC, Lee CF, Ngai YY (2002) Landslide risk assessment and management: an overview. *Eng Geol* 64:65–87
- Daniel G (1977) *Aspect of climate and water balance in Ethiopia.* Addis Ababa University press, Addis Ababa, p 79
- Fall M, Azzam R, Noubactep C (2006) A multi-method approach to study the stability of natural slopes and landslide susceptibility mapping. *Eng Geol* 82:241–263
- FAOUN (1986) (Food and Agriculture Organization of the United Nations), *Ethiopian Highlands Reclamation Study*, Food and Agriculture Organization of the United Nations, Rome, pp. 334
- Girma F, Raghuvanshi TK, Ayeneu T, Hailemariam T (2015) Landslide hazard zonation in Adda Berga District, Central Ethiopia—a GIS based statistical approach. *J of Geomatics* 9:25–38
- GSE (Geological survey of Ethiopia) (2000) *Geology of the Gimbi area.* Compiler Alemu, T. and Abebe, T., *Memoir* 15: p. 157
- GSE (Geological survey of Ethiopia) (2005) *Explanatory notes to the hydrogeological and hydrochemical maps of the Gimbi area.* Compiler, Demis A, Muhedin A, Kefale T, Andarege M, Bisrat L, Michek R, Jiri S, Viona, IP.142. [https://doi.org/10.1016/S0169-555X\(99\)00078-1](https://doi.org/10.1016/S0169-555X(99)00078-1)
- Guzzetti F, Carrara A, Cardinali M, Reichenbach P (1999) Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, central Italy. *Geomorphology* 31(1–4): 181–216
- Hamza T, Raghuvanshi TK (2016) GIS based landslide hazard evaluation and zonation—a case from Jeldu District, Central Ethiopia. *Journal of King Saud University–Science.* <https://doi.org/10.1016/j.jksus.2016.05.002>
- Hoek E, Bray JW (1981) *Rock slope engineering (revised third edition).* Institute of Mining and Metallurgy, London, p 358
- Kanungo DP, Arora MK, Sarkar S, Gupta RP (2006) A comparative study of conventional, ANN black box, fuzzy and combined neural and fuzzy weighting procedures for landslide susceptibility zonation in Darjeeling Himalayas. *Eng Geol* 85:347–366
- Kazmin V (1973) *Geological map of Ethiopia.* Ministry of Mines, Energy and Water Resources, Geological Survey of Ethiopia, First edition. Addis Ababa
- Keefer DV (2000) Statistical analysis of an earthquake-induced landslide distribution—the 1989 Loma Prieta, California event. *Eng Geol* 58: 231–249
- Lan HX, Zhou CH, Wang LJ, Zhang HY, Li RH (2004) Landslide hazard spatial analysis and prediction using GIS in the Xiaojiang watershed, Yunnan. *China Eng Geol* 76:109–128
- Lee S, Min K (2001) Statistical analysis of landslide susceptibility at Yongin. *Korean Environ Geol* 40:1095–1113 <https://doi.org/10.1007/s002540100310>
- Lee S, Rhyu JH, Won JS, Park HJ (2004) Determination and application of the weights for landslide susceptibility mapping using an artificial neural network at south. *Korean Eng Geol* 71:289–302
- Leroi E (1997) Landslide risk mapping: problems, limitation and developments. In: Cruden F (ed) *Landslide risk assessment.* Balkema, Rotterdam, pp 239–250

- Parise M, Jibson RW (2000) A seismic landslide susceptibility rating of geologic units based on analysis of characteristics of landslides triggered by the 17 January, 1994 Northridge, California earthquake. *Eng Geol* 58:251–270
- Raghuvanshi TK, Ibrahim J, Ayalew D (2014) Slope stability susceptibility evaluation parameter (SSEP) rating scheme—an approach for landslide hazard zonation. *J Afr Earth Sci* 99:595–612
- Raghuvanshi TK, Negassa L, Kala PM (2015) GIS based grid overlay method versus modeling approach—a comparative study for landslide hazard zonation (LHZ) in Meta Robi District of west Shewa Zone in Ethiopia. *Egypt J Remote sensing Space Sci* 18(2):235–250
- Suzen ML, Doyuran V (2004) Data driven bivariate landslide susceptibility assessment using geographical information systems: a method and application to Asarsuyu catchment. Turkey *Eng Geol* 71:303–321
- Terefa M (1991) Geology of the Kurmuk and Asosa area: preliminary report. Ethiopian Institute of Geological Surveys, pp 112
- Varnes DJ (1984) Landslide hazard zonation: a review of principles and practice. UNESCO, Paris, pp 1–63
- Wang X, Niu R (2009) Spatial forecast of landslides in three gorges based on spatial data mining. *Sensors* 9:2035–2061
- Woldaregay K (2013) Review of the occurrences and influencing factors of landslides in the highlands of Ethiopia. *Momona Ethiop. J. Sci. (MEJS)* 5(1):3–31