MULTICRITERIA BASED LANDSLIDE HAZARD ASSESSMENT AND VULNERABILITY STUDIES FOR THE STATE OF SIKKIM, INDIA

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Abstract

Many landslides which in past which were either induced by rainfall or by earthquakes, have caused severe damages to infrastructures and human in the hilly regions around the world. In India, the most sensitive areas of landslides are the Himalayan region, regions in the Northeast and the Western ghats. As the steep slopes in the Himalayas and Northeast India are in the proximity of one of the most active plate boundary regions in the world, the seismic induced landslide hazard is very high in these regions. The 2011 earthquake of magnitude (M_w) 6.9 along the India-Nepal border, has triggered more than 300 landslides in Sikkim, affecting transportation and power infrastructures in the state. The Nepal earthquake of 2015 M_w 7.8 has also triggered landslides in various part of Nepal-China border and Sikkim, India. Many landslide zonation works have been carried out in the recent past for various part of India. However, the amount of work has published toward the zonation based on quantitatively assessed landslide hazard, especially at a macro-level is very limited. Hence this study presents a comprehensive landslide hazard assessment considering both earthquake as well as rainfall induced, for the state of Sikkim, India, situated in the Himalayas. It is evident that the landslide hazard at a location is influenced by many factors such as intensity of rainfall, seismic ground shaking, terrain slope and landcover. In this paper these landslide hazard parameters are quantitatively assessed and integrated to hazard index on a GIS platform using Analytical Hierarchy Process (AHP). The Analytic Hierarchy Process (AHP) has found its widest of applications in multicriteria decision. This paper presents a comprehensive landslide hazard zonation map, based on the spatial distribution of these hazard index (HI), representing the consolidated effect of both earthquake and rainfall on landslide initiation at a given location. A landslide hazard and vulnerability map at macro-level can provide key information which is helpful while planning big construction projects. Further, based on the land-use map developed from remote sensing images, a landslide vulnerability study for the study area is carried out and presented in this paper.

Keywords: PHA, GIS, Landslide

1. Introduction

Landslide hazard poses major threat to most of the hilly regions in the world. The statistics provided by disaster management authority of India reveal that about 15% of the total land area (0.49 million km^2) is considered to be affected by landslide hazard [1]. Several of landslides occurred in the past have caused severe damages to infrastructures in the hilly region, road and rail networks, transmission towers and power stations etc. Factors that can trigger landslides are intense or prolonged rainfall, earthquake shaking, snow melting, etc. However, apart from these external factors, the possibility of landslide at given location also depends upon the slope features such as geotechnical properties of the soil, drainage pattern, land cover and slope gradient. Unlike other natural hazard like earthquakes and floods, the landslides are local events and their impact is restricted to a smaller region. Major rain induced landslides occurred in various parts of India during the last decade itself have claimed more than 300 lives. Notable rain induced landslide disasters include, the 1948 Guwahati (Assam) landslide, the 1968 Darjeeling (West Bengal) landslide, the 1998 Malpa (Uttarakhand) landslide, 2001 Amboori landslide in Kerala the 2009 Karwar landslide, the 2013 Kedarnath landslides in Uttarakhand and 2014 Malin landslide in Maharashtra. Apart from rain induced landslide, severe damages in various parts of India have been have been also reported due to earthquake induced landslides which include landslides took place due to 1991 Uttarkashi earthquake on the Uttarkashi-Harsil road. The seismically-induced ground movements during the 1999 Chamoli earthquake not only triggered new landslides, but old as well as stabilized landslides also get reactivated [2], the 2011 earthquake of magnitude (M_w) 6.9 along the India-Nepal border, has triggered more than 300 landslides in Sikkim, affecting the road network in the state [3]. The Nepal earthquake of 2015 M_w 7.8 has also triggered landslides in various part of Nepal-China border and Sikkim, India.

In this paper, an integrated landslide hazard map is developed for the state of Sikkim, considering the effect of all major factors like earthquake ground motion and rainfall intensity, that can trigger a landslide. These landslide hazard factors were integrated to a landslide hazard index value using multicriteria analytical hierarchical approach (AHP). This paper also presents a macro-level landslide vulnerability map for the state of Sikkim, based on the land-use map and landslide hazard map. The land-use map for the state of Sikkim was developed from LANDSAT-8 remote sensing data.

2. Geology and Seismicity of the Study Area

Sikkim is a state in India, located in the Himalayan belt. Sikkim shares it boundary with Tibet in the north, Nepal to in west, Bhutan in the east and the Indian state West Bengal to the south (fig. 1).

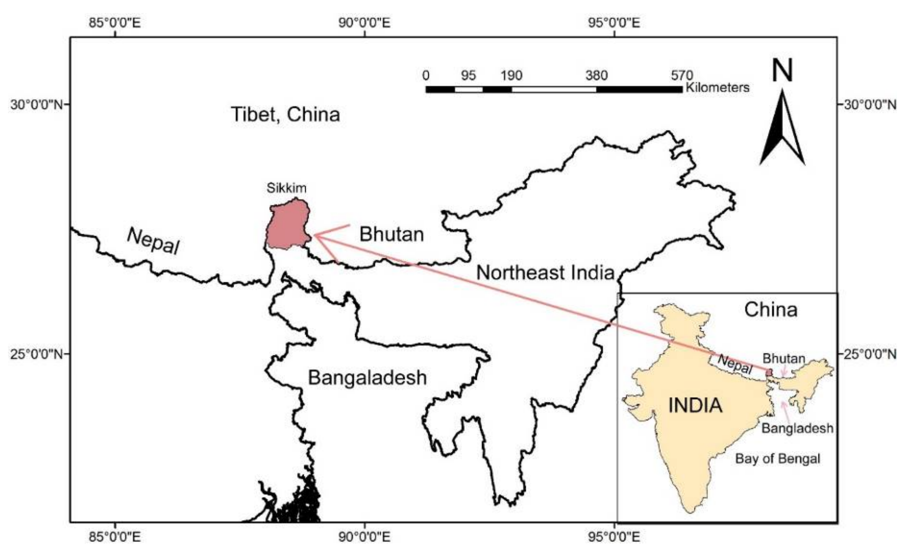


Fig 1. Location of the Study Area

The state of Sikkim has a total geographical area of approximately 7,300 km^2 with a human population of 607,688. Geologically Sikkim forms the part of Lesser Himalayas, consisting mostly four major rock formations (fig.2). These are, Everest Pelitic Formation, Sikkim Group, Chungthang Formation and Kanchenjunga Gneiss Group [4]. The Sikkim Group of rocks consists of schists and gneisses which are metasedimentary in nature.

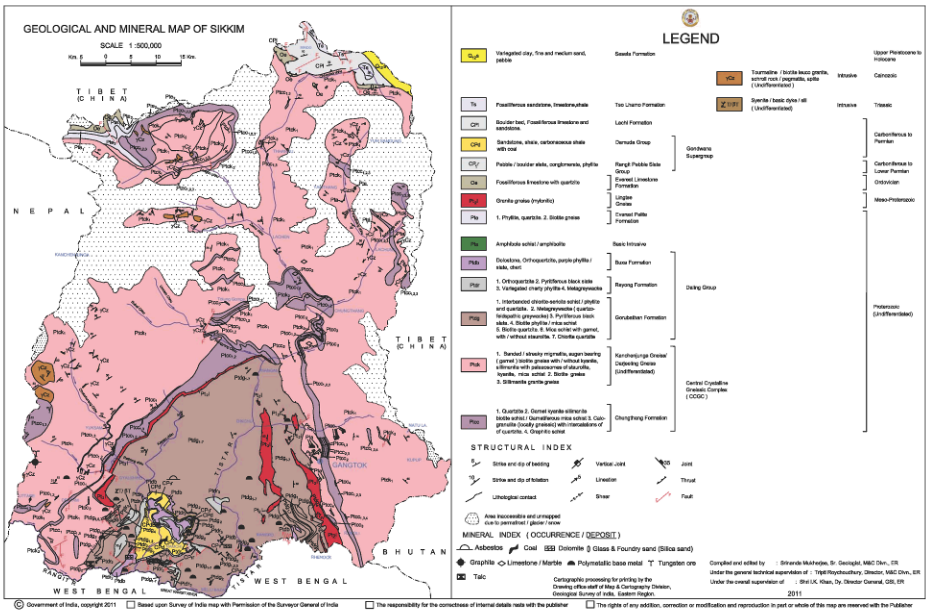


Fig.2 Geological map of Sikkim [5]

In East Sikkim two fairly continuous sheets of thrust-bounded deformed granite run almost north-south and coalesce in the centre [6]. As per [7] "*many thrust-bounded granite bands show textural zoning with phyllonitic and banded blastomylonitic borders which are succeeded inward by augen mylonite and by least deformed granite at the core*". The Chungthang Formation consists of quartzites, garnet-kyanite-staurolite bearing biotite schist, calc-silicate rock, graphitic schist and amphibolite [6]. The rocks of this formation are also exposed in the districts of east Sikkim and west Sikkim. Kanchenjunga / Darjeeling Gneiss are extensively exposed in the northern part of the Sikkim, to the south of the Tethyan sequence. The gneisses, dominantly comprising quartz, feldspar and biotite.

Tectonically, the state of Sikkim encompasses parts of Lesser Himalayas, bounded by two major shear zones, which are, 1) Main Boundary Thrust (MBT) in the south and the 2) Main Central Thrust (MCT) in the north [6]. Main boundary thrust (MBT) just passes through region which lies slightly south of Sikkim-West Bengal border. Main Frontal Thrust (MFT) between Siwaliks and Neogenesediments is located further south. Main Central Thrust (MCT) passes through the Central part of the State. [8] have reported the occurrence of tectonic pinching and swelling, tear apart and scattered occurrence of Tethyan sequence all along the northeastern part of Sikkim.

The state of Sikkim lies in a high seismic zone along the Himalayan belt, where several large magnitude earthquakes like 1934 M=8.4 Bihar-Nepal earthquake, have occurred in the past. As a first towards the seismic hazard analysis, the earthquake data for the study area was compiled (fig. 3). Further on analysis, it was found that there are about 2830 seismic events occurred in the study area within the span of 113 years. There are about 11 events in the study area, having a magnitude above 7. Hence, it can be concluded that the Sikkim state is located in very high seismically active region, Himalayas, where large magnitude earthquakes have occurred in the past at regular time interval.

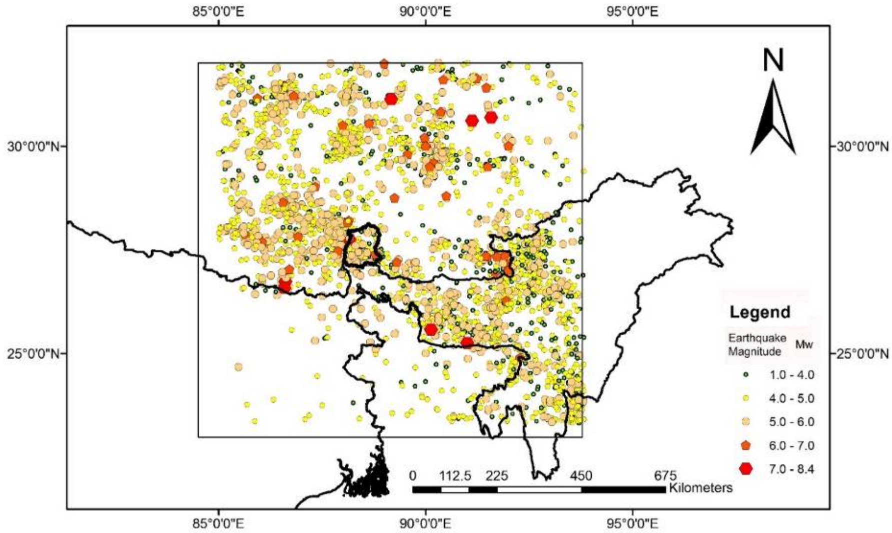


Fig.3 Earthquake events within 500 Km from the Sikkim's boundary [9]

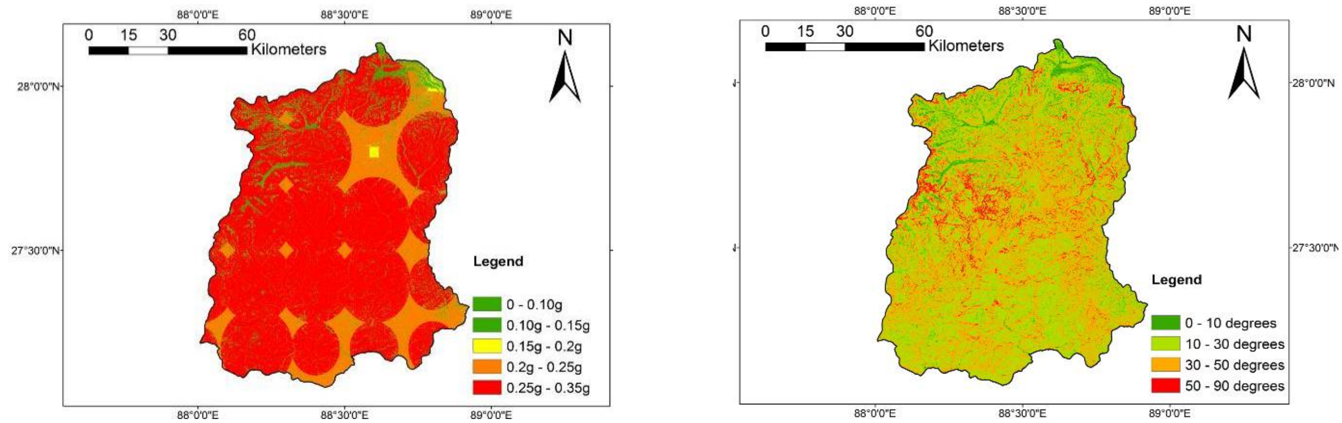
3. Integrated Landslide Hazard Maps

A qualitative landslide hazard zonation map of India was developed by the Geological Survey of India (GIS). Several authors have employed the GIS tool for preparing landslide hazard maps of India and its various regions [10, 11, 12]. Studies have also been carried out toward the assessment of earthquake induced landslides also [13, 14]. [9,15] have carried out the seismic landslide hazard assessment for the states of Karnataka and Sikkim, in terms of the critical static factor of safety required to resist landslide estimated using Newmark's analysis.

In the present study, the integrated landslide hazard index was evaluated for the entire state of Sikkim using multicriteria analytical hierarchical approach (AHP). It is evident that the landslide hazard at a location is influenced by many factors such as intensity of rainfall and seismic ground shaking, terrain slope and seismic amplification at surface level. Hence, the assessment of landslide hazard can be treated as a multicriteria problem. Studies have shown that the Analytical Hierarchy Process (AHP) most suitable for multicriteria problems. The Analytic Hierarchy Process (AHP) proposed by Saaty (1980) is widely applied for multicriteria decision making in the field of engineering, finance and management. The multicriteria problems are modelled in a hierarchical structure in AHP where, each criterion is initially sorted and prioritized in a hierarchical fashion based on the user discretion. Once the hierarchy is built a pairwise comparison is carried out to establish relations within the structure, thus facilitating the decision making process by weighing the priority level of each criterion on the overall outcome.

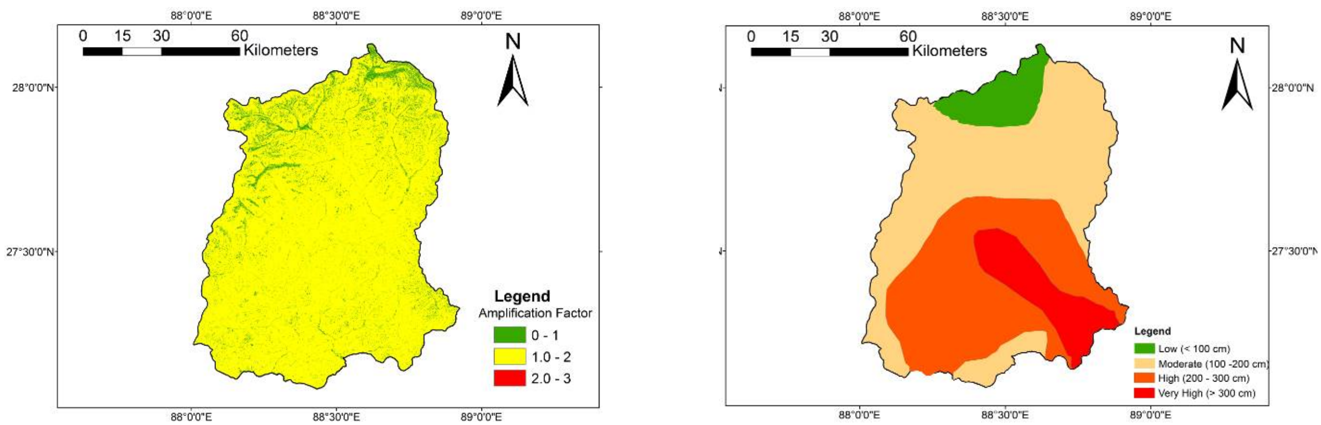
3.1 Landslide Hazard Parameters

Major seismic hazards considered in the evaluation of landslide hazard index are 1) terrain slope, 2) peak horizontal acceleration (PHA) 3) rainfall intensity and 4) amplification factor. Digital elevation models (DEMs) are raster data files containing terrain information for a specified region in the form of pixels is ude to derive the terrain slope map. The ASTER Global Digital Elevation Model (ASTER GDEM) was developed by the Ministry of Economy, Trade, and Industry (METI) of Japan and National Aeronautics and Space Administration (NASA) United States. It covers about 99% of the global land area with a resolution of 1 arc-second (30 m). The slope map of the study area was developed from ASTER DEM using ArcGIS 10 (fig. 4(b)). In the present study, the PHA for the study area has been evaluated using deterministic seismic hazard analysis (DSHA), and its spatial variation is presented in fig.4(a) (a) [7]. The Indian Meteriological Department (IMD) has classified the state of Sikkim into 4 major agro-climatic zones based on rainfall. They are 1) Low rainfall zone (<100cm), 2) Moderate rainfall zone (200 to 100 cm), 3) Heavy rainfall zone (200 to 300 cm) and 4) Very heavy rainfall zone (> 300 cm).



(a) (b)

Fig 4. (a) Digital Elevation Model and (b) Slope map of the study area



(a) (b)

Fig 5. (a) Spatial variation of PHA values throughout Sikkim using DSHA
(b) Agro-climatic zones based on mean annual rainfall [16]

Figure 5(b) delineates various rainfall zones in the state of Sikkim. [9] have estimated the surface level PHA using a non-linear site amplification technique [17,18]for all grid points which are having slope value greater than or equal to 10 degrees. The amplification factor is the ratio of surface level PHA to the PHA at bedrock was evaluated for the entire state of Sikkim (5(a)).

3.2 Landslide Hazard Index

The hierarchical arrangement of landslide hazard parameters (LHP) along with their corresponding weights used in this study is presented in table 1. In the present work, the terrain slope was given highest weightage as it is the most fundamental. Subsequent priorities were allotted to peak horizontal acceleration (PHA) 3) rainfall intensity and 4) amplification factor. A matrix was constructed (Table 2) showing the pairwise comparisons (ratios) between the landslide hazard parameters (LHP). The pairwise comparisons will result in a normalized weight for each parameter and the sum of the normalized weights is unity.

Table 1- Parameter and weights used for generating landslide hazard index map

Landslide Hazard Parameter (LHP)	**Weights**
Terrain Slope (TS)	4
Peak ground acceleration at bedrock (PGA)	3
Rainfall Intensity (RF)	2
Amplification factor (AF)	1

Table 2 – Normalized weights of each landslide hazard parameter (LHP)

LHP	**TS**	**PGA**	**RF**	**AF**	**Normalized weights**
TS	4/4	4/3	4/2	4/1	0.4
PGA	3/4	3/3	3/2	3/1	0.3
RF	2/4	2/3	2/2	2/1	0.2
AF	1/4	1/3	1/2	1/1	0.1

Further, each LHP was categorized into various ranges and for each category a rating or ranking was assigned as described in table 3. These ranks (for each LHP category) were then normalized using Eqn.(1).

$$X_i = \frac{R_i - R_{min}}{R_{max} - R_{min}} \tag{1}$$

Here, R_i is the rank assigned to each category of a single theme, R_{min} and R_{max} is the minimum and the maximum rating value of that theme. The landslide hazard index values were then estimated based on normalized weights and ranks by integrating of all themes using the following Eqn.(2).

$$LHI = \begin{pmatrix} TS_w \times TS_r + PGA_w \times PGA_r + \\ RF_w \times RF_r + AF_w \times AF_r \end{pmatrix} / \sum w \tag{2}$$

Where LHI is the landslide hazard index, ’w’ is the normalized weight of the landslide hazard parameter (EHP) and ’r’ is the normalized rank of a category in the EHP.

4. Landslide Vulnerability Map

Vulnerability is defined as the degree of loss to be expected for a given set of assets. These assets can be the human population, property and infrastructre within a given area. Proper vulnerability analysis along with hazard studies is required for effective decision making. In order to carry out any landslide vulnerability studies at the macro - level (such as a state or a country) it is necessary to develop a land-use map for the study area. A typical land-use map show the spatial distribution of various terrains classes having different utility and characteristics, such as 1) vegetations, 2) road, infrastructures and other built-ups 3) open area and agricultural land, 4) snow covered lands and 5) water bodies. A land-use map can either be prepared by manual survey or it can be generated from remote sensing images that are captured by earth orbiting satellites. Once the land-use map and landslide hazard map was developed, the landslide vulnerability map of the study área generated using AHP framework.

Table 3 – Normalized rating for each EHP category for micro-level hazard integration

LHP	Value range	Weight	Rank	Normalized Rank
TS	<10 degrees	0.4	1	0
	10 – 30 degrees		2	0.33
	30 – 50 degrees		3	0.67
	50 – 90 degrees		4	1
PGA	<0.1g	0.3	1	0
	0.1g – 0.15g		2	0.25
	0.15g – 0.2g		3	0.5
	0.2g – 0.25g		4	0.75
	>0.25g		5	1
RF	<100 cm	0.2	1	0
	100 cm – 200cm		2	0.33
	200 cm – 300cm		3	0.67
	>300cm		4	1
AF	< 1	0.1	1	0
	1 - 2		2	0.5
	2>		3	1

4.1 Generation of Land-use Map of the Study Area

In this study, the land-use map for the state of Sikkim is generated using LANDSAT-8 satellite images. The Landsat 8 satellite, which is a joint venture of NASA and USGS, images the entire Earth every 16 days and these images are freely downloadable. Landsat-8 carries two pushbroom type of sensors, Operational Land Imager (OLI), and the Thermal Infrared Sensor (TIRS). The OLI sensor captures the spectral bands in visible, near infrared and short-wave infrared (SWIR). The TIRS instrument collects spectral bands in thermal infra-red (TIR) range for thermal imaging.. The resolution of the Landsat-8 image fig. 6 (a) is 1 arc-second or 30m.

The Landsat-8 images of the study area were acquired on 13/5/2015 as it has the least cloud cover. The electromagnetic energy detected by imaging sensors of satellite is affected by the atmosphere, due to scattering, absorbing, and refracting light. The visible and NIR bands of the Landsat-8 images having 30 meter resolution are subjected to atmospheric correction by dark object subtraction (DOS) method [19]. Since the study area is highly undulated with hills and valleys, topographical correction [20, 21, 22] is also applied for reflectance values.

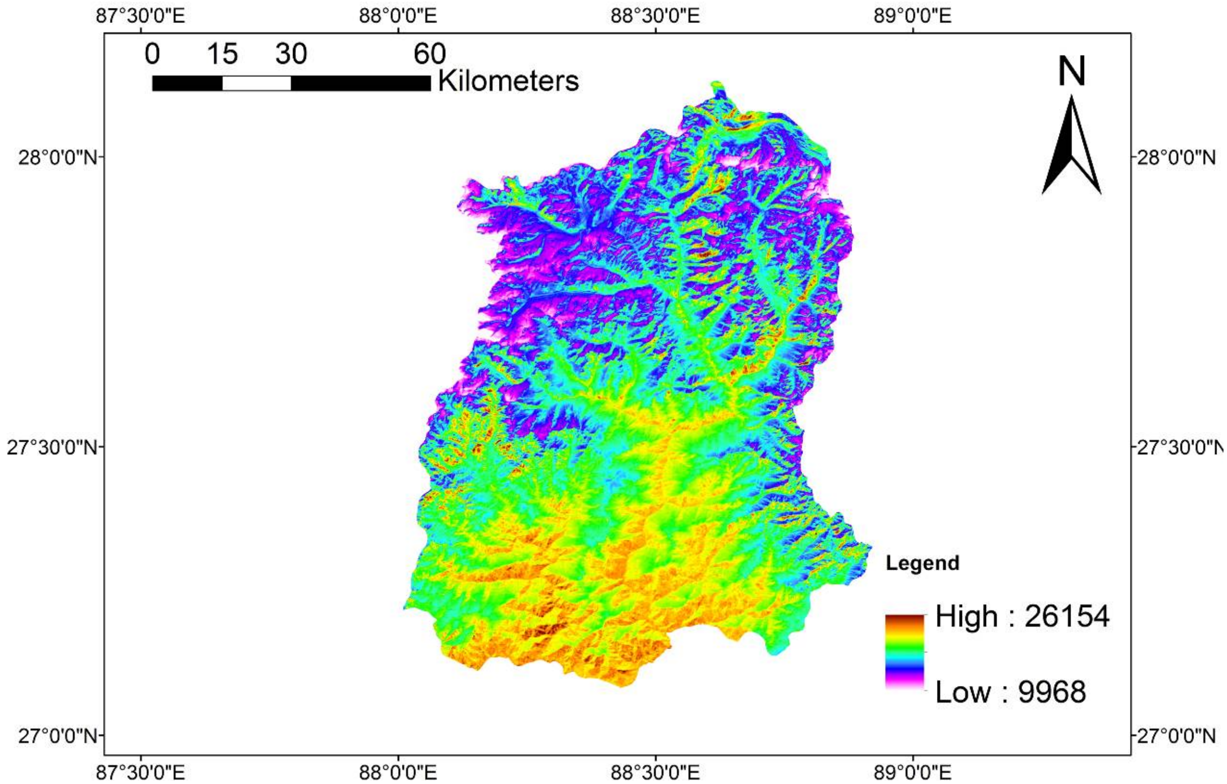


Fig. 6 LANDSAT- 8 thermal band image of the study area,

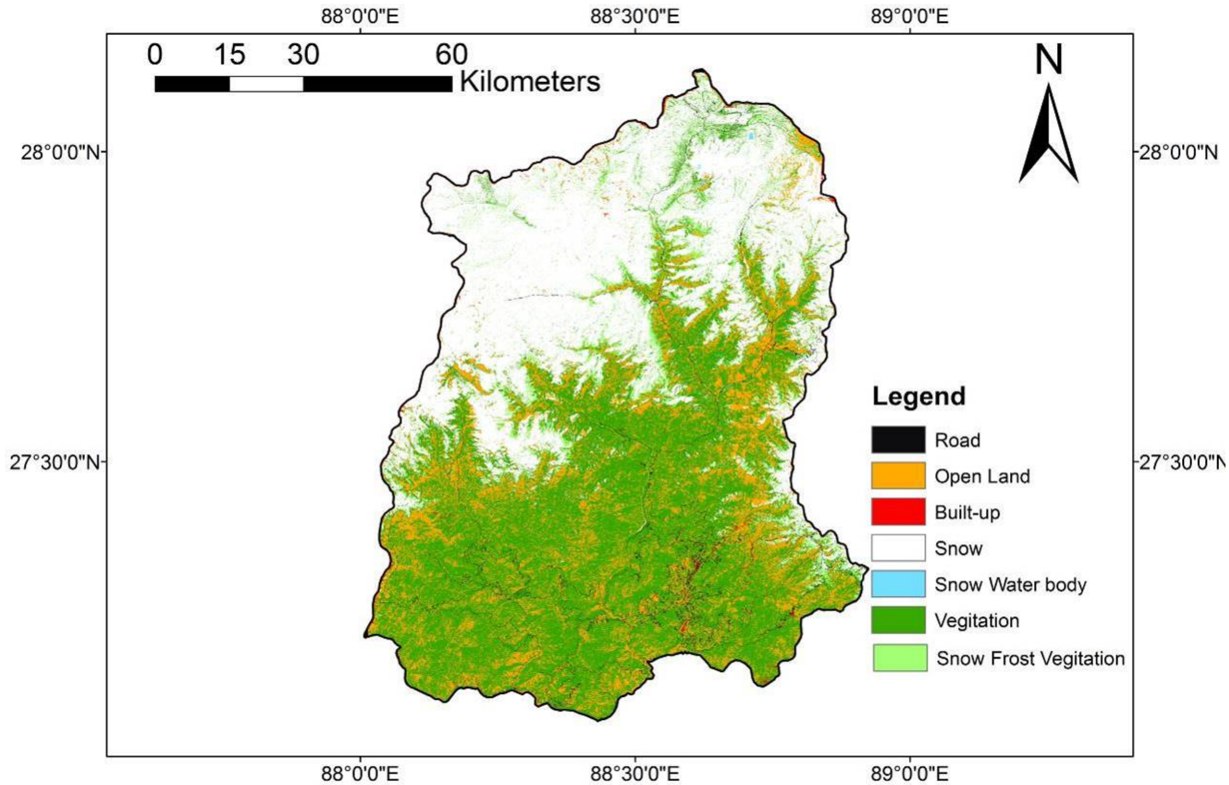


Fig. 7 Land-use map of Sikkim, derived from Landsat-8 image

In the present study, the Cartosat DEM having 30 m resolution is used for the topographic normalization. The raster image is then classified by using the nearest neighborhood classification method in ERDAS 2014 [23]. The classified image is generated in the raster format having a resolution of 30m and each cell/pixel value of raster represent a particular terrain class. Each of these terrain categories were verified by comparing with available high resolution images available (like Google and Bing Maps). Figure 7 presets the land-use map for the state of Sikkim.

4.2 Generation of Landslide Vulnerability Map of the Study Area

In the present study, the landslide vulnerability of the entire state of Sikkim was presented in terms of the landslide vulnerability index (LVI). A similar procedure for the evaluation landslide hazard index (LHI) as presented in section 3, is adopted for determining the vulnerability index throughout the study area. As a first step, the landslide vulnerability parameters are identified and sorted in a hierarchical form. In the present study, the land-use characteristics and the landslide hazard index (LHI) are identified as vulnerability index parameters. The weights and normalized weights of these landslide vulnerability parameters were evaluated as described in table 4.

Table 4 – Normalized rating for each EHP category for micro-level hazard integration

LVP	**Value range**	**Weight**	**Rank**	**Normalized Rank**
Land-use values (representing different terrain)	20, 25,30,50 (Vegetation and snow cover)	0.67	1	0
	1, 35, 37, 42, 57 (Open land)		2	0.5
	0, 5, 60 (Road, Built-up and airport)		3	1
Landslide hazard index (LHI)	0 – 0.2	0.33	1	0
	0.2 – 0.4		2	0.25
	0.4 – 0.6		3	0.5
	0.6 – 0.8		4	0.75
	0.8 – 1.0		5	1

Table 4 presents the normalized weights and ranks associated with each of the vulnerability index parameters. Finally, these parameters are integrated to the landslide vulnerability index (LVI) similar to the determination of landslide vulnerability index (LVI) as per Eq.(2).

5. Results

Figure 8 presents the landslide hazard index map of the study area using multicriteria AHP is a framework. Based on the range of hazard index (HI), [24] has broadly classified regions into 5 zones. They are the low hazard zone ($0 \leq$ HI ≤ 0.2)’, moderate hazard zone ($0.2 \leq$ HI ≤ 0.4), high ($0.4 \leq$ HI ≤ 0.6)’, moderately high ($0.6 \leq$ HI ≤ 0.8) and very high hazard regions ($0.8 \leq$ HI ≤ 1).

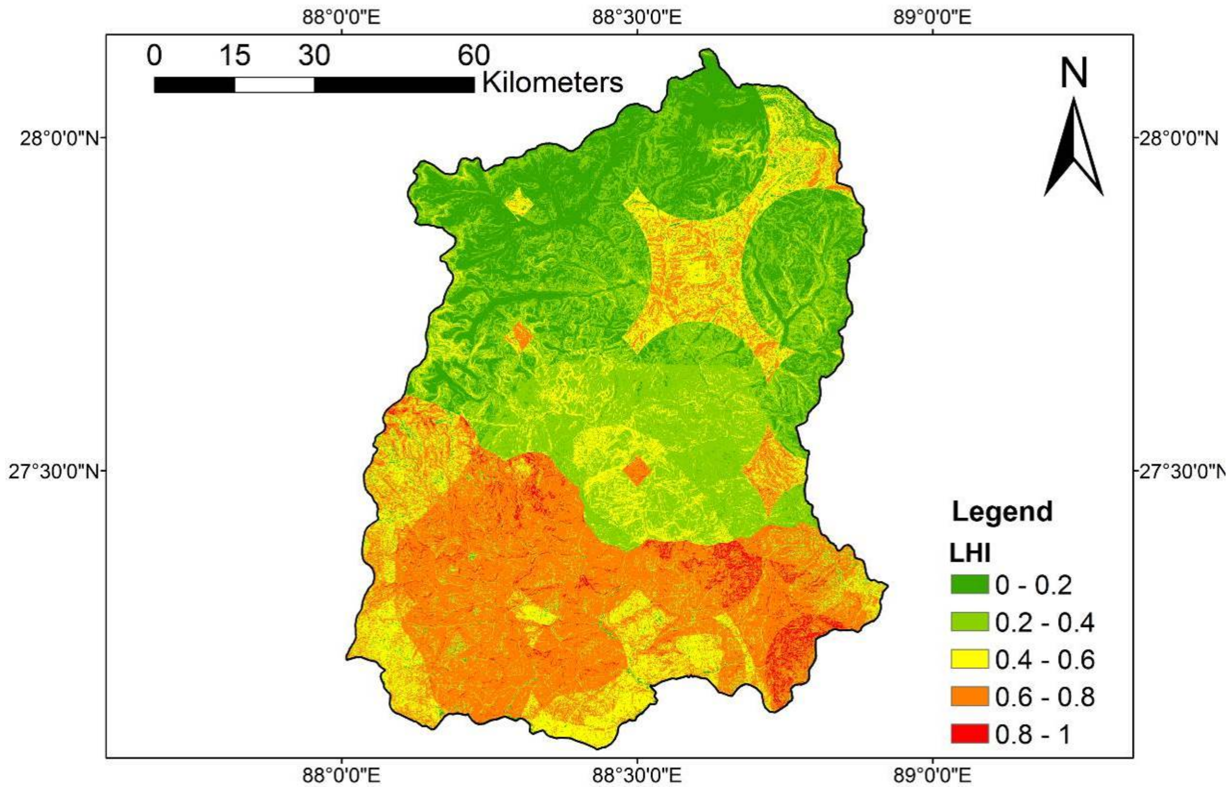


Fig 8. Integrated landslide hazard index map of Sikkim

From fig. 8 it can be observed that the, southern part of Sikkim can be categorized as moderately high to high hazard region. Such a high value of hazard index is mainly contributed by LHPs such as PHA and rainfall. However, the significant area of north Sikkim can be categorized as low to moderate hazard region. The landslide vulnerability index of the state of Sikkim is presented in fig. 9. Similar the categorization landslide hazard zone based on the LHI, the study area can be categorized into 1) low vulnerable zone (0 < LVI < 0.2) 2) moderate vulnerable zone (0.2 < LVI < 0.4) 3) moderately high vulnerable zone (0.4 < LVI < 0.6) 4) high vulnerable zone (0.6 < LVI < 0.8) and 5) very high vulnerable zone (0.8 < LVI < 1). As per fig. 9, the northern part of Sikkim fall in low to moderate vulnerable zone as major portion is covered by forest and snow. Very few human settlements/infrastructures can be found in this región. However, the southern part of Sikkim can be categorized as moderately high to very high vulnerable region. From the land-use map, it can be observed that the majority of human settlement and infrastructures are situated in the southern Sikkim.

6. Summary and Conclusions

This paper presents the application of microzonation principles in carrying macro-level landslide hazard and vulnerability assessment for the state of Sikkim. Even though the landslides are local phenomena, affecting the small region, a macro-level landslide hazard zonation map is very essential for disaster mitigation/management purpose. In the present study, major factors that can trigger a landslide are identified as terrain slope, peak ground acceleration (PGA), rainfall intensity and amplification factor. The terrain slope map of the study área was derived from digital elevation model (DEM) to a resolution of 30m. The peak ground acceleration was estimated using the deterministic methodology. The rainfall intensity map of the study area was obtained from the Indian Meteorological Department (IMD) report. The amplification factor was estimated using the non-linear site amplification technique. These landslide hazard parameters were integrated to landslide hazard index (LHI), using Analytical Hierarchy Process (AHP). The landslide hazard index represents the consolidated effect of all landslide hazard parameters.

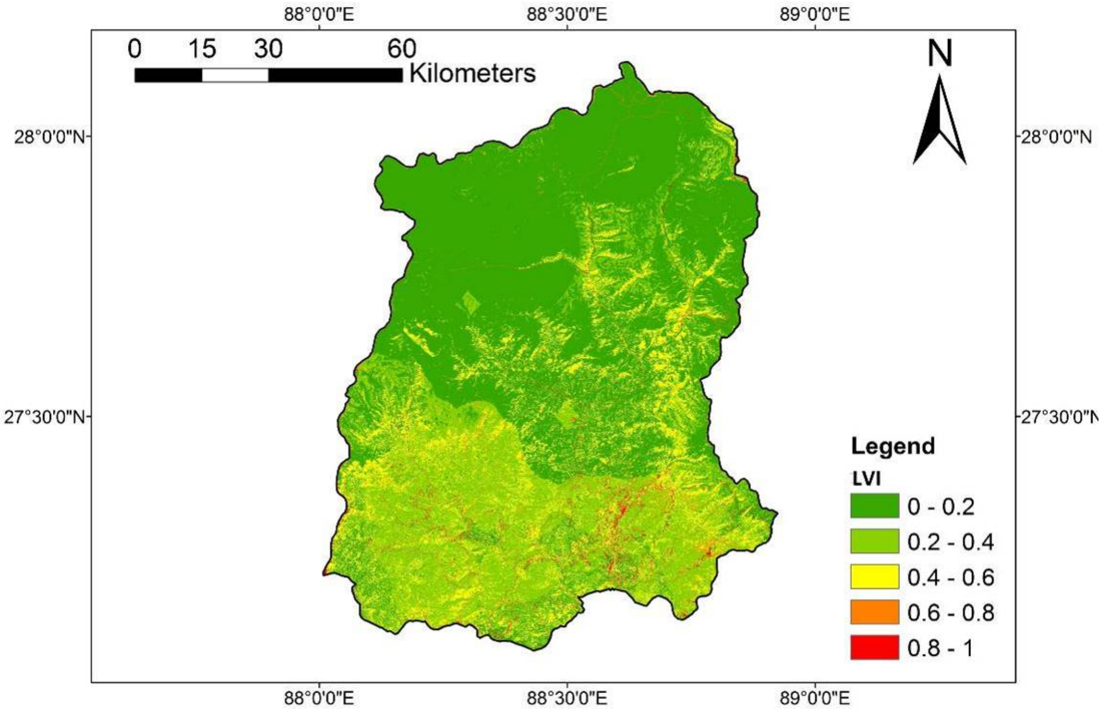


Fig. 9 Landslide vulnerability map of Sikkim

Further, this paper also presents the landslide vulnerability assessment carried out for the state of Sikkim. As a first step towards the landslide vulnerability assessment, the land-use map for the entire state of Sikkim was developed from LANDSAT-8 images. Finally, the land-use map and the landslide hazard index map were integrated to the landslide vulnerability index map using Analytical Hierarchy Process (AHP).

The study can help identify vulnerable zones in order to plan mitigation efforts and provide a good database for decision-making while planning big projects. A high vulnerable region can be defined as a high hazard region having a significant human population. These are to be considered as the most sensitive and a rigorous analysis is required in this region for the accurate estimation landslide hazards. It is highly recommended to perform extensive site investigation and set-up landslide alarm systems for regions, where significant human population/settlements are exposed to the high landslide hazard. In these regions, several landslides counter measures can be adopted like construction of strong retaining walls, rock bolting with wire mesh and shotcreting or soil nailing or control of surface water infiltration by providing appropriate drainage and/or planting of vegetation The most important part of any landslide mitigation program is to create awareness among the local people. Proper care should be taken while carrying out any activity such as agriculture or construction of an infrastructure on a sloped terrain. Moreover, landslides are more predictable than an earthquake, hence their damage potential can very well be mitigated by proper planning and adopting other countermeasures.

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