

# Chapter 8

## Interactive Approach for Earthquake Scenario Development and Hazards Resource Estimation



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**Abstract** Indian subcontinent attained present physical form due to vast tectonic movements that resulted into large number of earthquakes. In studies it has been found that more than 50% area in the country is prone to damaging earthquakes. The northeastern part of India as well as the entire Himalayan belt is susceptible to earthquake of magnitude more than 8.0. The present study is principally aimed at understanding the intricate seismological processes in the study area, Sikkim which is on hilly terrain of Eastern Himalayas. Sikkim is situated in a region where major cause of earthquake is displacement of the Indian plate toward the Eurasian plate having complex geology. Remote sensing and GIS model builder and syntax were proven for hazard and vulnerable map creation used in earthquake scenarios development, planning, management, and resource estimation. In this study the preliminary factors including geology, topography, slope, relief, land use/cover, major roads, and historical epicenter were used with mechanical weightage, and overlay categorization was used for hazard index map and zone identification.

**Keywords** Earthquake scenarios management · Hazard index map · Overlay analysis

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## 8.1 Introduction

India has faced several serious world's enormous earthquakes, and about more than 50% of the country region is said to be vulnerable of earthquake (Sengar et al. 2013). The most vulnerable region of earthquake is the northeastern regions of India, including the entire Himalayan (Kaila and Narayan 1976). Earthquake is identified as natural sudden shaking of the ground earth due to movement on earth's rocks and surface (Armas 2012; Armas and Gavris 2013). Earthquake occurs when the plate tectonic is unexpectedly separated to form a fault or fold and releases energy in form of seismic waves and tremble ground surface (Pavel and Vacareanu 2016; Chemenda et al. 1995; Fekete 2009; Walker et al. 2014). Seismograph or Seismometer is used to detect and record the seismic waves. The major cause of earthquake is a sudden release of energy due to sudden breaks in the underlying rocks along the faults that leads to procreation of seismic waves. Plate tectonic refers to the explanation of the movements of the earth surface in an existing place or the past experienced places. The spot under the ground where the earthquake occurs is known as focus, and the place perpendicularly above the focus is termed as the epicenter (Chen et al. 2011; Pavel et al. 2016; Rufat 2009). The focus of the earthquake is an underground point where rocks first begin to move and the seismic waves travel outward from the earthquake's focus. The epicenter is the point on the earth's surface which is directly above the focus point. Lower magnitude of earthquake even causes mass destruction even more than an atom bomb, so hazard resource estimation and scenarios development are very important (Skarlatoudis et al. 2004).

The major cause of earthquake is the shifting of tectonic plates which forms the folds and faults feature. Another reason could be due to the volcanic inflation, explosions, deep penetrations bombs, geothermal energy, stress transfer, groundwater extraction which decreases the pore pressure, surface quarrying, and many reasons more (Allen and Kanamori 2003; Ansal et al. 2004; Strasser et al. 2008; Toma-Danila et al. 2015). Earthquake scenarios help in management of hazardous resources which refers to the series of actions for maintaining the influence areas or zones to reduce the disaster (Champatiray et al. 2005). It does not completely reduce the influence of disaster, but it brings out the outcome or plans to decrease the risk factor. There is no such planning or arrangements for the disaster management that would lead to the worst-case scenario and include the loss of life as well as damage to the properties (Roustaei et al. 2005; Trifunac and Todorovska 1997; Lillesand et al. 2008). India has faced many powerful impacts of the world's greatest earthquakes; therefore, greater amount of area of the country is evaluated to be prone to earthquakes (Zhou et al. 2009).

The spectacular geomorphic-tectonic features as exhibited by the Indian lithosphere plate include the continental mountain systems, plateaus, and uplands (Glennie et al. 1990; Wilson 1965; Ouma et al. 2011; Lang et al. 2012). The reason behind the occurrence of earthquake in this particular region is due to the displacement of the Indian plate which is shifting toward the Eurasian plate and also collides with it which leads to the creation of the convergent boundaries. The Indian plate is bounded by some major and minor plates from all direction: the African plate in the west, the

Arabian and Iranian microplates in the north-west, the Eurasian plate toward north, the Chinese plate toward east and southeast, and Antarctic plate in the south.

Geographic information system is a unified application of the scientific knowledge which refers to computer science, topography, technology, and most importantly geography (Gong Jianya 2004). GIS uses all input factors for analyzing and assigning different weightage priority and various mechanisms in handling and inspecting the spatial data (Bai Yungang et al. 2004). It has been proven successfully to an enormous field including geography (Chen et al. 2006). This conception is being used widely throughout the world for various purposes which include the identification of the risk regions. It is capable for identifying risk factors and vulnerable prone areas for earthquake (Morrow 1999; Zhou et al. 2009). The utilization of GIS for earthquake disaster is substantially focused on the hazards emerging from the earthquakes commence from the active fault locations frequently termed from the inter plate earthquakes.

The representation of these maps has been done by using two software, that is, ERDAS Imagine and ArcGIS. The GIS technology is being used widely for the seismic fields including analyzing approach for seismic forecasting, resistance to earthquake, prevention of disaster, and mitigation and emergency command (Weiwei et al. 2009). GIS is growing in a vast approach toward analyzing the vulnerability and risk zones (Sun et al., 2008). GIS is used for mapping, land use, planning, water conservancy, and civil engineering as every connection is linked toward the earthquake disaster and these processes are interlinked to the geographical location.

## 8.2 Study Area

Sikkim, one of the states of India, is situated in the Eastern Himalayas which comes under the world's third highest mountain Khangchendzonga which is of 8585 m, restrained by the people of Sikkim as their protective deity. Sikkim is parted from the Singalila range from Nepal in the west, Chola range from Tibet and Bhutan, and also the Rangeet and Rango rivers from the borders. Sikkim is located at the 27.33°N and 88.62°E; therefore the total area covered by is about 7096 Sq. Km<sup>2</sup> (Fig. 8.1). The elevation of Sikkim ranges from 300 m to about 8583 m above the mean sea level, Mt. Khangchendzonga being the highest. It aggregates 82.31% (Sikkim ISFR 2017) of the total land which is covered with forest, consisting of the 8 species of the tree ferns, 11 species of the oak trees, along with the 20 species of bamboos, 300 species of ferns, and for about 400 species of the flowering plants. Its population is around 6.11 Lakhs (Census of India 2011). It is one of the states in India which receives the regular snowfall and the heavy rainfall, and hence there is an increased chance for landslides (Onagh et al. 2012; Lin et al. 2006). The land area of Sikkim is not fit for agricultural activities, but still most of its hill slopes are converted in the form of terrace farming land. The hills of the state mainly comprise of the gneiss rock and the schist rocks which are likely to erode due to the process of weathering and erosion. The geology

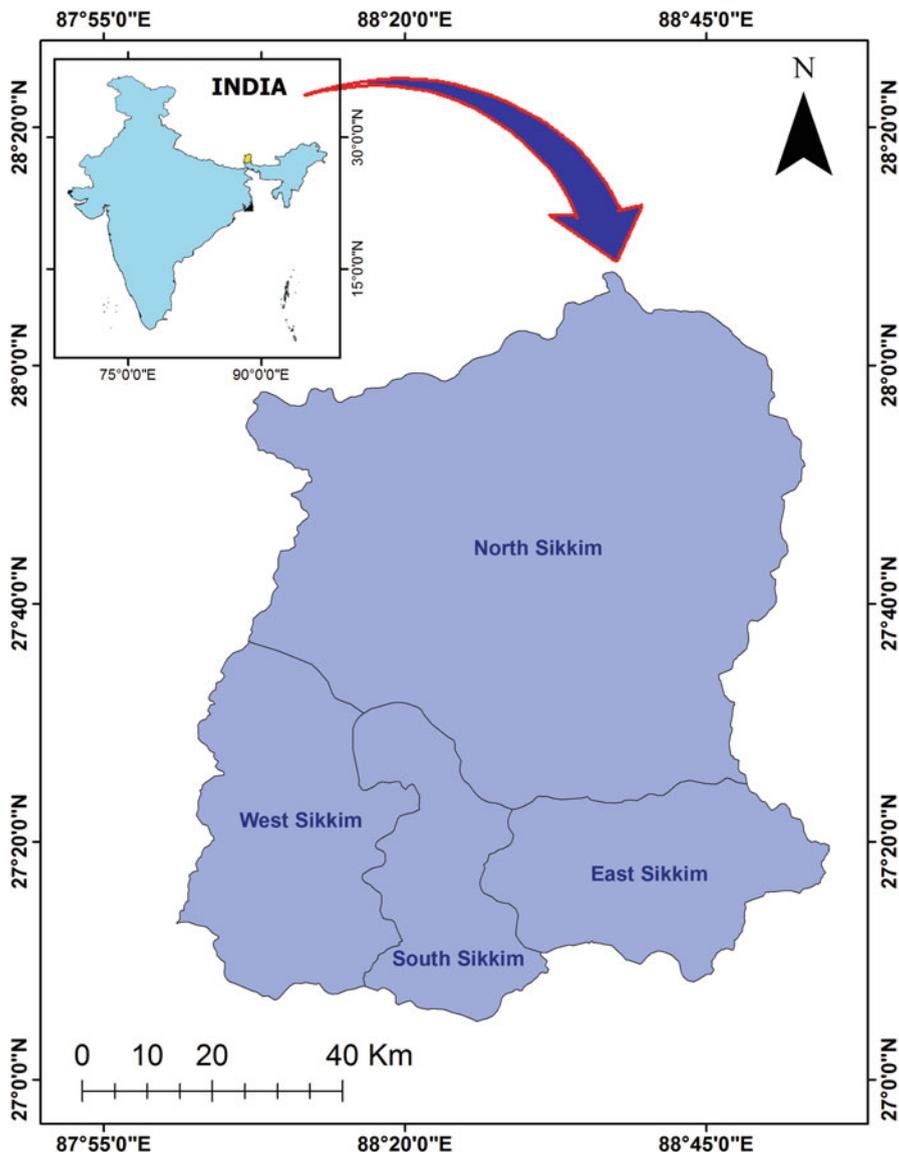


Fig. 8.1 Study area map

of Sikkim largely comprises of the infertile soil, inappropriate for the agricultural purposes. Sikkim comprises of the three important rocks named half-schistose, gneissose, and the Precambrian. Precambrian rock is established and is significant part of Sikkim geology that is made up of schists and phyllites. The existence of the schist's and phyllites forms the gradients of the region that are prone to weathering

and erosion. Earthquakes in India show some striking aspects which can be implemented for planning the earthquake disaster management. Sikkim falls under the category of zone IV having high damage risk zone. The study area Sikkim, India, is chosen due to its earth structure, located at highly terrain of Eastern Himalayas, displacement of the Indian plate toward the Eurasian plate, moderate population in open area, and statistical earthquake, falling into earthquake zone IV (Sarkar and Nandy 1974).

### 8.3 Material and Methodology

Consolidating geospatial technology is accompanied in conception of informations and experiences during earthquake for constructing a hazard map for risk-prone regions that will be helpful for future planning and strategy making (Chen et al. 2006). Therefore, the limitation envisages by using GIS, and maps are classified into three classes. After formative criteria assessment ranges, the ranking of the class values from 1 to 3 is assigned with respect to scientific codes and postulation.

The foremost factors used for the study and categorization (Table 8.1) for geology, soil, slope, land use, and road are also vital mechanisms of dwindling modeling development and are together mapped. In this study classification is done to organize the factors used for categorizing the map so as to help the decision-makers understand the situation and distribute the mechanism rapidly by visualizing the map. The whole procedure for GIS data and investigation is carried out by using the model builder tool. In this way a mechanical GIS system may also be a significant element for classification-based researches. The weight and individual features (Table 8.1) are made flexible to transform through a user interface.

Material used for study Landsat-8 Operational Land Imager (OLI) Image, Cartosat Stereo pairs, major roads source DIVA-GIS, and historical earthquake data are used to derive useful hazard index.

#### 8.3.1 Land Use/Land Cover

The land cover figure documents how any area is enclosed by forests, wetlands, and impervious surfaces, agricultural together with the other land and water types, whereas the land use represents how people utilize the landscape whether for growth, preservation, or diverse uses. Land cover can be resolved by analyzing satellite and the aerial imagery (Metternicht et al. 2005). Land cover maps endow with the statistics to assist the managers paramount and recognize the existing landscape (Fig. 8.2). The term land use and land cover are used interchangeably. Using Landsat 8 OLI, image was used for land use-land cover classification using maximum likelihood classifier to classify into nine classes specifically agricultural, snow and glacier, alpine scrub, alpine meadow, oak forest, conifer forest, roads, alpine thicket, and the alder forest.

**Table 8.1** Representing weightage rank for five basic factors related to earthquake

S. No	Themes	Weightage	Individual factors	Rank/Value for individual entity	Weightage* rank assigned
1	Geology	0.15	Metamorphic	1	0.15
			Gabbros	2	0.3
			Chert/limestone facies	3	0.45
			Gabbros and Ultrabasics	4	0.6
			Fluviatile deposits	5	0.75
			Ultrabasics-peridotite, Precambrian rock	6	0.9
2	Soil	0.1	Torrifluvents, Torriorthents and rock outcrops, clay-rich soil	1	0.1
			Rock outcrops, torripsamments, and calciorthids	2	0.2
3	Slope (in percentage)	0.15	Low (0–30)	1	0.15
			Medium (30–60)	2	0.3
			High (>60)	3	0.45
4	Land use	0.1	Green areas	1	0.1
			Water bodies	2	0.2
			Scrub land	3	0.3
			Rock outcrop, dunes, and crushers	4	0.4
			Built-up	5	0.5
5	Road (m)	0.05	1500	1	0.05
			1000	2	0.1
			500	3	0.15

### 8.3.2 Cartosat DEM

Cartosat is an exclusive stereoscopic undertaking with the ability of attaining the along track stereo imagery with the unchanging B/H ratio. It holds two payloads which are the fore camera and the aft camera. These two panchromatic cameras with the 2.5 m spatial resolution are to obtain two descriptions concurrently. ERDAS IMAGINE Photogrammetry is used to create elevation model of 15 m.

### 8.3.3 Slope Approach

A slope map represents the variations in altitude which simultaneously shows the aspect and degree of slope for a terrain. Slope map is made up of Cartosat 15 m

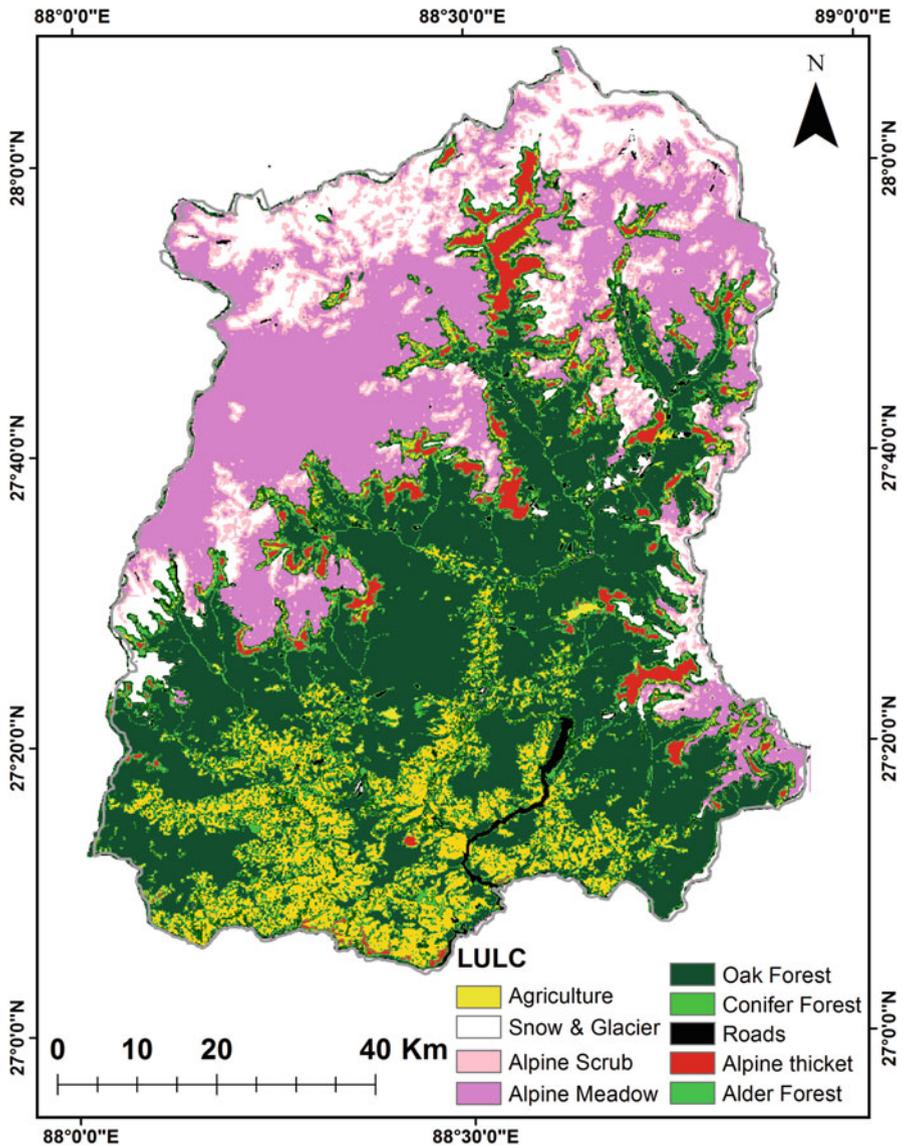


Fig. 8.2 Land use and land cover of the study area

DEM. It represents the direction and steepness of the slope for a terrain for continuous surfaces. They are characterized as a symbolized such as the combination of the hues such as the red, yellow, orange, and green.

### 8.3.4 Relief

Relief map basically displays the altitude and topography. They are more better-quality adaptation of the topographic maps as the topographic map utilizes equivalent elevation to generate two-dimensional models. The relief map attempts to depict the physical appearance of the ground based on its shape and height. The relief of topography has an important impact on the earthquake response of a region. The climate and weather of any region largely determines the variation in altitude which influences the rock and soil type found in the region.

### 8.3.5 Weightage Assignments

Weightage assignment is taken as important preliminary factors to set up parameters to study any seismic study. The most important authority of geologic environment on both strong trembling description and consequential damage pattern are integrated in this study. The relationship between gray scales, statistical sample gray value, and earthquake intensity has been established and analyzed for affected area from the change image and published report. Model the probability distribution of the gray value in different intensity zones by Eq. (8.1).

$$F_j(x_i) = \text{pnorm}(x_i, \mu_i, \sigma_i) \quad (8.1)$$

$F_j(x_i)$  denotes the probability density function of the gray value in intensity  $j = 5, 6, 7, 8, \dots$ , and  $x_i$  is the gray value of the change image.  $\mu_i, \sigma_i$  are the mean and standard deviation of statistical sample gray value in intensity  $j$ , respectively. A map projection conversion is directed with a suitable location of the origin of coordinates or false northing and false easting to make all XY coordinates positive, and then the contours were generated.

Take  $a_j = \max(x_{ij})$ ,  $b_j = \min(x_{ij})$ ,  $c = \max(y_{ij})$ , and  $d = \min(y_{ij})$ , where  $I$  is for identification of the sample point,  $j$  is for intensity,  $e = \min(j)$ ,  $f = \max(j)$ , and  $x_{ij}, y_{ij}$  are the coordinates of point  $i$  with intensity  $j$ . The circle contour can be stated by the following (Eq. 8.2).

$$R_j^2 = (x_j - x_0)^2 + (y_j - y_0)^2 \quad (8.2)$$

$$x_0 = \frac{1}{2(f - e + 1)} \sum_{j=e}^f (a_j + b_j)$$

$$y_0 = \frac{1}{2(f - e + 1)} \sum_{j=e}^f (c_j + d_j)$$

$$R_j = \frac{1}{2} \sqrt{(a_j - b_j)^2 + (c_j - d_j)^2}$$

where  $(x_0, y_0)$  is the coordinate of a circle center and  $R_j$  is the equivalent radius of the region with intensity  $j$ . If the rupture direction is recognized (in 0–90 degree), an ellipse can be determined in Eq. 8.3.

$$\frac{((x_j - x_0)\alpha_j + (y_j - y_0)\beta_j)^2}{A_j^2} + \frac{((y_j - y_0)\alpha_j + (x_j - x_0)\beta_j)^2}{B_j^2} = 1 \tag{8.3}$$

$$A_j = R_j, B_j = \max\left(\sqrt{(a_j - b_j)^2 + (c_j - d_j)^2}\right)$$

$$\alpha_j = \cos \varphi_j, \beta_j = \sin \varphi_j, \quad \varphi_j = \arctan\left(\frac{c_j - d_j}{a_j - b_j}\right)$$

where  $A_j$  is the radius along the major axis and  $B_j$  is the radius along the major axis.

### 8.3.6 Trend Surface Analysis

The trend surface analysis is the most widely applicable global surface-fitting procedure. It is a global procedure with an inexact interpolation used for obtaining smooth and approximate value points with known values using a polynomial equation (Chang, 2006). A cubic polynomial surface such as in Eq. (8.4) can be used to model the trend of the spatial distribution of the RS variables. After global polynomial interpolation by Eq. (8.4), the contours without a given shape can be generated by horizontal cuts. The mapped data are approximated by a polynomial expansion of the geographic coordinates of the control points, and the coefficients of the polynomial function are found by the method of least squares, insuring that the sum of the squared deviations from the trend surface is a minimum. Each original observation is considered to be the sum of a deterministic polynomial function of the geographic coordinates plus a random error.

$$Z(x, y) = b_0 + b_1x + b_2y + b_3x^2 + b_4xy + b_5y^2 + b_6x^3 + b_7x^2y + b_8xy^2 + b_9y^3 \tag{8.4}$$

where  $Z(x, y)$  is the surface equation and  $b_0, b_1, b_2, b_3, b_4, \dots, b_9$  are coefficients to be fitted in the regression.

### 8.3.7 Co-Kriging

Co-Kriging is a geo-statistical analyst module that is considered as a point interpolation. It needs point data as input which is used to yield raster data with approximations of an optionally inaccurate data. It is a multivariate variant of the usual kriging operation that predicts for a poorly tested variable (predictor) with support of a well-sampled co-variable, where they should be highly correlated using Eq. 8.5. This paper considers intensity as the primary variable and statistical sample gray value as the secondary variable.

$$P^*(u_0) = \sum_{k=1}^n \lambda_k * p(u_k) + \sum_{l=1}^m \varpi_l * q(u_l) \quad (8.5)$$

Where  $P^*(u_0)$  is for the co-kriging estimate at point  $u_0$ ,  $n$  is for the number of  $p(\cdot)$  points, and  $m$  is for the number of  $q(\cdot)$ . The  $p(u_k)$  is for the intensity at point  $u_k$  and  $q(u_l)$  for the statistical sample gray value at point  $u_l$ , respectively. The corresponding weights  $\lambda_k, \varpi_l$  are from the solution of co-kriging equations of intensity semivariogram, statistical sample gray value semivariogram and cross-covariance of intensity, and statistical sample gray value.

### 8.3.8 Isoseismic Line

Concentric loops are the most implied isoseismic lines but are very coarse. Ellipses are better with two structures but are still not compliant since the form gets fixed. The lines with different roman numerals, V, VI, VII, IX, and X, respectively, denote intensity zones. Both the co-kriging and trend surface methods can generate isoseismic lines quite well. Isoseismic lines acquired from the trend surface model are very smooth, and those from the co-kriging model must be further leveled. The larger the numbers of “n” and “m,” the smoother the isoseismic lines, and it can be smoothed using other mathematical tools.

## 8.4 Results and Discussion

### 8.4.1 Land Use/Land Cover

The land use and land cover map is a chief principle for regulating the earthquake risk zones. In the present study, nine land use and land cover classes specifically agricultural, snow and glacier, alpine scrub, alpine meadow, oak forest, coniferous forest, roads, alpine, teaks, and the alder forest have been classified from the LANDSAT-8 image using Maximum likelihood classifier. The supervised

classification was done along with the image analysis keys such as the tone, association, texture, etc. (Fig. 8.2).

### **8.4.2 Cartosat DEM**

The Cartosat digital elevation model (DEM) of 15-meter resolution was used for generating the slope and relief map for the study area (Fig. 8.3). The map represents the digital elevation model of Sikkim, and the value of the map varies from 188 (low) to 8387 (higher).

### **8.4.3 Slope Map**

A slope map represents the variations of altitude within a distance. Slope map is made up of Cartosat DEM (Fig. 8.3). It represents the direction and steepness of the slope for a terrain for continuous surfaces. Slope map is categorized on the basis of combination of the hues such as the red, yellow, orange, green, etc. (Fig. 8.4). A slope map specifies in the direction of the topography of a region alongside with a study of topographic description as they have inclined and may persist to authority the enlargement of land. The slope map is determined of steepness characteristic comparative to the horizontal plane. The surface topography is one of the most influential determinants for the site effects during an earthquake. The slope resolution is classified into five classes for slope degree in between 0 and 87.5 values (Fig. 8.4).

### **8.4.4 Relief**

The relief of topography has an important impact on the earthquake response of a region. The variation in altitude is greatly affected by the climate and the weather which determines the rock and soil type found in the region. The relief map was extracted from the Cartosat DEM classified into five classes ranging from 0 to 8340 m (Fig. 8.5).

### **8.4.5 Earthquake Mapping**

Earthquake transpire when the plate tectonic unpredictably disengage to form a fault or fold during the time of seismic activity and makes ground to tremble (Fig. 8.6). An earthquake map is prepared by contemplating the past fault and the earthquake

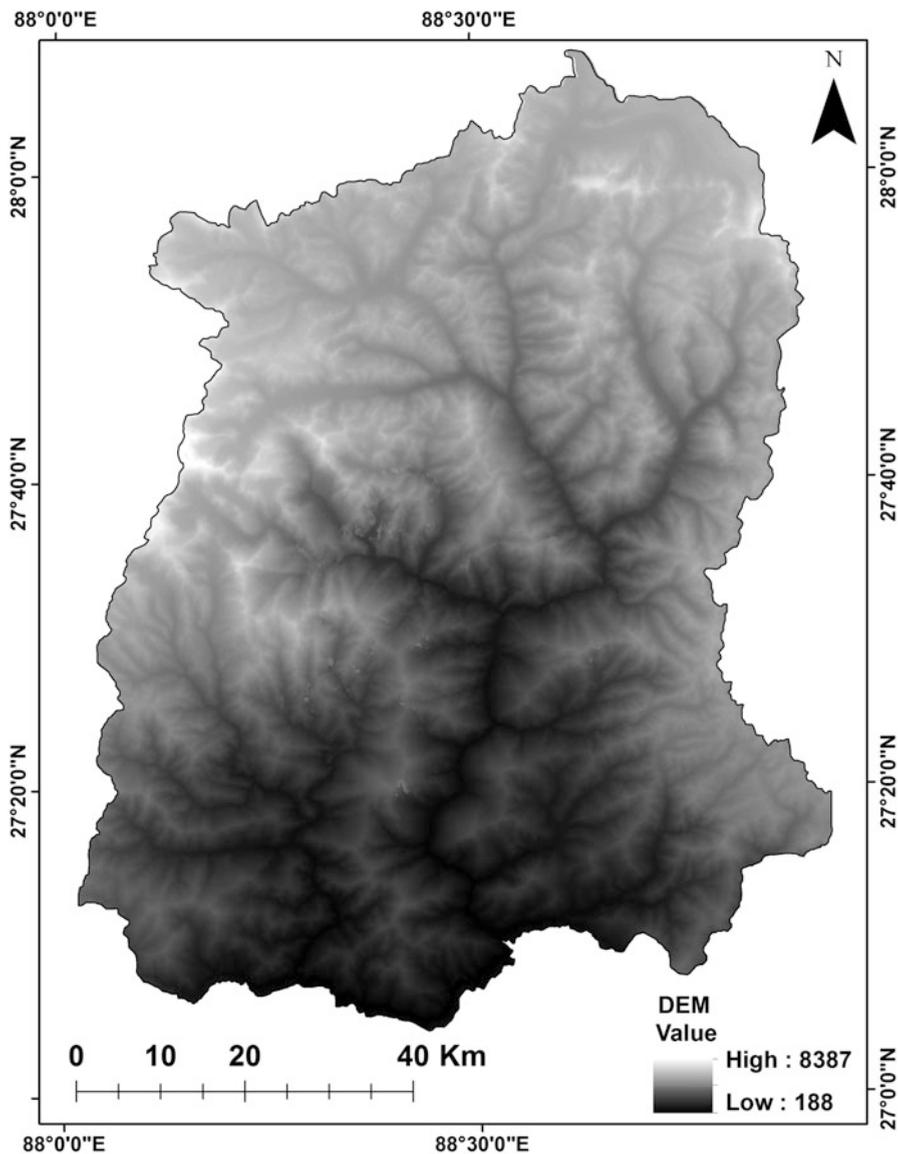


Fig. 8.3 Cartosat digital elevation model (DEM) of the study area

activities as well as the performance of the seismic waves traveling in different direction. An earthquake map can be utilized for the development of a land use, alleviation, and the crisis response. The earthquake map represents different probabilities selected to provide an overview of relative range of seismic activities. It shows areas that were affected by the earthquake along with the hazard intensity. The intensity of earthquake varies from lowest 6 to 8.5 which are of highest intensity (Fig. 8.6).

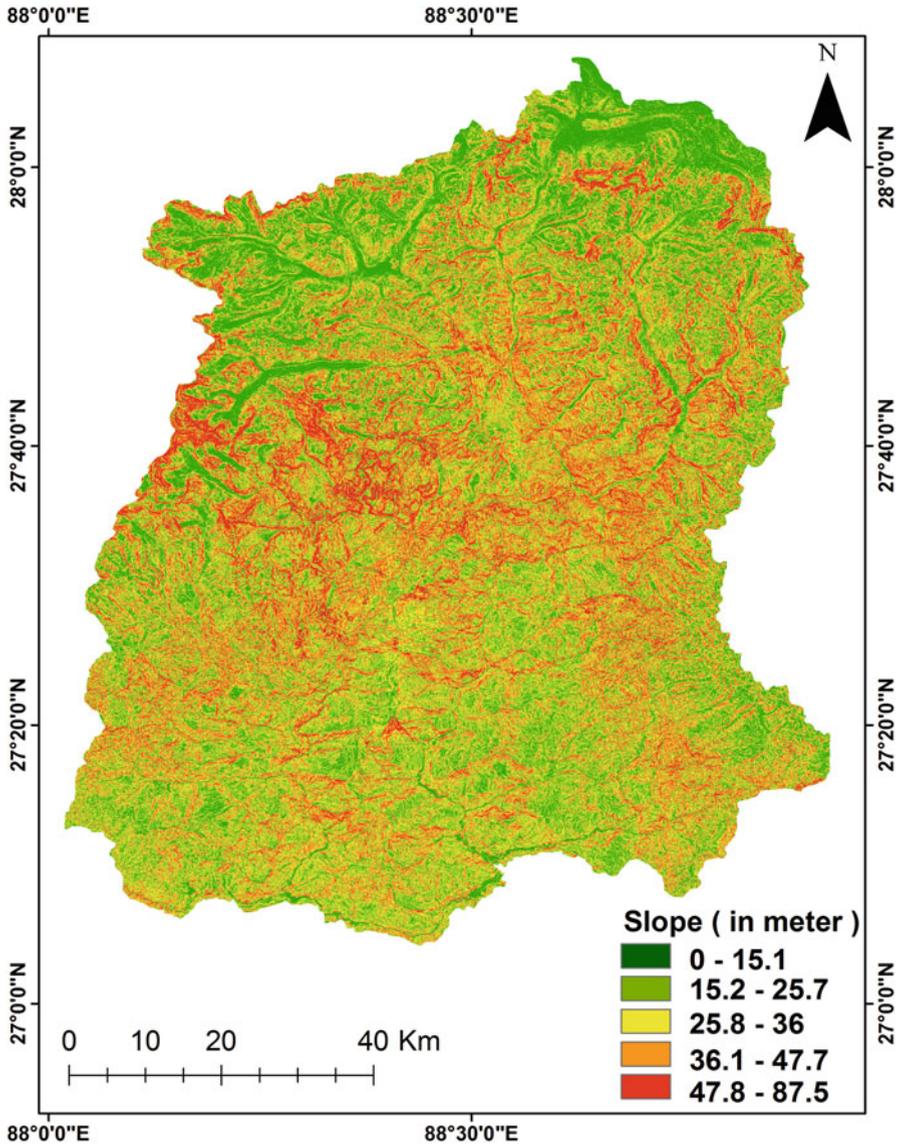


Fig. 8.4 Slope map of the study area

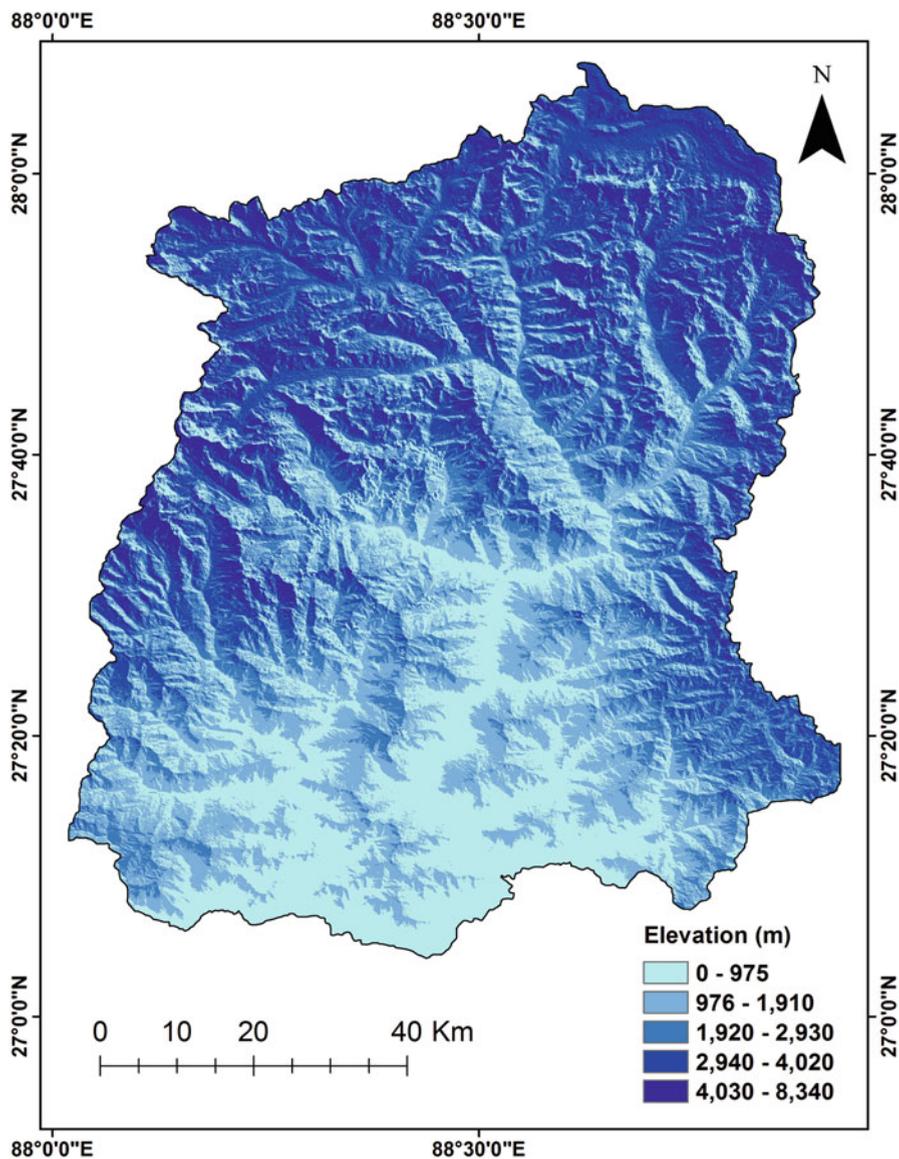


Fig. 8.5 Relief map of the study area

#### 8.4.6 Seismic Hazard Map

Based on the parameters such as geology, slope, soil, land use and land cover pattern, and the earthquake mapping (USGS 2014), the potential risk zones of the earthquake vulnerable areas were studied (Fig. 8.7). Map describes that complication

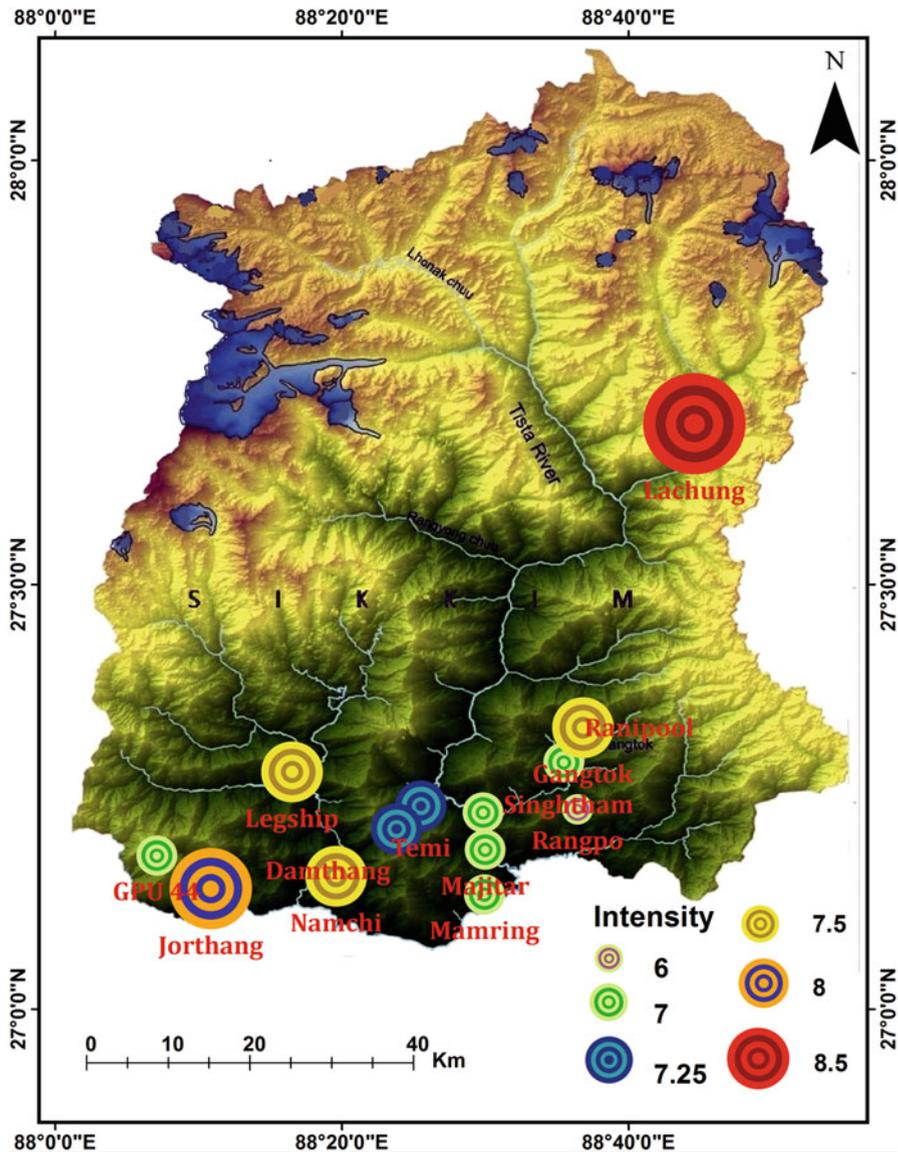


Fig. 8.6 Earthquake mapping of the study area

of the risk is not fully restricted to the state of the potentially exposure and the socially tempered acknowledgement. Therefore risk is considered to be the feature of the urban society that can be an admittance through an arrangement of the ecological aspect that are related with the physical environment of the geographic space where the urban society is situated or the social situation of the population in that region

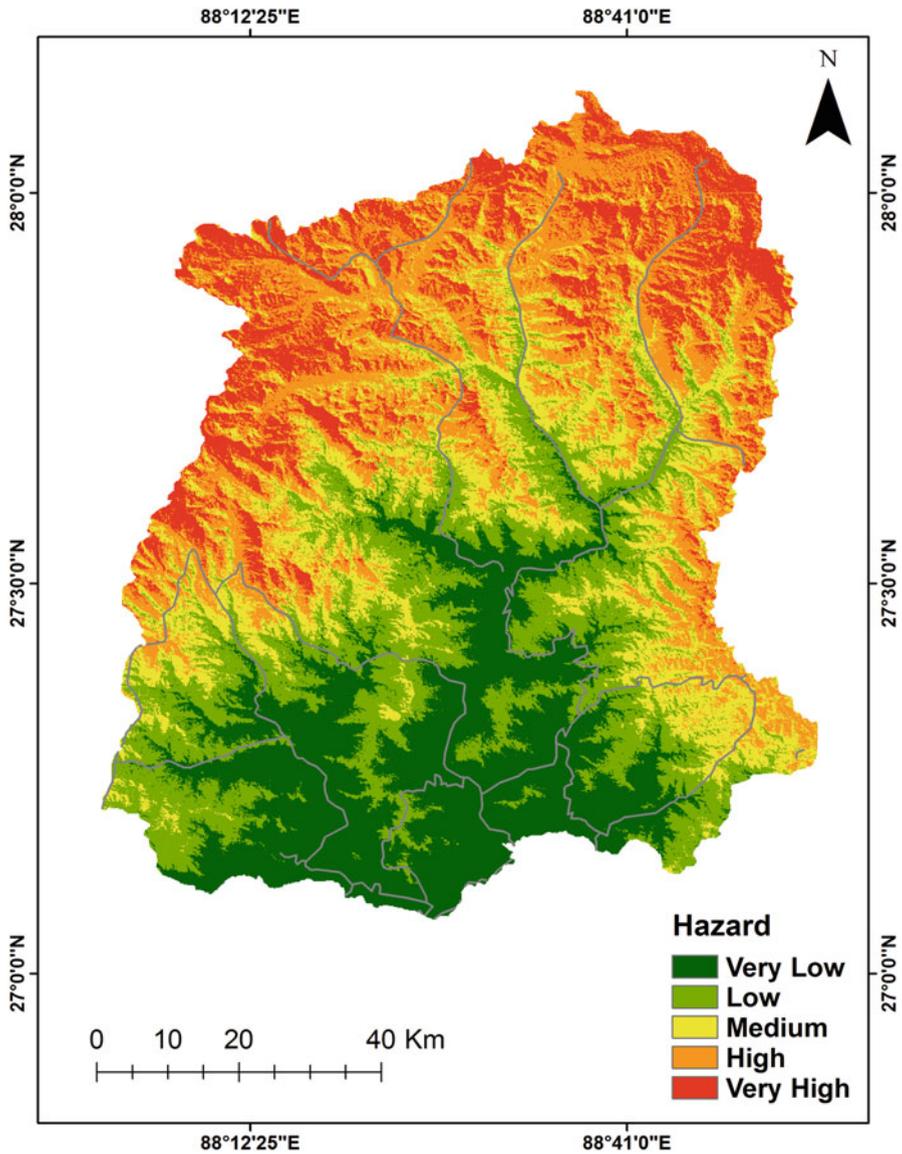


Fig. 8.7 Hazard map of the study area

(Fischhoff et al. 1981). Through the study of risk or the vulnerability zones, the highly prone areas are easily identified and differentiated from the other regions within the study area. The risk zone is considered to be the spatial problem which involves the observant confirmation of the risk zones based on the weighted analysis

(Keeney 1995). By the use of GIS-based spatial multi-measurement, the problem toward the risk analysis can be tackled.

Exploration and analysis are still continued to be done and grow on the earthquake mapping and the hazard mapping in a large-scale format. The shift in the hazard to disasters has continued, and the spotlight on human vulnerability has been maintained (White et al. 2001). The affiliation between a hazard and its prospect can be used to finish off the on the whole level of risk. The surroundings can be expensive in economic and social term; a direct hazard to life is the most severe threat. Risk is occasionally taken as identical with hazard, but risk has extra implication of the possibility of exact hazard actually happening. Hazard is paramount viewed as a physically taking place or human-induced process, or occasion, with impending to generate loss. Risk is the actual exposure of something of human value to a hazard and is often regarded as the product of probability and loss (Okrent 1980).

## 8.5 Conclusion

The research characterizes the attempt to study and mapping of the earthquake for the state of Sikkim which lies in the zone-IV category classified as the great vertical extend zone. The research emphasizes on the areas that were affected by the earthquake or the areas that are vulnerable to earthquake. This has been calculated via various algorithms and with the use of ArcGIS and ERDAS Imagine. The concluded map is the overlay analysis map representing all the combination of factor maps that slope map, relief map, digital elevation model map, and land use and land cover map. The research was taken into account to analyze the five criteria that are geology, soil, slope, road, and the land use/land cover using the GIS to create the earthquake hazard map. This map is concluded to increase the awareness, management, and preparedness among the people invulnerable areas in Sikkim.

## References

- Allen RM, Kanamori H (2003) The potential for earthquake early warning in southern California. *Science* 300:786–789
- Ansari A, Biro Y, Erken A, Gulerc U (2004) Seismic microzonation: a case study. In: Ansari A (ed) *Recent advances in earth quake geotechnical engineering and microzonation*. Kluwer Academic Publishers, The Netherlands, pp 253–266
- Armas I (2012) Multi-criteria vulnerability analysis to earthquake hazard of Bucharest. Romania *Nat Hazards* 63(2):1129–1158
- Armas I, Gavris A (2013) Social vulnerability assessment using spatial multi-criteria analysis (SEVI model) and the social vulnerability index (SoVI model)-a case study for Bucharest. Romania *Nat Hazards Earth Syst Sci* 13:1481–1499
- Census of India (2011) *Census of India*, Government of India, 2011.

- Champatiray PK, Perumal RJ, Thakur VC, Bhat MI, Malik MA, Singh VK et al (2005) A quick appraisal of ground deformation in Indian region due to the October 8, 2005 earthquake, Muzaffarabad, Pakistan. *J Indian Soc Remote Sens* 33(4):465–473
- Chang KT (2006), Spatial interpolation, introduction to geographic information systems, 3rd ed., chapter 16, Beijing: Science Press and McGraw-hill Education (Asia) Co., China
- Chen LC, Liu YC, han KC (2006) Integrated community-based disaster management program in Taiwan: a case study of Shang-An village. *Nat Hazards* 37:209–223
- Chen M, Wood MD, Linstead C, Maltby E (2011) Uncertainty analysis in a GIS-based multicriteria analysis tool for river catchment management. *Environ Model Softw* 26(4):395–405
- Chemenda AI, Mattauer M, Malavieille J, Bokun AN (1995) A mechanism for syn-collisional rock exhumation and associated normal faulting: results from physical modelling. *Earth Planet Sci Lett* 132:225–232
- Fekete A (2009) Validation of a social vulnerability index in context to river-floods in Germany. *Nat Hazards Earth Syst Sci* 9(2):393–403
- Fischhoff B, Lichtenstein S, Slovic P, Derby SL, Keeney RL (1981) *Acceptable risk*. Cambridge University Press, New York
- Glennie KW, Boef MGA, Hughes-Clarke MW, Moody-Stuart MN, Pilaar WFH, Reinhart BM (1990) Inter-relationship of Makran–Oman Mountains belts of convergence. In: Robertson AHF, Searle MP, Ries AC (eds) *The geology and tectonics of the Oman region*, vol 49. Geological Society Special Publication, London, pp 773–786
- Jianya G (2004) Review of the progress in contemporary GIS. *Geomatics Spat Inf Technol* 27(1):5–11
- Kaila KL, Narayan H (1976) Evolution of the Himalaya based on seismotectonics and deep seismic soundings. *Him Geol Em, Sec II B, New delhi, Geol Surv Ind Misc Pub No 41, Part-IV*, pp 1–26
- Keeney RL (1995) Understanding life threatening risks. *Risk Anal* 15:627–637
- Lang D, Molina-Palacios S, Lindholm C, Balan SF (2012) Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania. *J Seismol* 16(1):67–88
- Lillesand TM, Kiefer RW, Jonthan WC (2008) *Remote sensing and image interpretation*, 6th edn. Wiley, New York
- Lin CW, Liu SH, Lee SY, Liu CC (2006) Impacts of the chi–chi earthquake on subsequent rainfall-induced landslides in Central Taiwan. *Eng Geol* 86:87–101
- Metternicht G, Hurni I, GOGU R (2005) Remote sensing of landslides: an analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments. *Remote Sens Environ* 98:284–303
- Morrow Betty H (1999) Identifying and mapping community vulnerability. *Disasters* 23(1):1–18
- Okrent D (1980) Comment on societal risk. *Science* 208:372–375
- Onagh M, Kumra VK, Rai PK (2012) Landslide susceptibility mapping in a part of Uttarkashi district (India) by multiple linear regression method. *Int J Geol* 2(2):102–120
- Ouma Y, Kipkorir EC, Tateishi R (2011) MCDA-GIS integrated approach for optimized landfill site selection for growing urban regions: an application of neighborhood-proximity analysis. *Ann GIS* 17(1):43–62
- Pavel F, Vacareanu R (2016) Scenario-based earthquake risk assessment for Bucharest, Romania. *Int J Disaster Risk Reduct* 20:138–144
- Pavel F, Vacareanu R, Douglas J, Radulian M, Cioflan CO, Barbat AH (2016) An updated probabilistic seismic hazard assessment for Romania and comparison with the approach and outcomes of the SHARE project. *Pure Appl Geophys* 173(6):1881–1905
- Roustaei M, Nazi H, Amirmotallebi N (2005) The Seismotectonic and Zonation Map of Salmas Vastness by GIS modeling according to Landsat Satellite Images (ETM+) and Aeromagnetic data. Paper presented at the Map Middle East, 23–25 April, 2005, Dubai, UAE
- Rufat S (2009) From mural map to GIS: mapping urban vulnerability in Bucharest. In: Krek A, Rumor M, Zlatanova S, Fendel E (eds) *Urban and regional data management: UDMS*. Taylor and Francis Group, London, pp 301–313

- Sarkar, E and D.R. Nandy (1974) Structure and tectonics of Tripura-Mizoram area, India, sem. Vol. on tectonics and metallogeny of S. and E. Asia, Mis. pub.no.34, geol Surv Ind, Part I, pp. 141–148
- Sengar SS, Kumar A, Ghosh SK, Wason HR, Raju PLN, Murthy YVNK. 2013. Earthquake-induced built-up damage identification using fuzzy approach. *Geomat Nat Hazards Risk* v4: 320-338
- Sikkim ISFR (2017) Indian state forest report by forest survey of India, Government of India, 2017
- Skarlatoudis AA, Theodulidis N, Papaioannou C, Roumelioti Z (2004) The dependence of peak horizontal acceleration on magnitude and distance for small magnitude earthquakes in Greece. In: 13th world conference on earthquake engineering, Vancouver, Canada, August, 2004
- Strasser FO, Bommer JJ, Sesetyan K, Erdik M, Cagnan Z, Irizarry J, Goula X, Lucantoni A, Sabetta F, Bal IE, Crowley H, Lindholm C (2008) A comparative study of European earthquake loss estimation tools for a scenario in Istanbul. *J Earthq Eng* 12(2):246–256
- Sun CG, Chun SH, Ha TG, Chung CK, Kim DS (2008) Development and application of a GIS-based tool for earthquake-induced hazard prediction. *Comput Geotech* 35:436–449
- Toma-Danila D, Cioflan CO, Balan SF, Manea EF (2015) Characteristics and results of the near real-time system for estimating the seismic damage in Romania. *Math Modelling Civil Eng* 11 (1):33–41
- Trifunac MD, Todorovska MI (1997) Northridge, California, earthquake of 1994: density of pipe breaks and surface strains. *J Soil Dyn Earthquake Eng* 16:193–207
- USGS (2014) Reports <http://www.sott.net/article/236229-USGS-Reports-Record-Number-Of-Strong-Earthquakes-In-2011>. Accessed 10 July 2014
- Walker BB, Taylor-Noonan C, Tabbernor A, McKinnon T, Dal H, Bradley D, Schuurman N, Clague JJ (2014) A multicriteria evaluation model of earthquake vulnerability in Victoria, British Columbia. *Nat Hazards* 74(2):1209–1222
- Weiwei W, Jiansi Y, Yirui L, Lingchun F (2009) Applications and development tendencies of WebGIS in earthquake disaster management. *Recent Dev World Seismol* 2009(3):20–27
- White GF, Kates RW, Burton I (2001) Knowing better and losing even more: the use of knowledge in hazards management. *Environ Hazards* 3:81–92
- Wilson TJ (1965) A new class of faults and their bearing on continental drift. *Nature* 207:343–347
- Yungang B, Liqiang C, Chengliang W et al (2004) Application of geographical information system to comprehensive disaster reduction. *J Coll Disaster Prev Tech* 6(3):16–20
- Zhou YX, Liu GJ, Fu EJ, Zhang KF (2009) An object-relational prototype of GIS-based disaster database. In: Proceedings of the 6th international conference on Mining Science & Technology, *Procedia Earth and Planetary Science* 1:1060–1066