GIS Based Landslide Susceptibility Mapping — A Case Study in Indian Himalaya

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Abstract

The paper presents GIS based spatial data analysis for landslide susceptibility mapping in parts of Sikkim Himalaya. Six important causative factors for landslides were selected and corresponding thematic data layers were prepared in GIS. The input data were collected from the topographic maps, satellite image, field data and published maps. Numerical weights for different categories of these factors were determined based on a statistical approach and then integrated in GIS environment to arrive at landslide susceptibility map of the area. The landslide susceptibility map classifies the area into five classes of landslide susceptible zones i.e., very high, high, moderate, low and very low. An attempt was also made to validate the map with the existing landslides of the area.

Keywords: landslide susceptibility, GIS, Sikkim Himalya, statistical approach

Introduction

The losses due to earthquakes and floods in India are much more than landslides, however, landslide occurrence being more frequent is considered to be a major geological hazard. Recently few landslide disasters in Himalaya have made tremendous impact on the society. As a result of increase urbanization, hill slopes are being disturbed due to various construction activities particularly the road construction. It is therefore necessary to know the landslide prone zones before any construction activity begins so that adequate control measures can be applied well in time. Landslide susceptibility mapping, which delineates the potential landslide zones, is useful for such purpose.

Over the past few years, Geographic Information System (GIS) has gained significant importance for spatial data analysis. It has been proved to a very powerful tool for landslide study. In recent years, GIS has been employed globally for spatial data analysis for landslide hazard zonation mapping (Gupta and Joshi, 1990; Carrara et al, 1991; Westen, 1994; Chung et al, 1995; Nagrajan et al, 1998; Dhakal et al, 2000; Saha et al, 2002; Sarkar and Kanungo, 2004).

The present paper deals with thematic data layer generation and their spatial analysis in GIS environment for landslide susceptibility mapping of parts of Sikkim Himalaya. Landslide occurrences are quite common in the Sikkim Himalaya, and the magnitude of damages caused every year in various parts of the state is quite large (Bhasin et al, 2002).

Study area

The Sikkim state in India is bounded by Nepal in the west, Bhutan in the east and China in the north. The present study is focused in the East District of Sikkim, which lies within the latitude 27° 10′ N–27°23′ E and longitude 88°25′–88°45′ E, and covers an area of about 549 km^2 (Figure 1). The maximum elevation in the area is 3250 m in the extreme north eastern part. The area is bound on three sides by the rivers Rangpochu in the south, Tista in the west and Dikchu in the north. The annual average rainfall at Gangtok, which is the capital town of Sikkim state, is of the order of 3500 mm (Bhasin et al, 2002). The maximum rainfall occurs during the monsoon months from April to September. Topographically the area is traversed by many ridges and valleys and the Ranikhola river dissects the area into the northwest and southeast part. The area is dominated by the slopes ranging between 15°–45°, while steep slopes of > 45° occupy smaller areas.

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Fig. 1. Study area

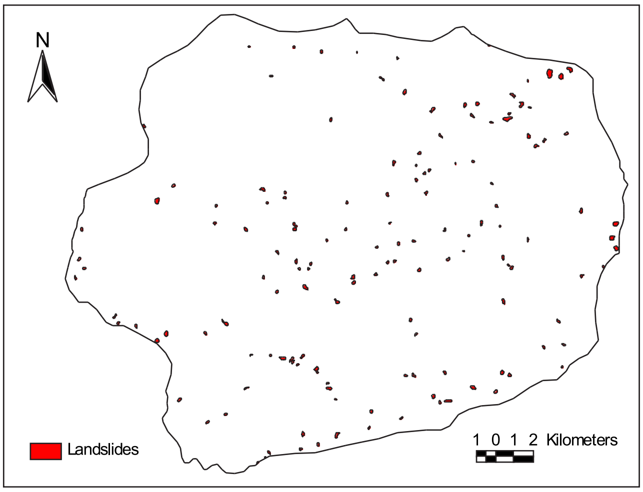

Fig. 2. Landslide distribution map

Landslide distribution

In this study, IRS LISS II image was used for landslide inventory. Landslide inventory on satellite imagery largely depends on the contrast of the spectral difference between the landslide and its surroundings. Landslides show high reflectance as they in general are scarce of any vegetation. Interpretation of the satellite images carefully has led to mapping of landslides in the area. A few of the landslides mapped were confirmed in the field and the map was modified accordingly. Finally, we have inventoried 144 landslides (Fig. 2). Hence the landslide density of the area is 0.262 per km^2. Landslides are distributed in the whole area; however, major concentrations are in the central and northeastern part. Majority of the landslides in this area are rock and debris slide, however, some of the landslides are of rotational type. The causative factors as observed in the field are weathered gneisses, steep slope and erosion along the 1st and 2nd order streams.

Methodology

Landslides are governed by several factors; however it is not always possible to obtain all the data. In the present study six factors were considered for landslide susceptibility mapping. They are lithology, fault, drainage, slope, slope aspect and landuse. Though rainfall and earthquakes are the two important triggering

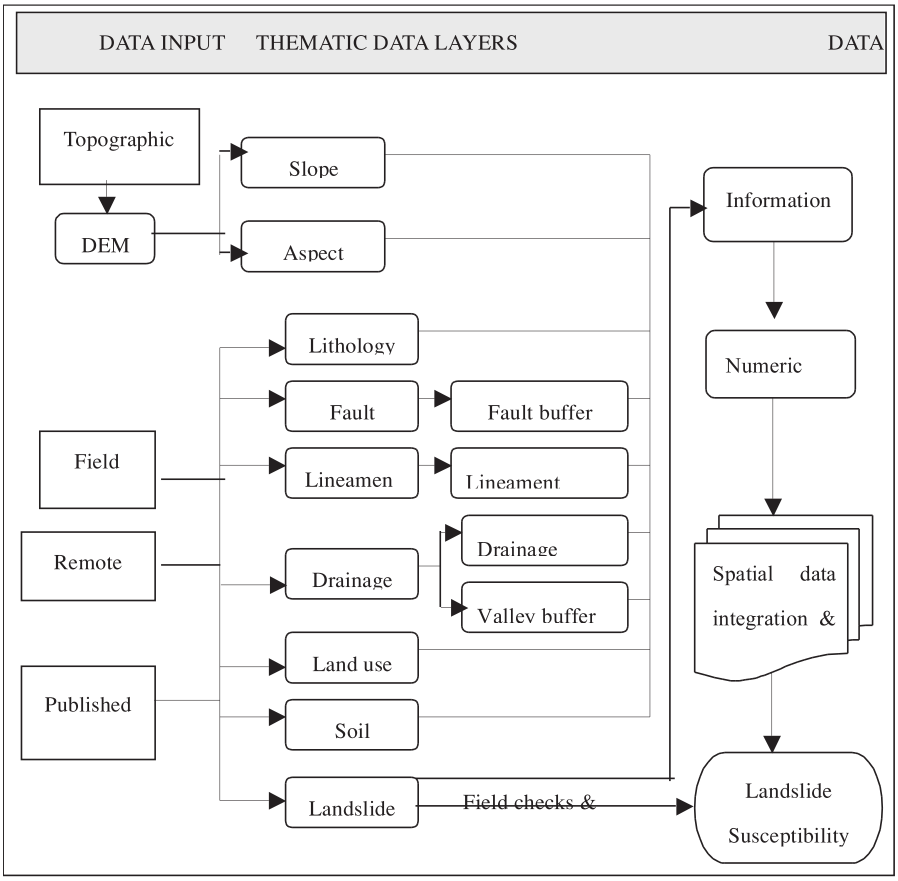

Fig. 3. Flow diagram showing methodology

factors for landslides, these are not considered in this study due to non-availability of sufficient data. The factors considered here are essentially the preparatory factors, which can be collected easily from the field and available information. The thematic data layers for each of the factors were prepared in GIS based on topographic, remote sensing and field data.

A rating scheme is generally employed to assign numerical weights to the factors based on their importance for landslide. There are basically two ways to determine the weights. One is subjective approach where a person assigns weights based on expert opinion or his own experience (Anbalagan, 1992; Sarkar and Kanungo, 2004) and the other is the statistical approach where factors are correlated with landslide distribution (Carrara, 1983; Yin and Yan, 1988, Jade and Sarkar, 1993; Sarkar and Gupta, 2005). In the present study the categories of the selected factors were assigned the numerical weights following information value method, which is a statistical approach based on the frequency distribution of landslides in different factor categories. The landslide susceptibility map was finally prepared by integrating the data in GIS and classifying the integrated values into different classes of landslide susceptibility. The landslide susceptibility map was then validated with the landslide distribution of the terrain. The outline of the methodology is shown in the flow diagram (Fig. 3).

Input data layers

Thematic data layers corresponding to the six factors were prepared in GIS. The data used to prepare these maps were collected from the topographic maps (1:50,000 scale), remote sensing data (IRS LISS II with resolution 36.25 m), published literatures and field investigation. A brief description of these layers is given below.

DEM and its derivatives

DEM (digital elevation model) is digital representation of a topographic surface with the elevation above a geodetic datum. The DEM (25m grid cell size) of the study area was prepared from the contour

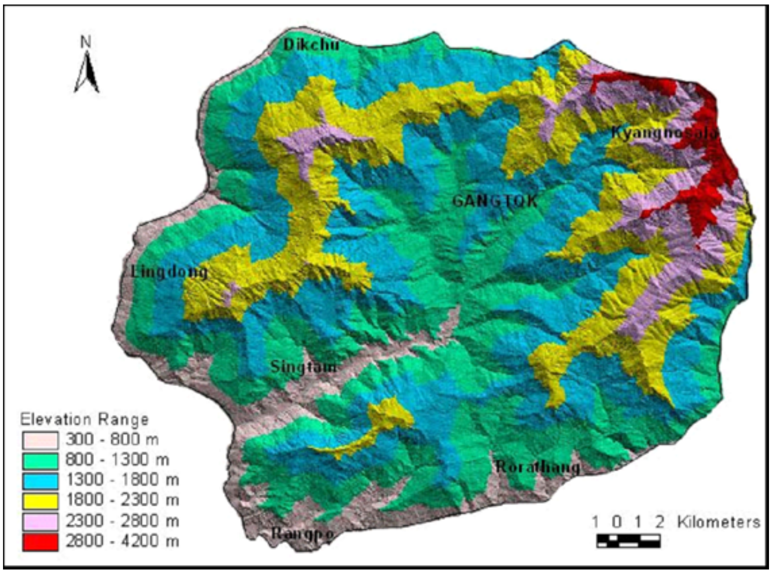

Fig. 4. DEM showing the elevation classes

information given in the topographic maps using TIN module of Arc View 3D Analyst (Fig. 4).

The slope map was then derived from the DEM. The slope map was classified into 5 classes following classification of earlier workers (Dhakal et al, 2000; Sarkar and Kanungo, 2004).

The map was dominantly occupied by the slope classes of 15°–25° and 25°–35°, followed by 35°–45°. A slope aspect map, which shows direction of slope, was also derived from the DEM.

Lithology

The major geological formations of the area belong to Chungthang Formation, Sikkim Group and Darjeeling Group of Precambrian age (Raina and Srivastava, 1979). The lithology map was prepared in GIS following the published geological maps and field checks. There are six rock types present in the area. These are gneiss, schist, quartzite schist, quartzite phyllite, quartzites and phyllite. The dominant lithology is schists. At higher elevation the schists become coarser and the foliation becomes more distinguished. Around north of Gangtok town the rocks are more gneissic occurring at higher elevation on the north eastern part of the area. Quartzites alternating with schists are found in the south west of Gangtok town. Phyllites are exposed in the south while quartzites alternating phyllites predominate along the western boundary of the study area. The quartzites and quartzites with phyllites are prominent than the other rocks in the whole area. However, all the rocks have been subjected to tectonic activity, resulted into highly sheared facies and show high weathering along the drainage channels and the thrust/faults.

Thrust/Faults

There is a major thrust called Chungthang thrust in the north eastern part of the area. This thrust is clearly outcropped near the place called Panchmil on Jawaharlal Nehru road. Besides this, a major fault trending N-S is also present. For our analysis buffer map of faults was prepared in GIS showing buffer width of 1 km from these two faults. The map was classified into four buffer zones i,e, 0–1km, 1–2 km, 2–3 km and > 3 km.

Drainage

The drainage information was derived from the topographic maps on 1:50,000 scale. The drainage lines were digitized and the map was prepared in GIS. The drainages were then classified based on stream order. Since landslides in this area are mostly associated with 1st and 2nd order stream, a drainage buffer map was prepared in GIS considering 1st and 2nd order streams. The buffer widths considered were 0–50m, 50–100m and > 100m.

Land use

The land use map of the area was prepared from the remote sensing data. Ground truth data were collected from the field and also perceived from the topographical maps. IRS LISS II satellite image was interpreted for various land use in terms of vegetation cover. The land use map, thus prepared, classifies the area into thick forest, moderate forest, sparse forest, agriculture land and barren land. The area is mostly covered by moderate and sparse forest categories, followed by agriculture land and thick forest respectively. The barren land, which occupies least area, is predominant at higher elevation in the northeastern part.

Information Value Method

Information value method is a statistical method for spatial prediction of an event based on the parameter and event relationship. It has been very useful method for landslide susceptibility mapping by determining the influence of parameters governing landslides in an area and this method has been used by several workers (Yin and Yan, 1988; Jade and Sarkar, 1993).

The information value Ii for a parameter i is:

$$I_i = \log \frac{S_i/N_i}{S/N} \tag{1}$$

Where, N = total number of data points (grid cells); S = number of grid cells with landslide; S_i = number of grid cells involving the parameter and containing landslide; N_i = number of grid cells involving the parameter.

Now the total information value in a grid cell j is:

$$I_j = \sum_{i=1}^{M} X_{ji} \times I_i \tag{2}$$

Where, X_{ji} is value of parameter $i, j = 1, 2, ..., N$; and $i = 1, 2, ...M; = 1$, if parameter i exists in grid cell j and $= 0$, if parameter i does not exist in grid cell j; M = number of parameters considered.

The above model was used to determine the information value of each category of the factors and the total information value of each grid cell of the area. The more the total information value the more is the degree of landslide susceptibility.

GIS analysis for landslide susceptibility mapping

The six thematic data layers and the landslide distribution map were the input data layers for spatial analysis in GIS. The cell size selected for the analysis was 25m × 25m because the DEM is composed of 25 m grid cells. The total number of cells in the area is 878077. The number of cells occupied by each category of all the factors was calculated in GIS. Then each layer was multiplied to the landslide layer to determine the number of cells of each category of a factor containing landslides. From the above data using equation (1), information values of all the categories were computed. The categories of the six parameters and their information values are given in Table 1.

From this table it can be seen that within 33 categories belonging to six factors, the top ten important categories in terms of information values are the gneiss rock, barren landuse, 60–90° slope, south east aspect, 45–60° slope, south west aspect, 1–1000m fault buffer, agriculture land use, 35–45° slope and south aspect in descending order. Hence it may be inferred that the lithology, slope and land use seem to be the major controlling factors for landslide incidence. Assigning the information values as weights to the factor categories prepares the numerical data layers for further analysis.

Now to obtain the total information value for a grid cell as given in equation (2), the numerical data layers were integrated using Spatial Analyst Model of ARC View GIS. The data integration performs arithmetic overlay of the numerical data layers in raster mode. The total information value obtained for each grid cell gives the landslide potential index (LPI) of the cell. The LPI ranges from −1.514 to 0.916 for the 878077 cells of the area.

To classify the LPI values into different classes, the LPI values of all the cells were plotted with their frequency. At the first instance the graph shows many oscillations; therefore, it was difficult to classify. Hence the graph was smoothened by moving averages with averaging window lengths 5, 7, 9. It is noted that the window length 5 means the frequency value at any point is an average of the five consecutive values centered at that point. The graph with window length 9 shows the best segmentation for classification. The composite graph of window lengths 5, 7 and 9 is shown in Fig. 5. After interpreting the graphs carefully the class

Table 1. Information values of factor categories

Factors	Categories	Information value	Factors	Categories	Information value
Slope	1. 0-15° 2. 15-25° 3. 25-35° 4. 35-45° 5. 45-60° 6. 60-90°	-0.365 -0.068 0.333 0.114 0.153 0.164	Slope Aspect	1. North 2. North- East 3. East 4. South- East 5. South 6. South -West 7. West 8. North- West	-0.153 -0.189 -0.009 0.156 0.110 0.151 0.019 -0.144
Lithology	1. Gneiss 2. Schist 3.Quartzite-schist 4.Quartzite- phyllie 5. Quartzite 6. Phyllite	0.213 -0.094 0.0 -0.273 -0.147 0.024	Landuse	1. Thick forest 2. Moderate forest 3. Sparse forest 4. Agriculture land 5. Barren land	-0.256 -0.063 0.005 0.141 0.191
Fault Buffer	1. 0-1 km 2. 1-2 km 3. 2-3 km 4. >3 km	0.145 -0.002 -0.151 -0.011	Drainage Buffer	1. 0-50 m 2. 50-100 m 3. >100 m	-0.050 0.054 0.042

Table 2. Landslide Potential Index (LPI) and susceptibility class

Susceptibility class	
Very low	< -0.65
Low	-0.65 - -0.13
Moderate	-0.13 – 0.15
High	0.15 – 0.42
Very High	> 0.42

boundaries were drawn at significant changes in the gradients of the curves. Applying these class boundaries to the LPI values the area was classified into very high, high, moderate, low and very low classes of landslide susceptibility (Table 2).

The landslide susceptibility map is shown in Fig. 6. The northeastern part is an area of very high and high landslide susceptible class. It is mostly composed of gneissic rocks in the vicinity of Chungthang thrust on barren steep slopes with less vegetation. A few scattered zones of high susceptibility class in the southern and central portions of the area have also been recognized.

Map validation

In order to validate physically, the landslide susceptibility map prepared in GIS, was verified in the field at a few locations particularly showing the very high and high susceptibility. It was observed that slope instability signatures such as landslides, slope erosion, road subsidence, marked the areas of very high and high susceptible zones. Further for a quantified validation of the map, the landslide density of each class was computed (Table 3).

From the table it can be observed that landslide density values for very high and high susceptibility classes are 0.015 and 0.01 respectively, which are remarkably higher than the other classes. Further, there is a gradual decrease in density values from very high to very low susceptible class and there is also considerable separation in landslide density values in between the susceptibility zones. This reflects the validity of the landslide susceptibility map with existing slope instability conditions.

Conclusions

The present work is an attempt towards application of GIS for landslide susceptibility mapping. Different thematic data layers have been prepared and the numerical weights of the categories of the factors have been determined using Information value method. This method was found to be useful for landslide susceptibility mapping.

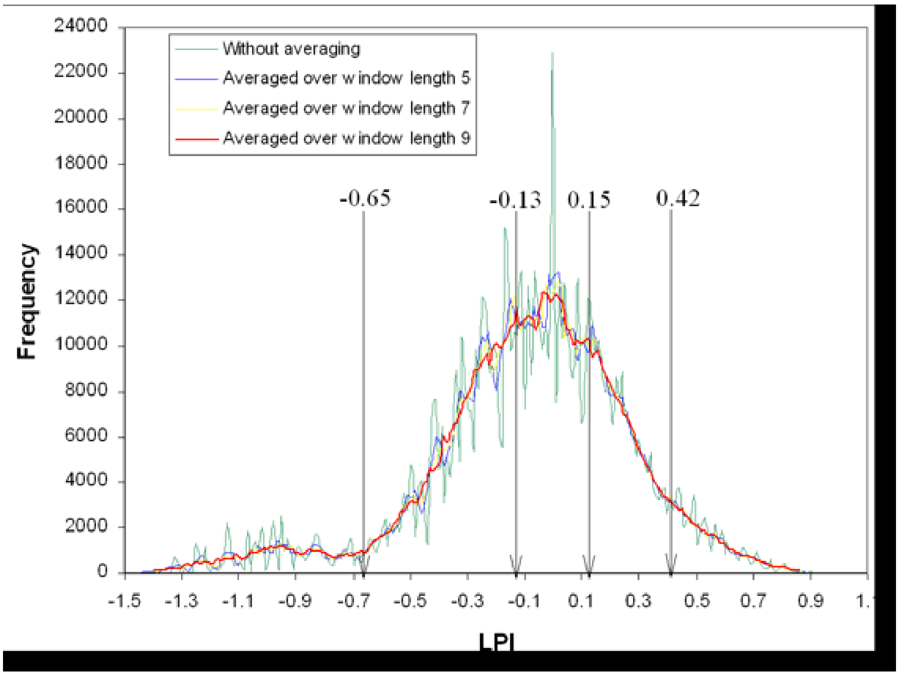

Fig. 5. Frequency distribution of landslide potential index

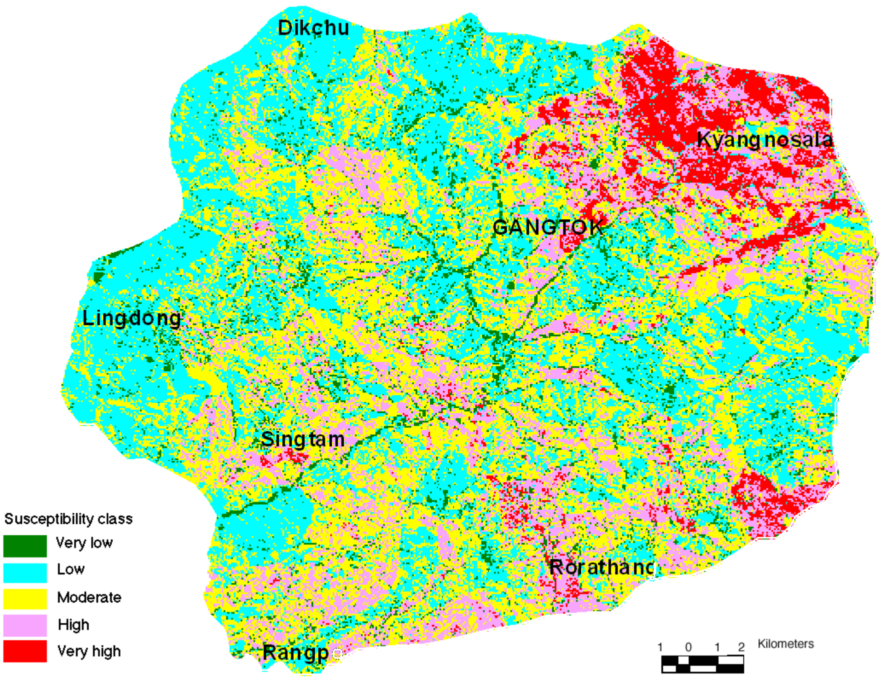

Fig. 6. Landslide susceptibility map

The areal distribution of different landslide susceptibility zones showed a normal distribution as desired. The susceptibility map was validated by determining landslide densities for susceptible zones and was found to be in coherence with the ground instability conditions. The distribution of landslide density values are skewed towards the higher susceptibility zones, as should be the case. GIS based landslide susceptibility mapping using information value method can be implemented in other Himalayan regions to prove its efficacy. However, very high and high landslide susceptible zones need to be investigated in detail for suggesting corrective measures before implementation of any hill developmental activity.

Table 3. Landslide density in different landslide susceptibility classes Susceptibility class

Susceptibility class	Area (km^2) (b)	Landslide area (km^2) (a)	Landslide density (a/b)
Very low	33.396	0.051	0.002
Low	189.526	0.607	0.003
Moderate	194.895	1.09	0.006
High	99.431	0.971	0.010
Very high	31.551	0.473	0.015

Acknowledgements

Authors are grateful to the Director, CBRI for his kind permission to publish the work.

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