Study of landslide hazard zonation in Mandakini Valley, Rudraprayag district, Uttarakhand using remote sensing and GIS

M. S. Rawat[1], D. P. Uniyal[1], R. Dobhal[1], Varun Joshi[2], B. S. Rawat[3], Anil Bartwal[4], Devendra Singh[5] and Ashok Aswal[5]

[1]Uttarakhand State Council for Science & Technology, Vigyan Dham Jhara, Dehradun 248 007, India
[2]Guru Govind Singh Indra Prastha University, Sector 16C, Dwaraka, New Delhi 110 078, India
[3]Dayanand Brijendra Swarup (PG) College, Dehradun 248 001, India
[4]Mandakini Hydropower Project, Phata 246 471, India
[5]Uttarakhand Space Application Centre, Vasant Vihar, Phase II, Dehradun 248 006, India

The Mandakini Valley of Rudraprayag district, Uttarakhand witnessed unprecedented damage to life, property, infrastructure and landscape on 16 and 17 June 2013 due to torrential rains. Run-off discharge data indicate that antecedent rainfall exceeded the limit and the overflow of rivers led to landslide in the region and flash floods in the downstream areas. Fragile geology of the area, close to Main Central Thrust (MCT), degradation processes and torrential rains are responsible for triggering landslides and flash floods. A landslide inventory was carried out in the affected areas based on pre- and post-flood high resolution satellite data (LISS-IV and Cartosat-2). A total of 290 landslides were identified from pre-flood satellite LISS IV (2011) imagery and 1665 were identified in post-flood satellite imagery along major rivers. Using remote sensing and geographic information system techniques, thematic layers were generated. Using the weightage rating system, a landslide hazard zonation map of the area was prepared. Each class within a thematic layer was assigned an ordinal rating from 1 to 9. Summation of these attribute values was then multiplied by the corresponding weights to yield different zones of landslide hazard. A landslide hazard zonation map having five different zones ranging from very low hazard zone to very high hazard zone was prepared with the objective to create a reliable database for post-disaster management and for planning developmental activities in the district.

Keywords: Flash floods, landslide hazard zonation, satellite data, thematic layers.

LANDSLIDES are one of the destructive geological processes that cause not only enormous damage to roads, bridges and houses, but also lead to loss of life. Hence, there is a need for landslide susceptibility mapping for identification of potential landslide areas. Landslides are a result of complex interaction among several factors, primarily involving geological, geomorphological and meteorological factors. The spatial information related to these factors can be easily derived from remote sensing data, ground-based information and several other data sources. Geographic information system (GIS) is a powerful tool for integrating different types of data. Over the past few years, there have been significant developments in GIS for spatial data analysis. Efficient landslide hazard zonation mapping can be carried out by combining GIS with image processing capabilities.

The state of Uttarakhand faced excessive damage to life, infrastructure and natural resources on 16 and 17 June 2013 due to torrential rains. Mandakini River Valley in Rudraprayag district of the state experienced maximum destruction caused by rainfall, followed by cloudbursts and flash floods. The history of the region indicates that Mandakini Valley is prone to cloudbursts and flash floods. Landslide tragedy occurred in August 1998 around Madhmaheshwar and the Kaliganga sub-watersheds; Phata cloudburst (2001), Lwara slide and Basukedar slide (1992) and cloudburst in Ukhimath (2012) are some examples of devastation in Mandakini Valley that caused large-scale loss of lives, damage to resources and associated environmental–social hazards[1]. Geologically the Mandakini Valley comprises two separable major litho-stratigraphical units, i.e. the Garhwal Group and the Central Crystalline Group. These groups are separated from each other by a major tectonic contact known as the Main Central Thrust (MCT), and this thrust contact is traceable in the area of Kund (A. K. Naithani, unpublished). The Valley appears to have undergone several phases of tectonic movements, which are depicted by local folds, faults and thrusts. The zone between Rudraprayag and Kund consists of quartzite, slate, schist, crystalline limestone, dolomite, marble, gneiss and occasionally intruded by meta-volcanic rocks of the Garhwal Group. Upstream of Mandakini River from Kund to Kedarnath and Kund to Mandal, and beyond, various

*For correspondence. (e-mail: manmohansinghrwt@gmail.com)

types of schist, gneiss, granite and amphibolite of the Central Crystalline Group occur. The frequency of landslides in Garhwal Himalaya varies from one place to another, depending on the underlying structures, physiographic setting and anthropogenic changes taking place. Every year, the road network in this region sustains damages at hundreds of locations due to landslides. Cloudburst is one of the natural disasters associated with triggering of the mass wasting landslide and flash flood in the Himalaya. Several areas in the Himalaya are severely damaged by incessant rains and cloudburst followed by debris flow and consequently death of humans and animals[2].

Study area

Rudraprayag district, covering an area of about 1982.09 sq. km lies between lat. 30°12′58.132–30°48′27.642N and long. 79°2′58.649–79°2′0.952E falling in the Survey of India toposheet nos 53J /14, 53J/15, 53N/1, 53N/2, 53N/3, 53N/4 and 53N/6 (Figure 1). The district is bounded by Uttarkashi in the north, Chamoli in the east, Tehri Garhwal in the west and Pauri Garhwal in the south. The headquarter of the district is Rudraprayag which comprises three tehsils, viz. Ukhimath, Rudraprayag and Jakholi and three development blocks, viz. Ukhimath, Augustmuni and Jakholi. The climate in this region is mainly governed by monsoon. Mandakini is the major river of the district having many tributaries. The altitude of Mandakini River catchment extends from 670 to 6000 m amsl. During the last decade extensive expansion of roads and settlements has taken place in this catchment. Sometimes, not guided by the geology of the area, roads have been constructed, triggering several landslides. Rockfall along the roadside is also a common feature.

These activities have impacted upon the surrounding natural resources to meet the demands of the inhabitants. In general, humidity is found throughout the year in the air causing moistening and chemical and mechanical weathering of rocks under day and night temperature rhythms. Ukhimath area of this district is known as the Cherapunji of Garhwal[3].

Data used for present study

The data used in this study were from IRS-P6 LISS IV and IRS-CARTOSAT satellites (Table 1), topographic maps of the Survey of India (SOI; 1 : 25,000 and 1 : 50,000 scale), and information from published geological maps. The topographic maps and false colour composites (FCCs) of satellite data were used as the base maps for the field data. Data on rock types, structural lineaments, slope, geomorphology, wasteland, land use and landslides were collected for cross-checking and improving the input data layers. Satellite data were processed using ERDAS Imagine (version 9.1) software.

Methodology

This work is broadly divided into three parts: pre-field interpretation, field work and post-field interpretation and analysis (Figure 2). SOI toposheets, and remote sensing LISS-IV pre- and post-flood satellite data have been used. Extensive field surveys were conducted in different phases for field check and identification of geology, geomorphology, land use, landslide, slope, lineament, etc. The area has been visited by many researchers after major disasters took place in the Mandakini Valley in the past. The methodology involved selection of factors, generation of data layers in GIS, numerical rating assignment to factors, data integration in GIS, computation of the landslide potential index, suitable classification of landslide susceptibility and validation of the resulting map[4]. An attempt was also made to validate the map with existing landslide distribution. Public observations around and adjoining the landslide zones believed to have caused landslide element assumed were also collected[5,6].

Geological set-up of the region

Geological map of Mandakini Valley is shown in Figure 3 *a*. Tectonically, the Mandakini Valley comprises two separable major lithostratigraphic units – the Garhwal Group and the Central Crystalline Group. These groups are separated from each other by a major tectonic contact known as the Main Central Thrust (MCT), and this thrust contact is traceable in the area of Kund (A. K. Naithani, unpublished). The rocks in Kund Valley appear to have undergone several phases of tectonic movement that are depicted by local folds, faults and thrusts. The zone between Rudraprayag and Kund consists of quartzites, slates, schists, crystalline limestone, dolomite, marble, gneiss and occasionally intruded by meta-volcanic rocks of the Garhwal Group. Upstream along Mandakini river from Kund to Kedarnath and Kund to Mandal, and beyond various types of schists, gneisses, granites and amphibolites of the Central Crystalline Group occur.

Lineaments in hilly terrain indicate joints, fractures, faults and other weak structural zones (Figure 3 *b*). They bear a direct relationship with landslides. Several active landslides are located in fault zones and major lineaments in the Okhimath and adjoining areas. A photo-lineament map was prepared using polygon-mode, ARC/INFO environment. The lineament map was developed with the help of the SOI toposheets and IRS-1C LISS III satellite data.

Land-use/land-cover pattern

Forest, agricultural land, evergreen forest, alpine forest, grassland, barren land, etc. were demarcated in the catchment area. Land-use pattern is largely controlled by the

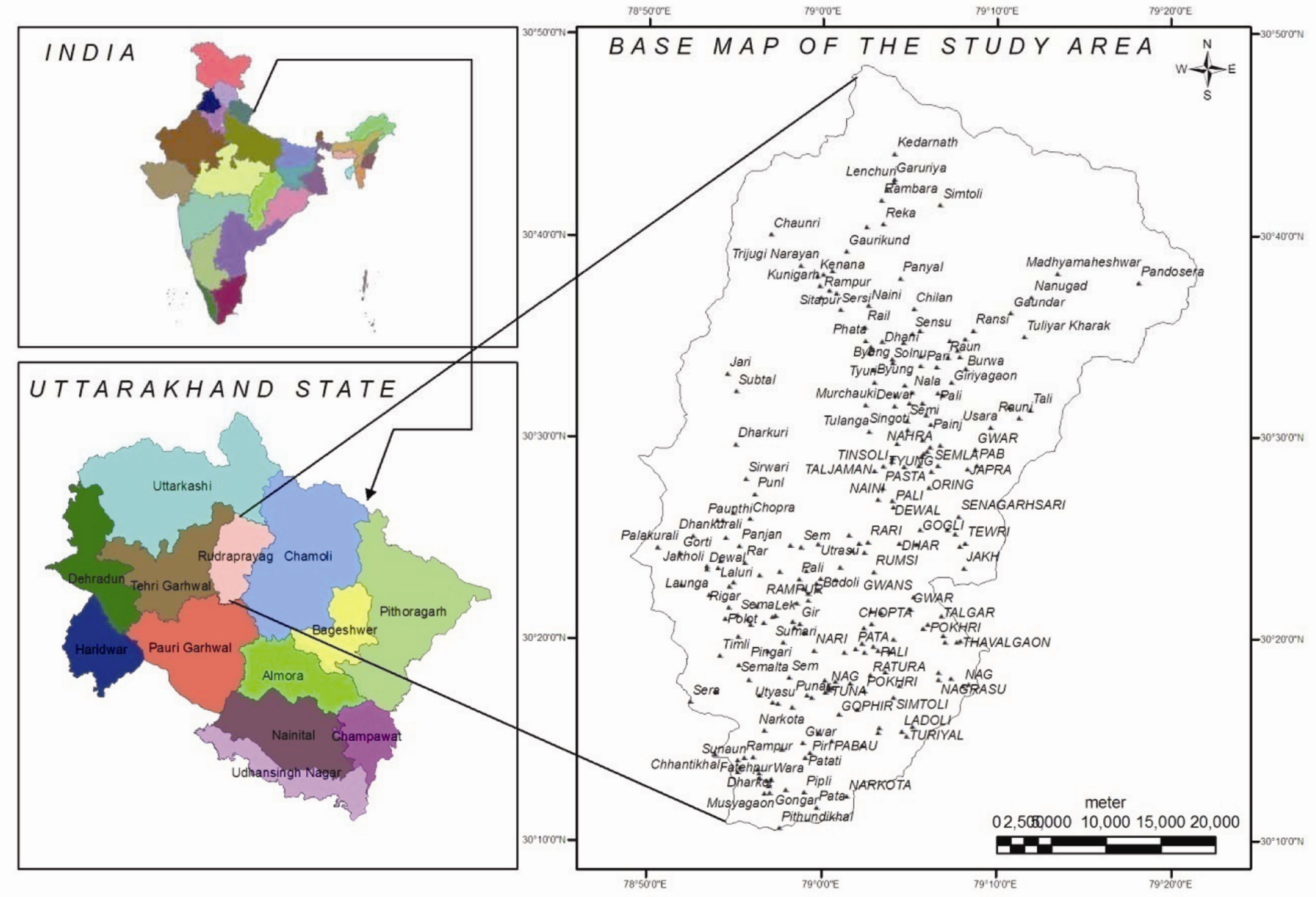

Figure 1. Location map of the study area.

Table 1. Details of satellites data used for the analysis

Satellite	Resolution (m)	Date of acquisition	Pre- and post-event
Resourcesat-2 LISS IV	5.8	June 2011	Pre-event
Resourcesat-2 LISS IV	5.8	June 2013	Post-event

Source: Satellite datasets, NRSC, Hyderabad.

underlying types, topography and hydrology. Human settlements are mainly in the shallow water zones or around springs. Agricultural practices are avoided and confined to areas of low relief which are underlain by weak rock formations, i.e. schists, phyllite, weathered gneisses and crushed quartzites. Forest is more frequent on steeper or moderate slopes (Figure 4 *a*). The Mandakini Valley of Rudraprayag district has a thick forest cover; most part of the Valley covered is non-wasteland. In this district there are very few places of degraded forest and degraded pasture (Figure 4 *b*). Fourteen prominent classes of land use/land cover were identified in the study area (Figure 5): forest evergreen/semi-evergreen (945.80 sq. km), agricultural land (339.28 sq. km), natural/semi-natural grassland and grazing land (190.51 sq. km), wastelands–barren rocky/stony waste (61.96 sq. km), scrub forest (70.08 sq. km), snow-covered/glacial area (14.13 sq. km), water bodies – river/stream – dry (6.96 sq. km), tree clad (74.92 sq. km), forest blank (0.59 sq. km), wastelands – scrub land (4.31 sq. km), built-up (0.07 sq. km), forest – deciduous (0.52 sq. km), permanent snow (266.67 sq. km) and water bodies – river/stream – perennial (6.29 sq. km).

Drainage

The drainage of the study area digitized from SOI 1962–63 edition toposheets nos 53J/14, 53J/15, 53N/1, 53N/2, 53N/3, 53N/4 and 53N/6 is depicted in Figure 6 *a*. The streams within a drainage basin form certain patterns, depending on the slope of the land, underlying rock structure as well as the climatic conditions of the area. Most of the drainage shows dendritic and radial patterns (Figure 6 *a*). The dendritic pattern develops where the river channel follows the slope of the terrain. Trellis pattern is observed at many locations on the ridge top. Generally, the drainage is controlled by underlying rocks and their structures. Mandakini, the main river, passes through the area that originates from the Central Crystalline Zone defined

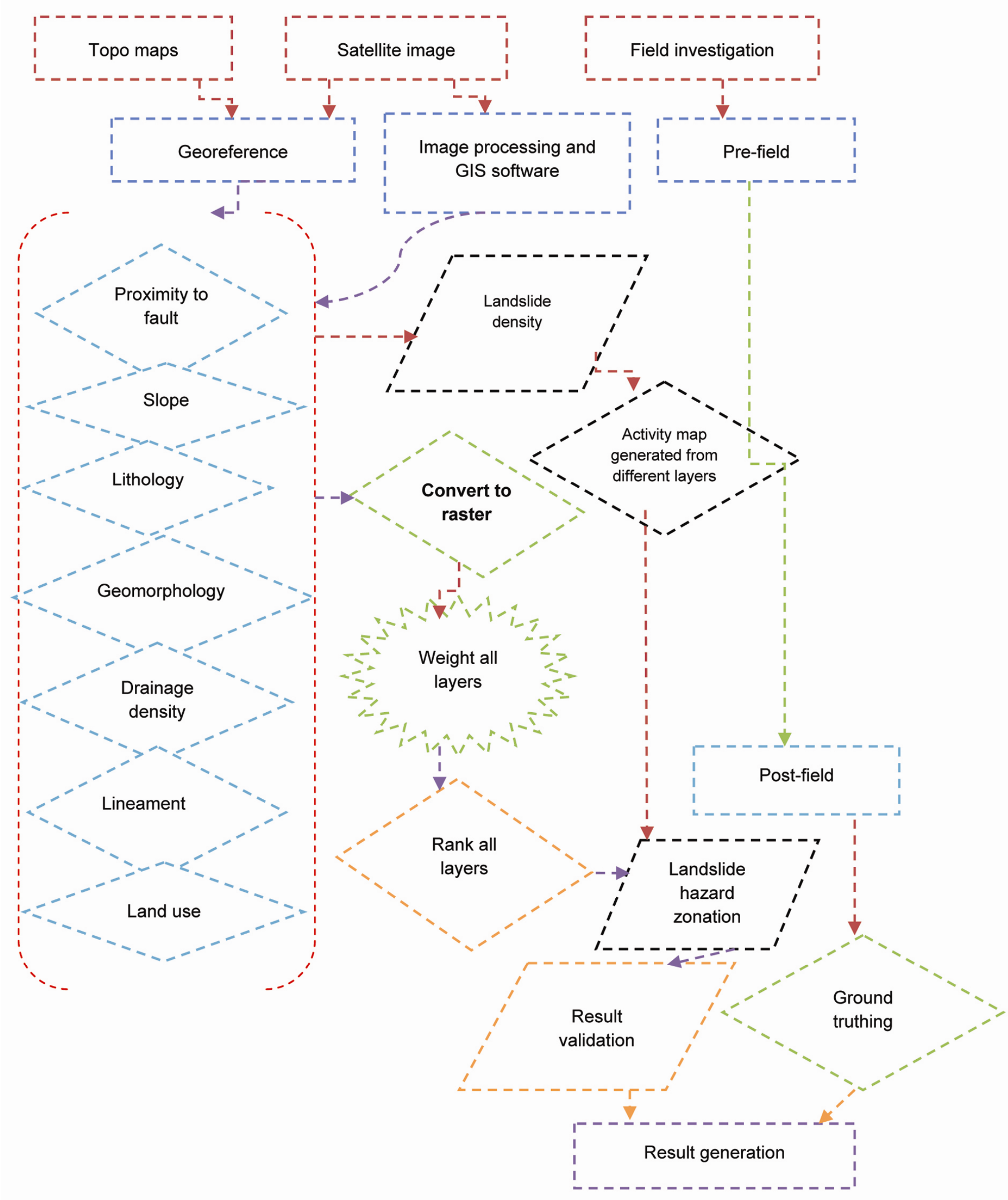

Figure 2. Methodology flow chart of the study area.

by high mountain ranges that are covered by glaciers. Almost all the streams originate from the higher altitudes and flow down by cutting deep gorges at lower altitudes, where each one ultimately joins the main Alaknanda River. A large number of landslides occur in the high drainage density areas, which are favourable for inducing landslides[7,8] (Figure 6 *b*).

Physiography

SOI toposheets have been taken as the spatial database for physiographic features along with the satellite data, GIS tools and ground realities. The strike ridges and valleys are the result of geological structure and lithology. Likewise, steep scarps, peaks and mass wasted scree slopes are the result of denudational processes (Figure 7 *a*). Differential weathering and erosion of various rock types has resulted in relief variations. The low relief area basically consists of weaker rocks such as schist and phyllite, while quartzite, and gneiss support higher relief with sharp-crested ridge because of relatively high resistance to weathering and erosion. Presence of steep scarps, deep narrow valleys, springs, and straight course of streams suggests that the area is still in its youthful stage of geomorphic cycle. ASTER images and digital elevation model (DEM) are used to delineate slope aspect for the area under study. Slope facing in the study area is

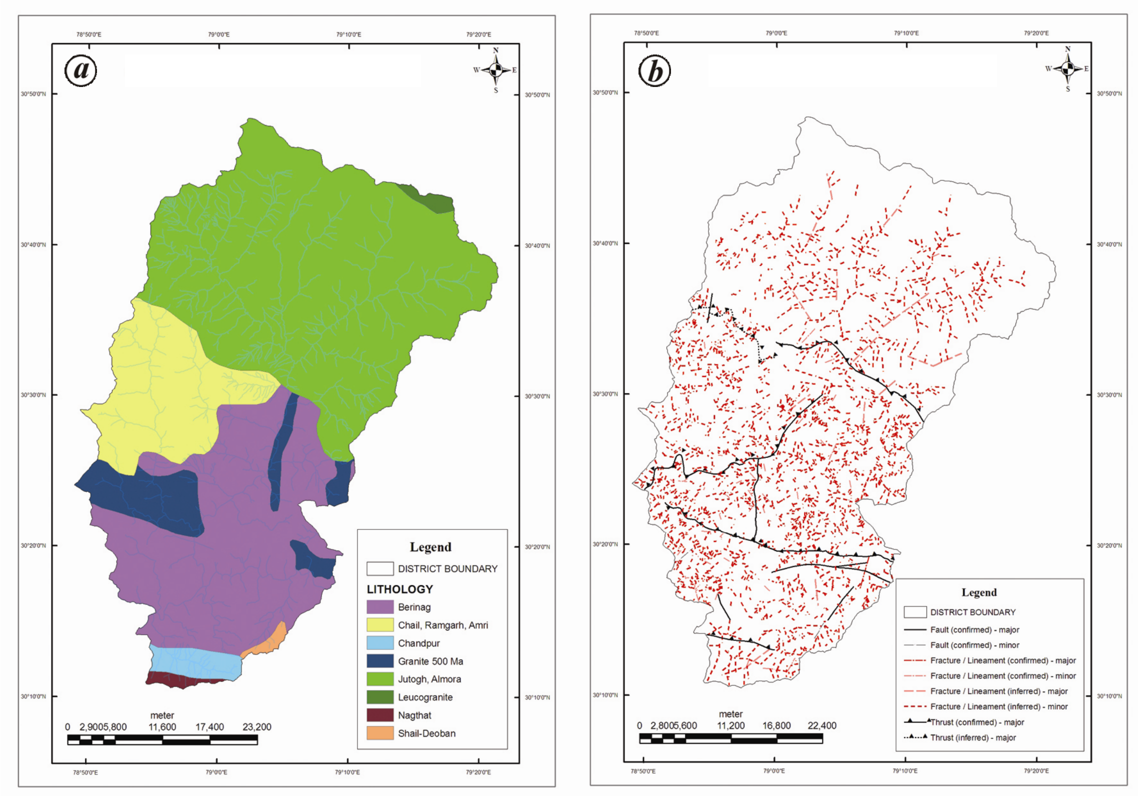

Figure 3. ***a***, Geological map; ***b***, Structural map of the study area (A. K. Naithani, unpublished).

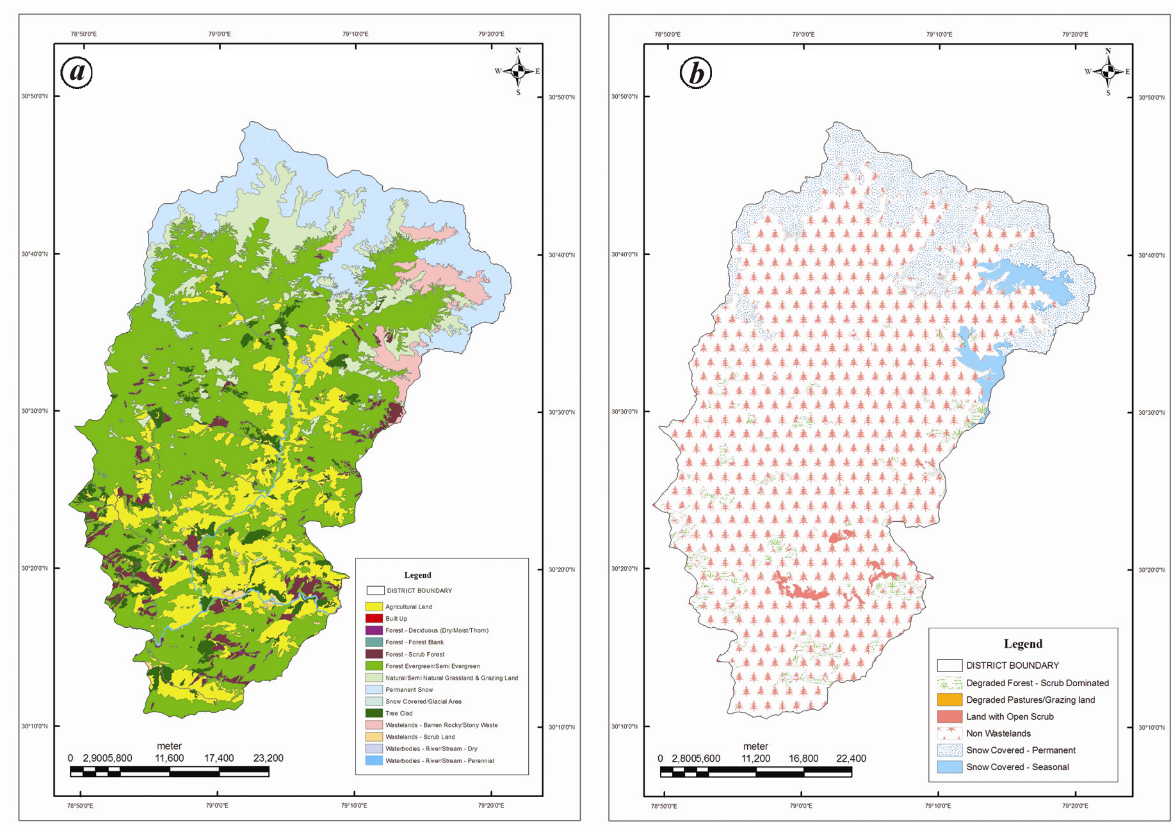

Figure 4. Land-use/land cover map (***a***) and wasteland map (***b***) of the study area.

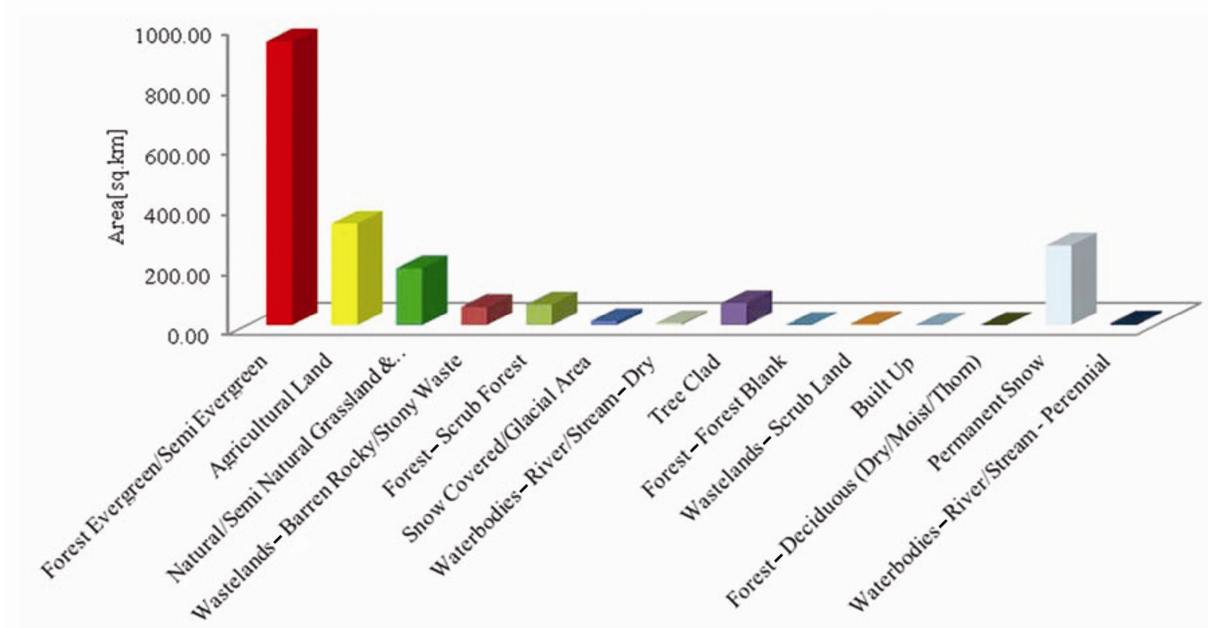

Figure 5. Graphical representation of land use/land cover of the study area.

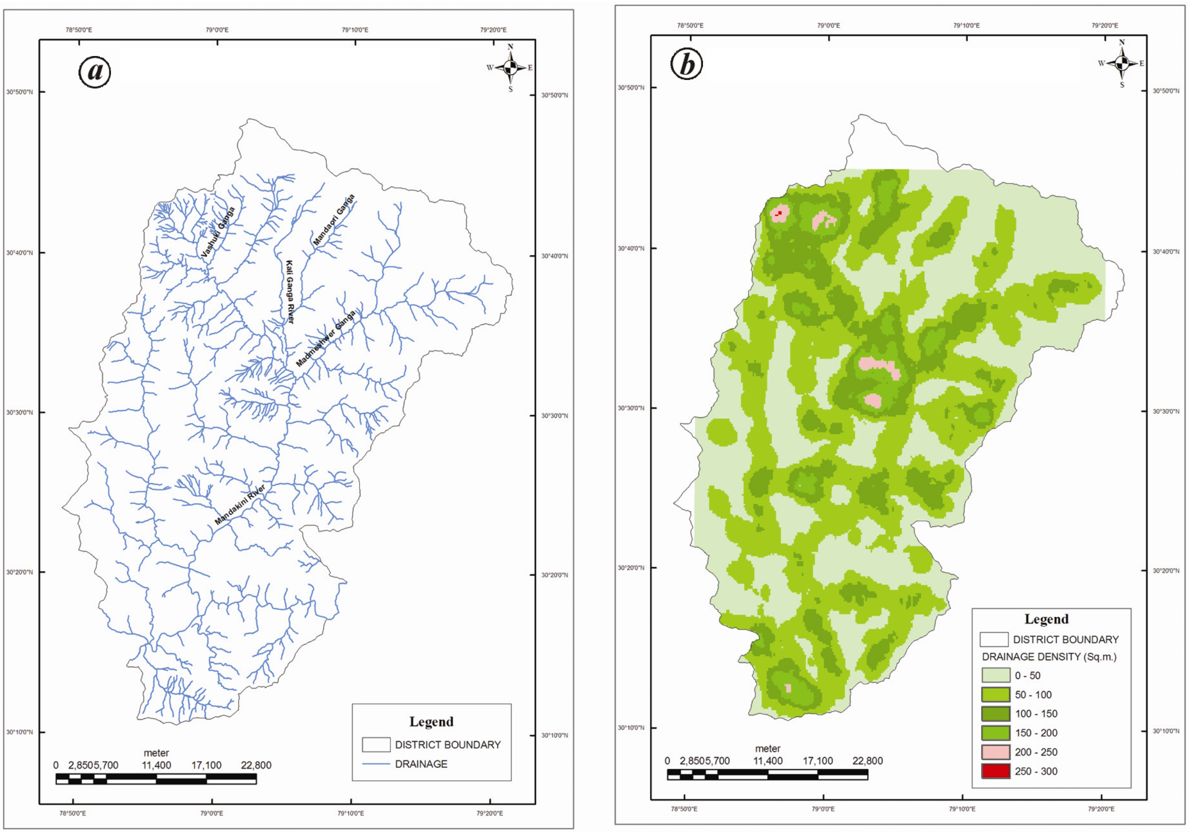

Figure 6. ***a***, Drainage map; ***b***, Drainage density map of the study area.

classified as: north-facing 337.5–22.50, NE 22.5–67.50, east-facing 67.5–112.50, SE 112.5–157.50, south-facing 157.5–202.50, SW 202.5–247.50, west-facing 247.5–292.50, NW 292.5–337.50. There is some association of landslides with the slope facing (Figure 7 *b*). Landslides appear preferentially on southeast to east-facing slopes. Deep-seated landslides however appear to be controlled by lithology and structure rather than slope facing.

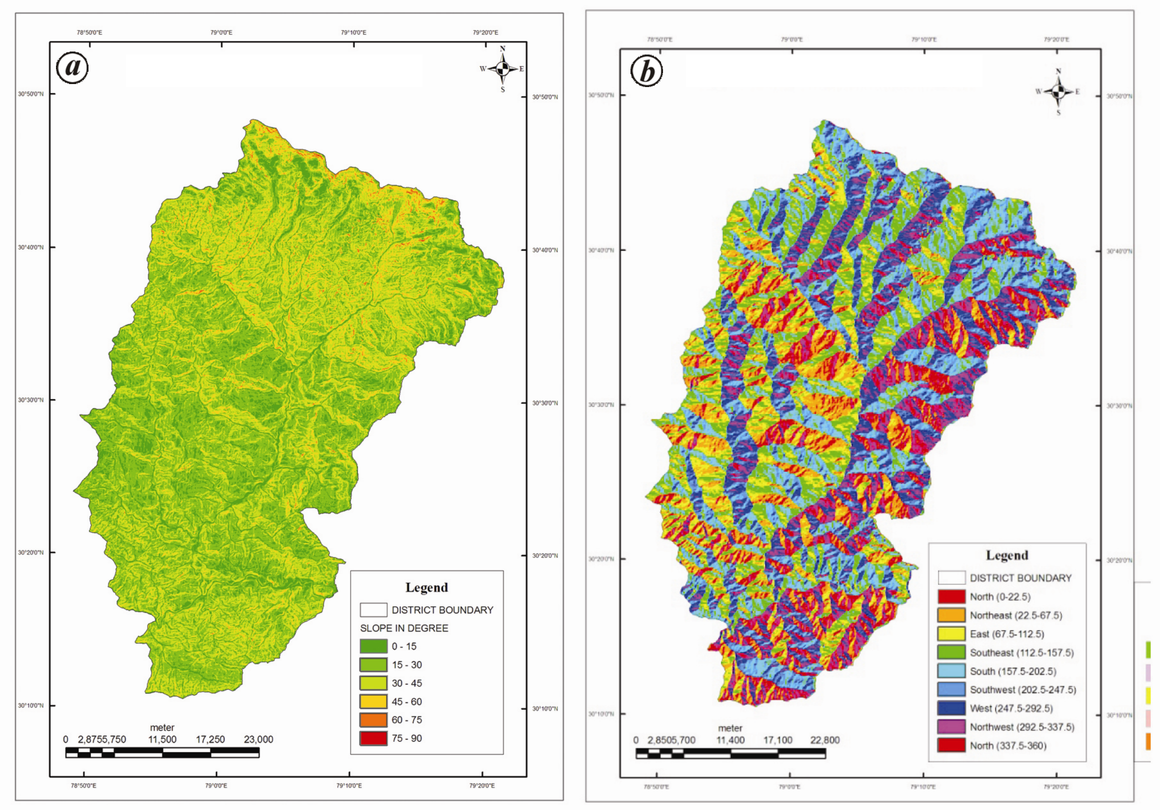

Figure 7. Slope map (***a***) and slope aspect map (***b***) of the study area.

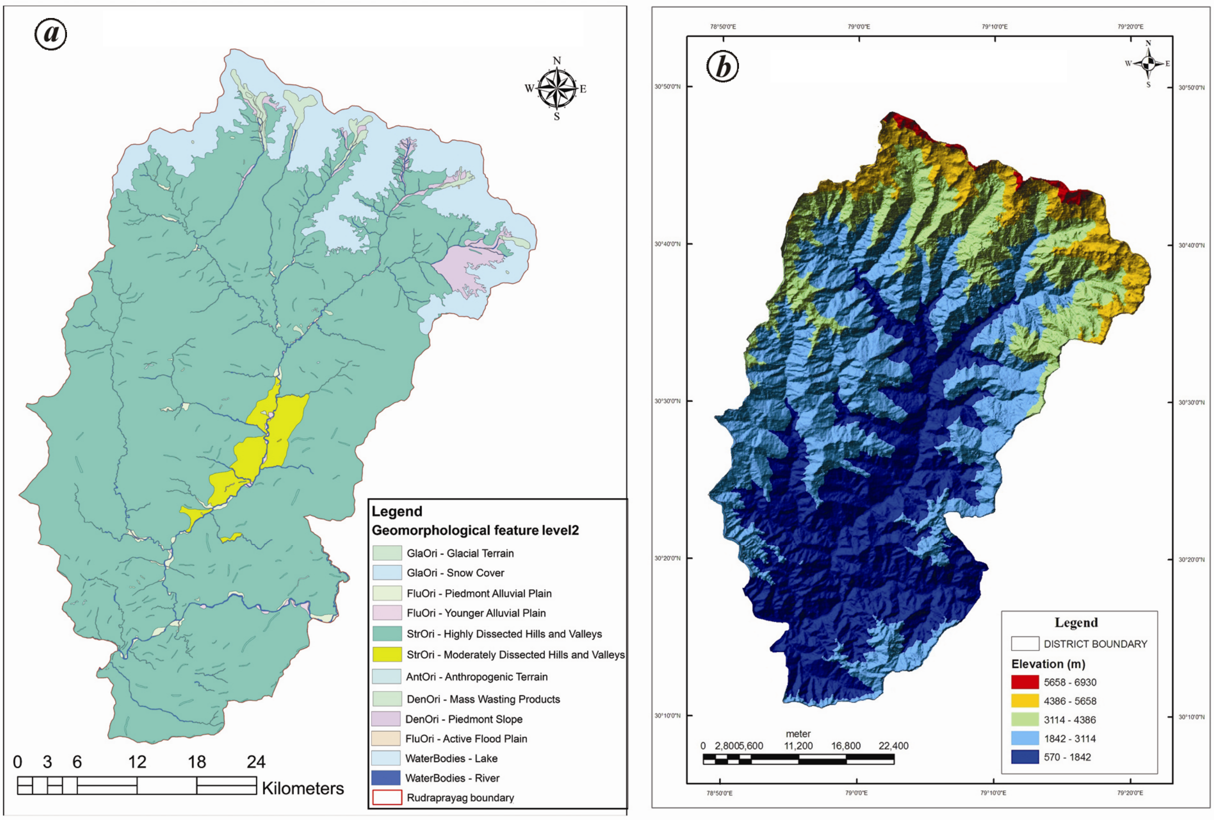

Figure 8. Geomorphological map (***a***) and TIN map (***b***) of the study area.

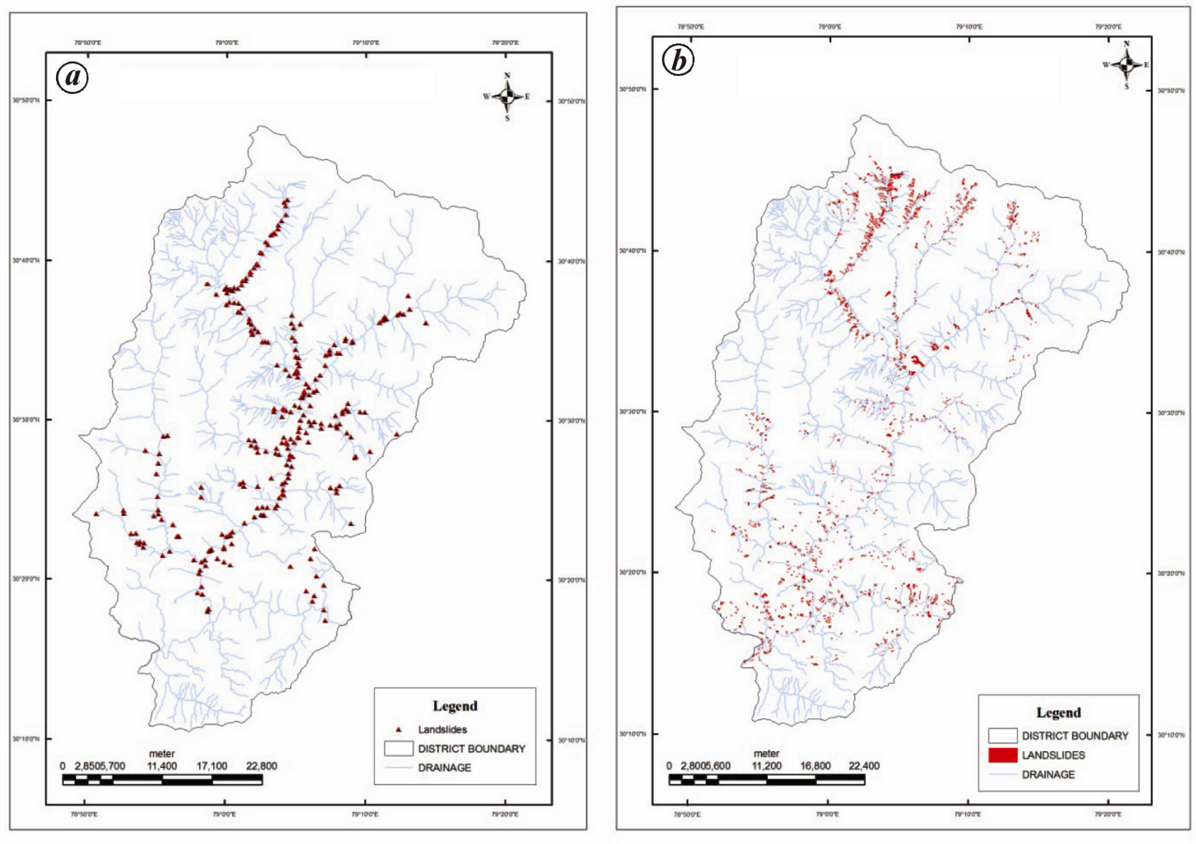

Figure 9. Landslide maps: (***a***) 2011 and (***b***) 2013 of the study area.

Geomorphology

The Mandakini Valley is mountainous, forming a part of the Western Himalaya. It is characterized by Himalayan topography with a series of criss-cross ridges and ravines. The altitude varies from 570 to 6930 m amsl. The Mandakini Valley has moderate dissected hills and valleys to highly dissected valleys as well as many denudational hills (Figure 8 *a*). The climatic condition of the state is determined almost exclusively by the differences in altitude. Almost all the rivers and streams in this area are in the older stage and have not attained a permanent regime even before entering the plains. The drainage basin of the present area is fan-shaped. A DEM for the study area was built based an ASTER (30 m) elevation data. Ground control points (GCPs) were added to the ASTER imagery and processed under the GIS environment. The common method of landslide hazard assessment using weighted overlay is heavily dependent on three-dimensional terrain visualization and analysis of high-resolution ASTER as used in this study (Figure 8 *b*).

Landslide inventory

Based on pre- and post-flood satellite data analysis, 290 landslides were observed in pre-flood imageries (Figure 9 *a*). As against this, the post-flood imageries show 1665 landslides in the Mandakini Valley. Maximum number of landslides was observed along Kedarnath–Gaurikund route, most of them triggered due to the June 2013 excessive rainfall event which caused loss of lives and property. From Gaurikund to Kedarnath a 14 km pedestrian route was totally damaged due to prolonged rainfall (Figure 9 *b*). Inventory of landslides in different stretches along the Mandakini Valley up to Rudraprayag is given in Table 2. Fragile geology, major, minor fractures/lineaments in the area, being close to the MCT, slope degradation processes and torrential rainfall are responsible for triggering landslides and flash floods in the area.

Rainfall and climate

The climate in this region is mainly governed by monsoon. The altitude of this Valley varies from 570 to 6930 m (snow-covered area). The high peaks, more than 3000 m, in the catchment area are perpetually covered with snow. Below this altitude the snow lasts for three months in winter when the temperature falls below freezing point. Rainy season is restricted between mid-June and mid-September, when >60% of the mean annual rainfall of about 1734 mm is received. In the study area, maximum rainfall of 2257 mm is recorded at Ukhimath

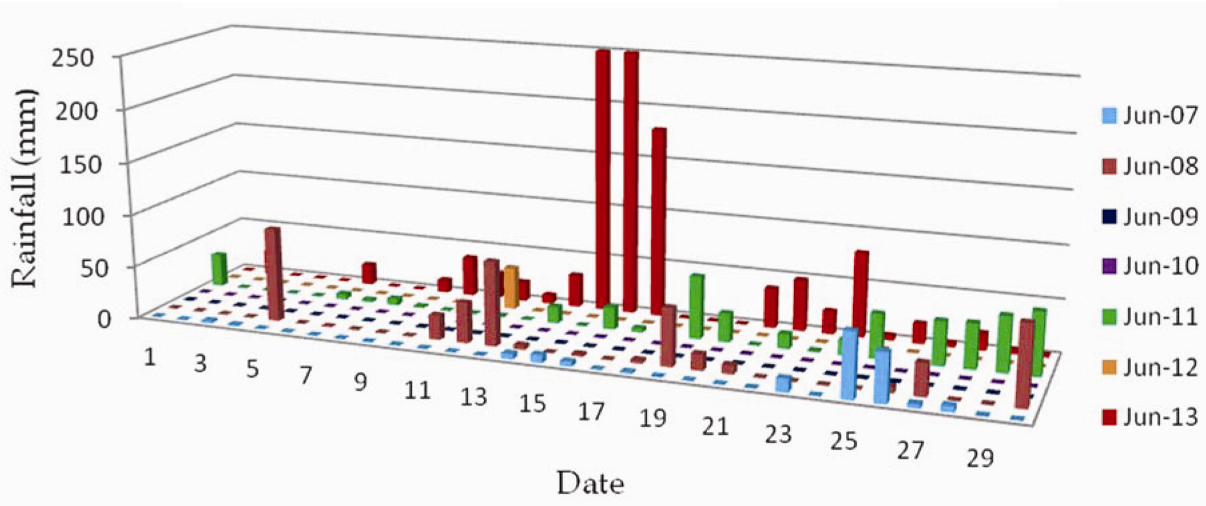

Figure 10. Average rainfall distribution (2007–2013) in the study area (courtesy: LANCO).

Table 2. Details of landslide inventory in the Mandakini Valley

Place/river/stream	Pre-satellite	Post-satellite
Kedarnath to Gaurikund	40	168
Along Vasuki Ganga to Sonprayag	20	86
Sonprayag to Narayankoti	10	83
Along Kali Ganga to Kotmaheshwari	50	62
Along Madhmeshwer Ganga to Kotmaheshwari	20	122
Along Markanda Ganga to Nanugad	15	156
Khuna to Narayankoti (Kalimath)	15	37
Narayankoti to Masta	20	3
Nala to Kund	25	173
Kund to Rudraprayag	15	296
Along Lastar Gad to Bhimali	10	136
Chamshil to Rudraprayag	40	230
Along Bhardari Gad-Nagaon	10	113
Total	290	1665

while the minimum of 1210 mm is recorded at Rudraprayag[9]. On 16 and 17 June 2013, heavy rains breached moraine dammed lake Chorabari flooding the Saraswati and Mandakini rivers in Rudraprayag district[9].

It was observed that the antecedent rainfall saturated the area during 15–17 June 2013 (680 mm), more than the average rainfall from 2007 to 2012 (17.23 mm) of the area, which is one of the reasons for activation of landslides and flash floods in the Mandakini Valley (Figure 10). Run-off discharge data collected at Gaurikund in the Mandakini River, also indicate that antecedent rainfall (15–17 June 2013) led to overflow of rivers 5.682 to 5.917 m^3/sec (LANCO Mandakini Hydro Energy Pvt Ltd) and also to flash floods in downstream areas (Figure 11). In association with the onset of early monsoon, during peak summer (tourist and pilgrimage season) heavy to extremely heavy rainfall was reported all over the state from 16 to 18 June 2013. This caused flash floods in the tributaries in the upper catchments of the Ganga and Yamuna rivers in this region, resulting in widespread loss of human life and property. The network of rain gauges of India Meteorological Department (IMD) and the Uttarakhand Government, numerical models and remote observation sources such as satellites and radars captured this widespread heavy rainfall episode[10].

Numerical rating scheme

The identification of potential landslide areas requires the factors to be organized based on their relative importance. This may be achieved by developing a rating scheme, in which the factors and their classes are assigned numerical values. A rating scheme was developed based on the associated causative factors for landslides surveyed in the field and on the knowledge from previous work[11]. In this scheme, the factors were assigned a numerical ranking on a 1–9 scale in order of importance. Weights were also assigned to the classes of the factors on 0–9 ordinal scale, where higher weightage indicates greater influence for landslide occurrence. The scheme was suitably modified based on the literature using different combinations of weights. The rating scheme is given in Table 3.

In the study area, it was observed that almost all the landslides were associated with drainage channels; hence, maximum weightage were assigned to high drainage density. The next important component was lineament density. Here, maximum weightage was given to the high lineament density, because highly fractured and jointed formations showed greater potential for landslides. Because steeper slopes are more prone to landslides, higher weightage was given to them, and lower weightage to gentle slopes. The competent rocks such as quartzite and greywacke are less susceptible to landslides than gneiss;

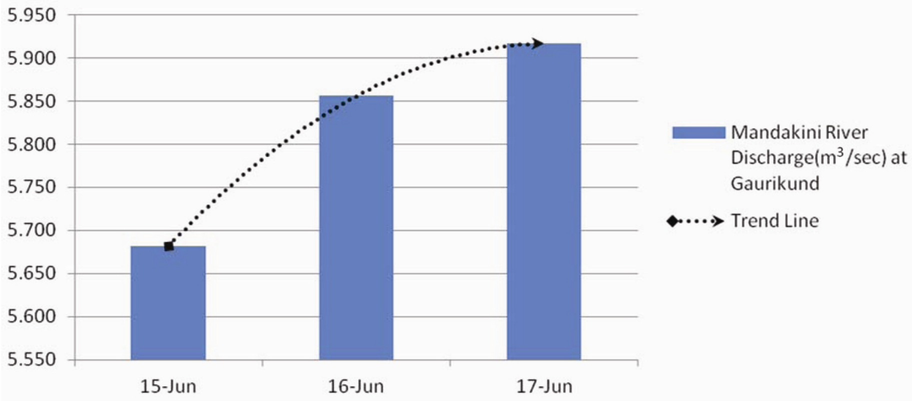

Figure 11. Run-off discharge in the study area (courtesy: LANCO).

hence, the weights for lithology were assigned accordingly after field observations. The presence of a fault in an area indicates a weak zone through the presence of shattered and weathered rock masses. To account for the influence of fault zones, a fault buffer zone of 250 m was considered because of signs of instability observed along the faults within this zone. A landslide event depends on the kind of land use. Barren slopes are more susceptible to erosion compared to areas with thick forests; hence, maximum weightage was assigned to barren slopes and minimum to thickly forested areas. Based on field observations, the weightage for other land-use classes fell between these two. It was also observed in the field, that at a few locations, erosion and toe cutting along major streams had influenced slope instability.

Results and discussion

Combining all the controlling parameters and by giving different weightages for all the factors, the final landslide hazard zonation (LHZ) map was prepared and categorized into 'very high', 'high', 'moderate', 'low' and 'very low' hazard zones (Figure 12). The output map was generated on the scale of 1 : 5,000. The various hazard classes are described below in detail.

Very high hazard zone

Geologically, this zone is highly unstable and is at constant threat from landslides, especially during and after an intense spell of rainfall. This is so because the area comprises steep slopes with loose and unconsolidated materials, and there is evidence of active or past landslips. Besides, the zone also includes areas which are located near faults and tectonically weak zones. This zone is manifested on the surface by subsidence of the land as observed in many parts of Rudraprayag district. It further includes areas where road-cutting and other human activities are intense. Therefore, the very high hazard zone is found predominantly in settlement areas. This zone is more prevalent in the southern and eastern parts of the district. It constitutes an area of about 118.31 sq. km and forms 5.96% of the total study area. Since the very high hazard zone is highly susceptible to landslides, it is recommended that no human-induced activity be undertaken here. Such areas have to be entirely avoided for settlement or other developmental purposes and preferably left for regeneration of natural vegetation to attain natural stability in due course of time. Such a very high hazard zone is seen in many of the villages and towns of the district, e.g. Gauriya, Song Chatti, Ghindur Pani, Kanchula, Rambara, Linchori, Jungle Chatti and Gaurikund.

High hazard zone

This zone includes areas where the probability of sliding debris is at a high risk through weathered rock and soil debris. It covers an area of steep slopes which when disturbed are prone to landslides. Most of the pre-existing landslides fall within this zone. Significant instability can occur during and after an intense spell of rainfall within the zone. Several lineaments, fractured zones and fault planes also traverse the high hazard zone. Areas which experience constant erosion by streams because of the soft nature of the lithology and loose overlying burden, fall under this class. Vegetation is generally either absent or sparse. The high hazard zone is well distributed over the entire study area. It is commonly found to surround the very high hazard zone as seen in many of the villages and towns. This zone occupies 451.66 sq. km, i.e. 22.78% of the total area. The high hazard zone is also geologically unstable, and slope failure of any kind can be triggered particularly after heavy rains.

Moderate hazard zone

This zone comprises the areas that have moderately dense vegetation, moderate slope angle and relatively compact and hard rocks. Although this zone can include areas that have steep slopes, the orientation of the bedrock and absence of overlying loose debris and human activity make the slope less hazardous. The moderate hazard zone is well distributed within the study area. Several human settlements also come under this zone. The zone covers an area of 334.39 sq. km, i.e. 16.87% of the total study area.

Table 3. Ranking and weightage of different thematic layers

Parameter	Rank	Category	Weight
Slope	9.5	0°–15°	1
		15°–30°	7
		30°–45°	9
		45°–60°	6
		60°–75°	5
		75°–90°	4
Lithology	9.3	Phyllite/quartzite	1
		Quartzite alternating with shale/slate/phyllite	6
		Quartzite alternating with schist	6
		Schist	7
		Schist with slate/phyllite	8
		Granites	2
		Gneiss	2
		Basic/metabasic/ulterabasic	3
Geomorphology	8.5	Low dissected hills and valleys	3
		Moderately dissected hills and valleys	6
		Highly dissected hills and valleys	8
		Alluvial fans	4
		River terraces	1
		Valley	1
		Escarpment	5
		Toe removal/erosion/cutting (by river)	9
Density of lineament	8	Low	1
		Moderate	3
		Moderately high	8
		High	9
Density of density	7.5	Low	2
		Moderate	3
		Moderately high	6
		High	9
Land use/land cover	7	Dense vegetation	1
		Degraded vegetation	3
		Scrub sand/ grass sand	6
		Forest blank	7
		Barren land (rocky)	8
		Waste land	9
		Agricultural land	2
		Built-up area	5
		Snow-covered area	3
Slope aspects	4	North-facing (337.5–22.5)	1
		NE (22.5–67.5)	3
		East-facing (67.5–112.5)	5
		SE (112.5–157.5)	6
		South-facing (157.5–202.5)	10
		SW-facing (202.5–247.5)	4
		West-facing (247.5–292.5)	2
		NW (292.5–337.5)	2

Low hazard zone

This zone includes areas where the combination of various controlling parameters is generally unlikely to adversely influence the slope stability. Vegetation is relatively dense and the slope angles are generally low, about 30° or below. Flatlands and areas having gentle slope fall under this zone. A large part of this zone lies prominently over hard and compact rock type. This zone is mainly confined to areas where anthropogenic activities are less or absent. As far as the risk component is concerned, no evidence of instability is observed within this zone, and mass movement is not expected unless major changes occur. Therefore, this zone is suitable for carrying out developmental schemes. It spreads over an area of about 425.90 sq. km and occupies 21.48% of the total study area.

Very low hazard zone

This zone generally includes valley fills and other flatlands. Playgrounds are prominent features within this zone. As such, it is assumed to be free from present and future landslide hazards. The dip and slope angles of the rocks are fairly low. Although the lithology can comprise of soft rocks and overlying soil debris in some areas, the chance of slope failure is minimum because of low slope angle. This zone extends over an area of about 651.82 sq. km and forms 32.88% of the total area.

Conclusions

The methodology for landslide hazard zonation mapping presented here involves the generation of thematic data layers, development of a suitable numerical rating scheme, spatial data integration and validation of results. In the present study, remote sensing and GIS have been extensively used. The merging of multispectral and panchromatic satellite data greatly improved the understanding of the quality of terrain features in the image. Application of GIS is found to be immensely useful for thematic data layer generation and for their spatial data analysis, which involves complex operations. The numerical rating scheme helps improve evaluating and optimizing the results. However, because the landslide contributing factors vary from region to region, this rating may not hold for other parts of the Himalaya. The landslide hazard zonation map divides the area into five hazard zone classes. The high hazard zone is in a geologically unstable area, and slope failure can be triggered particularly in this zone after heavy rainfall. The results are validated by landslide distribution in the area during field study. As such, allocation and execution of major housing structures and other projects within this zone should be discouraged. Afforestation scheme should

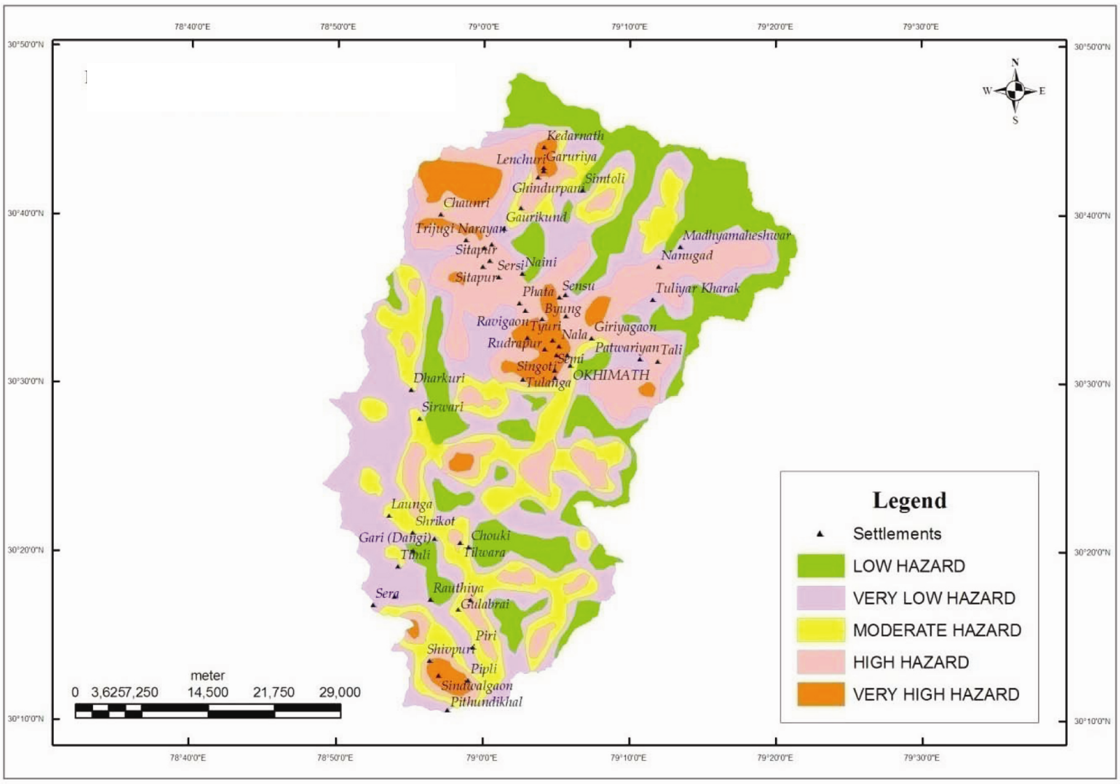

Figure 12. Landslide hazard zonation map of the study area.

Figure 13. Photographs showing devastation in (***a***) Kedarnath, (***b***) Rambara, (***c***) Sonprayag and (***d***) Tilwara.

be implemented in the zone. It can be noted that as seismic activity and continuous heavy rainfall may reduce the slope stability, it is recommended not to disturb the natural drainage, and at the same time, slope modification should be avoided as far as possible. Further, future land-use activity has to be properly planned to maintain its present status.

The statistically significant value of the chi-square test also validates the hazard zonation classes of the map. Hence, it can be concluded that the map correlates well with existing field conditions. From the post-flood satellite images, it was observed that in Kedarnath about 64 buildings were completely washed away and 47 buildings were partially damaged. Images also revealed that Rambara village was totally washed away and damage to structures was noticed in Gaurikund. From Gaurikund to Rudraprayag, five bridges were partly damaged and two were completely damaged. Road breaches were also observed in this stretch.

The landslide hazard zonation map may help in decision-making during the time of implementing a development project in the terrain. It is always better to avoid the highly hazard zone, but if this is not possible, corrective measures must be worked out to minimize the probability of landslide occurrences. Post-damage satellite data indicate that heavy rainfall during 15–17 June 2013 induced landslides and flash floods that had originated from the upper reaches along the Mandakini, Vasuki Ganga, Kali Ganga, Madhmeshwer Ganga and Markanda Ganga rivers. Induced debris material rolled down vigorously along the streams on steep slopes oriented in N–S direction towards downstream with a high magnitude, which was the main reason for damage to infrastructure, forests, agricultural fields, roads and amenities in the area (Figure 13).

Recommendations

For any developmental activities/construction in the study area, it is recommended that one adopts the following guidelines to avoid instability and landslides. As a general principle, construction on hills, particularly dams, tunnels, multi-storeyed buildings and roads should be on the basis of the landslide hazard zonation map.

1. Construction on steep hill slopes should be avoided.
2. Suitable drainage measures are essential since water seepage can cause stability problems.
3. Afforestation of the surroundings using site-specific species can help in the stability of slopes.
4. Construction of buildings adjoining active landslides, on the valley-fill materials of streams and near active tectonic lineaments should be avoided.
5. The risk of natural disasters has increased in the area as a result of increasing anthropogenic activities. This trend is likely to increase in future as activities such as pilgrimage, tourism, etc. will increase. The natural flow of the streams is obstructed due to the construction of man-made structures that results in diversion of the flow from its natural course.

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