Geoenvironmental Disasters

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Knowledge based landslide susceptibility mapping in the Himalayas

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Abstract

Background: Landslides are common geological hazard occurring in the mountainous region. The Himalayan belt is prone to landslide disasters, which is directly linked to the prosperity and development of the area. The present study was carried out around the Chamoli-Joshimath area, which is situated in the Northernmost-belt of the Garhwal Himalaya, India. A strategic road connecting Tibet which also links the famous Hindu temples Badrinath and Kedarnath traverses the area. The main purposes of the present study is to delineate the landslide susceptible zones in the area so that it could be helpful towards landslide disaster risk reduction and to highlight the applicability of knowledge based susceptibility mapping method in the Himalayas.

Results: The area comprises low-to-high grade metamorphic rocks as well as carbonate rocks such as limestone and dolomite. In the study area, most of the landslides occur along the road and river sections, and in the thrust or fault zones. The landslide zones are strongly controlled by the Main Central Thrust and other faults and the resulting geomorphic condition. Most of the unstable slopes are prone to plane and wedge failures. There are many active and dormant landslides (covered by vegetation) in the area. The active landslides are due to reactivation of pre-existing ones.

Conclusions: The predicted landslide susceptible zones are in good agreement with the historical landslide locations, which is good indication that knowledge based landslide susceptibility mapping can be successfully applied in the Himalayas provided the causative factors are thoroughly understood.

Keywords: Landslide susceptibility, Knowledge based approach, Himalaya, Remote sensing and GIS

Background

Landslides are important geological events in many parts of the world. Himalaya is extremely vulnerable to natural disasters due to its geology, steep slopes, high relief and monsoon climates. The active tectonics in the Himalaya is responsible for the generation of faults, crushed zones, and several sets of joints that make the rocks weak, resulting in steep hill slopes susceptible to sliding (e.g. Dadson et al. 2004; Kirby and Whipple 2012; Chen et al. 2015a, 2015b).

Satellite images and aerial photos are among important sources of data for mapping landslides, geology, geomorphology, lineaments, and thrust/faults. The lineament analysis using satellite images have been applied by many authors (e.g. Ali and Pirasteh 2004; Mostafa and Bishta 2005). Remote sensing data is commonly used for analysis and prediction of mass movement through the landslide inventories, susceptibility mapping, hazard zonation, change detection, and landslide monitoring. Most ground surface changes related to the movement of a pre-existing landslide can be identified through the use of temporal aerial photographs or high resolution satellite sensor's optical imagery (Rosin and Hervas 2005). Detecting landslides and monitoring their activity is of great relevance for disaster prevention, preparedness and mitigation in hilly areas. Landslide monitoring using remote sensing is a powerful method to point based ground surveying techniques (Keaton and DeGraff 1996; Pradhan 2010).

The landslide related parameters involved in landslide activity or triggering are the detection of anomalous patterns from contour map, surface drainage, slope profile and correlation with contour map, overburden thickness, geological structure, past movement evidences, rate of movements and so on. In this situation, the use of small scale aerial photograph together with

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the satellite images has significant role while studying landslides. While large-scale satellite data could serve to detect landslide bodies, smaller scale data will help in detection of parameters triggering it or characterizing it. Thus the interpretation of aerial photo together with satellite images can generate relevant landslide-related information that can help in landslide understanding and further study. The traditional visual photo-interpretation methods for landslide mapping and monitoring is still equally important even with the availability of latest generation space-borne digital imagery (Soeters and van Westen 1996).

The main purposes of the present study is to delineate the landslide susceptibility zones in the area so that it could be helpful towards landslide disaster risk reduction and to highlight the applicability of knowledge based susceptibility mapping method in the Himalayas through proper understanding of the various causative factors responsible for landslide in the study area. Present study utilized the remote sensing and GIS techniques in order to delineate landslide susceptible area. The geomorphologic and structural information has been given due importance in the analysis. Statistical methods are common approach in delineating the susceptibility zones but the present study successfully applied the knowledge based approach. This is especially important and useful when the researcher has thorough knowledge of the study area which enables strong control on the analysis. This study has opened up the possibility of utilizing this method in the Himalayas, including in Nepal Himalaya.

Study area

The area lies between 30°21′57.06″N to 30°34′57.48″N Latitude and 79°22′48.30″E to 79°37′ 41.88″E longitude. The total area covered is 338.7 km^2. It extends from Dhauli Ganga River in the north to Birhi Ganga River in the south. Administratively, the study area is in parts of Chamoli District of Uttaranchal State (Fig. 1). The important towns in the study area are Pipalkoti and Joshimath, whereas Birhi, Pakhi, Belakuchi, are the main villages. The study area falls on the Survey of India (SoI) topo-sheet numbers 53 N/6, 53 N/7, 53 N/10 and 53 N/11 (1:50,000 scale).

Fig. 1 Location of the study area (hatched area) in Uttaranchal, India

The field area lies about 250 km northward from Dehradun, the capital city of Uttaranchal State, and is connected by the National Highway, reaching up to Badrinath, the famous Hindu temple. The road is often disrupted in winter due to heavy snowfall and frequent landslides occurring in the rainy season. Since the area is falling under the Lower and Higher Himalayan region, the topography varies sharply, ranging from about 1000 m around the river valleys to around 4000 m, forming the peaks.

The area experiences subtropical climate with hot dry season around April-June, rainy season from July-September, and winter season from October-March. Snow fall during Jan-March is quite common in the area lying above the altitude of 2100 m. However, even at the altitude around 1300 m, snow fall can be observed during these months for short interval of time. The area is mostly covered by the forest area, followed by the rocky and barren land, cultivated area and settlements. The type and thickness of soils differs in steep slopes, valley side slopes, valleys and terraces. The barren, steep slope is consisting of shallow and loose textured soil, while densely vegetated areas are having comparatively thick soil that is rich in organic matters. The terraces consist of granular soils and are rich in moisture.

Geology of the study area

The study area and surroundings can be geologically described by rocks of various formations belonging to different geological groups namely Almora Group, Tejam Goup and Damtha Group of rocks (Valdiya 1980). The Almora Group of rocks are exposed north of the Helang village along Alaknanda valley (Fig. 2). This group mainly comprises of chlorite schist, garnetiferous mica schist, gneiss, schistose-quartzite and amphibolite with lenticular bands of crystalline limestone. Likewise, the Tejam Group of rocks are thrusted over by the Almora Group of rocks and consists of Pipalkoti and Berinag formations. Pipalkoti Formation consists of alternate beds of slate, dolomite and dolomitic limestone, while the Beringag Formation consists of quartzite, orthoquartzite and amphibolites (basic rocks). Damtha Group is considered to be the oldest and best-preserved supracrustal pelite-quartzite successions in the inner carbonate belt of the Lesser Himalaya (Valdiya 1998).

The study area mainly comprises of Almora Goup, Tejam Group, Ramgarh Group and Damtha Group of rocks. In general, the study area lies southwards from the Vaikrita Thrust (MCT), belonging to the Lesser Himalaya that mainly consists of dolomitic limestones,

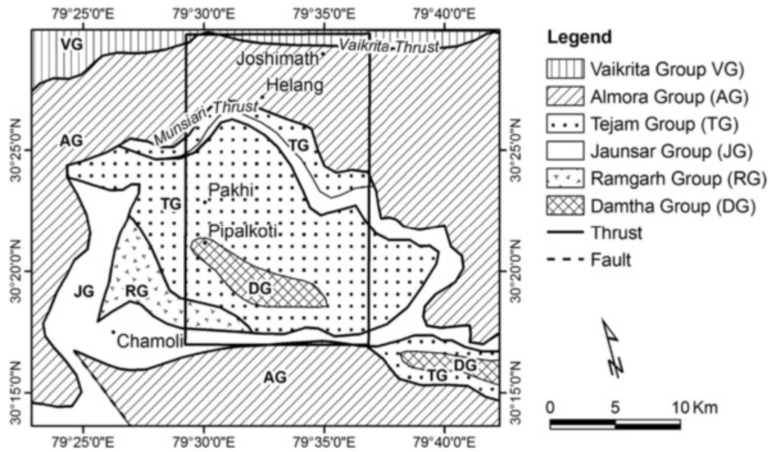

Fig. 2 Geological map of the study area (within rectangle) and surroundings (modified after Valdiya 1980)

limestone, quartzites, slate, schist and gneiss. Several thrust traverses the area.

Two important tectonic discontinuities of regional significance lying in the area are Vaikrita Thrust (VT) and Munsiari Thrust (MT) that are considered tectonically active (Valdiya et al. 1999). The VT is passing through the Joshimath area and the MT is passing through the Helang area in the study area. Several other faults and thrusts are branching/associated with these two major thrusts (Fig. 2). Birhi Thrust is the one passing through the southern part of the study area and the Gulabkoti Thrust lies south of MT. Most of these thrusts are dipping towards north. Lineaments are very common in the study area and plays vital role in the slope failure. There are several sets of joints/fractures and the intersecting joints are forming the wedge and hence resulting in the wedge failure.

Physiography

The study area is characterized by structural and denudational mountains. 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 (Fig. 3). Relief in the area is highly variable, ranging from about 1000 m to more than 5500 m.

Differential weathering and erosion of various rock types has resulted in such relief variation. The low relief area is basically consisting of weaker rocks like slate and phyllite, while quartzite, gneiss and dolomitic limestones give rise to higher relief with sharp crested ridge because of relatively resistant to weathering and erosion.

The scarp slopes formed by limestone can be seen around the Pipalkoti village and in Birhi Ganga valley. Presence of steep scarps, deep narrow valleys, springs, straight course of river suggest that the area is still in its youthful stage of geomorphic cycle.

Methods

The methodology followed in the study is presented in flow chart (Fig. 4). The satellite imageries (IRS LISS 3 and LISS 4) and aerial photographs were utilized to extract relevant information like geological structure, lineament, landslide and preparation of geomorphological map.

The actual landslide mapping can be done through visual analysis of aerial photographs, satellite images, topographic maps, geologic maps, field observations and the use of historic data. Satellite and aerial photo interpretation has been extensively carried out in the present study, which are the most common tools used for the detection and classification of landslides.

The aerial photographs taken during 1970's were partly available for the study area. Likewise, the satellite images

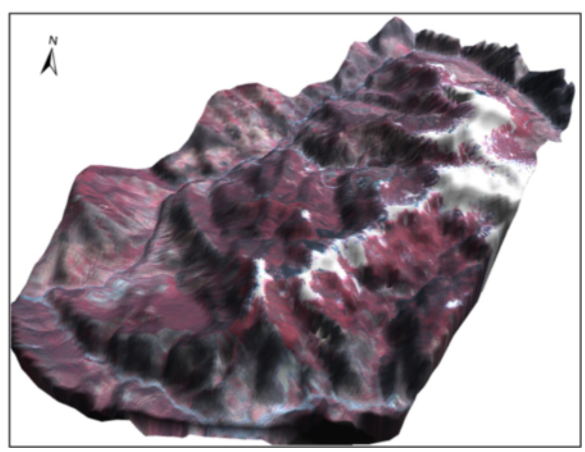

Fig. 3 Three-Dimensional view of the study area (Liss3-Pan merged image draped over DEM) showing the physiography of the area

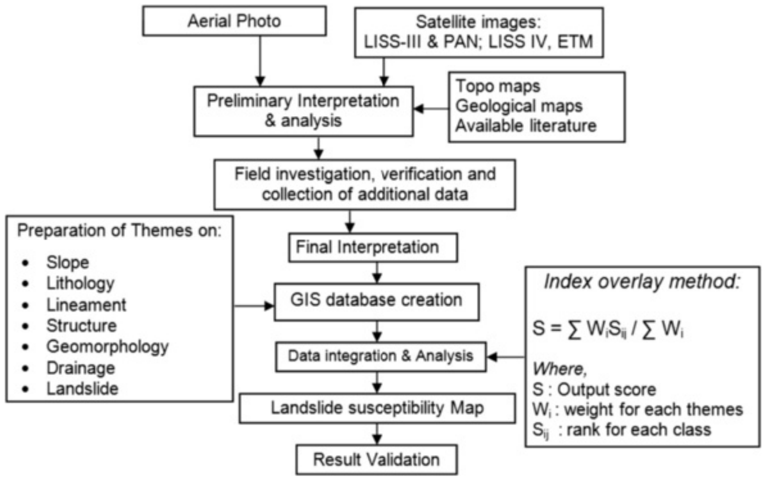

Fig. 4 Flow chart of the methodology adopted to prepare landslide susceptibility map

used were IRS LISS3 (23.5 m spatial resolution) and PAN (5.8 m spatial resolution) of 1999, IRS LISS4 (5.8 m spatial resolution) of 2004 and LANDSAT ETM image (28 m spatial resolution). Since the field area lies in the mountainous zone, most of the images were party covered either by ice or by cloud/fog. Therefore, it was necessary to use different images to extract the necessary information, otherwise, LISS4 image would have been a good choice.

Visual image interpretation of the satellite images and aerial photo were carried out for identification of the major geological lineaments, thrust/faults; demarcate different geomorphic units; spatial location and size of the landslides and preparation of geomorphic map. The verification of the landslides extracted from the remote sensing data along the major rivers (Alakananda, Birhi Ganga and Dhauli Ganga) revealed that most of the current landslides are the reactivation by pre-existing ones.

Digital image processing was carried out through several stages like geo-referencing, resolution merge (IRS Liss3 and PAN) to obtain output pixel size of 5.8 m and image enhancement (contrast enhancement, histogram equalization, filtering etc.). Image enhancement is especially useful to have better visualization of the images as well as for more clarity of the different geological structures and geomorphologic features. The major thrust and faults (roughly trending in east-west direction) as well as lineaments could be extracted from the remote sensing data. The regional structures like thrusts were initially identified and extracted from the LANDSAT image, which was later refined with the help of PAN image.

Contour and drainage lines were digitized from the topographic map and the geological map at hard copy was scanned and digitized. Different thematic layers like landslide, slope, lithology, lineament, structure, geomorphology, and drainage were prepared in GIS. During the field study, observations were taken mostly along the road to Badrinath that is basically constructed along the north-south flowing Alakananda River, along the Dhauli Ganga section, and along the Birhi Ganga river section. A preliminary landslide susceptible map was developed, which was verified in the field. This preliminary landslide susceptibility map was prepared from the secondary data, extracted from topographic map and remote sensing data (aerial photograph and satellite images). The proper knowledge of field condition was lacking at this stage.

An extensive field work was carried out to verify the preliminary susceptible map and additional data were collected. The field visit was carried out for about 21 days in the month of February-March. The area is mostly accessible through the motorable road except the Birhi Ganga section, which had to be covered by foot. Verification was made by comparing the susceptibility condition as predicted on the preliminary susceptibility map with the real field condition. This is particularly important to identify the dominant factor for the occurrence of landslides in the study area. This helped to revise the ranks and weights assigned to different thematic maps and its classes. The collected field data were lithology, geological structure, discontinuity, distribution of soil on slope, its type and thickness, landslide and its relationship with other factors (like geology, structure, slope, human activities, geomorphology etc.).

Various models have been applied to landslide susceptibility and hazard mapping (Lee 2007; Guzzetti et al. 1999; Pradhan and Lee 2009; Chung and Fabbri 2003; Remondo et al. 2003; Van Westen et al. 2003; Dahal et al. 2012; Bonham-Carter 1994). The knowledge based approach has been followed in the present study.

Based on the observation and knowledge gained regarding contribution of various parameters for creating the landslide susceptibility condition in the study area, weight for each theme and rank for each class within the theme were assigned. Each thematic layer were given weight ranging from 0 to 10 depending upon the degree of their effect for the occurrence of landslide. Likewise, in each thematic layer, the ranks to individual classes were also assigned within the value of 0 to 10 (Table 1). The most causative/triggering factors were given highest weight/ranks and the lowest value for the least factor. This judgement is totally based on the basis of expert knowledge of the study area gained through field observation.

Landslide susceptibility map was prepared by multiplying the weights of each thematic layer by the ranks of the classes (in raster). All the products were combined and divided by the total weights of the themes using Index Overlay Method, that can be expressed as:

$$S = \sum W_i S_{ij} / \sum W_i$$

Where,

S = output score

W_i = weight for each themes, and

S_{ij} = rank for each class

Thus prepared map was validated with the landslides dataset and an acceptable model was developed, which could better represent the landslide susceptibility condition in the study area.

Results and discussion

Geomorphic condition

The geomorphology can be described in terms of drainage and landform. These parameters plays important role in explaining the major geomorphic units of any area.

Drainage

Alaknanda River is flowing through the western part, Dhauli Ganga in the northern part and Birhi Ganga River in the southern part of the study area (Fig. 5). The Alakananda and Dhauli Ganga rivers meet near Joshimath in the north, while the confluence of Alakananda and Birhi Ganga is nearby the Birhi village in the south. The rivers are structurally controlled as they approximately flow across the strike of either the country rocks or along the major thrust zones. Further, the presence of joints and faults are responsible for local meandering and sudden change of river courses. Though the drainage pattern on steep slopes are parallel to sub-parallel, the overall drainage pattern is dendritic.

The drainage density map prepared from the drainage database provides information on the active soil erosion areas (where drainage density is high). It is observed that the northern part of the study area (east of Joshimath) is

Table 1 Weight and ranks for themes and classes

Themes	Rank
Geomorphology (Weight =7.0)	
Highly dissected denudo-structural hill	8.0
Moderately dissected denudo-structural hill	6.0
Low dissected denudo-structural hill	4.0
Alluvium	3.0
Colluvium	7.0
River Valley	2.0
Lithology (Weight = 9.5)	
Crystalline limestone with thin bands of slate	2.0
Dolomite/crystalline limestone with bands of slate	2.0
Dolomitic limestone with slate	4.0
High grade meta. rocks (gneiss, garnet schist)	5.0
Limestone and quartzite	3.0
Limestone and slate	2.0
Slate with quartzitic bands	9.0
Meta Basics	1.0
Slate and dolomitic limestone	7.0
Slate with dolomite	8.0
Slate with quartzitic bands	9.0
Quartzite	6.0
Slope in degree (Weight = 10.0)	
00–15	1.0
15–25	2.0
25–30	4.0
30–35	6.0
35–40	7.0
40–45	8.0
45–60	9.0
> 60	10.0
Lineament Density (Weight = 5.5)	
Low	4.0
Moderate	6.0
High	8.0
Drainage Density (Weight = 6.5)	
Low	4.0
Moderate	6.0
High	8.0
Debris Thickness (Weight = 7.5)	
Thick (>5 m)	8.0
Moderate (1–5 m)	6.0
Thin (<1 m)	4.0
Proximity to Fault (Weight = 8.5)	
Fault - 75 m buffer	5.0
Thrust - 200 m buffer	7.0

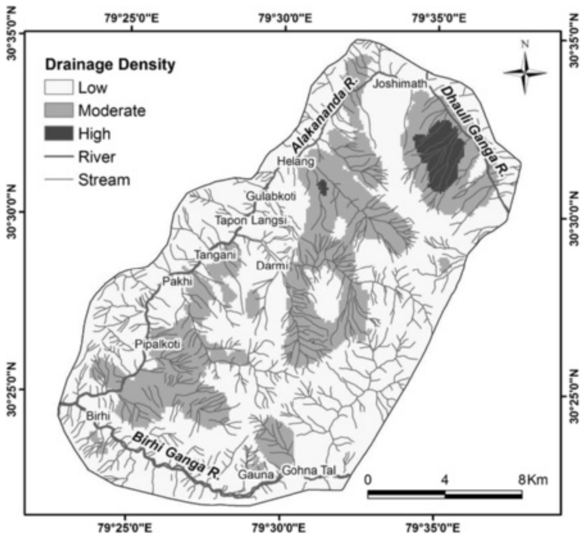

Fig. 5 Drainage map of the study area overlain on the drainage density

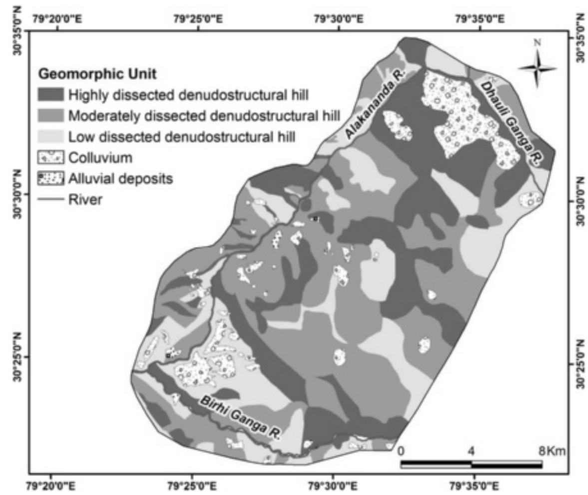

Fig. 6 Geomorphological map of the study area

having high drainage density. Likewise, parts of central (around Helang and Darmi village) and Pipalkoti in the south western part of the study area are represented by medium drainage density.

Landform

A geomorphologic map showing various types of landforms have been prepared through the use of aerial photograph, satellite image, topographic map and field investigation (Fig. 6). Based on the degree of dissection, the hills are sub-divided into highly dissected denudo-structural hills, moderately dissected denudo-structural hills and low dissected denudo-structural hills. This subdivision is quite appropriate regarding the landslide studies.

The following types of landforms are observed in the study area:

Fluvial landform

Though the study area is still under youthful stage of development, prominent fluvial landforms are not developed. However, alluvial fans of smaller dimension are present in the study area. These are basically developed at the confluence of tributary stream and major river. The terraces are developed around the confluence of Birhi and Alakananda (Birhi village). Further, because of bursting of the Gauna Lake (landslide dammed lake) in 1971, huge amount of sediments had been transported, which resulted in development of new terraces that are more than 5 m in thickness.

These small scale terraces can be seen along the Birhi Ganga River, downstream of Gauna Lake, notably along the right bank of river around the Gauna village (Fig. 7). Besides the fluvial deposits, fluvioglacial materials have been observed around the confluence of Alakananda River and its major tributaries. These materials are poorly sorted and sub-angular to angular rock fragments up to the boulder size of gneiss, quartzite and limestone.

Structural landform

Structure has played important role in developing some specific landforms in the study area. Anticlinal hills and synclinal valleys are good examples of structural landforms. Further, the triangular facets has been developed on the fault scarp. Cuesta and hogback are other structural landforms.

Denudational landform

Different denudational processes like sheet, rill and gully erosion together with the river bank erosion and mass wasting processes on the hill slopes are responsible for

Fig. 7 Terraces formed by the Gauna Lake outburst

the formation of denudational landforms. Steep scarps, ridges and valleys are some of the denudational landforms developed in the study area. Erosion due to channelized and un-channelized water flow results during the high intensity, long duration rainfall. Various forms of mass wasting processes taking place in the sediments and rocks in the forms of slide, fall and flows are very common in the study area (Fig. 8). South facing slopes are more vulnerable to the mass wasting processes. The colluvial materials deposited on the slopes are relatively porous in nature and hence the water percolating from the sediment/rock boundary may result in movement of the whole deposited materials. Likewise, these materials are much vulnerable to slope instability when the slope is relatively steeper.

Thin to thick layers of colluvial materials derived from either landslide or weathering are deposited on the slope. The thickness of such materials is considerable along the left bank of Dhauli Ganga. Terrace cultivation is widely practiced in these materials wherever the slope is relatively gentle and the deposited materials are suitable for the cultivation.

Landslide inventory

Present study area lie entirely in the Himalayan belt that experiences heavy rainfall annually during the monsoon season. The average annual rainfall data of the region between the period 2008 and 2012 were 1797 mm and the average cumulative rainfalls for the monsoon period (June to September) for the same period is 1536 mm (Kanungo and Sharma, 2014). Therefore, the fragile mountainous area is highly vulnerable to the landslide and debris flow (Fig. 9). Total of 121 landslides have been identified in the study area. The major landslides having significant impact to the settlement and infrastructures are briefly described below.

Fig. 8 Highly dissected hill

The Helang landslide is situated near Helang village at the left bank of Alaknanda River, 55 km southward from the famous Hindu temple the Badrinath. This landslide is affecting about 250 m of the road section. The main rocks are quartzite interbedded with dolomitic limestone. The Tangni landslide is located about 59 km south of Badrinanth at an altitude of 1450 m near the Tangni village. The height of the crown is 600 m from road and the toe of the slide extends to about 100 m below the road. About 25 m road section is affected by this slide (Fig. 10a). Main rock types in and around the slide are schist, slate, dolomite and phyllitic slate.

Patalganga landslide is situated along the Patalganga valley at a distance of 61 km from Badrinanth. The Munsiari thrust is passing through this landslide. The height of the crown and the depth of the toe of the landslide from the road are 80 m and 40 m respectively. Extensive toe erosion by Patalganga River can be observed. The main rock types in the slide zone are schist, dolomite, slate and phyllite. The Pakhi Landslide situated at 62 km southwards from Badrinath is another landslide that has affected around 50 m of road section. The main exposed rocks are dolomite interbedded with slate.

Pagna Landslide is located upstream of the Birhi Ganga River (on the right bank), near the Pagna village (Fig. 10b). The extensive toe cutting by the river is further triggering the landslide. The river has shifted towards the opposite bank due to the slide materials, which are up to 5 m x 4 m x 2 m sized boulders of dolomite and dolomitic limestones.

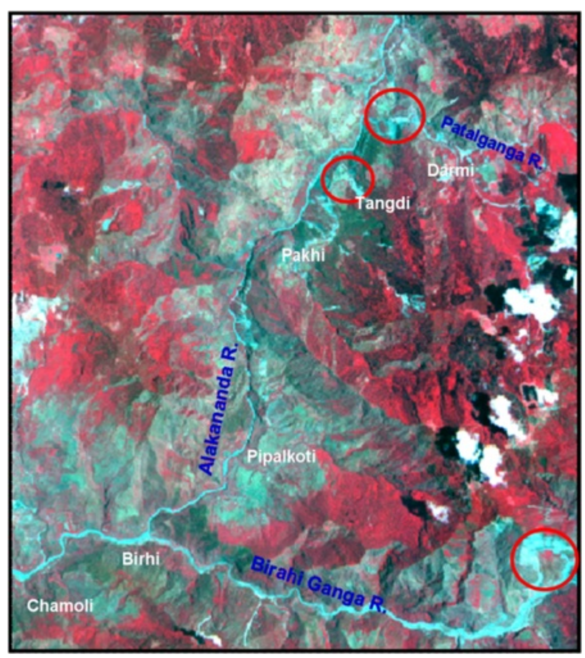

Fig. 9 LISS4 image of the parts of study area showing the major landslide (inside circle)

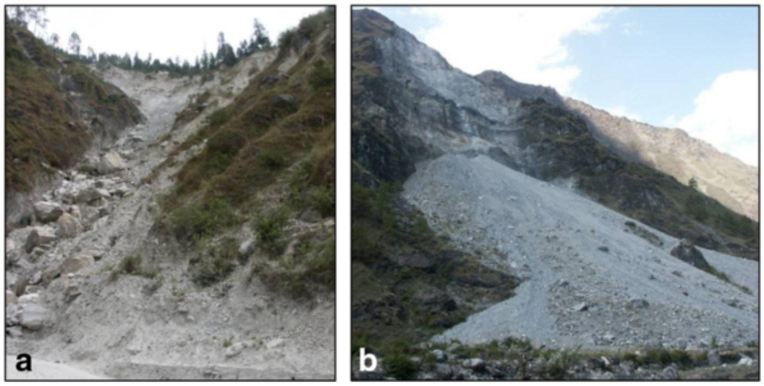

Fig. 10 Tangani Landslide (**a**) and Pagna Landslide (**b**)

In addition to the above mentioned major landslides, there are several other landslides that were identified on the aerial photographs, satellite image, topographic map and also mapped during the field visit. An inventory of landslides has been prepared, which is an important parameter to validate the landslide susceptible model prepared using the analysis of other causative factors (Fig. 11).

Assigning weight to thematic layers and rank to the classes

In the present study, seven thematic layers (drainage density, geomorphology, lithology, lineament density, slope, proximity from thrust/fault and thickness of debris) have been considered for the preparation of landslide susceptibility map. Different lithological units are shown in the lithological map (Fig. 12).

The northern part of the study area is dominantly covered by gneiss and quartzite while the carbonate rocks are prominently distributed in the rest of the area with bands of slate. The thrust and fault buffering was carried out based on their distance of influence for the occurrence of landslide (Fig. 13a). Likewise, lineament density map was prepared from the lineaments extracted from the satellite images (Fig. 13b). It is observed that the northern part of the study area has more lineament density in comparison to the other parts.

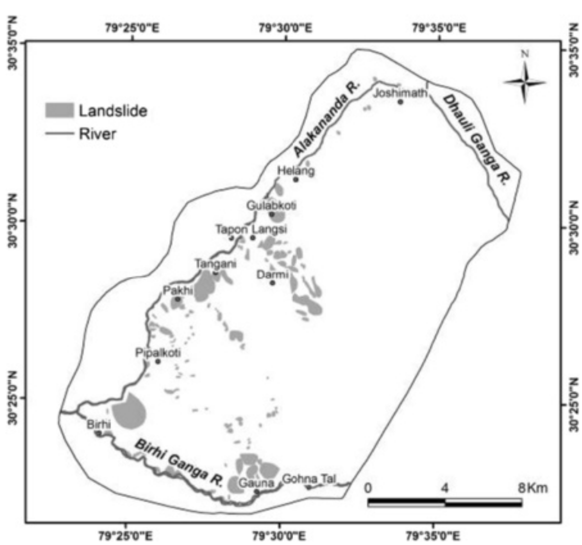

Fig. 11 Landslide inventory of the study area

Slope is another important factor governing the occurrence of landslide in any area. Maximum area (21 %) is occupied by slope class of 15–25° (Fig. 14).

The slope classes 25–30, 30–35 and 35–40 occupies almost equal area (around 14 % by each class). The steepest area (>60° slope) and most gentle area (<15° slope) occupies respectively, around 4 % and 10 % of the total study area. Similarly, the thickness of debris on the slope governs the amount of sediment production during the slope movement and hence is responsible for the degree of damages. The slope with thick pile of debris is more hazardous due to the chances of deeper failure plane when the sediments get saturated.

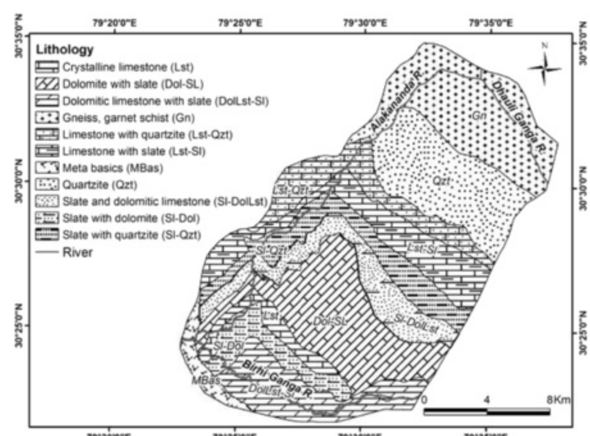

Fig. 12 Lithological map of the study area

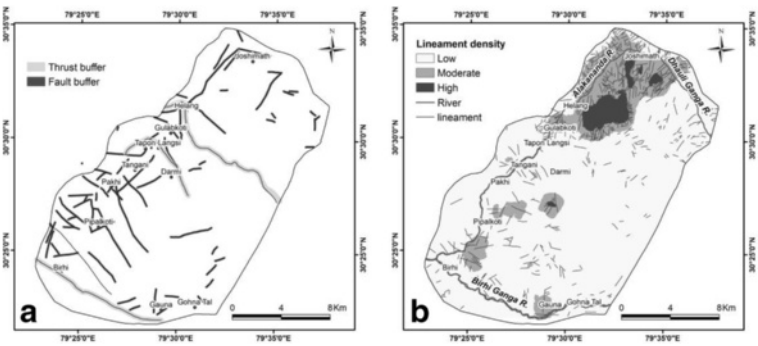

Fig. 13 Thrust and fault buffer (**a**) and lineament density map (**b**)

Landslide susceptibility map

Landslide susceptibility maps provide an indication of where landslides are most likely to occur in the future. Identification of the sites where there is a likelihood of occurrence of landslide events is the main task of landslide susceptibility mapping. Although landslides are often caused by single triggering events, such as heavy rains or human activity, they depend on several primary factors that make slopes susceptible to failure, such as geometry, lithological, structural and hydrographic characteristics. The landslide susceptibility map can be used as background information on the possibility of occurrence of landslides within the study area and in identification of the elements at risk within the high landslide susceptibility zones. Such information is the prerequisite in landslide disaster risk reduction activities.

A knowledge based weights (for each thematic layer) and rank (for each classes of the themes) were assigned. The model was calibrated comparing the predicted susceptibility classes to the actual landslides. Once the predicted susceptibility class shows good agreement to the historical landslide sites, the model was considered as an acceptable one. The final product was classified into five susceptibility classes, namely very low, low, moderate, high and very high (Fig. 15). Most of the area (43.24 %) is covered by low susceptibility class followed by moderate class (39.21 %), very low (8.99 %), high (8.19 %) and very High (0.38 %) susceptibility classes.

The high susceptibility area lies in the northern part of the study area, along the Alakananda River, and along Patal Ganga River valley (including Darmi village) and in the Birhi Ganga River valley (Birhi and Gauna village area).

Model validation

Visually, the predicted landslide susceptibility classes are in good correspondence with the actual landslide occurring in the study area. However, it was necessary to evaluate the model statistically, which was carried out by making a comparison between the landslide density, landslide percentage and susceptibility class percentage (Fig. 16). The actual

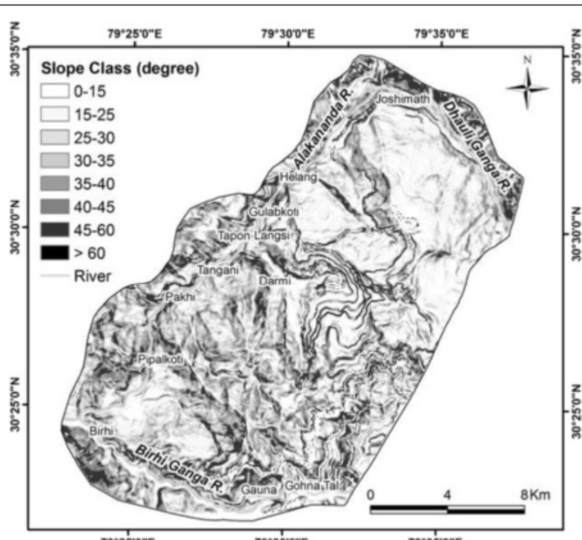

Fig. 14 Slope map of the study area showing area covered by different slope classes

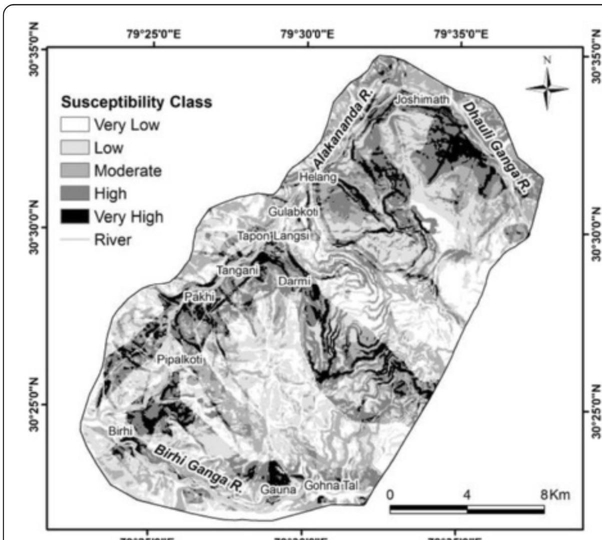

Fig. 15 Classified landslide susceptibility map

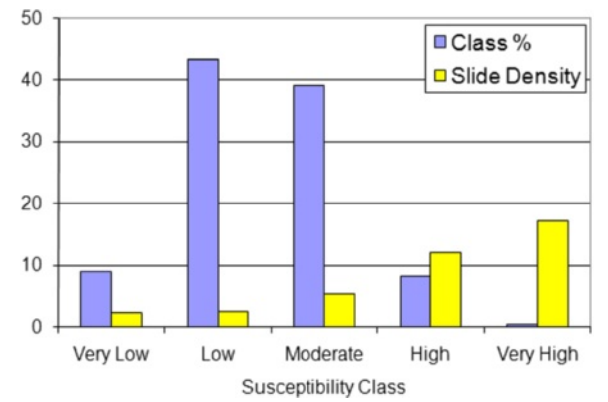

Fig. 16 Comparison between the percentage of each susceptibility class and landslide density in each class within the study area

number of landslide pixels, falling on each class was calculated based on the landslides inventory database.

The very high susceptibility class occupies minimum area while the slide density is maximum in this class. Maximum area is occupied by the low and moderate susceptibility classes. The higher slide density with higher susceptibility class justifies the model.

Conclusion

Landslides in the study area pose serious environmental and social problems. Several disturbed zones, dissected hills and hollows along the slopes are present, and are the main reasons for mass wasting process in the area. The study shows that most of the landslides occur along the road section, river section and in the thrust/fault zones. Most of the fresh landslides are the reactivation of pre-existing ones. The old landslides are covered by vegetation that, in some cases, makes the recognition of the phenomena difficult. These old, dormant slides can be reactivated by triggering factors like rainfall and man-made disturbance.

The landslide susceptibility is controlled by the occurrence of highly fractured rocks, as observed in quartzites and gneisses. The occurrence of landslide zones along Birhi Ganga section is mainly resulted due to the presence of Birhi Ganga Fault. Several old to active and small scale to large scale landslides can be observed in this section. The section is basically consisting of limestone, dolomite and slate. The Dhauli Ganga River is almost running along the Vaikrita Thrust. This is the reason huge amount of slide materials (colluvium) have been deposited along the left bank of the river. These materials are forming the potential sites of debris flow at the availability of discharging fluid, at the places where slope is rather steeper.

Construction/widening of roads have initiated a large number of slides in the area and the widening of the road to Badrinath that is aligned along the left bank of Alakananda River, is affected by the bank cutting resulting in the slope failure. Further, when the road crosses thrust zones, we can see landslides on huge scale. Remote sensing data is very useful to locate, identify and demarcate the different geologic features like lineament, thrust/fault, geomorphology.

The landslide susceptibility mapping of the study area, carried out by integrating different thematic layers like lithology, geomorphology, slope, lineament, drainage density, proximity to thrust/fault and debris thickness shows that the high susceptibility area lies in the northern part of the study area, along the Alakananda River, and along Patal Ganga River valley (including Darmi village) and in the Birhi Ganga River valley (Birhi and Gauna village area). The landslide susceptibility model well reflects the real field condition and also the model is well validated. The main purpose of the present study has been accomplished through the preparation of landslide susceptibility map through the application of knowledge based susceptibility mapping method in the Himalayas through proper understanding of the various causative factors responsible for landslide in the study area. Thus, the present study successfully applied the knowledge based landslide susceptibility mapping in the Garhwal Himalaya, which can be replicated to the other parts of Himalaya including Nepal Himalaya.

Competing interests

The author declares that he has no competing interests.

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