ASSESSMENT OF SNOW AVALANCHE SUSCEPTIBILITY OF ROAD NETWORK - A CASE STUDY OF ALAKNANDA BASIN

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Commission V, SS: Disaster Monitoring, Damage Assessment and Risk Reduction

KEY WORDS: AHP, ASTER GDEM, Hazard, Snow Avalanche, Susceptibility.

ABSTRACT:

Snow avalanche occurring in a micro-climatic condition causing hydro-geo (Hydrological and geological) hazard to the deployed armed forces and nearby inhabitant to the North Western Himalaya about 3000 MSL. In recent years, frequencies of snow avalanche have increase and consequently the death toll have also surged to many folds. These unavoidable occurrences not only cause road blocks which disrupts transportation connectivity in the rugged terrain of Himalaya as well as loss of infrastructure and life. Here, in this study an attempt has been made to assess the susceptibility of road network of Alaknanda Basin from snow avalanche. Potential avalanche formation zones have been generated using Analytical Hierarchical Process (AHP) of Multi-Criteria Decision Making (MCDM. Advance Thermal Emission Reflection Radiometer (ASTER) Global Digital Elevation (GDEM) 30 meter has been used to generate static parameters like slope, aspect, curvature etc. using GIS platform. ISRO-Geosphere Biosphere Program Land Use Land Cover (LULC) used as another static parameter. Weights are generated using comparison matrix and ratings to different static parameter layers assigned on the basis of field visit and literature review while the road network are digitized from Google earth. A methodology has been prepared to categorize the road stretches on the basis of potential snow avalanche formation zone including hydrological processing. Buffer zone are assigned with weights according to potential snow avalanche formation zones. Later roads are intersected with sub basin with assigned values that resulted very high avalanche potential zonation, considered as most susceptible to snow avalanche hazard.

1. INTRODUCTION

A snow avalanche (here after only avalanche word is used to define snow avalanche as mostly snow avalanche occur in India) is an enormous slide of snow, rock, ice or debris down a mountain slope. It can happen due to natural activities like heavy precipitation, earthquake etc. and manmade activities like by skier and controlled explosion. In the event of an avalanche, the fresh snow accumulates over the top of existing dense layer of snow, which starts slide down on the slope (Jacob et al., 2011). The falling material of avalanche and the frontal pressure creates air blast, which causes widespread destruction to whatever comes in the track of avalanche.

The avalanche is a common incidence in snow covered mountainous areas, which means glide of snow mass down the mountain slope. Large part of detached of debris such as snow, ice, rocks and vegetation slide down rapidly along the slope. The formation of avalanche depends on multiple factors which include static and dynamic parameters (Schweizer and Jamieson, 2003). Static parameter comprise of terrain conditions which is prerequisite and prime in triggering an avalanche. Terrain conditions are stationary in nature and hardly change with time, it includes slope, elevation, curvature, aspect, ground cover etc. Dynamic parameters are comprise of Snowpack characteristics and meteorological factors. Snowpack characteristics include snowpack thickness, stability, density, water content, grain size etc. and meteorological characteristics include air temperature, precipitation, wind speed, wind direction etc. the formation and release of an avalanche is combination of both the factors.

Generally, the most frequent fatalities are labours working in mine and transportation along with settlement in region including the armed forces during their patrolling session. Due to upsurge in population, recreational events, conveyance, infrastructures in high regions pushed locals to move into avalanche prone regions leading to in high risk (Fuchs and Bründl, 2005). The annual fatality figures also reveals that 10-12 person in Canada and USA (Stethem et al., 2003), 30 person in Austria (Höller, 2007) and in India this number is amid to 30-40 people. The avalanche prone area in India stretch alongside the Greater Himalayan Range involving the states of Jammu and Kashmir (J&K), Himachal Pradesh, Uttrakhand and Sikkim where 109, 91 and 16 villages in Himachal Pradesh, J&K and Uttrakhand respectively, are under persistent avalanche risk for the entire winter period (Ganju and Damari, 2004) (Figure 1).

Emergence of Remote Sensing and GIS has given great impetus in avalanche studies in recent decades. Use of Digital Elevation Model (DEM) has made it easier to map and model the avalanche in real time. Earlier mapping of avalanche were challenging and arduous task, because researchers had to go in field to map and locate avalanches, which used to cost them risk

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of life. Modelling and Visualisation of avalanches in now can be done easily using high resolution DEM, which gives several other parameters like velocity, snow height, pressure etc

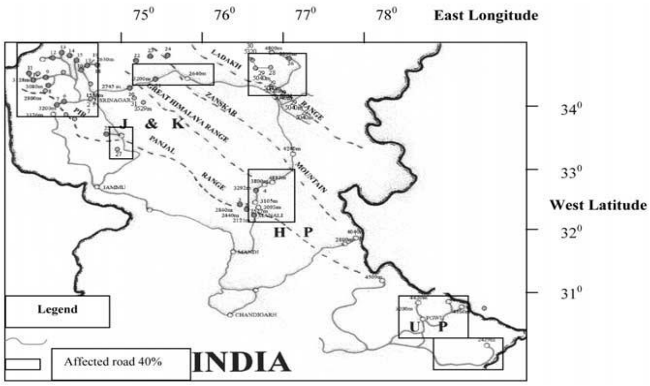

Figure 1 Snow avalanche hazards areas in North-West India (Ganju & Damari, 2004).

Countries like USA, Canada, Switzerland etc. has done lot studies in understanding of avalanche dynamics. The International Glaciological Society has held conference in 1992, 1996, 1998 and 2000, the snow dynamics and thermodynamics were topic of interest (Pudasaini and Hutter., 2007). The International Snow Science Workshop is an international conference that being organised biennial. The conference brings together avalanche specialists from all over the world. The major objective of the conference is to share knowledge, experience, research skills, also exhibit new products and brainstorm for solution of existing challenges.

Salzmann et al., 2004 developed a three-level downscaling model for the assessment of potential hazard of ice avalanche using remote sensing and GIS-modelling. Bulher et al., 2009 proposed methodology for the use of high resolution airborne data to detect and map the avalanche deposits in Davos, Switzerland. He also developed a tool for automatic detection of potential avalanche release area using high spatial resolution DEM, and validate over in Davos and applied it near Rohtang tunnel axis, India. Jacob et al, 2011 and Snehmani et al., 2014 used Multi Criteria Decision Making (MCDM) for avalanche hazard demarcation in Chowkibal-Tangdhar axis and Gangotri Glacier respectively. Kishor, 2017 also used AHP method to map the avalanche zones in ten major river basin of Uttrakhand. Eckerstorfer et al., 2016 in his review paper on *'Remote Sensing and Snow avalanche: Recent advances, potential, and limitations'* highlighted the use of different remote sensing in snow avalanche mapping and modelling. This review paper also discussed on the opportunities and limitation of RS & GIS technology in snow avalanche studies and its future challenges.

In India, study on avalanche started late in sixties, just after Sino-India conflict in 1962 which revealed an incredible vulnerability of military troops to avalanche hazards. Problems of survival in avalanche prone areas faced by the armed forces, literally re-minded the Indian government about a fact that enormous areas of India were affected so heavily by snow and avalanches. To combat this hazard and to enhance socio-economic growth of snowbound area. Later, in 1969 a special organisation was founded – Snow and Avalanche Study Establishment (SASE), under Defence Research and Development Organisation (DRDO) (Podolskiy et al., 2009). Since then SASE has done commendable job in avalanche research and provide avalanche related information to armed forces, district authority and Border Road Organisation (BRO).

Several researcher have used different sets of static parameters to mark the release or formation zone of avalanche using AHP and other algorithms. In this study an attempt has been made to assess the susceptibility of road network in Alaknanda basin using avalanche formation zone derived using static parameters those provide suitable location for formation of the avalanche.

2. STUDY AREA AND DATASETS

2.1 Alaknanda Basin

Alaknanda basin has been selected for this study as this region experience avalanche every year and least studied for avalanche activities. The Alaknanda basin lies in the Chamoli district of Uttrakhand. It meets Bhagirathi River at Devprayag and becomes Ganges. For study purpose upper part of basin is selected and to delineate basin Vishnuprayag is marked as outlet where it meets Dhauliganga. The Upper Alaknanda basin lies in Chamoli district of Uttrakhand. It extent from 79° 13' 29'' to 80° 14' 59''E longitudes and from 30° 16' 16'' to 31° 04' 20''N latitudes (Figure 2). The altitude of this area varies from 1200m to 7700m and total study area is 4644.47 km^2. It comprises of the hilly terrain, deep gorges and river valley terraces. Nandadevi, Kamet and Chaukhmba are major peaks of this study area (Kala, 2004).

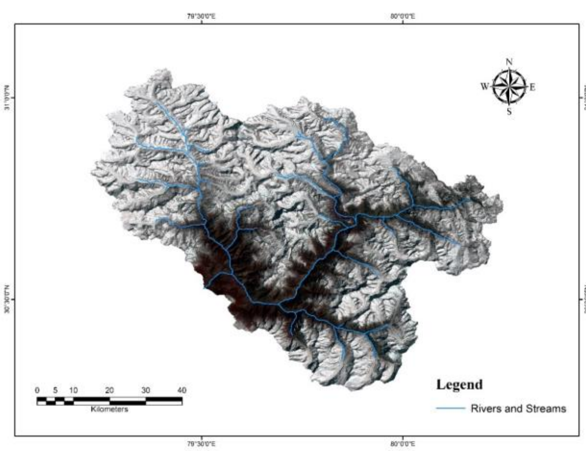

Figure 2 Alaknanda Basin shown on FCC image of Sentinel-2 (28-11-2017)

The upper Alaknanda basin is source of many small rivers. All the rivers in basin are perennial and snowmelt fed. Alaknanda is main river of the basin which originate from the confluence and feet of the Satopanth and Bhagirath Kharak Glaciers in 7 km west of Mana Village. Alaknada River flows southward and after meeting with Dhauliganga it flow toward south-west. Study area also comprises of few tributaries of Alaknanda river like Dhauliganga, it originates from Niti Pass and inlet into Alaknanda at Vishnuprayag, Sarswati River, a small tributary of Alaknanda, originate from great Himalayas and join

Alaknanda near Mana Village (Sati, 2008). The climatic condition of study area is classified as Cfb according to Koppen and Geiger classification. The varying physiography and altitudinal difference control the climatic condition of area. Despite varying physiographic features, sub-regional deviations in the mean seasonal temperature are not prominent (Sati, 2008). The highest temperature has been recorded in the month of June and lowest temperature in the month of January. Precipitation occur in the form of rainfall and snowfall. Rainfall occurs mostly during monsoon season and snowfall occurs during winter season. Snowfall occurs mainly in the area above 2000m msl. Occurrence of snowfall in North West Himalayas depends on the western disturbance also known as extra tropical pressure system.

2.2 Datasets

Advance Thermal Emission Reflection Radiometer (ASTER) Global Digital Elevation (GDEM) 30 meter has been used to generate static parameters like slope, aspect, curvature etc. using GIS platform. Global ASTER (GDEM) was prepared using visible-near infrared band of ASTER sensor on board on Terra satellite launched by NASA in 1999. It was a joint venture of The Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). ASTER GDEM was generated using stereo-pair images of ASTER sensor on board Terra satellite, first version was released in June 2009, and another update version (GDEM V2) with more vertical and horizontal accuracy, less artifacts and improved special coverage was released in October 17, 2011. METI and NASA provide data at free of cost as a support to Global Earth Observation System of Systems (GEOSS) (https://asterweb.jpl.nasa.gov/gdem.asp). ISRO-Geosphere Biosphere Program Land Use Land Cover (LULC) used as another static parameter. Road network of Alaknanda basin digitized from Google earth. GPS location of existing avalanche sites also collected during field visit to validate the result.

3. METHODOLOGY

The general methodology for this study can be divided in three part as following: part one field data collection and literature review, part two generation of potential avalanche formation zones using static parameters and by applying AHP method and third part includes assessment of road network for avalanche susceptibility and validation of results.

3.1 Field Survey and Data Collection

Alaknanda basin is hardly studied for avalanche studies therefore, it was tough to locate existing avalanche sites. It was done with help of locals and armed forces deployed there. During field visit some avalanche sites, where avalanche activities have happened earlier, were selected to collect the field data. Parameters like slope, aspect and elevation information (Table 1) were collected for six sites (Figure 3). It was also observed the few sites have experienced recent avalanche as visible in field photographs (Figure 4).

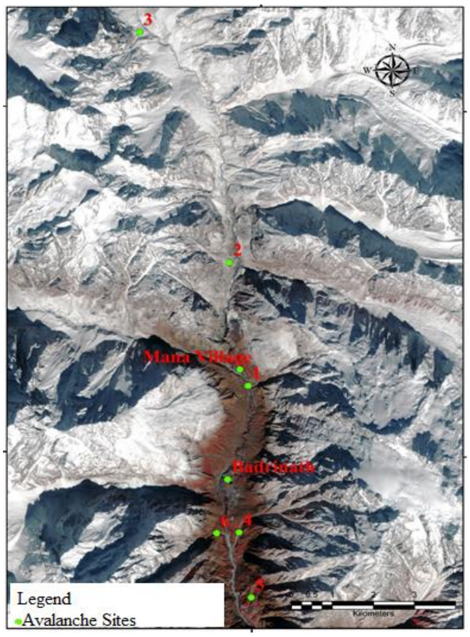

Figure 3 Location of avalanche sites where avalanche has occurred (Sentinel-2 image, 28-11-2017).

Figure 4 Field photographs of Alaknanda Basin Avalanche Sites

Table 1 Information of different avalanche sites in Alaknanda Basin

Sites	Elevation (Runout) (m)	Aspect	Slope (Degrees)	Elevation (Starting Zone) (m)
1	3102	N, NW	25.46	4547
2	3507	E, SE, S	29.24, 35.24	4869, 5025
3	4058	NE, E	40.34, 29.82	4869, 4794
4	3084	NW, W	35.52	4940
5	2955	SW, W	37.36	4524
6	3135	N, E, NE	38.01	4664

3.2 Methodology for Potential Avalanche formation Zone using Static Parameters

As stated earlier occurrence of avalanche depends on the static and dynamic parameters. Static parameters include favourable

https://doi.org/10.5194/isprs-archives-XLII-5-461-2018

Intensity	Preference Descriptor	Explanation
1	Equal importance	Two activities contribute equally to the object
2	Between 1 and 3	
3	Slight prevalence	Experience and judgement slightly over another
4	Between 3 and 5	
5	Medium prevalence	Experience and judgement strongly favour on activity over another
6	Between 5 and 7	
7	Strong prevalence	Dominance is demonstrated in practice
8	Between 7 and 9	
9	Extreme prevalence	Evidence favouring one over other of highest possible order of affirmation

Table 2 Preference Descriptor (Saaty, 1990)

terrain condition for the occurrence of avalanche. Static conditions are those terrain condition which do not change over time. It is prerequisite for occurrence of avalanche that terrain condition should favour, otherwise favourable dynamic parameter conditions don’t have relevance. Several researchers have used more or less similar static parameters for the mapping of avalanche potential formation area. Buhler et al., (2013) used slope, aspect ruggedness and forest for automatic mapping of potential release area, Maggioni and Gruber, (2003), used slope, aspect, curvature etc. parameters, Jacob et al., (2011) used Slope, Curvature, Ruggedness, Aspect, Altitude, Land cover, Vegetation density for Avalanche Hazard Zonation, and Snehmani et al.,(2014) also used slope, aspect, curvature, elevation and land cover to demarcate the potential avalanche sites in Gangotri Glacier. For this study following five static parameters have been considered to map potential avalanche formation zones and rated according to preference descriptor Table 2 (Saaty, 1980).

3.2.1 Elevation:

Elevation is major parameter in avalanche assessment. Snowfall occur in high altitude areas therefore occurrence of avalanche is also controlled by elevation. It has been observed that most of the avalanche release from the height between 4000 to 5000 meters in case of Alaknanda Basin but this is not an absolute range of height for avalanche release. Avalanche have also been reported at lower elevation. As avalanches occur mostly in range of 4000 to 5400 in Alaknanda basin therefore this range have been rated highest (Table 3).

3.2.2 Slope

The slope is paramount terrain parameter for avalanche activities. It is generally recognised that avalanches release from slopes between 30 and 50 degree (Schweizer and Jamieson, 2003; McClung & Schaerer, 2006). Snehmani et al., (2014) studied 58 sites of avalanche in Gangotri Glacier area and found 25 to 45 degree slope most prone to avalanche. Slope for the study area generated from ASTER GDEM 30 meter. Spatial analyst tool of ArcGIS has been used to calculate slope. The rate of change in horizontal and vertical direction of elevation from centre cell of 3×3 mask determine the slope in ARCGIS. It gives slope in degree and percent rise.

Table 3 Ratings for terrain data layers and their categories

Thematic layer	Categories	Ratings
Elevation	<2800	1
	2800-3200	1
	3200-3600	5
	3600-4000	7
	4000-4400	9
	4400-4800	9
	4800-5200	9
	5200-5600	7
	5600-6000	7
	6000-6400	3
	>6400	2
Slope	$<12^{o}$	1
	12^{o}-25^{o}	4
	25^{o}-45^{o}	9
	$>45^{o}$	3
Aspect	N	5
	NE	9
	E	9
	SE	3
	S	3
	SW	1
	W	6
	NW	9
	Flat	1
Curvature	<0	9
	0	4
	>0	1
Ground cover	Evergreen Needle Leaf Forest, Water Bodies, Built up	1
	Barren Land, Waste Land	7
	Sown and Ice	9
	Grassland and Shrub land	3

3.2.3 Aspect

Aspect is described as the direction of maximum slope of the topography surface with respect to compass. Aspect play strong role in snowpack properties formation, so in avalanche formation. From the avalanche site it has been observed that avalanche can occur at any aspect but most of avalanche in study areas have been experienced over NE, E and NW therefore maximum weightage value is given to them (Table 3).

3.2.4 Curvature

Curvature is another important static parameter that increase the avalanche possibility. Curvature is refers to deviation from a straight line. It is calculated as second derivative of the surface in ArcGIS. ArcGIS provide three different curvature maps one is plan curvature which is perpendicular to the direction of maximum slope; second is profile curvature, which is parallel to the slope and indicate the direction of maximum slope. Third is combination of both the curvatures. The profile curvature affects the acceleration and deceleration of flow and, thus, influences erosion and deposition. The plan form curvature influences convergence and divergence of flow. Therefore profile curvature is used in this study. In the profile output, a negative value shows the surface is upwardly convex at a cell. A positive profile defines the surface is upwardly concave at a cell. A value of 0 show the surface is flat (Moore et al., 1991; Zeverbergen et al., 1987). Convexity leads to an unstable condition in the snow cover because of tensile stress, whereas concavity favour the snow equilibrium as a result of compression. Therefore, highest weight is specified to convex slope surface.

3.2.5 Ground Cover

Land cover also controls the triggering of avalanche. Vegetated area have less susceptibility than barren land and snow covered area. Avalanche dynamic not only depends on flow regime, movement and velocity but also affected by standing vegetation. The composition of plants in release area and in path can cause hindrance to gliding motion of avalanche which lead to shortening of runout zone (Feistl., 2015). Vegetation provides more friction and stability to snowpack. Therefore, maximum value of preference is given to snow cover and barren land in comparison of vegetated area.

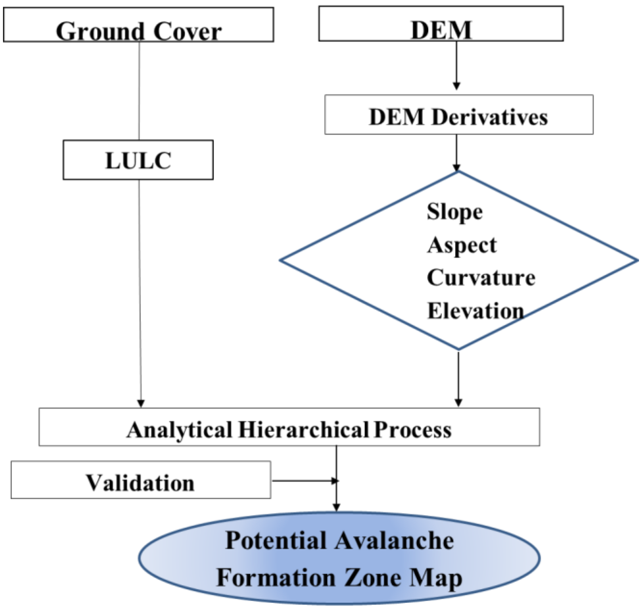

Figure 5 Methodology adapted for Potential avalanche formation zone

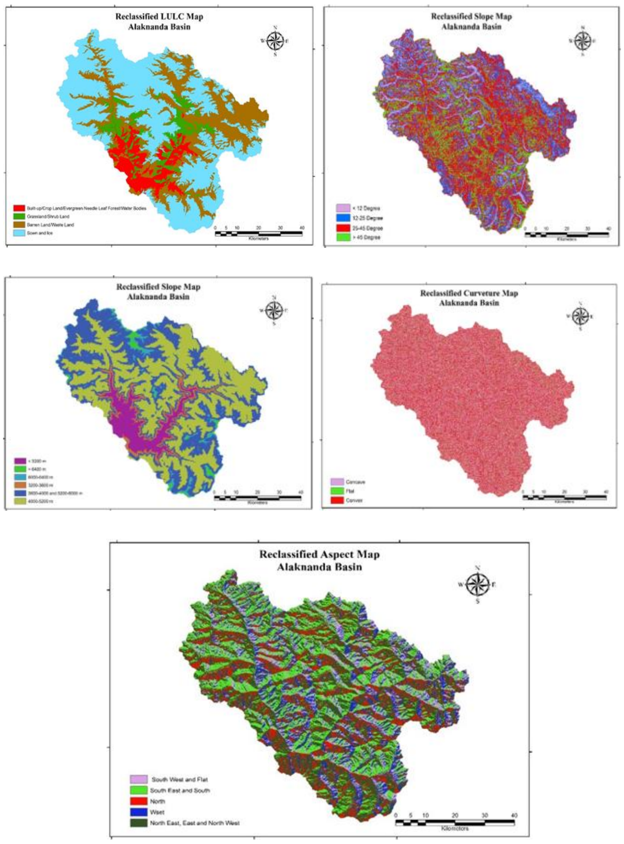

Figure 6 Reclassified maps of static parameters

3.3 Derivation of weights for different layers

Weights for different thematic layers of static parameters generated from DEM, are derived using AHP method propounded Saaty (1980). A pairwise comparison matrix was prepared and all the thematic layers were compared in reasonable way using AHP analysis. Preferences to the parameters under consideration are given using preference descriptor. To generate the weights matrix was synthesized.

Table 4 Pairwise Comparison Matrix

Class	Slope	Elevation	Curvature	Aspect	Land Cover
Slope	1.00	3.00	4.00	4.00	7.00
Elevation	0.50	1.00	2.00	2.00	4.00
Curvature	0.25	0.50	1.00	3.00	3.00
Aspect	0.25	0.50	0.33	1.00	3.00
Land Cover	0.14	0.20	0.50	0.50	1.00
Total	2.14	5.20	7.83	10.50	18.00

Table 2 Synthesized Matrix

Class	Slope	Elevation	Curvature	Aspect	Land Cover	Weight Value
Slope	0.500	0.571	0.510	0.387	0.375	**0.47**
Elevation	0.166	0.190	0.255	0.193	0.250	**0.21**
Curvature	0.125	0.095	0.127	0.290	0.125	**0.15**
Aspect	0.125	0.095	0.042	0.096	0.187	**0.11**
Land Cover	0.083	0.047	0.063	0.032	0.062	**0.06**
Total	1.00	1.00	1.00	1.00	1.00	1.00

https://doi.org/10.5194/isprs-archives-XLII-5-461-2018

All the thematic layers of static parameters are later multiplied to their respective weights and added in raster calculator in order to generate final map of potential avalanche formation zones map using following equation in map algebra tool in Arc Map

(Slope*0.47) + (elevation*0.21) + (curvature*0.15) + (aspect*0.11) + (land cover*0.06)

3.4 Methodology for susceptibility of road network in Alaknanda Basin

On the basis of static parameters road stretches have been categorised in different susceptibility. To categorise the road stretch with susceptibility following methodology given in Figure 7 has been used for Alaknanda basin. ASTER 30m DEM has been used for hydro-processing to delineate sub-basin of the Alaknanda basin. Buffer of 2km has been created from major road network as most of the avalanches occurred in this area have 1.5 to 2 km length from starting to end. Sub-basins are clipped with 2km buffer. Zonal stat tool is used to extract the highest area value of different potential formation zones with in particular sub-basin from potential avalanche formation zone maps of static parameters. Sub-basins are then intersected with road layer and finally road layer is categorised on the basis of avalanche susceptibility.

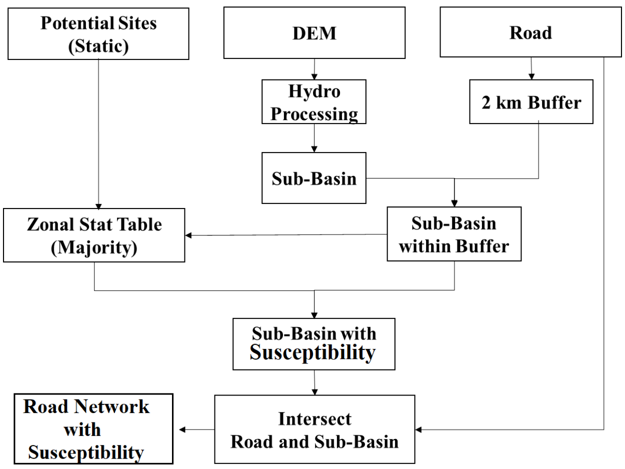

Figure 7 Methodology for Road susceptibility from Avalanche.

4. RESULTS AND DISCUSSION

4.1 Potential Avalanche formation site in Alaknanda Basin

Avalanche activities in Uttrakhand is mostly concentrated in Alaknanda basin. This basin has been poorly studied for avalanche dynamics and mapping. Different thematic layers were generated using ASTER GDEM 30. All the layers were given preferences based on field observations and literature reviewed. Weights are generated using AHP method of multi criteria decision making (MCDM) analysis for the layers. The weighted layers of each parameter has been added to generate the potential avalanche formation zone map. Generated map later classified in four classes, low potential site, medium potential site, high potential and very high potential site, using natural break (Jenks Method).

Figure 8 show the potential avalanche formation zones of Alaknanda basin, derived from static parameters considered in the study. It is clear from the figure that, mostly all the past avalanche site polygons laid over the map come under high to very high potential avalanche triggering zone. Therefore, it can be concluded that the static parameters considered in the study are enable us to identify the potential avalanche formation zones

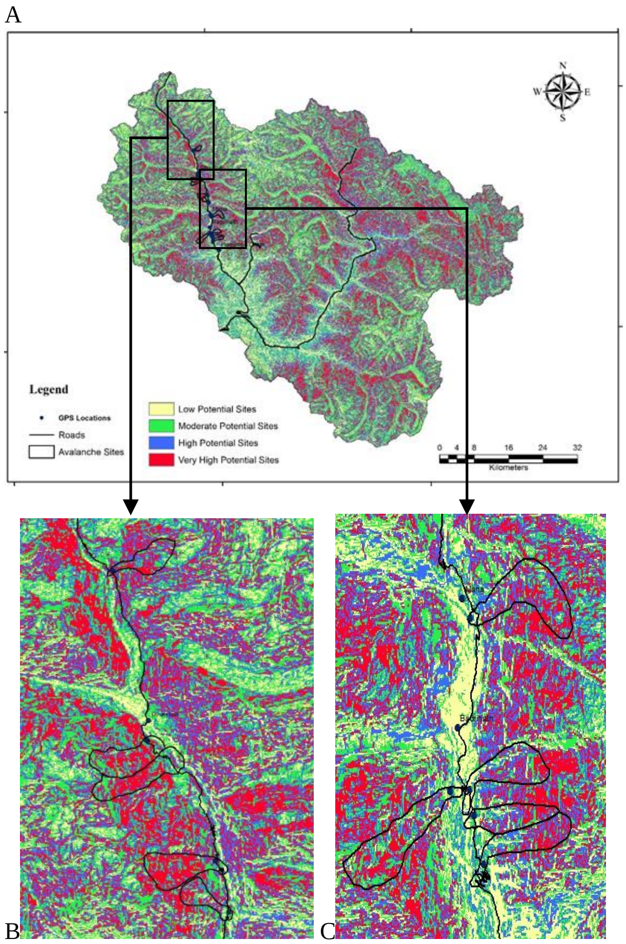

Figure 8 Potential Avalanche Formation zones Map Alaknanda Basin (ASTER) and avalanche site polygons overlaid after (B) and before (C) Mana Village

Table 4 Category-wise area distribution of avalanche site

Categories	Area (km^2)	Area (%)
Low Potential Sites	824.81	17.76
Medium Potential Sites	1470.08	31.66
High Potential Sites	1286.63	27.71
Very High Potential Sites	1061.42	22.86

Total area of Alaknanda basin is around 4643 km^2 out of which 22.86 percent lies in very high risk zone of avalanche. High and very high potential formation zones together constitute more than 50 percent of area which make is high vulnerable for avalanche activity. All the low lying areas and glacier valleys are coming under low potential avalanche sites zone, as less preferences were given to lower altitude and flat areas. High peak areas like Nandadevi and Kamet also come under less potential zone as this areas are more under stable weather condition due to high elevation. Access to Niti pass also have avalanche vulnerability after Malari village road become more vulnerable to avalanches, as elevation increases. Route to Hemkund also come under very high vulnerable avalanche zones. Even, few avalanche activities have been reported in these regions.

4.2 Avalanche susceptibility of road network in Alaknanda Basin

The Alaknanda Basin as discussed in the procedure of susceptibility estimation in section 3.4,it have a total road length of 233 km out of which low avalanche vulnerable constitute 91 km. Moderate, high and very high vulnerable constitute 32, 70 and 40 km respectively. It is clear from Figure 9 that road stretch in lower areas have low susceptibility, and susceptibility of road have increased with increase in height but upto a certain limit after that susceptibility lags. There are small moderate and high susceptible stretches in between low and very high vulnerable stretches of roads. To validate the susceptibility of roads, existing avalanche sites are overlaid and it is found that they lies in high and very high vulnerable road stretches. This map can be used while travelling in this area to avoid avalanche accident.

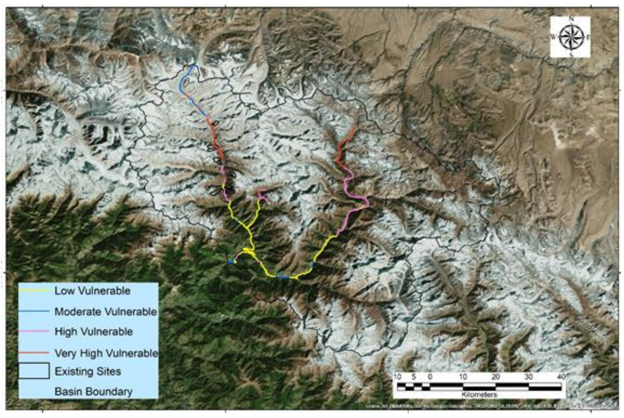

Figure 9 Avalanche susceptibility of road network in Alaknanda Basin

It can be concluded that using static parameters of avalanche formation not only avalanche sites can be marked, even road in avalanche prone areas can also be marked. Here is this study only five static parameters and 30 meter DEM have been used, to increase the accuracy more parameters like ruggedness, channelled un-channelled location etc. and high resolution DEM can be used. More field data can help in marking of road network vulnerable to avalanche as here only potential avalanche formation zones have been considered.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Indo-Tibetan Border Police (ITBP) Force for providing support during field visit for data collection in Mana Pass axis. It would have been difficult to validate the results if information related to avalanche activities and avalanche sites have not been provided by the ITBP force.

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