LANDSLIDE HAZARD ZONATION MAPPING USING STATISTICAL INFORMATION VALUE METHOD OF UPPER YAMUNOTRI VALLEY IN UTTARKASHI DISTRICT, UTTRAKHAND, INDIA

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Abstract

Landslide is the most devastating natural hazards by means of slow to rapid upward and downward movement of unstable rock and debris masses flow under the force of gravity in the Uttarakhand State of India. Monsoon rainfall and geological structure have played a key role for occurrence of landslide. “Landslide Hazard zonation Mapping” or “Susceptibility mapping” is very important to predict the zonation wise susceptible areas. In this work information value (Info Val) method was used for landslide hazard zo-nation mapping, considering these parameters - thematic layer slope, aspect, relative relief, land use/land cover, NDVI, lineament, geomorphology etc. This thematic layer has been created and information values were calculated for each and every layer. Then all information value maps are integrated for final zonation mapping or susceptibility mapping. Mainly this project was done for the creation of inventory map and combines each thematic layer for calcu-lation. The interpretations of the susceptibility map reveal that geology, slope, slope aspect, and relative relief played major roles in landslide occurrence and distribution in the Upper Yamunotri valley.

1. Introduction

Landslides constituted 4.89% of the natural disasters that occurred worldwide during the years 1990 to 2015 (www.em-dat.be). Landslides cause loss of life and property, and damage to natural resources, developmental projects and essential commodities, etc. It has been estimated that, on an average, the damage caused by landslides in the Himalayas costs more than US$ one billion, besides causing about 200 deaths every year, which amounts to 30% of such losses occurring worldwide, Naithani, 1999. Due to landslide blocking the communication links every year and it will happen in any time. Landslides triggered by heavy rainfall are the most common factor of Uttarkashi district. Especially in Uttarakhand district human influenced landslide are originating along the road corridor line and most of the landslides occurs along the riverside. Recently there have been many occurrences in Yamunotri. Landslide susceptibility assessment is a process directed to establish the likelihood that future landslides will occur in a given area based on suitable physical terrain factors (slope, land use, lithology, etc.). It is a common phenomenon especially in the lower Himalayas, which is a tectonically fragile and sensitive mountainous terrain (Ghosh & Suri., 2005). Asia undergoes the maximum damages / losses due to landslides in general and the south Asian nations, in particular, are the worst sufferers. Furthermore, among the south Asian countries, India is one of the affected countries by landslides.

The mountainous environment of Himalaya is highly vulnerable to landslides due to its weak topography, difficult geological set-up and tectonically active belt (Shroder and Bishop 1998, Jade 2004). Yamunotri valley, being a undulating landscape, is experiencing various types of slope failures, mainly for the duration of the monsoon period. This creates a number of miseries to everyone, resulting in failure of life and property, trouble of communication system, and also cause economic trouble in the society. The devastation by landslides along Yamuna valley has been repeatedly reported. In recent times, 14th to 17th July 2013 Uttarkashi was affected by a massive landslide due to cloudburst. It displaced more than 2000 people, and spoilt properties and businesses worth millions. Then in August 2009, about 50 people were killed and several houses were buried under the rubble in three villages in a huge landslide in the Pithoragarh district of Uttarakhand. In 1923, major earthquake destroyed this area. There is an increase in events of landslides frequencies in recent years in the western part of Himalaya. In the way of Yamunotri temple huge boulders destroying and carrying with it everything that is lying in its path. This is enough amount of historical information quantify the hazard with both temporal and spatial approaches. This work is to generate landslide hazard zonation or susceptibility mapping.

2. Objective of the study

The prime objective of the recent study to prepare landslide inventory map by visual interpretation using high resolution satellite imagery and develop susceptibility map using the information value (Info Val) method with the help of remote-sensing data and GIS techniques and also identifying the causes of landslides using information collected from field observation and using geospatial technology.

3. Geographical Location of the study area

Yamunotri Valley is located at an average height of 3,200 meter above mean sea level. In Uttarkashi district, upper Yamunotri Valley (Study area) extends between 30º55´57´´ to 31º2´25´´North latitudes and 78º20´58´´ to 78º29´41´´ East longitudes, covering total area 161 sq km (see Fig. 1). Yamunotri, the source of the Yamuna River is one of the four sites in India's char dham pilgrimage. The holy place of Yamunotri is the westernmost shrine in the Garhwal Himalayas. The actual source an ice-covered lake and glacier (Champasar glacier) situated on top of the mountain at the altitude of 4421 m above mean sea level.

4. Function of Information Value Method (Info Val Method)

Information value method is a bivariate statistical techniques suggested by Van Westen, in the year of 1997. It has been adopted for assessing the affect of various factors on the occurrence of landslides in terms of weights. It has been based on the following function,
Conditional probability = nslpix / ncpix
Prior probability = nslide / nmap
Information value = log (con_prob. / Pr. Prob.)
Where, nmap = total number of pixels in the map, nslide = total number of landslide pixels, ncpix = number of pixels in each class, nslpix = number of pixels with landslide.

From each thematic data layer weights are calculated by various classes. The resulting thematic data layers has been amalgamated in geographic information system. The contribution of each class of particular thematic data layer has been evaluated and determined by overlaying landslide distribution map over various thematic data layers one by one. The weights calculated using Info Val method for landslide hazard zonation mapping. The weights computed for each class of particular thematic layer indicate the relative importance of that class toward the occurrence of landslides.

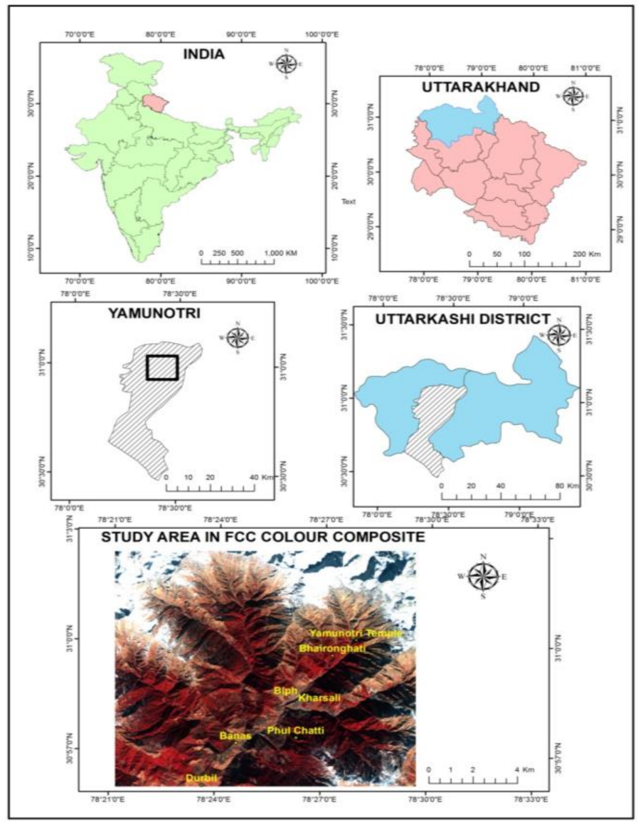

Fig. 1 Location of the study area (Yamunotri Valley)

Positive values indicate strong correlation with landslide and negative values indicate negative correlation with landslide.

5. Concept of Landslide Inventory

The inventories are an elementary form of susceptibility mapping because they emphasize the location and extent of recorded landslides. Landslides inventory maps provide useful information about the potential a future landslide prone area. Landslide assessment by preparing inventory of landslide having multiple scopes (Brabb, 1991). It might be documentation of landslide phenomena, like the extent of areas ranging from small to large and to some extent from regions to states or nations (Cardinali et al., 2001). Many country in the world are using this method, even presently India is using this particular method for rapid recovery in a landslide-affected areas. In this regard, a quick response for post event mitigation, assessment of landslide is essential for proper managerial initiative (Mckean & Roering, 2003). Nowadays, frequency ratio methods are mostly used distribution of landslides location.

6. Concept of Susceptibility Mapping

Landslide susceptibility zonation (LSZ), which can formally be defined as the division of land surface into near homogeneous zones and then ranking these according to the degrees of actual or potential hazard owing to landslides" (Varnes, 1984). Landslide susceptibility mapping is basically an indirect method describes the degree of landslide susceptibility on the basis of multiple factors focusing the occurrence of landslides which is being practiced by various scientists based on a number of factors like geology, slope classes, soil depth or land use etc. Moreover, GIS allow a frequent updating of the susceptibility assessment procedures, which should be an ongoing process (Aleotti & Chowdhury, 1999).

7. Data base and conceptual framework of Methodology

<table>
<tr><th>Satellite Data Sets</th><th>Ancillary's Data Sets Used</th><th>Field Data</th><th>Software Used</th></tr>
<tr><td>LISS IV data (14th Oct 2012),</td><td>Geological Map after Valdiya (1980) and Thakur (1999)</td><td rowspan="4">GPS Points</td><td>ArcGIS 10 (Arc Map & Arc Scene)</td></tr>
<tr><td rowspan="3">LISS IV data (21st July, 2013 & 20th Dec.)</td><td rowspan="3">Topo sheet (SOI)-53 I/8 & 53 J/5</td><td>ERDAS Imagine 2010</td></tr>
<tr><td>PCI Geomatica 2013</td></tr>
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7.1 Data Preparation for Landslide Inventory

It is difficult to arrive at all area to trace each and every landslide in mountainous area like the Himalayas. That's why remote sensing images are generally huge resource of information as they supply, using this imagery to make easily landslide inventory map. Recent studies on visual interpretation of high-resolution optical imagery being used for the identification and mapping of landslides. The high resolution image LISS IV (20-12-2013) multispectral of 5.8m spatial resolution that has taken after five month of landslide event (June 2013) as post event data also used (21th July, 2013). DEM were generated using contour digitize with the help of SOI Toposheets maps NO.53 I/8 & 53 J/5 (see Table 1). Besides the whole area has been affected by channelized debris flow therefore Google earth together with the DEM was extensively used for demarcation of the channelized debris flow. One of a major limitation was the similar tonal appearance exhibiting white to light grey colour of pixels for both the new debris flow, road and to some extend the buildup area in standard colour as well as false colour composition. Due to small areal extent of the study area, the visual interpretation method was adopted eventually contributed better results rather than computer software operated semi-automated or pixel-based change detection. Many of the landslides have also been validated with cross check of field observation (see Plate 1, 2, 3, 4, 5, 6, 7).

7.2 Data Preparation for Susceptibility Mapping

Used for landslide hazard zonation mapping, ten thematic data layers (Slope Map, Slope Aspect, Relative relief Map, Curvature Map, Soil texture, NDVI Map, Geomorphology Map, Lineament buffer Map, Stream buffer Map, Land use/Land cover Map)were prepared individual raster layers. A brief description of the same is given below.

a) SOI Toposheet (40 m contour interval) contour digitize that is used to generate DEM. This was used to derive topographic parameters like slope, slope aspect and relative height and curvature.
b) Geology is very important to define any areas past evidences that are taken from geological map, actually this map were generated from the compile of K.S.Valdiya (1980) & V.C.Thakur (1999).
c) NDVI map were generated from the LISS IV satellite imagery using this formula
d) Normalised Differential Vegetation Index = $\frac{NIR-IR}{NIR+IR}$

   Where,

   NIR means Near Infrared (Band 4)

   IR means Infrared/Red (Band 3)
e) Land use/Land cover was prepared through visual interpretation and digitized over LISS IV image. Since classification map was giving few mix classes, therefore visual interpretation was giving a quite better result for LULC map preparation; Moreover boundary between different geomorphic units was rather distinct in high resolution LISS IV image (multispectral) and easy to separate the different geomorphic units. The result land use/ land cover was further validated with Bhuvan portal using WMS service & LULC map of NRSC (2010).
f) Soil texture classes were generated from NBSS and LUP classification map and visual interpretation of satellite imagery. This final output map Validated with the help of field investigation.

g) Linear features lineament was prepared and updated with the help of digital image processing and from literature (Champati ray et al., 2013). Whereas lineament map was generated by spatial enhancement techniques mainly edge detection directional filters over LISS4 imagery. Moreover hillshed of SOI toposheet generated DEM was also being used to identify the lineaments throughout the investigate area. Subsequently these linear features were rasterized and created buffer zones using eucledian distance tool with distance interval 100 m for lineament. In the same way stream map was generated from topo map and 50 m buffer zones.

h) Geomorphological maps were generated from the visual interpretation of satellite imagery and field investigation. This final output map validated with Bhuvan portal.

On the basis of present studies which have been used input parameter is very important. There are various thematic layers were prepare to perform “Landslide Hazard Zonation Mapping” or “Susceptibility Mapping”. Slope Map, Slope Aspect, Relative relief Map, Curvature Map, Soil texture, NDVI Map, Geomorphology Map, Lineament buffer Map, Stream buffer Map, Land use/ Land cover Mapping and Geological Map were prepared with the help of ArcGIS 10.0 & 10.1, Erdas Imagine 2010, PCI Geomatica 2013 for Upper Yamunotri Valley region. Van Westen (1997) proposed the Landslide hazard zonation mapping using statistical information value method (Info Val) which is represents the prior probability and conditional probability of landslide origin within an area of each and every thematic layer (see Table 2 and Fig. 2).

The formula given below,

$$\mathrm{InW_i} = \mathrm{Inf}\left(\frac{\mathrm{Densclas}}{\mathrm{Densmap}}\right) = \mathrm{Inf}\left(\frac{\frac{\mathrm{Npix(Si)}}{\mathrm{Npix(Ni)}}}{\frac{\sum \mathrm{Npix(Si)}}{\sum \mathrm{Npix(Ni)}}}\right)$$

Where, Wi = the weight given to a certain parameter class (e.g. a slope class, soil types). Denclas = the landslide density within the parameter class. Npix (si) = number of pixel, which contain landslides, in a certain parameter class. Npix(Ni) = total number of pixels in a certain parameter class.

Physical setting of the study area

8.1 Geology of Study Area

This area is chiefly characterized by jointed gneissic rocks of Higher Himalaya (past Main Central Thrust-MCT zone) with main foliation plane plunging in north direction. The rocks of Higher Himalaya consist of mylonitised quartzite, granite gneiss, green schist, metapellite and phyllitic quartzite. This tract of land is made-up of rocks of Central Crystallines (undiscriminated). According to some researchers this region is covered by low grade metamorphics of Higher Himalaya. A main thrust named Vaikrita Thrust in NW-SE direction is in the vicinity of Yamunotri temple.

Table 2 Materials and methodology

SL No	Thematic Layers	Source
Landslide Inventory		
1	Landslide location map	Pre event: LISS IV data (14th Oct 2012),
		Post event: LISS IV data (21st July, 2013 & 20th Dec.)
Susceptibility Mapping		
2	Slope	Generated DEM: Digitized contour from S.O.I Topographical Map No. 53 I/8 & 53 J/5 (40m)
3	Aspect Slope	
4	Relative relief	
5	Curvature	
6	NDVI Map	Generated from LISS IV imagery (20th December, 2013)
7	Geomorphology	Source: Digitized with from Literature & validated with Bhuvan connectivity
8	Land use/Land cover	Digitized on the basis of visual interpretation of LISS IV data
		(Validate with BHUVAN WMS Service & Land use/Land cover Atlas NRSC (2010)
9	Lineament	Digitized from LISS IV data
		(Updated after Champati ray et al.2014)
10	Stream	Digitized from the LISS IV satellite imagery
11	Geology map	Geological map after Valdiya (1980) & Thakur (1999)

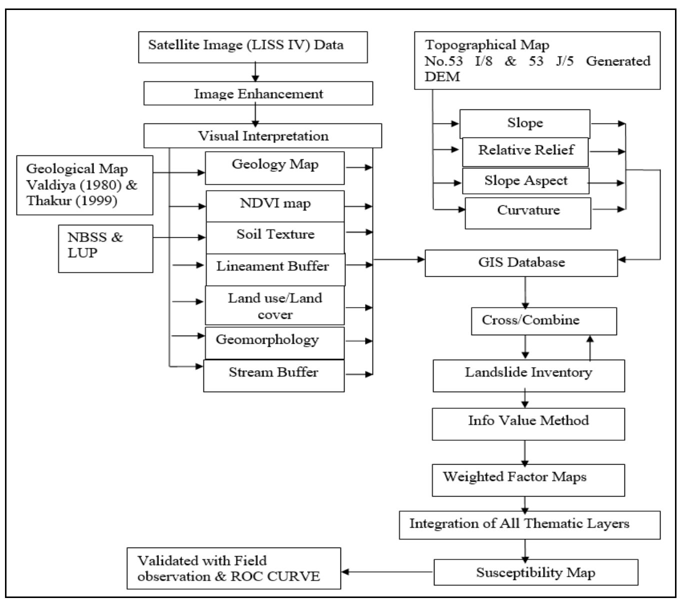

Fig. 2 Computational protocol of overall study.

This area is principally characterized by three sets of joints and major lineaments in north, north east and north-west direction. Yamunotri temple and area around is situated on the junction of two lineaments running from NE and NW. These two lineaments are off shoot of a main north-south lineament. Yamuna River flows along this lineament for about 1.65 km. It first deviates for about 300 m in NW direction and then in takes NE course and plunges in the deep gorge and ultimately takes a north-south course. The deviation occurs because of strike-slip fault alongside the direction of river flow in the gorge near Yamunotri temple (see Fig. 3).

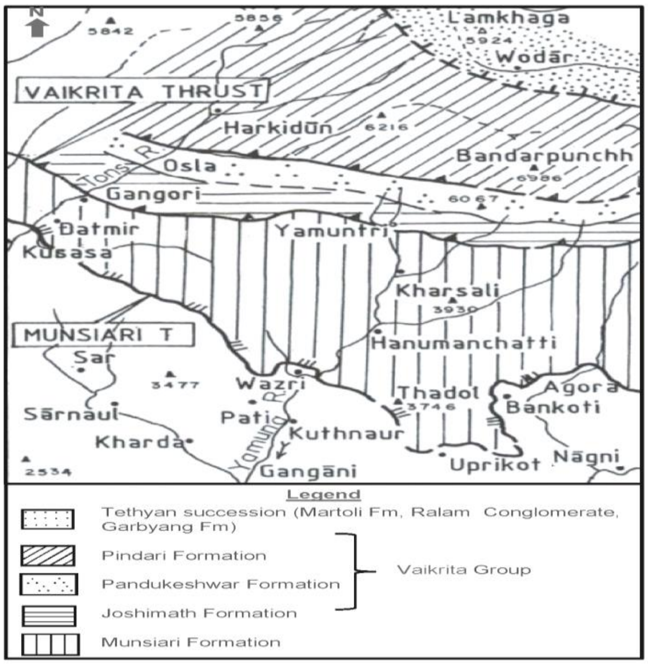

Fig. 0 Schematic Geological map of Yamunotri (after Valdiya, 1980).

8.2 Physiography

The maximum and minimum altitude in the study area is 3200 m and 2000 m from the mean sea level. The water from Yamuna River flows to the whole entire study area. Weathering and erosion process caused diverse rock types that have resulted in relief variation.

8.3 Climate

In summer season - Cool during the day and cold at night Min 6°C & Max 20°C. In winter season temperature variation between 7-5º C that's why Snow-bound areas occurs. Some time temperature very decreases and its near about sub-Zero. The climatic outline caused by adjust in geographic setting may well control landslide activities. Very high precipitation in tropical and sub-tropical climatic regions might be activating landslides, as in the Himalayas. The monsoonal weather significantly influences the study area. The annual precipitation of the study area is about 1098 mm (Koppen and Geiger climate classified).

9. Results and Discussions

9.1 Landslide Inventory

Landslides are identifying with the help of spectral characteristics, size, shape, contrast, and morphological appearance. Mainly landslide is depicted by the contrast that results from the spectral variation connecting the landslide and its surroundings area. High-resolution satellite imagery (LISS IV 5.8-m resolution) & (Google earth Geo-eye data) were used for landslide detection (see Fig. 4). The landslide area were mostly covered of barren area, they showed high reflectance, mostly circular to elliptical in shape landslide to be identify. A few of the landslides mapped were cross-checked in the field investigation and taking GPS points of landslides area. A number of thematic maps on particular factors related to the incidence of landslides, viz. soil texture, slope, aspect, relative relief, lithology, stream buffer, lineament, land use/land cover and NDVI have been generated.

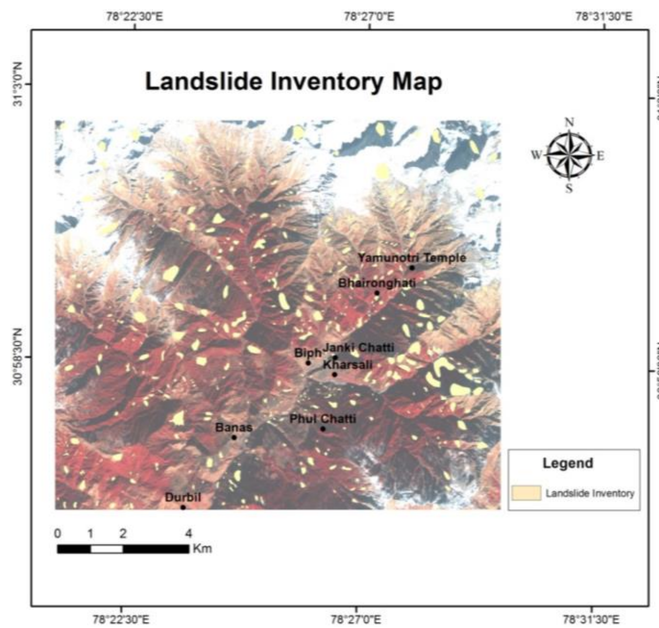

Fig. 4 Landslide Inventory Map showing in LISS IV data (FCC).

9.2 Landslide Susceptibility Zonation

9.2.1 Land Use and Land Cover

Total eight land use/land cover classes (see Fig. 5) are identified in the study area. Most of the evergreen and semi evergreen forest and barren land are occupy in this area. These all class Grassland/Grazing land, Snow and Glaciers, Deciduous, Evergreen/semi-evergreen, cropland, river, barren rocky area, built up area are validated with the BHUVAN

WMS Service & Land use/Land cover Atlas NRSC (2010). The satellite data (LISS IV data) of the study area was classified with supervised classification method using maximum likelihood classifier but result are not satisfied, so digitize all class with the help of visual interpretation of LISS IV data and Geo-eye data from Google earth. The grass land/grazing land covered 38.75 sq.km area, snow and glaciers occupy about 23.70 sq.km area, Deciduous forest covered about 1.06 sq.km, Evergreen/Semi-evergreen are occupy most of the area 71.66 sq.km, cropland occupied of about 7.15 sq.km, Barren rocky area covering 15.94 sq.km and river & built up area occupied accordingly 2.38 & 0.37 sq.km (see Table 3).

Table 3 Land use and Land cover statistics

Id	TYPE	Area (in sq. km.)	Area (in %)
1	Grass land/Grazing Land	38.75	24.07
2	Snow and Glaciers	23.7	14.72
3	Deciduous forest	1.06	0.66
4	Evergreen/Semi-evergreen forest	71.66	44.51
5	Cropland	7.15	4.44
6	River	2.38	1.48
7	Barren Rocky Area	15.94	9.9
8	Built up Area	0.37	0.23

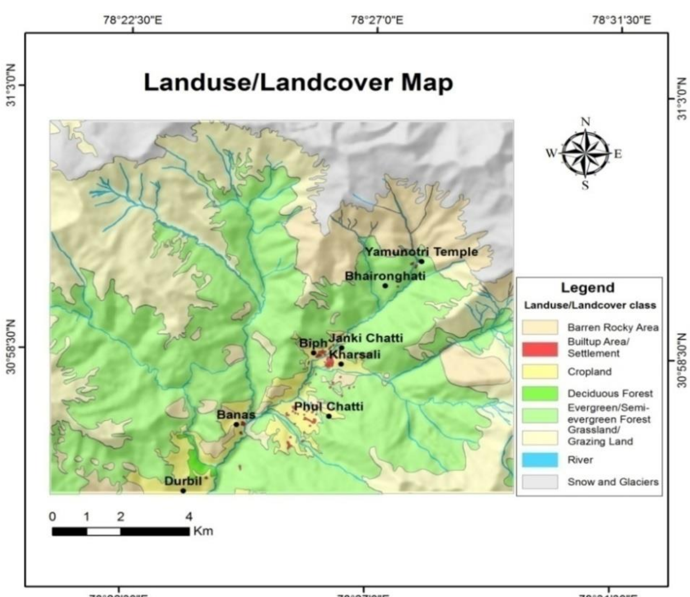

Fig. 0 Thematic Layer of Land use/ Land cover (Source: NRSC Atlas, 2006).

9.2.2 Geomorphology

Geomorphology gives a prediction of any area. This area clearly identifies dissected hills, snow, barren area, River, Piedmont Alluvial Plain, these type of variation indicate to occurring landslide area. Most of the landslide areas are concentrated in vegetation dissected hills and barren dissected hills. Some time landslide areas are investigate both side of river. Rocky area occupies 15.43 sq. km, vegetation dissected hills & barren dissected hills covering more than 118 sq km and rests are occupied others (see Table 4 and Fig. 6).

Table 4 Geomorphology Statistics

Id	Class	Area (in sq. km.)	Area (in %)
1	River	2.35	1.46
2	Snow and Glaciers	24.21	15.04
3	Rocky Area	15.43	9.59
4	Piedmont Alluvial Plain	0.92	0.57
5	Vegetation Dissected Hills	72.87	45.26
6	Barren Dissected Hills	45.21	28.08

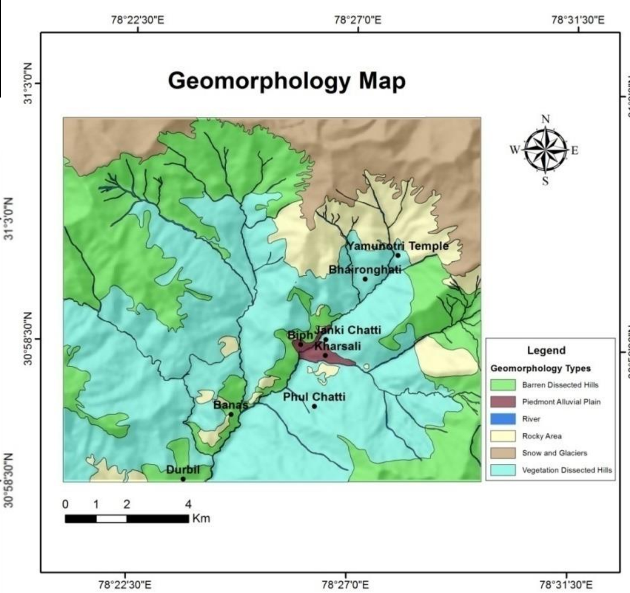

Fig. 6 Thematic layer of Geomorphology Map.

9.2.3 Normalized Difference Vegetation Index (NDVI)

NDVI map has been generated from LISS IV satellite images with spatial resolution 5.8 m. The NDVI value has been calculated by the following formula-

$$NDVI = (IR - R) / (IR + R)$$

Where, IR means Infrared, R means Red.

The NDVI is valuable to delineate vegetation quality. Vegetation cover investigation was done using Normalised Difference Vegetation Index (NDVI) that helps to identify physical cover including vegetation. NDVI is based up on the combination of visible red and near infrared bands and are broadly used to generate vegetation Indices. The values varying in between from –1 to 1, near (+1) indicating healthy vegetation cover and near (-1) indicating unhealthy vegetation. In this analysis it is clearly identified low and high vegetation cover areas. Mainly snow & glacier cover area show the value is low. But low and very low values are occupied major landslide area (see Table 5 and Fig. 7).

Table 0 Normalized Difference Vegetation Index (NDVI) Statistics

Id	Class	Area (in sq. km.)	Area (in %)
1	Very Low	30.11	18.7
2	Low	31.78	19.74
3	Medium	33.07	20.54
4	High	33.25	20.65
5	Very High	32.8	20.37

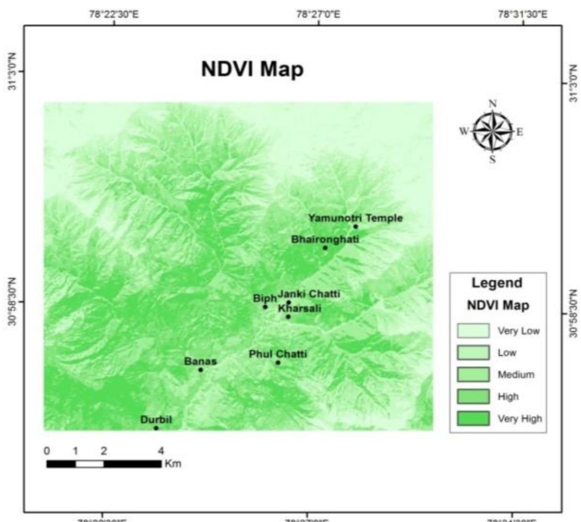

Fig. 7 Thematic Layer of NDVI Map.

9.2.4 Soil Type Map

Soil type is playing a critical role in Landslide. Basically the study area covered in four types of soils. Mostly loamy soil occupies 82.19 % area, Rock outcrop 13.16 %, loamy-skeletal soil 4.49 % and sandy soil only 0.16 % occupied (see Table 6 and Fig. 8).

Table 6 Soil type Statistics

Id	Class	Area (in sq. km.)	Area (in %)
1	Loamy Soil	132.32	82.19
2	Loamy-skeletal Soil	7.22	4.49
3	Sandy Soil	0.26	0.16
4	Rock Outcrop	21.19	13.16

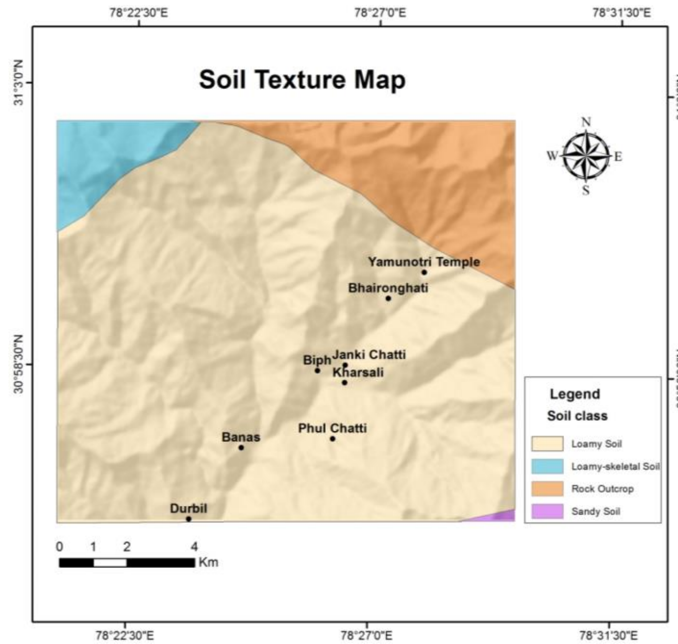

Fig. 8 Thematic Layer of Soil Texture Map (Source: NBSS & LUP Nagpur).

9.2.5 Linear Features (Lineament & Stream)

9.2.5.1 Distance from Lineament

The lineament distance map showing fractures, discontinuities and shear zones from visual interpretation of the LISS IV images. These distance mainly Euclidian distances for each class showing the total 0-400m distance and all distances are equally divided 100m (see Fig. 9, 10). This map was adopted with the help of literature (Champati ray et al. 2013). Lineament map are very important linear features to identify the weak zone of earth surface. These lineament maps are also validated with the help of BHUVAN portal.

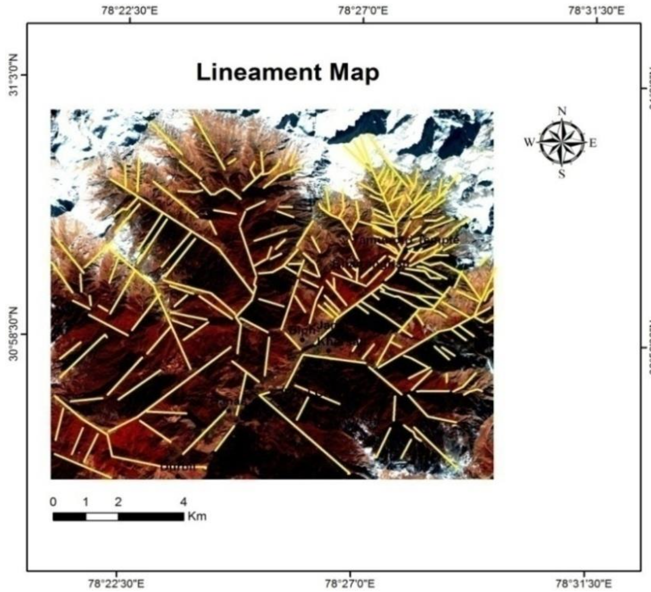

Fig. 9 Digitized Lineament map (Updated after Champati ray et al. 2013).

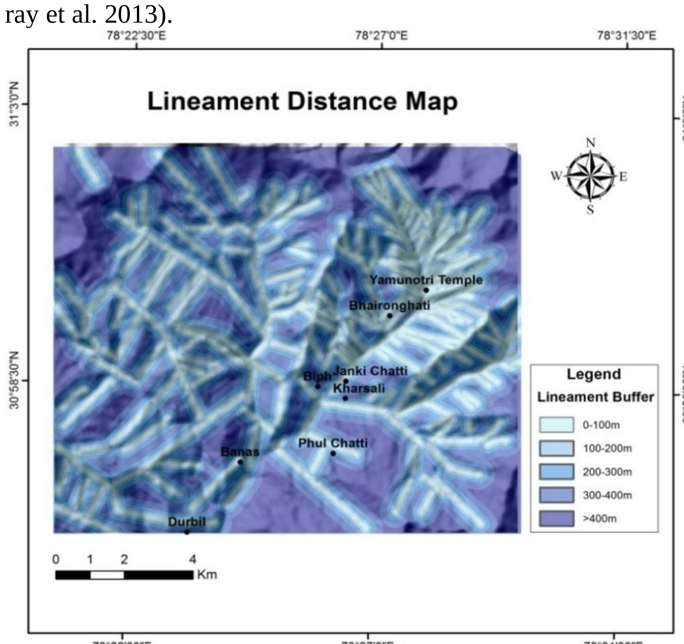

Fig. 10 Thematic Layer of Lineament Distance Map.

9.2.5.2 Distance from River

Streams may harmfully weight steadiness by eroding the slopes or by saturating the lower part of material when resulting increase in water level (Cevik and Topal, 2003; Yalcin, 2005). There are five buffer zones class are to be identified 0-100 m, 100-200 m, 200-300 m, 300-400 m, above 500 m (see Table 7). Five buffer areas (see Fig. 10) were formed within the study area to find out the degree of streams affected the slopes.

Table 7 Distance from River Statistics

Id	Class	Area (in sq. km.)	Area (in %)
1	0-100 m	29.41	18.27
2	100-200 m	32.21	20.01
3	200-300 m	30.48	18.93
4	300-400 m	29.3	18.2
5	Above 400 m	39.6	24.59

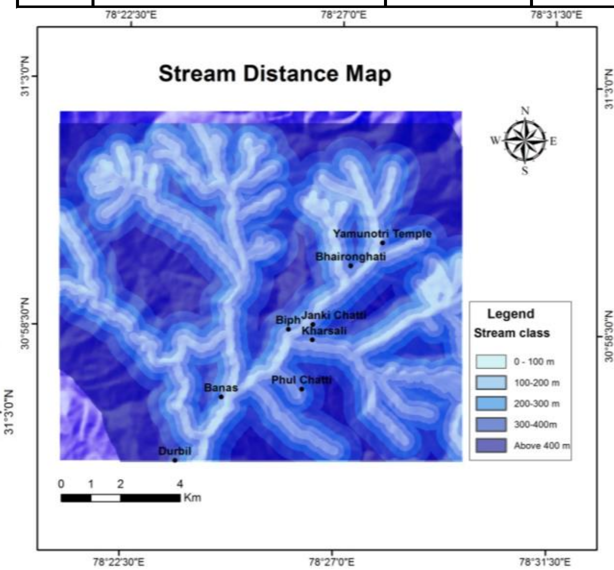

Fig. 10 Thematic Layer of Stream Distance Map.

9.3 DEM Generation and Map Derived

For generation DEM, digitized contour from SOI topographical map. This is the very tedious work to generate DEM. But this DEM very accurate to defined any area. DEM is used for derived various maps slope, aspect, curvature and relative relief (see Fig. 11 & 12).

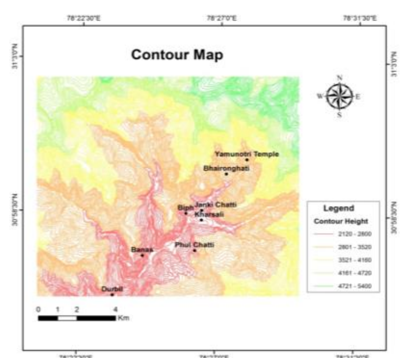

Fig. 11 Contour Map (Digitize from SOI toposheet Map).

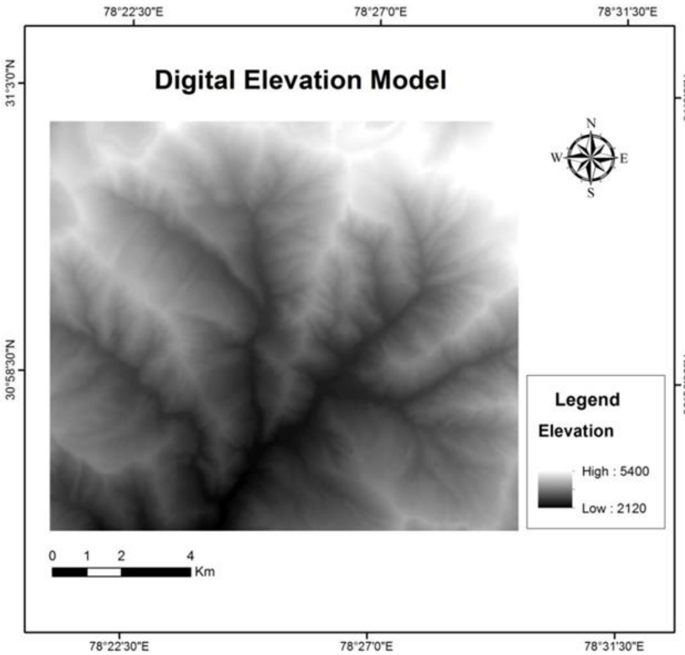

Fig. 12 DEM (Generated from contour Digitize).

9.3.1 Slope Map

The main parameter was the slope stability that depends upon the slope angle (Lee and Min, 2001). It was generally used to prepare landslide susceptibility map. Slope is the compute of surface gradient and measured in degrees. Slope varying in between 0 to 90°, where 0° represents the plane and 90° represents the straight down areas. Slope angle is very commonly used in landslide susceptibility mapping because landslide is directly related to the slope. The massive landslides mostly occur at high slope area.

The slope values in the Yamunotri area range between 0° and above 60°. The slope of the study area was separated into five slope class (see Table 8 & Fig. 13). The hilly/high slope indicates that most chances of the landslides. 80% Landslide occur on slope having 15 º-60 º angles. The slope map of the study area was generated from digitization of contours and Digital elevation model, as explained in the material and methodology part. Slope is an important layer for landslide hazard zonation mapping.

Table 8 Slope statistics

Id	Class	Area (in sq. km.)	Area (in %)
1	0-15 Degree	30.83	19.15
2	15-30 Degree	32.76	20.35
3	30-45 Degree	33.03	20.52
4	45-60 Degree	32.14	19.96
5	Above 60 Degree	32.24	20.03

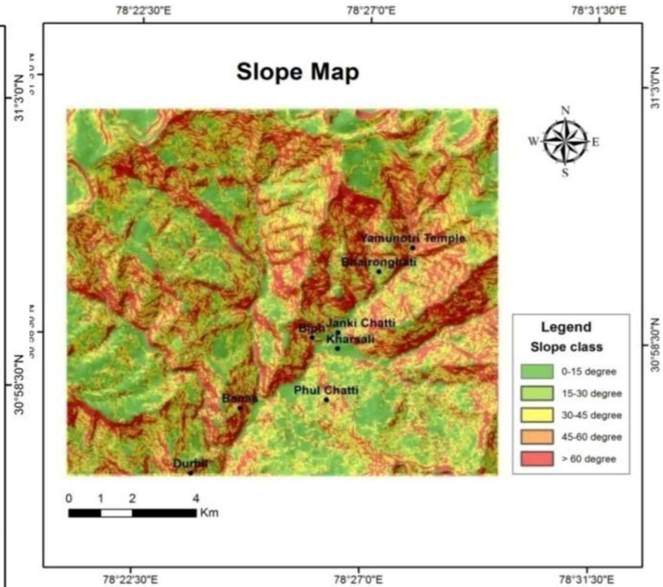

Fig. 13 Thematic Layer of Slope Map.

9.3.2 Aspect Map

Aspect is also considered as the important factors to prepare landslide susceptibility map. Aspect related parameters such as coverage to sunlight, winds (dry or wet), rainfall (degree of saturation), soil moisture and discontinuities may control the occurrence of landslides. The aspect map of the study area was generated from the DEM. This aspect map is showing the relationship between aspect and landslide. Aspects are divided in 9 types (see Table 9 & Fig. 14) these are Flat (-1º), North (1-22.5º& 337.5360º), North-East (22.5º-67.5º), East (67.5º-112.5º), South-East (112.5º-157.5º), South (157.5º-202.5º) and South-West (202.5-247.5).

Table 9 Aspect Statistics

Id	Class	Area (in sq. km.)	Area (in %)
1	Flat	18	11.18
2	North	18	11.18
3	N-E	18	11.18
4	East	18	11.18
5	S-E	18	11.18
6	South	18	11.18
7	S-W	17	10.56
8	West	18	11.18
9	N-W	18	11.18

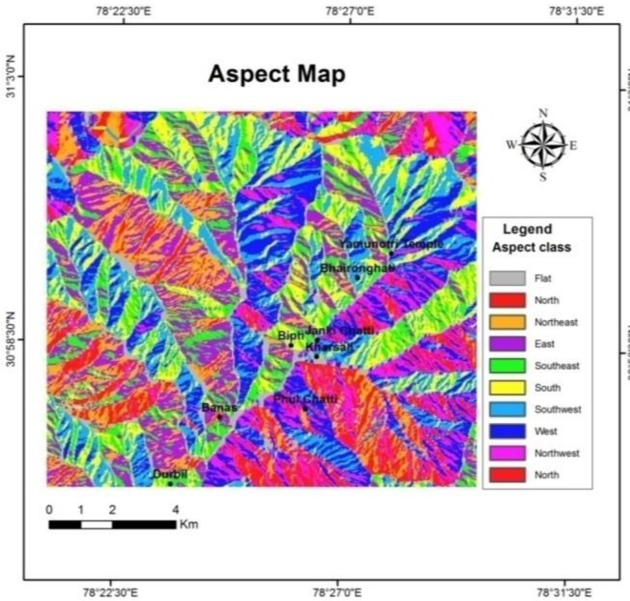

Fig. 14 Thematic Layer of Aspect Map.

9.3.3 Curvature Map

The curvature is a technique to measure morphological characteristics of the topography. The surface is convexity of any area implying a positive curvature and when the surface is upwardly concavity the curvature indicates negatively. The positive and negative values of curvature are more chances to occur in landslide area.

Table 10 Curvature Statistics

Id	Class	Area (in sq. km.)	Area (in %)
1	Concave	49.74	30.89
2	Plain	52.24	32.45
3	Convex	59.02	36.66

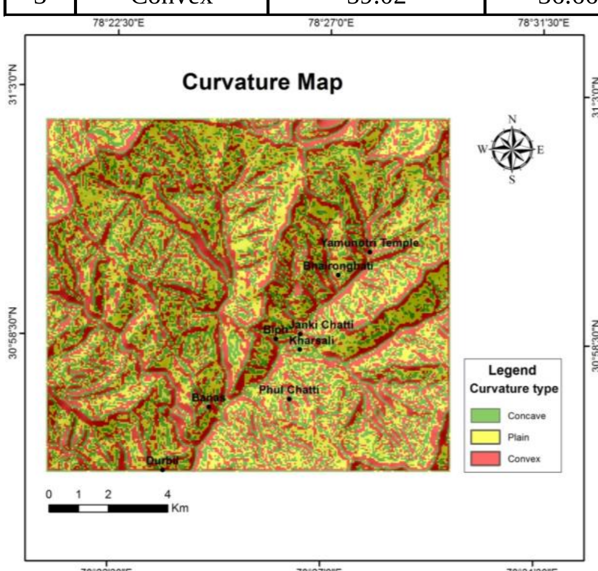

Fig. 15 Thematic Layer of Curvature Map.

9.3.4 Relative Relief Map

Relative relief plays an important role for susceptibility mapping. Relative relief is the range value between maximum height and minimum height. The maximum height of the study area varies in 5400 m and minimum height in 2120 m. In the study area relative class are divided into four classes 200-400m, 400-600 m, 600-800 m and above 800 m. After preparation of the relative relief it was sound that above 800 m relative relief area are less landslide prone area and others are more landslide.

Table 11 Relative relief Statistics

Id	Class	Area (in sq. km.)	Area (in %)
1	200-400m	42.53	26.42
2	400-600m	41.85	25.99
3	600-800m	39.95	24.82
4	Above 800m	36.66	22.77

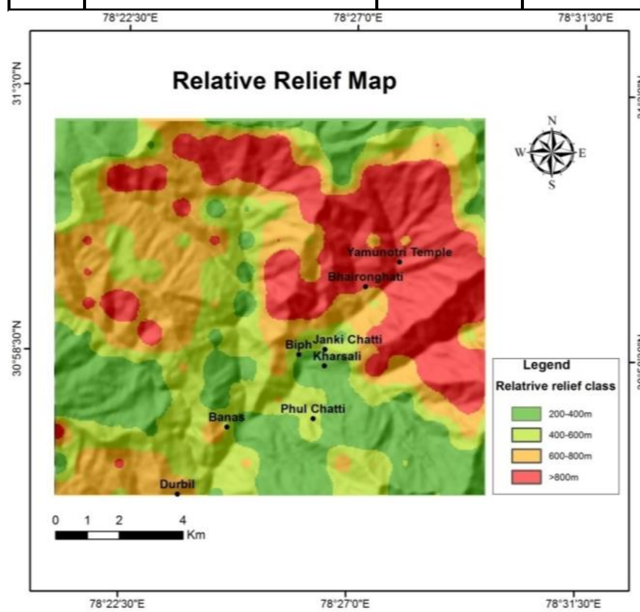

Fig. 16 Thematic Layer of Relative Relief Map.

9.4 Integration of All Thematic Layers for Landslide Hazard Zonation Mapping and validated with ROC curve

Landslide susceptibility map represents which areas landslides occur in future that contribute to landslides with the earlier period distribution of slope failures (Brabb, 1984). These maps are fundamental equipment for land-use forecast, particularly in hilly areas. Landslide Hazard Zonation map is mostly depends on the amount and excellence of available data. Eleven thematic layers were considered controlling factors in the occurrence of landslides in the Yamunotri valley (study area). At last integrate all thematic layers for susceptibility map or landslide hazard zonation map (see Fig. 17 & Table 12). The total number of pixel was 6454006 and the number of landslide pixel was 292337. The score of each class type was assigned from the relationship between a landslide and each factor shown in table no 13. In the information value it is clearly indicated the positive value mean the strongly correlation with landslide. Most of correlations (see Table 13) are showing in red colour. Among this class high correlation class are Aspect East (0.07633), Geomorphology Rocky area (0.27933), Lineament Buffer above 150 m (-0.2442), Geology- Granite-Granodiorite & Augen Gneiss (0.05473), Land use/Land cover- Barren rocky area (0.34744), NDVI High & Low (0.16378 & 0.02504), Relative relief above 800m (0.17706), Slope above 60degree (0.05548), Soil type Loamy soil (0.01591). Receiver-operating characteristic (ROC) plots can be used for this purpose validating the relationships of landslide and susceptible areas (Zweig and Campbell, 1993). This curve is actually showing the relationship between cumulative percentage of landslide area and cumulative percentage of susceptible area. The relationships of both parameters are highly positive (see Fig. 18).

Table 12 Landslide Susceptibility class Statistics.

Id	Landslide Susceptibility class	Area (in sq. km.)	Area (in %)
1	Very Low	28.92	17.96
2	Low	31.95	19.84
3	Medium	32.85	20.4
4	High	35.76	22.21
5	Very High	31.52	19.58

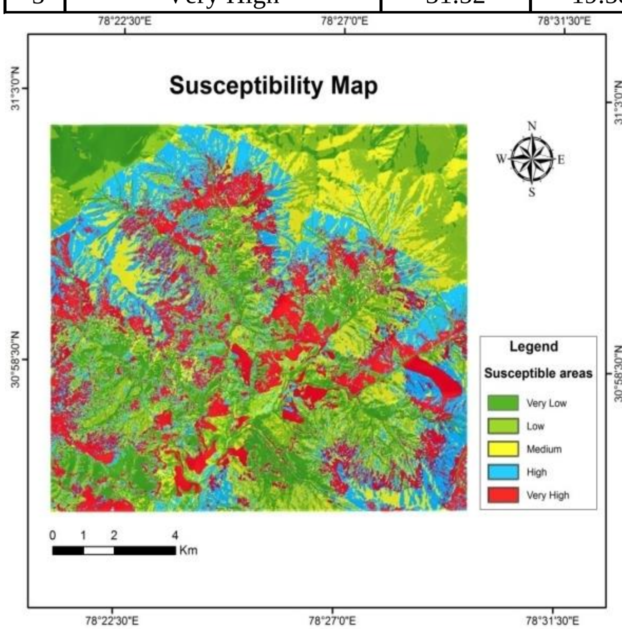

Fig. 17 Susceptibility/Landslide Hazard Zonation Map.

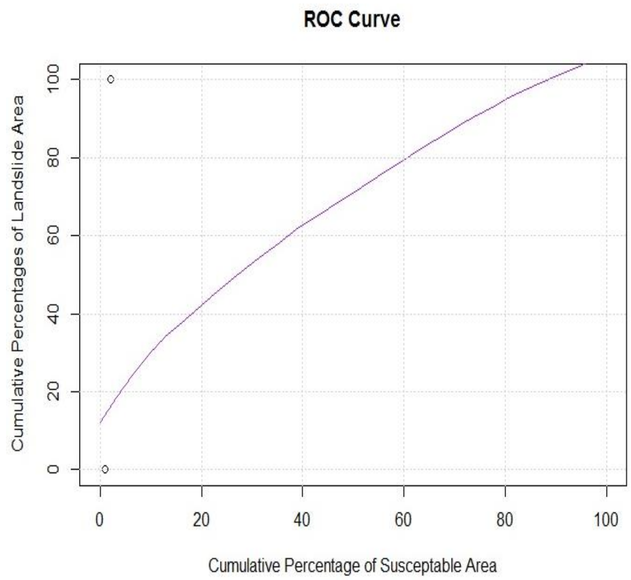

Fig. 18 ROC showing cumulative percentage of landslide pixel and susceptibility class pixel.

9.5 Conclusion and Recommendation

The Upper Yamunotri region is a naturally a hazardous prone zone, every year people suffer from mostly landslide disasters. It is very difficult to predict landslide like other natural hazards such as flood, earthquake and avalanche is difficult to predict. Landslide inventory map are created with the help of pre and post disaster imagery of LISS IV satellite data and SOI toposheet map are digitize for DEM generation. The relationship of landslide map and DEM driven parameters are highly correlated. It is recommended require for further study using satellite data. It was easy for study in summer session, in rainy season and winter season was very tuff for field visit.

Eleven thematic layers are created for landslide hazard zonation mapping which are the most powerful parameters for landslide. These are Slope, Aspect, Relative relief, Curvature, Land use/land cover, Geology, Stream buffer, Lineament, geomorphology, soil type, NDVI Map. For susceptibility mapping information values are calculate from all maps and finally integrated. The final results are validated with ROC curve and field investigation. To implement a development project in the terrain the landslide susceptibility maps help in decision making. Every year landslides cause massive loss of human life and property in hilly areas. Landslide susceptibility zonation map can be useful in identifying which area is more and less susceptible for disaster. The local authorities can make use of this landslide hazard zonation map for disaster preparedness and implement mitigation techniques.

Plate 1 Debris Flow run out (Near Phul chatti).

Plate 2 Landslide Initiation zone (Near Phul chatty).

Plate 3 Landslide Accumulation Zone (Near Phul)**chatti)**

Plate 4 Rock Fall (Near Yamunotri Temple)

Plate 5 Road disrupted by slide (Main Road connecting Dehradun and Yamunotri)

Plate 6 Landslide scar (Janki chatty)

Plate 7 Retaining wall to arrest further slide Movement (Near Yamunotri Temple Path)

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Appendices

Table 13 Statistical Information Value (Inf) calculated for Landslide Hazard Zonation Mapping of each selected thematic layer (Red colour showing highly correlated with landslide).

			LANDUSE/ LANDCOVER				
ID	CLASS	NCPIX	NSLPIX	CON_PROB	PRIOR_PROB	CP/PP	INF
1	GRASSLAND/GRAZING LAND	1550030	61630	0.039761	0.045566	0.87259	-0.05919
2	SNOW AND GLACIERS	947816	34077	0.035953	0.045566	0.78904	-0.10290
3	DECIDUOUS	17920	316	0.017634	0.045566	0.38700	-0.41229
4	EVERGREEN/SEMI-EVERGREEN	2866213	122914	0.042884	0.045566	0.94114	-0.02635
5	CROPLAND	285981	5559	0.019438	0.045566	0.42660	-0.36998
6	RIVER	95353	28	0.000294	0.045566	0.00644	-2.19082
7	BARREN ROCKY AREA	637654	64664	0.101409	0.045566	2.22555	0.34744
8	BUILTUP AREA	14716	436	0.029628	0.045566	0.65021	-0.18694
			NDVI				
ID	CLASS	NCPIX	NSLPIX	CON_PROB	PRIOR_PROB	CP/PP	INF
1	VERY LOW	1244319	54338	0.043669	0.045083	0.96864	-0.01384
2	LOW	1275660	60924	0.047759	0.045083	1.05936	0.02504
3	MEDIUM	1322673	57181	0.043231	0.045083	0.95893	-0.01821
4	HIGH	1329968	87424	0.065734	0.045083	1.45807	0.16378
5	VERY HIGH	1311836	32470	0.024752	0.045083	0.54903	-0.26041
			RELATIVE RELIEF				
ID	CLASS	NCPIX	NSLPIX	CON_PROB	PRIOR_PROB	CP/PP	INF
1	200-400M	1541381	40920	0.026548	0.046811	0.56712	-0.24633
2	400-600M	1593897	66479	0.041708	0.046811	0.89099	-0.05013
3	600-800M	1563125	71700	0.04587	0.046811	0.97988	-0.00883
4	ABOVE 800M	1546598	108839	0.070373	0.046811	1.50334	0.17706
			SLOPE				
ID	CLASS	NCPIX	NSLPIX	CON_PROB	PRIOR_PROB	CP/PP	INF
1	0-15 DEGREE	1233009	40665	0.03298	0.045227	0.72921	-0.13715
2	15-30 DEGREE	1310403	57688	0.044023	0.045227	0.97338	-0.01172
3	30-45 DEGREE	1321364	67172	0.050835	0.045227	1.12400	0.05077
4	45-60 DEGREE	1309331	60538	0.046236	0.045227	1.02230	0.00958
5	ABOVE 60 DEGREE	1289636	66274	0.05139	0.045227	1.13626	0.05548
			SOIL TYPE				
ID	CLASS	NCPIX	NSLPIX	CON_PROB	PRIOR_PROB	CP/PP	INF
1	LOAMY SOIL	5302553	249312	0.047017	0.045326	1.03732	0.01591
2	LOAMY-SKELETAL SOIL	288948	8329	0.028825	0.045326	0.63596	-0.19657
3	SANDY SOIL	10458	0	0	0.045326	0	0
4	ROCK OUTCROP	847715	34696	0.040929	0.045326	0.90299	-0.04432
			ASPECT				
ID	CLASS	NCPIX	NSLPIX	CON_PROB	PRIOR_PROB	CP/PP	INF
1	FLAT	716886	24906	0.034742	0.045227	0.76816	-0.11455
2	NORTH	711949	24224	0.034025	0.045227	0.75231	-0.12360
3	N-E	727076	35087	0.048258	0.045227	1.06701	0.02817
4	EAST	727871	39245	0.053918	0.045227	1.19215	0.07633
5	S-E	722415	37994	0.052593	0.045227	1.16286	0.06553
6	SOUTH	717446	34665	0.048317	0.045227	1.06832	0.02870
7	S-W	699262	26460	0.037840	0.045227	0.83666	-0.07745
8	WEST	728966	36755	0.050421	0.045227	1.11483	0.04721
9	N-W	711872	33001	0.046358	0.045227	1.02500	0.01073
			GEOMORPHOLOGY				
ID	CLASS	NCPIX	NSLPIX	CON_PROB	PRIOR_PROB	CP/PP	INF
1	RIVER	94114	38	0.000404	0.045278	0.00892	-2.04976
2	SNOW AND GLACIERS	968523	34247	0.035360	0.045278	0.78096	-0.10737
3	ROCKY AREA	617345	53179	0.086141	0.045278	1.90251	0.27933
4	PIODMONT ALLUVIAL PLAIN	36749	240.00	0.006531	0.045278	0.14424	-0.84092
5	VEGETATION DISSECTED HILLS	2931375	136794	0.046665	0.045278	1.03065	0.01311
6	BARREN DISSECTED HILLS	1808420	67836	0.037511	0.045278	0.82847	-0.08172
			LINEAMENT BUFFER				
ID	CLASS	NCPIX	NSLPIX	CON_PROB	PRIOR_PROB	CP/PP	INF
1	0-50 M	779412	38035	0.048800	0.091594	0.53278	-0.27345
2	50-100 M	832629	43873	0.052692	0.091594	0.57528	-0.24012
3	100-150 M	798844	41908	0.052461	0.091594	0.57275	-0.24203
4	ABOVE 150 M	780767	40756	0.052200	0.091594	0.56990	-0.24420
			GEOLOGY MAP				
ID	CLASS	NCPIX	NSLPIX	CON_PROB	PRIOR_PROB	CP/PP	INF
1	GRANITE-GRANODIORITE & AUGEN GNEISS	1515181	77848	0.051379	0.045295	1.13430	0.05473
2	NAGTHAL-BERINAG FMS	649869	25907	0.039865	0.045295	0.88011	-0.05546
3	NATHUAKHAN BETALGHAT M. BHATWARI & BARKOT UNITS	1706852	84860	0.049717	0.045295	1.09762	0.04045
4	JUTOGH ALMORA	2582104	103721	0.040169	0.045295	0.88683	-0.05216