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RESEARCH ARTICLE

# LANDSLIDE HAZARD ZONATION OF DISTRICT RUDRAPRAYAG OF GARHWAL HIMALAYA

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**ABSTRACT**

The degree of hazard due to landslide in any region is difficult to assess manually. Landslides are considered as one of the most destructive geological processes causing not only the enormous damage to roads, bridges, houses but even cause loss of life. Though, landslide hazards cannot be completely prevented but their intensity and severity can be minimized by taking effective mitigation measures and by planning for disaster preparedness. For this purpose, landslide hazard zonation maps are prepared. The landslide hazard zonation is the spatial prediction of landslide potential areas and they are useful for planning and implementation of various developmental schemes in hilly areas. The main aim of this study is to prepare the landslide hazard zonation of Rudraprayag District. The Landslide hazard evaluation factor(LHEF) rating scheme have been used to prepare landslide hazard zonation (LHZ) of this region. LHEF Rating scheme is an empirical approach, which demarcates hill-slopes into zones of varying degree of stability on the basis of their relative hazards. The inherent and external causative factors responsible for slope instability has been taken input parameters and then integrated in GIS environment to arrive at landslide zonation map of the area. The landslide hazard zonation map classifies the area into four classes of landslide susceptible zones i.e., very high, high, moderate and low hazards.



## INTRODUCTION

Landslides are among the major hydro-geological hazards that affect large parts of the country. Most of the Himalayan region is bristling with landslides of bewildering variety. Uttarakhand region, because of its continued evolution, fragile geological formation and structures, is highly prone to mass movement causing landslides. Since landslides are mostly triggered by events of heavy rainfall and seismicity, which could be followed by flood in the plains, the local populace fills the impact of this location caused by landslides. Landslide can be considered as one of the most destructive geological processes causing not only the enormous damage to roads, bridges, houses but even cause loss of life. Though, landslide hazards cannot be completely prevented but their intensity and severity can be minimized by taking effective mitigation measures and by planning for disaster preparedness. For this purpose, landslide hazard zonation maps are prepared. The landslide hazard zonation of an area aims at identifying the landslide potential zones and ranking them in order of the degree of hazard from landslides. In other words, it is the spatial prediction of landslide potential areas and they are useful for planning and implementation of various developmental schemes in hilly areas. Roads, building constructions, planning design and execution of developmental schemes, may not incorporate adequate details of geological and geotechnical considerations due to finance and time but detailed geological report even at the cost of increase in expenditure is highly desirable. These reports will adequately deal with hazard possibilities within the region. This also demonstrates the necessity of preparing landslide hazard zonation maps, based on various mountain conditions and using them as the basis for planning future development schemes. A landslide hazard zonation (LHZ) map classifies the land surface zones in to zones of varying degree of hazards probability based on the estimated significance of causative factors which influence the stability (Anbalagan 1992).

A landslide hazard zonation map divide the slope surface in to zones of varying degrees of stability based on an estimated significance of causative factors including instability. The Landslide hazard zoantion map is a rapid technique of hazard assessment of the land surface (Gupta and Anbalagan, 1995). The Rudraprayag district has been chosen for the Landslide hazard mapping. The study area is situated between latitude 30°19'00" and 30°49' North and longitude 78°49' and 79°21'13" East and occupies an area of 2439 sq. km. The study area is situated in the north western part of the Garhwal Himalaya. The district is bounded by Uttarkashi in the north, Chamoli in the east, Tehri Garhwal in the west and Pauri Garhwal on the south. The area falls under the central Himalayan zone of Garhwal, consisting of low to medium grade crystalline with intrusive of acidic and basic rocks. This area is traversed by two major thrusts, namely Main Central Thrust (MCT-II) which passes below Kund, and the Vaikriti Thrust (MCT-I)

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which passes above the area north of Gaurikund. This area is tectonically and seismologically a very sensitive domain. The strong tectonized rocks and the fragile mountain slope of the MCT zone in this area are vulnerable to rain, earthquakes, vibrations due to movement of heavy vehicles, excavation work, etc. A large number of catastrophic landslides reported from this area, indicate of the presence of a number of fractured zones. Landslides are frequently occurred in this region and damages life, land and property. Naturally the inhabitants in general look towards the geo-scientists for help and it becomes the prime duty of the later to study the nature and causes of landslides and give suggestions and remedial measures for this great environmental hazard. Keeping this point in view a study of landslides has been undertaken for Rudraprayag district of Garhwal Himalayan region.

**Review of The Previous Work On Landslide Hazard Zonation**

A number of workers have attempted landslide hazard zonation by using Remote Sensing and GIS techniques. Ali Yalcin and Fikri Bulut 2007; Lulseged Ayalew *et al.,* 2005, Carrara *et al.,* 1992; Mantovani *et al.,* 1996; Varnes 1984; Van Westen *et.al*. 1996; Crozier 1986 etc. attempted to review the underpinning issues, concepts, objectives and methodology for ultimately reducing hazard and risk arising from landslides. In Indian context many workers like Pachauri and Pant 1992; Gupta and Joshi 1990; Anbalagan 1992, Anbalagan and Singh 1996; Saha *et al*., 2002, etc. have carried out the studies of landslides in different regions of the country. Takei (1982) described methods for making debris flow hazard map taking in to account the type of rock, fracturing, weathering characteristics, springs, vegetation cover and valley slopes etc. while in the same year Badrinarayan and Seshagiri (1982) have carried out the zonation of Nilgiri areas considering slope, landuse, soil cover and drainage using numerical rating of these factors depending on frequency of landslide present. Hansen (1984) discussed two principal categories of landslide hazard mapping namely direct and indirect mapping. Brabb (1984) provided a useful review of development of landslide hazard mapping. Wagner *et al.* (1987) discussed preparation of rock and debris slide risk maps for road alignment purposes, using geological structural slope and geomorphological factors. Inspection of the literature reveals that a few reviews of the concepts, principles, techniques and methodologies for landslide hazard evaluation have been proposed (Cotecchia,1978.,Crozier,1984,Varnes, 1984, Crozier, 1986. Einstein, 1988, Van Westen, 1994). Likewise, only few attempts have been made to define, conceptually or operationally, landslide risk (Yong *et al.*, 1977; Ahlberg *et al.*1988., Fell, 1994). The majority of papers discuss specific attempts at the evaluation of landslide hazard in limited areas.

## METHODOLOGY

The present study deals with landslide hazards which are occurring frequently and effecting severely in the study area. The methodology is based on the guidelines of the LHZ mapping (Anbalagan, 1992 and Bureau of Indian standard, BIS 1998). LHZ map of the present study area has been prepared on the basis of varying degree on the estimated significance of the causative factors of instability like lithology, structure, slope morphometry, relative relief, land use and land cover and hydrogeological condition and seismicity and rainfall. GIS software like ARC-GIS 9.2, and ERDAS Imagine 9.1 was used for integrating different thematic maps and assigning their combined effect. These thematic maps were quantified by giving them a relative score.

**Preparation of Thematic/Base Maps**

The thematic/base maps of the study area were prepared using the Survey of India Toposheets (SOI) 53N/1, 53N/2, 53N/3, 53N/4, 53N/6, 53J/14, 53J/15 and 53J/16 on 1: 50,000 scale, Landsat Imageries (IRS-1C, LISS III with 23.5m spatial resolution of October 21, 2007) and available geological maps followed by detailed field survey. The base maps are used as a reference map for field survey, identification of landuse/ landcover patterns, active and old landslides, anthropogenic activities and other related analysis.

**Preparation of Facet Map**

Facet is a polygonal area of mountainous terrain which has more or less similar characters of slope, showing consistent slope direction and inclination. The slope facets are generally delimited by ridges breaks in slope, streams, spurs, gullies and rivers etc. The facet maps form the basis for the preparation of thematic maps in general and LHZ mapping in particular and individual facet is the smallest mappable unit. In all 610 facets including sub facets have been delineated from the study area on the basis of visual interpretation of topographic maps (Fig.2).

**Lithology**

The lithology is an important factor in controlling the stability of the slopes, and hence the maximum rating of 2 given. The lithology or rock type controls the nature of weathering and erosion and this point is taken care of while awarding the ratings. In this parameter, rocks are broadly classified into three categories. Type-I rocks consist of crystall9ine rocks (Igneous and metamorphic) along with massive calcareous rocks. These types of rocks suffer less erosion resulting in steep slopes. Type-II rocks mainly comprised of well and poorly cemented terrigenous sedimentary rocks. Type-III category consists of soft argillaceous rocks, their low grade metamorphic equivalents and well foliated gneissic rocks. Soft rocks like claystone, siltstone, mudstone, schist, phyllite and other such rocks erode much faster and easily and are easily weathered close to surface. Moreover, schist and phyllite have foliation plane along which sliding takes place. Same is the case with gneissic rocks with thick foliated bands. In Landslide Hazard Evaluation Factor (LHEF) rating scheme, weathering of fresh rocks is also included as a correction factor which is to be multiplied to the rating of respective fresh rocks, for Type-I and II. Type-III rocks usually have an inbuilt higher rating, for which there is as such no requirement to multiply with the correction factor. But depending on condition of weathering the rating can be suitably modified to represent the field condition. The maximum value of for Type-III can be increased to 2 as the worst possible condition. The ratings for different rock types are tabulated in Table 1. The geological map of the study area is shown in Figure 3.

**Structure**

Structure includes discontinuities in rocks such as beddings, joints, faults, thrusts, shear zones and unconformities. Degree of fracturing and shearing, attitude of bedding or jointing in relation to slope, and nearness to thrust zones are the important criteria in determining the slope stability. The faults, fractures and joints not only tend to destabilize the area through deterioration of the strength of the rocks, but also accelerate the weathering process. The probability of landslides is higher close to the faults. The major structural features observed in and around the study area are Vakrita thrust (MCT-I), Main Central Thrust (MCT-II), Ramgara Thrust and number of minor faults and folds (Fig.3). In addition to faults, a number of joint sets are also observed. These all discontinuity features are responsible for instability of the area. By analyzing various discontinuities, the joints which are most unfavorable are selected for rating the facet under consideration. The orientation data of selected joints, bedding and slope are plotted in the stereo plot and interpreted to know their effects on stability, then the ratings are awarded (Table 2, figure 3) according to following considerations.

**Slope**

In slope map, the terrain is divided into small facets of varying slope angles. The entire facets are to be marked with the direction as well. They define slope categories on the basis of frequency of occurrence of a particular angle of slope. The slope morphometry maps are prepared by dividing the larger topographical map in to smaller units within which the contour lines has the same standard spacing, that is, the same number of contour lines per km of horizontal distance. Slope facet map of the study area has been prepared by dividing the area into facets and has been used to categorize the area in to six types viz. escarpment/ cliff (>55º), very steep slope (45º-55º), steep slope (35º-45º), moderately steep slope (25º-35º), gentle slope (15º-25º) and very gentle slope (≤15º), (Fig. 4). It has been widely shown that landslides tend to occur more frequently on steeper slopes (McDermid and Franklin, 1995; Cooke and Doornkamp, 1990). Places where the slope angle is near to 0 are considered to be safer in terms of failure initiation. Slope failure tends to increase with slope angle but when the slope becomes near vertical, landsliding is scarce or absent altogether. The reason is the lack of soil development and debris accumulation in such topographic conditions (Selby, 1993). A long slope may include sections that can be affected by large movements originating further up the hillslope. The activity of slopes over different bedrocks depends on the rock characters and on the rate at which the material is denuded. The less resistance rocks have been rise to depressions, whereas the spurs, ridges, crest and projections are found on more resistant rocks like quartzites. Frequent mass wasting and tectonic disturbance cause the development of steep to very steep slope and also indicate the rejuvenation of the area. Considering the above conditions, individual facets are awarded accordingly (Table 3).

**RELATIVE RELIEF**

Relative relief represents the maximum height of a facet, from bottom (valley floor) to top (ridge/spur) along slope direction. Relief of a facet can simply be calculated by counting the difference between the elevations at bottom most point of a facet to the top most point of the same, along slope direction. For meso-zonation purpose, five classes of relief are considered (fig.5). Maximum rating under this parameter is 1.0. The classes and the respective ratings are given in table 4.

**Land Use and Land Cover**

Land use and land cover pattern is one of the important parameters governing slope stability. Vegetation has major role to resist slope movements, particularly for failures with shallow rupture surfaces. A well spreaded net work of root system increases the shearing resistance of the slope material due to natural anchoring of slope materials, particularly for soil slopes. Moreover, a thick vegetation or grass cover reduces the action of weathering and erosion, hence adds to stability of the slopes. On the other hand, barren or sparsely vegetated slopes are usually exposed to weathering and erosion action, thus rendering it vulnerable to failure. Agricultural activity is generally practiced in very gentle and gentle slopes, for higher slope angle, usually it is carried out when the slopes are made flat by making terraces. These slopes, apart from receiving natural precipitation, also get recharged by additional water for agriculture purpose. Because of the fact that even after many years of such practice they remain stable, it is quite logical to consider them as safe from landslide point of view. Similarly a populated land on a very gentle slope (<15) under normal circumstances is least expected to suffer from slope instability. Slope instability is also induced because of anthropogenic activities, i.e. urbanization, particularly on higher slope angles (>$30^0$). It not only removes vegetation cover but also adds to the natural weight of the slope as surcharge due to weight of civil structures. In a hill slope with higher slope angle, buildings are usually located by constructing local cut slopes and flat terraces. With this concept urbanization is broadly classified into three categories. A sparsely urbanization slope is where construction terraces are located far apart (more than 15m of horizontal spacing) providing a considerable distance between two terraces along the slope. a moderately urbanized slope is characterized by comparatively closer location of construction terraces but leaving an optimal horizontal spacing of 5-15m between individual terraces. In a heavily urbanized slope construction terraces are located very close to each other (≤5m horizontal spacing) in such a way that successive terraces almost touch each other at places. With increasing urbanization, water due to domestic usage may be released on the slope surface wherever the drainage measure is inadequate. This water may get added up to the subsurface water and may develop pore water pressure, leading to slope instability. Similarly barren land, affected by anthropogenic activities is also most vulnerable to landslides. All these factors are taken suitable account while awarding the rating (table 5, figure 6). The maximum rating for this parameter is 2.0.

**DRAINAGE DENSITY**

Drainage density is the ratio of the total length of streams to the area of the drainage basin, higher the drainage density, the lower the infiltration and the faster the movement of the surface flow. Most infiltration takes place close to the streams on slopes that have a high permeability such as alluvium. To prepare the map of drainage density of the study area, first, second and third order streams of the drainage network were taken into account (figure 8). The study area was split into seven drainage basins using ARC GIS 9.2. On the basis of values of drainage density, the entire area has been divided into five categories, viz. with very high (>4), high (3-4), moderate (2-3), low (1-2) and very low (<1) values of drainage density (fig.7). The drainage density is closely related to landslide occurrences, since a higher drainage density indicates a more rapid erosion and removal of rock debris. However continued accumulation of such debris makes the drainage density values moderate (Prasad and Verma, 1975). The places where the drainage density is high, water washes out the cementing material from soil and rock masses. Water pressure intension cracks not only push the slope forward but it also generates pore water pressure along joint or bedding planes. As the slide starts, the opening of the rough joints increases due to dilation. Thus, the plane of sliding acts as a natural channel for the flow of water. Pre-existing slip surface in old landslide areas can be reactivated because of adverse hydrological conditions (Deoja et al., 1991). The maximum rating 1.0 (table 6) were given to very high drainage density (>4.0), 0.8 to high drainage density (3.0-4.0), 0.5 to medium drainage density (2.0-3.0), 0.2 to low drainage density (1.0-2.0) and zero to very low drainage density (< 1.0).

**Seismicity and Rainfall**

Seismicity and rainfall may initiate slope movements and are called as triggering factors. Their effect is conspicuous over a large area. The location of study area is important keeping in view of regional seismicity and rainfall pattern. Seismically, India is divided into four major seismic zones where “Zone II” to “Zone V”, where “Zone II” represents an area of minimum seismic intensity while “Zone V” indicates the maximum intensity of seismicity. The ground shaking intensity increases proportionally from “Zone-II” to “Zone-V”. A slope which will be critically stable under existing slope conditions may become unstable it it falls in higher seismic zones and may result landslide phenomenon. Rainfall is the most triggering factor for the slope failure in the fragile Himalayan Mountains. Zones of high annual precipitation are also problematic as there is always a chance of sudden pore water pressure built up in slopes following a heavy spell of rain. After a critical limit shear stress of slope encompasses to shear strength of slopes and failure occurs. In the study area, it was found that majority of landslide events has been occurred during the monsoon season. These points are taken into while awarding ratings intensity of rainfall. The ratings of rainfall are indicating in the following table (Table 7).

**Landslide Hazard Evaluation Factor (Lhef) Rating Scheme**

LHEF rating scheme is a numerical weightage, governed by the major causative factors like lithology, structure, slope morphometry, relative relief, and land use/land cover of the slope instability. Each identified facet wise details of all these contributory factors was prepared for assigning Landslide Hazard Evaluation Factor (LHEF) rating for each factor. The maximum rating of individual contributory factors is shown in Table 8.

## RESULTS AND DISCUSSION

## Landslide hazard zonation

The landslide hazard zonation has been prepared by adding ratings of all the parameters to obtain total estimated hazard ratings (TEHD). Various zones of landslide hazard have been subsequently classified on the basis of total estimated hazard rating (TEHD) as given in Table 9. The results have been presented in the form of map. The terrain evaluation maps are prepared in the first stage showing the nature of facet-wise distribution of parameters. The terrain evaluation maps have been superimposed and THED have estimated for individual facets (Figure 3). Subsequently, LHZ maps are prepared based on facet wise distribution of TEHR values.

**Calculation of Total Estimated Hazard (Tehd)**

The total estimated hazard (TEHD) indicates the net probability of instability and is calculated facet-wise. The TEHD of an individual facet is obtained by adding the ratings of the individual causative factors obtained from the LHEF rating scheme. Total estimated hazard (TEHD) is sum of (lithology+ structure+ slope morphometry+ relative relief+ land use and land cover+ groundwater conditions + Seismicity and rainfall) On the basis of total Estimated Hazard (TEHD), four categories of landslide hazard zones have been identified for the area (Fig. 10 and table 10) Viz., low hazard (LH), moderate hazard (MH), high hazard (HH) and very high hazard (VHH). These zones are distributed in accordance with the geology and geomorphology of the area. The landuse area falling under different classes is given in table 5.11.

**Low Hazard Zone (LH)**

Low hazard zone (LH) has the least area of 54.15 $km^2$ which is 2.61% of the total area of the study area. The places found in this hazard category are Rudraprayag town, Dharkot, Syuni, Bagoli, Kamera, Warsi, Darmwari, Nagrasu, Kota, Rampur, Budoli etc. low hazard zone lies along the low relief and along the river terraces in the south of Rudraprayag district. This zone is considered safe and is suitable for settlement and Agriculture activities.

**Moderate Hazard Zone (MH)**

Medium hazard zone occupies an area of 880.12 $km^2$ which is 42.34% of the total area of Rudraprayag district. Moderate hazard zones are mostly distributed south, central and western parts of the Rudraprayag district (Figure 5.6). The important villages which lies in moderate hazard zone are Khankara, Chamdla, Dungra, Bansau, Dharkot, Bhatgaon, Bhatwari, Tilwara, Barakot, naira, Dadoli, Barsori, Sitapur Barasu, forest area in south, west and some glacier area etc. The Kedarnath temple also lies in medium hazard zone. This zone is also considered safe and the risk of landslides in this zone is least as the slope categories are less. This zone is safe for agricultural activities and Settlement.

**High Hazard Zone (HH)**

High hazard zone (HH) covers the maximum area of 977.60$km^2$ which accounts 47.02% of the total area of Rudraprayag district. This zone is found mostly in the northern part of the study area. The main towns and villages which lies in this zone are Guptkashi, Okhimath, Burwa, Byung, Maikhanda, Rudrapur, Dewar, Temriya, Damar, Bhiri, Dungar, Jawaharnagar, makku, Tyung and Meadows and glacier area etc. most of the active landslides where found in this zone. The risk of landslides is high in this zone. The

**Table 1: LHEF Ratings for rock types (after Anabalangan 1992)**

| Category | Rock types | Ratings |
|---|---|---|
| Type-I | Basalt, Quartzite and Massive Limestone and Dolomite | 0.2 |
| | Granite, Gabbro and Dolerite | 0.3 |
| | Granite Gneiss and Metavolcanics | 0.4 |
| Type-II | Well-cemented terrigenous sedimentary rocks (dominantly sandstone) with minor beds of stone and gneissic rocks | 1.3 |
| | Poorly- cemented terrigenous sedimentary rocks (dominantly sandstone0 with intercalations of clay or shale beds. | 1.0 |
| Type-III | Well foliated gneiss | 1.0 |
| | Shale, Slate, phyllite and other argillaceous rocks like siltstone, Mudstone and Claystone | 1.2 |
| | Schistose rocks | 1.4 |
| | Shale with inter-bedded clayey rocks (siltstone, mudstone, etc.) | 1.8 |
| | Weathered shale and other argillaceous rocks, Phyllite and Schistose rocks. | 2.0 |

**Table 2: LHEF Rating for Structure (Distance from the major Thrust in km)**

| Category | Distance from thrust/ Faults (km) | Ratings |
|---|---|---|
| I | <-0.5 | 2.0 |
| II | 0.5-1.0 | 1.5 |
| III | 1.0-2.0 | 1.0 |
| Iv | >-2.0 | 0.5 |

**Table 3: Rating for Slope Morphometry (after Anabalangan, 1992)**

| Slope type | Slope angle | Probable type of failure | Rating |
|---|---|---|---|
| Escarpment/ Cliff | $>55^0$ | Falls and Topples | 2.0 |
| Very steep slope | $45\text{-}55^0$ | Falls and Topples | 1.8 |
| Steep Slope | $35\text{-}45^0$ | Slides | 1.6 |
| Moderately steep slope | $25\text{-}35^0$ | Slides | 1.3 |
| Gentle slope | $15\text{-}25^0$ | Slides and creeps | 0.8 |
| Very gentle slope | $<15^0$ | Movement | 0.5 |

**Table 4: Ratings for relative relief (after Anabalangan, 1992)**

| Relief classes | Relative Relief (m) | Rating |
|---|---|---|
| Low | <100 | 0.3 |
| Medium | 100-200 | 0.6 |
| High | 200-300 | 0.9 |
| Very High | >300 | 1.0 |

**Table 5: LHEF Ratings for land use and land cover types (after Anabalangan, 1992)**

| Land use and land cover types | Rating |
|---|---|
| Cultivated and settlement land | 0.65 |
| Thickly forest area | 0.80 |
| Moderately forest area | 1.20 |
| Sparsely forested area | 1.50 |
| Alpine pasture | 1.50 |
| Glaciated land | 1.70 |
| Barren land | 2.00 |

**Table 6: LHEF Rating for Drainage Density**

| Category | Drainage density | Rating |
|---|---|---|
| I | <-1.0 | 0.0 |
| II | 1.0-2.0 | 0.2 |
| III | 2.0-3.0 | 0.5 |
| IV | 3.0-4.0 | 0.8 |
| V | >-4.0 | 1.0 |

**Table 7: ratings for Seismicity and Rainfall**

| Seismic zone | Ratings | Average annual rainfall of the area | Ratings |
|---|---|---|---|
| II | 0.2 | < 50cm | 0.2 |
| III | 0.3 | 50-100 cm | 0.3 |
| IV | 0.4 | 100-150cm | 0.4 |
| V | 0.5 | > 150cm | 0.5 |

slopes falling in this zone should be avoided. If unavoided, detailed study on 1:1000-2000 scale shall be done to evaluate the status of stability of these slopes. Suitable control measures shall be identified before taking up constructions in order to minimize related geo-environmental hazards.

## Very High Hazard Zone (VHH)

Very high hazard zone (VHH) covers an area of 167.01 $km^2$ which accounts 8.03% of the total area of the study area. The villages lies in this zone are Syari, Manjuli, Konda, kutli, Hondu, Dhureth, Upgad, bhurolgaon, Charkhandi, Dhar,

Fig.1: Location Map of District Rudraprayag

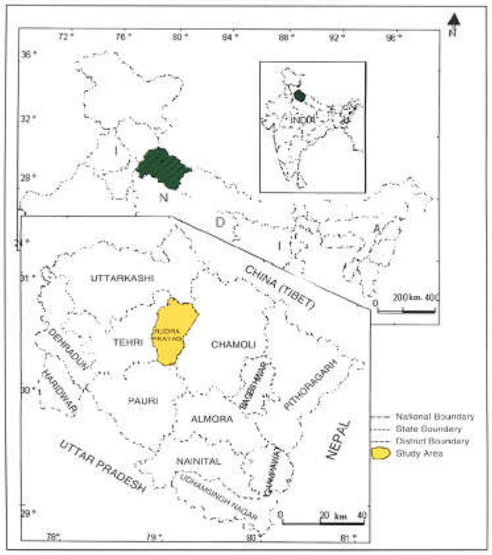


Fig.2: Facet Map of District Rudraprayag

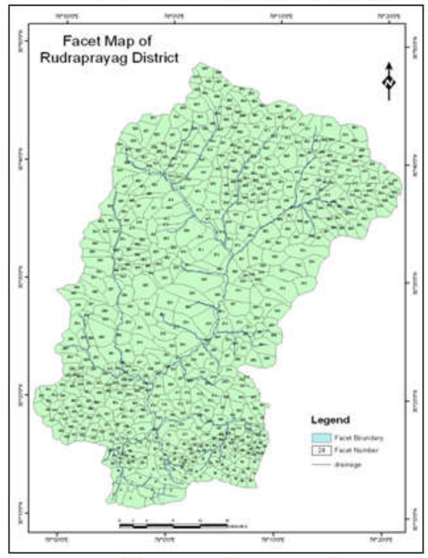


Fig.3: Geological Map of District Rudraprayag

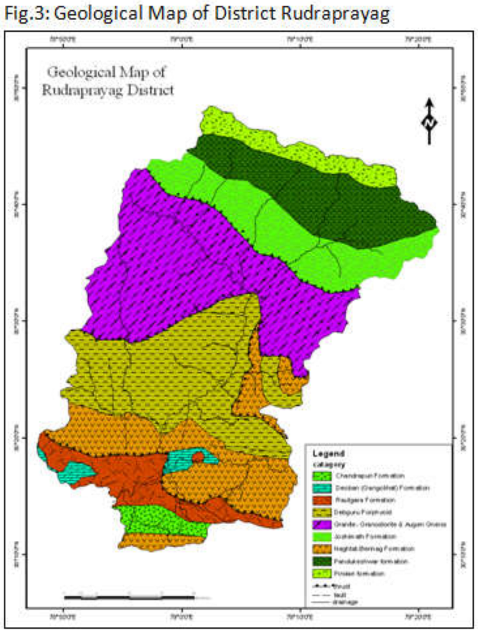


Fig. 4: Slope Map of District Rudraprayag

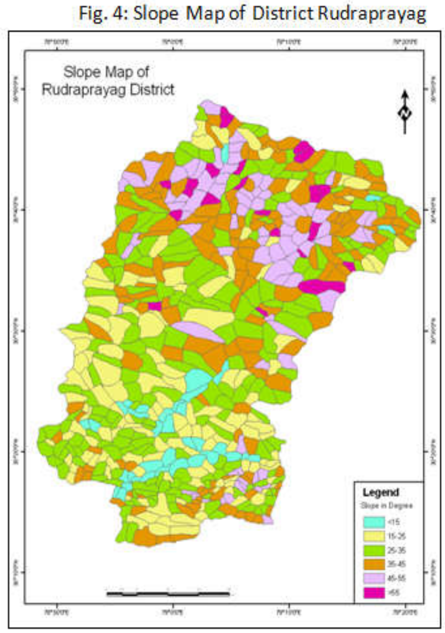


Fig.5: Relative Relief Map of District Rudraprayag

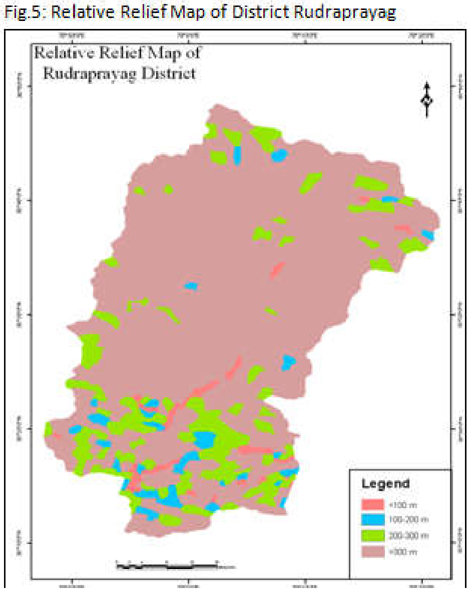


Fig.6: Landuse Map of District Rudraprayag

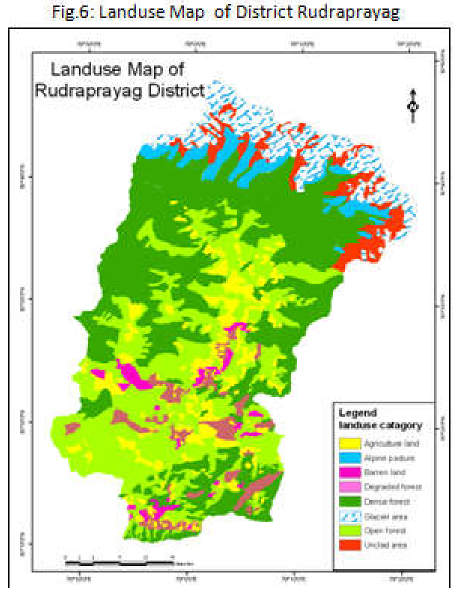

Fig.7: Drainage Density map of district Rudraprayag

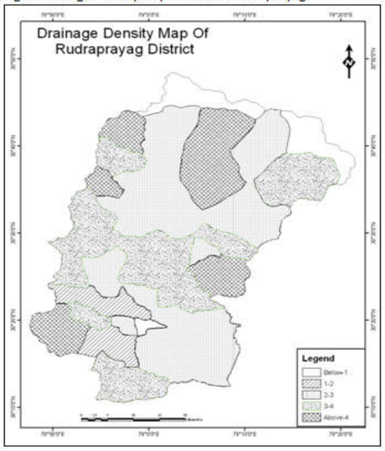


**Table 8: Proposed maximum LHEF rating for different contributory factors for LHZ mapping**

| Contributory Factor | Maximum LHEF Rating |
|---|---|
| Lithology | 2 |
| Relationship of structural discontinuities with slopes | 2 |
| Slope Morphometry | 2 |
| Relative Relief | 1 |
| Landuse and Landcover | 2 |
| Hydrology (Drainage Density) | 1 |
| Total | 10 |

**Table 9: Classification of landslide hazard zonation (after Gupta and Anabalagan, 1995)**

| Zone | Value of THED | Description of LHZ | Practical significance |
|---|---|---|---|
| I | <3.5 | Very low hazard (VLH) | Safe for development activities |
| II | 3.5-5.0 | Low hazard (LH) | Safe for development activities |
| III | 5.1-6.5 | Moderate Hazard (MH) | Local vulnerable zones of instabilities |
| IV | 6.6-7.5 | High hazard (HH) | Unsafe for development activities |
| V | >7.5 | Very high hazard (VHH) | Unsafe for development activities |

**Table 10: Landslide Hazard Zonation on the Basis of Total Estimated Hazard (TEHD)**

| Zone | TEHD Value | Description of zone | Area ($km^2$) | % |
|---|---|---|---|---|
| I | <3.5 | Very Low Hazard (VLH) Zone | Nil | Nil |
| II | 3.5-5.0 | Low Hazard (LH) Zone | 54.15 | 2.61 |
| III | 5.1-6.0 | Moderate Hazard (MH) Zone | 880.12 | 42.34 |
| IV | 6.1-7.5 | High Hazard (HH) Zone | 977.60 | 47.02 |
| V | >7.5 | Very High Hazard (VHH) Zone | 167.01 | 8.03 |

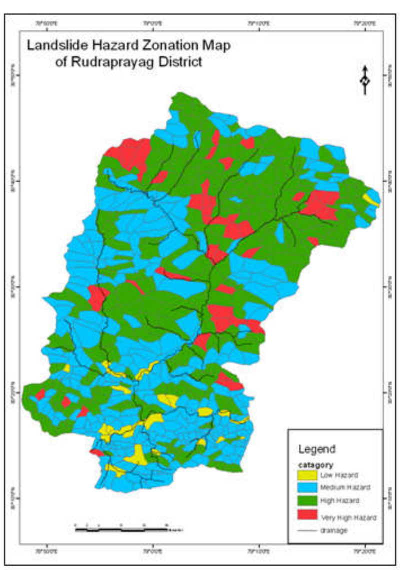


**Table 11: Relation between landslide hazard zonation and land use category**

| Landslide hazard class | Land use category | Area ($km^2$) | % to total hazard class |
|---|---|---|---|
| Very high hazard | Agriculture | 13.87 | 8.08 |
| Very high hazard | Dense forest | 53.48 | 31.18 |
| Very high hazard | Open forest | 51.88 | 30.24 |
| Very high hazard | Degraded forest | 4.82 | 2.81 |
| Very high hazard | Barren land | 9.64 | 5.62 |
| Very high hazard | Glacier | 14.03 | 8.18 |
| Very high hazard | pasture | 23.84 | 13.89 |
| High hazard | Agriculture | 52.65 | 5.53 |
| High hazard | Dense forest | 369.94 | 38.88 |
| High hazard | Open forest | 271.42 | 28.52 |
| High hazard | Degraded forest | 23.92 | 2.51 |
| High hazard | Barren land | 74.52 | 7.83 |
| High hazard | Glacier | 105.57 | 11.10 |
| High hazard | Pasture | 53.69 | 5.64 |
| Moderate hazard | Agriculture | 72.99 | 8.56 |
| Moderate hazard | Dense forest | 353.20 | 41.39 |
| Moderate hazard | Open forest | 278.27 | 32.61 |
| Moderate hazard | Degraded forest | 50.34 | 5.90 |
| Moderate hazard | Barren land | 31.55 | 3.69 |
| Moderate hazard | Glacier | 61.43 | 7.20 |
| Moderate hazard | Pasture | 5.55 | 0.65 |
| Low hazard | Agriculture | 10.17 | 18.80 |
| Low hazard | Dense forest | 9.01 | 16.65 |
| Low hazard | Open forest | 24.56 | 45.39 |
| Low hazard | Degraded forest | 4.32 | 7.99 |
| Low hazard | Barren land | 3.88 | 7.17 |
| Low hazard | Glacier | 2.17 | 4.01 |

dharasu, Jaghi, Bedula, Kunjethi, Ransi, some area in the south of Khankra etc. This zone is not suitable for construction purposes and the construction activities should be totally stopped in this zone.

## Conclusion

The present studies highlight the application of Remote Sensing techniques and GIS in preparation of landslide hazard zonation mapping of Rudraprayag District. The landslide hazard zonation of the study area was done by applying the methodology of landslide hazard evaluation factor rating scheme (LHEF) and then calculating the total estimated hazard (TEHD). Results from the studies highlight the Very High, High, Moderate and low landslide hazard zones in the study area. On the basis of total Estimated Hazard (TEHD), four categories of landslide hazard zones have been identified Viz., low hazard (LH), moderate hazard (MH), high hazard (HH) and very high hazard (VHH). These zones are distributed in accordance with the geology and geomorphology of the area. Low hazard zone (LH) has the least area of 54.15 $km^2$ which is 2.61% of the total area of the study area. Medium hazard zone occupies an area of 880.12 $km^2$ which is 42.34%, High hazard zone (HH) covers the maximum area of 977.60$km^2$ which accounts 47.02%, and Very high hazard zone (VHH) covers an area of 167.01 $km^2$ which accounts 8.03% of the total area of the study area. The Landslide hazard zonation map of Rudraprayag district will help the planners for the developmental activities in this area. The constructions on slopes falling in VHH and HH classes should be totally avoided. Low and medium hazard areas are safe for civil constructions but MH areas at times may contain local pockets of instability. The GIS data base of the landslide hazards for the study area may be used for future detailed geotechnical solutions to stabilize the landslides.

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