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Landslide Hazard Zonation in Kaliganga and Madhyamaheshwar valleys of Garhwal Himalaya: A GIS based approach

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Abstract : Himalaya represents a fragile ecosystem and its fragility stems from geological history of its evolution and structural set-up of the rocks. The fragility of the terrain is often manifested in the recurring natural hazards and was highlighted in August 1998 when landslides took regional proportions and a large portion of Garhwal-Kumaun was affected. Kaliganga and Madhyamaheshwar river valleys (tributaries of Mandakini river) of Garhwal Himalaya witnessed heavy losses and the death toll in these valleys crossed one hundred mark, Madhyamaheshwar river was dammed and vast tracts of hitherto fertile terraced land was rendered unsuitable for human interventions. Landslide hazard zonation (LHZ) and risk assessment studies have been carried out in these valleys under Geographical Information System (GIS) environment employing statistical index method. Geology, structure, landuse, old slides, slope, shape of the slope, slope aspect, and drainage are the different parameters affecting mass movement and have been considered for LHZ exercise. For risk assessment population (1991 census) has been considered the sole criteria as most infrastructure in the region is interwoven around population centres. This exercise has brought out areas and population groups that are particularly vulnerable to landslides.

Introduction

Himalayan ecosystem is fast approaching a stage of disequilibrium and there are clearly visible negative changes in the resources and the environment. Step by step, nature is being destroyed and human, terrestrial, and aquatic life are being shortened by the effects of development in the form of landslides, sedimentation, and eutrophication of reservoirs, lakes and rivers, drying up of springs, and others (ESCAP Report 1989). Conventional development paradigm has thus failed to take into account mountain specificities such as inaccessibility, fragility, marginality, diversity or heterogeneity, niche or comparative advantage, and human adaptation mechanisms. Of the specificities fragility (of the terrain) is of immediate concern and is expressed in recurring hazards that the region faces. These natural hazards are often aggravated by anthropogenic activities and take heavy toll of human lives, infrastructure and natural resources.

The fragility of the region stems mainly from the evolutionary history of the terrain. As the Tethys Sea intervening in-between Indian and Asian plates closed due to the plate motion, mammoth blocks of rock masses moved southward for tens of kilometres. This movement of the earth blocks initiated several weaknesses in the rocks of the region. From the Indus Suture Zone (along which the two alien plates are welded) southward Tethyan Thrust (TT), Main Central Vaikrita Thrust (MCVT), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Frontal Fault (HFF) form the major tectonic discontinuities along which major movement has taken place. Besides these there are numerous thrusts and faults intervening in-between. These have rendered the terrain highly folded, faulted, fractured and sheared; and thus fragile.

Fragility is thus associated with the terrain and the inhabitants have over generations adapted their lifestyles and have learnt to live and cope up with the specificities. Through experimentation and accumulated knowledge of generations they evolved their own traditional ways of overcoming the handicap imposed by the mountain specificities. The people well understood the relationship between the water entering the surface and recharge of the aquifers, as also the downslope mass movement. The recharge zones of springs were protected at various locations by invoking divine sanction and at the same time in order to safeguard habitations at vulnerable locations people devised ways of diverting rainwater directly into the main stream through a network of channels. This helped in keeping the pore water pressure within the threshold limits and the mass movement was averted. Such drains, locally referred to as jungle guls (unlined canals) were observed at Ransi and Kotma while those at Kalimath and Jagi- Bagwan have ceased to exist. These were built and maintained by the community without any support from the state and were regularly repaired and cleared before the onset of monsoon season. The traditional system however collapsed with the onslaught of modern state oriented system. The traditional genius of the ancestors was lost into oblivion and these structures that safeguarded the locality for generations died a natural death in neglect and seclusion.

Fragility of the mountainous terrain together with the vulnerability of the people habitating it was once again highlighted in August 1998 landslide tragedies that occurred in Madhyamaheshwar and Kaliganga river valleys of Garhwal Himalaya (Fig. 1). The death toll in these tragedies crossed one hundred mark.

Majority of landslides in both the valleys took place on 11-12 August 1998 (Fig. 2). Rains severely hampered the relief and rescue work and on 18-19 August 1998 Bheti slide (Fig. 3) blocked the course of Madhyamaheshwar river for about 24 hours. There was panic downstream up to Haridwar and the people at Srinagar, having witnessed the fury of rising waters in the past were particularly cautious. The incidence of 1970 tragedy was fresh in the memory of many residents and the overenthusiastic administration only added to the panic of the people by giving a call for evacuation even before assessing the magnitude of the threat. In this incidence the whole mountain side, that was probably weakened by 1991 Uttarkashi earthquake (M 6.1) and had reportedly developed cracks amid forestland, broke off overrunning three habitations; Bheti, Paun (Paundar) and

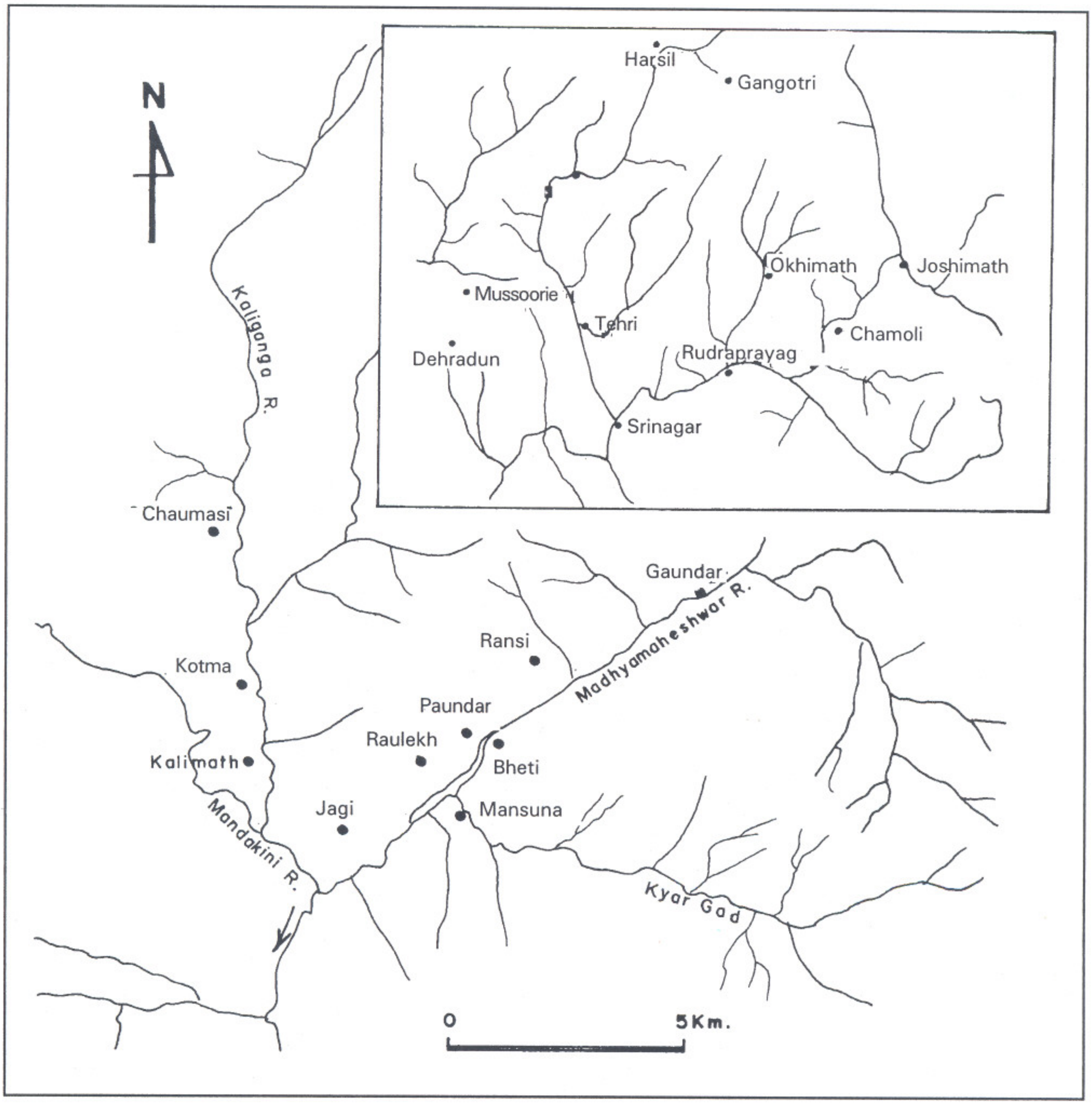

Fig. 1. Location map of the two Madhyamaheshwar & Kaliganga river valleys.

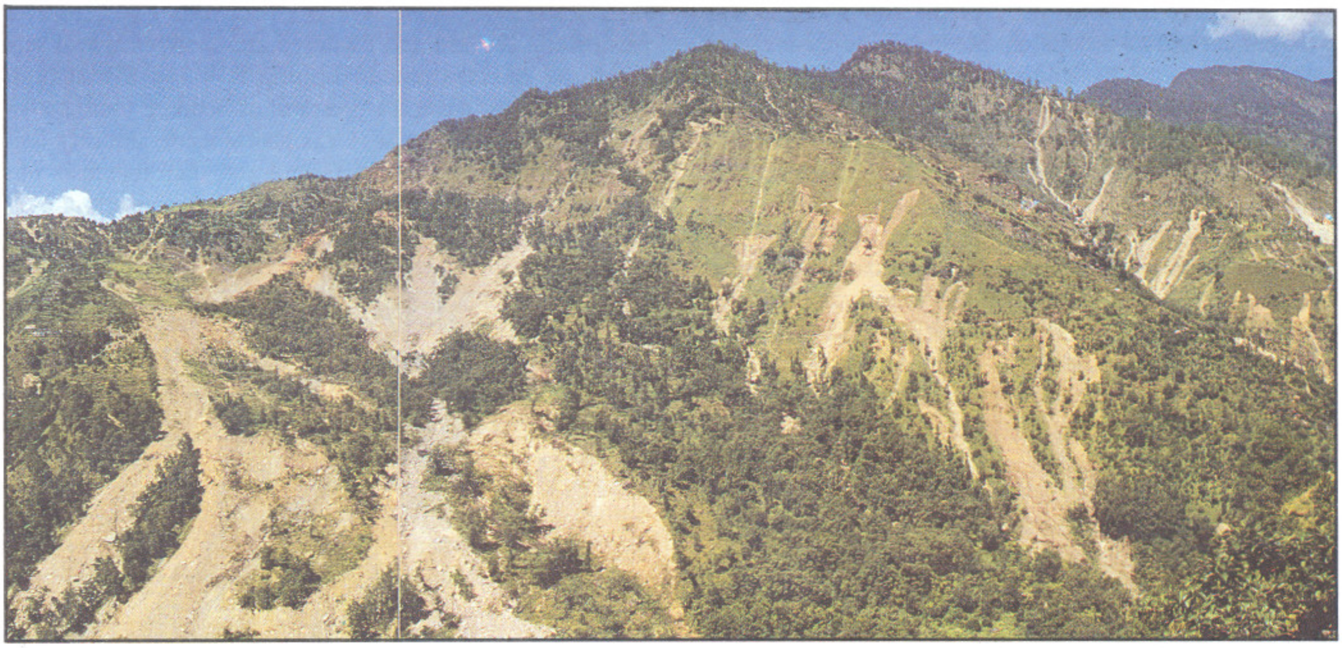

Fig. 2. View of the landslides in Madhyamaheshwar river valley across Mansuna.

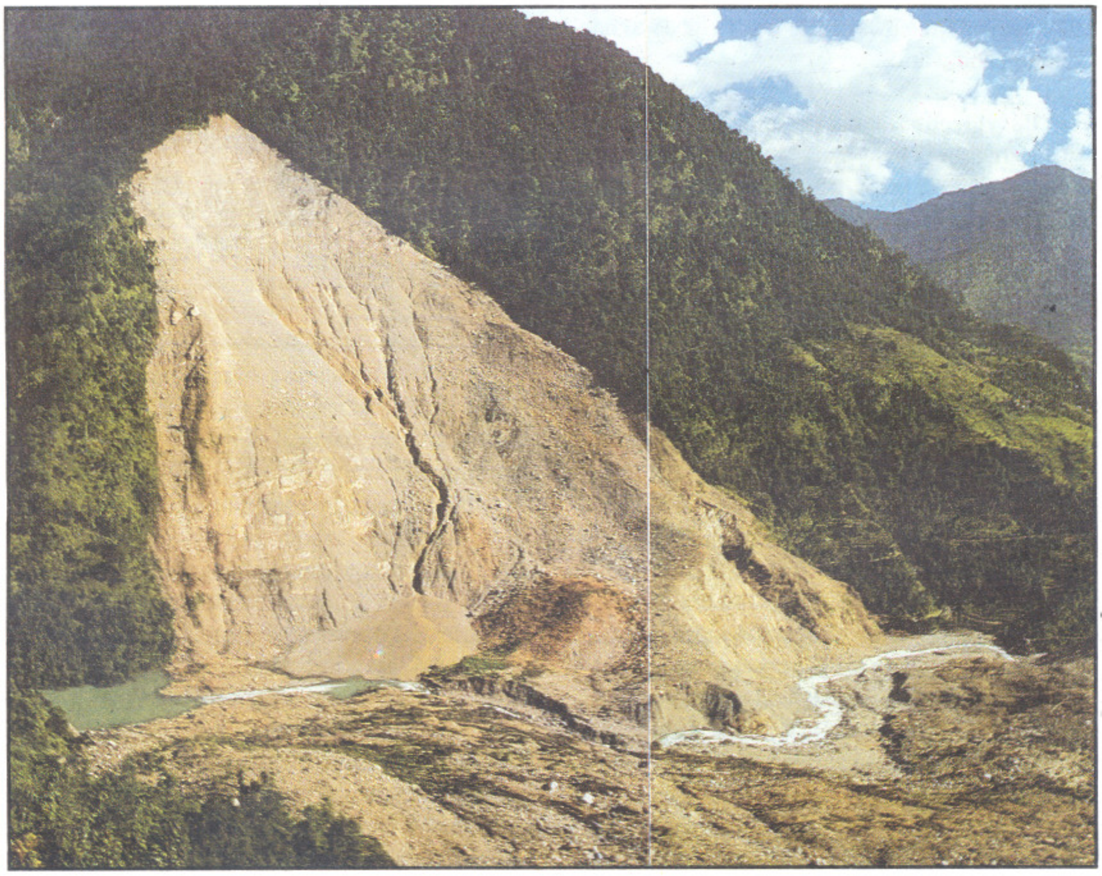

Fig. 3. View of the Bheti landslide of 18-19 August 1998 that blocked the course of the Madhyamaheshwar river for 24 hours.

Sem. Rescue and relief work was at the same time delayed by incessant rains, wide sway of the slides and lack of management and co-ordination. Madhyamaheshwar river is reportedly blocked by landslides at the beginning of the century. River morphology supports past history of blackade in the valley. The name Raulekh also suggests an erstwhile lake in the vicinity, as in local parlance Rau means whirling water pool.

Bheti landslide pushed the death toll over a hundred mark and changed the geomorphic set up of the surrounding area; the agricultural lands and habitations being replaced with heaps of boulders and debris and the two streams that used to meet Madhyamaheshwar river near Paundar lost their coarse amid the debris.

As goes the saying Prevention is better than cure; mitigative planning is required for the entire region so as to ensure that similar incidences are not repeated in future. Recorded history of landslides and landslide induced floods in the region outvocally shows the importance of hazard identification and management in reducing the loss of human lives. In 1894 partial breach of the Gauna lake that was forecast almost a year in advance by the British engineer Lt. Col. Pulford, though there was immense loss of property at Srinagar and downstream, the loss of life was reduced to one by timely evacuation and warning.

First step in this direction is the demarcation of hazard prone zones in the region. There are many approaches for preparing landslide hazard maps. In the present exercise statistical approach is employed under GIS environment.

Geological set-up

In the valleys under consideration (Madhyamaheshwar and Kaliganga) the rock types exposed mainly belong to Central Crystallines. This region has been studied in detail by Bist and Sinha (1982). The Munsiari Formation overlying the Bhatwari Unit along NE dipping Munsiari Thrust (MCT) is followed northwards by Joshimath Formation of Vaikrita Group (Fig. 4). This contact between Munsiari and Joshimath formations is designated Main Central Vaikrita Thrust (MCVT). Bhatwari Unit comprises of gneissose granites, augen gneisses, chlorite-sericite schists and amphibolites. Joshimath Formation comprises of biotite-garnet-kyanite-sillimanite psammitic gneisses, schists and migmatites and is overlain by Pandukeshwar Formation over which is thrusted Pindari Formation along Pindari Thrust (Valdiya 1998). Pandukeshwar Formation consists of quartzite, phyllonites and migmatites while the Pindari Formation consists of calcsilicate rocks, garnet-chlorite-sericite schists. General dip of the foliation planes is towards NE and there exists a strong NE trending stretching lineation. Close proximity of the tectonic planes causes these rocks to be highly sheared and fractured. Munsiari Formation is particularly sheared and fractured and there exist two sets of strong fracture planes dipping NW and SW at high angles. Besides these the presence of bedding joint is also observed. These secondary weak planes render this rock unit particularly susceptible to failure and therefore it is not surprising to note that most of the mass movement in both the valleys is confined to Munsiari Formation.

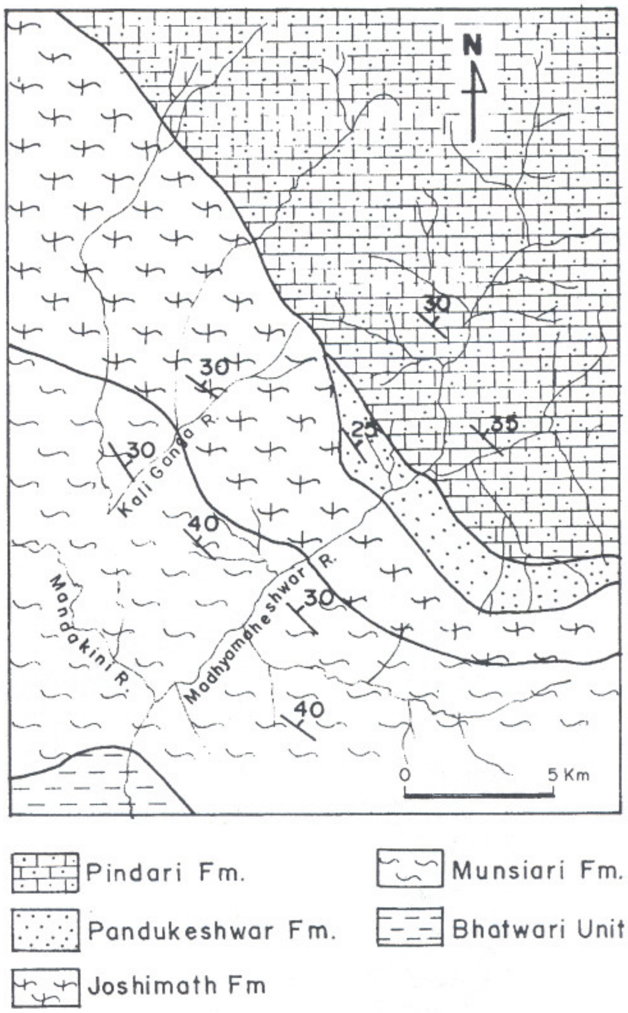

Fig. 4. Geological set-up of the area.

Landuse/Landcover

Being a direct expression of the terrain condition it gives important indication regarding the slope instability. The landuse in the Himalayan terrain has been influenced by the nature of terrain and the diversity of the climate. The vegetal cover has a considerable effect on erosion and weathering intensities. Shallow landslides are generally associated with areas having very sparse vegetation (open scrub). There are numerous examples where cutting down of the trees triggered landslides. Removal of the vegetal cover leads to accelerated erosion and shallow slides. Faster erosion and greater instability of the slopes are found in barren rock or soil surfaces as well as in the sparsely vegetated areas. On the other hand thickly vegetated areas are generally less prone to mass wasting processes due to the well developed root system that binds the soil particles, thus enhancing the shearing resistance of the slope material, except for the cases where deep seated failures take place. The anthropogenic activities greatly enhances the chances of slope failure. The cultivated land also behaves differently with different crops planted. The standing crops that require stagnant water sometimes result in increased pore water pressure in the soil mass underneath, resulting in mass movement. Prolonged rains that saturate the soils also cause similar effect.

The landuse features extracted from the SOI toposheet and updated with satellite data (IRD ID LISS III) show that the lower reaches of the valleys have most of the agricultural land and its distribution varies with aspect. Differential insolation on different aspects account for variations in landuse with aspect. Westerly and southerly aspect (NW, W, SW, S & SE) account for most of the barren land; former three in Kaliganga valley and latter three in Madhyamaheshwar valley account for more than half the barren land. Human interventions have left isolated forest patches on all the aspects. Easterly and southeasterly aspects show more land under cultivation.

These data indicate that the steep slopes with southerly aspect have comparatively less vegetal cover. This is in conformation with the observations in other Himalayan sectors and is attributed to the intense insolation on these slopes.

Correlation of landuse pattern with the slope amount show that gentle and moderate slopes have intensive agricultural activity (70% of the agricultural land in Madhyamaheshwar valley & 80% in Kaliganga valley) while most of the forests are confined to moderate and moderately high slopes (55% in Madhyamaheshwar valley & 60% in Kaliganga valley). Presence of agriculture even on steep slope (>60^0) indicates that the population pressure has forced people to cultivate unconventional slopes. Terracing of the steeper slopes requires higher embanking walls and these are perpetually in a destabilised state. Moisture often adds to the instability.

Landslides

In the dark hours of 11-12 August 1998 lower reaches of both Madhyamaheshwar and Kaliganga valleys were devastated by landslides. The lush green valley was scarred deeply (Fig. 2) and a large proportion of the agricultural land was lost together with 62 human lives. Most of the slides initiated at the steeper slopes of the valley and the rolling down debris took devastating proportions. Some of these slides were amid old slide zone. Large number of habitations in the hills are situated on stabilised landslide debris where cultivable fields are easy to prepare. These sites however pose a natural danger of reactivation of the slide.

On 18-19 August 1998 the mountain slope opposite Bheti slided down, ravazing habitations on the opposite bank and damming the river for 24 hours. The debris glided upslope on the opposite bank burying alive the inhabitants without any trace. This slide shows distinct structural control with three sets of penetrative joints observed in the rocks hosting this slide and widening of the joints due to earlier tectonic disturbances only increased the probability of failure. A wide crack was reportedly observed over the Bheti slide days in advance by the villagers. The water percolating through these weak planes facilitated movement along one of the dominant and pre-existing weak plane. The Bheti slide took place with a thunderous sound of rolling boulders and there was dust strom that covered a radius of more than two kilometers. The dust was not washed off and was observed over the vegetation days after the incidence.

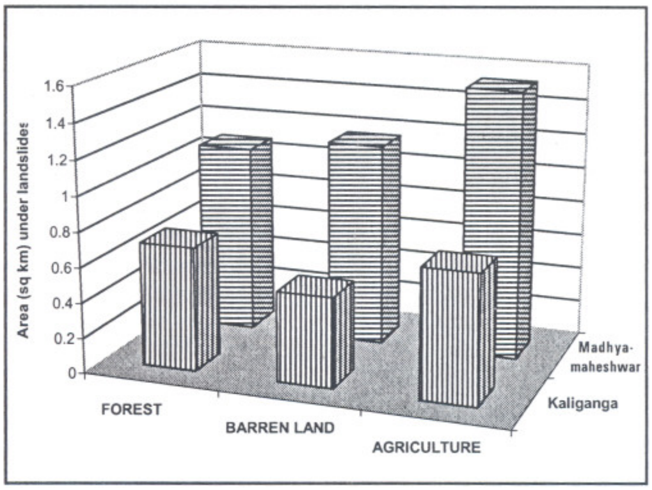

Fig. 5. Relationship between landslides and the landuse in Kaliganga & Madhyamaheshwar river valleys.

The relationship between landslides and landuse (Fig.5) show that landslides are not confined to a particular landuse type. These are almost evenly distributed amongst all the landuse classes with majority being confined to the agricultural lands. Most of the agricultural land that is devastated by the landslides come under high slope catagory. Natural compulsion of bringing more land under cultivation forces increase in the height of the embanking walls of the terraces. This in turn adds to the instability of these terraces. Water impounded in these soils due to prolonged rains further added to the instability of these slopes.

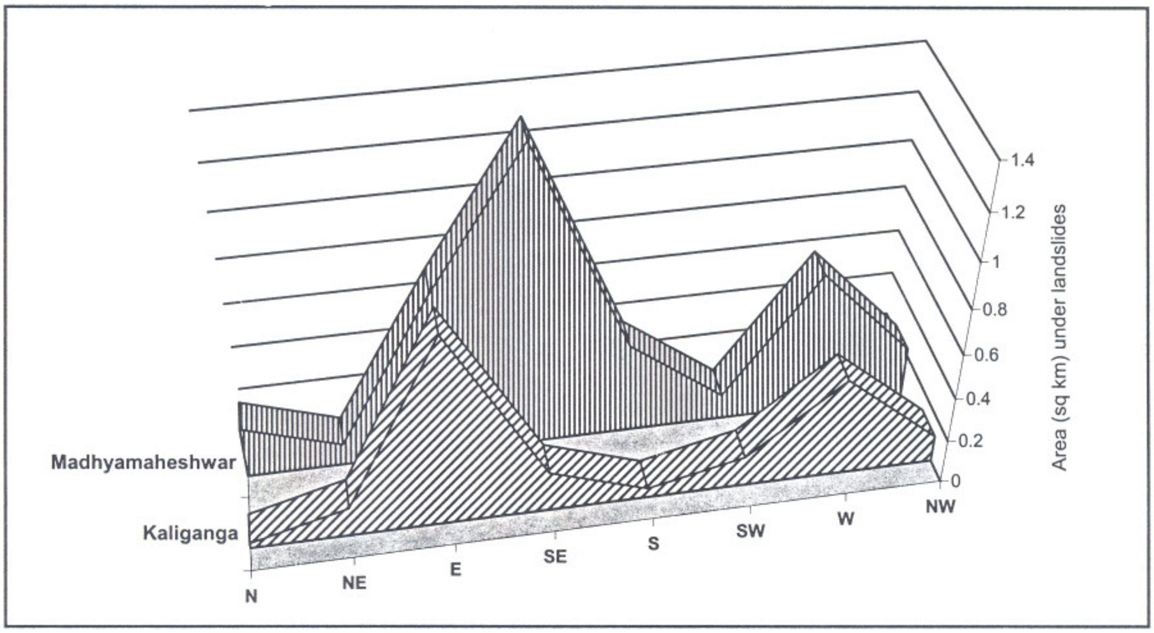

Fig. 6. Relationship between landslides and aspect of the slope in Kaliganga & Madhyamaheshwar river valleys.

The relationship between landslides and aspect of the slope (Fig. 6) show concentration of slides on easterly and southeasterly aspect (>50%). These are the slopes that have maximum area under agriculture. Correlation of landslides with the slope amount shows that moderate slopes in Kaliganga valley (41%) and gentle slope in Madhyamaheshwar (31%) valley show predominance of landslides (Fig. 7). In both the valleys these slope classes have a large area under cultivation.

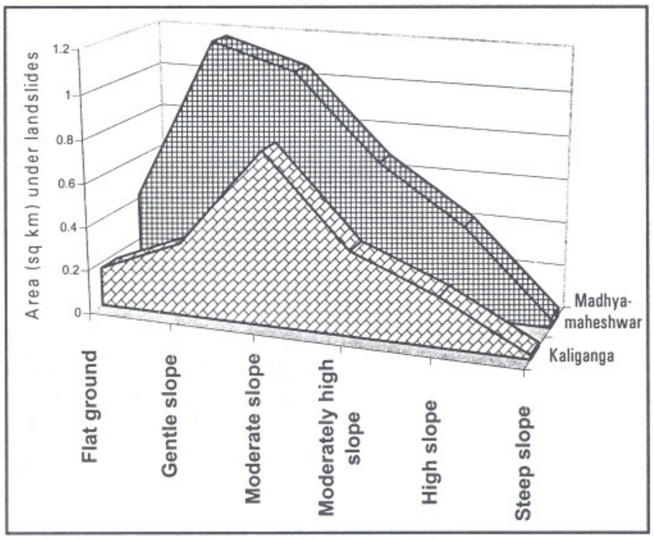

Fig. 7. Relationship between landslides and the slope class in Kaliganga & Madhyamaheshwar river valleys.

Straight slopes show shallow debris slides that initiate at higher topographic levels and take gigantic proportions downslope. Some slides also initiate in the unstable convex slopes at higher elevations and take along material resting on straight slopes. All the slides on the concave slopes are reactivated old landslides.

Presence of agricultural terraces on unconventional steep slopes that have been adversely affected by slides suggest violation of traditional farming dictums under pressure of increasing population and fragmentation of land.

Going through the landslide record one easily gathers the fact that most of the slides take place during the rainy season. It therefore becomes imperative to check in for anomalies in the rainfall record (Table 1). Analysis of rainfall data in Garhwal-Kumaun Himalaya shows that the average annual rainfall at different sites is about 1000 mm to 2500 mm of which 50 to 80 percent comes down during the monsoon and occasionally very heavy rains can be expected. Once in every 100 years, 200 mm to 500 mm of rain can be expected in one day. There are two zones of maximum precipitation in Himalaya – one near the foot of the mountains and another at an elevation between 2000 to 2400 m (Dhar *et al.*, 1986). A large portion of the area under present focus falls in the high rainfall zone.

The rainfall data shows that the rains were on the higher side during July-August 1998 (1421 mm). The first fortnight of August 1998 recorded more than 300 mm of rains. There were incessant rains for weeks before the incidence and the pore water pressure crossed the threshold. Water gushing out in the downslope regions was observed at many places

Table 1. *Monthly rainfall details (in mm) over the years at Okhimath.*

	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
January	282	15	14	117	96	11	68	35	42	0
February	34	170	53	106	101	2	90	105	28	63
March	53	247	133	55	120	0	32	60	58	71
April	19	46	125	5	21	77	24	13	129	52
May	78	164	35	121	97	0	12	33	91	36
June	253	166	90	76	242	200	136	505	250	85
July	563	524	414	523	352	534	616	535	597	796
August	931	784	537	904	336	452	489	479	383	625
September	242	203	175	411	361	141	230	109	191	
October	17	2	2	7	5	0	27	46	77	
November	38	24	8	5	0	0	0	0	50	
December	61	96	29	1	0	11	5	0	48	

together with the seepage in the fault scarp of the Bheti slide. Water lubricated the weak planes and the load of the mass resting on the steep slope increased beyond the threshold limits. Besides this the secondary structural weaknesses present in the host rocks have also played a significant role in mass movement.

Direct evidences of deforestation were not witnessed in both the valleys and massive landslides were witnessed amid well-forested areas. There is however no denying the fact that due to the growth of population masses have resorted to terrace cultivation in the steep slope. During 1998 monsoon rains, that were concentrated within a short period, saturated the soil and it did not get enough time to escape. Increased weight of the saturated soil under its own load destabilised the terrace walls and the gushing water set the whole process of devastation.

Bheti slide shows distinct structural control. Rain water entering through the fracture zones enhanced the pore water pressure and the whole mass moved downslope along a preexisting weak plane. The movement was so fast that the downward moving mass acquired enough momentum to move upslope (~200 m vertically) on the opposite bank were it destroyed the habitations and caused immense loss of human lives and property.

Landslide hazard zonation

Mass movements in mountainous terrain are natural degradational and one of the most important landscape building processes. Most of the terrain in mountainous areas has been subjected to slope failure at least once, under the influence of a variety of causal factors, and triggered by events such as earthquakes and extreme rainfall (van Westen 1994). Landslide is a natural process of mass wastage in which downslope movement of the rock mass takes place. Though occurring naturally, anthropogenic influence often accelerates this process. Mass movements become a problem when these interfare with the human activity and cause losses. In the areas under present focus landslides have caused heavy loss of lives, property and natural resources. Mitigation of the landslides disasters can be successful only when detailed knowledge is obtained about the expected frequency, character and magnitude of the mass movement in an area. The identification of landslide hazard must therefore be the basis for any landslide mitigation project and should supply planners and decision-makers with adequate and understandable information.

Based on the field studies and the remote sensing data (temporal multispectral and PAN digital data of IRS 1D LISS III) landslide distribution in Madhyamaheshwar and Kaliganga river valleys is delineated (Fig. 8). 142 active slides and 11 old slides are considered for this exercise in the two valleys. Lithology and structure play the major role in deciding the sites of ultimate failure. Besides these, landuse, drainage, slope and aspect are observed to influence the slides. These have therefore been considered while undertaking hazard zonation.

Landslide hazard maps delineate areas within which there is finite probability of being affected by slope instability. The approach of landslide hazard zonation is based on the empirical relationship between landsliding and individual causative factors. The comparison of the distribution of different factors allows the identification of areas with varying potential for landsliding. A landslide hazard zonation map depicts division of the land surface into zones of varying degree of stability based on the estimated significance of causative factors in inducing instability (Anbalgan 1992). The evaluation of landslide hazard or risk is appropriate in all

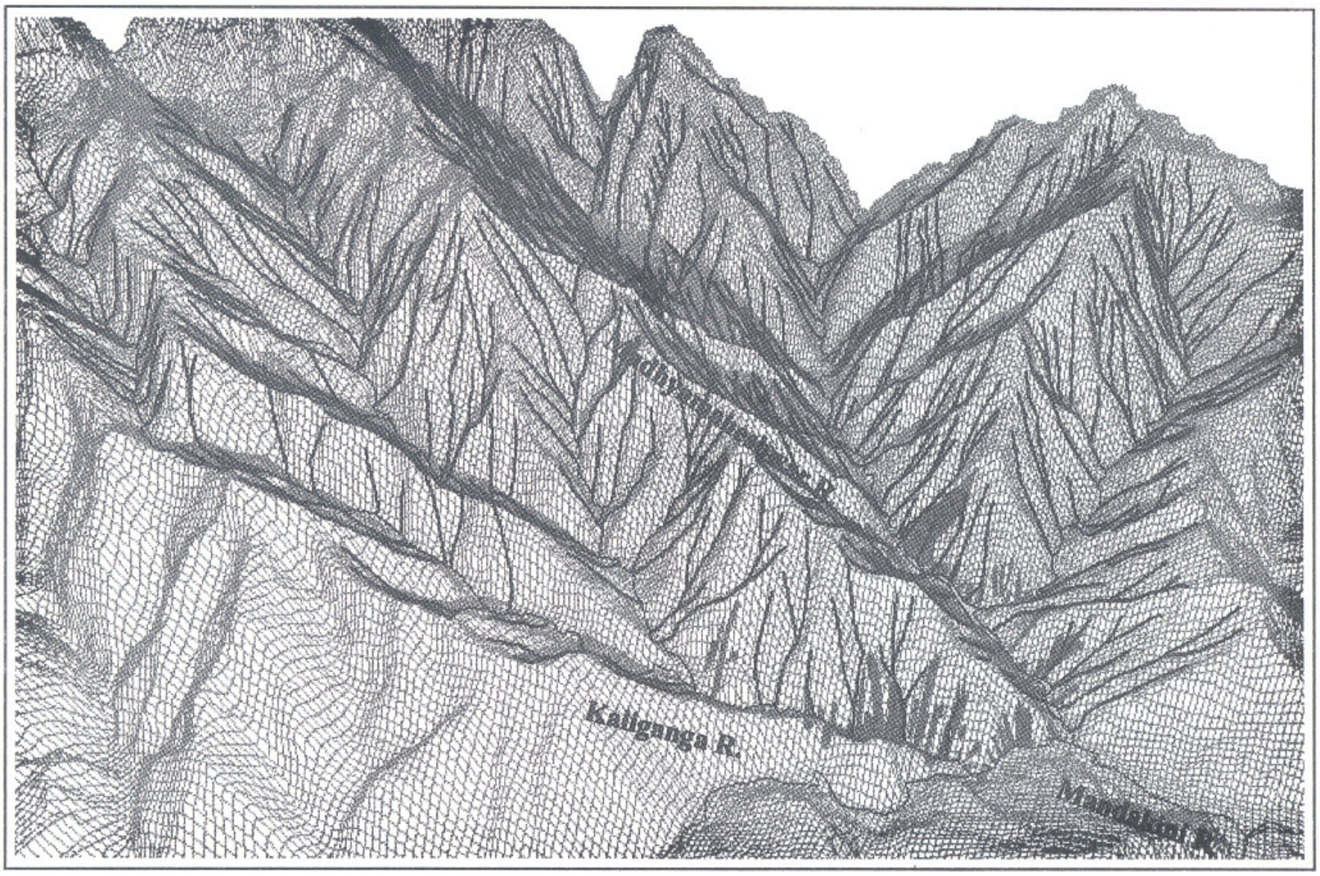

Fig. 8. Landslide distribution in Kaliganga & Madhyamaheshwar river valleys.

stages of the developmental activities from planning to maintenance.

Despite thorough researches the causative factors that should be considered for landslide hazard zonation are not all unanimously accepted. Different workers have come out with their own schemes (Radbruch & Wentworth 1971, Brabb *et al.*, 1972, Stevenson 1977, Carrara *et al.*, 1977, 1978, Seshagiri *et al.*, 1982, Kawakami & Saito 1984, Choubey & Litoria 1990, Mehrotra *et al.*, 1991, Pachauri & Pant 1992). Analysis of landslide hazard is a complex task as many factors can play a role in the occurrence of mass movement. The analysis requires a large number of input parameters, and techniques of analysis may be very costly and time consuming. Computers have however created opportunities of detailed and rapid analysis of landslide hazard and its use dates back to late 1970s (Burroughs 1986). Brabb (1984, 1995), Brabb and others (1989), Gupta and Joshi (1990), Pearson and others (1991) and Naranjo and others (1994), have contributed significantly to the field of landslide hazard zonation using computer based techniques.

In the present exercise statistical landslide index method is used for hazard zonation. In this method the weight value for a parameter class is defined as the natural logarithm of the landslide density in the class divided by the landslide density in the entire map (Van Westen 1997). The method is based upon the following formula:

$$\mathrm{Wi} = \ln \frac{\mathrm{Densclas}}{\mathrm{Densmap}} = \ln \frac{\dfrac{\mathrm{Npix\,(Si)}}{\mathrm{Npix\,(Ni)}}}{\dfrac{\sum \mathrm{Npix\,(Si)}}{\sum \mathrm{Npix\,(Ni)}}}$$

Where,

Wi	=	The weight given to a certain parameter class
Densclas	=	Landslide density within the parameter class
Densmap	=	Landslide density within the entire map
Npix (Si)	=	Number of pixels, that contain landslides, in a certain parameter class
Npix (Ni)	=	total number of pixels in a certain parameter class

The method is based on statistical correlation of a landslide map with different parameter maps. This correlation results in cross tables that can be used to calculate the density of the landslides per parameter class. Standardisation of these density values is obtained by relating these to the overall density of the entire area. In the present exercise the following parameter maps have been used for landslide hazard zonation:

Geological map	Slope map
Tectonic map	Shape of slope
Landuse map	Aspect map
Old slide zones	Drainage map

Using facilities available under GIS environment every map was crossed with the landslide map prepared on the basis of interpretation of the remote sensing data and the field data. Weighted maps were prepared and the same were integrated to have the valuation of all the parameters considered. Both the zonation of landslide hazard and the buffering along the linear features was undertaken with the aid of histograms.

The area under present study is finally divided into five landslide hazard zonation classes (Fig. 9). The landuse area falling under different classes is given in Table 2.

Most agricultural land in both Madhyamaheshwar and Kaliganga valleys falls under the highest hazard class and its proportion under other hazard classes is significantly low. It is a cause of concern as it is this land that houses most of the population and supports the economic activities of the masses.

Risk analysis

Vulnerability is defined as the degree of loss to a given set of elements resulting from the occurrence of the phenomenon. The elements at risk are the population, properties, infrastructure, economic activities and the others within a given area. The hazard maps without vulnerability analysis

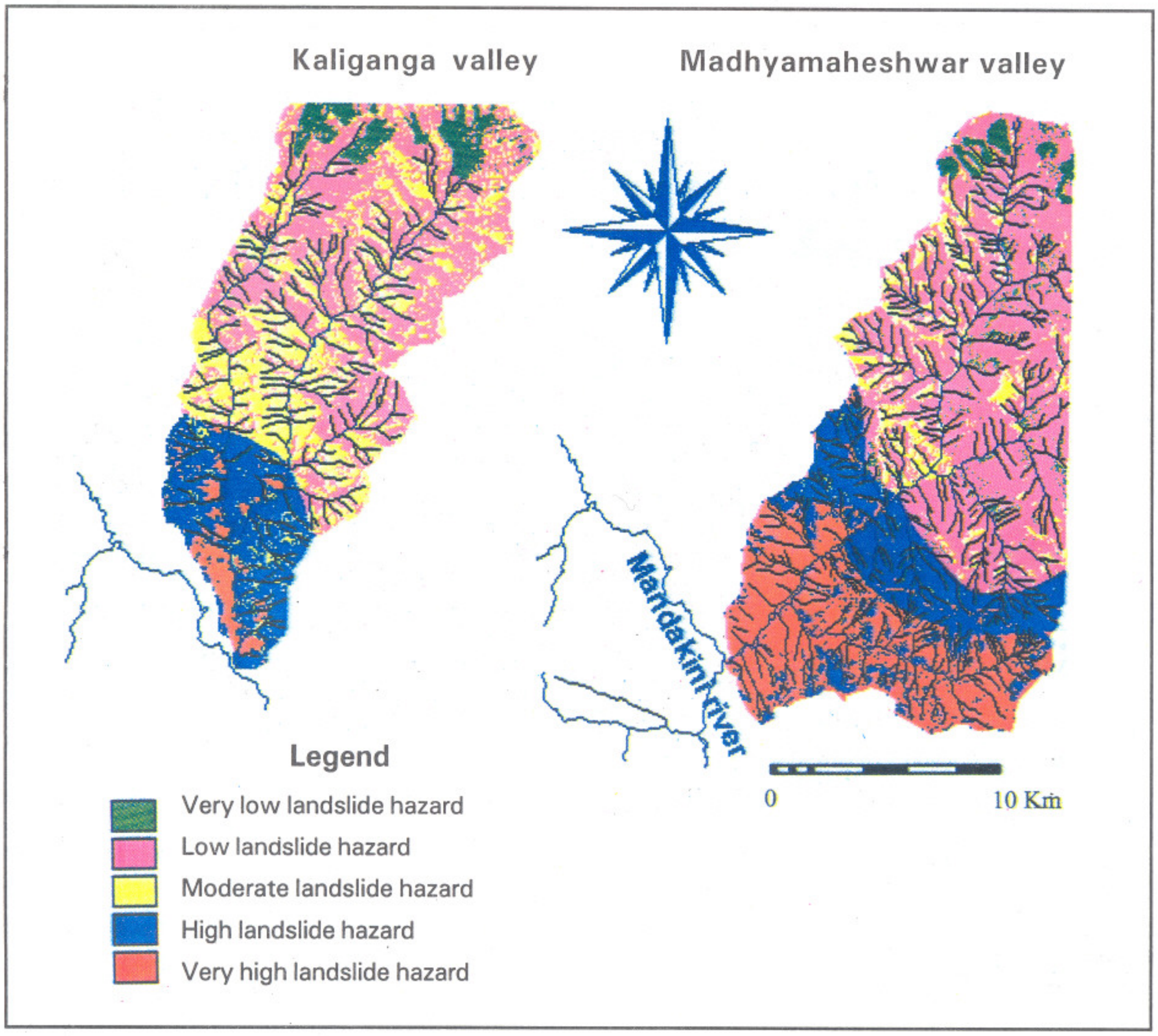

Fig. 9. Landslide hazard zonation map of Kaliganga & Madhyamaheshwar river valleys.

Table 2. *Relationship between landslide hazard class and landuse.*

Landslide hazard class		Distribution in the two valleys			
		Madhyamaheshwar		Kaliganga	
		Area (sq km)	%	Area (sq km)	%
Very high	Forest	29.43	48.5	2.23	35.9
Very high	Barren land	19.47	32.1	0.002	0.04
Very high	Agriculture	11.84	19.5	3.99	64.1
High	Forest	29.46	66.7	21.54	88.1
High	Barren land	14.45	32.7	2.71	11.1
High	Agriculture	0.25	0.6	0.22	0.9
Moderate	Forest	10.36	43.8	26.14	50.8
Moderate	Barren land	12.92	54.7	25.28	49.2
Moderate	Agriculture	0.35	1.5	0.0009	0.002
Low	Forest	59.91	56.0	13.75	18.9
Low	Barren land	47.01	43.9	57.31	78.8
Low	Agriculture	0.02	0.02	0	0
Very low	Forest	3.11	34.4	0	0
Very low	Barren land	1.57	17.4	0.01	0.1

are not meaningful for effective decision making. A small hazard in a densely populated strategic location may cause disaster many times greater than that at a sparsely populated area. Vulnerability maps are therefore prepared for Kaliganga and Madhyamaheshwar valleys using the population data and correlating it with the hazard maps prepared. Population is the sole criteria considered for this exercise because most infrastructure is interwoven around population centres. The population of these valleys (1991 census) has been classified into four classes and landlside risk analysis is undertaken in accordance with Table 3.

Risk map for Madhyamaheshwar and Kali river valleys is shown in Figure 10 while Table 4 shows the correlation between landuse and risk. The relationships between landuse and risk (Fig. 11,12) show that most of the agricultural land falls under high risk class.

Discussion

There exists a definite relationship between the distribution of slides and geological and tectonic set up of the area. This fact has been highlighted by the geologists in the past (Valdiya *et al.*, 1984, Valdiya 1998) and requires due attention on the wake of the present tragedies. Both in Kaliganga and Madhyamaheshwar valleys most slides are confined to sheared and fractured rocks of Munsiari Formation. There is a marked positive correlation between the distribution of landslides and landuse; in both the valleys most slides are confined to agricultural lands. This very fact makes the

Table 3. *Landslide risk classes based on landslide hazard zones and population distribution.*

		Landslide Hazard Zone				
		Very low landslide hazard	Low landslide hazard	Moderate land-slide hazard	High landslide hazard	Very high landslide hazard
Population class	Sparsely populated	Low landslide risk	Low landslide risk	Low landslide risk	Moderate landslide risk	Moderate landslide risk
Population class	Low population density	Low landslide risk	Low landslide risk	Moderate landslide risk	Moderate landslide risk	High landslide risk
Population class	Moderate population density	Low landslide risk	Low landslide risk	Moderate landslide risk	High landslide risk	High landslide risk
Population class	High population density	Low landslide risk	Moderate landslide risk	High landslide risk	High landslide risk	High landslide risk

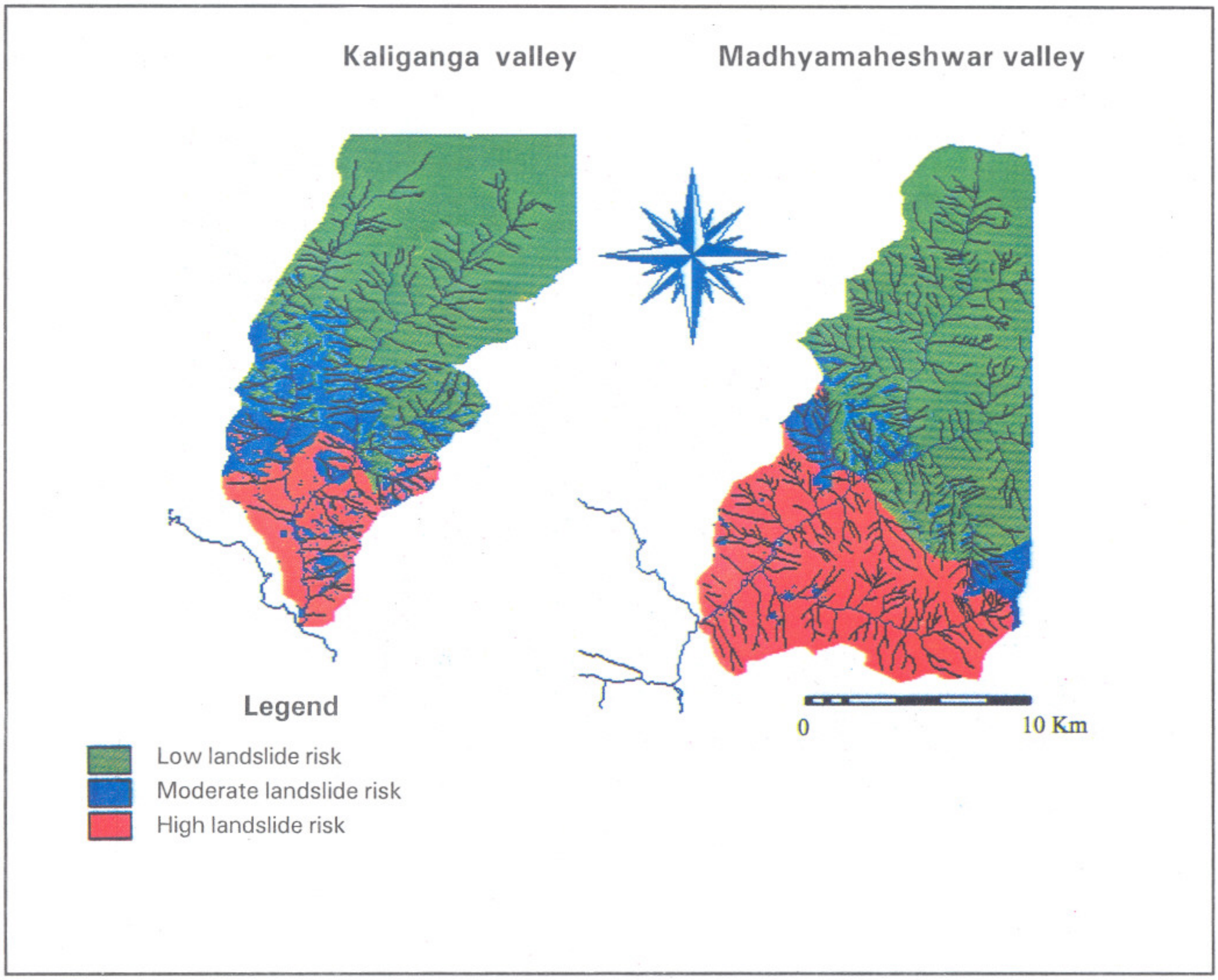

Fig. 10. Landslide risk map of Kaliganga & Madhyamaheshwar river valleys.

Table 4. *Relationship between the landuse class and the landslide risk class.*

Risk catagory	Landuse	Area (sq km) and percentage			
		Madhyamaheshwar		Kaliganga	
		Area (sq km)	%	Area (sq km)	%
Low risk	Forest	67.12	51.2	16.14	15.5
Low risk	Barren land	59.61	45.5	77.94	74.9
Low risk	Agriculture	0.05	0.03	0	0
Low risk	Glaciers	4.35	3.3	10.33	9.9
Moderate risk	Forest	12.29	59.0	29.01	84.7
Moderate risk	Barren land	7.45	35.7	4.92	14.4
Moderate risk	Agriculture	1.1	5.3	0.31	0.9
High risk	Forest	52.86	57.1	18.51	74.5
High risk	Barren land	28.35	30.6	2.45	9.9
High risk	Agriculture	11.32	12.2	3.89	15.7

populace of these valleys particularly vulnerable to landslides and requires detailed study of the changing landuse pattern in the recent times. Presence of agriculture on steep slopes show that the traditional landuse dictums have been violated under the compulsions of reducing land per capita. Agriculture is the sole source of livelihood in Himalaya and under compulsions of increasing population agriculture is often resorted to on steeper slopes by clearing the forest. This trend seems to have gripped the entire Himalayan terrain and therefore there is an urgent need for promoting non-land based economic activities in the region. Such an endeavour alone can relieve pressure upon land.

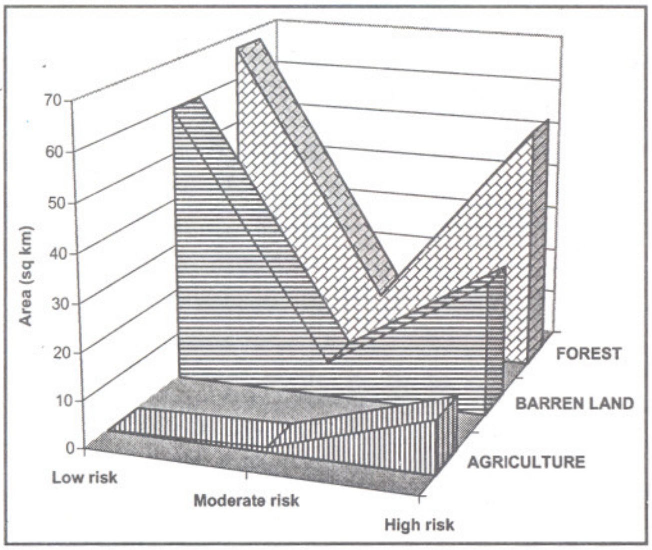

Fig. 11. Relationship between landslide risk and landuse in Madhyamaheshwar river valley.

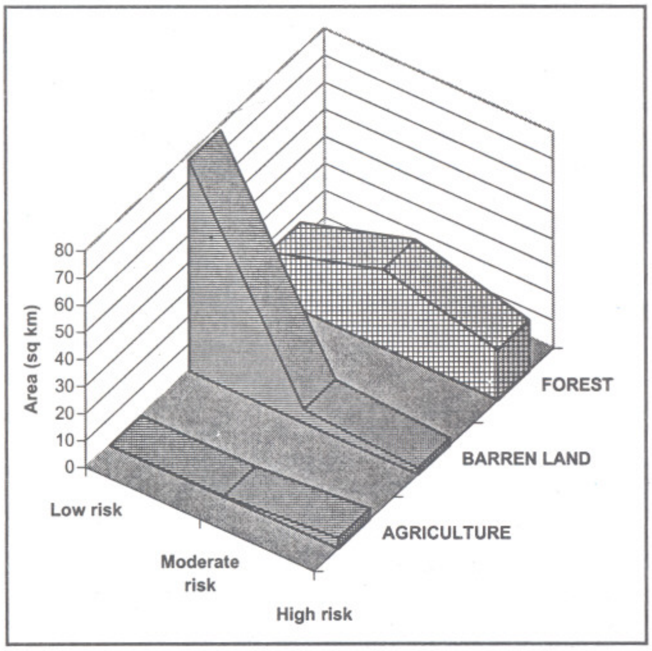

Fig. 12. Relationship between landslide risk and landuse in Kaliganga river valley.

A combination of factors, both natural and anthropogenic, have contributed to the present tragedy. Mounting pressure of population has forced people to practice agricultural activities on adverse slopes in the geologically and structurally fragile terrain of Madhyamaheshwar and Kaliganga valleys. The height of the embanking walls of the agricultural terraces has to be proportionately increased with increasing slope in order to bring equal area under cultivation. These terraces are in a destabilised position due to the mass of the soil and persistent rains saturating the soils only add to this. It is easy for the seasonal streams with high gradient to erode these terraces and trigger downslope movement. This process of mass movement is observed between Bedula and Raulekh in Madhyamaheshwar valley and between Bedula and Kalimath in Kaliganga valley. Traditional practice of maintaining jungle guls would have probably checked the level of saturation of the soils and the tragedy would not have taken this dimension. Increased pore water conditions are exhibited by the seepage and water emanating at many places amid the agricultural lands. At many places in the higher reaches of the valleys creep is also observed.

The Bheti slide that blocked the course of Madhyamaheshwar river is typical of slope failures in the Himalaya. This landslide occured on a slope that was covered with moderetely good forest. According to the local people a fissure running parallel to the valley was seen above the village after Uttarkashi earthquake. A road was under construction in the vicinity and dynamites used in the construction might have further widened the fissures. Toe erosion by Madhyamaheshwar only destabilised the slope and initiated movement along the pre-existing weak planes. Similar slides of smaller dimensions were also witnessed in the vicinity of Ransi village in Madhyamaheshwar valley.

Field evidences (water upwelling amid low lying fields and seepage in the fault scarp) show that the increased pore water pressure has played a major role in mass movement. The correlation between the quantum of rains and crossing of the threshold limits however require detailed and long research. Unless these questions are addressed, it would not be possible to constrain the timing and location of sliding.

Excessive water percolating underneath the ground has thus played a major role in these mass movements and even in the higher reaches of the watersheds where losses are not reported, active creeping is observed. At present many agencies are supporting developmental activities in the Himalayan region based on the watershed approach that seeks to maximise recharge of groundwater during rains so as to be available for productive purposes during lean periods, through a series of engineering, vegetative and allied activities in the watershed. Studies on Himalayan agriculture in Central Himalayan sector (Nepal) show that the terraces, especially on rainfed land, are often poorly constructed; these are outward rather than inward sloping and do not have a grassed bund on the edge. These are constructed on upper, steeper slopes that are inaccessible to irrigation systems and support traditional coarse cereals. These slope outward from the hillside so that the crops are not damaged by water-logging. The hill farmers are aware that increased accumulation of water on terraces (such as would result from inward sloping forms) would greatly accelerate the problem of landsliding by increasing the degree of soil saturation and adding weight of the ponded water itself (Johnson *et al.*,1982, Gurung 1988). Furthermore annual repair of the terraces would require a much larger labour input if these sloped inward. The monsoon rain is thus intended to run off the outward sloping terraces. The farmers traditionally do not engage in the bunding of hard to manage, far flung fields in the hilly terrain for the fear of downslope movement due to the enhanced weight of the saturated soils. In the valleys under focus (Madhyamaheshawar and Kaliganga) also rather than conserving the precipitation recourse was traditionally taken to easy dispersal of the excess precipitation through jungle guls. The strategy of development in the hilly regions thus needs reorientation, and water management needs to be given top priority. Participation of the masses, and revival of the traditional practice of maintaining jungle guls needs promotion for it is the most cost effective and time tested mitigative measure.

Though there exists no record of seismicity associated with present slides, the region lies in a seismically vulnerable zone (seismic gap). The region has been seismically active in the past (Fig. 13) and Madhyamaheshwar and Kaliganga valleys were visited by some shocks after the major landslide events (in November 1998). These valleys also suffered losses during the 1991 Uttarkashi earthquake (M 6.1) and the epicentre of 1999 Chamoli earthqake does not fall far away from this region. Microseismic studies are therefore warranted in the region.

Fieldwork, supplemented by the analysis of the secondary and primary data under GIS environment (ILWIS 2.1) has helped in preparing landslide hazard zonation maps for Kaliganga and Madhyamaheshwar valleys. Risk maps have also been prepared for these valleys. For preparing the risk maps population has been considered as the sole criteria as most of the infrastructure is closely interwoven around population centres. These can be used for effective mitigative planning in the region.

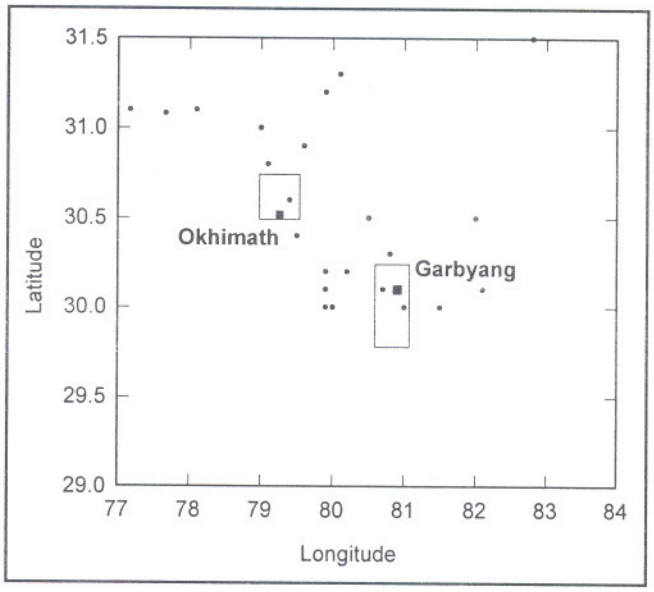

Fig. 13. Epicentres of the past earthquakes around the study area (data USGS).

A comprehensive strategy for relief and rescue also needs to be prepared keeping in view the fragility of the region that often destroys the conventional infrastructure at the time of the exigency and the bureaucracy should be well versed with the relief and rescue operations that they have to undertake.

Landslide hazard zonation needs to be undertaken in a systematic manner using the state of art technology so as to clearly demarcate high risk zones. The administration in these zones should be specially trained and should be engaged in regular drills of rescue operations so as to ensure that there is no mismanagement when the tragedy strikes. The opinion of the scientific community, as also the traditional beliefs and practices of the locals needs to be given due wieghtage while making various developmental policies for the high hazard prone areas.

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References

Anbalgan, R., 1992. Landhazard evaluation and zonation mapping in mountainous terrain. *Engineering Geology*, **32**, 269-277.

Bist, K.S. & Sinha, A.K., 1982. Some observations on the geological and structural setup of Okhimath area in Garhwal Himalaya: A preliminary report. *Him. Geol.*, **10**, 467-475.

Brabb, E.E., 1984. Innovative approaches to landslide hazard and risk mapping. *Proceedings Fourth International Symposium on Landslides,* Toronto, Canada, **1,** 307-324.

——————, 1995. The San Mateo Couinty California GIS project for predicting the consequences of hazardous geological processes *In*: Carrara A. & Guzzetti F. (eds), *Geographical Information Systems in Assessing Natural Hazards,* Kluwer Academic Publishers Netherland, 229-334.

——————, Pampeyan, E.H. & Bonlia, M.G., 1972. Landslide susceptibility in San Mateo county, California, *USGS Misc. Field studies map.*

——————, Wadge, G. & Reading, A.J., 1989. Designing a geographical Information System for the prediction of landsliding potential in the West indies. *Proceedings Economic Geology & Geotechnics of Active Tectonic Regions,* University College London.

Burroughs, P.A., 1986. *Principles of Geographical Information System for land resources assessment,* Clarendon Press, Oxford.

Carrara, A.E., Catalone. E.; Sorriso Volvo, M.; Realli, C. & Ossi, I. 1978. Digital terrain analysis for land evaluation. *Geological Applications Indogelogia,* **13,** 69-127.

——————, Pugliese-Carratelli & Merenda, L., 1977. Computer based data bank and statistical analysis of slope instability phenomenon. *Zeitchrift fur Geomorphologie,* **21,** 187-222.

Choubey, V.D. & Litoria, P.K., 1990. Terrain classification and land hazard mapping in Kalsi Chakrata area (Garhwal Himalaya), India. *ITC Jour.,* **1,** 68-65.

Dhar, O.N., Kulkarni, A.K. & Rakhecha, P.R., 1986. Meterology of heavy rainfall over Garhwal Kumaun regions of the Himalayas: A brief appraisal. *Proceedings of Workshop on Flood Estimation in Himalayan Region,* Central Board of Irrigation & Power, New Delhi.

(ESCAP) Economic and Social commission for Asia and Pacific, 1989. *Environmental management of mountain ecosystems in Asia and the Pacific,* Bangkok, Thailand: ESCAP.

Gupta, R.P. & Joshi, B.C., 1990. Landslide hazard zoning using Gis approach-A case study from Ramganga catchment, Himalaya. *Engineering Geol.,* **28,** 119-131.

Gurung, Sumitra M., 1988. *Beyond the myth of eco-crisis in Nepal: local response to pressure on land in the middle hills.* Unpublished Ph.D. thesis, University of Hawaii, Honolulu.

Johnson, K., Olson, E.A. & Manandhar, S., 1982. Environmental knowledge and response to natural hazards in mountainous Nepal. *Mountain Research & Development,* **2,** 175-88.

Kawakami, H. & Saito, Y., 1984. Landslide risk mapping by quantification method. *Proceedings of International Symposium on Landslides,* Toronto, 535-540.

Mehrotra, G.S., Sarkar, S. & Dharmaraju, R., 1991. Landslide hazard assessment in Rishikesh - Tehri area, Garhwal Himalaya, India. *Proceedings of the Sixth International Conference on Landslides,* New Zealand.

Naranjo, J.L., Van Westen, C.J. & Soesters, R., 1994. Evaluating the use of training areas in bivariate statistical landslide hazard analysis- A case study in Colombia. *ITC Jour.,* **3,** 292-299.

Pachauri, A.K. & Pant, M., 1992. Landslide hazard mapping based on geological attributes. *Engineering Geol.,* **32,** 81-100.

Pearson, E., Wadge, G. & Wislocki, A.P., 1991. An integrated expert system/GIS approach to modelling and mapping natural hazards. *Proceedings European Confernce on GIS (EGIS),* **26,** 763-771.

Radbruch, D.H. & Wentworth, C.M., 1971. Estimated relative abundance of landslides in the San Francisco Bay region, California. *US Department of the Interior, US Geological Survey.*

ɔeshgiri, D.N., Lakshmi Kanathan, C.B.; Upendran, R. & Subramanian, K., 1982. Landslide zonation in Nilgiri Plateau, Tamilnadu, India. *Proceedings of Fourth Congress of IAEG, New Delhi,* **1,** 379-390.

Stevenson, P.C., 1977. An empirical method for the evaluation of relative !andslide risk. *International Association of Engineering Geologists Bulletin*, **16,** 69-72.

Valdiya, K.S., 1998. Catastrophic landslides in Uttaranchal, Central Himalaya. *Jour. Geol. Soc. India,* **52,** 483-486.

——————, Virdi, N.S., Mehrotra, G.S., Bose, S. & Kumar, G. , 1984. *Aspects of landslides in UP hills: Remedial measures, public policy and legislative actions.* Subcommittee Report submitted to the Hill Development Department of UP Government on July 14, 1984.

Van Westen, C.J., 1994. Geographical Information Systems in landslide hazard zonation: A review, with examples from the Andes of Colombia, *In*: Price M.F. & Heywood D.I. (eds), *GIS applications for mountain areas,* Taylor & Francis, U.K., 135-166.

——————, 1997. Statistical landslide hazard analysis, In: *ILWIS 2.1 for Windows Application Guide,* ITC Publication,Enschede.