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ACKNOWLEDGEMENTS. Funds to carry out this project were provided by Technological Development Programme of National Remote Sensing Agency (NRSA), Department of Space, Government of India, Hyderabad, and the Tata Energy Research Institute, Delhi. We thank Sharad Lele and Shaily Menon for their suggestions to improve the manuscript. Thanks are due to Mr B. Gharai for assistance in image processing work. Encouragement and guidance from the Director and Deputy Director (Applications), NRSA are gratefully acknowledged. This also represents contribution number 76 of a programme in biodiversity conservation supported in part by the MacArthur Foundation, involving the Ashoka Trust for Research in Ecology and the Environment (ATREE), Bangalore, University of Agricultural Sciences, Bangalore, Pondicherry University, Pondicherry, Institute of Social and Economic Change, Bangalore, Tata Energy Research Institute, Delhi, and University of Massachusetts, Boston.

Received 25 February 2000; revised accepted 8 May 2000

An evidential weighted approach for landslide hazard zonation from geo-environmental characterization: A case study of Kelani area

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The interaction between various components of the geocomplex on the solid crust of the earth has always been of keen interest. In the present study we have attempted to understand and characterize the geo-environmental parameters over the Kelani area in Bino basin, located in the fringe of Garhwal and Kumaun Himalaya. Twelve geo-environmental parameters are considered for the landslide hazard zonation. Inclusion of such diverse parameters into the model possibly would have the bias of the observer. Using remote sensing data and Geographical Information System (GIS), we have attempted an evidential weighted approach, to delineate the spatial distribution of the landslide hazard zones, which is site-specific and bias free.

THE term geo-environment deals with the interaction between the various components of geocomplexes on the solid crust of the earth. The geocomplexes are materials of the crust, landforms, waterbodies, climate, hydrological cycle, natural processes, biotic and abiotic communities which form certain specific spatial interacting ecosystems in a regional set-up. The complex is also included in the different states of the atmosphere particularly the meso, macro and microclimates which are important ecological factors. The functional interactions are formed between geo-environmental factors and their spatial environment. Anthropogenic activities are also causing a major drastic modification in the composition of the ecosystem. The harmonious relationship between man and his environment ensures under the environmental geology[1]. Therefore, geo-environment can be approached both by geoscience and biological science. Studying the contribution of such diverse geo-environmental parameters for a particular application would certainly enhance our knowledge over the state and dynamics of that site.

The application of remote sensing and Geographical Information System (GIS) has been widely studied by many researchers[2–4], especially in the area of geosciences. Consideration of aerial photographs in preparing inventory of landslides is inevitable especially in the Himalayan region, conventionally[5,6]. For the present study remote sensing data and aerial photographs integrated with GIS are being utilized.

The main objectives of the present study are (i) to assess the geo-environmental factors; (ii) to prepare a landslide inventory; and (iii) to predict spatial distribution of landslide hazard zones.

The area of study, Kelani, is located at the centre of the Bino basin, a tributary of the western Ramganga in the Lesser Himalaya. Geographically the area is bounded by 79°9'29"E to 79°14'31"E and 29°52'48"N to 29°57'7"N which covers 64 km^2, at the height difference of 920 to 1820 m between the fringe of Garhwal (Pauri district) and Kumaun (Almora district) regions (Figure 1).

Kelani is a very popular village, with Ramnagar being the nearest railway station. Geologically the Kelani area forms the southern limb of Dudhatoli syncline where the Dudhatoli–Almora crystallines[7], phyllites[8] and schist are well exposed. One of the typical meta-sedimentary layers is found in the western flank of Kelani area (Figure 2) between two types of Dudhatoli granite-gneisses (coarse and fine-grained), which has not been reported so far. This formation is given the name Kelani Formation[9]. It is 20 to 30 m wide, consists of micaceous quartzite, carbonaceous slate, phyllite conglomerate and garnetiferous mica schist. The quartzite is massive in nature, sachuroidal texture and equigranular. Below the quartzite band, the bluish-grey coloured slate is well exposed, having a high siliceous content. Garnetiferous mica schist is found below the slate, having a high mica content with schistocity and fine to medium grains of garnet.

The Kelani Formation is highly fractured, folded, faulted and some places are highly weathered, being responsible for natural hazards, i.e. landslide, rockfall,

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Figure 1. Study area.

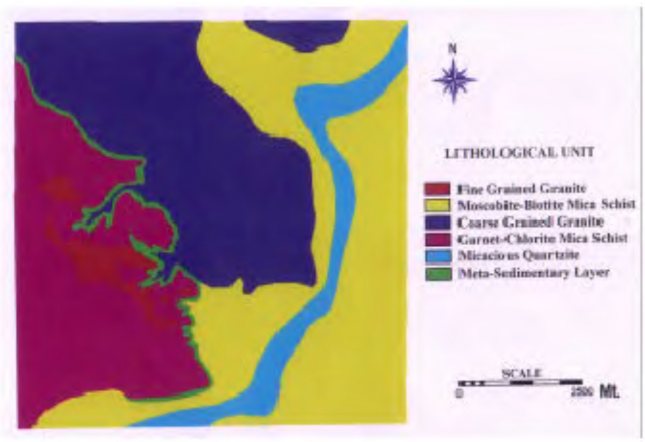

Figure 2. Geological map of Kelani area (Bino basin).

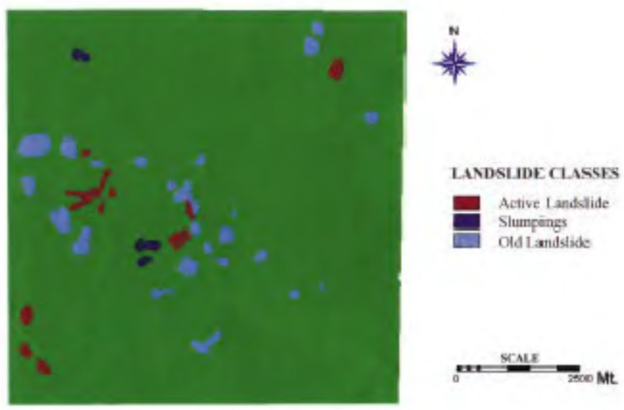

Figure 3. Landslide inventory map of Kelani area (Bino basin).

slumping and gully erosion. Thus mass movement in the Kelani area is quite common. Geohydrologically this belt is very important because schist and jointed granite form the pervious layers and metasedimentary layers form the impervious layers; wherever the impervious layer is displaced and fractured, springs and seepage of water appear.

The previous literature of the study area available is based on geological and geomorphological investigations. The region requires further systematic study of lithology, structures and environment. Middlemiss[10] was the first to carry out investigations regarding the geology of Dudhatoli region. Auden[11] described the Dudhatoli crystalline as a thrust sheet. Das[12] has also

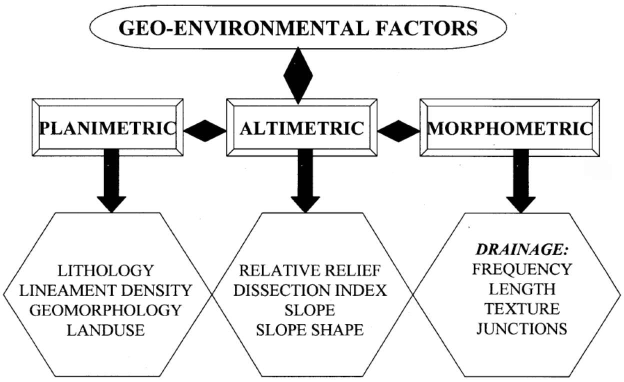

Figure 4. Geo-environmental parameters.

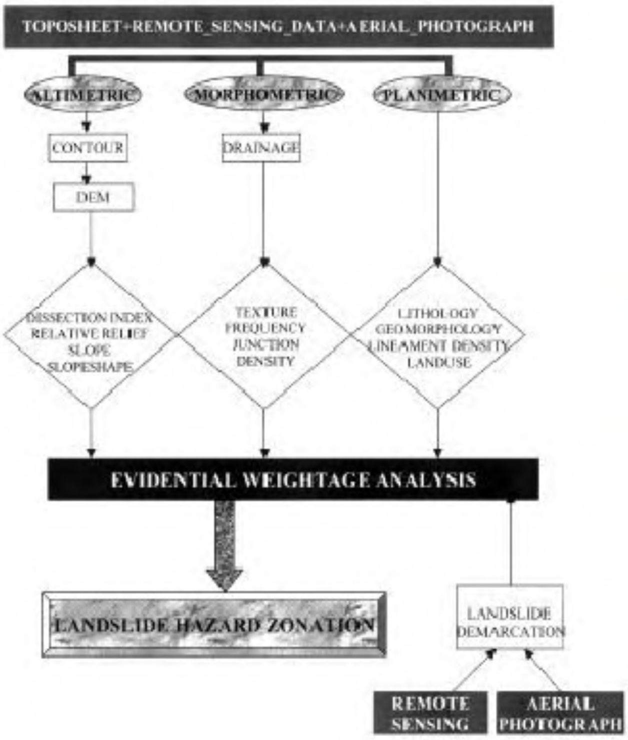

Figure 5. Flow of the analytical approach.

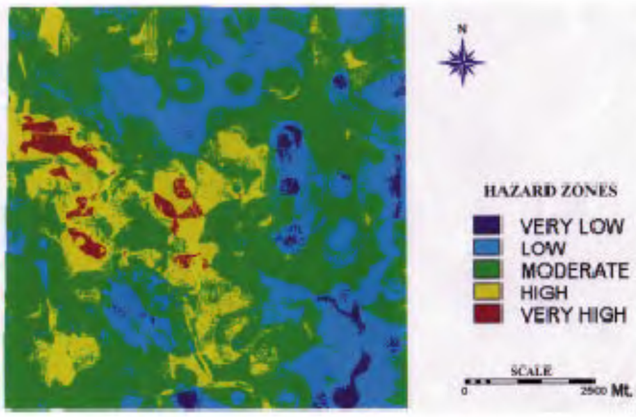

Figure 6. Landslide hazard zonation map of Kelani area (Bino basin)

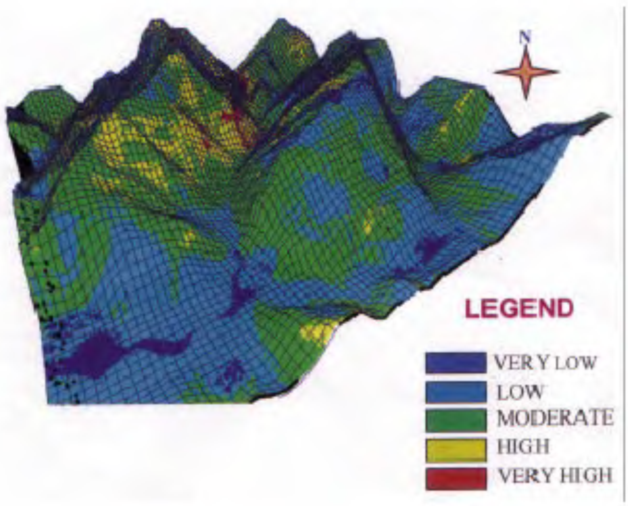

Figure 7. Landslide hazard zonation map.

studied the metamorphism in the Dudhatoli area and has shown that the rocks of this area have undergone metamorphization up to the sillimanite zone. A detailed geomorphological study of the Bino basin was carried out by Datt[13] using aerial photo-interpretation techniques. The study area is under human pressure from all sides. The impact of environmental degradation is reflected in many ways like increase in landslides, soil erosion, stream bank erosion, over-grazing and deforestation. Datt[14] studied the biomass flow system and environmental degradation of the Kelani village. Datt *et al.*[15] analysed the geo-environmental problems expected around the Tehri Dam reservoir using remote sensing and GIS techniques.

The present study was carried out in three major steps: data collection, coherent database generation and analysis. Study area locational information from Survey of India toposheet (53 O/1), set of aerial photographs in 1:40,000 scale (strips 44:28–33, 43:23–30), satellite data (IRS-1C LISS III, 1998) both soft and hard copy, and information related to geology (Figure 2) and landslides (Figure 3) of the study area collected from ground truth, various primary and secondary sources, were used.

The natural hazard map has been prepared on the basis of aerial photo interpretation and satellite imagery (IRS-1C, LISS III), digital image processing and ground truth collection. Active landslides, slumping, old landslides, soil erosion and floods are the main degradational features. Old landslide features are very common in the form of colluvial cones and fan-shaped debris flow along the scarp, steep and concave slopes. Sometimes secondary landslide patches can also be observed over the old landslide debris. Slumping is quite common on the concave seepage slopes whereas the old landslide debries is spread on the upper margin of spurs. The unconsolidated former glacial deposits are also found on the few gentle sloppy spurs up to a height of 1500 m (ref. 13). The lower margin of the debris is slumping in a very slow manner. Active landslides are seen along the rivulets in the highly jointed, fractured and faulted zones. Geohydrological characteristics, i.e. springs, seepage, perennial channels and numerous confluence points are also responsible for active landslides. In the present study large (10 to 500 m) landslides are considered and mapped. Small landslide patches (less than 10 m) frequently occur during the monsoon season, but they are not mapped.

Mainly 12 geo-environmental parameters (Figure 4) have been taken into consideration. These parameters jointly affect the surface chemistry and play a significant role in new land formation. These factors are grouped into two parts, i.e. natural and anthropogenic factors, but emphasis is given to the natural factors. Both these factors are very active in the Himalayan terrain. Natural factors are further grouped into three classes, i.e. planimetric (areal based), altimetric (relief based) and morphometric (drainage based).

Among the planimetric factors lithology, lineament density, geomorphic units, natural hazards and landuse are considered. Altimetric factors are based on the relief analysis (contours). Among them relative relief, dissection index, slope, aspects and slope morphology are prominent. Morphometric factors are based on the drainage analysis which includes the drainage frequency, drainage density, drainage texture and drainage junctions. Geohydrology plays a significant role in the natural hazards but due to the lack of data (e.g. water discharge, number of springs), it could not be included in the study. It is observed that most of the springs and seepages (locally known as *Simar*) are found along faults, fractures, joints and permeable layers.

Climatic factors are also considered for the natural hazard zonation but such data are not considered for the analysis due to lesser number of observation points. It is observed that most of the landslides occurred during the rainy season. High rainfall intensity accelerated the sliding and slumping in the existing hazard zones. The average annual rainfall over 4 years (1994–1998) is 215.7 cm for Kelani village. As far as anthropogenic factors are concerned, only landuse is considered for the analysis, but other activities like road, canals and settlements were also taken into account during the field visit. It is found through overlay analysis that their contribution to the landslide is very small, hence they have not been considered for the hazard zonation. For computation, the area of study is divided into one square kilometre grids and then the parameters are found. Further statistical analysis based on GIS techniques (Figure 5) was carried out. The final sliced map depicts the distributional pattern of each parameter of the landslide hazard (Figure 6).

The combination of different factors influences landslide hazards. Normally these factors are given weightages according to the researcher's observation. This method would reflect the relative importance of each map but would suppress the relative contribution of each class within a single map[16]. Moreover there would be a bias in determining the higher probable contributing elements. With the assumption that the influence of different geo-environmental parameters is site-specific, we have attempted to derive a statistical evidence-based approach for landslide hazard zonation.

We have considered the present study as a two-stage experiment. The first stage can be described by stating that exactly one of say, k possible outcomes must occur when the complete experiment is performed. Those possible outcomes will be denoted by $L_1, L_2, L_3, \ldots, L_k$ (i.e. active landslide, old landslide, slumps, etc.). They represent the possible causes that can produce them, through the outcome obtained in the second stage of the experiment. In the second stage there are, say, m possible outcomes, exactly one of which must occur. These will be denoted by $C_1, C_2, C_3, \ldots, C_m$ (classes within a map). The values of probabilities for each of the possible causes $C_1, C_2, C_3, \ldots, C_k$ are given and they are denoted by $p(C_1), p(C_2), \ldots, p(C_k)$. The values of all the conditional probabilities of the type $p(C_i/L_j)$, which represent the probability that the second stage event C_i will occur when it is known that the first stage event L_j is given. Our problem is to calculate the probability of having a landslide in a class, i.e. second stage event C_i (geo-environmental parameter class) when the first stage event L_j (landslide class) is known. This conditional probability is written as $p(C_i/L_j)$. In this approach we consider the inventory of landslides prepared from aerial photographs and satellite remote sensing data as the first stage and the classes which are causing it as the second stage.

Since the occurrence of landslides may depend on some of the parameter classes, we consider, in general, that the first stage event is not mutually exclusive of the second stage event. So according to Baye's theorem, the probability that a geo-environmental parameter layer class (C_1) contributes to the occurrence of a landslide class (L_1), when the latter is known, is

$$P(C_1/L_1) = P(C_1 \text{ and } L_1)/P(L_1). \quad (1)$$

$$\text{Prior probability of evidence} = P(C_1 \text{ and } L_1) = P(C_1)*P(L_1/C_1). \quad (2)$$

Table 1. Probability information table

Factor	Class	Domain class	Site-specific evidential weightage
Slope (degrees)	Less than 5	Gentle	0.14
	5 to 15	Moderate	0.29
	15 to 30	Moderately steep	0.19
	30 to 55	Steep	0.14
	> 55	Very steep	0.23
Relative relief (m)	< 200	Low	0.00
	200 to 300	Moderate	0.15
	300 to 400	Moderately high	0.41
	400 to 500	High	0.28
	> 500	Very high	0.16
Dissection index	< 0.2	Low	0.00
	0.20 to 0.25	Moderate	0.01
	0.25 to 0.30	Moderately high	0.00
	0.30 to 0.35	High	0.00
	> 0.35	Very high	0.99
Slope shape	–10 to 0.01	Concave	0.36
	0.01 to 0.1	Flat	0.28
	0.1 to 10	Convex	0.36
Drainage frequency	< 2	Low	0.00
	2 to 4	Moderate	0.18
	4 to 6	High	0.50
	> 6	Very high	0.31
Drainage density	< 2	Very low	0.09
	2 to 3	Moderately low	0.38
	3 to 4	Moderate	0.36
	> 4	Moderately high	0.17
Drainage texture	< 0.2	Very fine	0.00
	0.2 to 0.4	Fine	0.37
	0.4 to 0.6	Moderate	0.57
	0.6 to 0.8	Coarse	0.06
Stream junctions	< 2	Very low	0.04
	2 to 4	Low	0.47
	4 to 6	Moderate	0.38
	6 to 8	High	0.11
	> 8	Very high	0.00
Lithology	Class 1	Coarse-grained granite	0.11
	Class 2	Fine-grained granite	0.33
	Class 3	Meta-sedimentary layer	0.34
	Class 4	Micacious quartzite	0.03
	Class 5	Garnet-granite mica schist	0.14
	Class 6	Moscobite-bitite mica schist	0.04
Lineament density	Class 1	Low	0.07
	Class 2	Moderate	0.09
	Class 3	High	0.16
	Class 4	Very high	0.68
Geomorphic units	Class 1	Faulted valley	0.48
	Class 2	Scarp face	0.00
	Class 3	Strike valley	0.03
	Class 4	Structural hill	0.08
	Class 5	Transverse valley	0.12
	Class 6	Undifferential Meta-sedimentary zone	0.29
Land use	Class 1	Agriculture	0.15
	Class 2	Civil forest	0.24
	Class 3	Degraded forest	0.21
	Class 4	Dense forest	0.14
	Class 5	River bed	0.02
	Class 6	Waste land	0.24

Table 2. Area distribution of landslide classes

Hazard zones	No. of pixels	Area (sq km)	Area (in %)
Very low	10923	1.09	1.75
Low	180947	18.09	29.03
Moderate	320577	32.06	51.44
High	99983	10.00	16.05
Very high	10807	1.08	1.73

$$\text{Probability of evidence} = P(L_1) = P(C_1)^* P(L_1/C_1) + P(C_2)^* P(L_1/C_2) + \ldots = \sum P(C_i)^* P(L_1/C_i), \quad (3)$$

where $(1 \le i \le k)$.

Prior probability of a class $C_1 = P(C_1) = T(C_1)/T(\text{study})$,

and

$$P(L_1/C_1) = H(L_1)/T(C_1),$$

where $T(C_1)$ is the total number of cells having the class C_1, T(study) is the total number of cells in the study area and $H(L_1)$ is the number of cells of C_1 having L_1.

Using the values obtained from eqs (2) and (3) over eq. (1) the probability of a hazard being contributed by the class can be obtained. The obtained probability (Table 1) is considered as an evidential weightage for that class and the weighted sum of all the classes and all the geo-environmental parameters was calculated. The output map is the representation of spatial distribution of the landslide hazard zones. Further, the map was reclassified into 5 categories showing very low, low, moderate, high and very high landslide hazards zones (Figure 6). The final landslide hazard zonation map draped over the digital elevation model depicts the natural variability as on the ground (Figure 7).

The five classes of hazards and their aerial distribution, total pixels and area in percentage are given in Table 2. The results show that the very high hazard zone is occupied by only 1.73% of the total area. It is confined along the Ghat Gad, Gun Gad, Bino and Basola Gad in the north-western part of the study area. The area represented by the very high hazard zone correctly depicts the existing low angle stream junctions, steep to very steep slopes and scarp slopes, which are mainly occupied by the active and old landslides.

The maximum area of the north-western flank comes under the high hazard zone (Figure 6). The main localities are Bagdiyalgoon, Samaya, Ghuguti, Nahalgair, Sade, Rikhon and Patalgaon. About 16.1% of the study area is under high hazard zone. This area is highly dissected by drainage lines. The Kelani Formation of rocks are highly folded, faulted, fractured and displaced at many localities. The drainage lines are found over this structural features. During the field study, it is noted that most of the springs are found along these linear features. Therefore, geohydrologically Kelani Formation is very important and is the matter of further investigation. The presence of springs in the highly jointed and weathered impervious layers and structural features like iso-clynal folds dislocated axial planes, consecutive factors, tension cracks and faults are jointly responsible for natural hazards in the Kelani area. About 51.4% of the study area is under the moderate zone. Water divides, mid slopes and spurs come under this category. This category of hazards is almost equally distributed all over the study area except lower valley bottoms of Bino and Massangarthi. Mainly, sheared zone of schist rocks is under the moderate hazard zone.

Low hazard zone is occupied by the area of lower valley bottoms from Deghat to Palpur village in the Bino valley and Khaldua to Deghat in the Massangarthi valley. The gentle mid spurs also come in the low hazard zone. About 29.03% of the total area comes under this zone. Very little percentage of area (1.75%) is under very low hazard zone. Main valley bottoms and river terraces come under this class. The slope is very gentle and land is well managed by anthropogenic activities. River bank erosion during flood can be included in this class.

The overlay analysis reveals that moderate slopes have contributed more landslides in the past rather than very steep slopes (Table 1). Also high and very high morphometric parameters (drainage density, drainage texture, drainage frequency and stream junctions) have not contributed much to the landslides, but their moderate values or classes have contributed more. The contribution of land use elements seems to be fuzzy in nature. The lithological elements quartz and slate and granite–gneisses have contributed more. Faulted valley has contributed major landslides in the geomorphic units. Dissection index and lineament density authenticates that the more of these values certainly would contribute to the landslides. Slope shape contribution seems to be same for both types of shapes, i.e. convex and concave.

The above discussion concludes the following results: (a) The evidential weightage approach shows that most of the active landslides, old landslides and slumpings are concentrated in the very high and high hazard zones. (b) Most of the study area is under low and moderate hazard zones, with less area is under low hazard zones. (c) Higher altimetric and morphometric values have not contributed much to the landslides except higher dissection index. (d) Contribution of higher values of lineament density, a planimetric parameter, is vital.

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ACKNOWLEDGEMENTS. We thank Dr P. S. Roy, Dean, IIRS and Mr P. L. N. Raju, In-Charge, Geoinformatics Division, IIRS for their moral support during the study. We also thank the Vice-Chancellor, H. N. B. Garhwal University, Srinagar for permission to pursue the study at IIRS, Dehradun.

Received 1 December 1999; revised accepted 27 April 2000.