

Deforestation and land use changes in Western Ghats, India

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We estimated changes in forest cover between 1973 and 1995 in the southern part of the Western Ghats using satellite data. The study area of approximately 40,000 km² showed a loss of 25.6% in forest cover over 22 years. The dense forest was reduced by 19.5% and open forest decreased by 33.2%. As a consequence, degraded forest increased by 26.64%. There has been a great deal of spatial variability in the pattern of forest loss and land use change throughout the region. Our estimates of deforestation in the region for the contemporary period are the highest reported so far.

DEFORESTATION has many ecological, social and economic consequences, one of which is the loss of biological diversity. In India, the Eastern Himalayas and the Western Ghats constitute two of the 24 global hotspots of biodiversity¹. Although it is widely believed that tropical regions are experiencing losses of biodiversity at unprecedented rates, we lack information about the rate of habitat loss in these hotspots of biodiversity and elsewhere. Menon and Bawa² have estimated the rate of deforestation in the Western Ghats to be 0.57% annually during the period 1920–1990 and Prasad *et al.*³ have assessed 0.90% annual decline in natural forest cover in Kerala for the period 1961–1988. However, regional estimates for more recent periods have been lacking. It is true that the Forest Survey of India (FSI) does publish statistics on forest cover every two years^{4–6}, and in recent years has started to provide limited data for changes in forest cover, but the classification is coarse. For example, natural forest cover is not distinguished from tree plantations. Moreover, estimates of land cover for two different time periods are based on different data sources and methodologies. Other problems include arbitrary distinction between open and dense forests and lack of error estimation in assessment. Thus, the estimates of forest cover by FSI are often not in concordance with those of other organizations.

Here we report changes in forest cover in the southern half of the Western Ghats from 1973 to 1995. Our study departs from previous analyses in several ways. First, for the two time frames (1973 and 1995) we rely on remote sensing imagery of the entire study area, making

it feasible to compare land cover change with precision. Second, we use extensive ground truths to provide sufficient inputs for the training sets as well as for determining the mapping accuracy. Third, the change is detected for a more recent period, starting from the launch of the first remote sensing satellite to the launch of a new family of Indian satellites in the mid-nineties. Specifically, we address three questions pertaining to the southern Western Ghats: (1) What is the extent of overall change in the vegetation classes? (2) What is the level of variation if the magnitude of change is different among classes? (3) What is the degree of spatial variation in deforestation?

The study area (around 40,000 km²) extends from 8°0'N to 12°30'N latitude and 75°0'E to 78°30'E longitude. The hill ranges in the area rise to elevations of more than 2000 m at some places. Rainfall varies to a maximum of 7000 mm and declines as one moves from the south to the north and from the west to the east. The variability in precipitation and topographic diversity generates a wide variety of vegetation types, ranging from wet evergreen and semi-evergreen forests on the western side and at high altitudes to dry deciduous forests and scrub vegetation on the eastern slopes and lowlands. The major land use classes in the area are forests, tree plantations, agriculture, and coffee and tea estates. The Western Ghats is a stable land mass of Archaean and Precambrian rock formations⁷. Of the more than 16,000 species of flowering plants recorded from India, about 4000 species are found in the Western Ghats, including 1600 endemic species⁸. The study area covers districts in three states, Karnataka, Kerala and Tamil Nadu.

Deforestation and land use change were studied by comparing satellite images of 1973 Landsat MSS and 1995 IRS 1B LISS-I. These sensors have comparable ground resolutions, i.e. 80 × 80 m and 72.5 × 72.5 m, respectively. The area was covered in five Landsat MSS scenes and seven IRS 1B LISS-I full scenes. The LANDSAT MSS digital cloud-free data of the optimum season (January–March) of 1973 were acquired from EROS Data Center, Sioux Falls, USA, and the 1995 IRS 1B LISS-I digital data for the cloud-free optimum season (January–March) obtained from National Remote Sensing Agency (NRSA), Hyderabad. The MSS images were brought to the same pixel resolution as that of IRS LISS-I resolution in the digital domain through image to image correction procedures, following studies that have been carried out to resolve the problems of change detection in the vegetated areas using multi sensor and multi date images^{9,10}. Satellite data from two different dates were co-registered and classified separately, and area statistics for different districts were compared. The digital method of image differentiation was avoided in order to minimize the errors resulting from the artifacts of changing radiometric conditions that arise from a large number of scenes on different dates of passes.

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The digital image processing was performed using Easi/Pace software¹¹ on IBM RISC 9000 workstation platform at NRSA, Hyderabad. The various modules used were geometric correction, mosaicing and supervised classification. Both the LISS-I scenes and MSS data were first registered path-wise, and then the different strips of LISS-I scenes were mosaiced. Similarly, the different strips of MSS scenes were mosaiced. During the mosaicing procedure, radiometric matching was performed to minimize seamlines.

In order to geometrically correct the satellite data with reference to the Survey of India (SOI) toposheets, the following 1:250,000 scale toposheets of the SOI were used: 49M, 58A, 58E, 49N, 58B, 58C, 58G, 58D and 58H. The toposheets were individually fixed on the A0 size digitizer table and GCPs (Ground Control Points) were generated for the common points in the IRS 1B LISS-I image and the toposheets. Approximately 200 GCPs distributed all over the images were assigned. The image was resampled with a fifth-order polynomial with a root mean square error (RMSE) of around 100 m. The MSS mosaiced image was also co-registered with reference to IRS data with an RMSE of less than one pixel.

The unprocessed false colour composite (FCC) hard copies of the two images, i.e. 1973 MSS and 1995

Table 1. Accuracy assessment

Class	Dense	Open	Degraded	Grassland	Plantation	Row Total
Dense	32	3	0	0	3	38
Open	3	36	2	0	4	45
Degraded	0	4	39	3	5	51
Grassland	0	1	2	23	1	27
Plantation	2	5	3	2	48	60
Column total	37	49	46	28	61	221

Overall mapping accuracy = $178/221 = 80.54\%$.

User's accuracy for the different classes: Dense 84%; Open 80%; Degraded 76%; Grassland 85%; Plantation 80%.

Table 2. Changes in land use from 1973 to 1995 (km²)

Land use	Year		Difference
	1973	1995	
Dense	5940.98	4782.91	1158.06
Open	4728.24	3156.68	1571.56
Degraded	3059.35	3869.26	-809.913
Grassland	1139.30	1466.64	-327.34
Agriculture	15533.66	17266.84	-1733.18
Plantation	9108.31	9726.45	-618.14
Total geographical area	39357.66	39357.66	

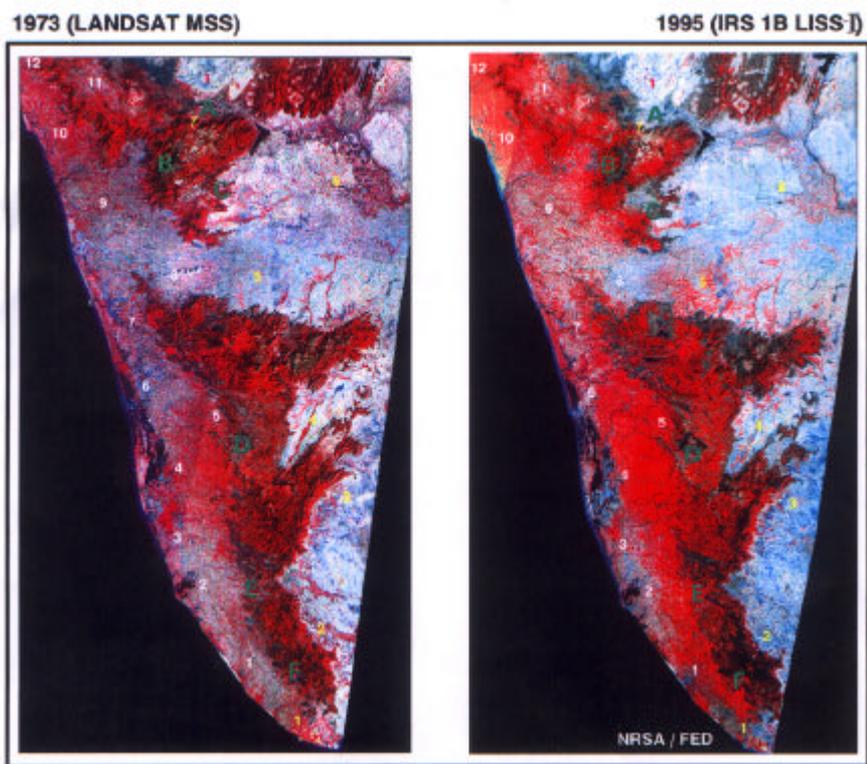


Figure 1. False Colour Composite of southern Western Ghats showing Landsat MSS of 1973 and IRS 1B LISS-I of 1995 covering the districts of Kerala and Tamil Nadu.

Table 3. Forest cover changes in the Western Ghats districts of Kerala and Tamil Nadu from 1973 to 1995 (km²)

District	Year	Vegetation cover classes								Area
		Dense forest	Open forest	Degraded forest	Grassland	Plantation	Water bodies	Agriculture	Cloud	
Coimbatore	1995	227.24	289.21	988.87	71.77	271.93	20.49	5532.33	0.00	7469.00
	1973	502.27	730.58	375.69	76.73	175.71	54.69	5486.15	0.00	
	Difference	275.03	441.38	-613.19	4.96	-96.21	34.21	-46.18	0.00	
Ernakulam	1995	15.42	15.40	84.30	0.00	233.40	87.96	1969.04	0.00	2408.00
	1973	15.79	92.86	84.71	0.32	166.41	328.56	1716.87	0.00	
	Difference	0.37	77.46	-0.41	0.32	-67.00	240.59	-252.16	0.00	
Idduki	1995	1557.40	273.92	664.61	593.16	1724.43	116.05	44.25	0.00	5061.00
	1973	1491.16	1056.50	981.22	606.99	770.52	46.41	18.46	2.54	
	Difference	-66.24	782.58	316.61	13.83	-953.91	-69.65	-25.79	2.54	
Kanyakumari	1995	196.51	0.77	114.85	145.57	201.98	37.49	955.50	0.00	1684.00
	1973	248.23	21.84	159.54	47.53	187.23	112.05	876.25	0.00	
	Difference	51.72	21.07	44.69	-98.04	-14.75	74.57	-79.25	0.00	
Kozhikode	1995	142.20	2.84	3.42	8.21	1680.06	12.15	501.23	0.00	2344.00
	1973	164.87	18.00	0.00	0.00	1977.50	64.10	125.65	0.00	
	Difference	22.67	15.16	-3.42	-8.21	297.43	51.95	-375.59	0.00	
Mallapuram	1995	305.82	619.49	61.01	13.54	1962.86	1.96	591.31	0.00	3674.00
	1973	393.70	370.72	85.10	31.76	1875.11	86.33	713.26	0.00	
	Difference	87.89	-248.77	24.09	18.22	-87.75	84.37	121.95	0.00	
Nilgiri	1995	293.48	921.26	447.76	573.86	199.54	84.20	9.53	0.00	2549.00
	1973	783.26	798.25	284.83	0.00	633.03	11.68	17.08	1.48	
	Difference	489.79	-123.01	-162.93	-573.86	433.48	-72.52	7.55	1.48	
Palghat	1995	338.05	347.52	515.79	44.44	593.67	37.19	2560.83	0.00	4392.00
	1973	610.45	648.60	339.51	49.85	235.72	43.07	2445.89	63.72	
	Difference	272.40	301.08	-176.28	5.41	-357.95	5.88	-114.94	63.72	
Trichur	1995	95.32	212.68	160.65	0.50	340.83	12.14	2197.04	0.00	3031.00
	1973	172.91	390.06	210.30	3.98	227.72	252.28	1761.91	0.00	
	Difference	77.59	177.38	49.66	3.48	-113.11	240.14	-435.13	0.00	
Wyanad	1995	468.52	335.21	276.31	8.34	868.47	0.41	156.51	0.00	2125.00
	1973	546.61	428.00	97.96	0.00	799.35	0.07	241.73	0.03	
	Difference	78.09	92.80	-178.35	-8.34	-69.12	-0.34	85.23	0.03	
Quilon	1995	1142.95	138.38	556.90	7.27	1649.28	156.08	968.82	0.00	4620.66
	1973	1011.71	172.82	440.48	322.13	2060.03	131.77	481.58	0.14	
	Difference	-131.24	34.45	-116.42	314.87	410.74	-24.31	-487.24	0.14	

LISS-I were generated on 1:250,000 scale to undertake reconnaissance level field verification. Based on the tonal variations as seen on FCCs, the southern stretch of the Western Ghats has been investigated. After the detailed field knowledge, maximum likelihood classification procedure has been adopted to discriminate various forest and other land cover classes. Based on the preliminary output of the classified forest output image, it was found that there was a fairly large amount of mixing in the spectral behaviour of non-forested and forested area classes.

The non-forested areas of the southern stretch of the Western Ghats predominantly consist of homesteads and plantations having evergreen and semi-evergreen species which exhibit similar spectral behaviour as that of natural forest. This obviously creates spectral confusion in segregating the forest and non-forest classes accurately. In order to enhance the spectral classification accuracy, a mask was created to segregate moun-

tainous, forested areas and non-forest areas. Further, the image was segmented as follows. The areas north and south of Palghat were distinguished to reduce radiometric confusion resulting from different scenes acquired for different dates. Then, in each area, mountainous and plains areas were delineated. Forested and non-forested areas were discriminated separately for mountainous and plains areas in each of the two zones, north and south of Palghat. Non-forested areas consist of various types of land use and water bodies. For the LISS-I image, supervised classification using the maximum likelihood method was performed to distinguish different vegetation and land cover classes. Similar training sets for the unchanged area (based on the interactive visual interpretation) were identified in the MSS image, which was also classified in the same way as the LISS-I image. The sensitivity/problems arising from some parts of the image due to improper season in case of non-availability of cloud-free data were taken care of by

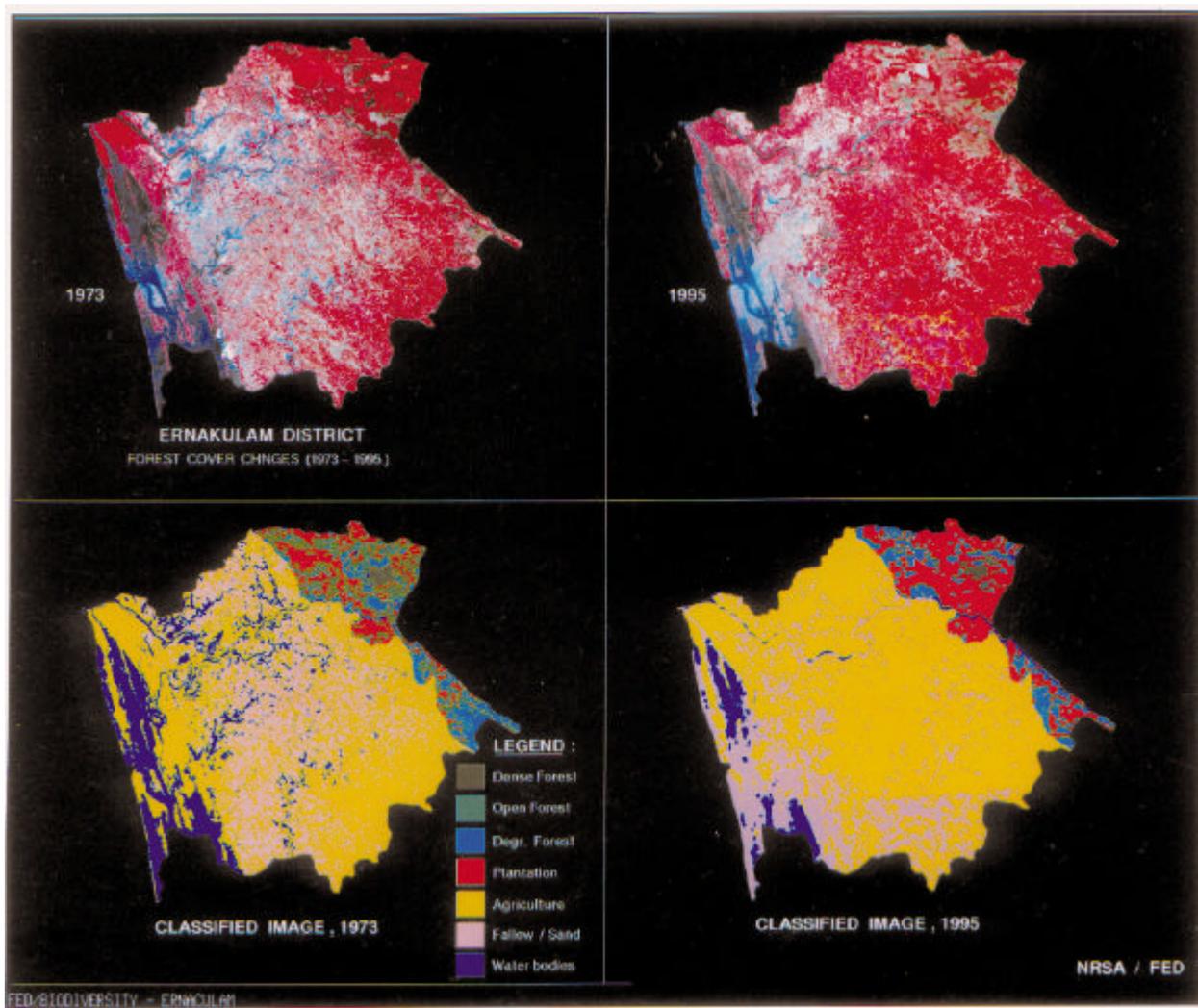


Figure 2. False Colour Composite and classified image of 1973 and 1995 for Ernakulam district.

giving the training sets for classification as well as by segmentation and post-classification image editing procedures for these specific areas.

The district boundary vector layer was registered with reference to the corrected images and overlaid on the image. Finally the district-wise area statistics were computed.

Mapping accuracy assessment was undertaken following Congalton¹² by estimating commission and omission errors. The 1995 classified satellite image in the form of a hard copy on a 1:250,000 scale was used for ground checking for the various vegetation classes. The Stratified Random Sampling approach was followed in allocating the sample points in different strata of forest cover classes. Depending on the accessibility in the dif-

ferent vegetation classes, 221 randomly distributed points were selected based on the proportional contribution in terms of aerial extent for the different forest class strata. The coordinates of these point locations were taken from the georeferenced classified image. On ground these points/patches were identified with the help of 10 channel hand-held global positioning system (Magellan Pro Max-X). The patches of different cover classes selected for accuracy assessment were more than 10 pixel by 10 pixel to avoid inaccuracies due to coarse resolution and the hand-held GPS receiver. The 1973 scenario being a retrospect, no such accuracy assessment similar to that of 1995 was possible and thus the accuracy of 1973 was taken care mostly with reference to the unchanged areas of the 1995 image. At the same

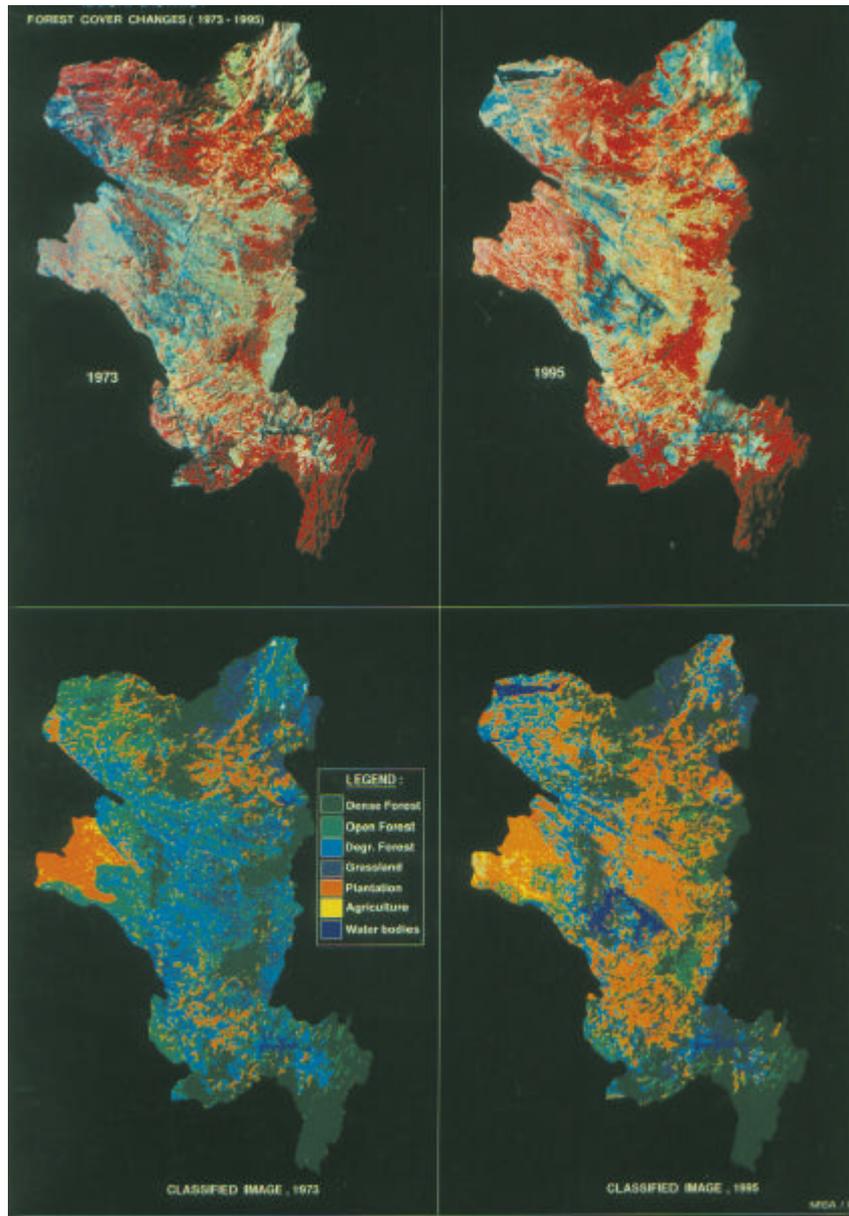


Figure 3. False Colour Composite and classified image of 1973 and 1995 for Idduki district.

time the changes identified were verified with inquiries made during the detailed ground truth visit as well as old forest records and literature.

The forested area was classified as follows: (1) Dense forest – having a canopy cover > 40%; (2) Open forest – having a canopy cover between 20% and 40%; (3) Degraded forest with < 20% canopy cover. This class also includes scrub vegetation and forest blanks. The choice of vegetation/forest classification was based on the sen-

sor resolution used for the study area which facilitated the discrimination of the mentioned classes. The overall mapping accuracy was found to be 80% (Table 1). The inaccuracies were mostly contributed by the commission of a few points of a forest crown density class to the forest class of the next crown density.

The southern stretch of the Western Ghats, an area of approximately 40,000 km² has experienced significant land use change during the period 1973–1995 (Figure

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1). There has been a loss of 2729 km² of forest, that is loss of forest cover with the crown density up to 20% or more, which amounts to 25.6% of the forest area (Table 2). Thus the annual rate of deforestation is 1.16% of the total forested area. The dense forest has shrunk by 19.5% or at an annual rate of 0.8%, and the open forest has decreased in area by 33.2%, or an annual rate of 1.5%. As a result, areas have increased under degraded forest (26.64%), grasslands (28.73%), plantations (6.78%), and agriculture (11.15%) (Table 2).

The changes in the forest and land cover in the southern region of the Western Ghats exhibit great spatial variation, as evident from the district-wise statistics (Table 3). The districts of Coimbatore and Palghat have experienced the highest annual rates of loss of dense forest, i.e. 2.4% and 2.1%, respectively, whereas the

districts of Ernakulum (Figure 2) and Kozhikode have experienced the lowest annual rates, 0.1% and 0.6%, respectively. The highest loss of open forest occurred in Kanyakumari and Kozhikode at an annual rate of 4.4% and 3.8%, respectively. The scenario for the degraded forest was reverse to that of dense forest as most of the districts show increase in degraded forest area as a result of conversion from dense and open forests, except Idduki (Figure 3), Kanyakumari and Mallapuram which have shown loss of degraded forest at an annual rate of 1.46%, 1.27% and 1.27%, respectively. Similarly, plantations increased most notably in Palghat and Idduki districts at an annual rate of 6.90% and 5.62%, respectively. Agricultural areas increased most notably in Kozhikode and Idduki districts at an annual rate of 13.58% and 6.35%, respectively.

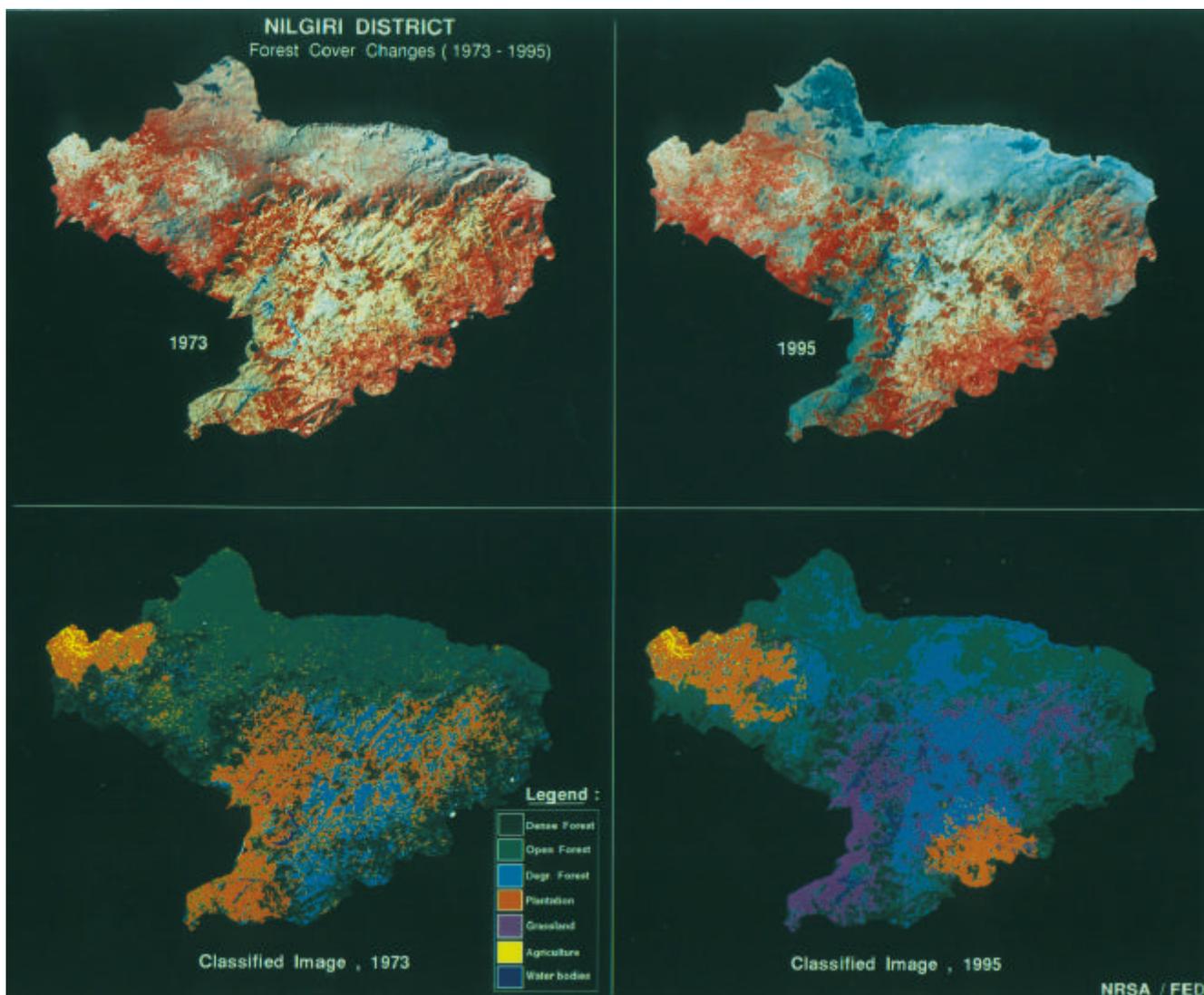


Figure 4. False Colour Composite and classified image of 1973 and 1995 for Nilgiri district.

Previous estimates of deforestation in India are for different regions and different time periods. The United Nation Food and Agriculture Organization¹³ estimated the annual rate of deforestation for India to be 0.60% during the period 1981–1990. For the same period, Ravindranath and Hall¹⁴ citing an NRSA report¹⁵ stated the rate to be 0.40%. Menon and Bawa¹⁶ reconciled the disparities by pointing out the differences in the methods and definitions of forests in the two reports. In particular, the NRSA report defined forests to include tree plantations, thereby severely underestimating the rate of deforestation.

At the regional level, Menon and Bawa¹⁶ found the annual rate of deforestation in the Western Ghats to be 0.57% during the approximately 70-year period from 1920s to 1990s. In the Agastyamalai region the rate was 0.33% during the time interval from 1920 to 1990 (ref. 17). In Kerala, forest loss has been estimated to be 0.28% every year^{3,18}.

There is obviously considerable spatial and temporal variation in the rates at which forests are being converted into other land uses. Spatial variation may occur over a relatively small scale. In Kerala, a substantial decline in evergreen and semi-evergreen forests, but an increase in the area covered by deciduous forests was noted^{3,18}. In our analysis, rates of deforestation vary from –0.73% to 1.84% per annum for various districts considering the total forested area. The negative rate may be due to increase in forest cover through protection.

The rate of forest conversion estimated here is the highest reported so far, and is almost two times that of the previous estimates. This raises the question if the rates of deforestation have accelerated in recent years, despite the conservation measures adopted by various agencies. The data from Agastyamalai region, indicating a five-fold increase in forest loss from the periods 1920–1960 to 1960–1990 (ref. 17), also suggest that the rates may be increasing. Improved methods to estimate loss of forests may have also led to more realistic estimates than in the past. In the present study, forest cover has been estimated by the same investigators using imagery from the same regions supported by verification on the ground. Moreover, in a recent study of deforestation in Amazonia¹⁹, groundwork supplemented by imagery and better analytical framework than used in the past also indicated rates of deforestation much higher than those reported in the past.

The high rate of forest loss reported here does not include forest degradation and habitat fragmentation that can also eventually contribute to the loss of forest conservation. If the existing forests were classified according to canopy cover and the contiguity of the areas, the area under forests that has at least 50% canopy cover and occurs in large contiguous blocks of at least 1000 km² will be substantially less than that indicated

by the current figures. Thus, the loss of forest and associated biodiversity extends far beyond the simple statistics of deforestation.

The decrease in forest area can be attributed to increase in plantations and agricultural areas. The most rapid change has occurred in Kerala, which has a high population density. The area under plantations increased most notably in the Idukki district, which also experienced the highest rate of conversion of open forest into other land uses (Figure 3). The increase in grasslands in Nilgiri district (Figure 4) has been due to removal of wattle (*Acacia mearnsii/A. dealbata*) plantations.

In this change analysis we were constrained by the limitations of cloud-free satellite data in different seasons and thus we could not address the changes in the water bodies. Changes in water bodies are very sensitive to variation in rainfall over seasons and years. The acquisition of multi-season microwave data could help in detecting such changes.

The high rate of deforestation should be a cause of serious concern. More detailed analyses of deforestation and its underlying causes are required for the Western Ghats and other areas of India. Such analyses will help design more effective mitigation strategies and conservation measures than in the past.

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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 inter-

acting 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 geology¹. 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 researchers²⁻⁴, 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 km², 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 crystallines⁷, phyllites⁸ 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 Formation⁹. 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, saccharoidal 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 schistosity 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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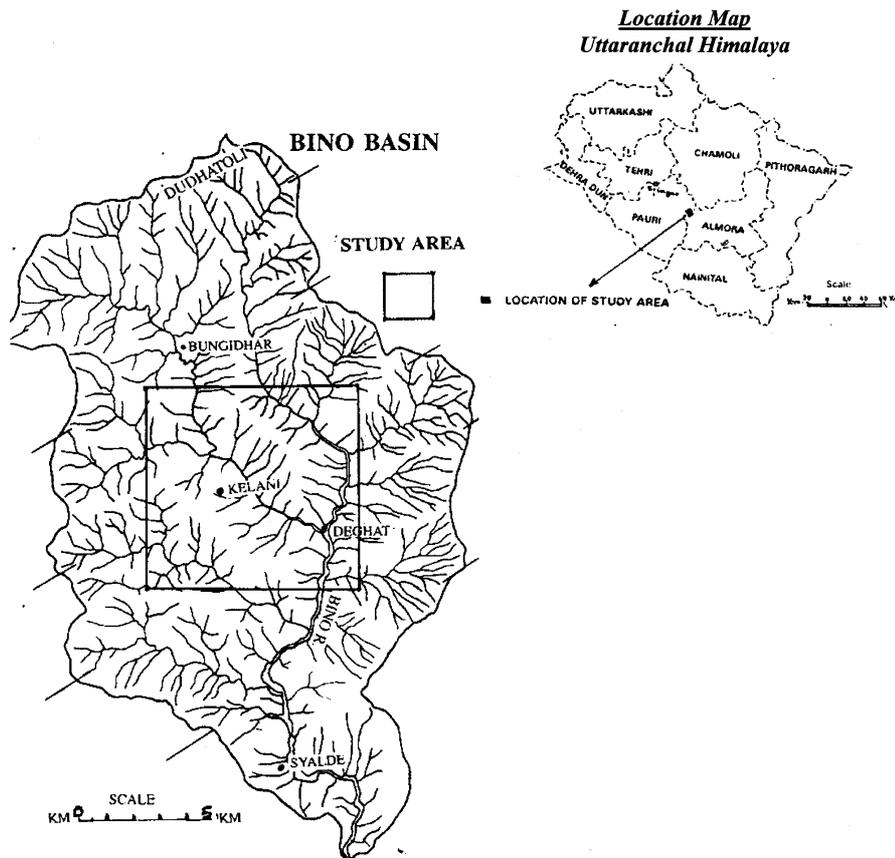


Figure 1. Study area.



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

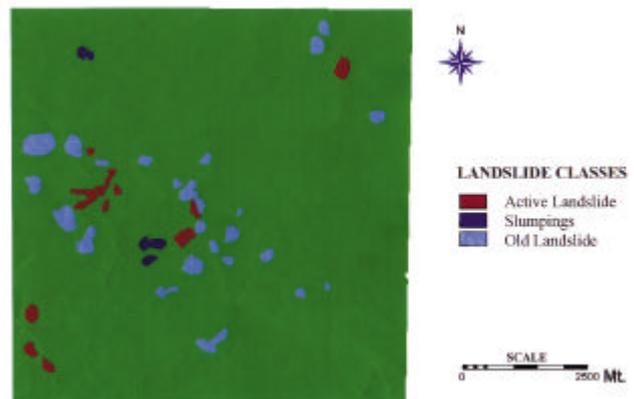


Figure 3. Landslide inventory map of Kelani area (Bino basin).

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. Middlemiss¹⁰ was the first to carry out investigations regarding the geology of Dudhatoli region. Auden¹¹ described the Dudhatoli crystalline as a thrust sheet. Das¹² has also

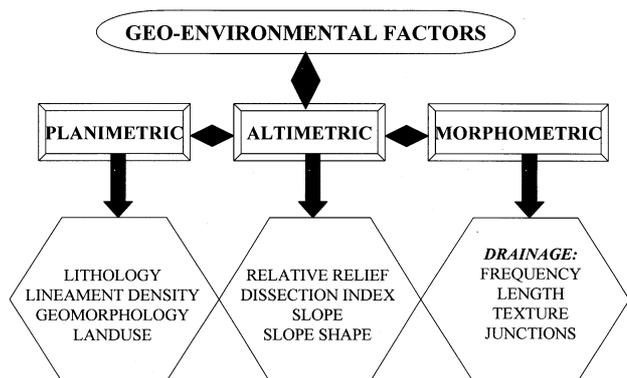


Figure 4. Geo-environmental parameters.

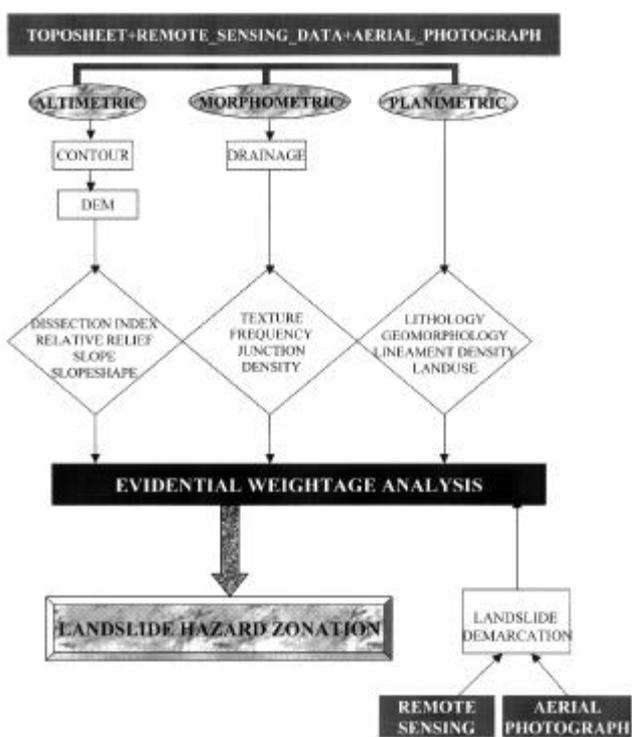


Figure 5. Flow of the analytical approach.

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 Datt¹³ 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. Datt¹⁴ 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.

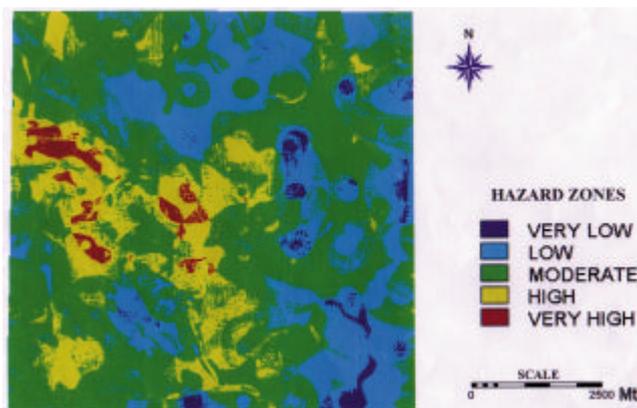


Figure 6. Landslide hazard zonation map of Kelani area (Bino basin)

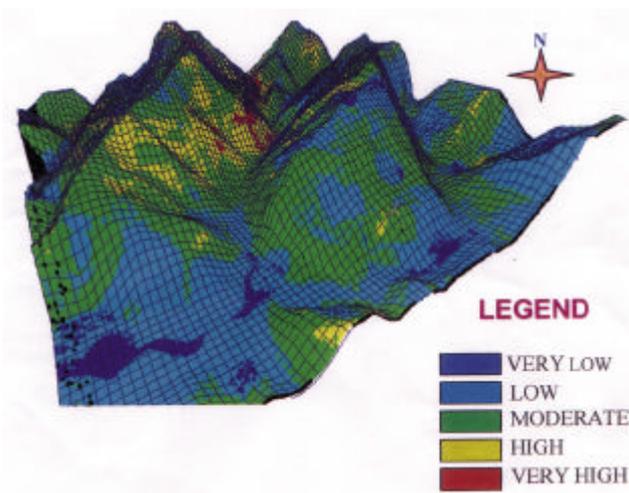


Figure 7. Landslide hazard zonation map.

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 degrada-

tional 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 debris 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 weight-ages 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 map¹⁶. 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 $L_1, L_2, L_3, \dots, L_k$ (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 $C_1, C_2, C_3, \dots, C_m$ (classes within a map). The values of probabilities for each of the possible causes $C_1, C_2, C_3, \dots, C_k$ are given and they are denoted by $p(C_1), p(C_2), \dots, p(C_k)$. 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

$$\begin{aligned} \text{Probability of evidence} &= P(L_1) = P(C_1) * P(L_1/C_1) \\ &+ P(C_2) * P(L_1/C_2) + \dots \\ &= \sum P(C_i) * P(L_1/C_i), \end{aligned} \quad (3)$$

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

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 , $T(\text{study})$ 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 Bagdiyagoon, 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 Massangarhi. 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 Massangarhi 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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