ORIGINAL PAPER

Modelling of stream run-off and sediment output for erosion hazard assessment in Lesser Himalaya: need for sustainable land use plan using remote sensing and GIS: a case study

Pradeep K. Rawat · P. C. Tiwari · C. C. Pant · A. K. Sharama · P. D. Pant

Abstract Assessment and inventory on soil erosion hazard are essential for the formulation of successful hazard mitigation plans and sustainable development. The objective of this study was to assess and map soil erosion hazard in Lesser Himalaya with a case study. The Dabka watershed constitutes a part of the Kosi Basin in the Lesser Himalaya, India, in district Nainital has been selected for the case illustration. The average rate of erosion hazard is 0.68 mm/year or 224 tons/km^2/year. Anthropogenic and geo-environmental factors have together significantly accelerated the rate of erosion. This reconnaissance study estimates the erosion rate over the period of 3 years (2006–2008) as 1.21 mm/year (398 tons/km^2/year) in the barren land having geological background of diamictite, siltstone and shale rocks, 0.92 mm/year (302 tons/km^2/year) in the agricultural land with lithology of diamictite, slates, siltstone, limestone rocks, while in the forest land, it varies between 0.20 mm/year (66 tons/km^2/year) under dense forest land having the geology of quartzwacke and quartrenite rocks and 0.40 mm/year (132 tons/km^2/year) under open forest/shrubs land having geological setup of shale, dolomite and gypsum rocks. Compared to the intensity of erosion in the least disturbed dense forest, the erosion rate is about 5–6 times higher in the most disturbed agricultural land and barren land, respectively. The erosion hazard zones delineated following scalogram modelling approach. Integrated scalogram modelling approach resulted in severe classes of soil erosion hazard in the study area with numerical values of Erosion Hazard Index (EHI) ranging between 01 (very low hazard) and 5 (very high hazard).

Keywords Natural hazards · High run-off · Erosion · Himalaya · India

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1 Introduction

Land use plays a significant role in driving hydrological processes within watersheds. Vegetation removal, which reduces evapotranspiration, can cause increased overland flow and groundwater inputs into streams (Bartarya 1991; Davies-Colley and Smith 2001; Rawat 1987; Sutherland et al. 2002 and Tiwari 2000). Conceivably, the most prominent land use increasing impermeable surface and affecting hydrology in Himalaya is settlement and agricultural development. Investigations have revealed that increases in a watershed's proportion of impermeable surface such as hardened soils, surficial bedrock or human-made structures such as pavement or buildings may considerably impact stream hydrology and produce both high magnitudes and early peaks in storm hydrographs (Dunn and Lilly 2001; Nearing et al. 2005; Randhir 2005). These alterations in hydrology can have dramatic effects on ecological processes within stream ecosystems (Bisht and Tiwari 1996; Haigh et al. 1988; Hundecha and Bárdossy 2004; Marshall and Randhir 2008; Marshall and Randhir 2008; Moore and Wondzell 2005; Poff et al. 2006; Rawat 1987; Bartarya 1991).

This study is one part of a multidisciplinary project on hydrological characteristics in Lesser Himalaya, sponsored by Department of Science and Technology (DST) Gov of India. Here, an attempt is made to assess land cover and human impacts on stream hydrology in Lesser Himalaya by quantifying the channel discharge characteristics.

Soil erosion is one of the major hydrological hazards in Himalayan river basins because the natural rate of erosion in the Himalaya is very high in comparison with those in most other parts of the world (Rawat and Rawat 1994). The geodynamically active Himalayan terrain is being denuded at the rate of varying from 0.09 to 1.7 mm/year (Gregory and Walling 1973; Valdiya and Bartarya 1989). There are several factors that may contribute to this acceleration, including deforestation, poorly managed agriculture, forest fire, over-grazing and substandard construction of roads and buildings on vulnerable sites. However, the pressure of human and animal populations on the scant land resources in the Himalaya has considerably intensified erosion hazard. Ives (1989) suggested that the process of erosion is accelerated in Himalaya by deforestation and torrential rain storms, whereas other leading investigations considered the land use/land cover change as a major controlling factor for erosion in Himalaya (Valdiya and Bartarya 1989; Rawat and Rawat 1994; Tiwari 2000). Jain et al. (1994) suggested high seismicity along the steep slops is the major responsible factor of soil erosion in Himalaya. Sing (2006) concluded in his work from Brahmaputra basin in Himalaya that higher run-off and higher relief have high erosion potential. Although, in recent past, a number of studies have been done on erosion problem in Himalaya as considered one or two controlling factors but there is no scientific basis to agree with the views expressed by them because there are several factors that may contribute to this acceleration, including steep slopes, stressed geology, active tectonics, changing land use pattern, stony hilly soil types, dynamic geomorphic features and high run-off rate, etc. Consequently, the present study carried out with integrated approach considering 7 key factors and their 35 classes or sub-factors to erosion hazard assessment. In order to that, 4 sample micro-watersheds have been identified to estimate erosion rate in terms of varied ecosystem, i.e. geology, geomorphology, average slope, soil types and land use pattern in Lesser Himalaya (Table 1). In view of this, the proposed work will fill up this highly realized gap and thus will have great scientific relevance in the field of erosion hazard and risk management in Himalaya and other mountainous parts of the world. In this paper, the authors presented data of erosion rates of sample micro-watersheds as suspended load, dissolved load and bed load under varied ecological conditions to drown erosion hazard zones of the study area and also suggested a remote sensing and GIS-based

Table 1 Selected four sample micro-watershed under varied ecosystem

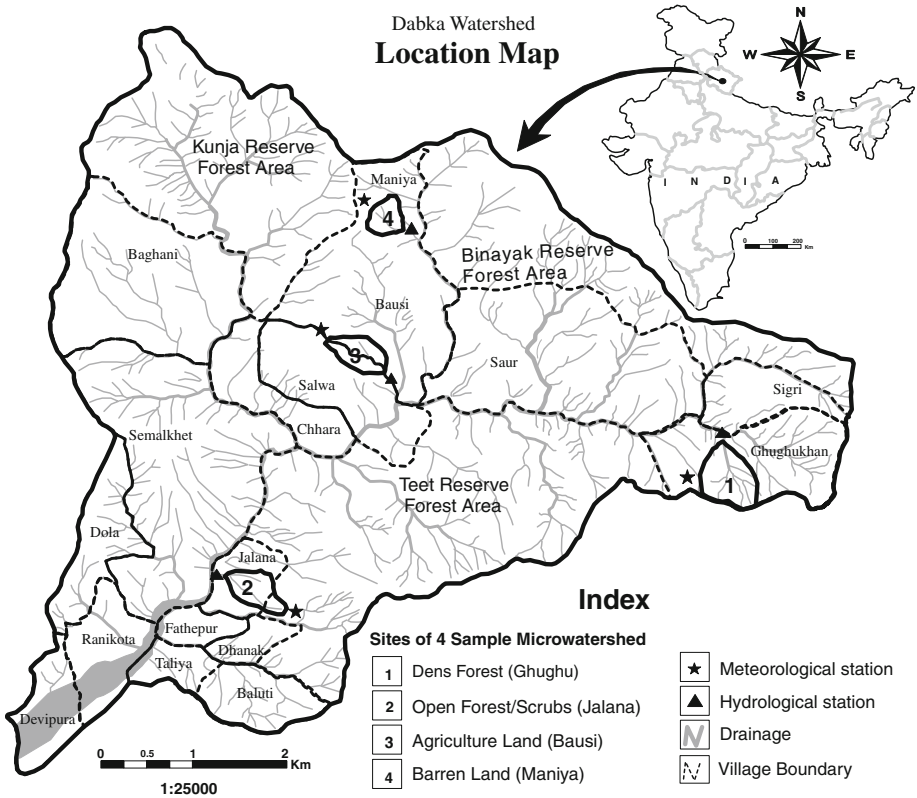| Sample micro-watersheds		Ecological conditions of the sample micro-watersheds						
S. no.	Exiting villages	Geology			Geomorphology (geomorphic landforms)	Average slope (°)	Soil types	Land use
		Lithological formations	Rock types	Specific gravity				
1.	Ghughu	Lariakanta	Quartzwacke Quartzarenite	2.62 2.63	Gullies, rills and denudational hills	30	Podzolic and conglomeratic sandy soil	Dense forest
2.	Jalna	Krol (ABCDE)	Shale Dolomite Gypsum	2.66 2.89 2.76	Depositional and erosional terraces, fluvial fans, bank cut area and flood plains	25	Fluvial sandy soil	Open forest and scrubs
3.	Bausi	Kailakhan and pangot	Diamictite Slates Siltstone Limestone	2.08 2.69 2.31 2.62	Moist area and sites of debris flow (active landslides their cons, fans)	18	Loumous soil	Agriculture land
4.	Maniya	Bhumiadhar	Diamictite Siltstone Shale	2.08 2.31 2.66	Erosional terraces and sites of debris flow (active landslides their cons, fans)	34	Stony hilly soil	Barren land
Dabka watershed		All above	All above	2.52	All above	27	All above	All above

sustainable land use plan for erosion hazard management in respect to existing geology, geomorphology, slope, soil types and vulnerability of erosion hazard.

Erosion is a major natural hazard in Lesser Himalaya because it is triggering several environmental problems in many ways. There is an undercutting of valley sides, which causes the mountainsides to become unstable and ultimately ends in landslides and slope instability that demolished the infrastructural development (road network, buildings, canals, communication connectivity, etc.) and natural resources, specially forest, land and water. In order to that, the study reveals decreasing trends of stream discharge during non-monsoon period because dry up of natural springs due to huge level deforestation. During floods, tremendous amounts of erosion occur on the banks of rivers and streams and washed away the crops and productive land, whereas some time moreover, unsorted sediments are deposited over agricultural fields and settlements especially during monsoons. There is an urgent need to produce quantitative, reliable model that can be used for erosion hazard and risk management to formulate a sustainable development plan for the study area that could be equally implemented through the Lesser Himalaya region and as well as other similar mountainous parts of the world. The Dabka watershed constitutes a part of the Kosi Basin in the Lesser Himalaya, India, in district Nainital has been selected for the case illustration because it encompasses all the geo-environmental characteristics of the Lesser Himalaya.

2 Study area

The watershed lies between the latitude 29°24′09″–29°30′19″N and longitude 79°17′53″–79°25′38″E in the north-west of Nainital town along the tectonically active Main Boundary Thrust (MBT) of Himalaya. The region encompasses a geographical area of 69.06 km² between 700 m and 2,623 m altitude above mean sea level (Fig. 1). In most of the mountainous part of the watershed, the surface gradient is steep and the topography is rugged. The average annual temperature of the Dabka watershed is 18°C. The average annual rainfall in the watershed is about 200 cm (2,000 mm) that produced water with the rate of 5,490 m³/km²/day The average annual humidity of the basin is 72.14%, which varies between 62.00% (in the barren land) and 79.84% (in the forested areas). The watershed includes 16 villages (Fig. 1). The population density is 76.02 person/km². About 95% population of the total population depends on agriculture and forest resources, but the forest cover is decreasing 0.67 km²/year that accelerating the hydrological hazards in the watershed.

Geologically, the study area is located in the southeastern extremity of the Krol belt forming outer part of Lesser Himalaya in Kumaun (Auden 1934; Pant and Goswami 1998; Pant and Goswami 2003). The watershed encloses rocks of the Blaini-Krol-Tal succession, which are thrust over the autochthonous Siwalik Group along the Main Boundary Thrust (MBT).The rocks of the area are divisible into Blaini and Krol Groups (Rawat Pradeep 2009). The Blaini Group has been further sub-divided into Bhumiadhar, Lariakantha, Pangot and Kailakhan formations in an ascending order of succession (Fig. 2) The oldest rocks exposed in the watershed comprise quartzwacke, quartzarenite, diamictite, siltstone and shale (Bhumiadhar formation) followed upward by predominantly arenaceous Laria-kantha formation, which inturn is followed by the diamictites, purple grey slates, siltstone and lenticular pink siliceous dolomitic limestone of the Pangot formation. The upper most Kailakhan formation comprises dark grey carbonaceous pyritous slate and siltstone. The Blaini Group transitionally grades into the Krol Group. The lower most formation of the

Fig. 1 Location map showing selected sample micro-watersheds with all 16 villages and location of hydrological and meteorological station installed in the study area

Krol Group is characterized by argillaceous marly sequence of the lower Krol formation (=Krol A). The formation grades upward into purple green slates and yellow weathered dolomites with pockets of gypsum of the Hanumangarhi formation (=Krol B). The formation constitutes a marker horizon in the Krol belt. The upper Krol formation (Krol C,D,E) is characterized by an assemblage of dolomitic limestone at the base followed by carbonaceous shales, fenestral dolomite showing cross-bedding, brecciation and oolites and cryptalgal laminites. The upper most part is made up of massive stromatolitic dolomites locally cherty and phosphatic at places. The youngest Tal formation comprises purple green slates interbedded with cross-bedded fine-grained sandstone and siltstone. The lower most southern part of the watershed comprises Siwalik formation with massive sandstones. These lithotectonic and physiographic units constitute geomorphically a very youthful massif. The dissected denudation hills, active landslides and their cones and fans (which are the main sites for debris flow), erosional terraces, fluvial terraces, fluvial fans, fluvial rills, gullies, flood plains, old river channels, moist areas and bank cut areas are the principal geomorphic features of the region identified and mapped.

Four categories of slopes have been identified in the study area, viz. gentle, moderate, steep and very steep slope. The parts of watershed having average surface slope <10° have been classified as gentle sloping areas. About 4.79% area of the watershed mainly along the master stream and its mouth has slope <10°. These areas constitute depositional
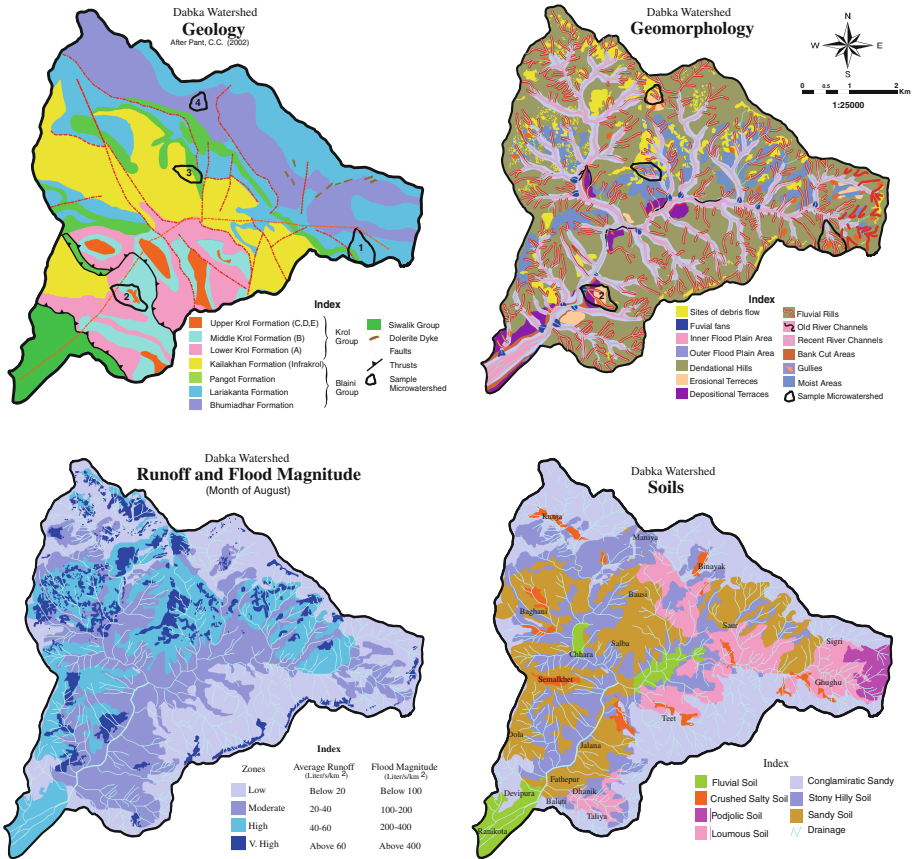
Fig. 2 Sample micro-watershed has been selected under varied geological and geomorphological, soil and run-off existence

landform, such as river terraces and debris fans. About 8.33% area of the watershed has moderate slope from 10 to 20°. The convex and concave mid-crest slopes in Fatfepur and down slopes in Baluti village fall in the category of moderate surface slope. A considerably large proportion of the geographical area of the watershed (35.48%) has steep surface slope varying from 20 to 30°. The steep slope areas constitute mainly landslide debris fans and their upslope areas in the western mountainous part of watershed, in villages Baghani, Jalna, Dola, Semalkhet, Saur, Gwalakhutti, Sigri and Hariyal. About 35.5 km² area that accounts for as much as 51.40% of the total watershed area falls in very steep slope zone of >30°. These very steep slopes are mainly occupied by different types of forests and barren and scrubland. All high altitudinal areas mainly in the eastern part of the watershed have steep slope.

The main soils types found in the region include (i) conglomeratic sandy soils that are mainly found in dense forests at higher elevations, (ii) loumous soils have very coarse texture and composed of pebbles and cobbles. These soils are found mainly around Saur, Gwalakhuti, Dau, and in Bansi and Ghghukhan area of the watershed, (iii) podzolic soils, which consist of high, humus contents extend over an area of 10% of the catchment in Sigri and Ghughukhan villages of the region, (iv) crushed salty soil are seen in somewhere

patches along the thrusts, faults and other structural feature, (v) stony hilly soils are found around the upper slope of Ghughukhan, Sigri, Binayak, Bansi, Baghani and Dola-Jalna area and (vi) sandy soils are found near Aniya and Chhara villages and in Fatehpur and Dhanak villages in the watershed.

The existing land use pattern suggested that the forest emerged as the major land use category in the study area (Rawat Pradeep 2009). A geographical area of 36.77 km^2, which accounts for nearly 53% of total area of the watershed, has been classified as forests. Due to complexities of terrain and other geomorphic features, the forests of the watershed are diversified in nature. Out of the total forest, 22.20% (15.33 km^2) is under mixed forest, 19.56% (13.51 km^2) is under oak forest and 11.48% (7.93 km^2) is under pine forests (Table 4). The hilly and mountainous parts of the watershed are covered with oak and pine species, whereas in the lower elevations in the south, mixed type of vegetation is very common. Agriculture and settlement are now confined to 20.40 km^2 or 29.54% of the total area. Scrub land, barren land and riverbeds and water bodies, respectively, extend over 6.22 km^2 (9.01%), 3.39 km^2 (4.91%) and 2.28 km^2 (3.30%) of the total geographical land surface of the study area (Table 4 and Fig. 6a). The agricultural land engaged throughout the year by broadly two types of the crop pattern, i.e. monsoon corps (June–September) and non-monsoon crops (October–May). Rice, bajra, maize, ragi, groundnut, Maduwa, madir, Soyabean, pumpkin, ginger, turmeric, beans, vegetables, etc. are the major monsoon crops, whereas wheat, sorghum, gram, millets, pea, potato, onions, mustards, chilly, etc. are the major non-monsoon crops.
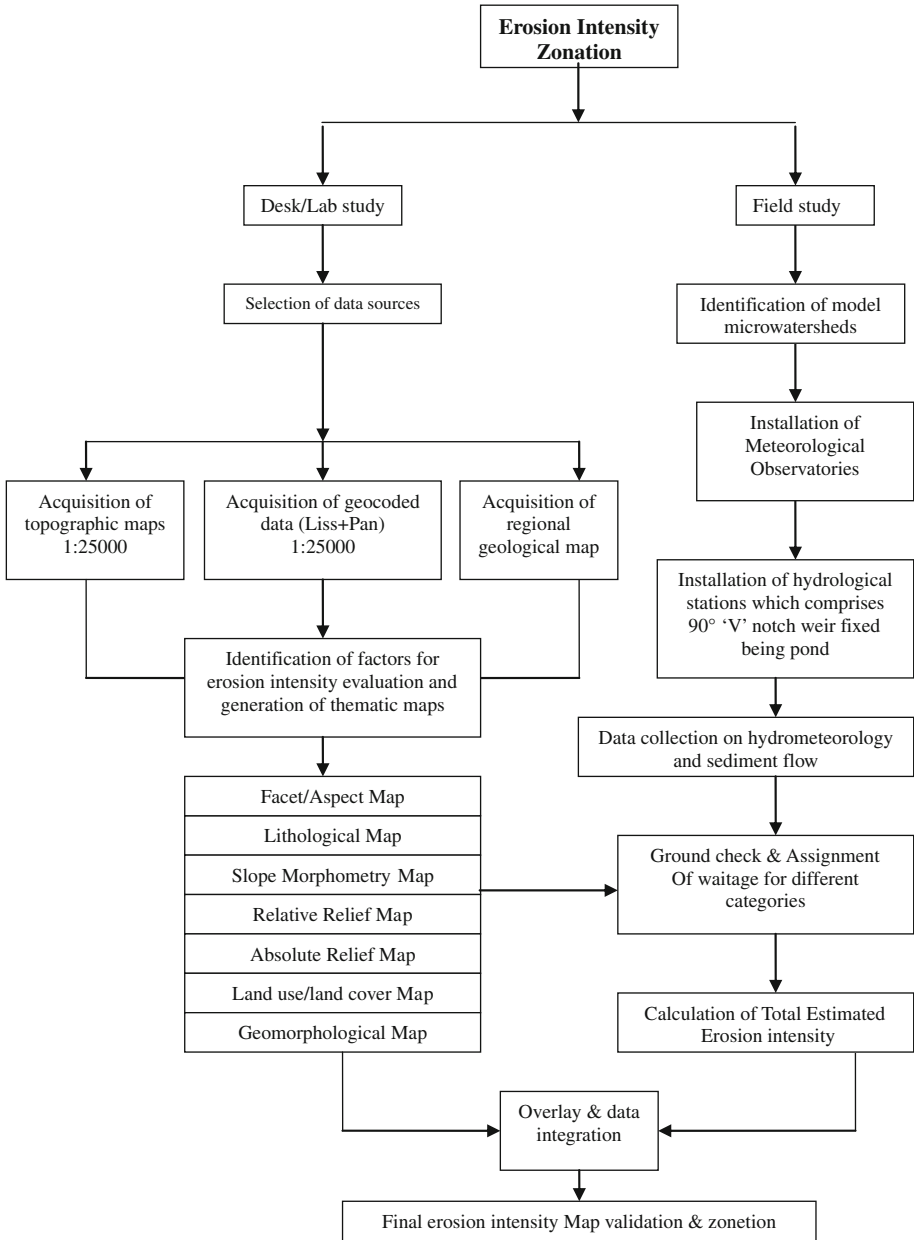
3 Methodology

The study comprises mainly two components: (a) lab/desk study and (b) field investigations. Litho-structural maps were prepared during field study, and details were verified and modified with other maps prepared during the desk study. Facet-wise field studies were carried out to generate required data for estimating the total erosion intensity of the identified facets. The procedure adopted for erosion intensity zone mapping has been outlined in Fig. 3 and discussed as below:

3.1 Hydro-meteorological modelling

Hydrometeorological modelling comprises a comprehensive study on stream run-off, sediment flow and climatic conditions of the watershed. Figures 1, 6a depicting four sample micro-watersheds were identified for modelling in the Dabka watershed on the basis of varied geology, geomorphology, average slope, soil types and land use pattern (Table 3). At the mouth of each micro-watershed, a hydrological station was installed. The station comprises a 90° 'V' notch weir fixed being pond and packed by sediment trap and water level stage recorder with standard chart stranded above the pond (Fig. 4a). A meteorological observatory was installed in each of the sample micro-watersheds in the catchment. This comprises Stevenson Screen with temperature/humidity recorder, self-recording rain gauge and pan-evaporation (Fig. 4b).

One litre water sample was collected every day during monsoon months and once every week during non-monsoon months for determining the suspended and dissolved load. For calculation of the suspended load, one litre water was filtered and the material collected was measured. Filtered water was then evaporated in an oven at 100°C, for the calculation of dissolved load using gravimetric method. The measurement of bed-load flow was taken

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                        ┌──────────────────────┐
                        │  Erosion Intensity   │
                        │     Zonation         │
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Facet/Aspect Map

Lithological Map

Slope Morphometry Map

Relative Relief Map

Absolute Relief Map

Land use/land cover Map

Geomorphological Map

Desk/Lab study

Selection of data sources

Acquisition of topographic maps 1:25000

Acquisition of geocoded data (Liss+Pan) 1:25000

Acquisition of regional geological map

Identification of factors for erosion intensity evaluation and generation of thematic maps

Field study

Identification of model microwatersheds

Installation of Meteorological Observatories

Installation of hydrological stations which comprises 90° 'V' notch weir fixed being pond

Data collection on hydrometeorology and sediment flow

Ground check & Assignment Of waitage for different categories

Calculation of Total Estimated Erosion intensity

Overlay & data integration

Final erosion intensity Map validation & zonetion

Fig. 3 *Flowchart* showing the procedure adopted for erosion intensity hazard zone mapping

by cleaning the sediment pond after measured the volume in m^3 of deposited sediment in the sediment pond than converted in tons. This exercise was done once every month during the post- and pre-monsoon periods and once every week during the rainy season (but for heavy rainfall, it was repeated three times in a week). The assessment of total annual load that includes both mechanical load (suspended and bed load) and chemical load (dissolved

Fig. 4 a Hydrological station installed at the mouth of each sample micro-watershed. **b** Meteorological station installed at high altitude of each sample micro-watershed

load) has been used to calculate the rates of sheet erosion in all four sample micro-watersheds and through the study area by using Gregory and Walling (1973) formula

$$\text{Rate of sheet erosion (in mm/year)} = \frac{\text{Total annual load in tons}}{\text{Total area } \left(\text{km}^2\right) \times \text{Specific gravity of rocks}} \Big/ 1000$$

where 1,000 is kiloannum (1,000 years) that used to estimate erosion rate in tons^2/year to mm/year.

To measure the river flow at the hydrological stations, four project personnel (field assistant) belong to local community of the respective sample micro-watersheds were appointed for each hydrological stations having a Pigmy Current Meter to collect samples of daily discharge from the sample micro-watershed. Daily discharge data used to calculate average monthly discharge that analysed by following equations:

$$\text{Stream discharge} = A \times V \qquad (1)$$

Table 2 Land use interpretation key

Land cover/land use classes	Enhanced LISS—III + PAN satellite data	
	Tone	Texture
Oak	Red, bright red in south aspects or gentle slopes, dull red and dull tar green in north and steep slopes	Fine
Pine	Green in the north aspects, red in the south aspects or on the ridges	Coarse
Mixed forests	Red interspersing with reddish and dull green	Coarse
Cultivated land	Reddish and yellowish	Medium/coarse
Scrub/Barren land	Light cyan interspersing with reddish or yellowish in both the aspects	Medium
River beds and water bodies	Black and blackish	Coarse

where A is cross-sectional area of the water channel and V is Velocity of the water discharge.

In order to that, the discharge estimated in $m^3\ s^{-1}$ as follows:

$$\text{Cross sectional area in meter}^{-2} \times \text{Velocity in meter second}^{-1} \qquad (2)$$

Value of the water discharge in $m^3\ s^{-1}$ was often used to calculate the run-off rate in $m^3\ km^{-2}\ day^{-1}$, as follows:

$$\text{Runoff rate(in } m^3 km^{-2} day^{-1}) = \frac{\text{Discharge } m^3 second^{-1} \times 24\,h}{\text{Total area of sample micro-watershed (km}^2)} \qquad (3)$$

3.2 Thematic mapping

Survey of India toposheet published in 1986 on 1:25,000 scale (No53O/7, 53O/6), and Indian Remote Sensing Satellite (IRS-1C) LISS III and PAN merged data of February 2006 were used for preparing base map employing visual and digital interpretation techniques. Digital interpretation was used for getting land use maps. In order to overcome these constraints and also to attain the best possible level of accuracy in the interpretation, intensive ground truth surveys were carried out in the study region and a visual inter-pretation key was evolved for primary land use classification (Table 2). This was followed by the digital classification of finale land use and geomorphology maps through on-screen visual recording and rectification, whereas geology, geomorphology, slop gradient and slope aspect maps, etc., were carried out by comprehensive field mapping following grid and isopleth's technique (Wentworth 1950 and Strahler 1956) based on Survey of India Topographical Maps at scale 1:25,000 beside visual interpretation of satellite data. In order to that whole study area divided in 1 cm grids, each grid covers about 0.25 km^2 area.

3.3 Erosion intensity hazard zonation

The precise quantity of sediment has been determined and mapped taking into account all critical factors such as slope, lithology, soil types, run-off rate, land use/land cover and dynamic geomorphic features (Table 4). Erosion intensity zones have been delineated through the super imposition of lithology, slope, land use and geomorphological maps

following scalogram modelling approach. In scalogram modelling approach (Cruz 1992), an arithmetic operation was combined with the corresponding numerical weights for the main factors and sub-factors to generate a score that includes attributes. According to this modelling approach, soil erosion hazard was assessed using an Erosion Hazard Index (EHI).

In order to prepare the Erosion Hazard Index (EHI) of the study area, total 7 major erosion hazard controlling factors and their 35 classes were transformed into weight maps by assigning weight to each class of major factors (Table 4). Five major factors such as slope, geology, land use pattern, soil types and geomorphic features have been identified by comprehensive field and GIS mapping, whereas two key factors, i.e. run-off and soil erosion intensity, have been estimated through stream discharge and sediment load modelling under four sample micro-watershed in terms of slope, geology, geomorphology, soil type and land use pattern. Each main factor has five classes or sub-factors that have been used to assign weightage. These sub-factors are given in Table 4, which suggests that 1,2,3,4 and 5 weights are, respectively, indicative of very low, low, moderate, high and very high causative factor for soil erosion. The numerical weights of the sub-factors, respectively, are variable and can be chosen based on field experience and experimental study results of a region. On the basis of these factors and sub-factors in the present study, the following Scalogram model was used for soil erosion hazard assessment (After Cruz 1992).

$$\text{EHI (score)} = \frac{[X1(An) + X2(An) + X3(An) + X4(An) + X5(An) + X6(An) + X7(An)]}{Xn}$$

where EHI is Erosion hazard index, X1, X2, X3, X4, X5, X6 and X7 are major factors, respectively, slope, geology, land use, geomorphology, run-off rate and erosion rate (Table 4), 'An' is the total weight score (such as $1 + 2 + 3 + 4 + 5 = 15$) of excising sub-factors or classes (A1, A2, A3, A4, A5) of a major factor (Table 4), Xn is the total number of major factors (Table 4).

In order to that, a spatial variation (hazard zones) map of the erosion hazard was prepared following grid and isopleth's technique (Wentworth 1950 and Strahler 1956) by using the weight value calculated by above equation for each 0.25 km^2 grid in respect to existing major factors and their classes or sub-factors. After assign a score value of erosion hazard (EHI) for each grid, the isopleth's (having equal erosion rates) has been delineated. Four isopleth's (75, 150, 225, and 300 t/km^2) have been delineated due to large spatial variability of erosion rate throughout the study area. These four isopleth's provided five zones of erosion intensity, viz. very low (<75 t/km^2), low (75–150 t/km^2), moderate (150–225 t/km^2), high (225–300 t/km^2) and very high (>300t/km^2).

4 Discussion and results

The average monthly budget of erosion and stream run-off during 3-year period (2006–2008) has been summarized in Table 3. Measurements suggested that in the period of 3-year study, the Dabka watershed produced a total sediment load of 15,500 tonnes/year at the rate of 224.45 tons/km^2/year. Out of this amount, nearly 80% was transported during the rainy season (June–September).

The amount of sediment load carried by stream channels depends on rainfall pattern, structure and lithology of rocks, geomorphic landforms, soil types, run-off rate and pattern

Table 3 Monthly run-off rate, rainfall and sediment load delivery from the Dabka watershed and its sample micro-watershed under varied ecological conditions based on 3-year measurements (2006–2008)

Hydro-meteorological Parameters	January	February	March	April	May	June	July	August	September	October	November	December	Annual	Denudation rate in mm/year
(A) Sample micro watershed														
Geo-environmentally stressed														
Dense forest (Ghughu)														
Run-off (l/s/km²)	1.83	1.94	2.08	1.04	7.14	9.74	18.24	20.67	9.87	0.93	0.86	0.84	6.27	0.20
Flood Magnitude (l/s/km²)	4.79	6.96	10.63	8.54	26.75	37.95	47.34	58.12	38.5	3.17	1.86	1.21	20.49	
Bed load (t/km²)	0.00	0.00	0.78	0.59	1.17	5.90	7.80	10.90	7.80	2.34	1.95	0.00	39.00	
Suspended load (t/km²)	0.13	0.04	0.18	0.07	0.18	2.70	3.60	5.40	3.60	1.08	0.90	0.18	18.00	
Dissolved load (t/km²)	0.07	0.02	0.06	0.03	0.07	1.20	1.80	2.40	1.68	0.56	0.08	0.07	8.00	
Total erosion load (t/km²)	0.20	0.06	1.02	0.69	1.42	9.80	13.00	19.50	13.00	3.25	2.60	1.30	65.80	
Fairly dense forest scrubs land (Jalna)														
Run-off (l/s/km²)	1.34	2.14	4.34	0.65	19.64	21.34	29.84	33.94	15.74	1.54	1.04	1.04	11.05	0.40
Flood Magnitude (l/s/km²)	7.19	10.44	15.95	12.81	40.13	56.93	71.01	87.18	57.75	4.76	2.79	1.82	30.73	
Bed load (t/km²)	0.00	0.00	1.58	1.19	2.37	12.00	16.00	22.10	15.80	4.74	3.16	0.00	79.00	
Suspended load (t/km²)	0.24	0.07	0.34	0.14	0.34	5.10	6.80	10.20	6.80	2.04	1.70	0.24	34.00	
Dissolved load (t/km²)	0.15	0.05	0.14	0.07	0.15	2.60	3.70	5.10	3.57	1.19	0.17	0.15	17.00	
Total Erosion load (t/km²)	0.39	0.12	2.06	1.39	2.86	20.00	26.00	39.00	26.00	6.50	5.20	2.60	132.00	
Agricultural land (Bausi)														
Run-off (l/s/km²)	3.24	4.16	5.26	0.41	27.07	29.38	47.21	53.15	27.27	3.58	1.36	1.71	16.98	0.92
Flood Magnitude (l/s/km²)	17.96	26.10	39.86	32.03	100.31	142.31	177.53	217.95	144.38	11.89	6.98	4.54	76.82	
Bed load (t/km²)	0.00	0.00	2.88	2.16	4.32	22.00	29.00	40.30	28.80	8.64	7.20	0.00	144.00	
Suspended load (t/km²)	0.50	0.14	0.72	0.29	0.72	11.00	14.00	21.60	14.40	4.32	3.60	0.72	72.00	
Dissolved load (t/km²)	0.59	0.20	0.53	0.26	0.59	9.90	15.00	19.80	13.90	4.62	0.66	0.59	66.00	
Total erosion load (t/km²)	1.10	0.34	4.13	2.71	5.63	45.00	60.00	90.00	60.00	15.00	12.00	6.00	302.00	

Table 3 continued

Hydro-meteorological Parameters	Months												Annual	Denudation rate in mm/year
	January	February	March	April	May	June	July	August	September	October	November	December		
Barren land (Maniya)														
Run-off (l/s/km²)	6.36	11.16	14.54	0.23	53.75	61.97	75.14	84.56	56.87	13.71	9.76	7.97	33.00	1.21
Flood Magnitude (l/s/km²)	71.85	104.40	159.45	128.10	401.25	569.25	710.10	871.80	577.50	47.55	27.90	18.15	307.28	
Bed load (t/km²)	0.00	0.00	4.72	3.54	7.08	35.00	47.00	66.10	47.20	14.20	11.80	0.00	236.00	
Suspended load (t/km²)	0.77	0.22	1.10	0.44	1.10	17.00	22.00	33.00	22.00	6.60	5.50	1.10	110.00	
Dissolved load (t/km²)	0.42	0.14	0.38	0.19	0.42	7.10	10.00	14.10	9.87	3.29	0.47	0.42	47.00	
Total erosion load (t/km²)	1.19	0.36	6.20	4.17	8.60	59.00	79.00	118.00	78.60	19.70	15.70	7.86	398.00	
(B) Dabka watershed (average)														
Run-off (l/s/km²)	3.00	4.85	6.56	0.78	26.90	30.61	42.61	48.08	27.44	4.92	3.27	2.90	16.82	0.68
Flood Magnitude (l/s/km²)	101.79	147.90	225.89	181.48	568.44	806.44	1,005.98	1,235.05	818.13	67.36	39.53	25.71	435.31	
Bed load (t/km²)	0.00	0.00	1.87	2.49	1.87	18.73	24.95	34.85	24.90	7.48	6.03	0.00	124.50	
Suspended load (t/km²)	0.41	0.12	0.24	0.59	0.24	8.95	11.60	17.55	11.70	3.51	2.93	0.56	58.50	
Dissolved load (t/km²)	0.31	0.10	0.14	0.28	0.14	5.20	7.63	10.35	7.26	2.42	0.35	0.31	34.50	
Total erosion load (t/km²)	0.72	0.22	2.24	3.35	2.24	33.45	44.50	66.63	44.40	11.11	8.88	4.44	224.45	
Temperature (°C)	10.00	12.00	16.00	19.00	31.00	27.00	24.00	23.00	21.00	20.00	14.00	12.00	19.08	
Humidity (%)	52.00	64.50	64.00	56.50	51.00	58.00	81.50	79.00	65.00	56.50	48.50	48.50	52.00	
Evaporation rate (mm)	36.00	45.33	49.33	51.00	34.00	38.67	55.67	55.00	50.00	51.00	32.33	32.33	36.00	
Rainfall (mm)	11.50	68.65	76.27	12.33	76.27	261.78	486.24	566.34	261.47	30.88	12.71	9.34	2,003.90	

of land use. The dense forest of Ghughukhan village and open forest/shrubs land of Jalna village represent anthropogenically least disturbed or natural condition, while the agricultural land of Bausi village and the barren land of Maniya hamlet (village Bausi) are quit most disturbed area of the watershed and have been selected as a sample micro-watershed (Fig. 1, 6a). Various parameters of sediment load in stream flow analysed and the results are as follows:

4.1 Run-off

Table 3 depicting the average annual rainfall in Dabka watershed is about 2,003.90 mm and in respect to that the average water producing rate of the rainfall is about 5,490.14 m^3/km^2/day out of which 62% (3,411.92 m^3/km^2/day) runs-off down in the streams of the watershed. In order to that, the hydrological modelling of four sample micro-watersheds having varied ecological characteristics suggesting that due to high peak discharge during monsoon months (June–September), the average surface run-off is, respectively, 2–1.3 times higher in the most disturbed barren land (4,477 m^3/km^2/day that is about 82% of the water produced by rainfall) and agriculture land (3,440 m^3/km^2/day that is about 63% of the water produced by rainfall) than that in the least disturbed dens oak forest (2,944 m^3/km^2/day that is about 59% of the water produced by rainfall) and fairly dens pine and mixed forest (3,248 m^3/km^2/day that is about 52% of the water produced by rainfall) (Table 3). The results suggested that higher run-off rate accelerating erosion hazard and risks in the study area.

4.2 Sediment output

The sediment output assessment includes both mechanical load (bed load and suspended load) and chemical load (dissolved load) assessment, which have been used to calculate the rates of erosion throughout the watershed. The results on sediment output (bed load, suspended load and dissolved load) are as follows:

4.2.1 Bed load

Streams of the Dabka basin carry bed load throughout the year except those emitting from the least disturbed forest and shrubs land (Table 3). Compared to the forest land (39 tons/km^2/year), the streams coming from the disturbed land (agricultural and barren land) have 5–8 times higher bed load (144 and 236 tons/km^2/year). The average rate of bed load of the Dabka watershed stands on 124.50 tons/km^2/year (Table 3).

4.2.2 Suspended load

The stream flowing across forests transport suspended sediment mainly in July, August and September but the streams releasing from the anthropogenically most disturbed (agricultural and barren land) micro-watersheds carry suspended material throughout the year (Table 3). The suspended load is maximum in the stream flowing through the barren land (110 tons/km^2/year), which is 5 times higher than that of the forest land (18 tons/km^2/year). In the agricultural land, it is 4 times higher (72 tons/km^2/year), and in shrubs land, it is 2 times higher (34 tons/km^2/year). The average rate of suspended load of the Dabka watershed stands on 58.50 tons/km^2/year (Table 3).

4.2.3 Dissolved load

Dissolved organic and inorganic ions constitute the dissolved load that is carried by streams throughout the year. Nearly 12% (8 tons/km^2/year) of the total annual dissolved load is removed from the least disturbed dense forest land, whereas 20% (47 tons/km^2/year) from the barren land that is 9 times higher than that of the forest land. In the agricultural land, the dissolved load is 8 times higher (66 tons/km^2/year), and in shrubs land, it is 2 times higher (17 tons/km^2/year). The average rate of dissolved load of the Dabka watershed stands on 34.50 tons/km^2/year (Table 3).

4.2.4 Total load

Under natural circumstances, the total sediment load of streams varied from 66 tons/km^2/year in the dense forest to 398 tons/km^2/year in the barren land in the watershed. Anthropogenic activities have accelerated the rate of load generation by 7 times (302 tons/km^2/year) in agricultural land and by 8 times (398 tons/km^2/year) in barren land, whereas the average rate of total load of the Dabka watershed stands on 224.45 tons/km^2/year (Table 3).

4.2.5 Rate of erosion

Under different land use type, the annual rate of erosion in the Dabka watershed is given in Table 3. The rate of erosion under least disturbed land varied from 0.20 mm/year in the dense forest land to 0.40 mm/year in the open forest or shrubs land. Under most disturbed land, these rates are terrifyingly high, i.e. more than 6 times higher (1.21 mm/year) in the barren land and more than 5 times greater (0.92 mm/year) in the agricultural land. The average annual rate of erosion of the Dabka watershed stands on 0.68 mm/year.

4.3 Erosion intensity hazard zonation

To analyse the impact of erosion in the region, an erosion intensity hazard zone map of the study area has been prepared, whereas the precise quantity of sediment has been determined and mapped taking into account all critical parameters such as slope, lithology, land use and geomorphic features (Table 4). This map shows five major classes, namely very low, low, moderate, high and very high erosion intensity zones that have been illustrated in Fig. 5.

4.3.1 Area under very low erosion hazard zone

Fairly dense forest area near up slopes of Kunja, Binayak, Ghughu, Teet, Talliya, Baluti, Dola, Jalna, and plain surface areas near villages Ranikota and Devipura have been mainly identified as very low erosion intensity zone (Fig. 5). Out of the total area of the Dabka watershed, 16.25 km^2 or 23.54% is under very low erosion intensity zone (Table 5, Fig. 5).

4.3.2 Area under low erosion hazard zone

Dense forest areas having gentle slope near villages Baghani, Jalna, Binayak, Teet and Devipura have been mainly identified as low erosion intensity zone (Fig. 5). Out of the

Table 4 Erosion hazard index includes main factors (X) and sub-factors (A) have been considered for weight assignment to erosion intensity hazard zone mapping for throughout the Dabka watershed

Sub-factors (A)	Main factors (X)							Erosion intensity weightage index	Severity for erosion hazard
	Slope classes (X1) [°]	Geology or litho-units (X2)	Land use (X3)	Geomorphic features (X4)	Soil types (X5)	Run-off (m³/km²/day) (X6)	Erosion (t/Km²/y) (X7)		
A1	<10	Assemblage diamictite of pangot formation	Settlement and Dens Forest Land	Depositional and Erosional Terraces,	Conglomeratic sandy soil	<3,000 Or (< 35 l/s/km²)	<75	1	Very low
A2	10–15	Diamictite, and shales of Bhumiadhar formation	Open forest land	Con and Fluvial fans	Podzolic and sandy soil	3,000–3,200 Or (35–37 l/s/km²)	75–150	2	Low
A3	15–20	Quartzwacke, quartzite, siltstone and shales of Lariakantha formation	Scrubs land	Scree Slopes Denudational hills	Loumous soil	3,200–3,400 Or (37–39 l/s/km²)	150–225	3	Moderate
A4	20–25	Siwalik sandstones and shales	Agricultural land with road and Brittle Paths	Landslide/rock fall, flood plains and moist area	Stony hilly soil	3,400–3,600 Or (39–42 l/s/km²)	225–300	4	High
A5	>25	Krol and infrakrol slates and carbonates	Barren land and river beds	Debris flows, bank cut area, gulling and rills	Fluvial sandy soil	3,600–4,500 Or (42–52 l/s/km²)	>300	5	Very high
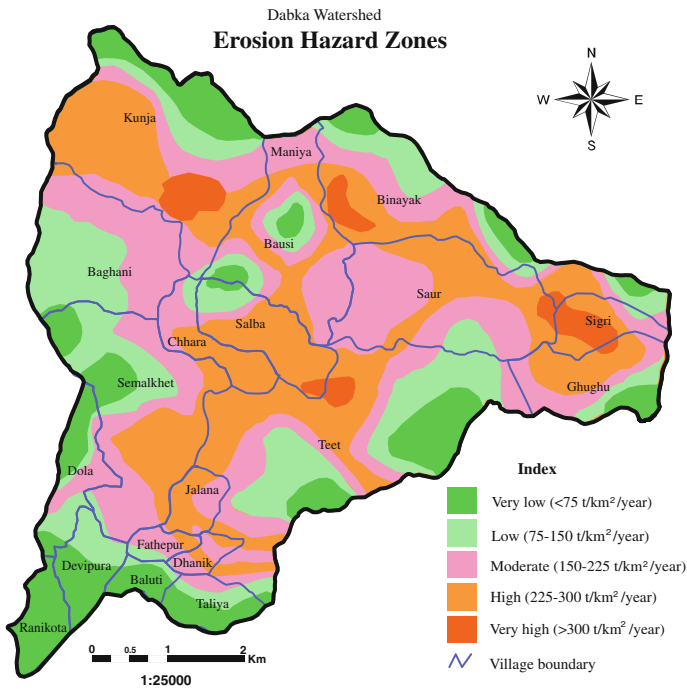
Fig. 5 Erosion hazard zones with village boundary

Table 5 Erosion intensity hazard zones showing erosion rate (t/Km^2/year), covered area and existing villages having major proportion of the respective hazard zone

Erosion hazard zones	Erosion rate (t/Km^2/year)	Area covered		Exiting villages having major proportion of respective hazard zone
		Km^2	%	
Very low	Below 75	16.25	23.54	Ranikota, Devipura, Dola, Kunja, Teet, Talliya, Baluti
Low	75–150	11.22	16.25	Baghani, Jalna, Binayak, Teet and Devipura
Moderate	150–225	17.9	25.92	Saur, Bausi, Baghani, Semalkhet and Kunja
High	225–300	20.51	29.7	Kunja, Salba, Chhara, Bausi, Binayak, Ghughu, Sigri
Very high	Above 300	3.17	4.59	Kunja, Binayak, Sigri and Teet
Total	<75 to > 300	69.06	100	Dabka watershed

total area of the Dabka watershed, 11.22 km^2 or 16.25% is under low erosion intensity zone (Table 5, Fig. 5).

4.3.3 Area under moderate erosion hazard zone

Shrubs land and loped area under forests having moderate slope has been identified as moderate erosion intensity zone (Fig. 5). Out of the total area of the Dabka watershed, 17.90 km^2 or 25.92% is under moderate erosion intensity zone (Table 5, Fig. 5). Villages

Saur, Bausi, Baghani, Jalna and Kunja have the major proportion of the moderate hazard zone (Table 5, Fig. 5).

4.3.4 Area under high erosion hazard zone

Agricultural land and lopped forest areas have been mainly identified as areas of high erosion intensity (Fig. 5). Out of the total area of the Dabka watershed, 20.51 km^2 or 29.70% is under high erosion intensity zone (Table 5, Fig. 5). Villages Kunja, Teet, Janal, Salba, Chhara, Bausi, Binayak, Saur, Ghughu and Sigri have the major proportion of the high hazard zone (Table 5, Fig. 5).

4.3.5 Area under very high erosion hazard zone

Barren land and debris flow areas have been identified as very high erosion intensity areas (Fig. 5). Out of the total area of the Dabka watershed, 3.17 km^2 or 4.59% is under high erosion intensity zone (Table 5, Fig. 5). Villages Kunja, Binayak, Sigri and Teet have the major proportion of the very high hazard zone (Table 5, Fig. 5).

4.4 Sustainable land use plan for erosion hazard and its risks mitigation

As first step towards the mitigation of soil erosion hazard, a comprehensive land use plan has been evolved and proposed for Dabka watershed. The land use framework has been designed taking into consideration the parameters of geology, geomorphology, slope, soil types and erosion hazard maps of the study area. The land use plan evolved for the region has been presented in Table 6 and Fig. 6 and described in the following sections:

4.4.1 Forest land

The conservation, protection and sustainable development of forest resources are essential for the management of erosion, landslides and flood. In view of this, the forest area of the Dabka watershed has been proposed to be increased from the existing 36.56 to 43.00 km^2. This increase would be possible by bringing additional 6.22 km^2 of lopped forest area under reforestation programme in erosion hazard prone zones (Table 6, Fig. 6). The lopped forest area proposed to be afforested is already a part of dense forest, but it is under highly

Land use classes	Existing area		Proposed area	
	Km^2	%	Km^2	%
1. Dense forest	36.56	52.94	43.00	62.26
2. Lopped forest/ scrub land	06.22	09.01	00.00	00.00
3. Barren land	03.39	09.01	00.00	00.00
4. Cultivated land	20.61	29.84	16.30	23.60
5. River bed	02.28	03.30	02.28	03.30
6. Horticulture	00.00	00.00	03.00	04.34
7. Shrubs land	00.00	00.00	04.48	06.49
Total	69.06	100.00	69.06	100.00

Table 6 Exiting and proposed land use and land cover
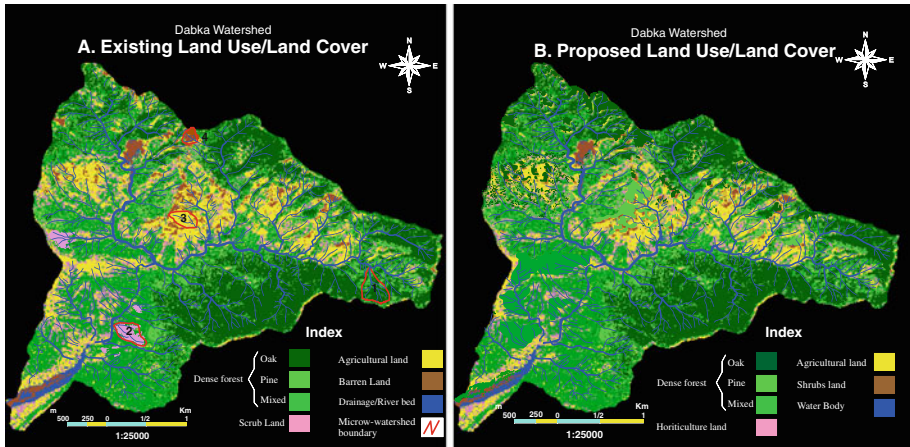
Fig. 6 **a** Exiting land use/land cover and four sample micro-watershed in different land use pattern. **b** Proposed scientific land use/land cover for erosion hazard mitigation in Dabka watershed

degraded condition and therefore has been characterized and classified as lopped forests in land use map (Table 6, Fig. 6).

4.4.2 Agricultural land with settlements

Out of total existing agricultural land (20.51 km^2), 20% (4.31 km^2) that has high risk of hazards due to soil erosion has been proposed to be diverted to shrubs land and to horticultural practices (Table 6, Fig. 6).

4.4.3 Horticulture

In view to reduce the impact of hydrological hazard, and having observed the favourable geographical conditions for the production of a variety of fruits in the watershed, and community demand for horticultural development, 3 km^2 area of existing barren and cultivated land which lies has high risk of flood and erosion has been recommended to be brought under horticultural development in the watershed (Table 6, Fig. 6).

4.4.4 Shrubs land

As much as 4.48 km^2 area under existing barren and cultivated land lying in hazard zones and therefore highly vulnerable to several kinds of natural disasters and hazards due to soil erosion has been suggested to developed as shrubs land (Table 6, Fig. 6).

5 Conclusion

This investigation is an effort to assess the sound effects of an increasing human impact and geo-environmental impact upon stream run-off, accelerating soil erosion in the critical and vulnerable areas of the Lesser Himalaya. These preliminary results suggest that deforestation and unscientific agricultural practices increase the vulnerability of erosion

hazards. The rate of total sediment yield was minimum (66 tons/km^2/year) in the least disturbed dense forest land with the lithology of quartzwacke and quartrenite rocks and maximum (398 tons/km^2/year) in the most disturbed barren land under lithology of dia-mictite, siltstone and shale rocks. It can be concluded that the ratio of erosion intensity was 1:2:4:6, respectively, for dense forest, open forest/shrubs land, agricultural land and barren land. The average rate of soil erosion in the Dabka watershed stands on 0.68 mm/year or 224.45 tons/km^2/year. The results also advocated that the accuracy level of the investigated data on erosion hazard is above 95% because it is carried out through comprehensive field data measurements in different geo-environmental systems. It is therefore time to move from environmental consciousness to articulation of an environmentally friendly strategy for integrated sustainable development of Himalaya. This makes it necessary to take up an integrated and comprehensive land use policy for the entire Himalaya based on the scientific interpretation of the crucial linkages between land use, soil erosion, stream run-off and sediment output. The study would help the village, district and state development authority to formulate their policies and programme for alternate planning and management for the Himalaya region.

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