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Geo-hydrological database modeling for integrated multiple hazards and risk assessment in Lesser Himalaya: a GIS-based case study

Pradeep K. Rawat · Prakash C. Tiwari · Charu C. Pant

Abstract The main objective of the study was to assess the integrated multiple hydrological hazards and their environmental and socio-economic risks in Himalaya through geographical information system (GIS) and database management system (DBMS). The Dabka Watershed constitutes a part of the Kosi Basin in the Kumaun Lesser Himalaya has been selected for the case illustration. The Dabka DBMS is constituted of three GIS modules, that is, geo-informatics, hydro-informatics and hazard-informatics. Through the integration and superimposing of these modules prepared Hydrological Hazard Index to identify the level of vulnerability for existing hydrological hazards and their socio-economic and environmental risks. The results suggested that geo-environmentally most stressed barren land areas have high rate of runoff, flood magnitude, erosion sediment load and denudation during rainy season particularly in the month of August (i.e., respectively, 84.56 l/s/km^2, 871.80 l/s/km^2, 78.60 t/km^2 and 1.21 mm/year), which accelerates high hazards and their socio-economic and environmental risks, whereas geo-environmentally least stressed dense forest areas experience low rate of stream runoff, flood magnitude, erosion sediment load and denudation in the same season and month (i.e., respectively, 20.67 l/s/km^2, 58.12 l/s/km^2, 19.50 t/km^2 and 0.20 mm/year) comparatively have low hazards and their socio-economic and environmental risks. The other frazzled geo-environment that also found highly vulnerable for natural hazards and their risks is agricultural land due to high stream runoff, flood magnitude, erosion sediment load and denudation rates (i.e., respectively, 53.15 l/s/km^2, 217.95 l/s/km^2, 90.00 t/km^2 and .92 mm/year). This makes it necessary to take up an integrated and comprehensive sustainable land use policy for the entire Himalaya region based on the scientific interpretation of the crucial linkages between land use and hydrological hazards, that is, floods, erosion, landslides during rainy

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season and drought due to dry-up of natural springs and streams during summer season. The study would help the village, district and state development authority to formulate decision support system for alternate planning and management for the Himalaya region.

Keywords Integrated hydrological hazards · Database management system · Geo-informatics · Hydro-informatics · Hazard-informatics

1 Introduction

Though each and every part of the world is more or less susceptible to natural calamities, the Himalaya region due to its complex geological structures, dynamic geomorphology and seasonality in hydro-meteorological conditions experience natural disasters very frequently, especially hydrological hazards. The region is highly vulnerable for all type of hydrological hazards such as flood, erosion, landslide in monsoon period and drought in non-monsoon period due to drying up of natural water springs and streams (Muller 1968; Hamilton 1987; Haigh et al. 1988; Scheling 1988; Ives 1989; Jain et al. 1994). The geo-dynamically active Himalayan terrain is being deforested at the rate of 0.36 km²/year (Rawat et al. 2011a). There are several anthropogenic factors that may contribute to this acceleration, including poorly managed agriculture, forest fire, overgrazing and substandard construction of roads and buildings (Valdiya and Bartarya 1989; Rawat and Rawat 1994; Tiwari 2000). This is further evident by upslope shifting and destruction of forest land due to climate change (Rawat et al. 2011b). The land use degradation and deforestation reduced the protective vegetal cover; as a result, the significant proportion of rainfall goes waste as flood water without replenishing the groundwater reserve (Imhoff et al. 1987; Townsend 2001). It is experiencing that the ground water level throughout the region gradually going down due to deforestation and high flood runoff (Jain et al. 1994; Sing 2006; Bajracharya et al. 2007). Recent studies suggesting that out of total annual disaster in Himalaya region, 14 % are earthquake and landslide disaster, 48 % are hydrological disasters (i.e., 36 % flood, 9 % mass movement, 3 % drought), whereas 38 % are other types of disasters such as storm (23 %), wild fire (1 %), extreme temperature (6 %) and epidemic (8 %). Results concluded that hazard events are increasing with the growth rate of 6 % each year in the region and subsequently human casualties increasing with the rate of 9 % each year, whereas affected people and infrastructural loss increase with that rate of, respectively, 6 and 4 % each year (Nibanupudi et al. 2012).

Although the Himalaya region is highly vulnerable for all type of natural hazards, in recent past, its observed that flood hazard causing a major threat for the entire Himalaya tract because it is also accelerating erosion and landslide hazard and their risks (Anbalagan and Singh 1996; Gupta et al. 2001; Nearing et al. 2005; Shrestha 2009; Rawat et al. 2012). Mainly two types of floods are common throughout the region, that is, flash flood and river-line flood, which are among the more devastating types of hazard as they occur rapidly with little lead time for warning and transport tremendous amounts of water and debris at high velocity. Flash floods and river-line floods affect thousands of people in the Himalaya region every year by losing their lives, homes and livelihoods along with expensive infrastructure. There are several different causes of flash flood and river-line flood in Himalaya such as intense rainfall (IRF), glacial lake outburst (GLO), landslide dam outburst (LDO), rapid snow melt (RSM) and failure of dams and other hydraulic structures (Zhou et al. 2000; Larson and Pasencia 2001; Overton 2005; Jonkman 2005). But IRF is very frequent cause for flash flood and river-line flood in the

Himalaya, which play a key role for flash flood and river-line flood. Flash flood in the region causes great loss to life and property and poses serious threat to the process of development, which has far-reaching economic and social consequences. On the other hand, the river-line flood is triggering several environmental socio-economic problems in many ways. River-line flood is undercutting of valley sides which causes the mountainsides to become unstable and ultimately ends in landslides and slope instability, which demolished the infrastructural development (road network, buildings, canals, communication connectivity, etc.) and natural resources especially forest, land and water. 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 (Ali and Qadir 1989; Brivio et al. 2002; Apel et al. 2006; Brody et al. 2007; Birkland et al. 2003; Buchele et al. 2006). Thus, the impacts of natural hazards are multi-dimensional, affecting environmental, social and economic systems (Clandillon and De Fraipont 2000; Islam and Sado 2000; Jain et al. 2005; Sharma et al. 1996; Delmeire 1997; Bates et al. 1997, 2003).

In order to that, there is an urgent need to produce quantitative, reliable model that can be used for integrated multiple hydrological hazard and risk management to formulate a sustainable development plan for the study area that could be equally implement through the Himalaya region and as well as other similar mountainous parts of the world. An attempt has been made in the present investigation through a case study of a geo-environmentally fragile watershed located near a seismic and tectonically active region of the Himalaya region.

2 Study area

The Dabka Watershed constitutes a part of the Kosi Basin in the Kumaun Lesser Himalaya has been selected for the case illustration. The watershed lies between the latitude 29°24′09″–29°30′19″E and longitude 79°17′53″–79°25′38″N in the north west of Nainital town adjacent to neotectonically active main boundary thrust (MBT) of Himalaya (Fuchs and Sinha 1978). The region encompasses a geographical area of 69.06 km^2 between 700 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 19 °C. The average annual rainfall in the watershed is about 2,000 mm. The average annual humidity of the basin is 52 %, which varies between 62.00 % (in the barren land) and 79.84 % (in the forested areas). The watershed includes 16 Villages (Fig. 1). About 95 % population of the total population depends on agriculture and forest resources, but the forest cover is decreasing 0.67 km^2 per year, which is accelerating the hydrological hazards in the watershed.

3 Methodology

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 were used as a base map for the study. The study comprises mainly two components: (a) laboratory/desk study and (b) field investigations. Geo-structural maps were prepared during field study,
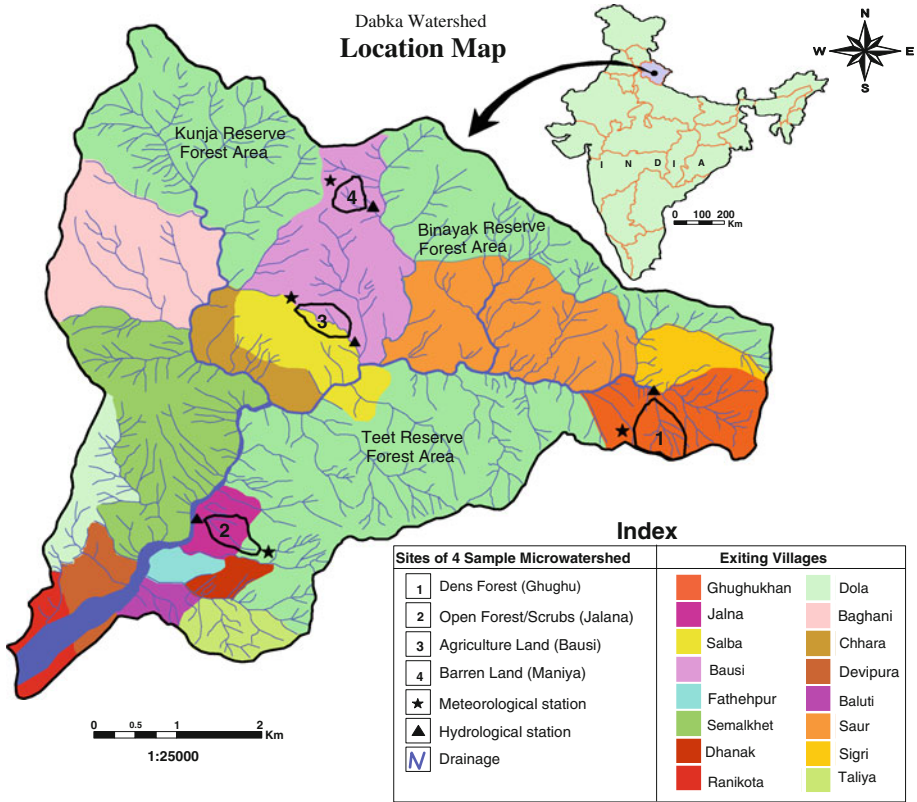
Fig. 1 Location map showing selected sample micro-watersheds with existing villages and location of hydro-meteorological station installed in the study area

and details were verified and modified with other maps prepared during the desk study. The procedure adopted for the study has been outlined in Fig. 2 and discussed as below:

3.1 Geo-hydrological database management system (DBMS)

DBMS is a set of computer programs for managing an integrated spatial and attribute database for such a task as map and data input storage, search, retrieval, manipulation and output. Geo-hydrometeorological DBMS is constituted of three different GIS modules consisting of spatial map layers with their attribute data. These three GIS modules are geo-informatics, hydro-informatics and hazard-informatics. The geo-informatics module consists of spatial distribution maps with their attribute data of seven different geo-sectors, that is, slope, geology, lineament, geomorphology (emphasizing particularly fluvial landforms), soils, land use pattern and spatial distribution of landslides, which carried out by comprehensive field mapping and GIS mapping. The hydro-informatics module consists of daily, monthly and annual record of hydrological parameters (i.e., rainfall, runoff, flood magnitude, suspended, dissolved and bed load, total erosion load and gross rates of denudation) and hazard-informatics module consists of spatial and attribute database of several hydrological hazards, that is, drought hazard in non-monsoon period and flood, erosion and landslide in monsoon period.
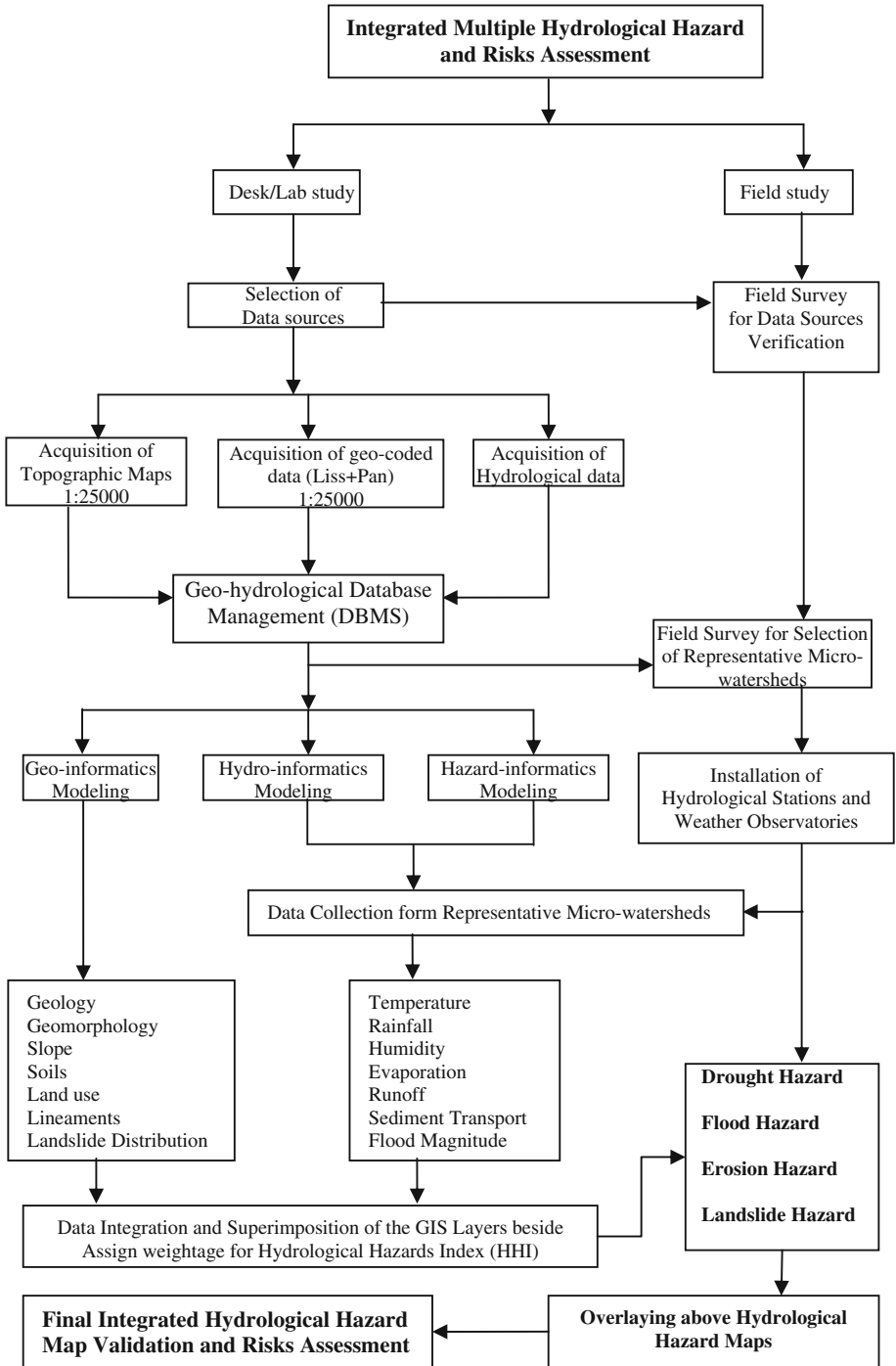
Fig. 2 Flowchart showing the procedure adopted for the study

3.2 Representative micro-watershed approach

A representative micro-watershed contains within its boundaries a complex of landforms, geological settings, land use and similar size throughout a particular region. Thus, a representative micro-watershed is the region within which hydro-meteorological similarity is presumed. Four sample micro-watersheds (representative of different ecological conditions, Figs. 1, 8a) were identified for hydro-informatics database modeling in the Dabka Watershed on the basis of varied geology, geomorphology, average slope, soil types and land use pattern (Table 1). A weather observatory was installed in each of the sample micro-watersheds in the catchment for weather monitoring. This comprises Stevenson Screen with temperature/humidity recorder, self-recording rain gauge and pan evaporation (Fig. 3a). At the mouth of each micro-watershed, a hydrological monitoring 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. 3b).

3.3 Monitoring strategy of representative micro-watershed

These hydrological and meteorological stations are watched, and data are recorded over by the local trained inhabitants (appointed as a Project Field Assistants) whose houses are close by the stations. The recorded data are collected on weekly basis by a Data Collector for the all hydrological and meteorological stations. The Data Collector submits the collected data to the Research Scientists (Authors) at hydrological laboratory, in the University Campus. The hydrological and meteorological stations are inspected on couple of week by the Research Scientists throughout the study period. The row data submitted weekly by the Data Collector often used to develop hydro-informatics DBMS in computer excel program (Table 2). The weather-informatics (i.e., temperature, rainfall, humidity, evaporation) database developed on the basis of daily, monthly and annual recorded raw data at four representative ecological weather observatories, that is, dense forest, fairly dense forest or shrubs land, barren land and agricultural land. Hydro-informatics database developed by monitor runoff, flood magnitude, sediment load and denudation rates. In order to that, to measure the streams discharge at the hydrological stations, each Field Assistant had a Pigmy Current Meter to collect samples of daily discharge from the sample micro-watersheds. Daily discharge data used to calculate monthly and annual average discharge rate. Following equations have been used to calculate discharge rates:

$$\text{Stream discharge} = A * V \tag{1}$$

where A is cross-sectional area of the water channel in m^2, V is Velocity of the water discharge in m/s. Volume of the water discharge in m^3/s was converted in l/s ($1\ m^3 = 1{,}000\ l$) than calculate the runoff rate (l/s) in a unit area (km^2) as follows:

$$\text{Runoff} = \frac{\text{Discharge l/s}}{\text{Total area of sample micro} - \text{watershed (km}^2)} \tag{2}$$

The sediment load monitored as bed load, suspended and dissolve load. One liter water sample was collected every week during monsoon months (but for heavy rainfall, it was repeated three times in a week) and once every month during non-monsoon months for determining the suspended and dissolve load. For calculation of the suspended load, 1 l 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

Table 1 Selected four sample micro-watershed (representative of varied ecosystem) for hydro-meteorological modeling

Sample micro-watersheds		Ecological conditions of the sample micro-watersheds						
		Geology			Geomorphology (fluvial landforms)	Average slope	Soil types	Land use
S. no.	Exiting village	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	Fairly dense forest and scrubs land
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 sits 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

Fig. 3 **a** Meteorological station installed at high altitude of each sample micro-watershed. **b** Hydrological station installed at the mouth of each sample micro-watershed

method. The measurement of bed-load flow was done by cleaning the sediment pond after measured the volume 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

Table 2 Monthly and annual hydro-informatics database from the Dabka Watershed (section B) and its sample micro-watershed under varied ecological conditions (section A) based on 5-year measurements (2006–2010)

(A) Sample micro watershed	Hydrological Parameters	Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual	Denudation rate in mm/year
Geo-environmentally Least Stressed															
Dense Forest (Ghughu)	Runoff (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)	Runoff (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	
Geo-environmentally Most Stressed															
Agricultural Land (Bausi)	Runoff (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	
Barren Land (Maniya)	Runoff (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)	Runoff (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	806.04	1005.98	1235.05	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 (in °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 (in %)	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**	**2003.90**	

once every week during the rainy season (but for heavy rainfall, it was repeated three times in a week). The assessment of total annual erosion load that include both mechanical load (suspended and bed load) and chemical load (dissolved load) has been used to calculate the denudation rate in all four sample micro-watersheds and throughout the study area by using Gregory and Walling (1973) formula.

$$\text{Denudation Rate} = \frac{\text{Total annual load in tons}}{\text{Total area}\,(\text{km}^2) \times \text{Specific gravity of rocks}}/1,000 \qquad (3)$$

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

3.4 Data integration and superimposition for hydrological hazards mapping

The geo-informatics module (i.e. geomorphology, slope, drainage density, drainage frequency, soils, geology and land use pattern), The hydro-informatics module (i.e. daily, monthly and annual record of precipitation, evaporation, temperature, runoff, flood magnitude, suspended, dissolved and bed load, total erosion load and gross rates of denudation) integrated and superimposed to identify vulnerable areas for each hydrological hazard (i.e. drought, flood, erosion and landslide) following scalogram modeling approach (Table 3). In scalogram modeling 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.

In order to prepare the Hydrological Hazard Index (HHI) of the study area, total 11 major hazard triggering factors and their 44 classes were transformed into weight maps by assigning weightage to each class of major factors (Table 3). Seven major factors such as slope, geology, lineaments, geomorphic features, soil types land use pattern and spatial distribution of landslides have been identified by comprehensive field and GIS mapping using 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 data, whereas three key factors, that is, runoff, flood magnitude and soil erosion intensity, have been estimated through stream discharge and sediment load modeling under four sample micro-watershed in different ecological conditions. Each main factor has four classes or sub-factors that were used to assigned weightage for hydrological hazards potential. These sub-factors are given in Table 3 which suggests that 1, 2, 3 and 4 weights are, respectively, indicative of low, moderate, high and very high causative factor for hazard. 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 their sub-factors, the following Scalogram model was used for drought, flood, erosion and landslide hazard zone assessment (After Cruz 1992):

$$\begin{aligned} \text{HHI(Score)} = &[X1(An) + X2(An) + X3(An) + X4(An) + X5(An) + X6(An) \\ &+ X7(An) + X8(An) + X9(An) + X10(An) + X11] \end{aligned} \qquad (4)$$

where HHI is Hydrological Hazard Index, X1, X2, X3, X4, X5, X6, X7, X8, X9, X10 and X11 are major factors, respectively, slope, geology, structural lineaments, soil types, land use, geomorphology, landslide distribution, rainfall, runoff, flood magnitude and erosion rate (Table 3). 'An' is total weight score (such as $1 + 2 + 3 + 4 = 10$) of excising sub-factors or classes (respectively, A1, A2, A3, A4,) of a particular major factor (Table 3).

Table 3 Hydrological Hazard Index (HHI) includes 11 main factors (X) and 44 sub-factors (A) of GIS modules which have been considered for weightage assignment to multiple hydrological hazard zones mapping for Dabka Watershed

| Sub-factors (A) | GIS modules with main factors (X) | | | | | | | | | | | Vulnerability for hydrological hazards | |
| | Geo-informatics module | | | | | | | Hydro-informatics module | | | | Hazard-informatics | |
	Slope classes (X1)	Geology with rock types (X2)	Structural lineament (X3)	Soils types (X4)	Land use pattern (X5)	Geomorphology (fluvial) (X6)	Existing types of landslide (X7)	Rainfall (mm) (X8)	Runoff rate (l/s/km^2) (X9)	Flood magnitude (l/s/km^2) (X10)	Sediment transport (t/y/km^2) (X11)	Assigned weightage	Hazard zones
A1	Below 10°	Siwalik sandstones and shales	Joints	Fluvial sandy soil	Dense and fairly dense forest land	Denudational hills and scree slopes	Old stable	Below 1,650	Below 20	Below 100	Below 75	1	Low
A2	10°–20°	Krol and Infrakrol slates and carbonates	Fractures	Conglomeratic and fine sandy Soil	Scrubs land	Erosional terraces and cones	Old sub-stable	1650–1700	20–40	100–200	75–150	2	Moderate
A3	20°–30°	Quartzwacke, quartzite, siltstone and shales of Lariakantha Formation	Faults	Loumous and podzolic soil and crushed salty soil	Settlement, agriculture land with road and brittle paths	Depositional terraces and alluvial fans	Reactive	1700–1750	40–60	200–400	150–225	3	High
A4	Above 30°	Diamictite of Pangot Formation diamictite, and shales of Bhumiadhar Formation	Thrusts	Stony hilly soil	Barren land and river beds	Flood plains, fluvial fan, moist area, landslide and debris flows areas, bank cut area, gulling & rills	Active	Above 1,750	Above 60	Above 400	Above 225	4	Very high

In order to that, a spatial variation (hazard zones) map for each hydrological hazard prepared following grid and isopleth's technique (Wentworth 1950; Strahler 1956) by using the weight value calculated by above equation for each 0.25-km^2 grid. This integrated weight values ranged from 11 to 44 throughout the study area and have been grouped into four zones, that is, low- (below 12), moderate- (12–24), high- (24–36) and very-high-hazard zone (above 36) for each hydrological hazard (i.e., drought, flood, erosion and landslide). Consequently, the integrated hydrological hazard map generated after overlaying drought, flood, erosion and landslide hazard maps.

3.5 Risks assessment

The integrated risks of multiple hydrological hazards also carried out following above scalogram modeling approach (Cruz 1992). In order to prepare the integrated Risks Index (RI) of the study area, total 6 sets of socio-economic and environmental parameters (X) and their 18 sub-parameters (A) have been taken into account. The major parameters include houses and built-up areas, land use pattern, road network, drinking water storage, canals and transmission lines and natural water springs. Each parameter has three classes or sub-parameters that have been used to assigned weightage for scalogram modeling. These sub-parameters suggests that 1, 2 and 3, respectively, denotes low-, moderate- and higher-risk potential according to the distance of houses, etc. from the location of hazards and refers to as buffer distance, and the relative importance of the parameters is considered. Values for the combined weight map ranged from 6 to 18. In order to prepare a composite risk map of the study area, these values have been grouped into three classes, that is, low- (below 8), moderate- (8–16) and high-risk zones (above 16).

4 Results and discussion

The main objective of the study was to develop geo-hydrological database management system (DBMS) to integrate and superimposition of the attribute and spatial data for multiple hydrological hazard and risks assessment. The geo-hydrological DBMS constituted of three different GIS modules these are geo-informatics, hydro-informatics and hazard-informatics. The detailed results on all three modules are as follow:

4.1 Geo-informatics

The geo-informatics module consists of spatial distribution maps with their attribute data of seven different geo-sectors, that is, geology, lineament, geomorphology, slope, soils, land use pattern and spatial distribution of landslides. A brief description of geo-information based on this geo-informatics module of the Dabka DBMS is given below:

4.1.1 Geology

Geologically, the study area is located in the southeastern extremity of the Krol belt forming outer part of Lesser Himalaya in Kumaun (Auden 1934; Fuchs and Sinha 1978). The watershed encloses rocks of the Blaini-Krol-Tal succession, which are thrust over the autochthonous Siwalik Group along the MBT of Himalaya. The rocks of the area are divisible into Blaini and Krol Groups (Pant and Goswami 2003; Rawat et al. 2011a).

The Blaini Group has been further subdivided into Bhumiadhar, Lariakantha, Pangot and Kailakhan formations in an ascending order of succession (Fig. 4). 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 intern is followed by the diamictites, purple gray slates, silt-stone and lenticular pink siliceous dolomitic limestone of the Pangot Formation. The upper most Kailakhan Formation comprises dark gray carbonaceous pyritous slate and siltstone. The Blaini Group transitionally grades into the Krol Group. The lower most formation of the 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 Forma-tion (=Krol B). The formation constitutes a marker horizon in the Krol belt. The Upper Krol Formation (Krol C, D and 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. The vulnerability of the above rocks for multiple hydrological hazards is categorized as low, moderate, high and very high and presented in Table 3.

4.1.2 Lineament and structural setting

A lineament is a linear feature in a landscape, which is an expression of an underlying geological structure and controls the hazard vulnerability such as a fault, thrust, etc. (Rawat et al. 2011c). Typically, a lineament will comprise a fault-aligned valley, a series of fault or fold-aligned hills, a straight coastline or indeed a combination of these features. Fracture zones, shear zones and igneous intrusions such as dykes can also give rise to lineaments. Lineament orientations are dominantly found in NE to SW and NW to SE orientations in the study area (Fig. 4).

4.1.3 Geomorphology

Geomorphologically, the watershed is constituted of as many as 27 types of landforms of different genetics, viz. fluvial, pluvial and tectonic, but the present study is mainly emphasizing on fluvial landforms as for multiple hydrological hazard assessment. The fluvial landforms (i.e., landforms caused by the erosional and depositional processes of streams and rivers) in the watershed are low- and middle-level alluvial terraces, high-level bedrock erosional terraces, small alluvial cones and fans, bank cut, narrow floodplains, sites of debris flow, moist areas, rills and gullies on alluvial terraces (Fig. 4). The pluvial landforms (i.e., landforms caused by erosional and depositional processes of rainwater) in the watershed are unchanneled concave valleys or hollows, knolls, cols, convex hill spurs (all erosional) and sheetwash cones and fans (depositional). Apart from these fluvial and pluvial landforms, the watershed is characterized by tectonic landforms (i.e., landforms caused by tectonic uplift) such as vertical rock and terrace scarps, abandoned valleys, waterfalls, rapids, soil and rock creeping zones, slumping zones, debris fall, rock fall and block gliding. Results suggested that fluvial landforms are the major multiple hydrological
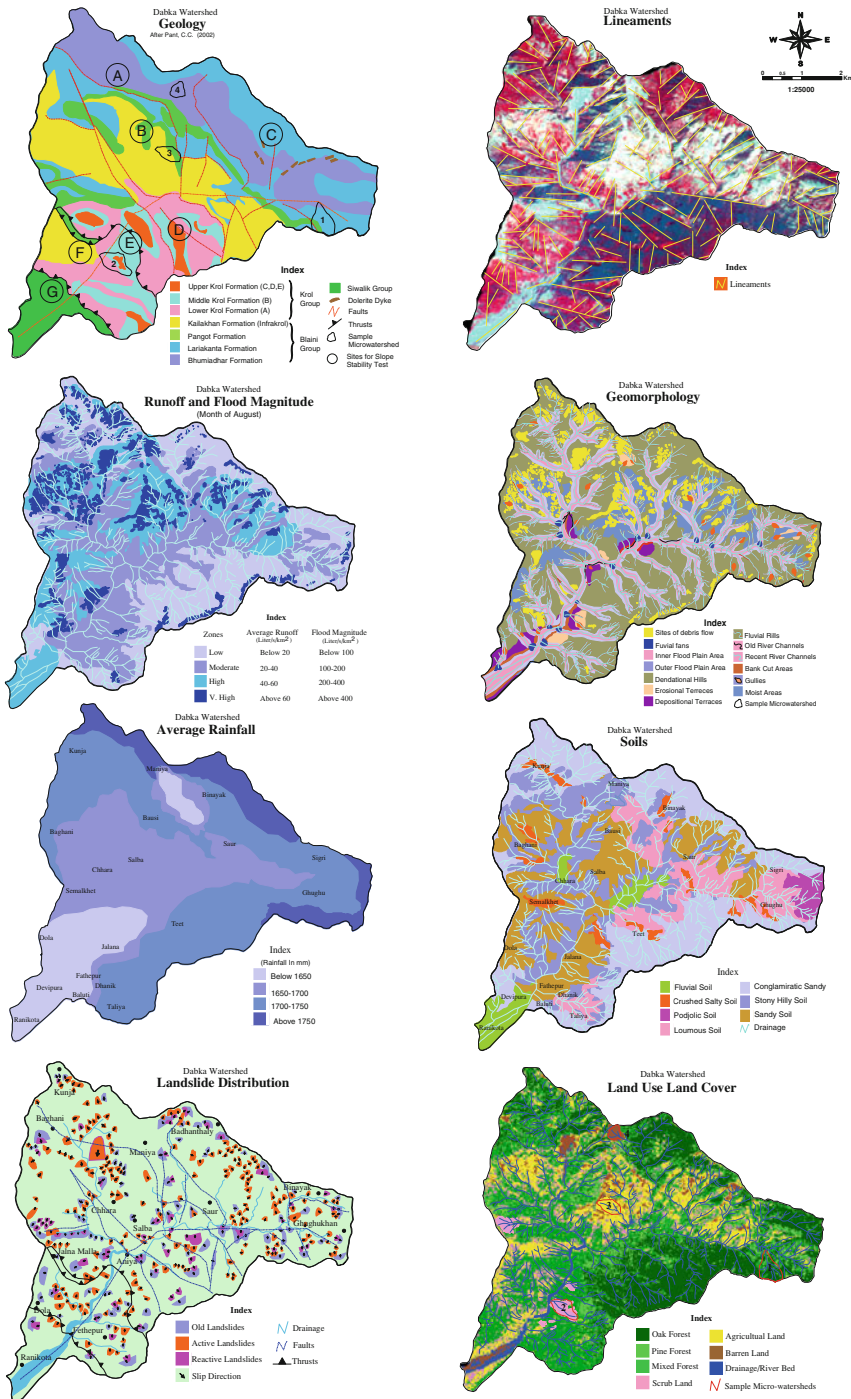
Fig. 4 Geo-hydro-informatics GIS maps for multiple hydrological hazard assessments

hazards triggering factors and, respectively, their vulnerability for that presented in Table 3.

4.1.4 Slope

Four categories of slopes have been identified in the study area, viz. gentle, moderate, steep and very steep slope. The minimum parts of watershed having average surface slope less than 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 less then 10°. These areas constitute depositional landforms, such as river terraces, debris fans. About 8.33 % area of the watershed has moderate slope from 10° to 20°. The convex and concave mid-crest slopes in Fathepur and down slopes of 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-km^2 area that accounts for as much as 51.40 % of the total watershed area falls in very steep slope zone of greater than 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 results suggest that the areas having slopes below 10° are very highly vulnerable for flood hazard and areas having slopes above 30° are very highly vulnerability for erosion and landslide hazard, whereas areas of 10°–20° and 20°–30° slopes are highly vulnerable for drought hazard (Table 3).

4.1.5 Soils

The main soils types found in the region include (1) conglomeratic sandy soils that are mainly found in dense forests at higher elevations, (2) loumous soils have very coarse texture and composed of pebbles and cobbles, which found mainly around Saur, Gwalakhuti, Dau and in Bansi and Ghghukhan area of the watershed, (3) podzolic soils, which consist of high, humus contents extend over an area of 10 % of the catchment in Sigri, Binayak and Ghughukhan villages of the region, (4) crushed salty soils are seen in somewhere patches along the thrusts, faults and other structural feature, (5) stony hilly soils are found around the upper slope of Bansi, Baghani and Dola-Jalna area, (6) fine sandy soils are found near Aniya and Chhara villages and in Fathepur and Dhanak villages and (7) fluvial soil found around Ranikota and Devipura areas in the watershed. It is observed that the soil composed by loss materials is high vulnerability for several hydrological hazards such as sandy soils and fluvial soils (Fig. 4; Table 3).

4.1.6 Land use pattern

The existing land use pattern suggested that the forest emerged as the major land use category in the study area. A geographical area of 36.77 km^2, which accounts for nearly 53 % of total area of the watershed, has been classified as dense forests. Due to complexities of terrain and other geomorphic features, the forests of the watershed are diversified in nature. Out of the total dense forest, 22 % (15.33 km^2) is under mixed forest, 20 % (13.51 km^2) is under oak forest, and 11 % (7.93 km^2) is under pine forests (Figs. 4, 8a). 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 20.61 km^2 or 30 % of the total area. Shrubs land, barren land and riverbeds and water bodies, respectively, extend over 6.22 km^2 (9 %), 3.39 km^2 (5 %), 2.28 km^2 (3 %) of the total geographical land surface of the study area (Fig. 4). Table 2 suggests that the agricultural land and barren land are, respectively, high to very high vulnerability, whereas forested land has low vulnerability for hydrological hazards (Table 3).

4.1.7 Spatial distribution of landslide

Total 248 landslides have been investigated throughout the study area by comprehensive field work. About 97 identified as active landslides, 91 identified as reactive, and 83 found old landslides which area is tectonically stable (Fig. 4). The stable or old landslides are further classified as recently stable completely stable as per the field observation (Table 3). The landslide distribution map suggests that the active landslides were found in areas occupied by Lariakanta Formation of steep slopes. The major rock units of Krol Formation, which are exposed in the vicinity of MBT along the MBT the rocks, are sheared and shattered; therefore, it is considered as a potential zone for slope failure especially during rainy season (Valdiya and Bartarya 1989). It was observed that dense forest has less density of landslides in the region. Tit Ka Danda area has lesser number of active landslides compared to other areas of the region. This may be due to the presence of dense vegetation cover in the area (Fig. 4). But deforestation due to climate change and anthropogenic interference such as road construction extension of agriculture land, mining has caused active slides in many places in the region. However, high runoff and denudation rate due to heavy rainfall has been a major factor in causing landslides in the weaker zones of the area in monsoon period. The reactivated landslides associated with the old stable landslides because of reactivation of old stable landslides due to accelerated land use dynamics, high runoff and erosion occurring by the combination of anthropogenic and climate change factors (Rawat et al. 2011b).

4.2 Hydro-informatics

The hydro-informatics module of the Dabka DBMS contains daily, monthly and annual record of hydrological parameters (i.e., rainfall, water discharge, flood rates, water balance, suspended, dissolved and bed-load erosion, and gross rates of denudation) of four different stations of different ecological conditions. Summary of these hydrological records is given in Table 2. A brief description of the hydrological parameters is presented below:

4.2.1 Precipitation

The watershed receives about 2,004 mm annual rainfall (Table 2). The average annual rainfall within the watershed varies between 1,623 mm and Maniya located in environmentally stressed barren hill slope and 2,187 mm at Ghughu located in dense forest hill slope. On other stations, the annual rainfall amount stand at 1,969 mm at Bausi located in agricultural land and 2,086 mm at Jalna located in fairly dense forest/shrub land (Table 2). The spatial distribution pattern of the rainfall has been shown in Fig. 4.

4.2.2 Runoff

The daily hydrographs of different micro-watersheds and of the Dabka were summarized, and the results are presented in Table 2, suggesting that the average runoff rate is 16.82 l/s/km^2 and it varies considerably depending upon the ecological conditions (Fig. 4; Table 2). It varies between 6.27 l/s/km^2 in the dense forest micro-watershed to 31.8 l/km^2/year on the barren micro-watershed. On the fairly dens forest and agricultural micro-watershed, the average rate of runoff stands at 11.05 and 16.98 l/s/km^2, respectively (Table 2). These data advocate that the dense forested land due to broad-leaved spices of trees has very high and the deforested barren land has very low water retention capacity within their hydrological system. The annual hydrograph of the watershed reveals the following salient characteristics:

1. April is the month of approaching segment of the hydrograph when the watershed discharges water at average rate of 0.78 l/s/km^2. It is base flow of stream, which is maximum in dense forest land (1.04 l/s/km^2) and minimum in barren land (0.23 l/s/km^2).
2. May (26.90 l/s/km^2), June (30.61 l/s/km^2) and July (42.61 l/s/km^2) are the months, which communicate rising segment of the hydrograph.
3. August is the month of peak water discharge when the watershed discharges water at the average rate of 48.08 l/s/km^2. It is maximum in barren land micro-watershed, that is, 84.56 l/s/km^2 and minimum in dense forest micro-watershed (20.67 l/s/km^2).
4. September (27.44 l/s/km^2) to December (2.90 l/s/km^2) are months of recession segment of the hydrograph.
5. January (3.00 l/s/km^2) is the month of rising segment of winter rains and
6. February (4.85 l/s/km^2) is the month of winter peak discharge.

4.2.3 Flood magnitude

It is maximum peak discharge rate during rainy season. The flood records of the study period were examined, which reveals that the Dabka Watershed has capacity to generate maximum flood during rainy season (particular in the month of August) at the rate of 431.3 l/s/km^2 having wide variations depending upon ecological conditions (Fig. 4; Table 2). The broad-leaved spices of trees in dense forest areas help in controlling the floods as the maximum flood generating capacity of this forest is only 58.12 l/s/km^2. The highly stressed deforested barren land has the maximum flood generating capacity where the flood magnitude is recorded during study period about 871 l/s/km^2; it is about 15 times higher than the flood magnitude of the dens forest land. On other ecological conditions, the magnitude of maximum flood rate recorded 90, 310, 430 and 630 l/s/km^2 on fairly dense forest/shrubs land and agricultural land micro-watershed, respectively (Table 2). A combined spatial distribution map for runoff and flood magnitude (Fig. 4) carried out using maximum average runoff and flood magnitude data, that is, in the month of August (Table 2). This map depicting four zones of runoff and flood magnitude from low to very high, respectively, denotes as low, moderate, high and very high vulnerable for flood hazard (Table 4).

4.2.4 Bed load

Streams of the Dabka basin carry bed load throughout the year except those emitting from the least disturbed dens forest land (Table 2). Compared to the forest land (39 tons/km^2/

Table 4 Spatial database for multiple hydrological hazards

Multiple hydrological hazards	Hazard zones with covered area									
	Low		Moderate		High		Very high		Total	
	km²	%	km²	%	km²	%	km²	%	km²	%
Drought hazard	44.20	64	11.05	16	8.98	13	4.83	7	69.06	100
Flood hazard	27.87	40	16.19	23	13.56	20	11.43	17	69.06	100
Erosion hazard	30.39	44	17.96	26	16.57	24	04.14	06	69.06	100
Landslide hazard	19.10	28	11.40	17	09.50	14	29.06	42	69.06	100
Integrated hazard	18.38	27	10.48	15	14.32	21	25.88	37	69.06	100

year), the streams coming from the disturbed land (Agricultural and barren land) have 5–8 times higher bed load (144 and 236 tons/km²/year). The average rate of bed load of the Dabka Watershed stands at 124.50 tons/km²/year (Table 2).

4.2.5 Suspended load

The stream flowing across forests transport suspended sediment mainly in rainy season but the streams releasing from the anthropogenically most disturbed (agricultural and barren land) micro-watersheds carry suspended material throughout the year. The suspended load is maximum in the stream flowing through the barren land (110 tons/km²/year), which is 5 times higher than that of the forest land (18 tons/km²/year). In the agricultural land, it is 4 times higher (72 tons/km²/year), and in shrubs land, it is 2 times higher (34 tons/km²/year). The average rate of suspended load of the Dabka Watershed stands at 58.50 tons/km²/year (Table 2).

4.2.6 Dissolved load

Dissolved organic and inorganic ions constitute the dissolved load, which is carried by streams throughout the year. Nearly, 12 % (8 tons/km²/year) of the total annual dissolved load is removed from the least disturbed dense forest land, whereas 20 % (47 tons/km²/year) from the barren land, which is 9 times higher than that of the forest land. In the agricultural land, the dissolved load is 8 times higher (66 tons/km²/year), and in fairly dens forest/shrub land, it is 2 times higher (17 tons/km²/year). The average rate of dissolved load of the Dabka Watershed stands on 34.50 tons/km²/year (Table 2).

4.2.7 Total erosion load

Under natural circumstances, the total sediment load of streams varied from 66 tons/km²/year in the dense forest to 398 tons/km²/year in the barren land in the watershed. Anthropogenic activities have accelerated the rate of load generation by 7 times (302 tons/km²/year) in agricultural land and 8 times (398 tons/km²/year) in barren land, whereas the average rate of total load of the Dabka Watershed stands at 224.45 tons/km²/year (Table 2).

4.2.8 Rate of denudation

Under different land use type, the annual rate of erosion in the Dabka Watershed is given in Table 2. 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 fairly dens forest/shrub land. Under most disturbed land, these rates are terrifyingly high, that is, 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 (Table 2). A spatial distribution map (Fig. 4) for erosion and denudation rate has been carried out using gross annual mechanical load (suspended and bed load) and chemical load (dissolved load) presented in hydrological database (Table 2).

4.3 Hazard-informatics

As mentioned in methodological section, the hazard-informatics module is carried out through overlaying geo-informatics and hydro-informatics GIS module (Table 3). The hazard-informatics module consists of spatial and attribute GIS database of several hydrological hazards, that is, drought hazard in non-monsoon period, whereas flood, erosion and landslide hazard in monsoon period. A brief discussion of each hydrological hazard is given below:

4.3.1 Drought hazard

The spatial distribution of drought hazard comprises the integrated effect of three types of drought (i.e., decreasing underground water, drying up springs and decreasing stream discharge) in a unit area. In order to that, throughout the study area, four zones of drought hazard have been determined, that is, low, moderate, high and very high in respect to potential for drought hazard. Very-high-hazard zone have the maximum area, that is, about 44.20 km^2 or 64 % of the watershed, whereas very-low-hazard zone has minimum area (04.83 km^2 or 7 % of the watershed). The low- and moderate-drought-hazard zones account, respectively, about 08.98 km^2 or 13 % and 11.05 km^2 or 16 % areas of the watershed (Table 4; Fig. 5).

4.3.2 Flood hazard

The spatial database shows four zones of flood hazard namely low-, moderate-, high- and very-high-flood intensity zones. All the up slope areas of the denudational hills around village Baghni, Ghughu, Dorla, Saur, Aniya, Jalna, Saur, Chhara, Aniya, Janla identified as low-flood-hazard potential (Fig. 5). Out of the total area of the Dabka Watershed, 27.87 km^2 or 40 % is under low-flood-hazard zone (Table 4; Fig. 5). The areas having morphology of cons and erosional terraces around lower parts of the Saur, Chhara, Aniya, Janla villages identified as moderate-flood-hazard potential (Fig. 5). Out of the total area of the Dabka Watershed, 16.19 km^2 or 23 % is under moderate-flood-hazard zone (Table 5; Fig. 5). The areas having morphology of depositional terraces and alluvial fans around lower parts of Baghni, Ghughu, Saur, Aniya, Jalna, Ranikota identified as high-flood-hazard potential (Fig. 5). Out of the total area of the Dabka Watershed, 13.56 km^2 or 20 % is under high-flood-hazard zone (Table 4; Fig. 5). Flood plains, fluvial fan, moist area, landslide and debris flows areas, bank cut area, gulling and rills around all the villages located along streams and sub-streams have been mainly identified as very high intensity

Dabka Watershed
Multiple Hydrological Hazards
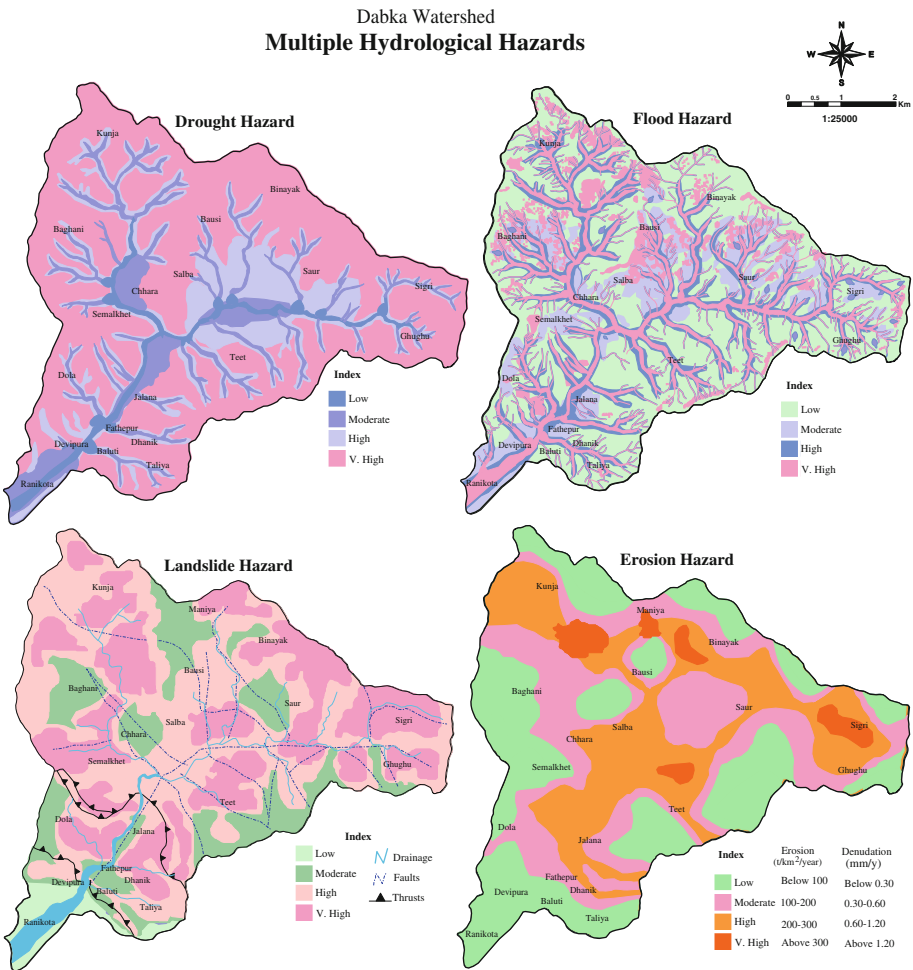
Fig. 5 Hazard-informatics module consists of multiple hydrological hazard maps (Consists of drought, flood, erosion and landslide hazards)

for flood hazard (Fig. 5). Out of the total area of the Dabka Watershed, 17 % or 11.43 km^2 is under very-high-flood-hazard potential (Table 4; Fig. 5).

4.3.3 Erosion hazard

Dense forest areas having gentle slope near village Baghani, Jalna, Binayak, Teet and Devipur have been mainly identified as low-erosion-hazard zone (Fig. 5). Out of the total area (69.06 km^2) of the Dabka Watershed 44 % (30.39 km^2) is under low erosion hazard intensity zone (Table 4; Fig. 5). The rate of total sediment load delivery in this zone stands below 100 t/km^2/year, which denuded the area as the rate of 0.30 mm/year (Table 4; Fig. 5). 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, 17.96 km^2 or 26 % is under moderate sediment load delivery zone (Table 4; Fig. 5).

Table 5 Risks Index (RI) includes six parameters (X) and 18 sub-parameters (A), which have been considered for weight assignment to risks zone mapping for Dabka Watershed

Sub-parameters (A)	Main parameters (X)						Assignment of weightage for Risks Index	Risk potential
	Houses and built-up areas (distance from hazard events in m) (X1)	Land use pattern (GIS mapping) (X2)	Rods, bridle paths and bridges (distance from river bed in m) (X3)	Irrigation cannels and transmission lines (distance from river bed in m) (X4)	Drinking water storage and supply lines (X5)	Natural water springs (X6)		
A1	Above 80	Forest land, river beds	Below 15	Below 15	Below 15	Perennial	1	Low
A2	40–80	Shrubs land,	15–30	15–30	15–30	Seasonal	2	Moderate
A3	Below 40	Agricultural land	Above 30	Above 30	Above 30	Dried	3	High

Village Saur, Bausi, Baghani, Jalna and Kunja have the major proportion of the moderate sediment load delivery zone (Table 4; Fig. 5). The rate of total sediment load delivery in this zone varies from 100 to 200 t/km^2/year, which denuded the area with the rate of 0.30–0.60 mm/year (Table 4; Fig. 5). 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, 1,657 km^2 or 24 % is under high-erosion intensity zone (Table 4; Fig. 5). Village Kunja, Teet, Janal, Salba, Chhara, Bausi, Binayak, Saur, Ghughu and Sigri have the major proportion of the high sediment load delivery zone (Table 4; Fig. 5). The rate of total sediment load delivery in this zone varies from 200 to 300 t/km^2/year, which denuded the area of this particular zone with the rate of 0.60–1.20 mm/year (Table 4; Fig. 5). 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, 4.14 km^2 or 6 % is under very-high-erosion-hazard zone (Table 4; Fig. 5). Village Kunja, Binayak, Sigri and Teet have the major proportion of the very high sediment load delivery zone (Table 4; Fig. 5). The rate of total sediment load delivery in this zone stands on Above 300 t/km^2/year, which accelerated rate of denudation in that particular zone with the rate of 1.20 mm/year (Table 4; Fig. 5).

4.3.4 Landslide hazard

Dense forest areas having gentle slope near village Baghani, Jalna, Binayak, Teet and Devipur have been mainly identified as low-landslide-hazard zone (Fig. 5). Out of the total area of the Dabka Watershed, 19.10 km^2 or 28 % is under low-landslide-hazard zone (Table 4; Fig. 5). Shrubs land and loped area under forests around village Saur, Bausi, Baghani, Jalna and Kunja having moderate slope have been identified as moderate-landslide-hazard zone (Fig. 5). Out of the total area of the Dabka Watershed, 11.40 km^2 or 17 % is under moderate-landslide-hazard zone (Table 4; Fig. 5). Agricultural land and lopped-forest areas have been mainly identified as areas of high-landslide-hazard zone (Fig. 5). Out of the total area of the Dabka Watershed, 9.50 km^2 or 14 % is under landslide hazard zone around village Kunja, Teet, Janal, Salba, Chhara, Bausi, Binayak, Saur, Ghughu and Sigri. Barren land, and debris flow areas have been identified as very-high-landslide-hazard zone along the major streams and their sub-streams (Fig. 5). Out of the total area of the Dabka Watershed, 29.06 km^2 or 42 % is under very-high-landslide-hazard zone around village Kunja, Binayak, Sigri and Teet have the major proportion of the very-high-sediment load delivery zone (Table 4; Fig. 5).

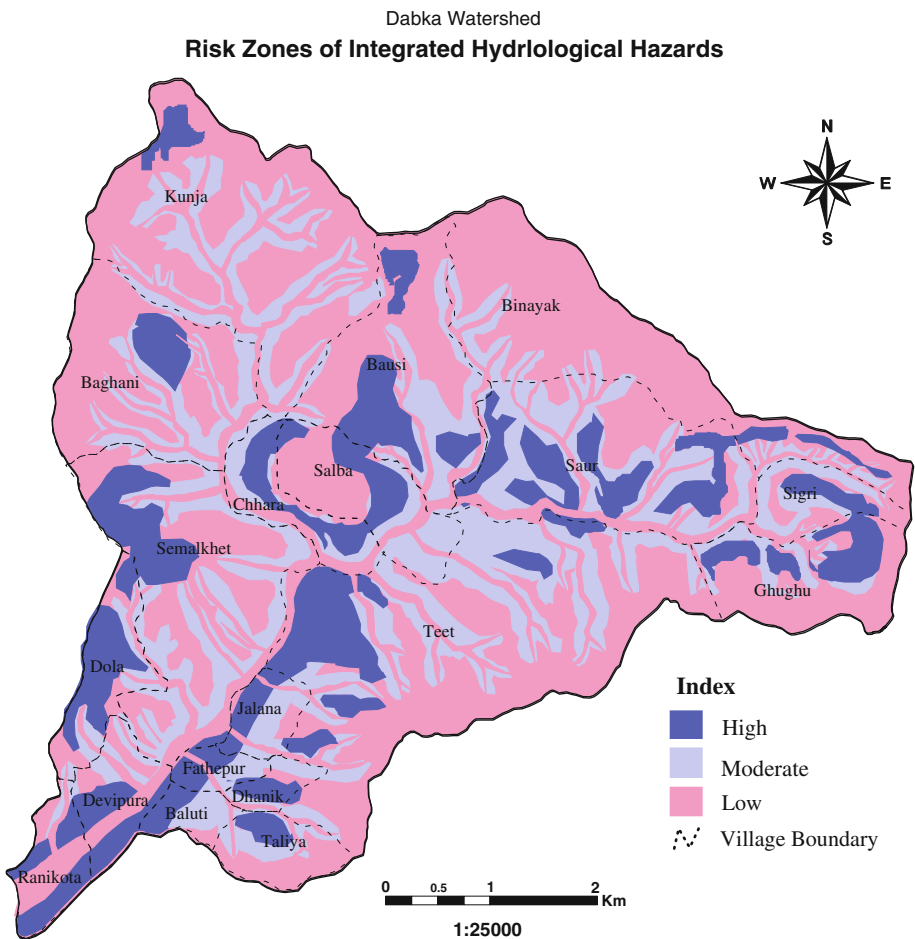### 4.4 Integrated multiple hydrological hazards

The integrated hazard map generated after overlaying drought, flood, erosion and landslide hazard maps shows four hazard zones in the watershed (Fig. 6). On evaluating the area statistics, it was found that out of the total area of the watershed, 34 % is under high hazard, 21 % under moderate hazard, 17 % under low hazard and 28 % is under very-low-hazard zone (Table 4). On the basis of overall assessment of the watershed, it can be said that high-hazard areas are mostly found on the steep slopes with the lithology of Lariakantha–Bhumiadhar Formation and along major streams of the watershed and moderate-hazard areas are found in moderately steep areas and along major tributary streams, whereas low- and very-low-hazard areas are confined to dense forests with the lithology of Krol Formation and human managed landscape, like agriculture and pasture land, etc. (Fig. 6).

Dabka Watershed

(A) Overlaying GIS Maps of Multipal Hydrological Hazards
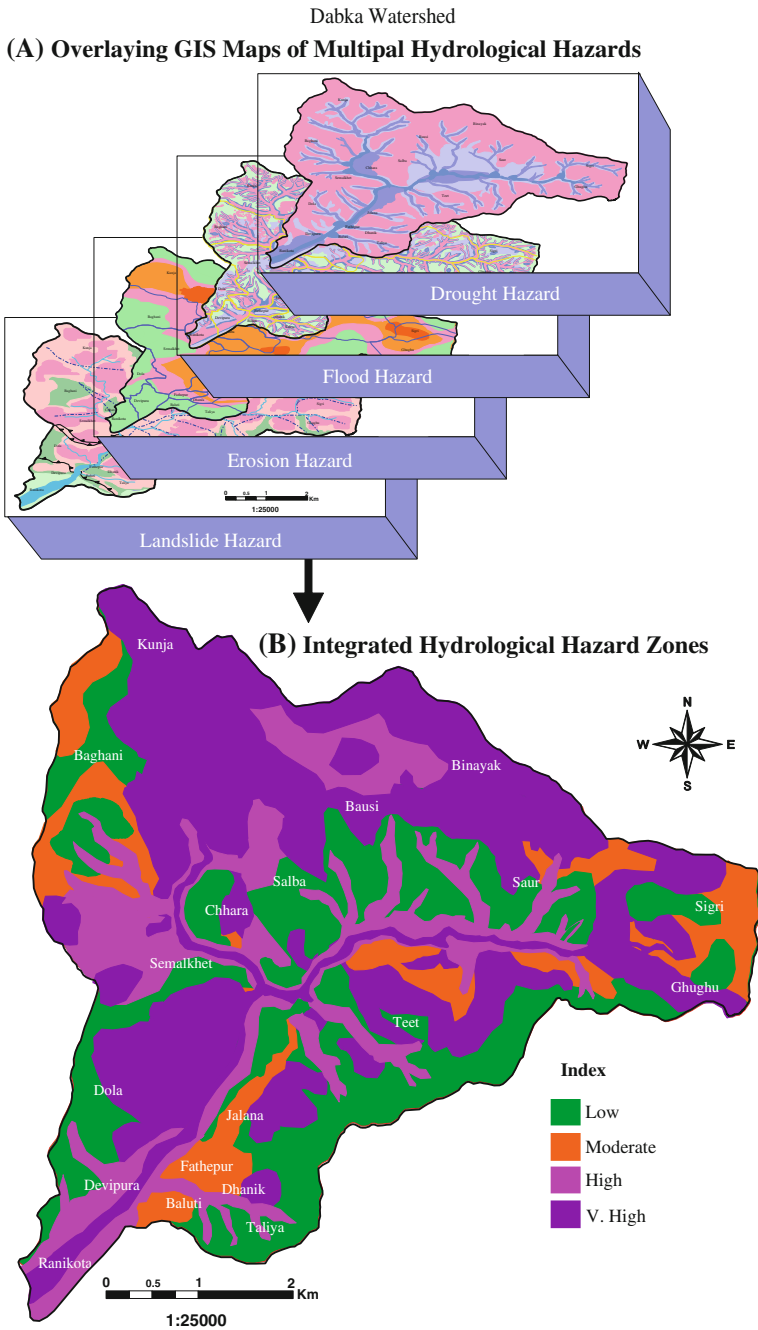
Fig. 6 Integrated hydrological hazard map carried out through overlaying GIS maps of multiple hydrological hazards (i.e., drought, flood, erosion and landslide)

4.5 Environmental and socio-economic risks of integrated multiple hydrological hazards

As already discussed in methodological section to prepare the RI of the study area, total 6 sets of socio-economic and environmental parameters (X) and their 18 sub-parameters (A) have been taken into account. The major parameters include houses and built-up areas, land use pattern, road network, drinking water storage, canals and transmission lines and natural water springs (Table 5). To appraise the environmental and socio-economic consequences of multiple hydrological hazards in the study area, a risk map has been prepared (Table 5). This map shows three risks class namely low, moderate and high. Low category of risk has been mainly identified in the areas of high altitudinal zones such as ridges and structural and denudational hills. These areas mainly fall under forest, wasteland, channel beds and scrubland of the watershed (Fig. 7). Out of the total area of the Dabka Watershed, 56.37 km^2 or 82 % is under low-risk potential zone of integrated hydrological hazards


Fig. 7 Environmental and socio-economic risks zones of integrated hydrological hazards (i.e., drought, flood, erosion and landslide)

(Fig. 7). Pediment areas have been identified as the areas showing moderate potential to the risk. The moderate-risk potential areas are generally confined to agricultural land (Fig. 7). Out of the total area of the Dabka Watershed, 6.06 km² or 9 % is under moderate-risk potential zone (Fig. 7). Human settlements, water-mills, roads, canals and cultivated land, river terraces and plantation surfaces of the watershed have been identified as the areas subjected to high-risk potential (Fig. 7). Out of the total area of the Dabka Watershed, 6.63 km² or 10 % is under high-risk potential zone of integrated hydrological hazards (Fig. 7).

5 Sustainable land use plan for multiple hydrological hazard and their risks mitigation

As first step toward the mitigation of multiple hydrological hazards and their risks, a comprehensive land use plan has been evolved and proposed for Dabka Watershed that could be implemented throughout the Himalaya region because of eco-friendly and low-cost measures. The land use framework has been designed taking into consideration the parameters of geo-informatics module (consist of geomorphology, slope, drainage density, drainage frequency, soils, geology and land use pattern), hydro-informatics module (consist of temperature, rainfall, humidity, evapotranspiration loss runoff, sediment transport, etc.) and hazard-informatics module (consist of drought, flood, erosion and landslide hazard). The land use plan evolved for the region has been presented in Table 6 and Fig. 8 and described as following:

1. The conservation, protection and sustainable development of forest resources are essential for the management of hydrological hazards such as flood, erosion, landslide in monsoon period and drought in non-monsoon period (i.e., drying up of natural water springs and streams). In view of this, the forest area of the Dabka Watershed has been proposed to be increased from the existing 36.56 to 45.00 km². This increase would be possible by bringing additional 8.22 km² of lopped-forest area or shrubs land and agricultural land (having high vulnerability for hydrological hazards) under reforestation program (Table 6; Fig. 8). The lopped-forest areas under barren, shrubs and agricultural land proposed to be afforested are already a part of forest, but it is under highly degraded condition (Table 6; Fig. 8).

Table 6 Proposed land use to mitigate multiple hydrological hazards and their environmental and socio-economic risks

Land use classes	A. Existing area		B. Proposed area	
	km²	%	km²	%
Dense forest (oak, pine and mixed)	36.56	53	45.00	65
Shrubs land	06.22	09	02.00	03
Barren land	03.39	05	00.00	00
Cultivated land	20.61	30	16.30	24
River bed	02.28	03	2.28	03
Horticulture	00.00	00	3.48	05
Total	69.06	100	69.06	100
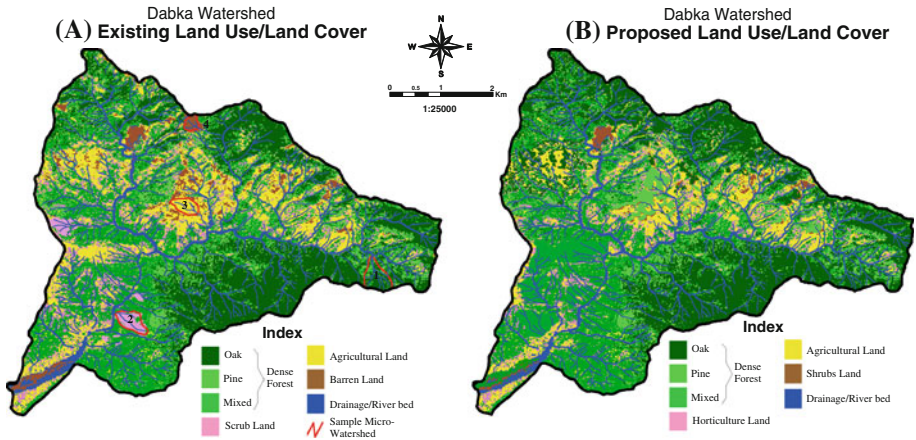
Fig. 8 a Exiting land use and four sample micro-watershed in different land use pattern. **b** Proposed scientific land use for erosion hazard mitigation

2.   Out of total (20.51 km^2) existing agricultural land, 16 % (4.31 km^2) that have high risk of hydrological hazards has been proposed to be diverted to shrubs land and to horticultural practices (Table 6; Fig. 8).

3.   The favourable geographical conditions for the production of a variety of fruits in the watershed, and community demand for horticultural development, 5.48 km^2 area of existing barren, shrubs and cultivated land which have high risk of hydrological hazard has been recommended to be brought under horticultural development in the watershed (Table 6; Fig. 8).

4.   As much as 2-km^2 area under existing barren and cultivated land lying in hazard zones, and therefore highly vulnerable to several kinds of hydrological hazards due to high rate of runoff and denudation, has been suggested to developed as shrubs land (Table 6; Fig. 8).

6 Conclusion

This investigation is an effort to assess the sound effects of an increasing anthropogenic and geo-environmental impacts upon geo-hydrological system, which resulted in several water-related hazards (i.e., floods, erosion, landslides during rainy season and drought due to dry-up of natural springs and streams during summer season) in the critical and vulnerable areas of the Himalaya region. The results concluded that geo-environmentally most stressed barren land areas have high rate of runoff, flood magnitude, erosion sediment load and denudation during rainy season particularly in the month of August (i.e., respectively, 84.56 l/s/km^2, 871.80 l/s/km^2, 78.60 t/km^2 and 1.21 mm/year), which accelerates high hazards and their socio-economic and environmental risks, whereas in geo-environmentally least stressed dense forest areas experience low rate of stream runoff, flood magnitude, erosion sediment load and denudation in the same season and month (i.e., respectively, 20.67 l/s/km^2, 58.12 l/s/km^2, 19.50 t/km^2 and 0.20 mm/year) comparatively have low hazards and their socio-economic and environmental risks. It is, therefore, time to move from environmental consciousness to articulation of an eco-friendly strategy for

integrated sustainable development of Himalaya region. This makes it necessary to take up an integrated and comprehensive sustainable land use policy for the entire Himalaya region based on the scientific interpretation of the crucial linkages between land use pattern and hydrological hazards. The study would help the village, district and state development authority to formulate decision support system (DSS) for alternate planning and management for the Himalaya region.

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