Database management system for Khulgad Watershed, Kumaun Lesser Himalaya, Uttarakhand, India

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We report here an attempt to develop a Database Management System (DBMS) of bio-geo-hydro-meteorological parameters needs of the stakeholders of local level planning for a representative watershed (viz. the Khulgad in Almora district) of Kumaun, Lesser Himalayan terrain in the Uttarakhand. The Khulgad DBMS is constituted of five Geographic Information System (GIS) modules, i.e. geo-informatics, weather-informatics, hydro-informatics, biodiversity-informatics (flora, agricultural crops, fauna and pests) and socio-informatics. Through these modules, the users can retrieve information and develop thematic maps and action plans suited to their needs related to different bio-geo-hydrometeorlogical parameters by a few clicks on a computer.

Keywords: Biodiversity-informatics, Database Management System, geo-informatics, hydro-informatics, socio-informatics, weather-informatics.

THIS study conducted during 2004 and 2006 constitutes a part of the bio-geo database and ecological modelling of the Himalaya programme of the Natural Resources Data Management System (NRDMS) division of the Department of Science and Technology (DST), Government of India which aims to develop integrated bio-geo-hydro-meteorological Database Management System (DBMS) of the Khulgad Watershed. 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[1].

Methodology

Information needs

To develop database for watershed management and ecological modelling, first, information need assessment of the stakeholders of the local level planning (i.e. Jal Nigam, Jal Sansthan, Departments of Forest, Agriculture, Horticulture, Watershed Management, Irrigation, Minor Irrigation, Forest, Public Works Department, etc.) was done through a users' need assessment workshop for identifying their information needs related with formulation and implementation of different development projects. After preparing a list of users' data/maps needs[2], attempts were made to develop DBMS for the Khulgad – a representative watershed of the Lesser Himalayan terrain of the Kumaun Division in Uttarakhand.

Study area

The study area, viz. the Khulgad Watershed (29°34′30.20″–29°38′48.03″N lat. and 79°32′20.71″–79°37′11.19″E long.) lies 25 km west of the Almora town in the Hawalbagh Development Block of Almora District in the Uttarakhand. Khulgad is a tributary of the Kosi River which joins the Western Ramganga in the plains of Uttar Pradesh.

Data collection and integration

Under different research projects of the NRDMS division of DST, the bio-geo-hydrometeorological data of the Khulgad Watershed were collected by seven different institutions/organizations as detailed in Table 1. In order to develop DBMS of the Khulgad Watershed, integration of all the collected spatial and attribute data layers of five different information sectors (Table 1), i.e. geo-information, biodiversity-information, hydro-information, weather-information and socio-information, was done at one common scale, i.e. 1 : 25,000 using very low cost users friendly indigenous Geographic Information System (GIS) software, viz. GRAM++ (Geo Reference Area Management). The advantage of this software is that the stakeholders of the local level planning (i.e. district or below level) can make use of this software.

Khulgad DBMS

Khulgad DBMS is constituted of five different GIS modules consisting of more than 200 spatial map layers with their attribute data. These five GIS modules are: geo-

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Table 1. Information sectors and names of organization by whom data were generated for the Khulgad Watershed under bio-geo database programme of the NRDMS division, DST, New Delhi

Sectors of information	Parameters recorded/studied	Organization by whom study was contacted
Geo-information	*Watershed morphology:* Spatial distribution and characteristics of tectonic landforms, tectonically controlled landforms, pluvial landforms, fluvial landforms and anthropogenic landforms.	Kumaun University
	Relief morphometry: Digital elevation model (DEM) at 20 m and 100 m resolutions, slope map, aspect map, triangulated irregular network (TIN), hill shading and 3D map.	
	Drainage morphometry: Automated watershed delineation, stream ordering, watershed hierarchy, view shed analysis, stream length, drainage density, watershed circularity ratio.	
	Geology: Spatial distribution of rocks types and structure.	
	Land use type: Spatial distribution of land use categories.	
	Soils: Colour, depth, texture, stoniness, soil drainage, rockiness, soil pH, soil irrigability, land capability, crop suitability maps for peer, soyabeen, wheat, paddy, potato, rapeseed mustard, maize, mandua and citrus.	NBSS, New Delhi
Hydro-information	*Water discharge:* Daily, monthly and annual records of water discharge recorded at five different hydrological stations representative of different ecological conditions.	Kumaun University
	Sediment, dissolved and bedload flow: Monthly, seasonal and annual suspended, dissolved and bed load flows recorded at five different hydrological stations representative of different ecological conditions.	
	Rate of denudation: Annual rates of mechanical, chemical and gross denudation, and their spatial variability.	
Weather information	Daily, monthly and annual records of temperatures, humidity, rainfall, wind velocity, evaporation recorded of five different meteorological stations representative of different ecological conditions; and sunshine hours recorded near the centre of the Khulgad Watershed, viz. at the Khunt meteorological station.	Kumaun University
Bio-information	*Flora:* Spatial distribution of vegetation types of the watershed in 1988, 1994, 1988 and 2002; forest areas converted into non-forest areas during 1988–1994, 1994–1998, 1998–2002 and 1988–2002; non-forest areas converted into forest areas during 1988–1994, 1994–1998, 1998–2002 and 1988–2002; characteristics of forest data and grazing data in the watershed; species wise details of trees and herbs production; and details of stems and growing stocks, and weed data of the watershed.	Forest Survey of India
	Fauna: Spatial distribution of wild animals (monkey, languor, leopard, fox, jackal, barking deer, wild bore, porcupine and pheasant, and mammals.); and density, diversity, richness and evenness of birds in summer and winter seasons.	Aligarh Muslim University
	Agricultural crops: Spatial distribution during rabi and kharif seasons of per unit per cent area; of Simpson Index; of Shannon Diversity; of Shannon Diversity; of Crop Diversity; and of Weed Intensity in the watershed	Delhi University
	Pests: Incidences of pests in different crops of rabi and kharif seasons.	IARI, NewDelhi
Socio-informatics	Village distribution, Nyay Panchyat and road maps, spatial distribution of education and health centres; characteristics of roads, health and education centres; village demography and socio-economic characteristics.	JNU New Delhi/Kumaun University

informatics, weather-informatics, hydro-informatics, biodiversity-informatics and socio-informatics (Figure 1).

Geo-informatics

The geo-informatics module consists of spatial distribution maps with their attribute data of six different geo-sectors, i.e. watershed morphology, watershed relief, drainage morphometry, soils, geology and land use pattern. The users can quickly retrieve information from these GIS modules related to the above geo-sectors of watershed by a few clicks on a computer. A brief description of geo-information based on this geo-informatics module of the Khulgad DBMS is given below.

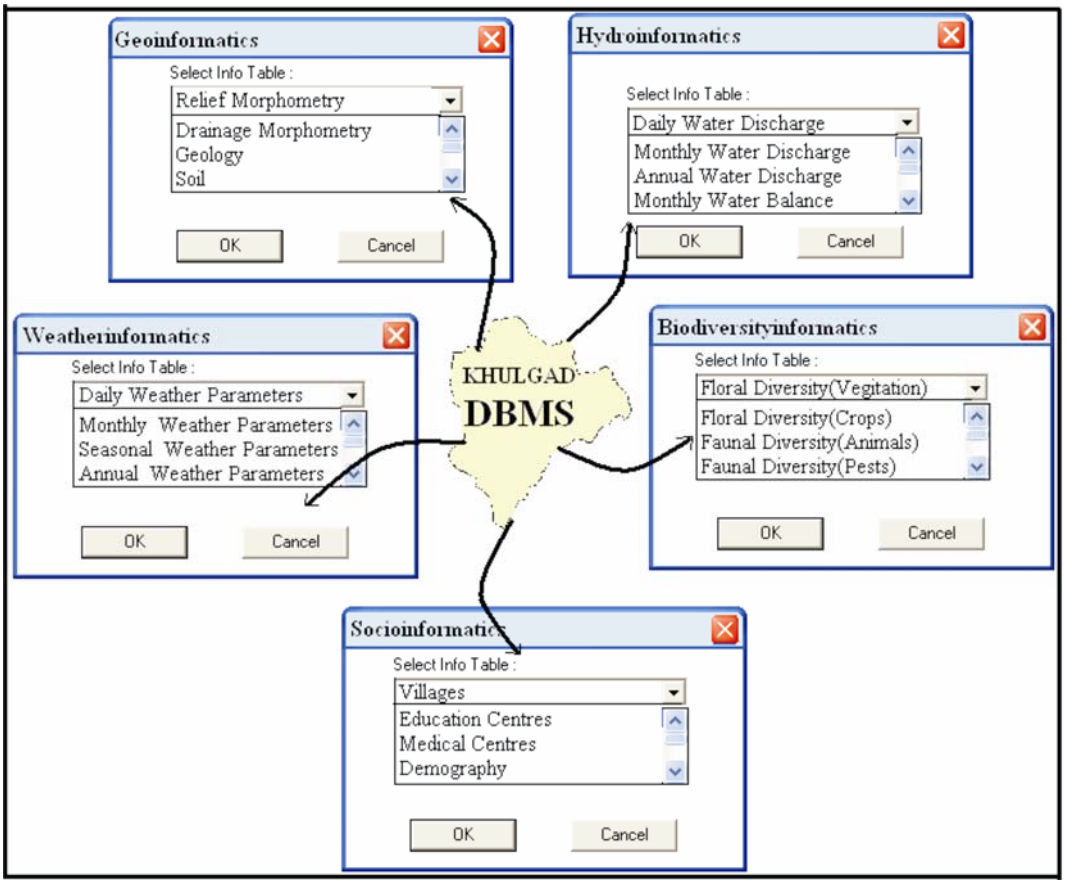

Figure 1. The Khulgad Watershed Database Management System and its Geographic Information System modules, i.e. geo-informatics, hydro-informatics, weather-informatics, biodiversity-informatics and socio-informatics.

Watershed morphology: Morphologically, the watershed is constituted of as many as 24 types of landforms of different genetics, viz. pluvial, fluvial and tectonic. The pluvial landforms (i.e. landforms caused by erosional and depositional processes of rainwater) in the watershed are unchannelled concave valleys or hollows, knolls, cols, convex hill spurs (all erosional), and sheetwash cones and fans (depositional). 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, narrow floodplains, rills and gullies on alluvial terraces. Apart from these pluvial and fluvial landforms, the watershed is characterized by tectonic landforms (i.e. landforms caused by tectonic uplift)[3] 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.

Relief morphometry: As basic elements for analysing and visualizing relief morphometric characteristics, i.e. digital elevation mode (DEM), slope, aspects, triangulated irregular network (TIN) and 3D are important in studies of watershed units[4]. The digital model with an array of uniformly spaced elevation data in a raster format[5], of the watershed developed at 10 m resolution (Figure 2 *a*) reveals that maximum and minimum altitude of the Khulgad Watershed varies between 1150 m at its mouth and 2269 m at the Syahidevi hill top on the southern part. Table 1 contains distribution of area under different altitudinal zones which reveals that a large part (i.e. 48.72%) of the watershed falls under medium altitudinal relief zone (i.e. 1400–1700 m). Slope measures the rate of change of elevation at a surface location[6]. The digital slope map (Figure 2 *b*) prepared based on a 10 m contour resolution suggests that the average slope of the watershed stands at 19°. A large part, i.e. 47.2% area of the watershed falls under the steep slope (i.e. 15–25°) category (Table 2). The aspect map (Figure 2 *c*) derived on eight principal directions, i.e. north, northeast, east, southeast, south, southwest, west and northwest depicts spatial distribution of these different aspects in the watershed. The northern aspect covers maximum (i.e. 21%) area of the watershed whereas about 15% area of the watershed has northern slope aspect (Table 2).

Drainage morphometry: The drainage morphometry of the watershed is summarized in Table 3. About 94.14% streams of the watershed are ephemeral, 5.15% are inter-

Table 2. Relief, slope, aspect and land use/land cover statistics of the Khulgad Watershed

	Parameters	Area (km^2)	Area (%)	Category
Relief zones (m)	< 1200	0.66	2.03	Low
	1200–1300	3.31	10.08	
	1300–1400	7.57	23.09	
	1400–1500	7.44	22.70	
	1500–1600	5.22	15.92	Medium
	1600–1700	3.31	10.10	
	1700–1800	2.53	7.72	
	1800–1900	1.36	4.13	High
	1900–2000	0.67	2.04	
	2000–2100	0.45	1.36	
	2100–2200	0.27	0.81	Very High
	> 2200	0.01	0.02	
Slope group	0°	0.66	2.0	
	< 5°	1.44	3.5	Gentle
	5–10°	2.36	7.2	
	10–15°	11.02	33.6	Moderate
	15–20°	10.14	30.9	
	20–25°	5.35	16.3	Steep
	> 25°	2.13	6.5	Very steep
Aspect	Level	0.66	2	Level land
	337.5–22.5°	6.89	21	Northern
	22.5–67.5°	5.58	17	Northeastern
	67.5–112.5°	4.88	15	Eastern
	112.5–157.5°	4.27	13	Southeastern
	157.5–202.5°	4.59	14	Southern
	202.5–247.5°	1.98	6	Southwestern
	247.5–292.5°	1.65	5	Western
	292.5–337.5°	2.30	7	Northwestern
Land use/land cover types	Dense broadleaved oak forest with dense scrubs	1.93	4.9	Slightly degraded
	Dense pine forest with dense scrubs	0.85	2.6	Degraded
	Pine forest without scrubs	1.54	4.7	Highly degraded
	Scattered pine forest without scrubs	3.38	9.3	
	Regenerated pine forest	3.77	10.5	Recovering
	Barren grass land	9.68	32.5	Very highly degraded
	Agricultural land	10.33	31.5	Extremely highly degraded
	Horticultural land	1.32	4.0	

mittent and only 0.51% are perennial. According to the Strahler's stream ordering[7], Khulgad is a sixth order stream which has 2 fifth order, 6 fourth order, 24 third order, 103 second order and as many as 444 first order or branchless streams (Figure 2 *d*). The drainage morphemetric parameters, i.e. bifurcation ratio[8], total stream length, watershed area, drainage density[9], stream frequency of the watershed stand at 3.0, 210.25 km, 32.82 km^2, 6.41 km/km^2, 18 $streams/km^2$ respectively (Table 3).

Soils: A large part of the watershed has moderately shallow soil where the soil depth varies between 25 and 50 cm. Only 9.9% area of the watershed has deep soil (100–200 cm) whereas very shallow soil accounts for 7% of the total watershed. About 50% area of the watershed has sandy loam soil. The sandy clay loam accounts for only 5.1% of the watershed area. The soils are slightly (5–15%) to moderately (15–40%) stony which are excessively drained in 53.4% area and well drained in only 6.1% area of the watershed. The soils of the watershed are saline having pH value less than 7. On more than 50% of the area (59.7%) of the watershed the soil pH varies between 5 and 5.5.

Geology: Geologically, the watershed is made up of six different types of rocks[10] of the crystalline unit. Figure 2 *f* depicts the spatial distribution of rocks which reveals that about 18.8% of the area in the southern part of the watershed is composed of highly fractured and deformed gneisses. These gneissic rocks are underlained by garnetiferous mica-schist covering about 18.8% area of the watershed. About 28% of the area in the eastern part of the watershed is made up of massive highly jointed quartzites. The northern part of the watershed is charac-

Table 3. Drainage morphometry of the Khulgad Watershed

Parameters	Stream order					
	I	II	III	IV	V	VI
Streams number	444	103	24	6	2	1
Drainage type	Ephemeral	Ephemeral	Intermittent	Intermittent	Perennial	Perennial
Streams (%)	76.55	17.76	4.14	1.04	0.34	0.17
Bifurcation ratio	4.31	4.29	4	3	2	–
Stream length (km)	131.84	39.31	20.03	9.99	3.36	5.72
Mean stream length	0.30	0.38	0.83	1.67	1.68	5.57
Watershed area (km^2)	20.28	20.61	20.82	22.32	24.29	32.80
Mean watershed area (km^2)	0.046	0.200	0.867	3.72	12.15	32.80
Drainage density (km/km^2)	6.50	1.91	0.96	0.45	0.14	0.17
Stream frequency (no/km^2)	21.89	4.99	1.15	0.268	0.164	0.03

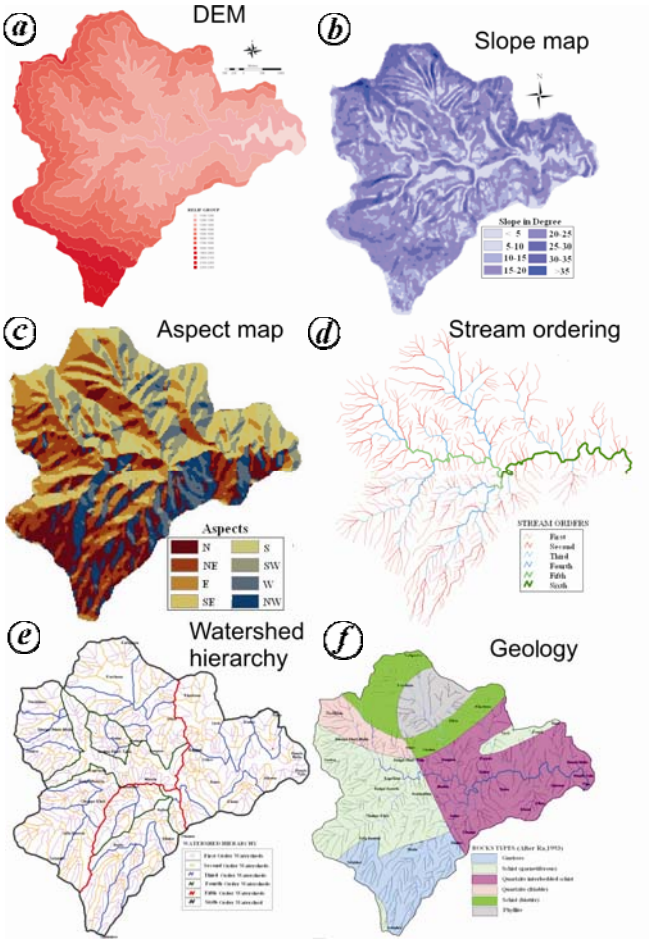

Figure 2. DEM (***a***), slope (***b***), aspect (***c***), stream ordering (***d***), watershed hierarchy (***e***) and geological (***f***), maps of the Khulgad Watershed.

terized by three different rocks, i.e. friable quartzite (in 8% area), biotite-schist (in 15% area) and phyllite (in 8% area).

Landuse pattern: A large part (65.08%) of the watershed is deforested having very stressed environment. About 28.26% of the area of the deforested land falls under barren land whereas the remaining area (37.52%) is being used for cultivation of different crops of subsistence agriculture. The forest cover of the watershed has complex environment which is further divisible into five different categories. These are: dense broadleaved oak forest with scrubs (4.9%), dense pine forest with scrubs (2.6%), pine forest without scrubs (4.7%), scattered pine without scrubs (9.3%) and regenerated pine forest (10.5%). A small part (4%) of the agricultural land on the north-facing slopes is being used for horticulture purpose for cultivation of temperate fruits mainly apple.

Weather informatics

The weather-informatics module (Figure 1) consists of daily, monthly and annual weather data recorded at five different stations of different ecological stations, i.e. oak forest, pine forest, barren land, agricultural land on the crest and mid-crest. Summary of these weather records is presented in Table 4. A brief account of the characteristics of weather parameters is as follows.

Temperature: The annual maximum, minimum and average temperature of the Khulgad Watershed stand at 23.9°C, 12.4°C and 18.5°C respectively (Table 4). The extreme maximum and minimum temperature records stand at 41°C in June on the south-facing barren land and 0°C in January at each station. The spatial distribution maps of mean maximum and minimum temperatures (Figure 3 *a* and *b*) depict temperature variability pattern within the watershed.

Rainfall: The watershed receives about 913 mm annual rainfall. The average annual rainfall within the watershed varies between 827 mm at Jyoli located on environmentally stressed barren hill slope and 980 mm at Sitlakhet located nearby the dense oak forest hill slope. On other stations, the annual rainfall amount stand at 937 mm at Salla Rautela located in pine forest hill slope, 923 mm at Khunt located on mid-crest agricultural land and 887 mm

Table 4. Average annual weather parameters of the micro-watersheds in the Khulgad Watershed

		Micro-watersheds of varied ecological conditions						
	Parameters	Oak forest	Pine forest	Barren land	Agricultural land on crest	Agricultural land on mid-crest	Tectonically weak zone	Average
Meteorological parameters	Max temp (°C)	22.2	20.2	25.6	24.6	25.6	25.6	23.97
	Min temp (°C)	11.5	12.5	13.3	13.1	12.1	12.1	12.43
	Avg temp (°C)	16.8	16.3	19.4	18.8	18.8	18.8	18.15
	Ex max (°C)	39	36	41	39	40	40	41
	Ex min (°C)	0	0	0	0	0	0	0
	Rainfall (mm)	980.2	936.8	826.9	887.3	922.7	922.7	912.77
	Max rainfall 24 h (mm)	130.0	128.0	124.5	128.0	129.0	129.0	130.0
	No. of rainy days	77	75	72	73	75	75	75
	Humidity (%)	82.3	80.2	69.5	77.7	79	79	77.95
	Wind velocity (km/day)	19.7	19.1	25.7	24.8	26.5	Na	19.7
	Sunshine (h/day)	Na	Na	Na	Na	6.5	Na	6.5
Hydrological parameters	Specific water discharge rates (l//s/km^2)	3.3	4.7	31.8	25	12.6	4.6	13.67
	Maximum flood rate (l/s/km^2)	52.0	310	1076	430	630	90.0	431.33
	Runoff depth (mm)	85	140	590	240	320	116.1	248.51
	Evapotranspiration	659.4	786.7	1072.3	811.4	862.1	622.10	802.33
	Water balance (mm)	235.8	10.1	–835.4	–164.1	–259.5	184.52	–138.1
	Water balance (%)	24.1	1.1	–10.1	–18.5	–28.1	20.0	–1.92
Erosion rates	Suspended load (t/yr/ km^2)	111.37	341.5	520.2	504.2	447.29	5987.32	1318.65
	Dissolved load (t/yr/ km^2)	79.44	101.2	208	215	219	850.25	278.82
	Bed load (t/yr/km^2)	5.4	13.5	75.2	45.3	55.0	806.02	166.74
	Total load (t/yr/km^2)	196.21	456.2	787.4	764.5	721.29	7643.59	1761.53
Denudation rates	Mechanical (mm/yr)	0.06	0.21	0.36	0.33	0.30	4.61	0.98
	Chemical (mm/yr)	0.04	0.06	0.15	0.13	0.13	0.25	0.13
	Gross denudation (mm/yr)	0.10	0.27	0.51	0.46	0.43	4.86	1.11

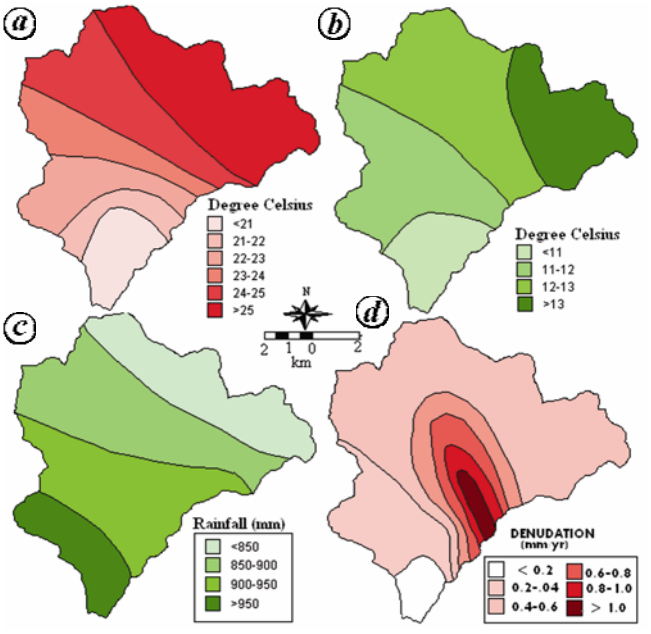

Figure 3. Spatial variation in the distribution of annual maximum temperature (***a***); minimum temperature (***b***); annual rainfall (***c***); and rate of denudation (***d***) in the Khulgad Watershed.

at Deolikhan located on top of the hill on agricultural land. Pattern of spatial variation in the annual rainfall distribution in the watershed is depicted by Figure 3 *c*.

Humidity: The average annual humidity of the watershed stands at 78% which varies between 82.3% in the oak forest area and 69.5% in the south-facing barren land. On other ecological conditions it stand at 80.2% in the pine forest, 79% on the agricultural land on mid-crest and 77.7% on the agricultural land on hill-crest area (Table 4).

Wind velocity: The wind blows at an average rate of 19.7 km/day in the Khulgad Watershed which varies from month to month. The wind velocity approaches maximum up to 34.6 km/day in April and drops down to 8.7 km/day in November. February, March, May and June are other important months when the wind velocity ranges between 29 and 32 km/day. In other months the velocity rate is recorded less than 15 km/day. Spatially speaking, the maximum velocity of wind is found at the Khunt located at the mid-spur on the southern part of the Khulgad Watershed where wind blows at an average rate of 26.5 km/day. Jyoli on barren land and Deolikhan on agri-

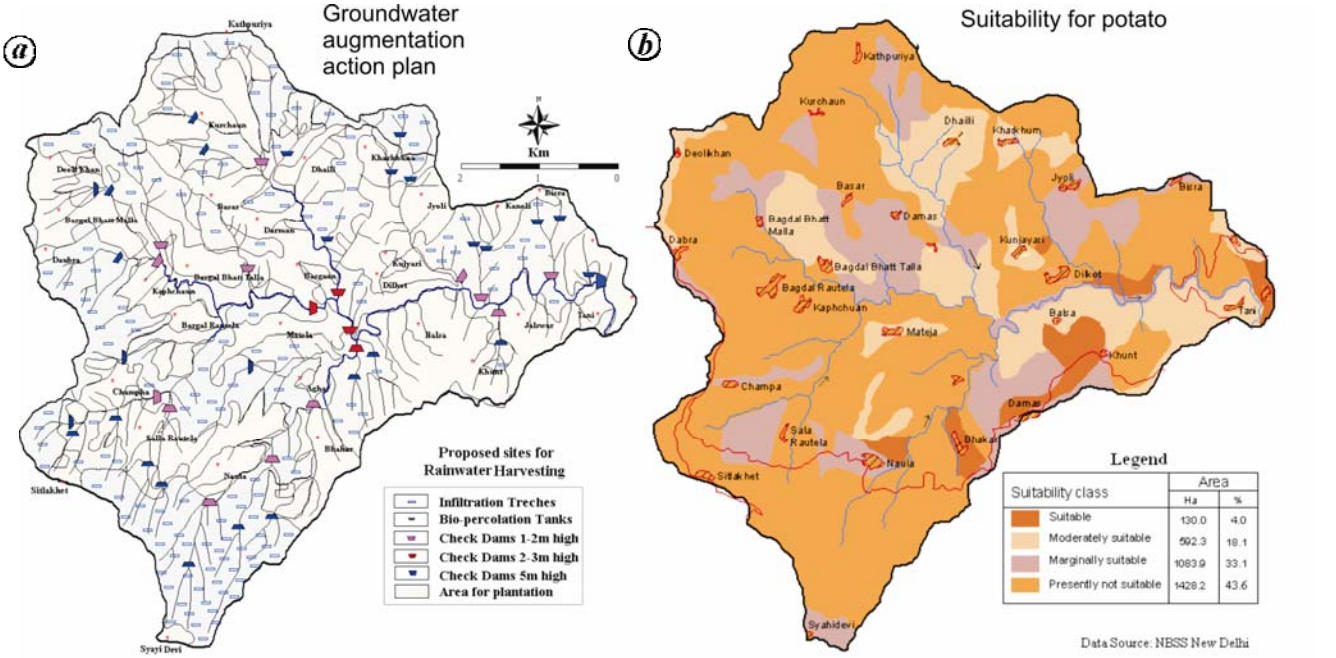

Figure 4. Location of proposed suitable sites for construction of rainwater harvesting structures for (***a***) groundwater augmentation and (***b***) suitability map for cultivation of potato in the Khulgad Watershed.

cultural mid land are other important places where the wind blows at an average rate of 25.7 and 24.8 km/day respectively (Table 4).

Evapotranspiration loss: The actual annual evapotranspiration loss[11,12] of the watershed in about 802.3 mm which approaches maximum up to 1072.3 mm on the south-facing barren land and drops down to 659.4 mm on the north-facing oak forest areas of the watershed. On other environmental conditions it was found 786.7 mm, 811.4 mm, 862.1 mm on the pine forest, agricultural land on mid-crest and agricultural land on hill crest area respectively (Table 4).

Sunshine hours: Summary of the sunshine recorder, installed at south-western part of the watershed, viz. at Khunt, reveals that the average sunshine hours in the watershed stands at 6.5 h/day.

Hydro-informatics

The hydro-informatics module of the Khulgad DBMS (Figure 1) contains daily, monthly and annual record of hydrological parameters (i.e. water discharge, flood rates, water balance, suspended, dissolved and bedload erosion, and chemical, mechanical and gross rates of denudation) of six different stations of different ecological conditions originally established in 1992 (ref. 13) following the concept of the Animal Park hydrological project[14]. Summary of these hydrological records is given in Table 4. A brief description of the hydrologic parameters is presented below.

Water discharge: The daily hydrographs of different micro-watersheds and of the Khulgad were summarized and the results are presented in Table 4. Khulgad Watershed discharges water at the average specific rate of 13.67 l/s/km^2. The annual hydrograph of the watershed, reveals the following salient characteristics:

(i) April is the month of approaching segment of the Khulgad hydrograph when the watershed discharges water at average specific rate of 1.46 l/km^2/s.
(ii) May (2.55 l/km^2/s), June (7.54 l/s/km^2) and July (23.7 l/s/km^2) are the months which correspond rising segment of the hydrograph.
(iii) August is the month of peak water discharge when the watershed discharges water at the average rate of 30.8 l/s/km^2.
(iv) September (29.9 l/s/km^2) to December (2.85 l/s/km^2) are months of recession segment of the hydrograph.
(v) January (3.68 l/km^2/s) is the month of rising segment of winter rains, and
(vi) February (4.34 l/km^2/s) is the month of winter peak discharge.

The average rate of water discharge (i.e. 13.67 l/s/km^2) of the Khulgad Watershed varies considerably depending upon the ecological conditions. It varies between 3.3 l/s/km^2 in the oak forest watershed and 31.8 l/km^2/yr on the barren watershed. On the pine forest and tectonically weak fault zone watersheds, this rate was recorded 4.7 and 4.6 l/s/km^2 respectively. On the hill crest and mid-crest agricultural areas, the average rate of water discharge stand at 25 and 12.6 l/km^2/s respectively (Table 4).

These data advocate that the broadleaved oak forest has very high, tectonically weak fault zone and pie forest have high, and the deforested barren land has very low water retention capacity within their system.

Runoff depth: Runoff means the flowing off of precipitation of a watershed through a surface channel. The depth of runoff is measured by dividing the total water yield of watershed by its area. The average annual runoff depth in the Khulgad Watershed stands at 248.51 mm/yr. The runoff depth is only 85 mm/yr on the oak forest whereas it is recorded 590 mm on the barren watershed. On other conditions, i.e. on tectonically weak fault zone, pine forest, agricultural land on crest and mid-crest the average runoff depth is found 116.1, 140, 240 and 320 mm/yr respectively (Table 4).

Maximum flood rates: The flood records of the study period were scanned which reveal that the Khulgad Watershed has capacity to generate maximum flood during rainy season at the rate of 431.3 l/s/km^2 having wide variations depending upon ecological conditions. The broadleaved oak forest help in controlling the floods as the maximum flood generating capacity of this forest in only 52 l/s/km^2. The highly stressed deforested barren land has the maximum flood generating capacity where the flood magnitude is recorded up to 1076 l/s/km^2 which is about 21 times higher than the flood of the Oak forest watershed. On other ecological conditions, the magnitude of maximum flood rate recorded 90, 310, 430 and 630 l/s/km^2 on tectonically weak fault zone, pine forest, agricultural on crest and on mid-crest watersheds respectively (Table 4).

Water balance: The water balance data derived following Hewlett[15] (Table 4) reveals that the Khulgad Watershed has deficit annual water budget which stands at (–) 138.1 mm or (–) 1.92% of the annual rainfall. The month wise details of water balance indicate that during the whole year, water balance of the watershed is surplus only in two months, i.e. July and August when it accounts for 18% (or 164.2 mm) and 16.4% (or 149.2 mm) of the rainfall. In all other ten months of the year there is always the problem of water deficit which varies between (–) 1.3% in the month of January and (–) 10.1% in the month of April. The water balance under different micro-watersheds suggests that only the forest and tectonically weak fault zone watersheds have surplus water balance which varies between 24.1% (or 235.8 mm) in oak forest and 1.1% (or 10.1 mm) in the pine forest. On the anthropogenically disturbed systems the water balance varies between (–) 28.1% (or –295.5 mm) on agricultural watersheds and (–) 10.1% (or –269.5 mm) on barren land (Table 4).

Sediment and solute flow: The weekly suspended, dissolved and bed load flow data collected during the study period are summarized in Table 4 which reveals that the streams of the Khulgad Watershed transport sediment and solutes at the rate of 1761.53 t/km^2/yr out of which 74.85% (1318.65 t/km^2/yr) flows in the form of suspended load, 9.5% (166.74 t/km^2/yr) in the form of bed load flow and 15.8% (278.82 t/km^2/yr) in the form of solutes or dissolved load. Spatial variation in the sediment and solute flow rates is alarming in the Khulgad Watershed which ranges between 196.21 t/km^2/yr in the oak forest land and 7643.59 t/km^2/yr or 39 times higher on the tectonically weak fault zone. On other ecological conditions this rate was recorded 456.2 t/km^2/yr in the pine forest, 787.4 t/km^2/yr on the barren land, 721.29 t/km^2/yr on the agricultural land on mid-crest and 764.5 t/km^2/yr on the agricultural land on crest (Table 4).

Rate of denudation: Using the sediment and solute data, chemical, mechanical and gross rates of denudation of the different micro-watersheds and the Khulgad Watershed were worked out. The results are presented in Table 4 which suggests that the Khulgad Watershed is lowering at the rate of 1.11 mm/yr (i.e. 0.98 mm/yr by mechanical and 0.13 mm/yr chemical denudation). This rate of denudation of the Khulgad Watershed is about 37 times higher than the average rate of denudation, i.e. 0.03 mm/yr of the earth[16] and slightly higher than the average denudation rate of the Himalaya, i.e. 0.915 mm/yr[17,18]. There is high variability in the distribution of denudation rates in the watershed (Figure 4D). Under least disturbed forest watershed, the annual rate of denudation varies from 0.10 mm/yr in the oak forest to 4.86 mm/yr in the tectonically weak fault zone. Under anthropogenically disturbed systems these rates are high, i.e. 0.51 mm/yr on deforested barren land and 0.43 mm/yr to 0.46 mm/yr on the agricultural lands.

Biodiversity-informatics

The biodiversity module of the Khulgad Watershed (Figure 1) consists of four sub-modules, i.e. floral diversity, agricultural crop diversity, pest diversity and faunal diversity. The information related with these different sectors of biodiversity in terms of their spatial distribution maps and their attribute data are given below.

Floral diversity: The floral diversity module is constituted of spatial distribution of vegetation types of the watershed in different years, i.e. 1988, 1994, 1988 and 2002; forest areas converted into non-forest areas during 1988–1994, 1994–1998, 1998–2002 and 1988–2002; non-forest areas converted into forest areas during 1988–1994, 1994–1998, 1998–2002 and 1988–2002; and characteristics of forest and grazing data; species wise details of trees and herbs production; and details of stems and growing stocks, and weed data of the Khulgad Watershed.

Agricultural crop diversity: The agricultural crop diversity module contains spatial distribution of Simpson index, Shannon diversity, crop diversity, weed intensity and of per unit percent area of kharif and rabi crops in the Khulgad Watershed.

Pests diversity: This module includes names, predator name, predator population and incidences of pests recorded at 123 different sites of watershed in the rabi crops (i.e. wheat, barley, gram, lentil, methi, mustard, onion, peas, potato, coriander, onion and garlic) and at 133 different sites of kharif crops (i.e. paddy, maize, finger millet, foxtail millet, cowpea, amaranthus, kulthi, mans, reddish, sesamun, turmeric, chillies and colocasia).

Faunal diversity: The faunal GIS module includes spatial distribution of wild animals, i.e. leopard, languor, monkey, barking deer, fox, jackal, wild bore, porcupine and pheasant, and mammals; and density, diversity, richness and evenness of birds in the watershed during summer and winter seasons.

Socio-informatics

The socio-informatics GIS module (Figure 1) of the Khulgad Watershed (having 28 revenue villages with a total population of 9292, two Nyay Panchyats, six patwari areas, 13 public distribution shops, eight helipads and three primary health centres) is constituted of the following 24 spatial data layers and six non-spatial data sectors.

Spatial data: The spatial data layers include distribution of villages, Nyay Panchyats, different road types, education centre, health centres, pooling booths, panchyat ghar, barat ghar, agan bari, power lines, telephone lines, rest house, hand pumps, naulas, springs, water tanks, drinking waters gravity flow schemes, afforested areas, patwari headquarter and public distribution shops.

Non-spatial data: The non-spatial data sectors are demographic and socio-economic characteristics. of villages, characteristics of roads, education centres, health centres, pooling booths, patwari areas, hand pumps, panchyat ghars, etc.

Applications

The Khulgad DBMS, constituted of a huge multidisciplinary data, is a useful decision support system (DSS) for the stakeholders of local level planning for developing policies and action plans for development and management of different natural (land, soils, water, forest) and human (roads, education, health, agriculture, horticulture, irrigation and human environment, etc.) resources. Based on this DBMS, different action plans have been developed for the Khulgad Watershed. Some of the important action plans developed as per user's needs are groundwater augmentation and soil conservation strategy (Figure 4 *a*), land capability classification, land irrigability, identification of areas suitable for cultivation of potato (Figure 4 *b*), paddy, wheat, maize, soya been, madira, madua, citrus, etc.

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