

Watershed Morphometry and Land Characteristics for Watershed Hydrological Response Analysis: A Remote Sensing and GIS-based Approach

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Abstract: Remote sensing techniques, tailored with Geographic Information System, were used to study the major hydro-geomorphic variables of seven sub-watersheds (area 53 to 170 km² each), belonging to the sub-catchment of lower and middle Parbati and Kuno rivers, and to analyze potential soil erodibility and effect of surface condition on erosion. Some of the hydro-geomorphic variables were found to be significantly correlated with each other. Based upon the hydro-morphic and morphometric characteristics and their influence on sediment generation and transport potential, the sub-watersheds were classified into 5 categories (very high to low priority category), and the nature of flood discharge pattern in them was compared. Two sub-watersheds (2D1B3B and 2D1C6C) could be rated as belonging to high priority category. Only 2D1B3B was in medium priority category, but due to its circular shape, a sharp run-off peak for short duration could give rise to flash flood. All other sub-watersheds were of oblong to elongated shape and, hence expected to have low and extended flood flow that are easier to control, and belonged to low priority category. Efficient flood control measures are feasible in 2D1C6A and 2D1C6C, but the strategy is expected to be more complex for 2D1B3B.

Key words: Remote sensing, GIS, morphometry, watershed priority, run-off, hydrology.

Water balance of drainage basins is influenced by rainfall kinetics, land characteristics and vegetation cover. Apart from rainfall, soil, vegetation and slope, the quantitative hydro-morphological characteristics, i.e., basin shape and stream network, also decide the stream flow hydrograph, run-off volume, run-off intensity and peak flow. Hence, quantitative evaluation of hydro-morphometric features of a basin is important in modelling run-off and thereby the sediment yield from the drainage basins (Singh, 1994). This also helps in identification of probable sites for water harvesting/retention structures and designing. The method of quantitative analysis of drainage

basins was developed by Horton (1945), and modified by Strahler (1964), but very few attempts have been made to combine morphometry, soil, geology, slope and vegetation cover to arrive at micro-level perspective planning of land and water resources on a sustained basis. Satellite remote sensing, dovetailed with ARC/INFO GIS, is a sophisticated tool to convert heterogeneous spatial information into unified, well-structured database for handling large quantities of spatially varied data at micro-level as well as at basin scale. One of the major advantages of GIS is its capability to overlay multi-thematic data, which could be used in hydrological models or in

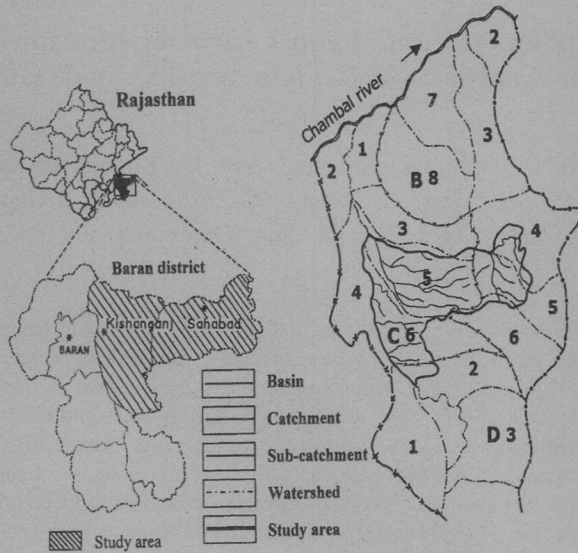


Fig. 1. Index map of the study area.

integrated landuse planning. The results, thus obtained, are much more realistic, comprehensive and less time consuming. Keeping these points in view an effort was made to evaluate the hydro-morphological and land characteristics of some sub-watersheds belonging to the Parbati and Kuno river sub-catchments of the lower Chambal catchment for assessment of erosion and to characterize their run-off and sediment yield potentials.

The study area is bounded by $76^{\circ}12'E$ and $77^{\circ}26'E$ longitudes and $24^{\circ}25'N$ and $25^{\circ}25'N$ latitudes, and lies in Baran district of Rajasthan (Fig. 1). Major area is covered by forest (50%), followed by agricultural land (28%), and wastelands (9.5%). The drainage pattern is dendritic to sub-dendritic but the density varies with sub-surface lithology and surface condition. The density is very high for shale formation and low

for sandstone. The drainage hierarchy is given in Fig. 2.

The geomorphology of the area is highly influenced by the lithology and structure of the underlying formations. The horizontal to gently dipping sandstone formation is exposed in the major part of the study area as a vast plateau with an escarpment that is deeply dissected and is irregular in plan (Fig. 3). The eastern half of the escarpment is of shale formation. The morphopedological characteristics of this area include dissected plateau, dissected pediments, buried pediments, valley fills, ravinous area, alluvial plains and structural hills. The climate is sub-humid, with water surplus in the months of July, August and September. The average annual rainfall is 900 mm with 42 rainy days.

The work was carried out as a part of the study on Integrated Mission for

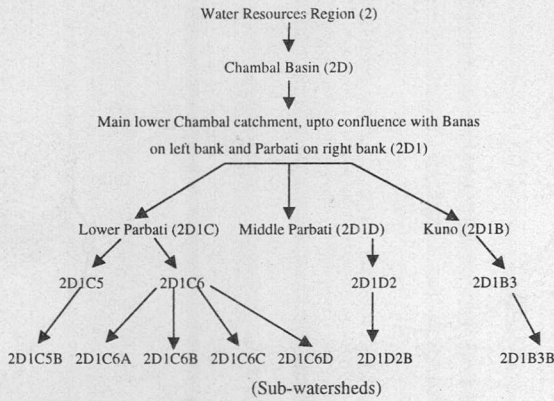


Fig. 2. The basin hierarchy.

Sustainable Development plan for Kishanganj and Sahabad tehsils. Only seven complete sub-watersheds are covered within the tehsils, and were taken for comparative study where the main emphasis was analysis of the sub-watersheds for their run-off and sediment yield potentials, as influenced by their shape,

drainage, geology and other land characteristics.

Materials and Methods

The drainage map of the study area was prepared using Survey of India toposheets at 1:50,000 scale, aerial photographs of

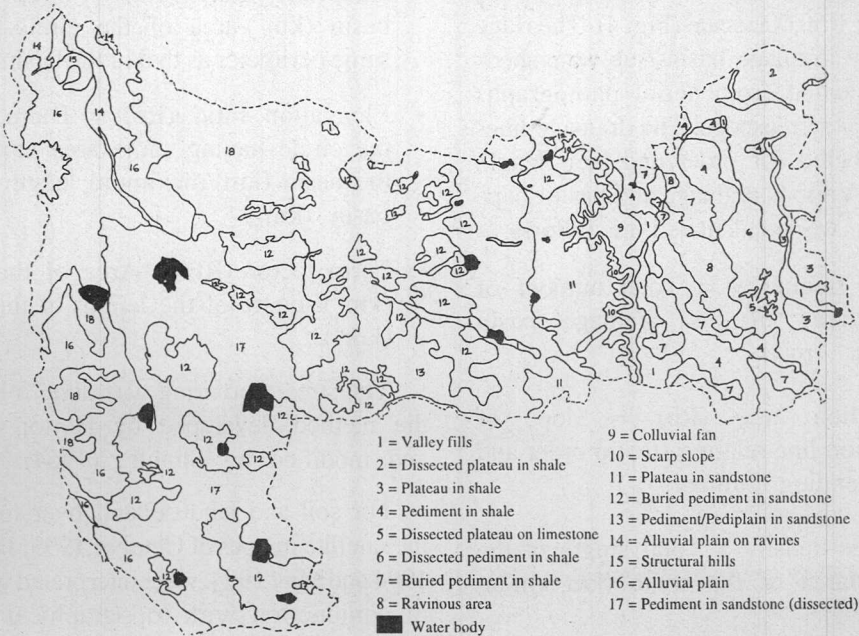


Fig. 3. Hydrogeomorphology map.

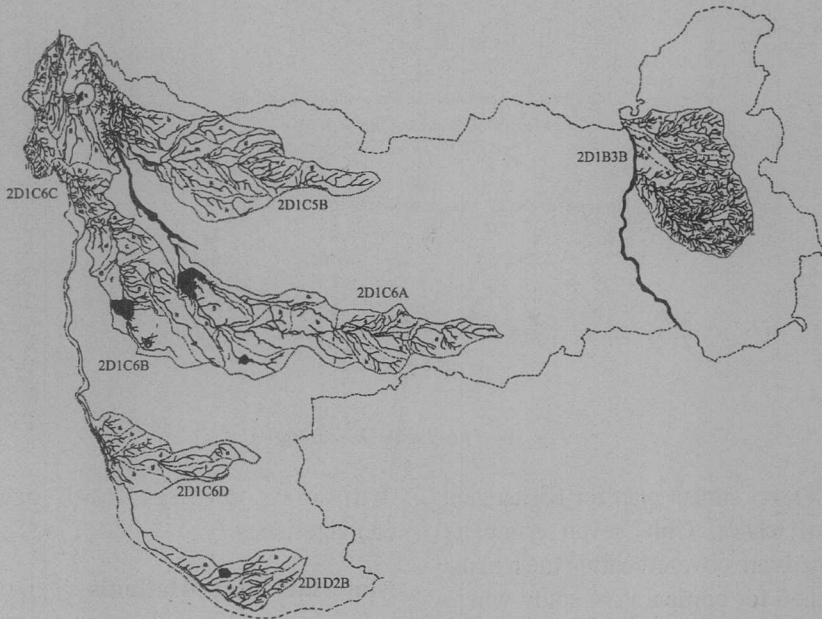


Fig. 4. Drainage and sub-watershed map.

1:25,000 scale and IRS LISS II geocoded imagery of 1:50,000 scale (Fig. 4). The ridge lines of the drainage basins/sub-watersheds were delineated from aerial photographs using mirror stereoscope. The drainage lines were numbered for order and their length measured. Various drainage and basin shape parameters were calculated as follows:

- Stream frequency = Total number of streams/area of the drainage basin (number km^{-2});
- Bifurcation ratio (Rb) = Slope of regression line relating stream order and corresponding number;
- Drainage density = Total length of the streams/area of the basin (km km^{-2});
- Constant of channel maintenance = $1/\text{drainage density}$ ($\text{km}^2 \text{ km}^{-1}$);
- Circularity ratio (Rc) = Area of the basin (km^2)/area of the circle having same perimeter as that of the basin (km^2);
- Elongation ratio (Re) = Diameter of the circle having same area to that of the basin (km)/maximum length of the basin (km);
- Form factor (Rf) = Area of the basin (km^2)/square of the length of the basin (km^2).

The stream ordering was done following the method developed by Horton (1945) and modified by Strahler (1964).

For soil and landuse/landcover mapping the satellite images of October, 1993, January, 1994 and May 1994, were interpreted visually in conjunction with topographical maps, existing GSI maps, as well as other reports and revenue records. Soil physiographic

association map was prepared using the stratified approach, as suggested by National Bureau of Soil Survey and Land Use Planning, Technical bulletin no 13. In case of landuse/landcover mapping, classification was done upto the 3rd level following the manual for Integrated Mission for Sustainable Development (Anon., 1995). Final maps were prepared adopting a four tier approach, consisting of: (i) pre-field interpretation and

mapping; (ii) field checking of different mapping units and modification, if necessary; (iii) post-field modification and correlation with existing informations; and (iv) final mapping after field validation.

To maintain uniformity the maps on drainage, watershed, soil, landuse/landcover, and landform were visually interpreted in conjunction with lithological maps and toposheets. The maps on mylar paper were

Table 1. Stream analysis

Sub-watershed	Parameters	Stream order					
		1st	2nd	3rd	4th	5th	6th
2D1B3B	Stream length (km)	195.0	54.75	42.50	38.50	6.50	9.00
	Cum. stream length (km)	195.0	249.75	292.25	320.75	327.25	336.25
	No of streams	297	81	18	7	2	1
	Mean stream length (km)	0.65	0.67	2.36	4.07	3.25	9.00
2D1C5B	Stream length (km)	148.75	70.85	24.00	8.50	-	9.00
	Cum. stream length (km)	148.75	219.60	243.60	252.10	-	261.10
	No of streams	150	32	4	2	-	1
	Mean stream length (km)	0.99	2.21	6.00	4.25	-	9.00
2D1C6A	Stream length (km)	160.0	58.5	24.00	26.00	-	27.50
	Cum. stream length (km)	160.0	218.5	242.50	268.50	-	296.0
	No of streams	172	35	6	1	-	1
	Mean stream length (km)	0.93	1.67	4.0	26.0	-	27.50
2D1C6B	Stream length (km)	68.75	28.60	15.20	8.00	-	-
	Cum. stream length (km)	68.75	97.35	112.60	120.60	-	-
	No of streams	64	13	3	1	-	-
	Mean stream length (km)	1.07	2.20	5.08	8.00	-	-
2D1C6C	Stream length (km)	102.75	35.50	9.25	12.00	26.50	-
	Cum. stream length (km)	102.75	137.25	146.50	158.50	185.0	-
	No of streams	145	30	6	3	1	-
	Mean stream length (km)	0.70	1.15	1.54	4.0	26.50	-
2D1C6D	Stream length (km)	41.50	14.25	9.50	5.75	10.50	-
	Cum. stream length (km)	41.50	55.75	65.25	71.00	81.50	-
	No of streams	40	10	3	1	1	-
	Mean stream length (km)	1.03	1.42	3.16	5.75	10.50	-
2D1D2B	Stream length (km)	39.00	13.30	6.00	7.50	5.00	-
	Cum. stream length (km)	39.00	52.30	58.30	65.80	70.80	-
	No of streams	37	8	3	1	1	-
	Mean stream length (km)	1.05	1.66	2.00	7.50	5.00	-

Cum. stands for cumulative.

Table 2. Quantitative hydro-morphometric and drainage characteristics of the sub-watersheds

	Sub-watersheds of 2D1 catchment						
	B3B	C5B	C6A	C6B	C6C	C6D	D2B
Area (km ²)	152.80	170.60	138.80	120.10	101.80	72.30	53.00
Perimeter (km)	51.50	85.55	155.10	53.6	57.70	53.30	45.10
Length of watershed (km)	15.48	34.710	54.23	16.60	17.15	12.70	9.25
Bifurcation ratio (Rb)	3.66	4.68	4.91	4.92	4.83	4.00	4.62
Circularity ratio (Rc)	0.72	0.29	0.07	0.52	0.38	0.32	0.33
Elongation ratio (Re)	0.73	0.39	0.18	0.57	0.55	0.54	0.59
Form factor (Rf)	0.64	0.14	0.05	0.44	0.35	0.45	0.62
Drainage density (km km ⁻²)	2.20	1.53	2.13	1.00	1.81	1.12	1.33
CCM (km ² km ⁻¹)	0.45	0.65	0.47	1.00	0.55	0.89	0.75
Stream frequency (number km ⁻²)	2.65	1.10	1.54	0.67	1.41	0.76	0.94

CCM = Constant of channel maintenance.

passed through a black and white scanner for electronic capturing of the visual maps into its digital analogue form. The scanned maps were saved as bitmaps/images and subsequently used in GIS environment for vector analysis and manipulation.

The source data (bitmap) was converted to vector form via rasterization process. The vector map files (coverages) were then projected to desired geographic coordinate system for 1:1 correspondance with all the other theme maps and true representation of geographic area and coordinates. After projecting and transforming the maps, these were edited to remove all the errors pertaining to spatial data using ARCEDIT module of ARC/INFO GIS. From the georelational database feature attributes were added as per the original maps and the database of all the maps were made ready for spatial overlay and modeling. Measurements of all linear features, polygons, etc., were made using the statistics function of GIS. For quantitative analysis of criticality of the sub-watersheds in relation to potential sediment loss and run-off, weightage was given to each theme and class. The higher

weightages meant greater chances of potential soil loss and run-off.

Results and Discussion

Different stream parameters like orderwise stream length, cumulative stream length, stream number and mean stream length (Table 1), as well as hydro-morphometric characteristics (Table 2) are discussed below.

Stream characteristics

Stream characteristics like number and length of different order streams, cumulative stream length, mean stream length and intensity of dissection influence hydrological behavior of a basin. Stream length is indicative of the contributory area of the basin of that order. In the present study the plot of the stream number and cumulative stream length as a function of stream order yielded an exponential fit (Fig. 5 and 6), indicating that the ratio between mean stream length and the corresponding orders was constant throughout the successive order of the watersheds and suggested that geometric similarity was preserved within the streams of increasing order. The sizes of the

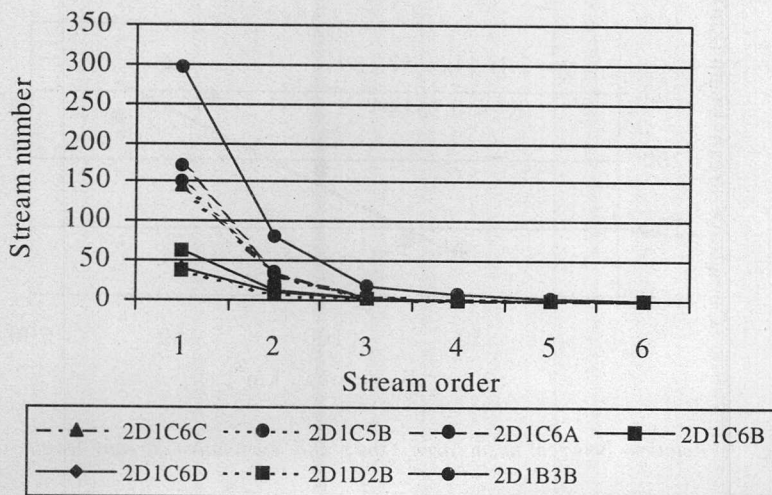


Fig. 5. Relation between stream order and number

sub-watersheds also increased with total stream length (Fig. 7), except in 2D1C5B and 2D1C6B, and influenced the average and peak discharge. The streams of shorter length might result in more rapid discharge and slower infiltration than the streams of

longer length. The sub-watersheds 2D1D2B and 2D1C6D had streams of shorter length and corresponded to rapid discharge. Numerous 1st order streams carry streamflow out of the basin rapidly and in shortest possible time. The number of 1st and 2nd order

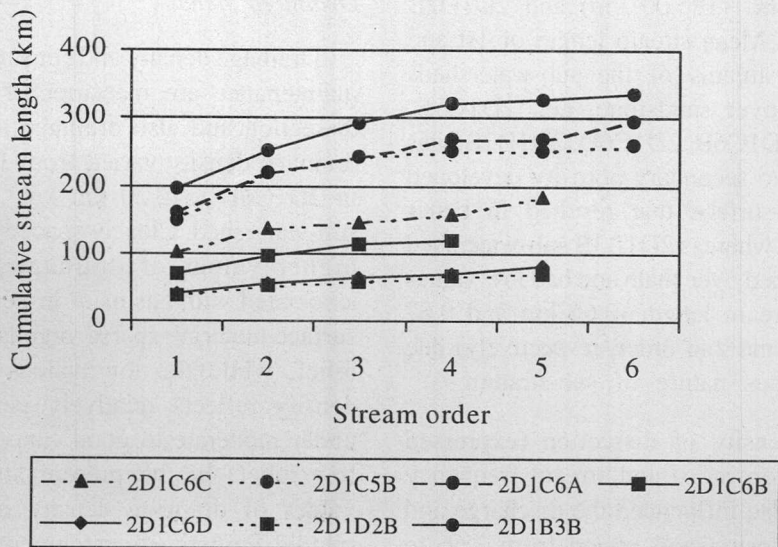


Fig. 6. Relation between stream order and cumulative stream length (km)

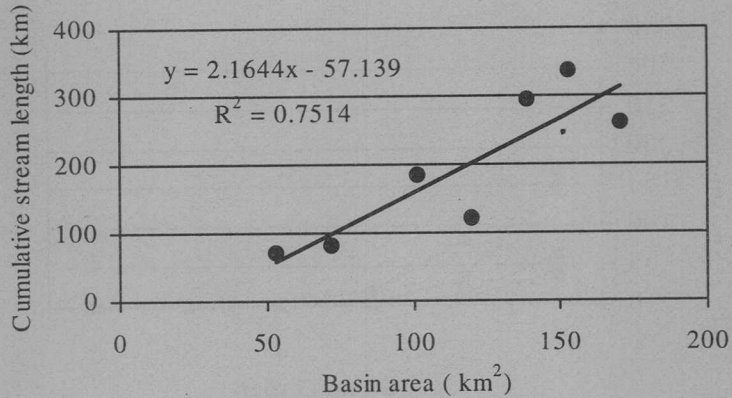


Fig. 7. Relation between basin area (km²) and cumulative stream length (km).

streams were very high, i.e., 297 and 81, respectively, in 2D1B3B (Table 1) and the least, i.e., 37 and 8, respectively in 2D1D2B sub-watershed. Hence, the disposal of run-off is expected to be very quick in 2D1B3B and slowest in 2D1D2B. Similar to stream number, cumulative stream length was also very high in 2D1B3B (336.25 km), followed by 2D1C6A (296 km), 2D1C5B (261.10 km), 2D1C6C (185.00 km) and 2D1D2B (70.80 km). Mean stream length of 1st and 2nd order streams of the sub-watersheds developed over sandstone, i.e., 2D1C5B, 2D1C6A, 2D1C6B, 2D1C6D, 2D1D2B, was higher due to secondary porosity developed in the sub-surface that resulted in better percolation, whereas 2D1B3B sub-watershed was developed over shale and had low values of mean stream length (0.65 km and 0.67 km for 1st and 2nd order, respectively) due to impervious nature of sub-stratum.

The intensity of dissection (expressed as bifurcation ratio) and stream frequency (Table 2) also influenced the discharge and run-off intensity, and varied from 3.66 to 4.92 and 0.67 to 2.65, respectively. Higher bifurcation ratio (Rb), i.e., 5, indicates a

geologic control (Verstappan, 1983) that tends to produce a low but extended flood discharge. In the present study all the sub-watersheds have Rb values less than 5 and hence expected to produce a sharp peak. Hydro-morphometric characteristics of the sub-watersheds are presented in Table 2.

Drainage density

Drainage density and constant of channel maintenance are measures of intensity of dissection and also drainage network. The drainage density varied from 1.12 km km⁻² in 2D1C6D to 2.20 km km⁻² in 3D1B3B sub-watershed. Closely spaced streams with higher values of drainage density are associated with basins of impermeable sub-surface material, sparse vegetation and high relief, while the low values of drainage density reflects relatively permeable soil under moderate to good canopy cover and low relief. In the present study the low values of drainage density in lower and middle Parbati sub-catchment (2D1C and 2D1D) are due to relatively flat topography with moderately good vegetation, developed

Table 3. Soil physiographic association

Soil mapping unit	Physiography	Slope (%)	Taxonomic classification	Weights assigned
1	Alluvial plains	0-1	Fine vertic Haplustalfs	11
2	Alluvial plains	1-3	Fine loamy typic Ustochrepts Fine typic Haplustalfs	13
3	Alluvial plains	1-3	Fine typic Haplustalfs Fine loamy typic Ustochrepts	14
4	Ravines/gullies	3-5	Fine loamy aridic Ustochrepts Coarse loamy typic Ustorthents	18
5	Ravines/gullies	1-3	Fine loamy typic Ustochrepts Fine typic Ustochrepts	16
6	Valley fills	0-1	Fine loamy aeric Haplaquepts Fine vertic Ustochrepts	9
7	Buried pediments	0-1	Fine typic Haplustalfs Fine vertic Haplustalfs	11
8	Pediments	1-3	Frag. lithic Ustorthents Frag. shallow typic Ustochrepts	13
9	Structural hills	10-15	Frag. lithic/ruptic Ustorthents/ Ustochrepts	15
10	Sub-recent flood plains	0-1	Coarse loamy aeric Haplaquepts Coarse loamy typic Ustipsamments	11
11	Buried pediments	0-1	Fine typic Chromusterts Fine vertic Haplustalfs	11
12	Plateau	1-3	Loamy skl typic/lithic Ustorthents Loamy skl typic/lithic Ustochrepts	13
13	Ravines	3-5	Loamy skl typic Ustorthents Loamy skl aridic Ustochrepts	18

over a permeable sandstone that is mostly dissected and fractured. Broadly, the drainage density in sub-watersheds can be grouped under high (2D1B3B, 2D1C6A), medium (2D1C6C, 2D1C5B, 2D1D2B) and low (2D1C6B, 2D1C6D) categories.

The constant of channel maintenance is the reciprocal of drainage density and is a measure of the area required to maintain each unit length of the stream. It ranges between $0.45 \text{ km}^2 \text{ km}^{-1}$ and $1.0 \text{ km}^2 \text{ km}^{-1}$.

Basin shape

The shape of the basin influences streamflow hydrograph and peak flow. The important parameters describing the shape of the basin area are form factor (Rf), circularity ratio (Rc) and elongation ratio (Re). Different shape parameters are presented in Table 2. Form factor is a dimensionless ratio and is a good indicator of the outline form of a basin. Smaller the value of Rf, the more elongated the basin is and consequently flatter peak flow

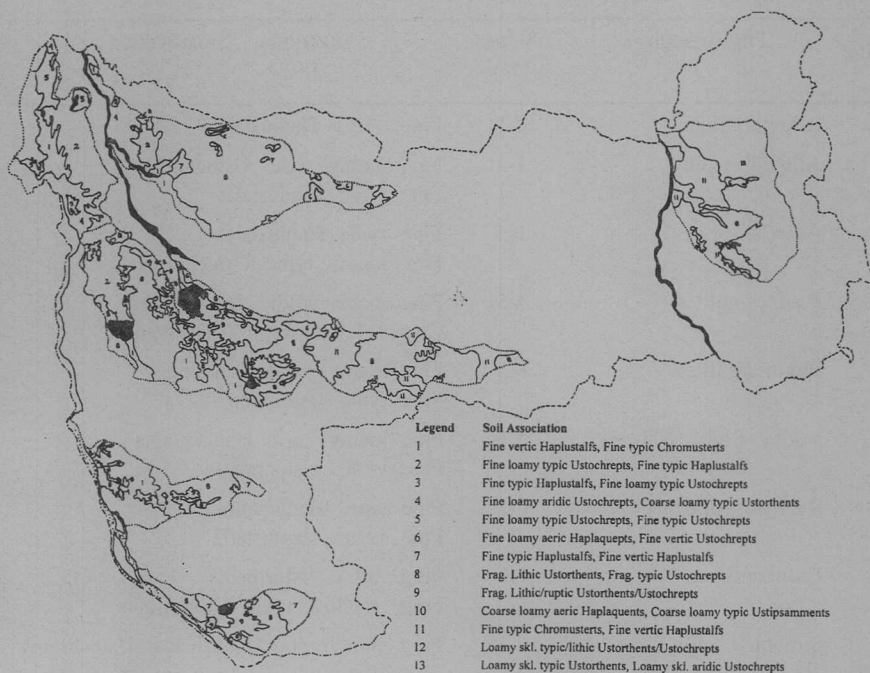


Fig. 8. Physiographic soil association map.

for longer duration occurs. High value of Rf assumes higher peak flow for shorter duration. The values of circularity ratio (Rc) and elongation ratio (Re) varied from 0.07 to 0.72 and 0.18 to 0.73, respectively. Sub-watersheds 2D1C5B and 2D1C6A had lower values of Rf, and expected to have flatter peak flow for longer duration. On the contrary, 2D1D2B and 2D1B3B could be expected to generate higher peak flow for shorter duration. The value of Rc was maximum in 2D1B3B, which was in agreement with its shape. Similar to Rf, Re and Rc also had higher values in 2D1B3B and the lowest in 2D1C6A. The shape parameters were blended with soil, landuse and drainage characteristics of the sub-watersheds to characterize the runoff behavior. Higher values of elongation ratio

may give rise to elongated peak flow that is easier to manage than in a circular basin.

Soil erodibility

Different soil-physiographic associations developed over sandstone and shale are given in Table 3 and their spatial distribution is depicted in Fig. 8. Sub-watershedwise distribution of different soil types is shown in Table 4. The soils were regrouped on the basis of physiography and slope, along with inherent characteristics, and accordingly weights were assigned (Table 3), keeping in view their contribution to sediment yield potential. The values assigned ranged from 9 to 18. A 10 point scaling was considered enough for assessing the soil erosion potential. Here any value above 10 indicates soil loss and less than 10 means deposition

as normally occurs in valley fills. Soils, associated with severely broken/eroded land, both in sandstone and shale system, were given higher weightages whereas minimum values were assigned to the soils associated with valley fill areas.

Landuse/Landcover

Proportion of forest land is very high in 2D1C5B, followed by 2D1C6A, 2D1C6B and 2D1D2B (Fig. 9, Table 5). Considerable

area is under forest blank in 2D1C5B (86.46 km²), 2D1C6B (37.94 km²) and 2D1C6A (28.87 km²). The volume of soil loss is very high in forest blank as well as in highly degraded forests, due to less infiltration opportunity time as a consequence of shallow soil mantle. The situation becomes worse under shallow sandstone pediments. Within agricultural lands double cropped area was less, except in 2D1B3B, due to the existence of large number of small surface tanks. In

Table 4. Sub-watershedwise distribution of soils (km²)

Soil legend	Sub-watersheds						
	B3B	C5B	C6A	C6B	C6C	C6D	D2B
1	—	11.07 (6.49)	10.84 (7.81)	17.47 (14.54)	15.6 (15.32)	31.98 (44.23)	—
2	—	10.13 (5.94)	23.66 (17.04)	27.65 (23.02)	38.39 (37.71)	—	—
3	—	—	—	6.0 (4.99)	—	2.12 (2.93)	—
4	1.04 (0.68)	17.52 (10.27)	5.92 (4.26)	0.35 (0.29)	28.97 (28.46)	3.65 (5.05)	—
5	—	—	5.58 (4.02)	1.94 (1.61)	15.55 (15.27)	—	—
6	1.60 (1.05)	5.23 (3.06)	9.14 (6.58)	—	—	1.48 (2.05)	—
7	—	4.64 (2.72)	2.92 (2.10)	—	—	3.98 (5.50)	17.04 (32.15)
8	43.54 (28.49)	122.01 (71.52)	76.47 (55.09)	66.69 (55.52)	—	29.09 (40.22)	34.06 (64.26)
9	—	—	4.45 (3.20)	—	—	—	—
10	—	—	—	—	3.29 (3.29)	—	1.9 (3.58)
11	23.68 (15.49)	—	—	—	—	—	—
12	72.51 (47.45)	—	—	—	—	—	—
13	10.44 (6.83)	—	—	—	—	—	—
Total	152.80	170.60	138.80	120.10	101.80	72.30	53.00

Figures in parantheses represent per cent of sub-watershed area.

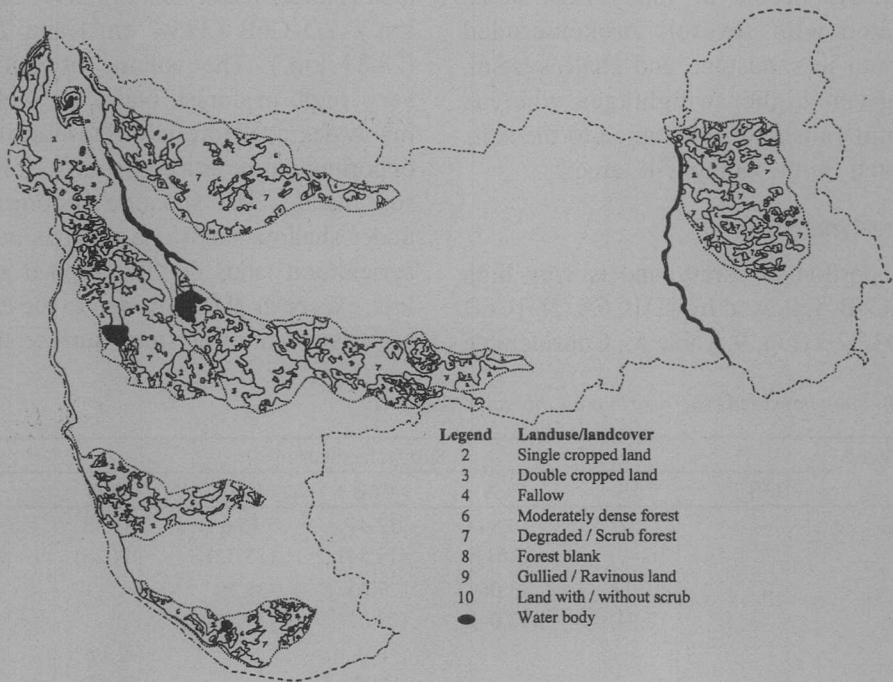


Fig. 9. Landuse/landcover map.

single-cropped areas the land was mostly cultivated during rabi season. In kharif season the land remains fallow and is susceptible to raindrop impact. Although the wastelands have very high soil detachability and transport capacity, their distribution was less in all the sub-watersheds.

Spatial averaging of weights and relative ranking

Various factor layers were assigned weights based on the susceptibility to erosion. For soils, the weights were assigned after comparative study of landform, slope and soil *per se*, but crop factor values (*c*) were taken directly, which are standard for various surface cover types used for soil loss equation by USLE method. To get a representative

value for the entire watershed spatial averaging was done as follows:

$$W_{av} = (\sum a_i w_i) / A$$

where,

W_{av} = weighted average, a_i = area under given weights for category i , w_i = weightage value of the category i , A = area of the watershed.

Priority watersheds

In order to determine the development priorities of the sub-watersheds for proper soil and water conservation measures, the values given in Table 6 were divided into 4 quartiles and ranked from 1 to 4. Higher rank values indicated high priority (Table 7). The individual ranks were summed up to get the cumulative rank value. Based

Table 5. Watershedwise distribution of landuse/landcover (km²)

Landuse/ Landcover	Sub-watersheds							Weight*
	2D1C6C	2D1C5B	2D1C6A	2D1C6B	2D1C6D	2D1D2B	2D1B3B	
Good forest	8.22 (8.07)	0	1.19 (0.85)	0	0	0	0	0.006
Degraded forest with grass	1.48 (1.45)	38.55 (22.59)	36.54 (26.32)	17.69 (14.73)	09.94 (13.73)	20.14 (38.00)	0	0.090
Forest blank	0.07 (0.07)	86.46 (50.66)	28.87 (20.79)	37.94 (31.59)	13.94 (19.26)	13.76 (25.96)	0	0.420
Highly degraded forest	21.03 (20.65)	20.15 (11.80)	20.10 (14.47)	15.34 (12.77)	05.93 (8.19)	0.78 (1.47)	66.99 (43.84)	0.109
Single crop area	50.18 (49.28)	15.74 (9.22)	25.41 (18.30)	26.84 (22.35)	31.79 (43.93)	14.36 (27.09)	13.17 (8.62)	0.529
Wasteland (ravines)	09.41 (9.24)	0.04 (0.02)	01.43 (1.03)	0	0.50 (0.69)	0	02.94 (1.92)	0.640
Double crop area	11.42 (11.21)	9.73 (5.70)	25.31 (18.23)	22.28 (18.55)	10.27 (14.19)	03.96 (7.47)	69.81 (45.68)	0.207
Total	101.81	170.67	138.85	120.10	72.37	53.0	152.80	-

The figures in the parantheses represent per cent of watershed area.

* Weightages were taken from Verma *et al.*, 1986, under similar vegetation cover condition.

on soil, landuse/landcover, drainage density, stream frequency and bifurcation ratio, 2D1C6C and 2D1C6A were rated as high, 2D1B3B, 2D1C5B, 2D1D2B as medium, and 2D1C6B, 2D1C6D as low priority watersheds.

When the shape factors, viz., elongation ratio, circularity ratio and form factor, were added with the soil, crop and drainage

parameters the priority changed and only 2D1B3B could be classified as medium, whereas 2D1C5B, 2D1C6B and 2D1D2B were shifted to low priority category. However, the high priority group remained unchanged.

Ranking on the basis of all the factors are supposed to be more scientific as the entire episode of water erosion could be

Table 6. Spatial averaging of weights for the sub-watersheds

Weights for	Sub-watersheds of catchment 2D1						
	B3B	C5B	C6A	C6B	C6C	C6D	D2B
Soil	13.66	13.15	31.18	12.93	14.75	12.24	12.46
Crop and surface cover	0.200	0.306	0.267	0.316	0.36	0.368	0.303
Drainage density	2.20	1.53	2.13	1.00	1.81	1.12	1.33
Stream frequency	1.52	1.01	1.07	0.93	1.41	0.96	0.94
Bifurcation ratio	3.66	4.68	4.91	4.92	4.83	4.00	4.62
Elongation ratio	0.73	0.39	0.18	0.57	0.55	0.54	0.59
Circularity ratio	0.72	0.29	0.07	0.52	0.38	0.32	0.33
Form factor	0.64	0.14	0.05	0.44	0.35	0.45	0.62

Table 7. Comprehensive ranking of the sub-watersheds

Rank values for	2D1B3B	2D1C5B	2D1C6A	2D1C6B	2D1C6C	2D1C6D	2D1C6B
Soil	1	1	4	1	1	1	1
Crop and surface cover	1	3	2	3	4	4	3
Drainage density	4	2	4	1	3	1	2
Stream frequency	4	1	1	1	4	1	1
Bifurcation ratio	1	4	4	4	4	2	4
Elongation ratio	1	3	4	2	2	2	1
Circularity ratio	4	2	1	3	2	2	2
Form factor	4	1	1	3	3	3	4
	20	17	22	19	23	16	18

visualized as a two way process, viz., (i) sediment generation potential that depends on soil, landuse and landform, and (ii) sediment transport potential that depends on drainage and basin shape factors.

Assuming that rainfall amount does not change much in the study area, the morpho-hydrological, shape parameters and geophysical parameters were integrated in the priority rating process to demarcate the watersheds having more chances of soil erosion. This changed the priority sequence to 2D1C6C > 2D1C6A > 2D1B3B > 2D1C6B > 2D1D2B > 2D1C5B > 2D1C6D (Table 8). Out of 7 sub-watersheds, flood control is feasible and easier in 2D1C6C and 2D1C6A than in 2D1B3B that has a circular shape and where a sharp run-off hydrograph is expected.

Seven sub-watersheds (53-170.6 km²) of lower Chambal catchment, formed over sandstone and shale, were studied for priority rating by blending the hydro-morphometric parameters with soil, physiography and surface cover, the three major factors controlling erosivity and surface run-off. The number of 1st and 2nd order streams is very high (378) in 2D1B3B sub-watershed (shale formation) and least (45) in 2D1D2B (sandstone formation). Mean length of 1st and 2nd order streams are very high in sandstone formation due to secondary porosity developed at sub-surface and thereby providing better percolation. On the contrary, the same is low in 2D1B3B sub-watershed (0.65), by virtue of higher drainage density and closely spaced streams developed over impervious sub-stratum, sparse vegetation and higher relief. The

Table 8. Priority rating and run-off behavior

Watershed	Priority	Run-off behavior
2D1C6A	High	Very much elongated basin, flatter peak flow, easier to control
2D1C6C	High	Oblong basin, low and extended flood flow
2D1B3B	Medium	Circular basin, sharp run-off peak
2D1C5B	Low	Oblong basin, low and extended flood flow
2D1C6B	Low	Oblong basin, low and extended flood flow
2D1C6D	Low	Oblong basin, low and extended flood flow
2D1D2B	Low	Moderately elongated basin, flatter peak flow, easy to control

drainage density in lower and middle Parbati sub-catchment varies between 0.98 and 2.12 km km⁻² with an average of 1.40 km km⁻², significantly less than that for 2D1B3B (2.19 km km⁻²) in shale formation. The high value of Rc in 2D1B3B (0.73) is indicative of a circular basin with sudden and high peak flood flow.

The soils of the sub-watersheds vary from coarse loamy skeletal to fine loamy and clayey type. Based on the sediment yielding potential, soils were assigned weights. Relative distribution of landuse/landcover reveals that forest covers maximum area in 2D1C5B (85%), and least in 2D1C6C, i.e., 30%. As the proportion of forest area is very high, the relative contribution by agricultural land is less and only 3 sub-watersheds, viz., 2D1C6C, 2D1C6D and 2D1B3B have more than 50% area under cultivation. The area under wastelands is very less or absent except in 2D1C6C (9%). Similar to soils, landuse/landcover classes were assigned weights keeping the sediment generation in view. To decide the development priorities of the watersheds, an integrated approach using both morphometry and land characteristics was followed. Based upon soil, physiography, landuse/landcover, and drainage characteristics, and the basin shape factors, viz., form factor (Rf), circulatory ratio (Rc) and elongation ratio (Re) 2D1C6C and 2D1C6A come under high priority category. The 2D1B3B is the only sub-watershed of medium priority, and 2D1C6B, 2D1D2B, 2D1C5B and 2D1C6D are under low priority. Considering the hydrological response it can be inferred that 2D1B3B sub-watershed is moderately circular and will have sharp run-off peak

that is difficult to control, whereas 2D1C6A is very much elongated and characterized by flatter peak flow with low and extended flood discharge that is easy to control. Rest of the sub-watersheds are oblong to elongated in shape and, hence, the run-off pattern is expected to be low and extended.

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