

Prioritization of watershed through morphometric parameters: a PCA-based approach

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Abstract Remote sensing (RS) and Geographic Information Systems (GIS) techniques have become very important these days as they aid planners and decision makers to make effective and correct decisions and designs. Principal Component Analysis (PCA) involves a mathematical procedure that transforms a number of (possibly) correlated variables into a (smaller) number of uncorrelated variables. It reduces the dimensionality of the data set and identifies a new meaningful underlying variable. Morphometric analysis and prioritization of the sub-watersheds of Shakkar River Catchment, Narsinghpur district in Madhya Pradesh State, India, is carried out using RS and GIS techniques as discussed in Gajbhiye et al. (Appl Water Sci 4(1):51–61, 2013b). In this study we apply PCA technique in Shakkar River Catchment for redundancy of morphometric parameters and find the more effective parameters for prioritization of the watershed and discuss the comparison between Gajbhiye et al. (Appl Water Sci 4(1):51–61, 2013b) and the present prioritization scheme.

Keywords Watershed · GIS · Remote sensing · Morphometric analysis · Prioritization · Principal component analysis

Introduction

India supports 16 % of world population on 2.42 % of global land area. An estimated 175 million hectares (M ha) of land constituting about 66 % of total geographical area suffers from deleterious effect of soil erosion and land degradation. Active erosion caused by water and wind alone accounts for 150 M ha of land, which accounts for soil loss of about 5300 million tons of top soil. In addition, 25 M ha is degraded due to ravine and gullies, shifting cultivation, salinity/alkalinity, water logging, etc. (Gajbhiye 2015).

The watershed management planning highlights the management techniques to control erosion in the catchment/watershed area (Gajbhiye et al. 2015a, b). Land and water resources are limited and their wide utilization is imperative, especially for countries like India, where the population pressure is continuously increasing (Sharma et al. 2014a, b). The growing pressures on land for food, fiber and fodder in addition to industrial expansion and consequent need for infrastructure facilities due to even increasing population have given rise to competing and conflicting demands on finite land and water resources (Biswas et al. 1999). The watershed is an ideal unit for planning and management of land and water resources (Gajbhiye et al. 2013a, b). Therefore, realistic assessment of the hydrological behavior of a watershed is important to develop an effective management plan (Sharma et al. 2014a, b). The watershed management concept recognizes the inter-relationships among the linkages between soil, slope, uplands, low lands, land use and geomorphology. Soil and water conservation is the key issue in watershed management while demarcating watersheds. However, while taking into consideration watershed soil-conservation work, it is not possible to take the whole area at once. Thus,

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the whole basin area is divided into several smaller units, as sub-watersheds or micro-watersheds, by considering its drainage system. Quantitative morphometric analysis of watershed can provide information about the hydrological nature of the rocks exposed within the watershed (Singh et al. 2014). Morphometric analysis is a significant tool for prioritization of sub-watersheds even without considering the soil map (Biswas et al. 1999). Morphometric analysis requires measurement of the linear features, gradient of channel network and contributing ground slopes of the drainage basin (Nautiyal 1994).

Many works have already been reported on morphometric analysis using Geographical Information Systems (GIS) and soil erosion (Shrimali et al. 2001); Sharma et al. 2015). Srinivasa et al. (2004) and Gajbhiye (2015) have used GIS techniques in morphometric analysis of sub-watersheds of Pawagada area, Tumkur district, Karnataka. Chopra et al. (2005) carried out morphometric analysis of Bhagra-Phungotri and Haramaja sub-watersheds of Gurdaspur district, Panjab. Khan et al. 2001 used RS and GIS techniques for watershed prioritization in the Guhiya basin, India. Nookaratnam et al. 2005 carried out a study on check dam positioning by prioritization of micro-watersheds using the sediment yield index (SYI) model and morphometric analysis using GIS. Gajbhiye et al. 2014b carried out a study on prioritization of watershed through SYI using RS and GIS approaches. Morphometric analysis and prioritization of eight sub-watersheds of Uttala river watershed, which is a tributary of Son River, was carried out by Sharma et al. (2010). Gajbhiye et al. 2013a, b Prioritizing erosion-prone area through morphometric analysis: an RS and GIS perspective. Many researchers (Gajbhiye et al. 2014a, b, c; Sharma et al. 2013a, b; Singh et al. 2013) have already reported on hypsometric analysis using Geographical Information System (GIS). Geographical Information System has been used for the calculation and delineation of the morphometric characteristics of the basin (Singh et al. 2013).

Factor analysis technique is very useful in the analysis of data corresponding to large number of variables; analysis via this technique produces easily interpretable results, and this method has been used successfully in hydro-chemistry for many years; surface water, ground water quality assessment and environmental research employing multi-component techniques are well described in the literature (Praus 2005). The application of different multivariate statistical techniques, such as cluster analysis (CA), principal component analysis (PCA) and factor analysis (FA) help identify important components or factors accounting for most of the variances in a system (Ouyang et al. 2006; Shrestha and Kazama 2007). They are designed to reduce the number of variables to a small number of indices while attempting to preserve the relationships

present in the original data. In recent years, many studies have been done using PCA in the interpretation of water quality parameters (Gajbhiye et al. 2010, 2015b), geomorphometric parameters (Sharma et al. 2009), etc.

The geomorphologic studies are helpful in regionalising the hydrologic models. Since most of the basins are either ungauged or sufficient data are not available for them, the study on geomorphologic characteristics of such basins becomes much more important. The linking of geomorphologic parameters with the hydrological characteristics of the basin provides a simple way to understand the hydrological behaviour of different basins. The need for accurate information on watershed runoff and sediment yield has grown rapidly during the past decades because of the acceleration of watershed management programs for conservation, development, and beneficial use of all natural resources, including soil and water (Gajbhiye and Mishra 2012; Mishra et al. 2013; Gajbhiye et al. 2014a). In this study, morphometric analysis and prioritization of sub-watersheds are carried out for Shakkar River Catchment in Narsinghpur district of Madhya Pradesh, India.

Our contribution

As outlined above, unfortunately, we found that not all the existing techniques have provided the optimum effective parameters for prioritization of a watershed. Therefore, our main contribution in this paper is to find the more effective parameters for prioritization of watershed and also show the comparison between previous prioritization by taking all the parameters in Gajbhiye et al. (2013b). Other researchers, as discussed above, also adopted the same approach by taking all the geomorphic parameters and then prioritizing the watersheds.

Organization

The rest of this paper is organized as follows: Study area is introduced in “Study area”. Materials and methods are discussed in “Materials and methods”. Result and discussion are explained in “Results and discussion”. Finally, “Conclusions and findings” concludes and discusses the paper.

Study area

The Shakkar river rises in the Satpura range, east of the Chhindi village, Chhindwara district, Madhya Pradesh, at an elevation of about 600 m at latitude 22°23'N longitude 78°52'E (Fig. 1). The watershed covers 2220 km² area. The climate of the basin is generally dry except for the southwest monsoon season. The southwest monsoon starts

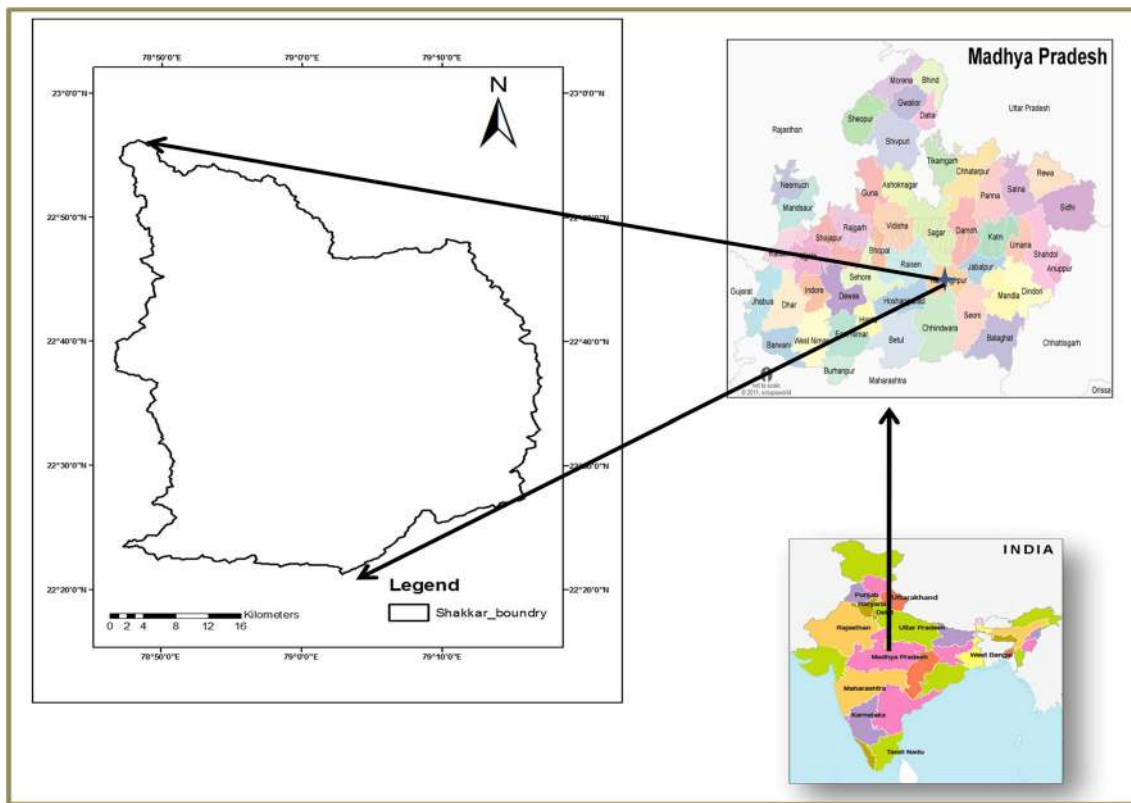


Fig. 1 Location map of the study area

from the middle of June and lasts till the end of September. October and middle of November constitute the post-monsoon or retreating monsoon season. The normal annual rainfall is 1192.1 mm. The normal maximum temperature during the month of May is 42.5 °C and minimum during the month of January is 8.2 °C. Soils are mainly clayey to loamy in texture with calcareous concretions invariably present. They are sticky and in summer, due to shrinkage, develop deep cracks. They generally predominate in montmorillonite and beidellite type of clays. In rest of alluvial areas, mixed clays, black to brown to reddish brown, derived from sandstones and traps are observed which is sandy clay in nature with calcareous concretions. Near the banks of the rivers and at the confluence, light yellow to yellowish brown soils are noticed which were deposited during the recent past. These soils are clayey to silt in nature (Gajbhiye et al. 2013b).

Shakkar river watershed has basaltic terrain upward and a broad alluvial terrain in its middle and lower reaches. The alluvial plain through which Shakkar river runs after cutting across the Satpura range emerges in openness at Hathanapur village. From Hathanapur down to confluence, it is generally, an alluvial plain. Alluvial soil face recession which is one of the prominent processes of badland formation and in this process; on gaining moisture the slope collapses because of no stress perpendicular to the face

resisting pore water pressure. In Shakkar watershed rolling land and broadening valley just before the confluence with Narmada can be seen in Fig 2.

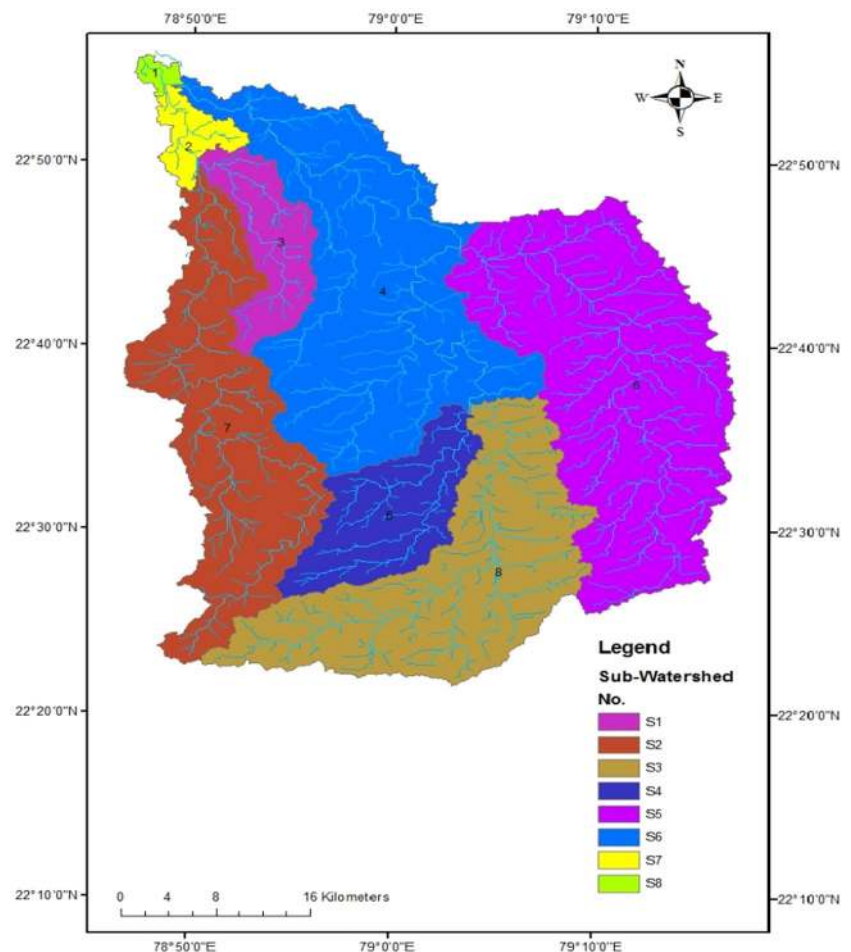
Materials and methods

For delineation of the Shakkar river watershed and preparation of drainage map the information regarding the topography is needed. In this study, a geo-coded digital elevation model (DEM) generated from Shuttle Radar Terrain Mapper (SRTM) data has been used. The DEM was downloaded from Global Land Cover Facility (GLCF) website, which was in Tagged Information File Format (TIFF) format with 30 m ground resolution. Further, the developed DEM was processed to generate or delineate the watershed (Fig. 3) and drainage network (Fig. 4), using the hydrology tool of spatial analyst module of ArcGIS. SRTM DEM based hydrological evaluation at watershed scale is more applied and precise compared to other available techniques (Singh et al. 2014). The designation of stream order is the first step in morphometric analysis of drainage basin, based on the hierarchical making of stream proposed by Strahler (1964) has been used in the present study. The fundamental parameters, namely, number of streams, stream length, area, perimeter and basin length were derived from the drainage layer. The

Fig. 2 In Shakkar watershed rolling land and broadening valley just before the confluence with Narmada



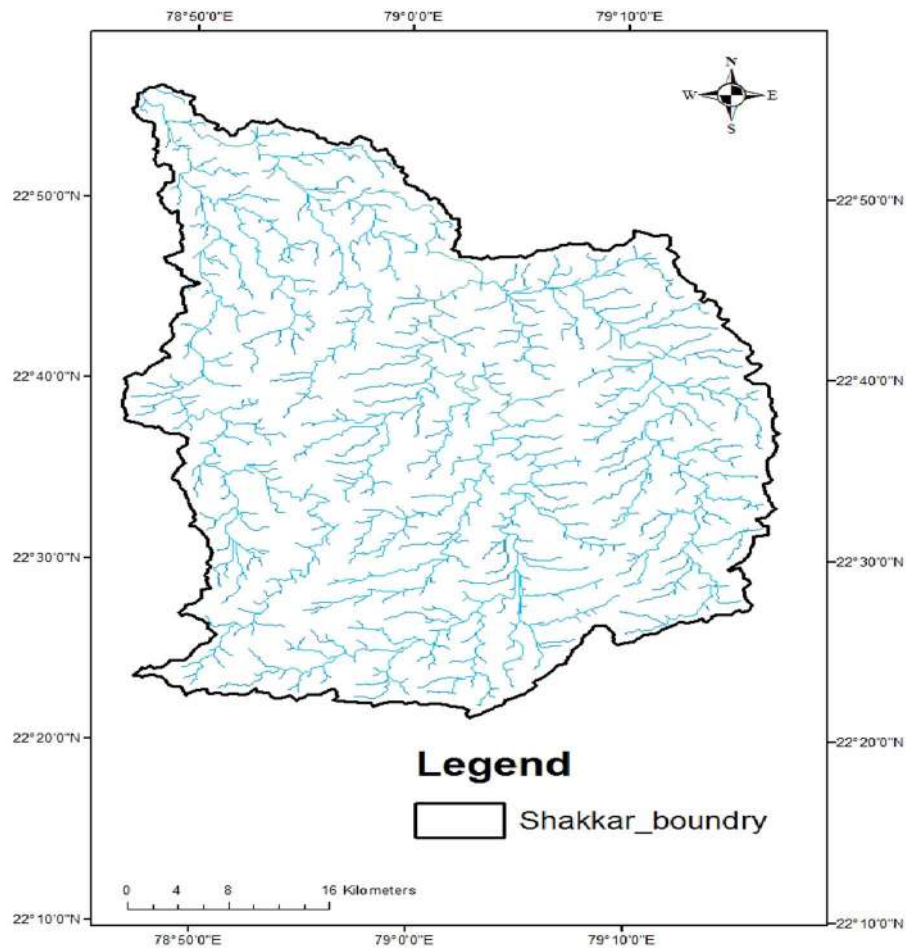
Fig. 3 Sub-watershed of the catchment



morphometric parameters for the delineated watershed area were calculated based on the formula suggested by Horton (1945), Strahler (1964), Hardy (1961), Schumm (1956),

Nookaratanam et. al. (2005) and Miller (1953) and are given in Table 1. The basic morphometric parameters are area, perimeter and length shown in Table 2.

Fig. 4 Drainage map of the study area



The morphometric parameters, i.e., mean bifurcation ratio (R_{bm}), drainage density (D_d), mean stream length (L_{sm}), compactness coefficient (C_c), stream frequency (F_s), texture ratio (T), length of overland flow (L_o), form factor (R_f), circulatory ratio (R_c) and elongation ratio (R_e) are also termed as erosion risk assessment parameters and have been used for prioritizing sub-watersheds. The linear parameters such as drainage texture, drainage density (D_d), stream frequency (F_s), bifurcation ratio (R_b), length of overland flow (L_o) have a direct relationship with erodibility; higher the value, more is the erodibility (Singh et al. 2013; Nookaratnam et al. 2005). Hence for prioritization of sub-watersheds, the highest value of linear parameters was rated as rank 1, second highest value was rated as rank 2 and so on, and the least value was rated last in rank. Shape parameters such as elongation ratio, compactness coefficient, circulatory ratio, basin shape and form factor have an inverse relationship with erodibility (Nookaratnam et al. 2005; Javeed et al. 2009); lower the value, more is the erodibility. Thus the lowest value of shape parameters was rated as rank 1, next lower value was rated as rank 2 and so on and the highest value was rated last in rank. Hence, the ranking of the sub-

watersheds has been determined by assigning the highest priority/rank based on highest value in case of linear parameters and lowest value in case of shape parameters. After the ranking has been done based on every single parameter, the ranking values for all the linear and shape parameters of each sub-watershed were added up for each of the eight sub-watersheds to arrive at compound value (C_p). Based on average value of these parameters, the sub-watershed having the least rating value was assigned the highest priority; the next higher value was assigned second priority and so on.

Another approach using the Principal Component Analysis

The geomorphic parameters are usually many times correlated. The correlation indicates that some of the information contained in one variable is also contained in some of the other remaining variables. The method of components analysis involves the rotation of coordinate axes to a new frame of reference in the total variable space—an orthogonal or uncorrelated transformation wherein each of the n original variables is describable in terms of the

Table 1 Formula for computation of morphometric parameters

Morphometric parameters	Formula	References
Stream order (u)	Hierarchical rank	Strahler (1964)
Stream length (L_u)	Length of the stream	Horton (1945)
Mean stream length (L_{sm})	$L_{sm} = L_u/N_u$ where, L_{sm} = mean stream length L_u = total stream length of order u N_u = total number of stream segments of order u	Strahler (1964)
Bifurcation ratio (R_b)	$R_b = N_u/N_{u+1}$ where, R_b = bifurcation ratio N_u = total number of stream segments of order u N_{u+1} = number of stream segment of next higher order	Schumn (1956)
Mean bifurcation ratio (R_{bm})	R_{bm} = average of bifurcation ratios of all orders	Strahler (1964)
Basin length (L_b)	$L_b = 1.312 \times A^{0.568}$ where, L_b = length of basin (km) A = area of basin (km ²)	Nookaratnam et.al. (2005)
Drainage density (D_d)	$D_d = L_u/A$ where, D_d = drainage density L_u = total stream length of all orders A = area of the basin	Horton (1945)
Stream frequency (F_s)	$F_s = N_u/A$ where, N_u = total number of streams of all orders A = area of the basin (km ²)	Horton (1945)
Texture ratio (T)	$T = N_u/P$ where, N_u = total number of streams of all orders P = perimeter (km)	Horton (1945)
Form factor (R_f)	$R_f = A/L_b^2$ where, R_f = form factor A = area of the basin (km ²) L_b^2 = square of the basin length	Horton (1945)
Circulatory ratio (R_c)	$R_c = 4\pi A/P^2$ where, R_c = circulatory ratio A = area of the basin (km ²) P = perimeter (km)	Miller (1953)
Elongation ratio (R_e)	$R_e = (2/L_b) \times (A/\pi)^{0.5}$ where, R_e = elongation ratio L_b = length of basin (km) A = area of the basin (km ²)	Schumn (1956)
Compactness constant (C_c)	$C_c = 0.2821P/A^{0.5}$ where, C_c = compactness ratio A = area of the basin (km ²) P = perimeter of the basin (km)	Horton (1945)

new principal components. An important characteristic of the new components is that they account, in turn, for a maximum amount of variance of the variables. Principal component analysis is applied for all geomorphic parameters to calculate the correlation matrix and also to derive principal components and find out the most effective parameter. The first factor-loading matrix and the rotated factor-loading matrix are used in this analysis. The same process of the ranking of parameter is followed as discussed earlier (Javeed et al. 2009).

Results and discussion

The information about basic morphometric parameters such as area (A), perimeter (P), length (L), and number of streams (N) was obtained from sub-watershed delineated layer, and basin length (L_b) was calculated from stream length, while

the bifurcation ratio (R_b) was calculated from the number of streams. Other morphometric parameters were calculated using the equations as described in Table 1.

Stream order (u)

The first step in the geomorphological analysis of a drainage basin is the designation of stream order; stream ordering as suggested by Strahler (1964) was used for this study. Streams that originate at a source are defined as first-order streams. When two streams of a first order join, an order two stream is created and so on. The order of a basin is the order of the highest stream. After analysis of the drainage map, it was found that the Shakkar River catchment is of the 8th order type and the drainage pattern is dendritic to sub-dendritic. This pattern is developed where rocks offer uniform resistance in a horizontal direction and devoid of marked structural control suggesting uniform lithology

Table 2 Basic parameters of the Shakkar River catchment

SW No.	SW name	Basin area (km ²)	Perimeter (km)	Basin length (km)
1	S1	9.23	17.03	3.41
2	S2	37.87	41.11	9.00
3	S3	114.00	71.70	18.01
4	S4	538.22	171.78	43.00
5	S5	158.35	75.06	23.61
6	S6	581.45	150.45	36.89
7	S7	383.43	164.68	46.90
8	S8	397.96	131.84	25.27

Table 3 Linear aspect of the Shakkar River catchment

Sub-watershed	Stream order								Mean bifurcation ratio (R_b)
	I	II	III	IV	V	VI	VII	VIII	
Sub-watershed-1									
No. of streams	58	13	2	0	0	0	2	1	3.49
Stream length (km)	20.98	6.26	2.34	0	0	0	0.098	4.23	
Sub-watershed-2									
No. of streams	209	49	14	2	0	2	1	0	3.55
Stream length (km)	66	30	16	6	0	0.097	10	0	
Sub-watershed-3									
No. of streams	590	125	29	7	2	1	0	0	3.73
Stream length (km)	163	83	38	12	24	4.37	0	0	
Sub-watershed-4									
No. of streams	2992	646	138	28	5	3	1	0	4.30
Stream length (km)	867	411	185	72	58.12	0.18	75.66	0	
Sub-watershed-5									
No. of streams	913	211	52	8	2	1	0	0	4.17
Stream length (km)	246	121	52	40	20	7.36	0	0	
Sub-watershed-6									
No. of streams	3237	715	164	45	11	1	0	0	5.52
Stream length (km)	961	433	237	108	50	48.83	0	0	
Sub-watershed-7									
No. of streams	2165	463	117	25	3	1	0	0	4.93
Stream length (km)	633	286	127	71	29	42.68	0	0	
Sub-watershed-8									
No. of streams	2340	544	125	29	5	1	0	0	4.75
Stream length (km)	662	279	154	87	30	40.37	0	0	

(Cleland 1916). Sub-watershedwise stream analysis is presented in Table 3 Sub-watersheds 3, 5, 6, 7 and 8 are of the 6th order type; sub-watersheds 2 and 4 are of the 7th order type, and sub-watershed 1 is of the 8th order type.

Stream number

It is the number of stream segment of various orders and it is inversely proportional to the stream order. It is observed from Table 3 that the maximum frequency is in case of first-order streams. It is also noticed that there is a decrease

in stream frequency as the stream order increases. Sub-watershed-6 has maximum number of streams of 1st order ($N_u = 3237$), 2nd order ($N_u = 715$), 3rd order ($N_u = 164$), 4th order ($N_u = 45$), 5th order ($N_u = 11$), 6th order ($N_u = 1$), among all other comparisons.

Total stream length (L_u)

The stream lengths of the various segments are measured with the help of GIS software. All the sub-watersheds show that the total length of stream segments is maximum in

first-order streams and decreases as the stream order increases (Table 3). Sub-watershed-4 has the longest stream length ($L_u = 1268.96$ km), while sub-watershed-1 has the minimum value of $L_u = 33.91$ km.

Bifurcation ratio (R_b)

Horton (1945) considered bifurcation ratio as an index of relief and dissection. Strahler (1957) demonstrated that R_b shows only small variations for different regions in different environments except where powerful geological control dominates. Lower R_b values are the characteristics of structurally less disturbed watershed without any distortion in drainage pattern (Nag 1998). The sub-watershed-6 has maximum ($R_b = 5.52$) while sub-watershed-1 has minimum ($R_b = 3.49$). R_b characteristically ranges between 3.0 and 5.0 for watershed where the influence of geological structure on the drainage network is negligible (Verstappen 1983). The values of R_b for eight sub-watersheds are presented in Table 3.

Drainage density (D_d)

It indicates the closeness of spacing between channels and is a measure of the total length of the stream segment of all orders per unit area. It is affected by factors such as resistance to weathering, permeability of rock formation, climatic, vegetation, etc. In general, low value of D_d is the characteristic of regions underlain by highly permeable materials with vegetative cover and low relief. Whereas, high values of D_d indicate regions of weak and impermeable subsurface material, sparse vegetation and mountainous relief (Nautiyal 1994). Drainage density in the study area varies between 2.84 and 3.67 indicating low drainage density (Table 4).

Stream frequency/drainage frequency (F_s)

Stream frequency is the total number of stream segments of all orders per unit area (Horton 1932). The stream

frequency relates to permeability, infiltration capability and relief of watershed. A low value 6.61 is observed in sub-watershed-3, while a high value 8.23 is observed in sub-watershed-1. Stream frequency values indicate positive correlation with the drainage density of all the sub-watersheds suggesting increase in stream population with respect to increase in drainage density.

Form factor (R_f)

It is the ratio of basin area A , to the square of maximum length of the basin L_b . It is a dimensionless property and is used as a quantitative expression of the shape of basin form. The sub-watershed-1 has maximum value ($R_f = 0.79$) while sub-watershed-7 has minimum value of ($R_f = 0.17$). The smaller the value of form factor is, the more elongated the basin will be. The basin with a high form factor has high peak flows of shorter duration, whereas the basin with a low form factor has lower peak flows of longer duration. Therefore, sub-watershed-7 will have lower peak flows of longer duration. However, sub-watershed-1 will have high peak flows of shorter duration.

Circulatory ratio (R_c)

Miller (1953) introduced the circulatory ratio to quantify the basin shape. It is the ratio of the watershed area and the area of circle of watershed perimeter (P). Circulatory ratio (R_c) is influenced by the length and frequency of streams, geological structures, land use/land cover, climate, relief and slope of the basin. Values of circulatory ratio of all sub-watersheds are presented in Table 4. The sub-watershed-7 has minimum value ($R_c = 0.17$), while sub-watershed-1 has maximum value ($R_c = 0.40$). According to the Miller range, sub-watersheds are elongated in shape, with low discharge of runoff and high permeability subsoil condition.

Table 4 Aerial aspect of the Shakkar River catchment

Sub-watershed	Drainage density (D_d)	Stream frequency (F_s)	Circulatory ratio (R_c)	Form factor (R_f)	Elongation ratio (R_e)	Texture ratio (T)	Length of overland flow (L_o)	Compactness constant (C_c)	Ruggedness number (R_N)
1	3.673	8.232	0.403	0.794	1.006	4.464	0.136	0.126	0.147
2	3.383	7.315	0.283	0.468	0.772	6.739	0.148	0.048	0.203
3	2.845	6.614	0.281	0.351	0.669	10.516	0.176	0.021	1.682
4	3.101	7.085	0.231	0.291	0.609	22.197	0.161	0.007	1.896
5	3.071	7.496	0.356	0.284	0.602	15.815	0.163	0.015	1.659
6	3.161	7.177	0.325	0.427	0.738	27.738	0.158	0.006	1.865
7	3.100	7.235	0.179	0.174	0.471	16.845	0.161	0.009	2.483
8	3.147	7.649	0.290	0.623	0.891	23.088	0.159	0.008	1.825



Elongation ratio (R_e)

The elongation ratio is an indication of the shape of the watershed. According to Schumn (1956), elongation ratio is defined as the ratio of the diameter of a circle having the same area as the basin and the maximum basin length. The values of elongation ratio generally vary from 0.6 to 1.0 over a wide variety of climatic and geologic types. Values close to 1.0 are typical of regions of very low relief, whereas values in the range 0.6–0.8 are generally associated with high relief and steep ground slope (Strahler 1964). It is a very significant index in the analysis of basin shape, which helps to give an idea about the hydrological character of a drainage basin. A circular basin is more efficient in the discharge of runoff than an elongated basin. The value of elongation ratio of eight sub-watersheds is presented in Table 4. The lowest values of 0.47 (sub-watershed-7) and 0.97 (sub-watershed-1) indicate high relief and steep slopes, while remaining sub-watershed indicates a plain land with low relief and low slope.

Length of overland flow (L_o)

The overland flow and surface runoff are quite different; the overland flow refers to that flow of precipitated water, which moves over the land surface leading to the stream channels, while the channel flow reaching the outlet of watershed is referred as surface runoff. The overland flow is dominant in smaller watershed instead of larger watersheds. The length and depth of overland flow are small and found in laminar condition (Horton 1945). Sub-watershed-3 has maximum ($L_o = 0.17$ km) and sub-watershed-1 has minimum ($L_o = 0.13$ km) length of overland flow among 8 sub-watersheds (Table 4).

Relief ratio (R_h)

The relief ratio is defined as the ratio between the total relief of a basin and the longest dimension of the basin parallel to the main drainage line (Schumn 1956). In the study area, the values of relief ratio vary from 0.001 to 0.008 (Table 5). It has been observed that areas with high reliefs and steep slopes are characterized by high values of relief ratios. Low values of relief ratios are mainly due to the resistant basement rocks of the basin and the low degree of slope.

Average slope (S_a)

Average slope of the watershed, S_a has direct influence on the erodibility of the watershed. It has been proved by researchers that the more the percentage of slopes is, more is the erosion, if other factors remain unchanged. The values of Average slope vary from 9.27 to 88.50 (Table 5).

Table 5 Relief aspect of the Shakkar River catchment

Sub-watershed	Relative relief (R_h)	Relief ratio (R_r)	Average slope (S_a)	HI
1	0.012	0.002	6.036	0.498
2	0.007	0.001	4.099	0.471
3	0.030	0.008	10.085	0.501
4	0.014	0.003	9.803	0.497
5	0.023	0.007	11.67	0.488
6	0.016	0.004	9.329	0.491
7	0.017	0.005	14.818	0.483
8	0.023	0.004	13.071	0.508

Relative relief (R_r)

Relative relief (R_r) is the ratio of the maximum watershed relief to the perimeter of the watershed. The value of the relative relief for eight sub-watersheds is shown in Table 5. Sub-watershed-2 has minimum R_r (0.007), while sub-watershed-3 had the maximum value (0.030).

Ruggedness number (R_N)

The value of R_N for eight sub-watersheds is shown in Table 5. The sub-watershed-7 has maximum ruggedness number ($R_N = 2.48$), while sub-watershed-1 has minimum value ($R_N = 0.14$). The sub-watershed has overall high roughness, which indicates the structural complexity of the terrain in association with relief and drainage density. It also implies that the area is susceptible to more erosion.

Texture ratio (T)

Texture ratio is an important factor in drainage morphometric analysis, which depends on the underlying lithology, infiltration capacity and relief aspect of the terrain. The value of the texture ratio is shown in Table 5. The sub-watershed-6 has maximum ($T = 27.73$), while sub-watershed-1 has minimum ($T = 4.46$).

Compactness constant (C_c)

The value of the compactness constant is shown in Table 5. The sub-watershed-1 has maximum ($C_c = 0.12$), while sub-watershed-6 has minimum ($C_c = 0.006$).

Hypsometric integral (HI)

Hypsometric analysis was carried out or the relation of horizontal cross-sectional drainage basin area with elevation was developed in its modern dimensionless form by Langbein (1947). It is used to determine the geomorphic stages of development of a watershed and expresses simply

how the mass is distributed within a watershed from base to top. Figure 5 illustrates the definition of two dimensionless variables involved in hypsometric analysis. Taking watershed to be bounded by vertical sides and a horizontal base plane passing through the mouth, the relative height, y , is the ratio of height of a given contour, h , to total basin relief, H . Relative area, x , is the ratio of horizontal cross-sectional area, a , to the entire watershed area, A . The percentage hypsometric curve is a plot of the continuous function relating relative height, y , to relative area, x . As shown in the lower right part of the diagram, the shape of the hypsometric curve varies in early geologic stages of development of the watershed, but once a steady state (mature stage) is attained, tends to vary little thereafter, despite lowering relief. Several dimensionless attributes of the hypsometric curve are measurable and these can be used for comparison. One such is hypsometric integral, H_{si} , or the relative area lying below the curve, i.e. the ratio of area under the hypsometric curve to the area of the entire square. It is expressed in percentage and can be estimated from the hypsometric curves of the watersheds by measuring the area under the curve with the help of different methods, but the Pike and Wilson (1971) method (or ele-

vation-relief ratio method) is a less cumbersome and faster method and it is used in the study for estimating hypsometric integral. The relationship is expressed as:

$$E \approx H_{si} = \frac{\text{Elev}_{\text{mean}} - \text{Elev}_{\text{min}}}{\text{Elev}_{\text{max}} - \text{Elev}_{\text{min}}} \quad (1)$$

where E is the elevation-relief ratio equivalent to the hypsometric integral H_{si} ; $\text{Elev}_{\text{mean}}$ is the weighted mean elevation of the watershed estimated from the identifiable contours of the delineated sub-watersheds; Elev_{min} and Elev_{max} are the minimum and maximum elevations within the sub-watersheds. After obtaining the hypsometric integrals of the selected watersheds and comparing with the model hypsometric curves (Fig. 5, bottom right), the stages of development of the watersheds under study are determined with the following criteria:

- The watersheds will be in inequilibrium (youthful) stage if $H_{si} \geq 0.60$,
- The watersheds are considered to attain the equilibrium stage if H_{si} ranges between 0.35 and 0.60, and
- The watersheds are in monadnock phase if $H_{si} \leq 0.35$.

Fig. 5 Method of hypsometric analysis

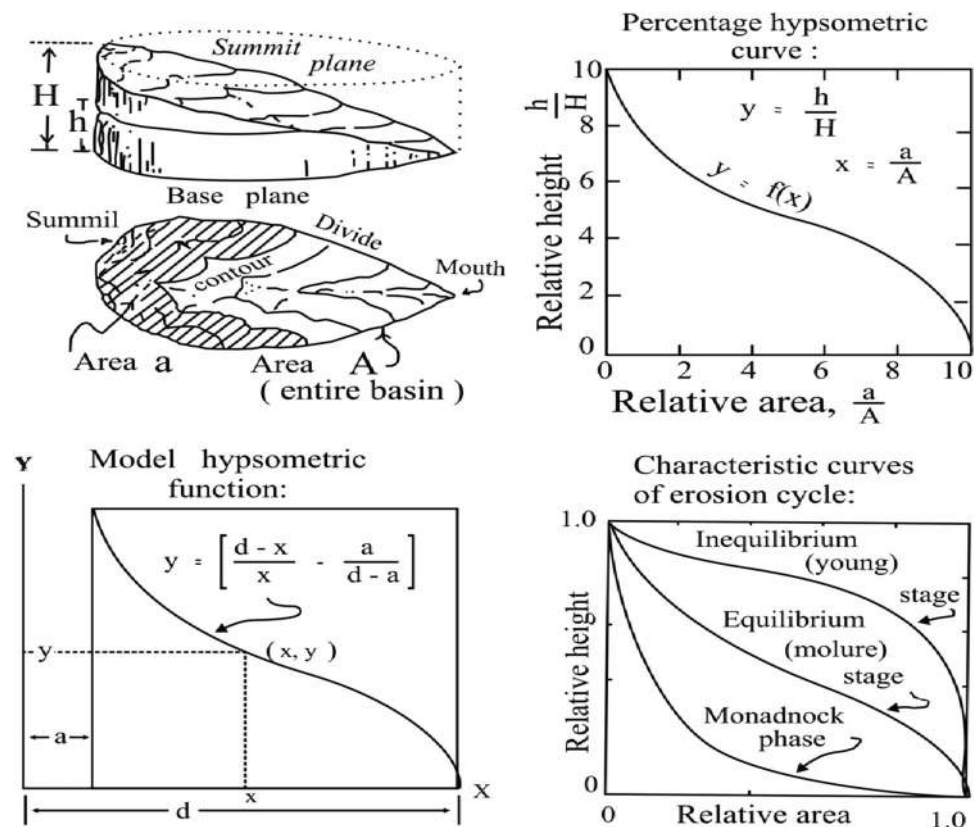


Table 6 Interrelation matrix of the geomorphological parameter of Shakkar watershed

	R_h	R_r	R_N	R_b	D_d	F_s	R_c	R_f	R_e	T	L_o	C_c	S_a	HI
R_h	1.00	0.92	0.55	0.13	−0.75	−0.41	−0.02	−0.24	−0.23	0.22	0.80	−0.43	0.62	0.05
R_r	0.92	1.00	0.60	0.15	−0.80	−0.51	−0.08	−0.51	−0.50	0.17	0.83	−0.48	0.62	−0.02
R_N	0.55	0.60	1.00	0.74	−0.78	−0.52	−0.61	−0.69	−0.71	0.75	0.75	−0.84	0.91	0.13
R_b	0.13	0.15	0.74	1.00	−0.35	−0.18	−0.33	−0.33	−0.33	0.90	0.29	−0.66	0.62	−0.04
D_d	−0.75	−0.80	−0.78	−0.35	1.00	0.84	0.52	0.73	0.69	−0.47	−1.00	0.85	−0.63	−0.48
F_s	−0.41	−0.51	−0.52	−0.18	0.84	1.00	0.60	0.72	0.67	−0.28	−0.85	0.70	−0.22	−0.69
R_c	−0.02	−0.08	−0.61	−0.33	0.52	0.60	1.00	0.69	0.71	−0.31	−0.48	0.63	−0.49	−0.62
R_f	−0.24	−0.51	−0.69	−0.33	0.73	0.72	0.69	1.00	0.99	−0.33	−0.70	0.74	−0.51	−0.36
R_e	−0.22	−0.50	−0.70	−0.32	0.69	0.67	0.71	0.99	1.00	−0.30	−0.66	0.69	−0.55	−0.30
T	0.21	0.16	0.75	0.90	−0.47	−0.27	−0.30	−0.33	−0.30	1.00	0.41	−0.77	0.57	0.10
L_o	0.79	0.83	0.74	0.28	−0.99	−0.84	−0.48	−0.70	−0.66	0.41	1.00	−0.80	0.60	0.46
C_c	−0.43	−0.45	−0.83	−0.65	0.85	0.69	0.62	0.74	0.69	−0.77	−0.80	1.00	−0.65	−0.54
S_a	0.61	0.62	0.90	0.61	−0.63	−0.22	−0.48	−0.51	−0.55	0.57	0.60	−0.65	1.00	−0.05
HI	0.04	−0.01	0.13	−0.03	−0.48	−0.68	−0.61	−0.36	−0.30	0.10	0.46	−0.54	−0.05	1.00

Interrelation among the geomorphic parameters

For obtaining the inter-correlation among the geomorphic parameters, a correlation matrix is obtained using SPSS 14.0 Software. The correlation matrix of the 14 geomorphic parameters of Shakkar watershed (Table 6) reveals that strong correlations (correlation coefficient more than 0.9) exist between relief ratio (R_h) and relative relief (R_r); between ruggedness number (R_N) and average slope (S_a); between drainage density (D_d) and length of overland flow (L_o); and between form factor (R_f) and elongation ratio (R_e). Also, good correlations (correlation coefficient more than 0.75) exist between R_h and D_d , L_o ; between R_r and D_d , L_o ; between R_N and bifurcation ratio (R_b), D_d , texture ratio (T), L_o , and compactness coefficient (C_c); between D_d and stream frequency (F_s), C_c ; and between F_s and L_o . Some more moderately correlated parameters (correlation coefficient more than 0.6) are R_N with circulatory ratio (R_c), R_f and R_e ; D_d with R_f , R_e and S_a ; F_s with R_f , R_e , C_c , and hypsometric integral (HI); R_c with R_f , R_e , C_c , and HI; and R_f with L_o and C_c . It is very difficult at this stage to group the parameters into components and attach physical significance. Hence, in the next step, the principal component analysis has been applied to the correlation matrix.

Here, grouping of the parameters into components at this stage is very difficult. Hence, in the next step, the principal component analysis has been applied. The correlation matrix is subjected to the principal component analysis.

Principal component analysis

The principal component analysis method was used to obtain the first factor-loading matrix, and thereafter, the rotated loading matrix using orthogonal transformation. The results are shown in the following sections.

First factor-loading matrix From the correlation matrix of 14 geomorphic parameters, the first unrotated factor-loading matrix is obtained. It can be seen from Table 7 that the first three components whose eigen values are greater than 1, together account for about 87.35 % of the total variance in the Shakkar watershed. It can be observed from Table 8 that the first component is strongly correlated (more than 0.90) with R_N , D_d , L_o , and C_c and correlated satisfactorily (more than 0.75) with R_f , R_e , F_s , and S_a , and moderately (loading more than 0.60) with R_r , R_c and T . The second component is moderately correlated with HI and the third component moderately with R_h for Shakkar watershed. It is observed from these results that R_b does not show any correlation with any of the components. Some parameters are highly correlated with some components, some moderately, and some parameters do not correlate with any component. Thus, at this stage, it is difficult to identify a physically significant component. It is necessary to rotate the first factor-loading matrix to get a better correlation.

Rotation of first factor-loading matrix The rotated factor-loading matrix is obtained by post-multiplying the

Table 7 Total variance explained of Shakkar watershed

Component	Initial eigen values			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	8.17	58.33	58.33	8.17	58.33	58.33	4.46	31.84	31.84
2	2.10	14.99	73.31	2.10	14.99	73.31	3.98	28.42	60.26
3	1.97	14.05	87.36	1.97	14.05	87.36	3.79	27.10	87.36
4	0.99	7.05	94.41						
5	0.52	3.69	98.10						
6	0.18	1.27	99.36						
7	0.09	0.64	100.00						
8	0.00	0.00	100.00						
9	0.00	0.00	100.00						
10	0.00	0.00	100.00						
11	0.00	0.00	100.00						
12	0.00	0.00	100.00						
13	0.00	0.00	100.00						
14	0.00	0.00	100.00						

Table 8 Unrotated matrix

	Component		
	1	2	3
Component matrix			
R_h	0.618	0.237	0.711
R_r	0.703	0.156	0.676
R_N	0.917	0.336	−0.130
R_b	0.557	0.584	−0.507
D_d	−0.950	0.112	−0.248
F_s	−0.782	0.505	−0.068
R_c	−0.669	0.366	0.461
R_f	−0.830	0.271	0.136
R_e	−0.807	0.233	0.142
T	0.613	0.507	−0.451
L_o	0.922	−0.132	0.329
C_c	−0.923	−0.014	0.237
S_a	−0.015	0.535	0.019
HI	−0.108	−0.157	−0.043

Table 9 Rotated matrix

	Component		
	1	2	3
Rotated component matrix			
R_h	−0.010	0.964	0.117
R_r	−0.132	0.970	0.127
R_N	−0.366	0.476	0.781
R_b	−0.069	0.012	0.951
D_d	0.604	−0.721	−0.304
F_s	0.836	−0.412	−0.046
R_c	0.816	0.053	−0.355
R_f	0.754	−0.317	−0.334
R_e	0.714	−0.305	−0.350
T	−0.144	0.075	0.900
L_o	−0.578	0.767	0.233
C_c	0.634	−0.338	−0.626
S_a	−0.115	0.535	0.719
HI	−0.808	−0.057	−0.143

transformation matrix with the selected component of the first factor-loading matrix. It can be observed from Table 9 that the first component is correlated well with F_s , R_c , R_f , and HI; and moderately with C_c and R_e which may be termed as stage-form component. The second component is strongly correlated with R_h , R_r ; and good with D_d and L_o

and it can be termed as relief-density component. The third component is strongly correlated with R_b and T and good with R_N and moderately correlated with S_a and may be termed as organization-processes component for Shakkar watershed. As seen (Table 9), the most important

Table 10 Priorities of sub-watersheds and their ranks

Sub-watershed	R_b	D_d	F_s	R_c	R_f	R_e	T	L_o	C_c	R_N	R_h	R_r	S_a	HI	Compound parameter (C_p)	Final priority
1	8	1	1	1	8	8	8	8	8	8	7	7	7	3	5.93	7
2	7	2	4	5	6	6	7	7	7	7	8	8	8	8	6.43	8
3	6	8	8	6	4	4	6	1	6	5	1	1	4	2	4.43	6
4	1	5	7	7	3	3	3	3	2	2	6	6	5	4	4.07	5
5	5	7	3	2	2	2	5	2	5	6	3	2	3	6	3.79	3
6	1	3	6	3	5	5	1	6	1	3	5	5	6	5	3.93	4
7	2	6	5	8	1	1	4	4	4	1	4	3	1	7	3.64	2
8	3	4	2	4	7	7	2	5	3	4	2	4	2	1	3.57	1

Table 11 Priorities of sub-watersheds and their ranks

Sub-watershed	R_b	F_s	R_r	Compound parameter (C_p)	Final priority
1	8	1	7	5.33	7
2	7	4	8	6.33	8
3	6	8	1	5.00	6
4	1	7	6	4.67	5
5	5	3	2	3.33	3
6	1	6	5	4.00	4
7	2	5	3	3.33	2
8	3	2	4	3.00	1

parameter is F_s (stream frequency) followed by R_r (relative relief), R_b (bifurcation ratio), so finally these parameters have been taken for the prioritization.

Comparison of two approaches for prioritization of sub-watersheds

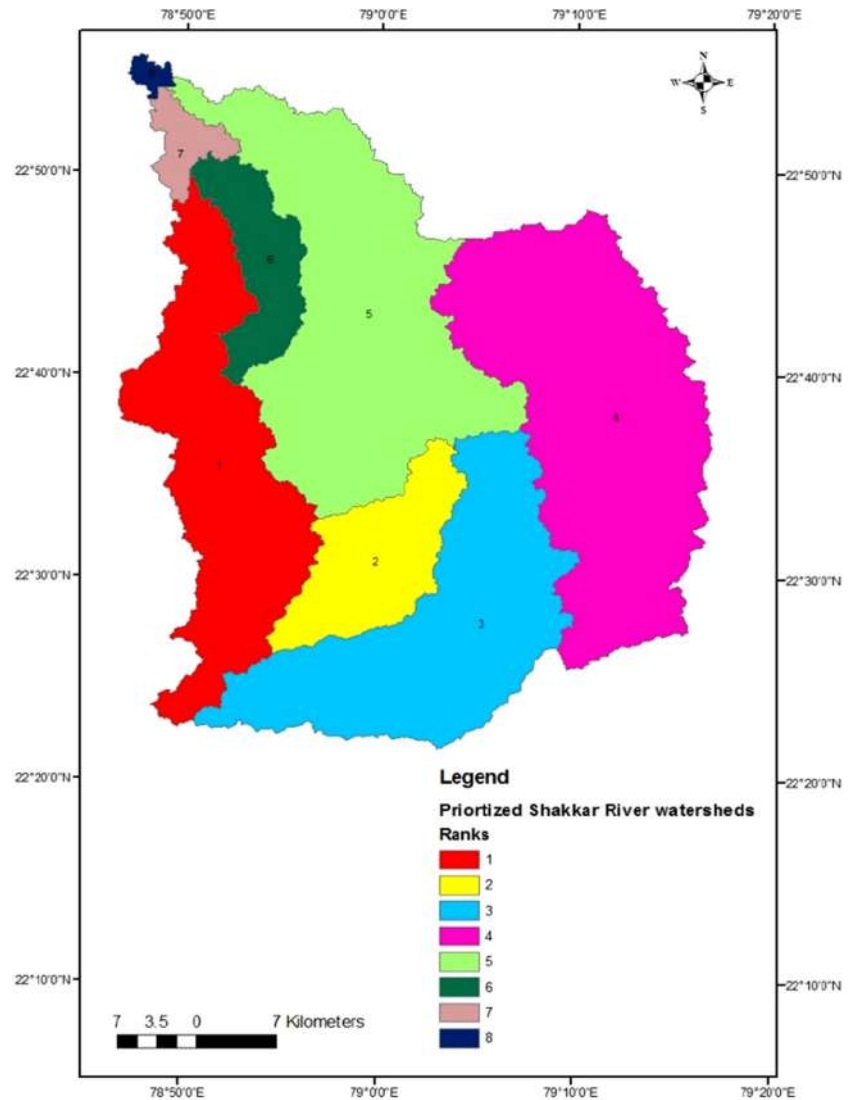
By taking all the geomorphic parameters, the compound parameter values of eight sub-watersheds of Shakkar River catchment were calculated and the prioritization rating is shown in Table 10. Sub-watershed 8 with a compound parameter value of 3.57 receives the highest priority (one) with next in the priority list is sub-watershed 7 having the compound parameter value of 3.64. After applying the PCA, and on the basis of selected parameters, the prioritization rating is shown in Table 11. Here sub-watershed 8 with a compound parameter value of 3.00 (minimum) receives the highest priority (one) and next sub watershed 7 having the compound parameter value of 3.33 receives the next priority (two). Highest priority indicates the greater degree of erosion in the particular sub-watershed and it

becomes potential area for applying soil conservative measures. The final prioritized map of the study area is shown in Fig. 6; thus soil-conservation measures can first be applied to sub-watershed area 8 and then to the other sub-watersheds depending upon their priority. It can be seen that both the prioritization schemes gave the same result. However, in the prioritization of sub-watersheds made by Gajbhiye et al. (2013b), 14 geomorphic parameters were taken, whereas in the PCA-based scheme, parameters were reduced from 14 to 3, which saves time. The results presented in this paper will assist fluvial geomorphologists and hydrologists to select parameters and also to save time.

Conclusions and findings

The quantitative morphometric analysis was carried out in eight sub-watersheds of Shakkar River catchment using GIS technique for determining the linear aspects such as Stream order, Bifurcation ratio, Stream length and aerial aspects such as drainage density (D_d), stream frequency (F_s), form factor (R_f), circulatory ratio (R_c), and elongation ratio (R_e). The prioritization based on different morphometric parameters is time consuming. However, PCA-based approach allows for more effective parameters for prioritizing watersheds. The morphometric analysis of different sub-watersheds shows their relative characteristics with respect to hydrologic response of the watershed. Results of morphometric analysis show that sub-watershed 7 and 5 are possibly having high erosion. Hence, suitable soil erosion control measures are required in these watersheds to preserve the land from further erosion. The present study demonstrates the utility of RS, GIS and PCA techniques in prioritizing sub-watersheds based on morphometric analysis.

Fig. 6 Prioritized rank map of the catchment



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