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Research Article

Prioritization of Sub-watersheds of a Western Himalayan Catchment Employing Morphologically based Compound Index and Sediment Production Rate

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ABSTRACT

Linking of morphological parameters with the hydrological response of a watershed is overwhelmingly used in hydrology especially for un-gauged catchments. Eventual outcomes from a watershed i.e. water and consequently soil/sediment travel through the drainage networks from the ridge points to outlet of the watershed and hence their rate/quantity are strongly correlated with the geometry, size, density, length, slope, and orientation of these drainage channels. This mutual relationship forms the strong basis for linking morphometry with hydrologic response of a watershed. In the present study, various morphological parameters representing one dimensional view via linear, two dimensional view via areal and three dimensional view via relief aspect of the catchment have been extracted in GIS environment by partitioning a western Himalayan catchment from Indian subcontinent into nine sub-watersheds (SW1 to SW9).The study catchment was found to be an eighth order drainage basin as per Strahler stream ordering scheme. The catchment is dominated by the trellis, parallel and dendritic drainage patterns in different sub-watersheds. Higher bifurcation ratios between the first and second order streams imply the presence of active gullies in the catchment. Medium to high drainage densities, ranging from 2.84 to 3.92 km km^{-2} were found in the study area indicating weak or impermeable subsurface material, high mountainous relief and fine drainage texture. Most of the sub-watersheds are characterized with high relief ratio, relative relief and average slope, which are favorable to generate significant runoff even for a small volume of rainfall. In order to prioritize the catchment, a compound index was calculated by considering the individual rank assigned to all nine sub-watersheds based on 13 morphological parameters. Study reveals that SW6 sub-watershed has top priority and SW1 watershed has least. To help decide the quantum of conservation work required in each sub-watershed, the quantitative assessment of soil loss has been done using sediment production rate (SPR). Sediment production rate of all sub-watersheds varies between 0.82 ha-m 100 km^{-2} yr^{-1} to 3.07 ha-m 100 km^{-2} yr^{-1}. These values are in concurrence with the design SPR values as adopted in most of the river valley projects constructed in the western Himalayan region of India. SPR values estimated as well as compound ranking evaluated using morphological parameters in the present study may be helpful in identifying the critical areas in an un-gauged catchment and accordingly deciding the treatment measures in volume and space.

Key words: GIS, Morphological parameters, Prioritization of watersheds, Sediment production rate

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Introduction

Land and water are two important natural resources since our relationship with them directly reflects the success of civilization. In scientific terminology, this Land-Water-Human relationship has been bounded by the term "Watershed". Watershed is the basic unit for development and planning of resources for the welfare of the communities. As these watersheds are the source of goods such as food, fodder, fiber and fuel wood and services like water for the local population, their scientific management is essential for sustainable development. Thus, watershed planning and management schemes play a vital role in ensuring efficient use of land and water resources in terms of quantity and quality to meet the present and future demands of the stake-holders.

The response to soil and water conservation measures for alleviating erosion would be different for different parts of a catchment due to their physiographical variability throughout the catchment or in other words, exhibit different physiographical settings in the sub-watersheds of the same catchment. Thus it is not only necessary to know the state of erosion of the watershed but it is equally important to quantify the rate of erosion within the watershed to proportionately allocate the funds for their treatment for achieving the best output. In developing countries like India, observations of discharge and suspended sediment yield are usually gauged only at the outlet of large watersheds normally when these rivers enter the plain areas. However, the major sources of sediment are the upstream hilly areas and eroded soils from these areas are transported through small mountainous tributaries, which are unfortunately un-gauged. Process of soil loss from a watershed is exclusively influenced by erosion, deposition and transportation sub-processes that continuously occur along the sediment flow path within the watershed (Merritt *et al.,* 2003; Aksoy and Kavvas 2005; Rawat *et al.,* 2013; Rawat *et al.,* 2016). Therefore, using sediment data from the outlet of a large watershed to identify the actual source areas of sediment within the watershed cannot be justified. To overcome this problem, various morphometric parameters (drainage density, drainage frequency, form factor, length of overland flow, elongation ratio, circulatory ratio, compactness coefficient, drainage texture, bifurcation ratio, etc.) have been correlated with surface and sub-surface features like slope, soil, rock resistance, structure and geological history of the watershed which are responsible for runoff and consequent erosion from the watershed. These morphometric parameters have been linked with hydrological behavior of an un-gauged watershed through popular GIUH theory (Jain and Sinha, 2003; Kumar and Kumar, 2008), stream profile analysis, prioritization of sub-watersheds for their vulnerability of soil erosion (Nookaratnam *et al.,* 2005; Mishra and Rawat, 2012; Singh and Singh, 2014), estimation of sediment production rate (Rymbai and Jha 2012), identification of artificial recharge locations (Ghayoumian *et al.,* 2005), permeability of underlying geological formation (Pakhmode *et al.,* 2003; Anbazhagan *et al.,* 2005) and many more.

Since, most of the morphometric parameters are in the form of ratio, scale does not limit their application while comparing for different watersheds. Due to lack of observed data, these morphometric approaches are very popular in characterization of sub-watersheds in reference to their strong relationships with the factors responsible for soil erosion and transportation. Manual estimation of geomorphologic parameters is a tedious and cumbersome process and often discourages the field engineers from developing regional methodologies for solving various hydrological problems of un-gauged catchments or in limited data situations (Singh *et al.,* 2003). With the advancement in the field of geo-spatial technologies like GIS and Remote Sensing (RS), geomorphological parameters can easily be extracted from the digitalized toposheets (Maathuis 2005; Hengl *et al.,* 2006; Nookaratnam *et al.,* 2005; Mishra and Rawat, 2012). Moreover, GIS tools are capable of handling spatial and temporal data, with the result that morphometric parameters can be updated whenever any change occurs (Apaydin *et al.,* 2006).

Considering the strong interaction between the morphology and hydrologic response of the watershed, morphological characterization of nine sub-watersheds of Tawi catchment has been done in the present study using geospatial technique. The prioritization of sub-watersheds has been done through the compound index based on morphometric parameters. The sediment production rates (SPR) from different sub-watersheds have also been estimated using morphological parameters to help in deciding the amplitude of the treatment activities in different areas or sub-watersheds of Tawi catchment.

Study area

Tawi River catchment located in Jammu division of Jammu and Kashmir State of India (Fig. 1) was selected for detailed morphometric analysis. River Tawi, a major river in Jammu region is the left bank tributary of river Chenab, originating from the lap of Kali Kundi glacier in Bhaderwah flows through some parts of Doda and Udhampur districts, reaches Jammu from where it enters Pakistan and finally merges into Chenab. The length of Tawi River from its originating point to Jammu is about 150 km. The important role of Tawi River for sustaining the most populous cities in the region, Jammu and Udhampur has been considered while selecting the basin. The Tawi River has a very high social impact as it is the only major source of water for drinking as well as agricultural and industrial needs of almost 20% population of Jammu and Kashmir State of India. However, this heavy population load causes ecological degradation (change in land use pattern, deforestation and low growth rate of vegetation, construction of new roads and bridges), which accelerates the already severe soil erosion in the catchment. The average annual rainfall of the study area is about 1000 mm. Huge sediment carried from the upstream hilly area by the flood water ultimately gets deposited along the banks and in the river channel when Tawi enters the plains. Consequently, the channel capacity reduces significantly and stage of the river gets elevated causing overflow. Every year this overflow causes flood in Tawi River, which claims huge loss of public and private property especially in the Jammu city.

Materials and methods

Data sources and analysis

In the present study, Tawi River catchment and its drainage network has been delineated from toposheets obtained from the Survey of India

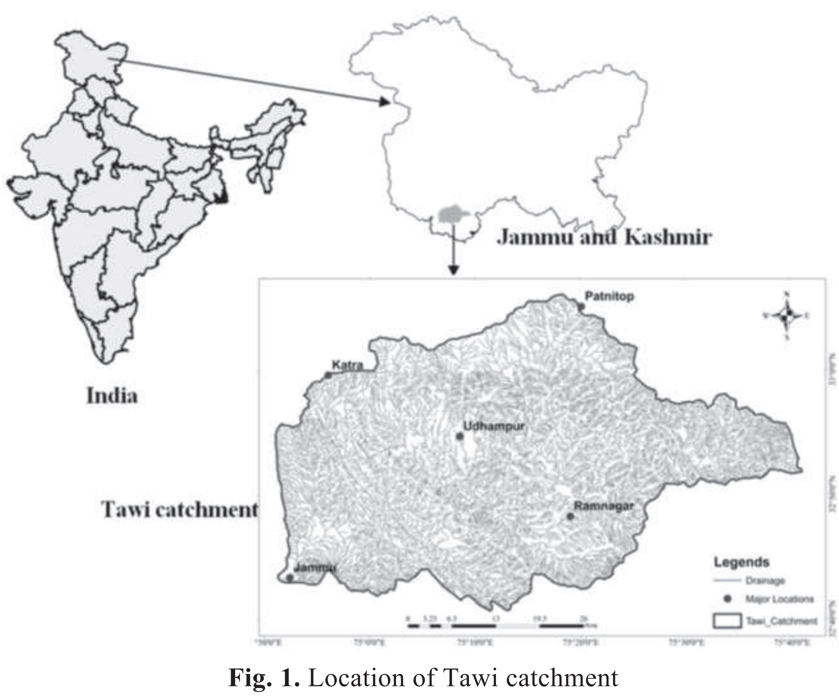

Fig. 1. Location of Tawi catchment

(SOI). Total eight toposheets of 1:50,000 scale viz., 43O4, 43O8, 43L13, 43P5, 43P9, 43L14, 43P2 and 43P6 have been geo-referenced in ArcGIS10.2 followed by digitalization of drainage network. By following the Strahler (1964) method, stream ordering has been carried-out for the entire Tawi catchment and it has found to be an eighth order catchment. According to the extracted drainage network, the entire drainage area of 2163 sq. km was subdivided into nine sub-watersheds having areas ranging from 97 sq. km to 487 sq. km for greater understanding of morphometric parameters and their correlation with hydrological response and consequent soil erosion in the catchment. In the subsequent discussions, these sub-watersheds will be termed as SW1 to SW9.The location of each sub-watershed is depicted in Fig. 2. The drainage networks of the nine sub-watersheds have been analyzed as per Horton's (1945) laws in ArcHydro module of ArcGIS. All sub-watersheds have been examined from all dimensional aspects i.e., linear aspect indicates one dimensional view of the watershed, aerial aspect shows two dimensional, while relief aspect explored three dimensional characteristics of the watersheds. Linear aspect comprises the study of stream order (N_u), stream length (L), and bifurcation ratio (R_b), whereas aerial aspect deals with drainage density (D_d), stream frequency (F_s), texture (T), form factor (R_f), circularity ratio (R_c), elongation ratio (R_e), compactness coefficient (C_c) and length of overland flow (L_o), while total relief (H), relative relief (R_r), relief ratio (R_o) and average slope (S_a) have been explored under the relief aspect of Tawi catchment. The formulae for computation of the morphometric parameters are shown in Table 1.

All thirteen morphological parameters pertaining to the one, two and three dimensional views of the watershed have been calculated for each sub-watershed of Tawi catchment. Keeping in view the nature of relationships (direct/inverse) of different morphological parameters with erodability, each sub-watershed has been ranked 1 to 9 based upon thirteen morphological parameters. Rank 1 indicates most severe, whereas 9 denotes least severe with respect to soil erosion. Final prioritization was worked out by considering all ranks of a particular sub-watershed, which were assigned on the basis of thirteen geomorphological parameters considered in the study. The sub-watershed having lowest

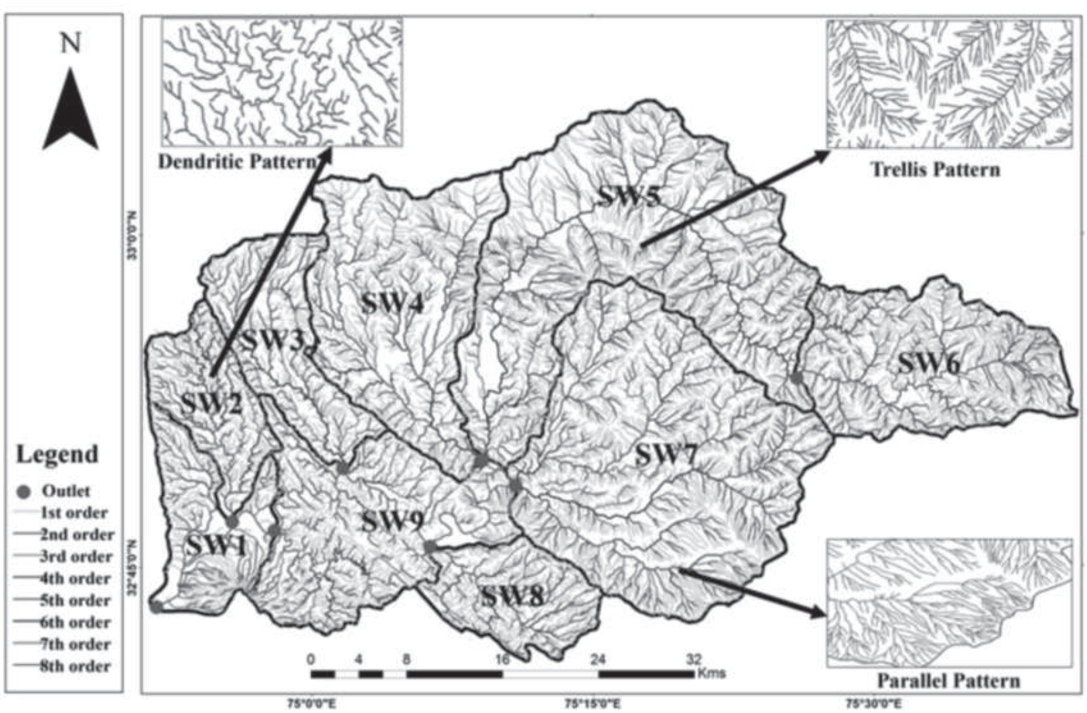

Fig. 2. Delineated sub-watersheds of Tawi catchment and their drainage network according to stream order

Table 1. Different morphometric parameters used in the study and their standard formulae

	Morphometric Parameter	Formula	Reference
Linear	Stream order(u)	Hierarchical rank	Strahler (1964)
	Basin Length(L)	L=1.31*2A0.568 Where L=Basin length (km) A=Area of the basin (km^2)	Nookaratnam *et al.,* (2005)
	Stream length(L_u)	Length of the stream	Horton (1945)
	Bifurcation ratio (R_b)	$R_b=N_u/N_{u+1}$ Where, Rb=Bifurcation ratio Nu=Total no. of stream segments of order 'u', Nu+1=Number of segments of the next higher order	Schumm (1956)
	Mean bifurcation ration (R_{bm})	R_{bm}=Average of bifurcation rations of all orders	Strahler (1957)
Areal	Drainage density (D_d)	$D_d=L_u/A$ where, D_d= drainage density, L_u= total stream length of all, A= Area of the basin	Horton (1945)
	Form factor(R_f)	F_f=A/L2 Where F_f=Form factor A=Area of the basin (km^2) L=Basin length(km)	Horton (1945)
	Stream frequency (F_s)	$F_s=N_u/A$ where, F_s=stream frequency, N_u=total no. of streams of all orders, A=area of the basin	Horton (1945)
	Drainage texture (T)	$T=N_u/L_p$, where N_u=total no. of streams of all orders, L_p=perimeter of th basin	Horton (1945)
	Infiltration number (I)	$I=F_f$ x D_d	Faniran (1968)
	Elongation ratio (R_e)	$R_e=1.128xA^{0.5}/L$ A=area of the basin (km^2) L=basin length (km)	Schumm (1956)
	Circularity ratio (R_c)	$R_c=4\pi A/P2$ Where Rc=circularity ratio A=Area of the basin (km^2) P=Perimeter (km)	Miller (1953), Strahler (1964)
	Rotundity factor (R_t)	$R_t=L^2/4A$ L=basin length, A=basin area	Chorley *et al.* (1957)
	Compactness Coefficient (C_c)	$C_c=0.282L_p/A^{0.5}$, where L_p=perimeter of the basin, A=area of the basin	Horton(1945)
	Length of overland flow (L_o)	$L_o=1/(2XD_d)$, where D_d= drainage density	Horton (1945)
Relief	Total Relief (H)	H= Difference between maximum and minimum elevation of the watershed	Schumm (1956)
	Relative Relief (R_r)	$R_r=H/L_p$ where, H=total relief, L_p=basin perimeter	Schumm (1956)
	Relief Ratio (R_o)	R_o=H/L where, H=total relief, L=basin length	Schumm (1956)

compound index value has given highest severity towards soil erosion and vice-versa.

Estimation of sediment production rate (SPR)

Prioritization discussed in the preceding section is only a qualitative representation of soil erosion severity problem faced by each sub-watershed. However, for planning the amplitude of conservation activities in any watershed, quantitative assessment of soil erosion from the area is indispensable. In the view of non-availability of observed data in the un-gauged watersheds/catchments, the actual estimation of soil erosion is almost impossible using traditional modelling approach. However, in such circumstances an alternative approach using Sediment Production Rate (SPR), which is the volume of sediment produced per unit watershed area per unit time can be implemented to provide quantitative assessment of soil erosion.SPR is normally used in designing of the dead storage of a reservoir and hence imperative to decide the life of the reservoir. Morphological based approach for estimation of probable SPR from a watershed may be preferred in absence of observed sediment data. In the present study, the sediment production rate of different sub-watersheds of Tawi River catchment have been estimated by morphological method suggested by Jose and Das (1982) and is expressed by the following equation:

$$\text{Log (SPR)} = 4919.80 + 48.64 \log (100 + R_t) - 1337.77 \log (100 + R_c) - 1165.64 \log (100 + Cc) \quad (1)$$

where, SPR is sediment production rate in ha-m 100 km^{-2} yr^{-1}, R_t is rotundity factor, R_c is circulatory ratio and Cc is compactness coefficient.

Results and Discussion

The various morphometric parameters of the Tawi catchment estimated in the present study are summarized in Tables 2 to 4. The basic parameters of all the sub-watersheds of Tawi catchment are shown in Table 2 and other parameters pertaining to linear aspects, areal aspects and relief aspects are described in subsequent sections.

Table 2. Basic Parameters of different sub-watersheds of Tawi River Catchment

Sub-watershed name	Basin area (km^2)	Perimeter (km)	Basin length (km)
SW1	108.4	62.4	18.78
SW2	97	49.55	17.63
SW3	137	62.83	21.42
SW4	276.3	83.64	31.96
SW5	487	128.5	44.10
SW6	230	70.6	28.80
SW7	483	94.89	43.89
SW8	104.1	47.25	18.36
SW9	238	88.5	29.36

Linear aspects

Linear aspect i.e. number and length of different streams ordered streams and corresponding bifurcation ratios are given in Table 3.

Stream ordering

Stream ordering is the first step to extract the geomorphological parameters of a catchment. Tawi catchment was adjudged as eighth order basin according to the Strahler (1964) hierarchical rank. The drainage map with stream order of the Tawi catchment is shown in Figure 2. As the stream order increases the total number of streams decreases as suggested by Strahler (1957) and shown in Table 3. The drainage pattern of an area reflects the nature of slope, geological structure and lithologic controls of the underlying rocks (Nag and Chakraborty 2003). Study area comprises three kind of drainage pattern viz., trellis, parallel and dentritic. In trellis type drainage pattern primary or secondary tributaries meet the main stream at near right angle. Such patterns are developed in the areas of folded sedimentary rocks of various resistances to erosion. In sub-watersheds SW5 and SW6, trellis is the dominant drainage pattern. However, in SW7, SW3 and SW1, parallel drainage pattern is the dominant drainage pattern. In parallel drainage system primary and secondary stream flow

Table 3. Extracted streams of different orders and their bifurcation ratios

SW	Parameter	Stream order								Mean bifurcation ratio (R_{bm})
		I	II	III	IV	V	VI	VII	VIII	
SW1	No. of Stream	370	75	18	3	2	0	0	1	4.15
	Stream Length(km)	197.9	71.2	50.1	8.0	5.2	0.0	0.0	17.8	
	Bifurcation ratio	4.93	4.2	6.0	1.50	-	-	-	-	
SW2	No. of Stream	369	81	18	6	1	0	0	0	4.51
	Stream Length(km)	189.4	64.6	34.1	37.8	20.7	0	0	0	
	Bifurcation ratio	4.6	4.5	3.0	6.0	-	-	-	-	
SW3	No. of Stream	418	96	19	7	2	1	0	0	3.52
	Stream Length(km)	236.8	86.4	46.5	24.0	9.6	13.6	0.0	0.0	
	Bifurcation ratio	4.4	5.05	2.71	3.5	2.0	-	-	-	
SW 4	No. of Stream	709	158	37	9	3	1	0	0	3.77
	Stream Length(km)	484.1	144.9	83.5	34.4	28.9	10.5	0.0	0.0	
	Bifurcation ratio	4.49	4.27	4.11	3.00	3.00	-	-	-	
SW 5	No. of Stream	1809	363	74	19	3	1	0	0	4.62
	Stream Length(km)	1051.3	276.4	126.2	61.7	8.2	61.9	0.0	0.0	
	Bifurcation ratio	4.98	4.90	3.89	6.33	3.0	-	-	-	
SW 6	No. of Stream	1110	207	45	11	2	1	0	0	4.31
	Stream Length(km)	617.4	139.2	71.0	43.9	29.6	0.9	0.0	0.0	
	Bifurcation ratio	5.36	4.6	4.09	5.5	2.0	-	-	-	
SW 7	No. of Stream	1849	370	84	20	6	2	1	0	3.66
	Stream Length(km)	1072.3	290.5	143.8	56.7	58.0	24.1	0.2		
	Bifurcation ratio	4.99	4.40	4.2	3.33	3.0	2.0	-	-	
SW 8	No. of Stream	446	89	24	8	1	0	0	0	4.92
	Stream Length(km)	239.9	60.0	42.7	27.1	13.1	0.0	0.0	0.0	
	Bifurcation ratio	5.01	3.7	3.0	8.0	-	-	-	-	
SW 9	No. of Stream	881	183	44	11	2	3	2	1	3.23
	Stream Length(km)	462.6	139.9	96.9	41.1	9.8	0.4	5.9	41.8	
	Bifurcation ratio	4.81	4.15	4.0	5.5	0.66	1.5	2.0	-	

parallel to each other and meet main channel at about same angle. Such drainage pattern is controlled by the regional slopes and normally starts from the water divide of the watershed. However, dentritic drainage pattern is found frequently in SW4, SW2 SW8 and SW9 sub-watersheds and some parts of other sub-watersheds. Dendritic type of drainage pattern reflects the homogeneity in texture, rock and lack of structural control.

Stream length

Streams of various orders in all sub-watersheds were counted and their lengths from mouth to drainage divide were measured with the help of GIS software and depicted in Table 3. Generally, the total lengths of stream segments are highest in first order streams and decreases as the stream order increases (Table 3). It can be observed from Table 3 that the number and length of first order streams in SW5, SW6 and SW7 sub-watersheds are proportionately higher as compared to other sub-watersheds. This can be attributed to the lithology of the underlying surface and local converging terrain, which facilitates quick conversion of rainfall into runoff and eventually early formation of drainage network (Singh and Singh, 1997).

Bifurcation ratio (R_b)

It is the ratio of the number of streams of given order u to the number of streams of next higher order u+1. In general, lower value of R_b is characteristic of watershed that has suffered less structural disturbances and whose drainage pattern has not been distorted by structural disturbances (Nag and Chakroborty, 2003). Abnormally high value of R_b might be expected in regions of steeply dipping rock strata. The value of R_b is also indicative of shape of the basin. An elongated basin is likely to have high R_b, where as a circular basin is likely to have a low R_b. In the study area, the values of R_b are in the middle range and vary from 3.0 to 5.0 (Table 3). The minimum and maximum values were found to be 3.23 and 4.93 for watershed SW9 and SW8, respectively. In general, it can be seen from Table 3, that the bifurcation ratios between the first and second order streams are higher than the higher order streams in all sub-watersheds, indicating that the catchment falls under areas of active gullies and ravines, hence prone to higher erosion rates.

Areal aspects

Areal aspects include different morphometric parameters, like drainage density (D_d), stream frequency (F_s), drainage texture (T), form factor (R_f), infiltration number (I), circulatory ratio (R_c), elongation ratio (R_e) and length of the overland flow (L_o) and compactness coefficient (C_c). The values of these parameters were calculated and results are given in Table 4.

Drainage density (D_d)

Drainage density is one of the important indicators of the areal scale of landform in stream eroded topography, and is defined as the ratio of total length of the streams of all order of basin to the area of basin. It is affected by the density of vegetation and geology of the area and hence it indicates the balance between the erosive power of overland flow and the resistance of surface soils and rocks. Drainage basin with high D_d indicates that a large proportion of the precipitation runs off. The drainage density, expressed in km km^{-2}, indicates closeness of spacing of channels, thus providing a quantitative measure of the average length of stream channel for the whole basin. Further, it also gives an idea of the physical properties of the underlying rocks. Low drainage density occurs in regions of highly resistant and permeable subsoil materials with dense vegetation and low relief, whereas high drainage density is prevalent in region of weak, impermeable sub-surface material which is sparsely vegetated and has high relief (Strahler 1964). Drainage density in the study area varies between 2.84 (SW4) and 3.92 (SW6) indicating medium to high drainage density (Table 4). High drainage density in SW6 sub-watershed may be resultant of weak or impermeable subsurface material, high mountainous relief and fine drainage texture. However, low drainage density in SW4, SW1 and SW3 sub-watersheds indicate areas of highly resistant or permeable subsoil material, low relief and coarse drainage texture.

Table 4. Aerial aspects of the Tawi River Catchment

SW	D_d (km km^{-2})	F_s (no. km^{-2})	I	R_c	R_f	R_e	T	L_o (m)	C_c
SW1	3.232	4.328	13.99	0.350	0.307	0.626	7.516	155	1.69
SW2	3.576	4.901	17.53	0.496	0.312	0.630	9.586	140	1.42
SW3	3.054	3.977	12.15	0.434	0.298	0.616	8.643	164	1.52
SW4	2.846	3.318	9.44	0.496	0.270	0.587	10.964	176	1.42
SW5	3.257	4.660	15.18	0.370	0.250	0.565	17.653	154	1.64
SW6	3.923	5.984	23.48	0.579	0.277	0.594	19.489	127	1.31
SW7	3.407	4.828	16.45	0.674	0.251	0.565	24.575	147	1.22
SW8	3.675	5.454	20.05	0.586	0.309	0.627	12.020	136	1.31
SW9	3.356	4.737	15.89	0.382	0.276	0.593	12.735	149	1.62

Stream frequency /drainage frequency (F_s)

Stream frequency is the number of streams per unit area of the basin. It mainly depends upon the lithology of the basin and reflects the texture of the drainage network. Stream frequency of the sub-watersheds varies from 3.32 to 5.98. Sub-watersheds SW6 and SW8 are associated with high stream frequency, while sub-watersheds SW4 and SW3 have low stream frequency. Drainage density and stream frequency are similar measures of stream network of a drainage basin. Table 4 shows close correlation between drainage frequency and drainage density indicating the increase in stream population with respect to increase in drainage density.

Drainage texture

Horton (1945) defined drainage texture as the total number of stream segments of all orders in a basin per perimeter length of the basin. It is important to geomorphology as it deals with the relative spacing of drainage lines. Drainage texture depends on the underlying lithology, infiltration capacity and relief aspect of the terrain. The drainage texture of all the nine sub-watersheds varied from coarse to very fine. The sub-watersheds located in the downstream part of the Tawi catchment (SW1, SW2, SW3, SW4 and SW9) comprises of coarse drainage texture; however, sub-watersheds of upstream part or hilly region (SW5, SW6 and SW8) have moderate to very fine texture. The finer the texture, more will be the dissection of the watershed, which will lead to higher erosion rates. Several studies (Reddy, 2004; Jaiswal and Krishnamurthy *et al.,* 2007) revealed that a watershed associated with high drainage density, stream frequency and texture ratio is normally prone to severe soil erosion. So, in case of ranking of sub-watershed for conservation prioritization based on morphometric parameters, the sub-watersheds having higher drainage density, stream frequency and fine texture were given the top ranks.

Form factor (R_f)

It is a dimensionless property and is used as a quantitative expression of the shape of basin form. The values of form factor of the studied sub-watersheds are between 0.2 and 0.3. According to the values of form factor SW5, SW7 and SW4 sub-watersheds are relatively more elongated with lower values of form factor. However, SW2, SW8 and SW1 are having relatively less elongated shape and so have higher values of form factor. The basins with high form factors, have high peak flows of shorter duration, whereas elongated drainage basin with low form factors have lower peak flow of longer duration.

Infiltration number (I)

The infiltration number is defined as the product of drainage density (D_d) and drainage frequency (F_s). Sub-watershed SW4 has the lowest infiltration number 9.44 and the SW6 has the highest infiltration number of 23.48. Higher the infiltration number, lower will be the infiltration and consequently, higher will be the runoff. It gives an idea about the infiltration characteristics which play vital role in transformation of rainfall into the runoff. High value of infiltration number in SW6 and SW8 reveal that these sub-watersheds may have impermeable lithology and higher relief.

Circularity ratio (R_c)

The circularity ratio is a similar measure as elongation ratio, originally defined by Miller (1953), as the ratio of the area of the basin to the area of the circle having same circumference as the basin perimeter. The value of circularity ratio varies from 0 (in line) to 1 (in a circle). The circularity ratio for all sub-watersheds is in the range of 0.35 to 0.67. It is clear from the Fig. 2 that SW5 is elongated and hence attributed to low value of circularity ratio (0.37), however, SW7 is circular in nature and associated with higher value of circularity ratio (0.674).

Elongation ratio (R_e)

It is defined as the ratio between the diameter of a circle with the same area that of the basin to the maximum length of the basin. The elongation ratio ranges from 0.0 to 1.0 over a wide variety of climatic and geological environments. High value (nearing 1) of elongation ratio is typical of regions of low relief, whereas low values are generally associated with strong relief and steep ground slopes. In Tawi catchment area, SW4, SW5, SW6, SW7 are having high relief (consisting high average slope) and hence associated with low values of elongation ratio. Elongated basin with high bifurcation ratio like SW5 yields a low but extended peak flow (Verstappen, 1983).

Length of overland flow (L_o)

The term length of overland flow is used to describe the length of flow of water over the ground before it becomes concentrated in definite stream channels. Horton (1945) expressed it as equal to half of the reciprocal of drainage density (D_d). This factor relates inversely to the average slope of the channel and is synonymous with the length of sheet flow to a large degree. Overland flow lengths range from 127 meters to 176 meters in Tawi sub-watersheds. SW6 has highest relief among all sub-watersheds and hence has lowest length of overland flow i.e. 127 meters. However, if the value of overland flow is smaller, the surface runoff will quickly enter the streams having well developed drainage network and higher slope. In such watersheds a significant amount of surface runoff will be contributed to the stream discharge for even a low amount of rainfall.

Compactness coefficient (C_c)

Compactness coefficient is used to express the relationship of a hydrologic basin with that of a circular basin having the same area as the hydrologic basin. A circular basin is the most hazardous from a drainage stand point because it will yield the shortest time of concentration before peak flow occurs in the basin. The values of C_c in the nine sub-watersheds of Tawi catchment varies from 1.22 to 1.69. It can be seen from Fig 2 that SW7 is almost circular in shape, which tends to have a low value of compactness coefficient (close to unity). However, SW1, SW5, SW9 have higher values of Cc due to their elongated shape.

Relief aspect

Relief aspects of drainage basin relate to the three dimensional features of the basin involving area, volume and altitude of vertical dimension of landforms wherein different morphometric methods are used to analyze terrain characteristics. Many landscape processes are driven by gravity and relief and so, are frequently used as indicators of erosion potential and denudation rates. In this study, relief aspect includes the analysis of total relief, relief ratio, relative relief and average slope of all nine sub-watersheds of the Tawi catchment (Table 5).

Total relief (H)

It is the maximum vertical distance between the lowest and highest point of the watershed. It is also known as maximum watershed relief. Watershed relief controls the gradient of drainage lines within the watershed and hence significantly influences the soil erosion of the watershed (Patton *et al.,* 1988; Ozdemir and Bird, 2009). SW5, SW6, and SW7 are characterized by high relief i.e. 2737 m, 2704 m, 2157 m, respectively and SW3, SW4, SW8 and SW9 display medium relief i.e. 1469 m, 1967 m, 1215 m and 1012 m, respectively. However, SW1 and SW2 are characterized by low relief i.e. 457 m and 561 m, respectively. Most of the watersheds display high relief and hence are severely prone to generation of significant runoff and consequent soil erosion.

Relief ratio (R_o)

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 (Schumm 1956). The advantage of relief ratio over the total watershed relief is that it removes the size effect by dividing the total relief by the basin length. In Tawi catchment, relief ratio varies from 19.19 m km^{-1} (SW2) to 82.74 m km^{-1} (SW6) (Table 5). Significantly high relief ratio especially in SW6 indicates the steepness of the principal flow path, which eventually eroded the bank of the stream.

Table 5. Relief aspect of the Tawi River catchment

SW	H (m)	R_o (m km^{-1})	R_r (m km^{-1})	S_a (%)
SW1	457	19.55	7.32	10.35
SW2	561	19.19	11.32	15.38
SW 3	1469	51.17	23.38	19.37
SW4	1967	61.87	23.52	24.05
SW5	2737	42.21	21.30	35.16
SW6	2704	82.74	38.30	44.44
SW7	2157	68.19	22.73	30.77
SW8	1215	61.21	25.71	20.23
SW9	1012	0.022	0.011	20.33

Relative relief (R_r)

It is the ratio of the maximum watershed relief to the perimeter of the watershed. The relative relief represents actual variation of altitude in a unit area with respect to its local base level. It means that the steeper the slope the higher is the surface above its base. The values of the relative reliefs for 9 sub-watersheds of Tawi catchment varies from 7.32 m km^{-1} to 38.3 m km^{-1}, indicating the terrain of Tawi catchment is highly undulating. Very high values of R_r for SW6 sub-watershed indicates that it is highly susceptible to soil erosion.

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 more the slope, more will be the erosion, if other factors remain unchanged. The average slope for different sub-watersheds varies between 10.35% (SW1) to 44.44% (SW6). It was observed that high relief ratio and relative relief sub-watersheds were characterized by high slopes and vice versa.

Prioritization of sub-watersheds using morphological parameters

For prioritization, all nine sub-watersheds were ranked based on their corresponding values of morphological parameters. Morphological parameters like drainage density, stream frequency, bifurcation ratio, infiltration number and texture ratio have direct relationship with erosivity. Therefore, the sub-watershed having highest numerical value of these individual parameters was ranked first, and next higher sub-watershed was ranked second and so on. Similarly, aerial parameters like elongation ratio, circularity ratio, form factor and compactness coefficient have inverse relationship with erosivity. Therefore, the sub-watershed having lowest value for these individual parameters was assigned first rank and next lower was second and so on. Similarly, sub-watersheds were ranked according to relief aspect as it had direct relationship with the erosivity. Finally, based on all individual ranking, a compound rank (CR) value was calculated for each sub-watershed and is depicted in Table 6. It is evident that SW6 has the first priority (lowest value of CR value i.e. 2.3) and SW1 has the least priority (highest value of CR value i.e. 7.2). The highest priority indicates the greater degree of erosion in the particular sub-watershed and it becomes a potential candidate for applying soil conservation measures. Thus in order to check soil erosion, treatment has to be started from SW6 and then to others depending on their priority. The priority map of Tawi catchment is shown in Figure 3.

Estimation of sediment production rate (SPR) using morphological parameters

The prioritization of sub-watershed discussed in the previous section only highlights the conservation ranking of each sub-watershed based on qualitative severity of soil erosion problem. However, in actual conservation planning and execution activity, the quantitative assessment of soil erosion is an indispensable input. In developing countries, most of the hilly catchments prone to sever soil erosion rates are un-gauged. The quantification of soil erosion from a watershed/catchment using traditional models will not be possible without observed field data. To overcome this limitation, in the present study Sediment production rates (SPR) of various sub-watersheds were estimated using Eq 1. The values of SPR for each sub-watershed are tabulated in Table 6. The highest SPR value of 3.07 ha-m 100 km^{-2} yr^{-1} for SW6 indicates that the sub-watershed produces significant amount of sediment load

Table 6. Prioritization of Sub-watersheds of Tawi catchment according to morphological parameters (CR: Compound rank, FR: Final rank, SPR: Sediment production rate)

SW	Ranking based on individual morphological parameter													CR	FR	SPR
	R_b	D_d	F_s	I	R_c	R_f	R_e	T	C_c	H	R_h	R_r	S_a			(t ha^{-1} yr^{-1})
SW1	5	7	7	7	1	7	7	9	9	8	8	9	9	7.2	9	0.82
SW2	3	3	3	3	5	9	9	7	6	9	9	8	8	6.3	8	2.62
SW 3	8	8	8	8	4	6	6	8	4	5	5	4	7	6.2	7	1.98
SW4	6	9	9	9	6	3	3	6	5	4	3	3	4	5.4	5	2.78
SW5	2	6	6	6	2	1	5	3	8	1	6	6	2	4.2	3	1.18
SW6	4	1	1	1	7	5	1	2	3	2	1	1	1	2.3	1	3.07
SW7	7	4	4	4	9	2	2	1	1	3	2	5	3	3.6	2	2.75
SW8	1	2	2	2	8	8	8	5	2	6	4	2	6	4.3	4	2.93
SW9	9	5	5	5	3	4	4	4	7	7	7	7	5	5.5	6	1.29

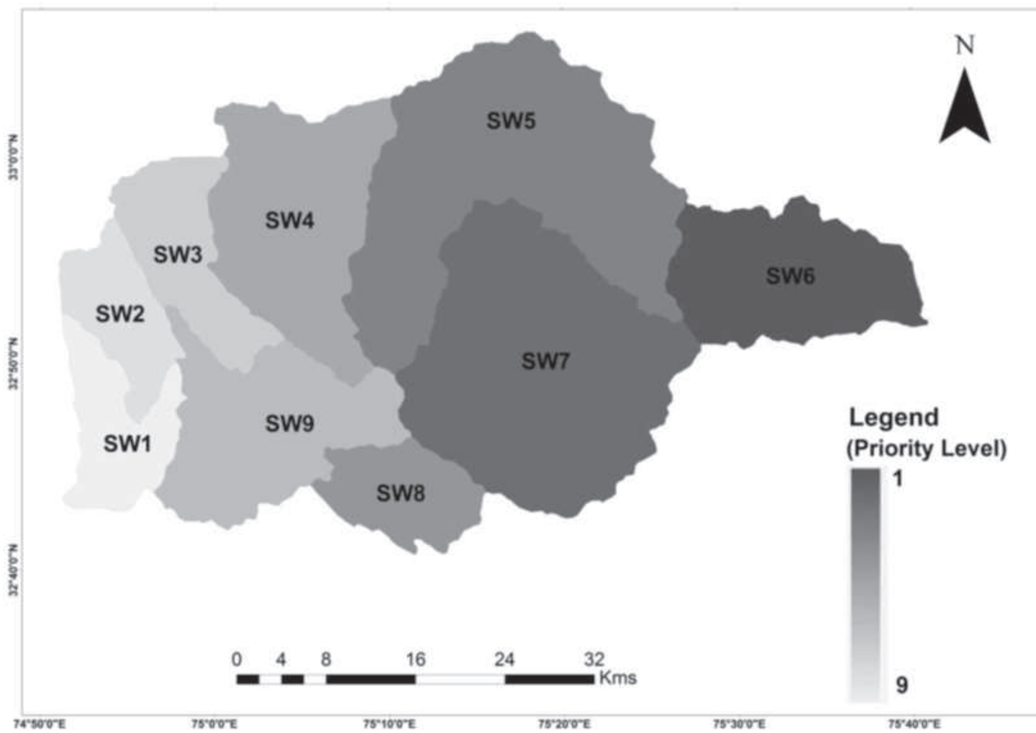

Fig. 3 Sub-watershed wise priority map of Tawi catchment

annually. Estimated SPR value is also close to the design SPR values (4.3 ha-m 100 km^{-2} yr^{-1}) for major river valley projects in Western Himalayan region viz. Beas in Himachal Pradesh, Bhakra-Nagal on Satluj in Punjab and Ramganga in Uttarakhand. It was found that the SPRs estimated for different sub-watersheds using Eq.1 are in general agreement with the priority as listed in Table 6. Compound rank (CR) assigned to each sub-watershed represents the susceptibility of sub-watershed towards soil erosion considering linear, areal and relief aspects of the catchment via various morphological parameters. However, SPR calculated in this study for an un-gauged catchment will not only play a key role in fixing the priority of sub-watershed but also will be a vital inputs in deciding the volume of the conservation measures to be applied to curtail soil loss from the watershed. Moreover, priority classification based on standardized SPR gave a better distribution of sub-watersheds between various priority categories.

Conclusions

Prioritization is to be the first and primary step for any watershed management and planning project. The success of such projects depends upon the accuracy in prioritization process. In developing countries like India where availability of observed data is a major constraint, to prepare a fruitful project plan, the morphological parameters based methodology as discussed in this paper has high practical utility. This study does not only consider the potential application of morphological parameters in identification of the areas susceptible to soil erosion but also estimate the amplitude of the erosion within the catchment. Hydrological response and consequent soil erosion characteristics of a western Himalayan catchment have been discussed using the morphological parameters as extracted in GIS environment. Besides, dendritic drainage pattern, a common drainage pattern in Himalayan areas, existence of trellis drainage pattern in some part of Tawi catchment indicates the presence of folded sedimentary rocks that has strong control on the drainage network. However, presence of parallel drainage pattern in some areas of the catchment indicates the dominance of regional slopes.

A moderate to high drainage density and stream frequency indicate moderate to steep slopes and presence of impervious subsurface layers in the sub-watersheds of the Tawi catchment. High total relief, relative relief and relief ratio especially in upstream catchments give less time to infiltrate the storm water into the ground and it immediately turns into runoff. High infiltration number and low overland flow length values calculated from morphological parameters for these particular sub-watersheds in the present study also implies the erosive nature of these sub-watersheds. Hydrologic responses and sediment production rates as evaluated in the present study for different sub-watersheds using morphological parameters suggest that the Tawi catchment produces moderate to high amount of sediments annually and the catchment is characterized by high runoff zone. The proposed methodology for prioritization of a catchment using morphological parameters in GIS environment is easy to use and very useful for an un-gauged catchment. Since most of the data used in the study are freely available, the proposed approach is parsimonious in terms of funds and also time saving. Identifying the criticality of these watersheds using morphological based approach would help in facilitating investment decisions and making best use of the available resources.

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