Catchment delineation and morphometric analysis using geographical information system

Manoj Kumar, Rohitashw Kumar, P. K. Singh, Manjeet Singh, K. K. Yadav and H. K. Mittal

ABSTRACT

The geographical information system (GIS) has emerged as an efficient tool in delineation of drainage patterns of watershed planning and management. The morphometric parameters of basins can address linear, areal and relief aspects. The study deals with the integrated watershed management of Baliya micro-watersheds, located in the Udaipur district of Rajasthan, India. Morphometric analysis in hydrological investigation is an important aspect and it is inevitable in the development and management of drainage basins. The determination of linear, areal and relief parameters indicate fairly good significance. The low value of the bifurcation ratio of 4.19 revealed that the drainage pattern has not been distorted by structural disturbance. The high value of the elongation ratio (0.68) compared to the circulatory ratio (0.27) indicates an elongated shape of the watershed. The high value of drainage density (5.39 km/km^2) and stream frequency (12.32) shows that the region has impermeable subsoil material under poor vegetative cover with a low relief factor. The morphometric parameters of relief ratio (0.041) and relative relief (0.99%) show that the watershed can be treated using GIS techniques to determine the morphometric presence of dendritic drainage pattern, with a view to selecting the soil and water conservation measures and water harvesting.

Key words | delineation, GIS, morphometry, stream frequency, watershed

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INTRODUCTION

The morphometric analysis of a watershed is an essential first step toward the basic understanding of watershed dynamics. Development of a drainage system and the flowing pattern of a water channel over space and time are influenced by several variables such as geology, geomorphology, structural components, soil, and vegetation of the area through which the water flows (Rekha *et al.* 2011). The term watershed applies to a naturally occurring hydrologic unit defined by natural boundaries and characterized by physical, topographic and climatic conditions (Clarke 1996; Kumar *et al.* 2012). It is a land area that contributes runoff to a common point along a single waterway, and is classified on the basis of its geographical area (Javed *et al.* 2011; Aravinda & Balakrishna 2013). For planning and management of a watershed, a proper delineation of it is a prerequisite. Geographical information system (GIS) techniques have already been used for assessing various terrain and morphometric parameters of a drainage basin. GIS provides a flexible environment and a powerful tool for the manipulation and analysis of spatial information, particularly for the future identification and extraction of information for better understanding of watersheds (Vijith & Satheesh 2006; Rekha *et al.* 2011). A watershed can be delineated either through manual methods or through modern GIS methods. The GIS technique is more accurate and less subjective of shape and size of a watershed as compared to conventional methods depending on real use.

Morphometric studies involve different parameters such as area, altitude, shape, size, slope and profiles of the watershed. The morphometric assessment helps to elaborate a hydrological diagnosis in order to predict approximate behavior of a watershed if correctly coupled with geomorphology and geology (Esper 2008; Rekha *et al.* 2011). The hydrological response of a river basin can be interrelated with the physiographic characteristics of the drainage basin, such as size, shape, slope, drainage density, and length of the streams (Gregory & Walling 1973). Watershed prioritization is the ranking of different sub-watersheds

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according to the order in which they have to be taken for treatment and soil conservation measures. Morphometric analysis could be used for prioritization of micro-watersheds by studying different linear and aerial parameters even without the availability of soil maps (Biswas *et al.* 1999). Many researchers have carried out morphometric analysis using remote sensing and GIS techniques (Balakrishna 2008; Mishra & Nagarajan 2010; Ahmad *et al.* 2012; Vandana 2013; Magesh *et al.* 2013). This study represents a better understanding of hydrologic behavior of the watershed parameters.

MATERIALS AND METHODS

Study area

The Baliya watershed is located in Gogunda tehsil of the Udaipur district of Rajasthan, India. The study area lies between 73°20′ and 73°25′E and 24°54′ and 25°01′N. The study area details are depicted on the map summarized in Figure 1. The study area falls in sub-humid Southern Plains and the Aravalli Hills agroclimatic zone IV of Rajasthan where the average annual rainfall is 633 mm. The maximum rainfall is received during the monsoon season (June–September). The distribution of annual rainfall for the last 30 years (1984–2013) is given in Figure 2. It is evident from Figure 2 that rainfall distribution in the monsoon season is uneven and erratic.

The Baliya watershed comprises undulating upland field and hills. The slope of the arable land varies from 1.84 to 15% and the non-arable land slope varies from 16 to 33%. Owing to the lack of irrigation facilities in the area, rains fed farming is a common practice. The total area of the watershed is 1411 ha, of which 346 ha is land under cultivation. The survey of India (SOI) toposheets No. 45 G/08 and 45 H/05 on 1:50,000 scales have been used to delineate the drainage for the morphometric analysis watershed using GIS techniques. The morphometric parameters of the watershed are divided into three categories: linear, areal and relief aspects, which were determined by adopting the method of Horton (1945). A specific framework was developed for delineation of the watershed. Geomorphological analysis was carried out using topographic information, derived from remote sensing information with ArcGIS 10.1. The information required for the study was procured from various sources. Soil information and a soil map of the area at a scale of 1:250,000 was gathered from the Regional Centre of the National Bureau of Soil Survey and Land Use Planning, Udaipur, Rajasthan. Satellite IRS-IC-LISS-III imagery dated 26 March 2009 was used for the analysis of cloud

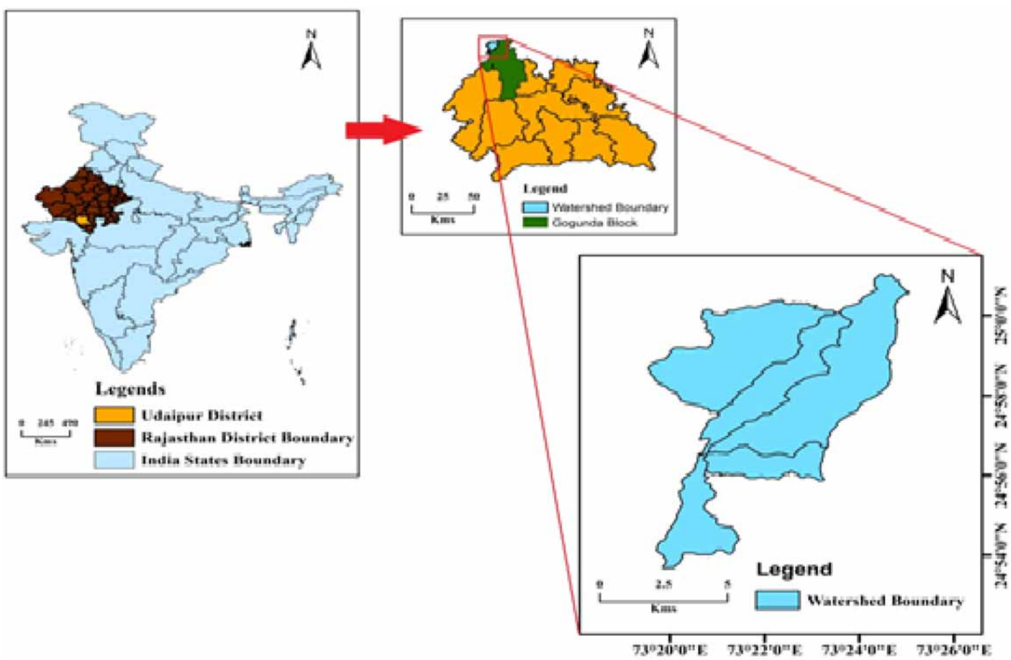

Figure 1 | Location map of the study area.

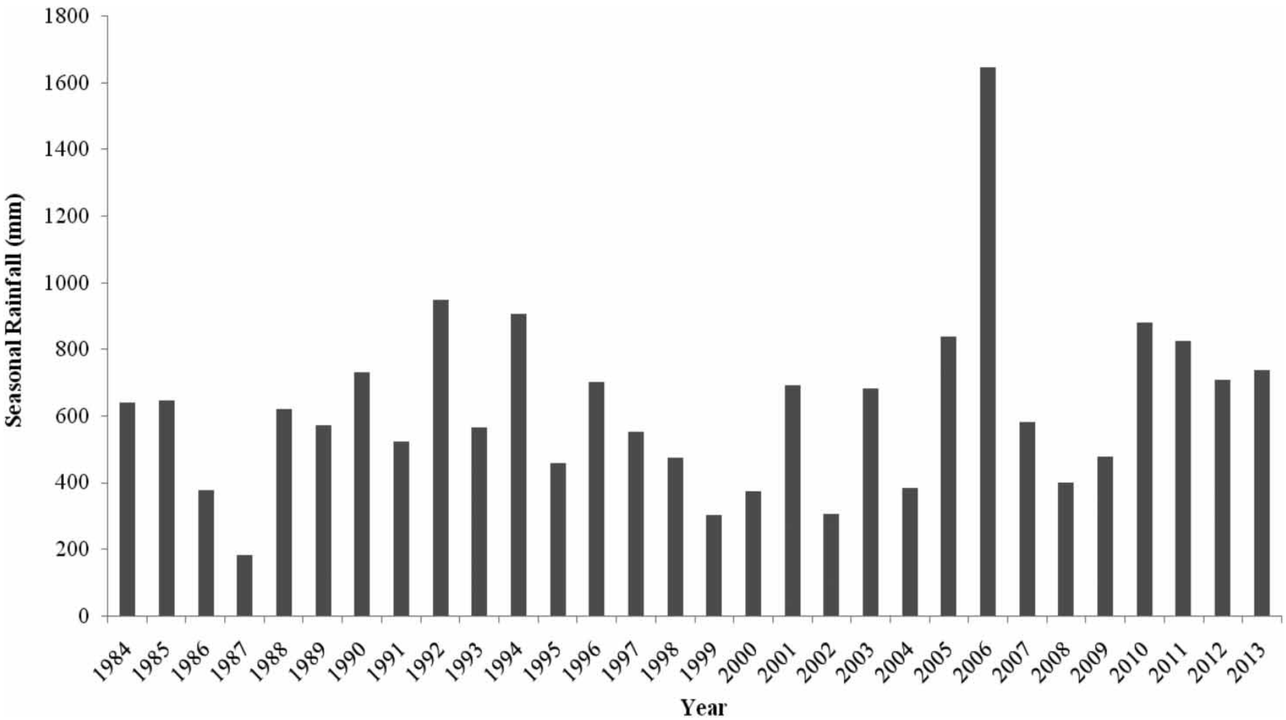

Figure 2 | Distribution of annual rainfall for 30 years (1984–2013).

percentage, atmospheric conditions, and corrections and classifications of image.

The GIS spatial database was composed for thematic information on topography, soil and vegetation. Topography, drainage patterns and soil information were scanned using HP Designjet cc800ps copier image software. The scanned maps were transferred into ArcINFO 10.1 and edited using Arc tools. These edited maps were used for further analysis. The entire base maps were transferred to a common format for further GIS analysis. A digital elevation model (DEM) was created using toposheets. The scanned toposheet was further projected using polyconic methods to determine the geographic coordinates system for 1:1 correspondence with all other maps and a true representation of geographic area and coordinates for accurate assessment of GIS layers. Further, ArcInfo GIS 10.1 contours were digitized and assigned an elevation, and a triangulated irregular network (TIN) was created. The TIN model stores the topological relationship between triangles and their adjacent neighbors. The final step extrapolates the digital contour map into a continuous raster DEM.

For GIS-based digital delineation of the watershed, grid data matrices are required. These are elevation, flow direction, flow accumulation and stream link grids. The elevation grid is the primary input data matrix, which leads to the generation of the remaining three secondary grid data matrices. The elevation grid represents the topography while the others represent the drainage of an area. The elevation grid is represented by DEM, which represents surface terrain. The ArcInfo GIS 10.1 tool was used to delineate watershed boundaries from DEM. The geomorphological analysis was made from the digitized drainage pattern and watershed boundary. Details of the watershed boundary and slope of the catchment are shown in Figure 3. It is shown in Figure 3 that elevation varies between 430 and 940 m. The morphological parameters directly or indirectly affect the runoff and sediment loss. The parameters were evaluated from the toposheet using GIS.

Strahler systems for stream parameters were analyzed in the present study. The Strahler number in morphometric analysis is a numerical measure of the stream's branching complexity. Strahler numbers were first developed in hydrology by Strahler (1952). The Strahler stream order is used to define stream size based on a hierarchy of tributaries. In the application of the Strahler stream order to hydrology, each segment of a stream or river within a river network is treated as a node with the next segment downstream. When two first-order streams come together, they form a

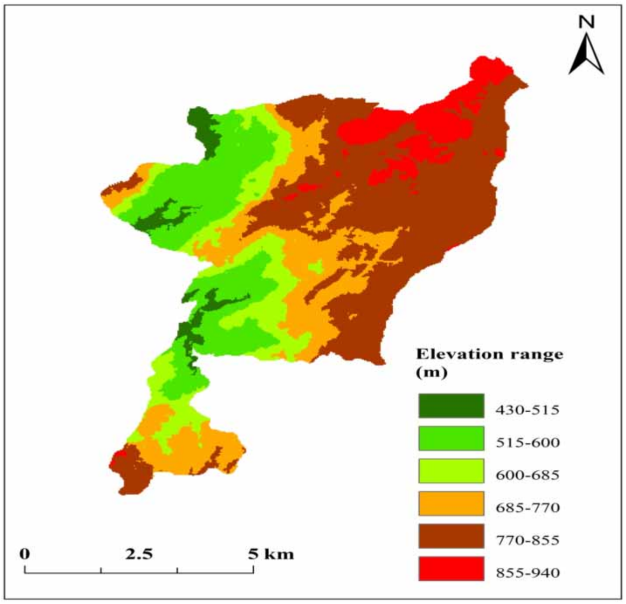

Figure 3 | Topographic map of the study area.

second-order stream. When two second-order streams come together, they form a third-order stream. Streams of lower order joining a higher order stream do not change the order of the higher stream. The methodology used in this study for analysis of morphometry parameters is illustrated in Figure 4. Different input files were derived from GIS techniques. Once these inputs were obtained, the values of different geomorphological parameters were computed using standard methods and formulae which are summarized in Table 1.

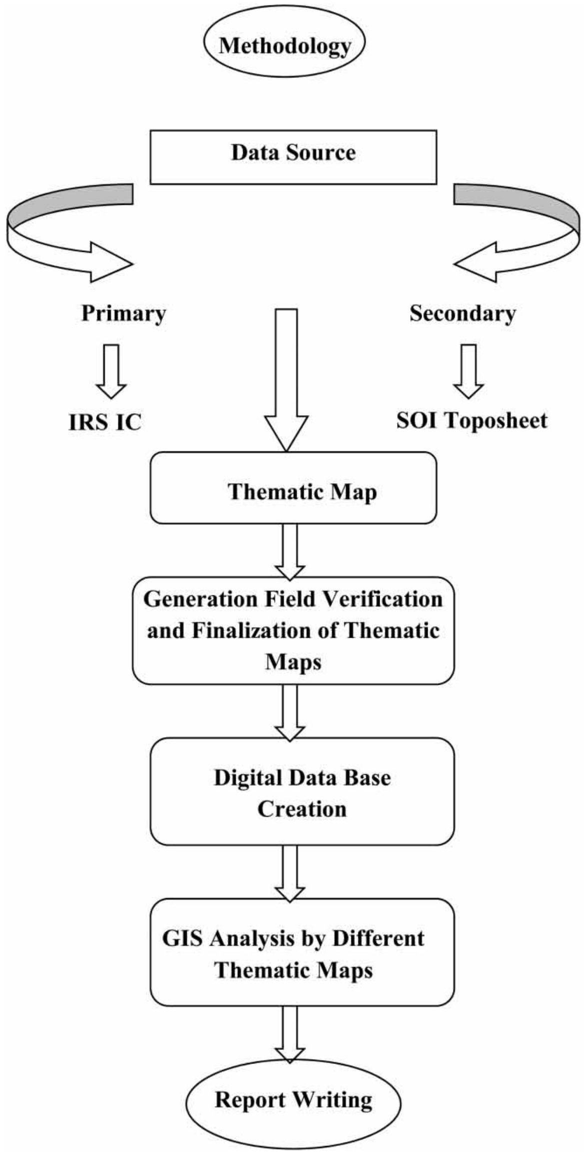

Figure 4 | Flow chart of adopted methodology.

RESULTS AND DISCUSSION

The Baliya watershed was delineated and geomorphological parameters were analyzed using remote sensing and GIS techniques. Different aspects of morphometric parameters were determined. The details of the determined linear, areal and relief parameters are summarized in Table 2. The TIN was generated from a digitized contour map of the study area. According to Horton's law, the plot of the logarithm of number of streams as a function of stream order should yield a set of points lying along a straight line. The graph plotted between log of the number of streams and stream order, shown in Figure 5, satisfies Horton's law. It is evident from Figure 5 that the correlation coefficient of the straight line relationship between log stream order and stream order of the watershed is 0.99, which is within a satisfactory range.

A relationship was also established between the stream order and the cumulative stream length. A graph plotted between logarithm of cumulative stream length and stream order, showing a straight line relationship, is illustrated in Figure 6. It is evident from Figure 6 that the ratio between cumulative stream length and the successive orders of a basin is constant. The correlation coefficient between cumulative stream length and stream order is 0.85, which is quite satisfactory.

Linear aspects of drainage refer to the analysis of stream order, stream number, bifurcation ratio and stream length

Table 1 | Formulae for the computation of morphometric parameters

S. no.	Parameter	Formula	Description
1.	Bifurcation ratio (R_b) (Horton 1945)	$R_b = N_u/N_{u+1}$	N_u = no. of streams of order u; N_{u+1} = no. of streams of order $u+1$
2.	Stream order (Horton 1945)	Hierarchical rank	–
3.	Stream length	$\bar{L}_u = \sum_{i=1}^{N} L_u/N_u$	L_u = length of stream of order u
4.	Stream length ratio (R_L) (Horton 1945)	$R_L = \bar{L}_u/\bar{L}_{u-1}$	$\bar{L}_u$ = average length of stream of order u; $\bar{L}_{u-1}$ = average length of stream of order u–1
5.	Form factor (R_f)	$R_f = A/L_b^2$	L_b = length of basin
6.	Basin shape factor (Horton 1932)	$S_b = L_b^2/A$	
7.	Circulatory ratio (R_c)	$R_c = (A/A_C) = (4A\pi/P^2)$	A_C = area of circle having equal perimeter as the perimeter of watershed; P = perimeter of watershed
8.	Elongation ratio (R_e) (Schumm 1956)	$R_e = (D_{c/}L_{bm}) = ((2\times\sqrt{A/\pi})/L_b)$	D_c = diameter of circle with the same area as the watershed; L_{bm} = mean length of basin
9.	Drainage density (D_d) (Schumm 1956)	$D_d = \sum_{i=1}^{K}\sum_{i=1}^{N} L_u/A$	K = principal order = highest order stream
10.	Constant of channel maintenance (C)	$C = (1/D_d) = (A/\sum_{i=1}^{K}\sum_{i=1}^{N} L_u)$	–
11.	Stream frequency (F)	$F = \left(\sum_{i=1}^{K} N_u/A_k\right)$	A_k = basin area of principal order (K)
12.	Relative relief (R_R)	$R_R = H/L_p \times 100$	H = watershed relief; L_p = length of perimeter
13.	Relief ratio (R_r) (Schumm 1956)	$R_r = H/L_b$	–
14.	Ruggedness number (R_N)	$R_N = H\times D_d$	
15.	Geometric number	G no. $= H\times D_d/S_g$	S_g = slope of ground surface
16.	Time of concentration (T_c)	$T_c = 0.0195\times L^{0.77}\times S^{-0.385}$	L = length of channel reach; S = average slope of the channel reach

ratio. Stream ordering is the first step of quantitative analysis of the drainage basin. The stream ordering was carried out using the Strahler method (Strahler 1964). After analysis of the results it was found that the watershed is of the fifth order type and the drainage pattern was dendrite (Mittal 2002). The number of streams of the first, second, third, fourth and fifth order was 534, 120, 26, 5 and 2, respectively, and their corresponding lengths were 191.50, 53.50, 31.99, 22.50, and 1.22 km, respectively. However, the number of streams of different orders decreases in a regular way with increasing order. The other important parameter is bifurcation ratio (R_b) which reflects the geological and tectonic characteristics of the catchment. The value of R_b was found to be 4.19, which confirms the research of Horton (1945).

Different morphometric parameter values indicate that the watershed has suffered less structural disturbance and the drainage pattern has not been distorted by structural disturbance (Nag & Chakroborty 2003). The average stream length ratio (R_L) estimated was 1.95 and $R_{L1,}$ R_{L2}, R_{L3} and R_{L4} are not close to each other which confirms the property that length ratio varies throughout the successive orders of steam segments in the watershed.

The areal aspects of the watershed give the description of the arrangement of elements, mainly watershed shape which affects stream flow hydrographs and peak flow. The important parameters that describe the shape of the watershed, i.e. form factor, circulatory ratio and elongation ratio, were computed (Table 2). The value of form factor (R_f), circulatory ratio (R_c) and elongation ratio (R_e) were 0.51, 0.27 and 0.68, respectively. The high value of R_e compared to R_c indicates that the watershed is approaching the elongated shape (Singh *et al.* 2003). The elongated watershed with low R_f indicates that the watershed has a flatter peak of flow for longer durations. The flood flow of such an elongated watershed is easier to manage than a circular watershed (Pandey *et al.* 2004).

Drainage density (D_d) and stream frequency are other important characteristics of the watershed. The drainage density of the watershed was 5.39 km/km^2, indicating the closeness of spacing of the channels. The high value of D_d indicates that the region has impermeable subsoil material under poor vegetative cover and watershed relief is low (Strahler 1964). The value of stream frequency was 12.32 per ha indicating that with an increase in stream numbers

Table 2 | Morphometric parameter analysis of the watershed

S. no.	Characteristics	Estimated value
	Linear aspects	
1.	Area	55.78 km^2
2.	Perimeter	51.05 km
3.	No. of streams in stream order	
	I	534
	II	120
	III	26
	IV	5
	V	2
4.	Stream length (L_u)	
	I	191.50 km
	II	53.50 km
	III	31.98 km
	IV	22.50 km
	V	1.22 km
5.	Average stream length	
	I	0.36 km
	II	0.45 km
	III	1.23 km
	IV	4.50 km
	V	0.61 km
6.	Bifurcation ratio (R_b)	
	R_{b1}	4.45
	R_{b2}	4.62
	R_{b3}	5.2
	R_{b4}	2.5
	Average	4.19
7.	Stream length ratio (R_{Lu})	
	R_{L1}	1.25
	R_{L2}	2.73
	R_{L3}	3.66
	R_{L4}	0.14
	Average	1.95
	Areal aspects	
8.	Form factor (R_f)	0.51
9.	Shape factor (S_b)	1.94
10.	Circulatory ratio (R_c)	0.27
11.	Elongation ratio (R_e)	0.68
12.	Drainage density (D_d)	5.39 km/km^2
13.	Stream frequency (F)	12.32 per km^2
14.	Constant of channel maintenance (C)	0.19
15.	Length of overland flow	0.09 km^2/km
	Relief aspects	
16.	Relief	508 m
17.	Relief ratio (R_r)	0.04
18.	Relative relief (R_R)	0.99%
19.	Ruggedness number (R_N)	2.74
20.	Geometric number	7.29
21.	Time of concentration (T_c)	98.10 min

(*continued*)

Table 2 | continued

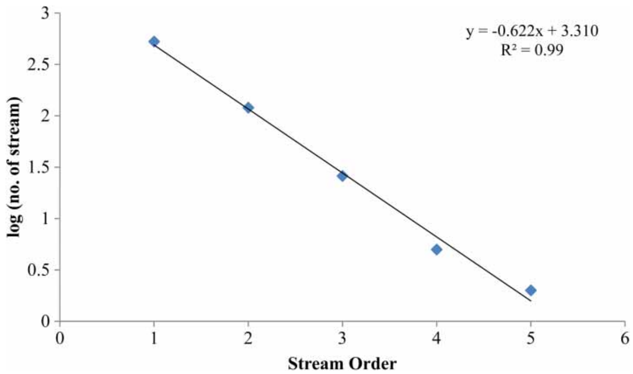

Figure 5 | Regression of logarithm of number of streams and stream order.

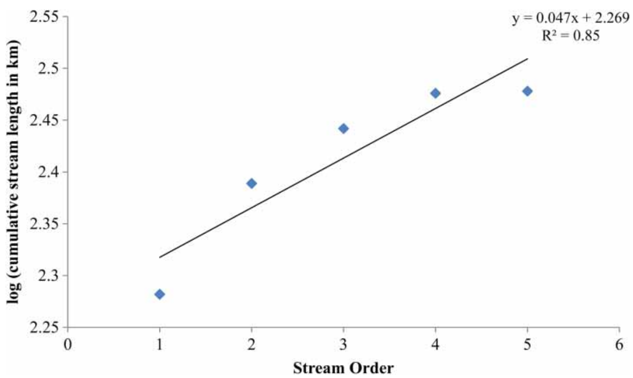

Figure 6 | Regression of logarithm of cumulative stream length and stream order.

there is an increase in drainage density. Further, related to D_d, another morphological characteristic property of the drainage basin is the constant of channel maintenance, which was found to be 0.19 km^2/km for the study area. It indicates the number of square metres of basin surface required to maintain one linear metre of channel.

Watershed relief is an important factor in understanding the denudation characteristics of the sub-watershed. This refers to the analysis of relief aspects of drainage

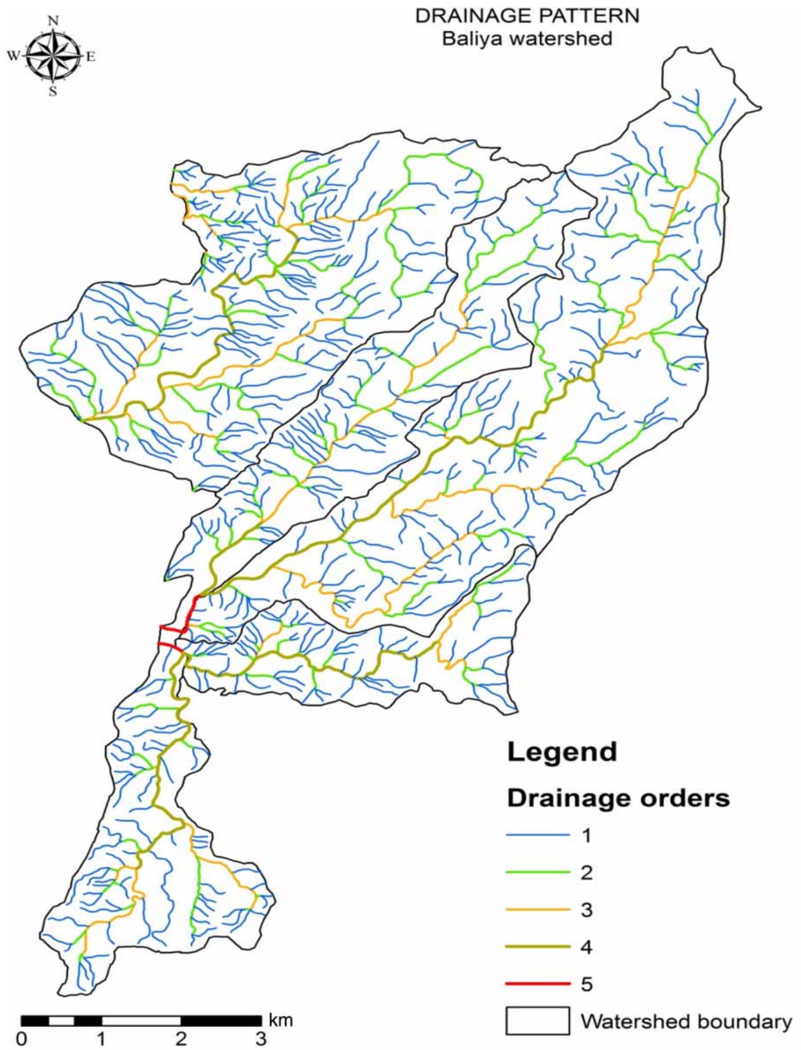

Figure 7 | Drainage pattern of Baliya watershed.

basin and channel networks. The estimated value of relief is 508 m, based on which relief ratio (R_r) and relative relief (R_R) were found to be 0.041 and 0.99, respectively. This indicates that the watershed is at risk of erosion and reflects that the watershed should be treated with soil and water conservation measures. In addition to these properties, ruggedness number and geometric number were computed and the values were found to be 2.74 and 7.29, respectively. It is evident from Table 2 that the low value of the ruggedness number (R_N) represents the gentle slope of the watershed. The drainage pattern and drainage order of the watershed using GIS techniques are shown in Figure 7. It is evident from Figure 7 that the drainage order is 1–5, which indicates that the watershed has higher drainage density.

CONCLUSIONS

The GIS technique has proved to be an accurate and efficient tool in drainage delineation and watershed management. The bifurcation ratio, length ratio and stream order of the basin indicates that the basin is a fourth order basin with a dendritic type of drainage pattern with a homogeneous nature, and there is no structural or tectonic control. Drainage morphometry of a sub-watershed reflects the hydro-geologic maturity of that catchment. Satellite data have the ability to obtain a synoptic view of a large area at one time, which is very useful in analyzing drainage morphometry. A high value of drainage density (5.39 km/km^2) and stream frequency (12.32) shows that the region has impermeable subsoil material under poor vegetative cover with a low relief factor, and the micro-watershed falls into a very high to high priority category based on the water morphometric analysis. Hence, this micro-watershed may be taken for conservation measures by planners and decision makers. Further, the morphometric parameters evaluated using GIS have helped us to understand various terrain parameters such as nature of bedrock, infiltration capacity and surface runoff. The advanced application of GIS techniques has led to the estimation of morphometric analysis based on different parameters, which helps in watershed planning and management.

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