



# Prioritizing sub-watersheds for soil erosion using geospatial techniques based on morphometric and hypsometric analysis: a case study of the Indian Wyra River basin

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Received: 4 February 2023 / Accepted: 14 June 2023 / Published online: 26 June 2023

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## Abstract

The hydrological availability and scarcity of water can be affected by geomorphological processes occurring within a watershed. Hence, it is crucial to perform a quantitative evaluation of the watershed's geometry to determine the impact of such processes on its hydrology. Geographic information systems (GIS) and remote sensing (RS) techniques have become increasingly significant because they enable decision-makers and strategists to make accurate and efficient decisions. To prioritize sub-watersheds within the Wyra watershed, this research employs two methods: morphometric analysis and hypsometric analysis. The watershed was divided into eleven sub-watersheds (SWs). The prioritization of sub-watersheds in the Wyra watershed involved assessing several morphometric parameters, such as relief, linear, and areal features, for each sub-watershed. Furthermore, the importance of the sub-watersheds was determined by computing hypsometric integral (HI) values using the elevation–relief ratio method. The final prioritization of sub-watersheds based on morphometric analysis was determined through the integration of principal component analysis (PCA) and weighted sum approach (WSA). SW2 and SW9 have had higher priorities using morphometric analysis, whereas SW6, SW7, and SW10 have obtained higher priorities using hypsometric analysis. SW4 is the most common SW that shares the same priority. The most vulnerable sub-watersheds are those with the highest priority, and therefore, programmes for soil and water conservation should pay more attention to them. The conclusions of the study may prove useful to various stakeholders involved in initiatives related to watershed development and management.

**Keywords** Morphometric analysis · Water · Hypsometric analysis · GIS · PCA-WSA

## Introduction

Land and water are two of the most valuable and necessary resources for life and various development endeavours (Nookaratnam et al. 2005; Mukta et al. 2022; Kudnar and Rajasekhar 2020; Rendana et al. 2023). Population growth has accelerated over time, leading in a shortage of both land and water assets. Rapid industrialization is also a time need, necessitating infrastructure; this, in turn, generates a feedback mechanism, putting more strain on precious land and water assets. It is appropriate to use the watershed technique to investigate different processes occurring at the surface of the ground, which is an area of the ground where the primary discharge is transferred to a single exit (Pande and Moharir 2017; Pande et al. 2020). Watersheds, or hydrological units, are regarded to be more efficient and appropriate for conducting necessary surveys and investigations, as well

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as planning and implementing various improvement initiatives including water and soil conservation, and assuring their long-term viability (Singha et al. 2022; Poongodi and Venkateswaran 2018; Shekar and Mathew 2022a; Krishnan et al. 2017). Therefore, watershed management should be given special attention to address water-related issues (Pande et al. 2018; Gautam et al. 2023).

A watershed is an area of land where all the water that falls within its boundaries drains or flows downhill into a particular body of water, such as a river, lake, or ocean. Land degradation can have a significant impact on watersheds by altering the natural processes of water flow and nutrient cycling. When land is degraded, such as through deforestation, overgrazing, or soil erosion, it can lead to the loss of vegetation cover and soil fertility, resulting in decreased water infiltration and increased runoff. This can cause erosion, sedimentation, and the degradation of water quality in downstream areas (Rekha et al. 2011; Bhattacharya et al. 2020). Floods are another significant impact of land degradation, particularly in areas with high levels of erosion. Erosion can reduce the capacity of soil to absorb water, leading to increased runoff and higher flood risks (Obeidat et al. 2021). Land-use practices such as conservation tillage, crop rotation, and cover crops, reforestation, and best management practices can mitigate the impacts of land use on soil erosion (Obeidat et al. 2019). Watershed management plans can be developed to guide land-use decisions and prioritize conservation efforts (Choudhari et al. 2018; Pande et al. 2023). The characteristics of a watershed have an effect on hydrological cycle within it, which can be examined using morphometric analysis (Pande et al. 2021a, b; Obeidat and Awawdeh 2021; Awawdeh et al. 2015).

Morphology is the study of the earth's surface using mathematics to describe its topographic reliefs (Abdo et al. 2023; Obi et al. 2002; Clarke 1966; Agarwal 1998). A detailed representation of the structure of a watershed and its stream channel needs the estimation of parameters of the channel system (Strahler 1964). Distinct academics from around the world have conducted morphometric analyses of various river basins on various continents. According to several morphometric researches, watershed morphologies reflect varied geological and geomorphological processes over time (Horton 1945; Strahler 1957).

GIS is a powerful tool used for computerized mapping and geographical analysis, which has advanced capabilities (Awawdeh et al. 2014). One such capability is the use of GIS-based evaluations with satellite image data, such as the Shuttle Radar Topographic Mission (SRTM), that allows for quick and accurate analysis of hydrological systems (Grohmann 2004). GIS techniques have been used to assess different morphometric features of stream watersheds and watersheds because they offer a comfortable workspace

and a useful tool for manipulating and analysing satellite information, especially for future information collection and recognition for a better awareness. The development of RS and GIS has enabled more accurate and affordable morphometric study of natural drains (Shekar and Mathew 2022c; Grohmann et al. 2007; Abdo 2020; Smith and Sandwell 2003; Shelar et al. 2022). Prioritization of watersheds based on morphometric features has also been done, as well as assistance in detecting soil erosion areas (Mishra et al. 2011; Sharma and Mahajan 2020; Wakode et al. 2011). Many researchers studied watershed prioritization based on morphometric parameters (Shekar and Mathew 2023a, 2023b; Kushwaha et al. 2022; Javed and Khanday 2011; Magalhaes et al. 2022; Abdo et al. 2023; Redvan and Mustafa 2021; Gupta et al. 2020; Javed et al. 2009; Esin and Akgul 2021; Mathew et al. 2022; Bogale 2021; Singh et al. 2021; Rais and Javed 2014; Sreedevi et al. 2005; Mathew and Shekar 2023; Jasmin and Mallikarjuna 2013; Lopez-Perez and Fernandez-Reynoso 2021; Sutradhar and Mondal 2023; Moharir et al. 2021).

The distribution of ground surface cross-sectional areas in respect to elevations is the subject of the hypsometric analysis (Strahler 1952). At different stages of erosion, it is utilized to define erosional landforms (Schumm 1956). Langbein (1947) was the first to establish the concept of hypsometry, which aided in the generation of parameters such as the hypsometric curve and hypsometric integral. HC is a relationship between the amount of soil mass in a watershed and the amount of erosion in relation to the watershed's remaining mass (Hurtrez et al. 1999; Ritter et al. 2002). The structure of HC for various drainage watersheds under similar hydrologic conditions can be compared to understand watershed in the past, soil displacement. As a result, the shape of HC describes the temporal variations in the original watershed's slope. According to the shape of the hypsometric curves, Strahler (1952) classified watersheds as young, peneplain, mature. The hypsometric integral can also determine the erosion cycle (Strahler 1952). HI is equivalent to the elevation–relief ratio (E) established by Pike and Wilson when the hypsometric curve is integrated (1971). The numbers from the hypsometric integral cycle erosion of soil show that the old catchment is completely stabilized, in equilibrium, and that it is at risk of soil erosion, while it is in equilibrium. The geologic stages of watershed development are characterized by HI, a geomorphological characteristic. It is significant in determining the erosion state of a watershed (Sharma et al. 2018; Shekar and Mathew 2022b).

In reality, the importance of parameters may vary across different sub-watersheds depending on their specific characteristics. Therefore, the study used two methods—morphometric and hypsometric analysis—to prioritize sub-watersheds for soil erosion management. The study

used several morphometric parameters, to assess the vulnerability of each sub-watershed to soil erosion. On the other hand, hypsometric analysis is based on the elevation data of the sub-watershed and examines the relationship between the area and the elevation range. This analysis helps in understanding the morphological characteristics of the sub-watershed and its hydrological behaviour. In the study, hypsometric analysis was used to determine the degree of erosion susceptibility of the sub-watersheds. Using both methods helps to identify sub-watersheds that have different characteristics and prioritize them based on their specific vulnerabilities to soil erosion. Moreover, these two methods provide a more comprehensive approach to prioritize sub-watersheds for soil erosion management. The objective of the present study is to prioritize sub-watersheds by conducting morphometric and hypsometric analyses of each sub-watershed for soil erosion. The prioritization of sub-watersheds based on morphometric analysis was carried out through the

integration of principal component analysis (PCA) and weighted sum approach (WSA). Furthermore, the study employs morphometric and hypsometric analyses to determine the sub-watersheds that have the priority in common.

### Study area

The Wyra watershed includes Telangana state and Andhra Pradesh. The Wyra River is shown in Fig. 1. The Wyra watershed is situated between the latitudes of 16° 40' 00" and 17° 35' 00" north and the longitudes of 80°05'00" and 80°55'00" east. The outlet of the Wyra watershed is 16° 43' 48" latitudes and 80°19'37" longitudes, respectively. It has an overall area of 3403 Km<sup>2</sup>. The Wyra watershed region experiences a semi-arid climate, characterized by hot summers and mild winters. The region receives most of its rainfall during the monsoon season, which lasts from June to September. Based on Sentinel-2 imagery from 2021,

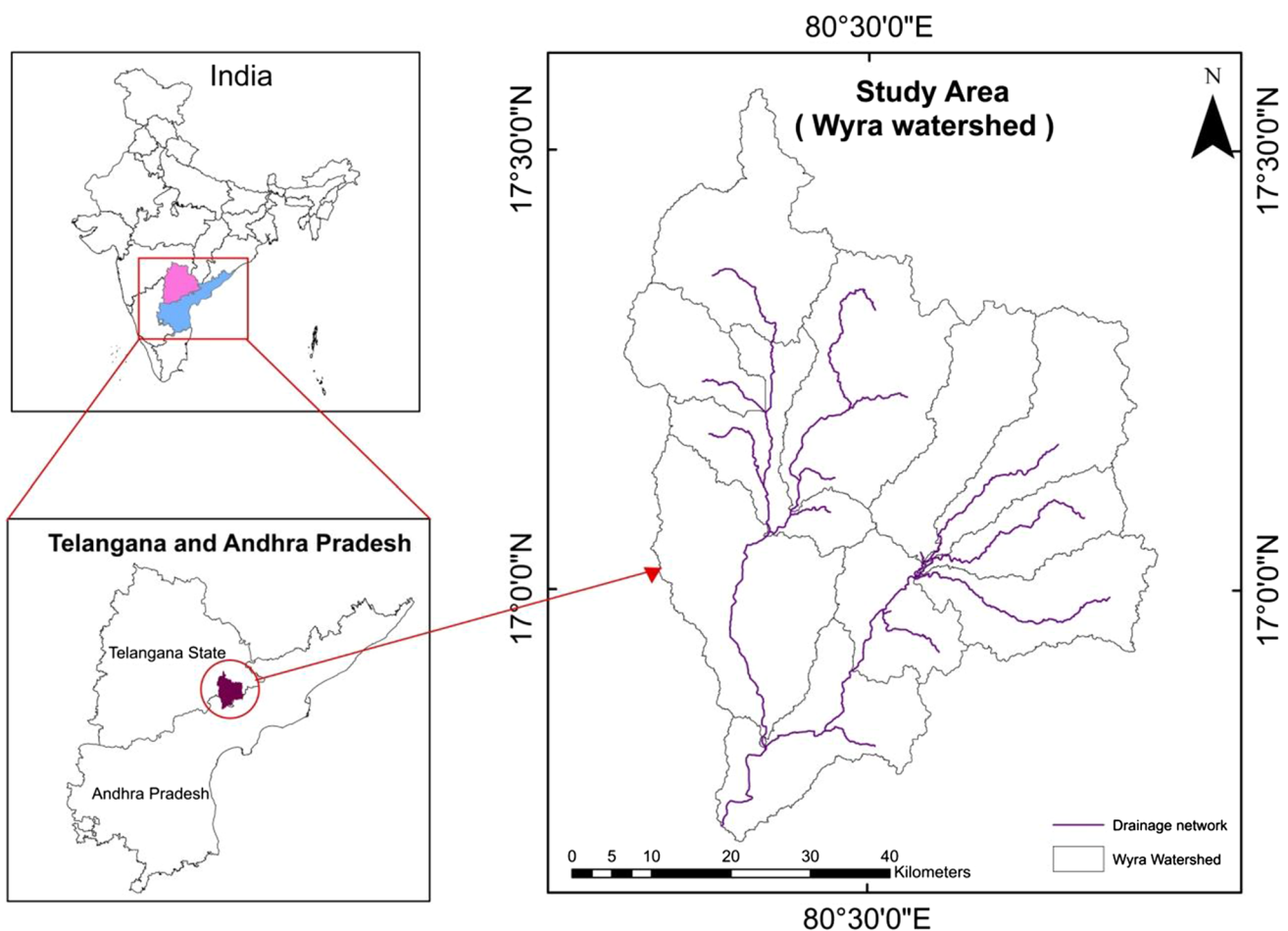
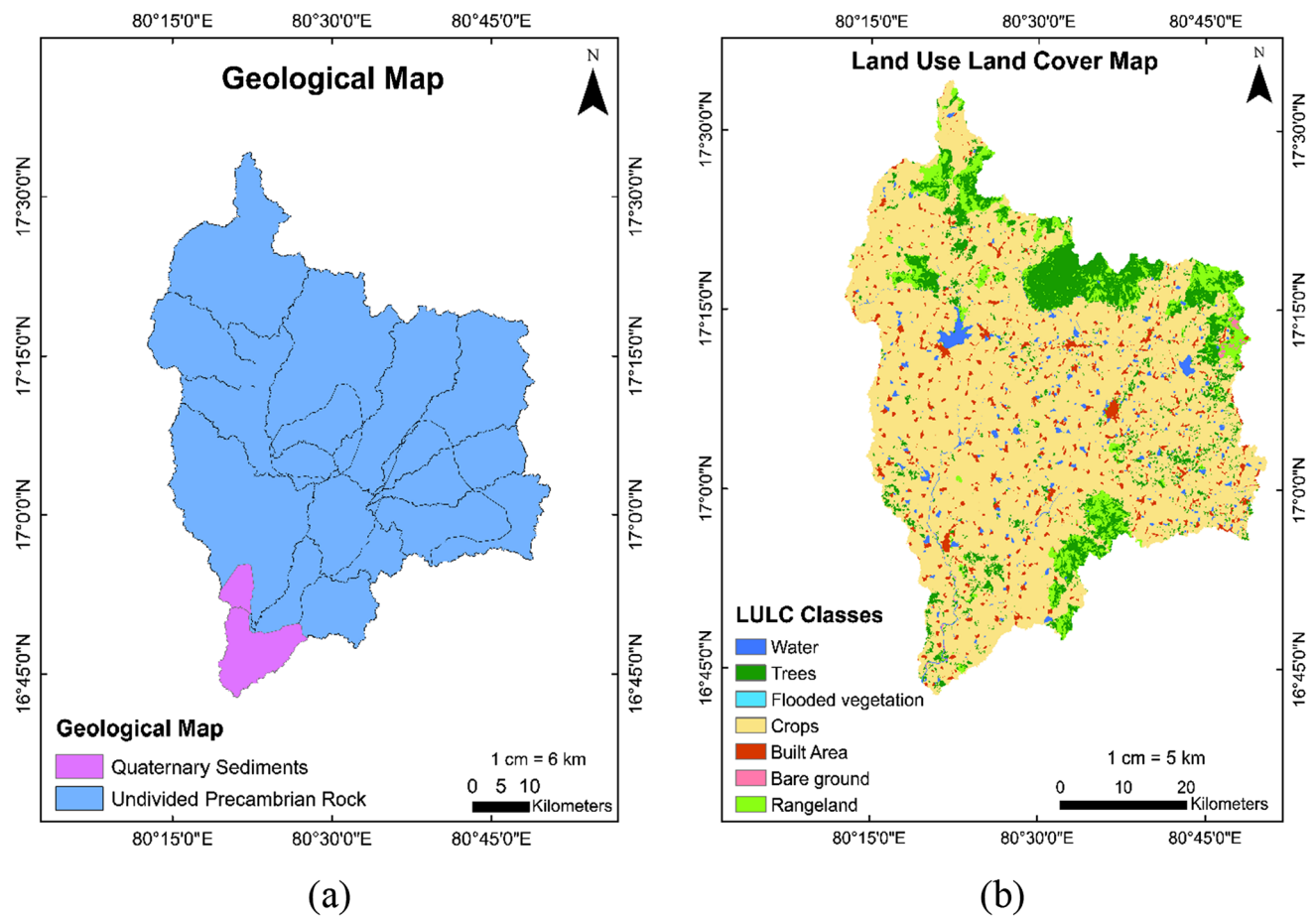


Fig. 1 Wyra River basin's geographical location



**Fig. 2** **a** Geology map of the study area and **b** LULC map of the study area

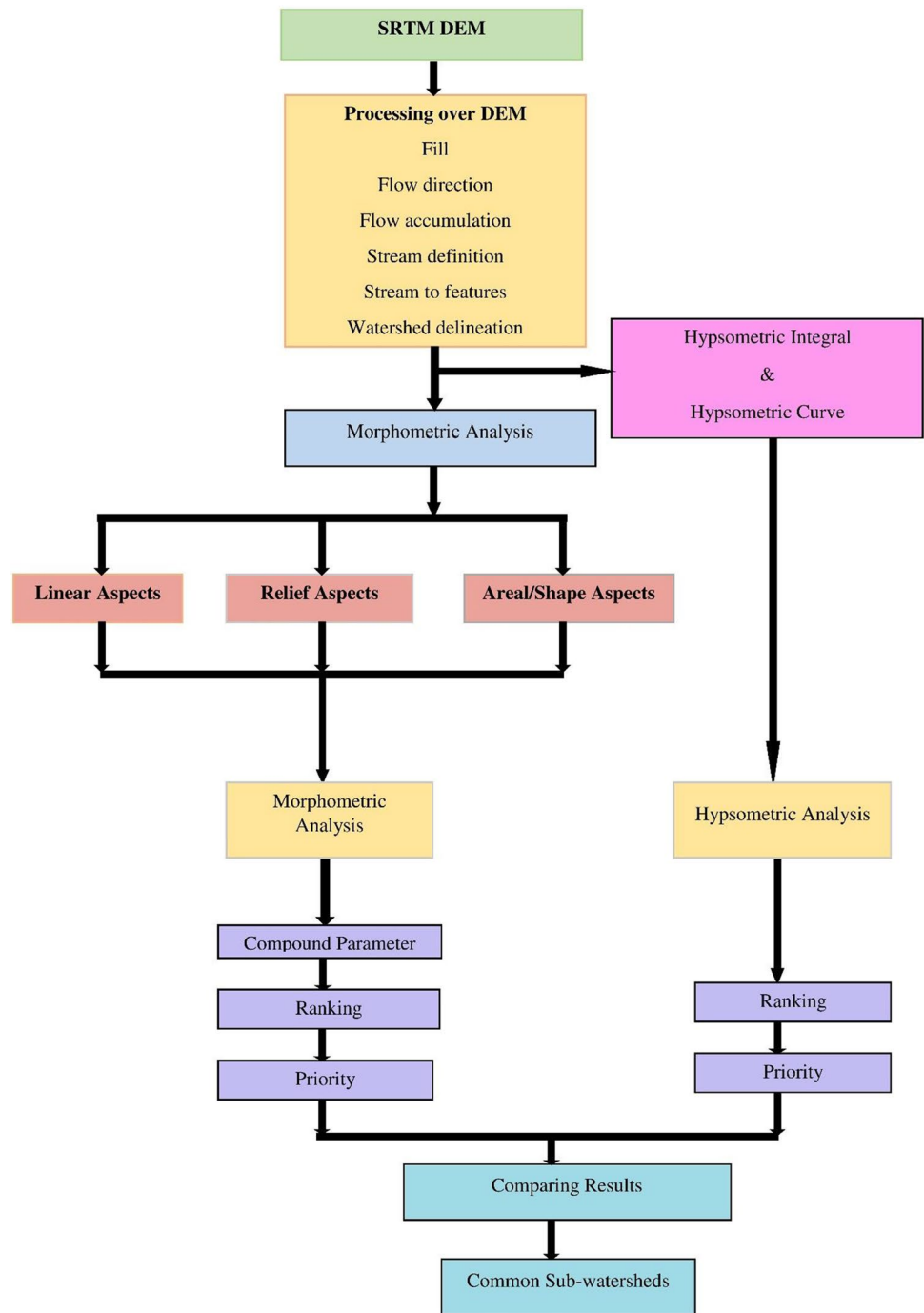
the land-use/land-cover (LULC) data can be classified into the following categories and respective percentages: water (2.38%), trees (11.51%), flooded vegetation (0.01%), crops (75.51%), built area (4.61%), bare ground (0.15%), and rangeland (5.83%) (Fig. 2). This information was obtained from the following source: <https://livingatlas.arcgis.com/landcover/> (Karra et al. 2021). Land use in the basin is dominated by agriculture, with the majority of the land under cultivation. The main crops grown in the basin include paddy, cotton, and pulses. According to the World Geologic Maps of the United States Geological Survey (USGS), the study area has two types of significant rocks. Quaternary sediments and undivided Precambrian are the geological age of two rocks (<https://certmapper.cr.usgs.gov/data/apps/world-maps/>). The Wyra watershed is 33 to 792 m above sea level, according to the digital elevation model (DEM) from SRTM (<https://earthexplorer.usgs.gov/>).

## Methodology

### Morphometric analysis

The current study's methodology includes employing ArcGIS 10.4.1 software to perform automatic extraction procedures for analysing the features of the Wyra watershed. Processing over DEM was calculated to determine the morphometric analysis, as shown in Fig. 3. Sub-watersheds are categorized (SW 1 to SW 11). The relationship between morphometric parameters and soil erosion can be direct or inverse, depending on the specific parameter (Pande et al. 2021a, b; Obeidat et al. 2023). For example, linear parameters such as drainage density, bifurcation ratio, stream length, stream length ratio, stream number, stream order, drainage intensity, mean bifurcation ratio, length of overland flow, mean stream length ratio, stream frequency, constant of channel maintenance, drainage texture, infiltration number, and rho coefficient are directly correlated with soil erosion, as they increase the potential for soil detachment and transport. Similarly, relief

**Fig. 3** Methodology of present study



parameters such as relief, relative relief, maximum elevation, ruggedness number, and minimum elevation can also have a direct correlation with soil erosion, as they influence the amount of water runoff and sediment deposition. On the other hand, shape parameters such as form factor, area of watershed, circulatory ratio, watershed length, compactness coefficient, elongation ratio, perimeter of watershed, lemniscate ratio, and shape index are typically inversely correlated with soil erosion, as they reflect the compactness and irregularity of the landscape. Table 1

provides a list of the many empirical approaches that were employed to identify these characteristics. Table 2 shows the estimated and reported Wyra River basin linear parameters (SW 1 to SW 11). In order of importance, SW with the high preliminary rank (PR) of relief and linear values was ranked first. In order of importance, SW with the low preliminary rank of shape values was ranked first. In this study, principal component analysis (PCA) was utilized to identify the significant parameters for morphometric analysis. As a multivariate statistical technique, PCA is

**Table 1** Formulae are utilized to calculate morphometric parameters

Parameters	Formulae or methods	References
<i>Linear aspects</i>		
Drainage density ( $D_d$ )	$D_d = (\sum L_u)/A$	Schumm (1956)
Bifurcation ratio ( $R_b$ )	$R_b = N_u/N_u + 1$	Strahler (1964)
Stream length ( $L_u$ )	$L_u = L_{u1} + L_{u2} + \dots + L_{un}$	Horton (1945)
Stream length ratio ( $R_l$ )	$R_l = L_u/L_u - 1$	Horton (1945)
Stream number ( $N_u$ )	$N_u = N_{u1} + N_{u2} + \dots + N_{un}$	Horton (1945)
Stream order ( $U$ )	Hierarchical rank	Strahler (1964)
Drainage intensity ( $D_i$ )	$D_i = F_s/D_d$	Faniran (1968)
Mean bifurcation ratio ( $R_{bm}$ )	Average of bifurcation ratio of all orders	Strahler (1957)
Length of overland flow ( $L_o$ )	$L_o = (1/(2D_d))$	Horton (1945)
Mean Stream length ratio ( $R_{lm}$ )	Average of the steam length ratio of all orders	Strahler (1964)
Stream frequency ( $F_s$ )	$F_s = (\sum N_u)/A$	Schumm (1956)
Constant of channel maintenance ( $C_{cm}$ )	$C = 1/D_d$	Schumm (1956)
Drainage texture ( $D_t$ )	$D_t = (\sum N_u)/P$	Schumm (1956)
Infiltration number ( $I_f$ )	$I_f = F_s \times D_d$	Faniran (1968)
Rho coefficient ( $\rho$ )	$R_{lm}/R_{bm}$	Horton (1945)
<i>Relief aspects</i>		
Relief ( $B_h$ )	$B_h = H - h$	Strahler (1952)
Relative relief ( $R_{hp}$ )	$R_{hp} = H \times 100/P$	Melton (1957)
Maximum elevation ( $H$ )	GIS software	
Ruggedness number ( $R_n$ )	$R_n = B_h \times D_d$	Strahler (1954)
Minimum elevation ( $h$ )	GIS software	
<i>Areal/shape aspects</i>		
Form factor ( $F_f$ )	$F_f = (A/Lb^2)$	Horton (1932)
Area of watershed ( $A$ )	GIS software	
Circulatory ratio ( $R_c$ )	$R_c = (4\pi A/P^2)$ , where $\pi = 3.14$	Miller (1953)
Watershed length ( $L_b$ )	$L_b = 1.312 \times A^{0.568}$	Nookaratnam et al. (2005)
Compactness coefficient ( $C_c$ )	$C_c = (P/2(\pi A)^{0.5})$	Horton (1945)
Elongation ratio ( $R_e$ )	$R_e = (2 * (A/\pi)^{0.5})/(L_b)$	Schumm (1956)
Perimeter of watershed ( $P$ )	GIS software	
Lemniscate ratio ( $K$ )	$K = (L_b^2/4A)$	Chorely (1957)
Shape index ( $S_b$ )	$S_b = 1/F_f$	Horton (1932)
<i>Hypsometric analysis</i>		
Elevation-to-relief ratio ( $E$ )	$E = (\text{Mean elevation} - \text{Minimum elevation} / \text{Maximum elevation} - \text{Minimum elevation})$	Pike and Wilson (1971)

employed to reduce the dimensionality of parameters. By converting the original data, PCA generates two or more principal components. The Kaiser criterion and varimax rotation of factor loading were used to select principal components with eigenvalues greater than 1 (Kaiser 1958). In order to enhance the correlation for defining the most significant parameters, a factor loading rotation was executed. Next, a weighted sum approach (WSA) was applied to the most significant parameters obtained from PCA. The final priority ranking and categorization were determined based on the compound values, which were calculated by multiplying the ranks from morphometric analysis with

their corresponding weights obtained through cross-correlation analysis of these parameters. The resulting compound factor was then used for the final prioritization of sub-watersheds. The determination of the weighted value of significant parameters (Wsp) was achieved by means of cross-correlation analysis, as expressed by Aher et al. (2014).

$$CV = PR_{sp} \times W_{sp}$$

where CV = compound value; PR<sub>sp</sub> = preliminary ranking of significant parameter; and W<sub>sp</sub> = weight of significant parameter. For all sub-watersheds, the priority rank was

**Table 2** The basin of the Wyra River’s linear parameters

	Stream order	Stream number	log <sub>10</sub> (Nu)	Stream length	log <sub>10</sub> (Lu)	Bifurcation ratio	Stream length ratio
SW1	1	225	2.35	215	2.33	No	No
	2	49	1.69	109	2.04	4.59	0.51
	3	12	1.08	60	1.78	4.08	0.55
	4	4	0.60	28	1.45	3.00	0.47
	5	1	0.00	15	1.18	4.00	0.54
		$\sum N_u = 291$		$\sum L_u = 427$		$\sum R_b = 15.68$ $\sum R_{bm} = 3.92$	$\sum R_l = 2.06$ $\sum R_{lm} = 0.51$
SW2	1	127	2.10	89	1.95	No	No
	2	27	1.43	52	1.72	4.70	0.58
	3	5	0.70	32	1.51	5.40	0.62
	4	1	0.00	18	1.26	5.00	0.56
		$\sum N_u = 160$		$\sum L_u = 191$		$\sum R_b = 15.10$ $\sum R_{bm} = 5.03$	$\sum R_l = 1.76$ $\sum R_{lm} = 0.59$
SW3	1	288	2.46	283	2.45	No	No
	2	136	2.13	152	2.18	2.12	0.54
	3	17	1.23	68	1.83	8.00	0.45
	4	3	0.48	46	1.66	5.67	0.68
	5	1	0.00	19	1.28	3.00	0.41
		$\sum N_u = 445$		$\sum L_u = 568$		$\sum R_b = 18.78$ $\sum R_{bm} = 4.70$	$\sum R_l = 2.07$ $\sum R_{lm} = 0.52$
SW4	1	156	2.19	150	2.18	No	No
	2	64	1.81	66	1.82	2.44	0.44
	3	9	0.95	26	1.41	7.11	0.39
	4	3	0.48	32	1.51	3.00	1.23
	5	1	0.00	7	0.85	3.00	0.22
		$\sum N_u = 233$		$\sum L_u = 281$		$\sum R_b = 15.55$ $\sum R_{bm} = 3.89$	$\sum R_l = 2.28$ $\sum R_{lm} = 0.57$
SW5	1	171	2.23	182	2.26	No	No
	2	77	1.89	76	1.88	2.22	0.42
	3	8	0.90	45	1.65	9.63	0.59
	4	3	0.48	19	1.28	2.67	0.42
	5	1	0.00	20	1.30	3.00	1.05
		$\sum N_u = 260$		$\sum L_u = 342$		$\sum R_b = 17.51$ $\sum R_{bm} = 4.38$	$\sum R_l = 2.48$ $\sum R_{lm} = 0.62$
SW6	1	97	1.99	140	2.15	No	No
	2	20	1.30	82	1.91	4.85	0.59
	3	4	0.60	30	1.48	5.00	0.37
	4	1	0.00	30	1.48	4	1
		$\sum N_u = 122$		$\sum L_u = 282$		$\sum R_b = 13.85$ $\sum R_{bm} = 4.62$	$\sum R_l = 1.95$ $\sum R_{lm} = 0.65$
SW7	1	102	2.01	98	1.99	No	No
	2	25	1.40	53	1.72	4.08	0.54
	3	4	0.60	21	1.32	6.25	0.40
	4	1	0.00	20	1.30	4	0.95
		$\sum N_u = 132$		$\sum L_u = 192$		$\sum R_b = 14.33$ $\sum R_{bm} = 4.78$	$\sum R_l = 1.89$ $\sum R_{lm} = 0.63$

**Table 2** (continued)

	Stream order	Stream number	log <sub>10</sub> (Nu)	Stream length	log <sub>10</sub> (Lu)	Bifurcation ratio	Stream length ratio
SW8	1	181	2.26	167	2.22	No	No
	2	40	1.60	80	1.90	4.53	0.48
	3	5	0.70	31	1.49	8	0.3875
	4	1	0.00	32	1.51	5	1.03
		$\sum N_u = 227$		$\sum L_u = 310$		$\sum R_b = 17.525$	$\sum R_l = 1.90$
SW9	1	138	2.14	115	2.06	No	No
	2	72	1.86	70	1.85	1.92	0.61
	3	8	0.90	38	1.58	9	0.54
	4	2	0.30	4	0.60	4.00	0.11
	5	1	0.00	10	1.00	2.00	2.50
	$\sum N_u = 221$		$\sum L_u = 237$		$\sum R_b = 16.92$	$\sum R_l = 3.76$	
SW10	1	299	2.48	249	2.40	No	No
	2	141	2.15	143	2.16	2.12	0.57
	3	14	1.15	77	1.89	10.07	0.54
	4	3	0.48	30	1.48	4.67	0.39
	5	1	0.00	18	1.26	3.00	0.60
	$\sum N_u = 458$		$\sum L_u = 517$		$\sum R_b = 19.86$	$\sum R_l = 2.10$	
SW11	1	185	2.27	177	2.25	No	No
	2	94	1.97	94	1.97	1.97	0.53
	3	8	0.90	48	1.68	11.75	0.51
	4	3	0.48	13	1.11	2.67	0.27
	5	1	0.00	9	0.95	3.00	0.69
	$\sum N_u = 291$		$\sum L_u = 341$		$\sum R_b = 19.38$	$\sum R_l = 2.00$	
					$\sum R_{bm} = 4.85$	$\sum R_{lm} = 0.50$	

assigned based on the lowest CV being given priority rank 1, the second lowest being assigned priority rank 2, and so forth. Following this step, the sub-watersheds were grouped into three categories based on their CV values.

### Hypsometric analysis

Hypsometric analysis is a method used to study the topographic relief of a landscape. It involves the analysis of the hypsometric curve, which is a plot of the cumulative area of a region at different elevations. In other words, it shows the proportion of the landscape at different elevations. Hypsometric analysis with a DEM is a powerful tool for understanding the topography and landscape evolution of a region. Hypsometric analysis is widely used in earth

science research, particularly in the fields of geomorphology and hydrology (Pande et al. 2021a, b). To conduct hypsometric analysis with a DEM, the elevations of the region are first extracted from the DEM and sorted into elevation intervals. The area of each interval is then calculated, and the cumulative area and elevation for each interval are plotted on a graph to create a hypsometric curve. SRTM-DEM and ArcGIS 10.4.1 were used to create a hypsometric curve for the Wyra watershed. Using attribute feature classes that take these variables into account, HC for the watersheds under study was plotted. The elevation–relief ratio approach is used to compute the HI values in this study, as shown in Table 1. After obtaining the HI values, divide them into 3 equal intervals to assign ranking, as the SWs were divided into 3 groups. The highest



**Table 3** Results of the Wyra watershed's morphometry

Sl No	Parameters	SW 1	SW 2	SW3	SW 4	SW5	SW 6	SW7	SW8	SW9	SW 10	SW11
1	Stream order	5	4	5	5	5	4	4	4	5	5	5
2	Stream number	291	160	445	233	260	122	132	227	221	458	291
3	Stream length	427	191	568	281	342	282	192	310	237	517	341
4	Bifurcation ratio	15.68	15.10	18.78	15.55	17.51	13.85	14.33	17.53	16.92	19.86	19.38
5	Stream length ratio	2.06	1.76	2.07	2.28	2.48	1.95	1.89	1.90	3.76	2.10	2.00
6	Mean bifurcation ratio	3.92	5.03	4.70	3.89	4.38	4.62	4.78	5.84	4.23	4.96	4.85
7	Mean stream length ratio	0.51	0.59	0.52	0.57	0.62	0.65	0.63	0.63	0.94	0.53	0.50
8	Stream frequency	0.76	0.92	0.92	0.87	0.89	0.37	0.74	0.82	1.08	0.92	0.91
9	Drainage density	1.11	1.10	1.17	1.06	1.17	0.86	1.07	1.12	1.16	1.04	1.07
10	Drainage texture	1.78	1.76	2.59	1.17	1.70	0.74	1.16	1.51	1.97	2.50	1.72
11	Length of overland flow	0.45	0.46	0.43	0.47	0.43	0.58	0.47	0.45	0.43	0.48	0.47
12	Rho coefficient	7.61	8.57	9.06	6.81	7.05	7.10	7.58	9.23	4.50	9.45	9.67
13	Drainage intensity	0.68	0.84	0.78	0.83	0.76	0.43	0.69	0.73	0.93	0.89	0.85
14	Infiltration number	0.84	1.01	1.08	0.92	1.04	0.32	0.79	0.91	1.25	0.96	0.98
15	Constant of channel maintenance	0.90	0.91	0.85	0.95	0.85	1.16	0.93	0.89	0.86	0.96	0.94
16	Maximum elevation	534	381	792	290	555	289	216	443	564	162	460
17	Minimum elevation	99	93	68	64	71	71	69	68	53	41	33
18	Relief	0.44	0.29	0.72	0.23	0.48	0.22	0.15	0.38	0.51	0.12	0.43
19	Relative relief	0.33	0.42	0.46	0.15	0.36	0.17	0.19	0.30	0.50	0.09	0.27
20	Ruggedness number	0.48	0.32	0.85	0.24	0.57	0.19	0.16	0.42	0.59	0.13	0.46
21	Watershed area	383.99	174.19	483.54	266.34	291.98	326.23	178.98	277.33	204.62	497.30	318.96
22	Watershed perimeter	163.24	90.66	172.07	198.80	152.53	165.29	114.07	150.11	112.01	183.38	169.47
23	Basin length	38.53	24.59	43.92	31.30	32.98	35.12	24.98	32.03	26.95	44.63	34.68
24	Circulatory ratio	0.18	0.27	0.21	0.08	0.16	0.15	0.17	0.15	0.20	0.19	0.14
25	Elongation ratio	0.57	0.61	0.57	0.59	0.58	0.58	0.60	0.59	0.60	0.56	0.58
26	Form factor	0.26	0.29	0.25	0.27	0.27	0.26	0.29	0.27	0.28	0.25	0.27
27	Lemniscate ratio	0.97	0.87	1.00	0.92	0.93	0.95	0.87	0.92	0.89	1.00	0.94
28	Shape index	3.87	3.47	3.99	3.68	3.73	3.78	3.49	3.70	3.55	4.01	3.77
29	Compactness coefficient	2.35	1.94	2.21	3.44	2.52	2.58	2.41	2.54	2.21	2.32	2.68

priority is given to the maximum interval values, the next interval values are given a medium priority, and the minimum interval values are given a low priority.

## Results and discussion

Morphological parameters are measurements that describe the shape and form of a landscape. In the context of the Wyra watershed, these parameters were computed using digital elevation models and GIS tools to analyse the topography of the area. Table 3 shows the computed morphological parameters for the Wyra watershed, which are categorized into three aspects: linear, relief, and areal.

### Morphometric analysis

The Wyra drainage watershed's morphometric study offers a quantitative description of the watershed geometry, which makes it easier to understand the geomorphological characteristics of the watershed and its responses to various hydrological processes (Chatterjee and Tantuley 2006). For analysis and discussion, the morphometry of the Wyra watershed is divided into three categories.

#### Linear aspects

**Stream order (U)** The assignment of stream orders based on a hierarchical classification of streams is the first step in drainage watershed study. The approach suggested by Strahler (1964) was used to rate streams in the current study. The watershed's drainage system is dendritic to sub-

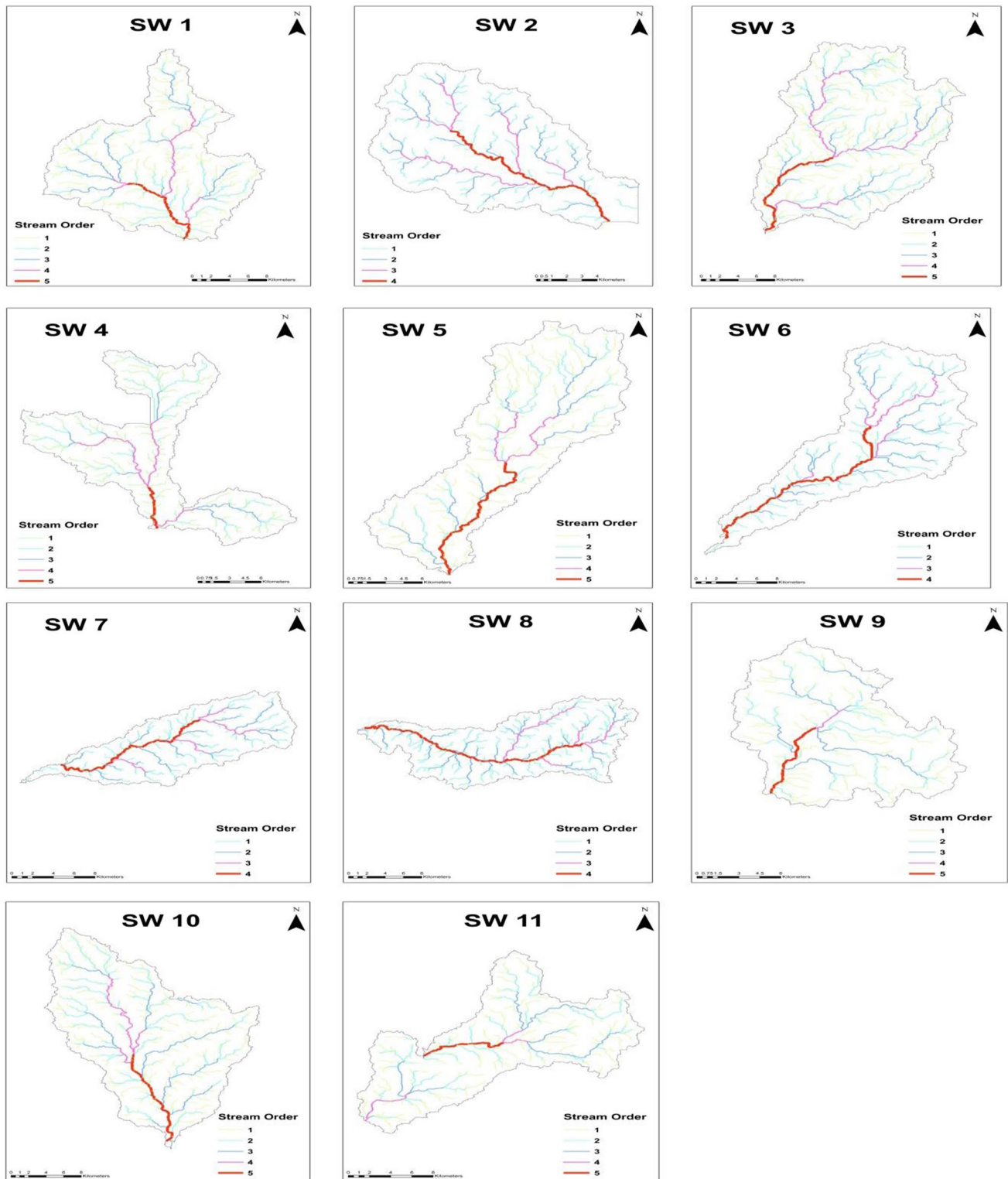


Fig. 4 Sub-watersheds and drainage networks

dendritic. In the Wyra watershed, SW1, SW9, SW3, SW10, SW5, SW11, and SW4 are in fifth-order, while SW6, SW2, SW7, and SW8 are in 4th order, as illustrated in Fig. 4.

**Stream number ( $N_u$ )** It is obvious that there are fewer streams overall when the stream order ( $U$ ) rises. In this

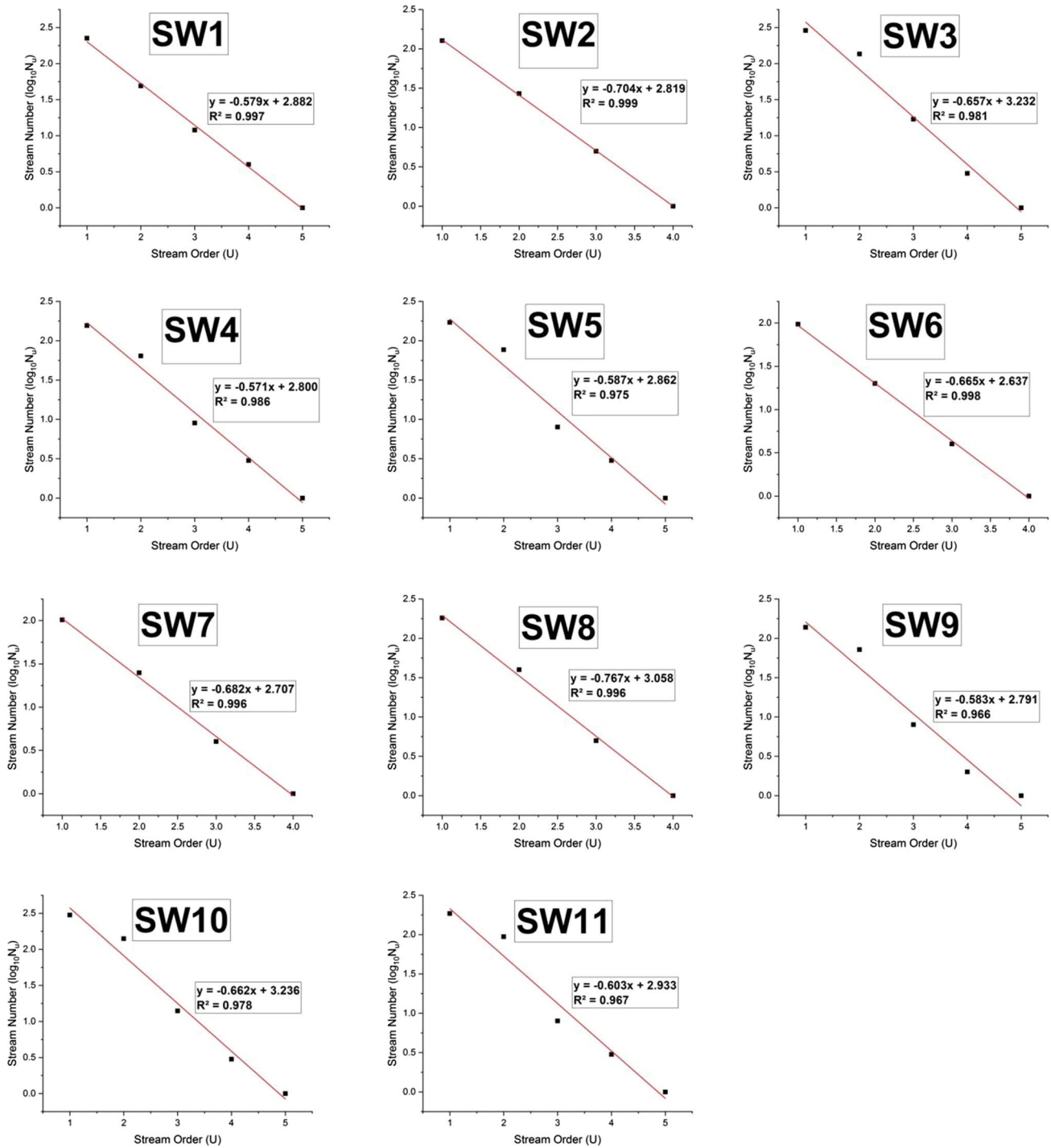


Fig. 5 Stream number and stream order

study, SW10 (458) has a high  $N_u$ , while SW6 (122) has a low  $N_u$ .

**Stream length ( $L_u$ )** Horton’s (1945) law was used to compute the length of the stream. One of a region’s key hydrological features is a stream’s length because it offers information on the characteristics of surface runoff. SW3 (568 km) has a long  $L_u$ , while SW2 (191 km) has a short  $L_u$  in this study.

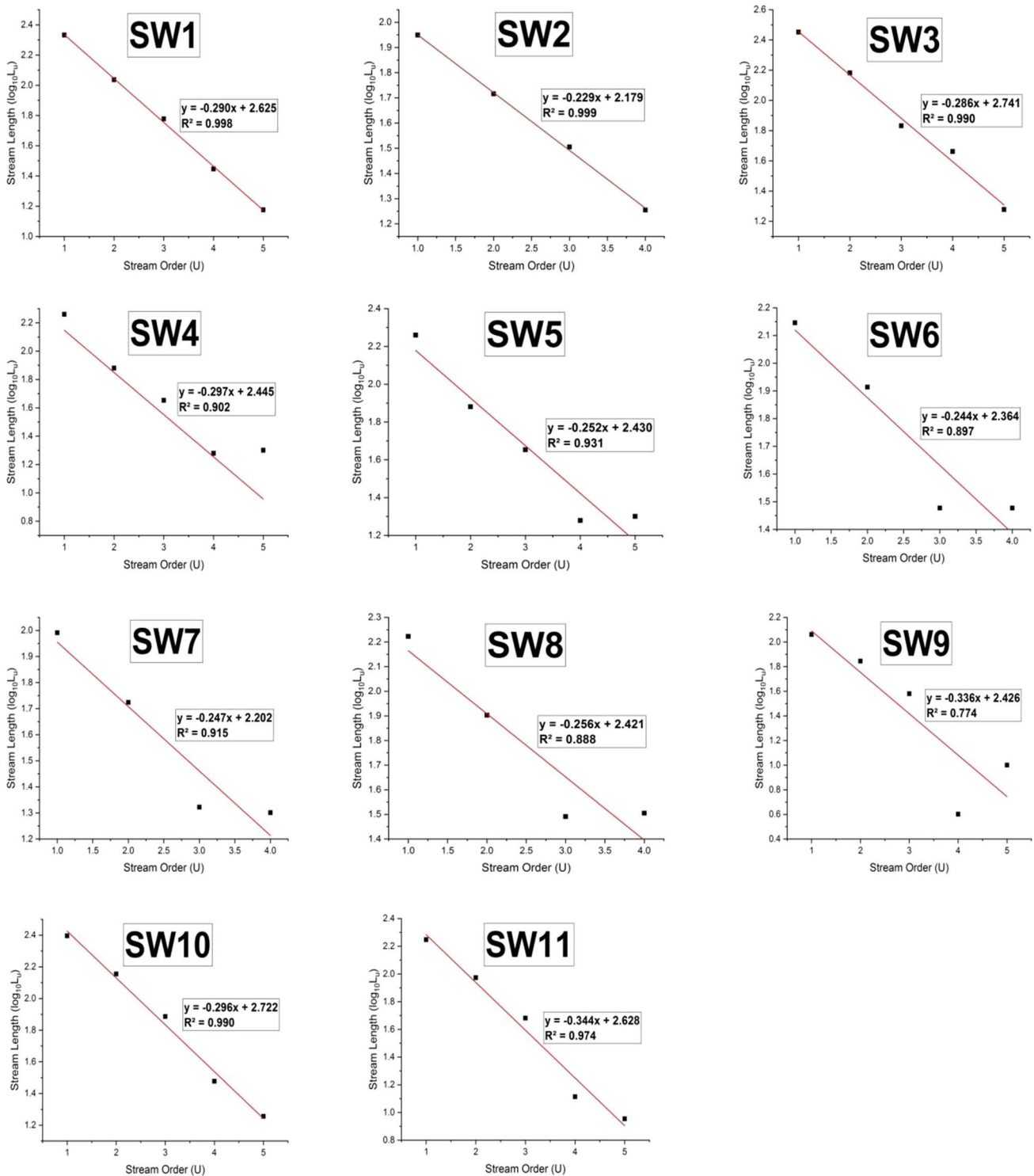


Fig. 6 stream length and stream order

**Bifurcation ratio ( $R_b$ )** It is the proportion of the number of streams in one order to those in the order above it. SW10 (19.86) has a high  $R_b$  in this study, while SW7 (14.33) has a low  $R_b$ .

**Stream length ratio ( $R_l$ )** It is the one order's segment divided by the mean stream length of the lower order segment. In this study, SW9 (3.76) has a high  $R_l$ , whereas SW2 (1.76) has a low  $R_l$ .

Horton (1945) identified two fundamental principles linking the number of distinct orders in a stream catchment and the length of a stream. Figure 5 demonstrates a strong correlation between stream order and stream number, with coefficients of determination in the range of 0.999 for SW2 and 0.966 for SW9. Similarly, Fig. 6 shows a significant correlation between stream order and stream length, with coefficients of determination in the range of 0.999 for SW2 and 0.774 for SW9.

**Stream frequency ( $F_s$ )** The total number of orders' streams in a certain area. SW9 (1.08) has a high  $F_s$  in this study, while SW6 (0.37) has a low  $F_s$ .

**Drainage density ( $D_d$ )** It is the proportion of the total length of all streams in a catchment to its entire area. It is a critical characteristic that is directly related to runoff speed, which is followed by precipitation. In this study, SW3 (1.17) has a high  $D_d$ , while SW6 (0.86) has a low  $D_d$ .

**Drainage texture ( $D_t$ )** One of the essential terms in geomorphology is drainage texture, which refers to the relative spacing of drainage lines. SW3 (2.59) has a high drainage texture in this study, while SW6 (0.74) has a low drainage texture.

**Length of the overland flow ( $L_o$ )** It is equal to half of  $D_d$  (Horton 1945). SW6 (0.58) has a long overland flow, while SW3 (0.43) has a short overland flow in this study.

**Drainage intensity ( $D_i$ )** It is the proportion of  $F_s$  to  $D_d$  (Faniran 1968). SW9 (0.93) has high drainage intensity in this study, while SW6 (4.50) has low drainage intensity.

**Rho coefficient ( $\rho$ )** It is the ratio of stream length to  $R_b$ . SW11 has a high rho coefficient in this study, while SW9 has a low rho coefficient.

**Infiltration number ( $I_f$ )** Faniran (1968) defines it as the result of the interaction between  $D_d$  and  $F_s$ . SW9 (1.25) has a high  $I_f$  in this study, while SW6 (0.32) has a low  $I_f$ .

**Constant of channel maintenance ( $C_{cm}$ )** It was initially proposed by Schumm in 1956, defined it as the inverse of  $D_d$ . SW6 (1.16) has a high  $C_{cm}$  in this study, while SW3 (0.85) has a low  $C_{cm}$ .

Fig. 7 A sub-watershed's areas

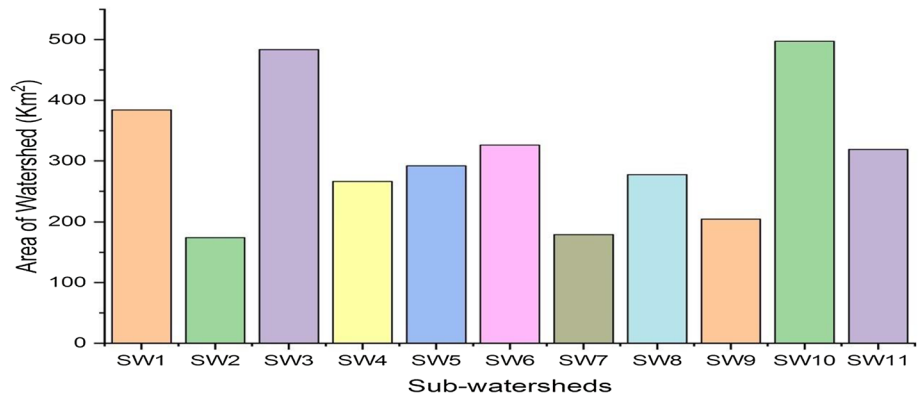
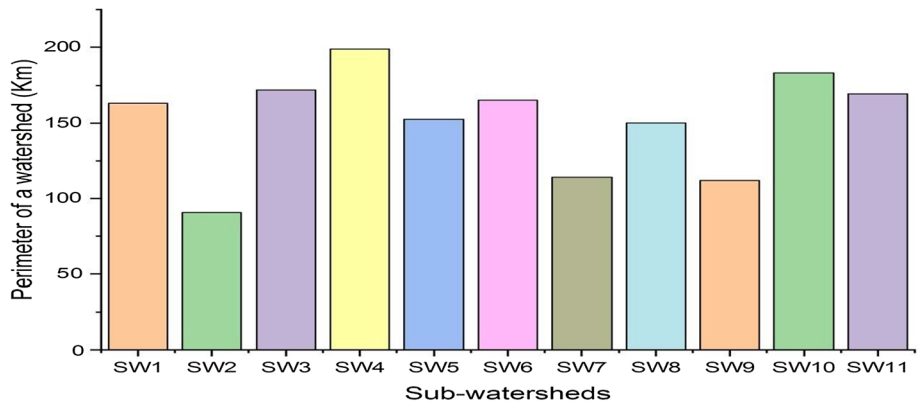
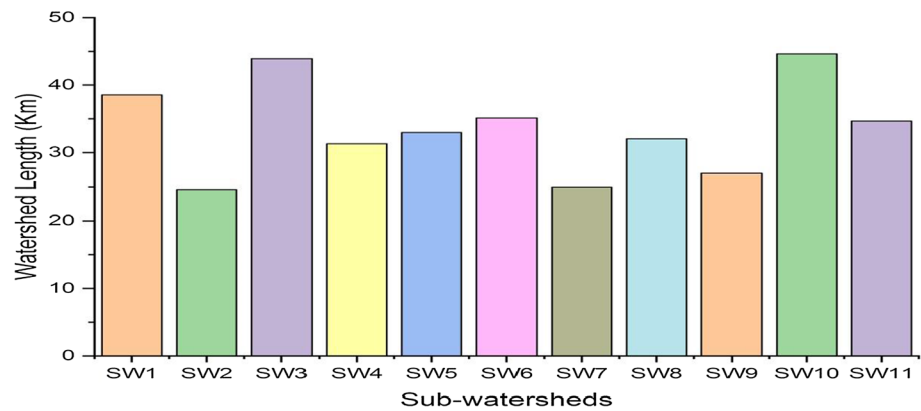


Fig. 8 A sub-watershed's perimeter



**Fig. 9** A sub-watershed's watershed length



### Relief aspects

**Relief ( $B_n$ )** The difference in elevation between the watershed's maximum and minimum elevations is known as a relief. In this study, SW3 (0.72) has a high relief, while SW10 (0.12) has a low relief.

**Relative relief ( $R_{hp}$ )** From the highest point on the catchment's border to the stream's mouth, the greatest amount of watershed relief was attained. In this study, SW9 (0.50) has a high relative relief, while SW10 (0.09) has a low relative relief.

**Ruggedness ratio ( $R_n$ )** The product of the watershed relief and  $D_d$  is the ruggedness number. In this study, SW3 (0.85) has a high ruggedness ratio, while SW10 (0.59) has a low ruggedness ratio.

### Areal aspects

**Area of watershed ( $A$ )** The amount of runoff a catchment generates is directly influenced by the watershed region. A total area of 3403 km<sup>2</sup> is covered by the watershed. SW10 (497.30 Km<sup>2</sup>) has a large watershed area, while SW2 (174.19 Km<sup>2</sup>) has a small area in this study, as shown in Fig. 7.

**Perimeter of a watershed ( $P$ )** The watershed perimeter is the outer limit of the catchment that defines its area. SW4 (198.80 km) has a large watershed perimeter, while SW2 (172.07 km) has a small watershed perimeter in this study, as shown in Fig. 8.

**Watershed length ( $L_b$ )** Among the fundamental dimensions of the main drainage channel, the catchment length is the most crucial. SW10 (44.63 km) has a large watershed length, while SW2 (24.59 km) has a small watershed length in this study, as shown in Fig. 9.

**Circulatory ratio ( $R_c$ )** It is the ratio of the area of the watershed to the surface area of a circle whose circumference equals the area of the catchment. In this study, SW2 (0.27) has a high  $R_c$ , while SW4 (0.08) has a low  $R_c$ .

**Elongation ratio ( $R_e$ )** According to Schumm (1965), it is the ratio of the diameter of a circle with the same area of the watershed to the maximum watershed length. In this current research, SW2 (0.61) has a high  $R_e$ , while SW10 (0.56) has a low  $R_e$ .

**Form factor ( $F_f$ )** According to Horton (1932), it is the ratio of catchment area to the square of catchment length. In this current research, SW10 (0.29) has a high  $F_f$ , while SW2 (0.25) has a low  $F_f$ .

**Lemniscate ratio ( $K$ )** Chorely et al. (1957) uses lemniscate's value to calculate the catchment's gradient. In this study, SW10 (1.0) has a high  $K$ , while SW2 (0.87) has a low  $K$ .

**Compactness coefficient ( $C_c$ )** Horton (1945) defined the compactness coefficient as the ratio of the catchment's perimeter to that of a comparable circular region. In this study, SW4 (3.44) has a high  $C_c$ , while SW2 (1.94) has a low  $C_c$ .

**Shape index ( $S_b$ )** The reciprocal of  $F_f$  is the shape index. Horton was the one who first recommended it (1932). In this study, SW10 (4.01) has a high shape index, while SW2 (3.47) has a low shape index, as shown in Fig. 10.

### Sub-watersheds prioritization of morphometric analysis based on PCA-WSA

The nineteen morphometric features representing linear, shape, and relief aspects were utilized to select sub-watersheds for soil conservation. Since soil erosion is directly correlated with the relief and linear features, rank one is given a higher value. However, because soil erosion is indirectly

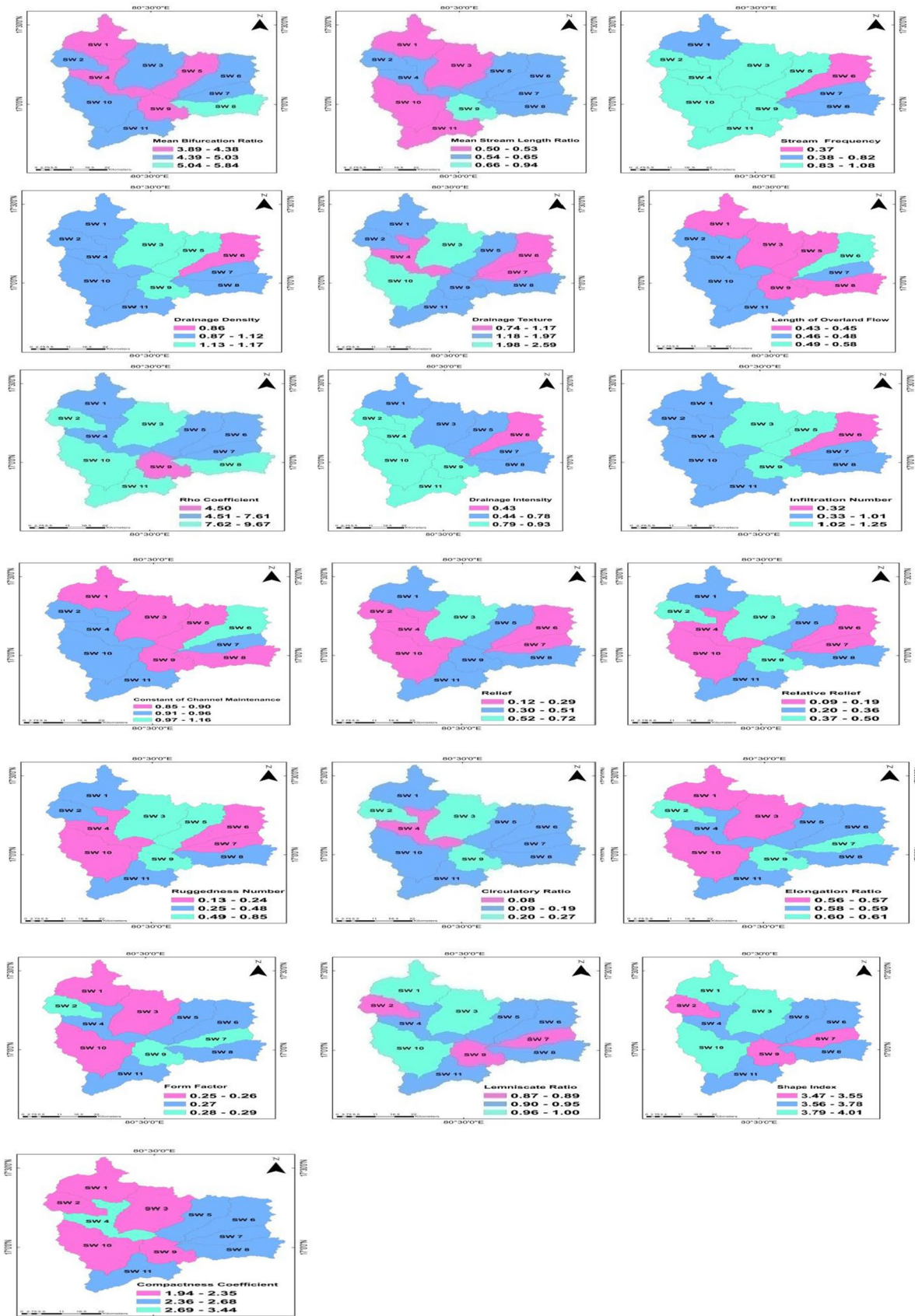


Fig. 10 Analysis of eleven sub-watersheds' morphometric parameters

**Table 4** Preliminary rank of nineteen morphometric parameters

Parameters	SW 1	SW 2	SW 3	SW4	SW 5	SW6	SW 7	SW8	SW 9	SW10	SW 11
Mean bifurcation ratio	10	2	6	11	8	7	5	1	9	3	4
Mean stream length ratio	10	6	9	7	5	2	4	3	1	8	11
Stream frequency	9	4	3	7	6	11	10	8	1	2	5
Drainage density	5	6	1	9	2	11	7	4	3	10	8
Drainage texture	4	5	1	9	7	11	10	8	3	2	6
Length of overland flow	7	6	11	3	10	1	5	8	9	2	4
Rho coefficient	6	5	4	10	9	8	7	3	11	2	1
Drainage intensity	10	4	6	5	7	11	9	8	1	2	3
Infiltration number	9	4	2	7	3	11	10	8	1	6	5
Constant of channel maintenance	7	6	11	3	10	1	5	8	9	2	4
Relief	4	7	1	8	3	9	10	6	2	11	5
Relative ratio	5	3	2	10	4	9	8	6	1	11	7
Ruggedness number	4	7	1	8	3	9	10	6	2	11	5
Circulatory ratio	7	11	10	1	5	3	6	4	9	8	2
Elongation ratio	3	11	2	8	6	4	10	7	9	1	5
Form factor	3	11	2	8	6	4	10	7	9	1	5
Lemniscate ratio	9	1	10	4	6	8	2	5	3	11	7
Shape index	9	1	10	4	6	8	2	5	3	11	7
Compactness coefficient	5	1	2	11	7	9	6	8	3	4	10

correlated with the areal features, rank one is given a lower value (Nookaratnam et al. 2005). The higher value gets a 1 preliminary ranking for relief and linear features, and so forth. A preliminary ranking of 1 was assigned to the shape feature with the lowest value, and so forth (Table 4).

The purpose of conducting PCA on all parameters is to assess their correlations, identify principal components, and reduce the parameter dimensionality to highlight the most significant ones. Table 5 displays the correlation matrix of all parameters. To analyse the correlation among geomorphic parameters, a correlation matrix is generated using SPSS 14.0 software. After analysing the correlation matrix of the 19 geomorphic parameters in Wyra watershed, it is evident that strong correlations (with a correlation coefficient exceeding 0.9) are present between  $D_i$  and  $F_s$ ,  $I_f$  and  $F_s$ ,  $L_o$  and  $D_d$ ,  $C_{cm}$  and  $D_d$ ,  $I_f$  and  $L_o$ ,  $C_{cm}$  and  $L_o$ ,  $I_f$  and  $D_i$ ,  $R_n$  and  $B_h$ ,  $C_c$  and  $R_c$ ,  $F_f$  and  $R_e$ ,  $K$  and  $R_e$ ,  $S_b$  and  $R_e$ ,  $K$  and  $F_f$ ,  $S_b$  and  $F_f$ ,  $S_b$  and  $K$ . The good correlation (correlation coefficient between 0.75 and 0.9) is between  $\rho$  and  $R_{lm}$ ,  $D_d$  and  $F_s$ ,  $L_o$  and  $F_s$ ,  $C_{cm}$  and  $F_s$ ,  $I_f$  and  $D_d$ ,  $R_{hp}$  and  $B_h$ ,  $R_n$  and  $R_{hp}$ . Moderately correlated parameters (correlation coefficient more than 0.6) are  $P$  and  $R_{bm}$ ,  $D_i$  and  $F_s$ ,  $D_i$  and  $D_d$ ,  $D_i$  and  $D_d$ ,  $B_h$  and  $D_d$ ,  $R_{hp}$  and  $D_d$ ,  $R_n$  and  $D_d$ ,  $L_o$  and  $D_i$ ,  $D_i$  and  $D_i$ ,  $D_i$  and  $D_i$ ,  $C_{cm}$  and  $D_i$ ,  $D_i$  and  $L_o$ ,  $R_{hp}$  and  $L_o$ ,  $R_n$  and  $L_o$ ,  $C_{cm}$  and  $D_i$ ,  $R_{hp}$  and  $C_{cm}$ ,  $R_n$  and  $C_{cm}$ . Correlation between parameters

indicates that there may be shared information across multiple parameters. However, it is often difficult to group these parameters into meaningful components and assign physical interpretations. To address this, one practical approach is to use principal component analysis (PCA) on the correlation matrix to reduce the parameter dimension (Meshram and Sharma 2017). Therefore, in the next step, PCA has been applied to the correlation matrix.

To obtain the first factor loading matrix, the principal component analysis method was utilized, followed by orthogonal transformation to obtain the rotated loading matrix. Using the correlation matrix of 19 geomorphic parameters, the first unrotated factor loading matrix was derived. Table 6 shows that the first five components, with eigenvalues greater than 1, account for approximately 94.41% of the total variance in the Wyra watershed. Table 7 indicates that the first component exhibits a strong correlation (above 0.90) with  $D_d$ ,  $L_o$ ,  $I_f$  and  $C_{cm}$ . It also shows a good correlation with  $F_s$  and  $R_{hp}$ , and a moderate correlation with  $D_i$ ,  $D_i$ ,  $B_h$ , and  $R_n$ . The second principal component exhibited a strong correlation with  $R_e$ ,  $F_f$ ,  $K$ , and  $S_b$ , and a moderate correlation with  $R_{lm}$ . The third principal component showed a strong correlation with  $R_{bm}$  and a moderate correlation with  $R_c$  and  $C_c$ . The fourth and fifth principal components exhibited no correlation with any of the ranges.



**Table 5** The correlation matrix among linear, areal, and relief parameters

Parameters	$R_{bm}$	$R_{lm}$	$F_s$	$D_d$	$D_i$	$L_o$	$\rho$	$D_i$	$S_b$	$C_c$
$R_{bm}$	1									
$R_{lm}$	-0.11	1								
$F_s$	-0.03	0.19	1							
$D_d$	-0.03	0.12	0.83	1						
$D_i$	0.09	-0.15	0.70	0.61	1					
$L_o$	0.05	-0.09	-0.86	-0.99	-0.62	1				
$\rho$	0.64	-0.80	-0.03	-0.05	0.32	0.04	1			
$D_i$	-0.02	0.13	0.97	0.66	0.65	-0.71	0.03	1		
$F_f$	-0.04	0.23	0.99	0.89	0.71	-0.91	0.03	0.91	1	
$C_{cm}$	0.01	-0.09	-0.84	-1.00	-0.62	1.00	0.01	-0.69	-0.90	1
$B_h$	-0.12	0.09	0.40	0.65	0.49	-0.59	-0.06	0.19	0.51	-0.90
$R_{hp}$	-0.05	0.40	0.50	0.69	0.41	-0.62	-0.27	0.30	0.60	-0.90
$R_n$	-0.12	0.10	0.45	0.70	0.54	-0.64	-0.06	0.24	0.57	-0.90
$R_c$	0.26	0.13	0.28	0.29	0.52	-0.25	0.11	0.21	0.31	0.31
$R_e$	0.12	0.53	0.14	0.12	-0.43	-0.11	-0.39	0.13	0.15	0.15
$F_f$	0.09	0.43	0.17	0.16	-0.42	-0.16	-0.34	0.16	0.16	0.16
$K$	-0.08	-0.52	-0.11	-0.10	0.51	0.10	0.42	-0.10	-0.11	-0.11
$S_b$	-0.05	-0.54	-0.09	-0.08	0.52	0.07	0.45	-0.08	-0.09	-0.09
$C_c$	-0.33	-0.18	-0.19	-0.27	-0.50	0.22	-0.12	-0.09	-0.24	-0.24
Parameters	$C_{cm}$	$B_h$	$R_{hp}$	$R_n$	$R_c$	$R_e$	$F_f$	$K$	$S_b$	$C_c$
$R_{bm}$	0.01	-0.12	-0.05	-0.12	0.26	0.12	0.09	-0.08	-0.05	-0.33
$R_{lm}$	-0.09	0.09	0.40	0.10	0.13	0.53	0.43	-0.52	-0.54	-0.18
$F_s$	-0.84	0.40	0.50	0.45	0.28	0.14	0.17	-0.11	-0.09	-0.19
$D_d$	-1.00	0.65	0.69	0.70	0.29	0.12	0.16	-0.10	-0.08	-0.27
$D_i$	-0.62	0.49	0.41	0.54	0.52	-0.43	-0.42	0.51	-0.27	-0.50
$L_o$	1.00	-0.59	-0.62	-0.64	-0.25	-0.11	-0.16	0.10	0.07	0.22
$\rho$	0.01	-0.06	-0.27	-0.06	0.11	-0.39	-0.34	0.42	0.45	-0.12
$D_i$	-0.69	0.19	0.30	0.24	0.21	0.13	0.16	-0.10	-0.08	-0.09
$F_f$	-0.90	0.51	0.60	0.57	0.31	0.15	0.16	-0.11	-0.09	-0.24
$C_{cm}$	1	-0.59	-0.64	-0.65	-0.29	-0.12	-0.18	0.11	0.09	0.27
$B_h$	-0.59	1	0.82	1.00	0.22	-0.15	-0.24	0.26	0.25	-0.26
$R_{hp}$	-0.64	0.82	1	0.83	0.58	0.32	0.22	-0.20	-0.22	-0.56
$R_n$	-0.65	1.00	0.83	1	0.25	-0.14	-0.22	0.25	0.24	-0.28
$R_c$	-0.29	0.22	0.58	0.25	1	0.20	0.19	-0.11	-0.13	-0.95
$R_e$	-0.12	-0.15	0.32	-0.14	0.20	1	0.94	-0.97	-0.97	-0.09

Table 5 (continued)

Parameters	$C_{cm}$	$B_h$	$R_{hp}$	$R_n$	$R_c$	$R_e$	$F_f$	$K$	$S_b$	$C_c$
$F_f$	-0.18	-0.24	0.22	-0.22	0.19	0.94	1	-0.98	-0.98	-0.12
$K$	0.11	0.26	-0.20	0.25	-0.11	-0.97	-0.98	1	1.00	0.04
$S_b$	0.09	0.25	-0.22	0.24	-0.13	-0.97	-0.98	1.00	1	0.05
$C_c$	0.27	-0.26	-0.56	-0.28	-0.95	-0.09	-0.12	0.04	0.05	1

Based on the first factor loading matrix, it can be observed that  $\rho$  is not correlated with any of the components. While some parameters show a high correlation with certain components, others exhibit a moderate correlation, and some parameters do not correlate with any component at all. As a result, it is difficult to determine the most significant parameters for each principal component. To establish better correlations and identify significant parameters, it is necessary to rotate the first factor loading matrix. The rotated factor loading matrix is presented in Table 8, which reveals that the first, second, third, fourth, and fifth principal components exhibited strong correlations with  $F_s$ ,  $K$ ,  $B_h$ ,  $C_c$ , and  $\rho$ , respectively. These parameters are also considered significant and are utilized in WSA and sub-watershed prioritization.

The compound value (CV), which was determined by incorporating the preliminary rank (PR) and the weight of significant parameters ( $F_s$ ,  $K$ ,  $B_h$ ,  $C_c$ , and  $\rho$ ), was utilized for the ultimate sub-watershed prioritization. The weightage of these critical parameters was determined by cross-correlation analysis among the five parameters listed in Table 9. By applying the weighted sum of essential parameters, the compound value (CV) was derived using Eq. (1). Subsequently, the sub-watershed with the lowest CV (3.82), i.e. SW2, was accorded the highest priority. Conversely, the sub-watershed with the highest CV (8.88), i.e. SW6, was deemed to be of the lowest priority.

$$\begin{aligned}
 CV = & (0.187 \times PR \text{ of } F_s) + (0.282 \times PR \text{ of } K) \\
 & + (0.235 \times PR \text{ of } B_h) \\
 & + (0.084 \times PR \text{ of } C_c) \\
 & + (0.213 \times PR \text{ of } \rho) \quad (1)
 \end{aligned}$$

For example, SW1 (CV) =  $(0.187 \times 9) + (0.282 \times 9) + (0.235 \times 4) + (0.084 \times 5) + (0.213 \times 6) = 6.85$  (Table 10).

The subdivision of the compound value into three categories for soil erosion is based on the level of erosion risk associated with each category. The three categories are known as the low, moderate, and high categories. The basis for this subdivision is the fact that different levels of soil erosion risk require different levels of intervention to prevent or mitigate erosion. If the compound value is in the low-risk category, it indicates that the erosion risk is minimal, and erosion control measures may not be necessary. In this case, the focus may be on maintaining current land-use practices and monitoring erosion levels to ensure they do not increase. If the compound value is in the moderate-risk category, it indicates that erosion control measures may be necessary to prevent erosion from causing significant damage. In this case, erosion control practices, such as vegetation management,

**Table 6** The total variance of principal components in the Wyra River basin

Principal component	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	7.598	39.987	39.987	7.598	39.987	39.987	5.589	29.418	29.418
2	4.96	26.104	66.092	4.96	26.104	66.092	4.674	24.6	54.018
3	2.244	11.809	77.901	2.244	11.809	77.901	3.229	16.996	71.014
4	2.002	10.535	88.436	2.002	10.535	88.436	2.425	12.762	83.776
5	1.135	5.976	94.412	1.135	5.976	94.412	2.021	10.636	94.412
6	0.631	3.322	97.734						
7	0.341	1.797	99.531						
8	0.063	0.333	99.864						
9	0.019	0.098	99.962						
10	0.007	0.038	100						
11	1.24E-15	6.54E-15	100						
12	5.32E-16	2.80E-15	100						
13	3.34E-16	1.76E-15	100						
14	2.38E-16	1.25E-15	100						
15	1.52E-16	8.00E-16	100						
16	-7.94E-18	-4.18E-17	100						
17	-4.91E-17	-2.58E-16	100						
18	-3.31E-16	-1.74E-15	100						
19	-4.35E-16	-2.29E-15	100						

**Table 7** First factor loading matrix of nineteen parameters in the Wyra River basin

Parameters	Principal component				
	1	2	3	4	5
$R_{bm}$	-0.011	0.018	0.755	-0.233	0.31
$R_{lm}$	0.236	-0.635	-0.19	0.364	-0.373
$F_s$	0.886	-0.024	-0.103	-0.387	-0.185
$D_d$	0.945	0.012	-0.113	-0.107	0.182
$D_t$	0.72	0.571	0.21	-0.093	-0.31
$L_o$	-0.931	-0.017	0.141	0.196	-0.144
$\rho$	-0.08	0.566	0.582	-0.425	0.367
$D_i$	0.743	-0.024	-0.085	-0.543	-0.299
$I_f$	0.943	-0.019	-0.118	-0.267	-0.119
$C_{cm}$	-0.933	-0.01	0.086	0.175	-0.17
$B_h$	0.694	0.303	-0.18	0.502	0.333
$R_{hp}$	0.802	-0.164	0.074	0.524	0.141
$R_n$	0.741	0.298	-0.172	0.466	0.307
$R_c$	0.479	-0.071	0.724	0.301	-0.296
$R_e$	0.154	-0.945	0.132	-0.025	0.146
$F_f$	0.155	-0.937	0.146	-0.152	0.129
$K$	-0.089	0.977	-0.078	0.108	-0.127
$S_b$	-0.081	0.984	-0.074	0.058	-0.105
$C_c$	-0.438	0.009	-0.736	-0.395	0.265

**Table 8** Rotated factor loading matrix of nineteen parameters in the Wyra River basin

Parameters	Principal component				
	1	2	3	4	5
$R_{bm}$	-0.045	-0.176	-0.077	0.333	0.755
$R_{lm}$	0.063	-0.476	0.072	0.25	-0.684
$F_s$	0.971	-0.063	0.129	0.108	-0.065
$D_d$	0.798	-0.1	0.547	0.062	0.034
$D_t$	0.684	0.531	0.169	0.453	0.096
$L_o$	-0.847	0.089	-0.469	-0.019	-0.035
$\rho$	0.04	0.344	-0.1	0.07	0.92
$D_i$	0.961	-0.039	-0.107	0.072	-0.046
$I_f$	0.942	-0.068	0.271	0.131	-0.088
$C_{cm}$	-0.824	0.107	-0.489	-0.058	-0.073
$B_h$	0.257	0.217	0.915	0.103	-0.087
$R_{hp}$	0.314	-0.22	0.776	0.431	-0.189
$R_n$	0.319	0.211	0.901	0.12	-0.086
$R_c$	0.176	-0.101	0.133	0.933	0.089
$R_e$	0.051	-0.968	0.014	0.091	-0.087
$F_f$	0.123	-0.969	-0.071	0.06	-0.032
$K$	-0.054	0.989	0.075	-0.008	0.101
$S_b$	-0.025	0.985	0.062	-0.033	0.139
$C_c$	-0.087	0.04	-0.192	-0.952	-0.094

**Table 9** The cross-correlation between the important parameters of Wyra River basin

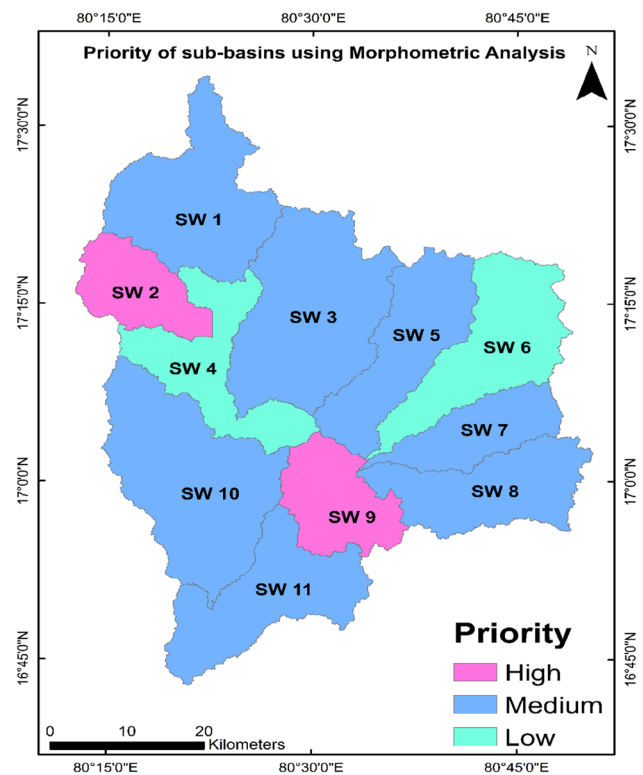
Parameters	$F_s$	$K$	$B_h$	$C_c$	$\rho$
$F_s$	1	-0.111	0.395	-0.187	-0.034
$K$	-0.111	1	0.261	0.035	0.42
$B_h$	0.395	0.261	1	-0.257	-0.06
$C_c$	-0.187	0.035	-0.257	1	-0.115
$\rho$	-0.034	0.42	-0.06	-0.115	1
Sum	1.063	1.605	1.339	0.476	1.211
Total	5.69	5.69	5.69	5.69	5.69
WSA	0.187	0.282	0.235	0.084	0.213

**Table 10** The final priority rank for sub-watersheds of Wyra watershed

SW	CV	Ranking	Final priority
SW 1	6.85	9	Medium
SW2	3.82	1	High
SW 3	4.63	3	Medium
SW 4	7.36	10	Low
SW 5	6.02	6	Medium
SW 6	8.88	11	Low
SW 7	6.77	7	Medium
SW 8	5.62	5	Medium
SW 9	4.09	2	High
SW 10	6.82	8	Medium
SW 11	5.13	4	Medium

may be implemented to reduce the risk of erosion. If the compound value is in the high-risk category, it indicates that erosion control measures are urgently needed to prevent significant soil loss and environmental damage. In this case, more intensive erosion control practices, such as the use of check dams and retention ponds, may be necessary to manage erosion effectively. Based on CV values, the SWs were divided into three main categories: high ( $\geq 3.82$  to  $< 5.51$ ), medium ( $\geq 5.51$  to  $< 7.19$ ), and low ( $\geq 7.19$  to  $< 8.88$ ). SW2 and SW9 are high-priority SWs; SW1, SW3, SW5, SW7, SW8, SW10, and SW11 are medium-priority SWs; and SW4 and SW6 are low-priority SWs.

Figure 11 shows the Wyra watershed's final priority map of sub-watersheds based on the morphometric study. The degree of erosion in a sub-watershed is directly proportional to its priority level, with higher priority indicating a greater extent of erosion. Such sub-watersheds are therefore considered as potential areas where soil conservation measures should be enforced. The analysis of morphometric parameters revealed that sub-watersheds SW2 and SW9 exhibit a particularly high susceptibility to

**Fig. 11** Morphometric analysis-based prioritization of sub-watersheds

soil erosion in the study area. The underlying parameters that make SW2 and SW9 a high-priority sub-watershed could vary based on the specific morphometric parameters used in the analysis. For instance, if the sub-watershed has a high stream frequency, it could also increase the risk of flooding during heavy rainfall events. Additionally, if sub-watershed has a high drainage density, which indicates a large number of streams and channels in the sub-watershed, it may be more susceptible to erosion and sedimentation. On the other hand, if the sub-watershed has a complex drainage pattern or a high relief, it may indicate a greater potential for soil erosion and landslides. The high-risk sub-watersheds must receive immediate attention, followed by the medium-risk sub-watersheds, and so on, until sufficient time and resources are available for the remaining sub-watersheds.

### Relation among morphometric features and hypsometric curve

The relief ratio and watershed volume represented by the hypsometric curve (HC), according to Vivoni et al. (2008), are useful in evaluating runoff and other hydrological processes. The hypsometric curves reveal not only the watershed's

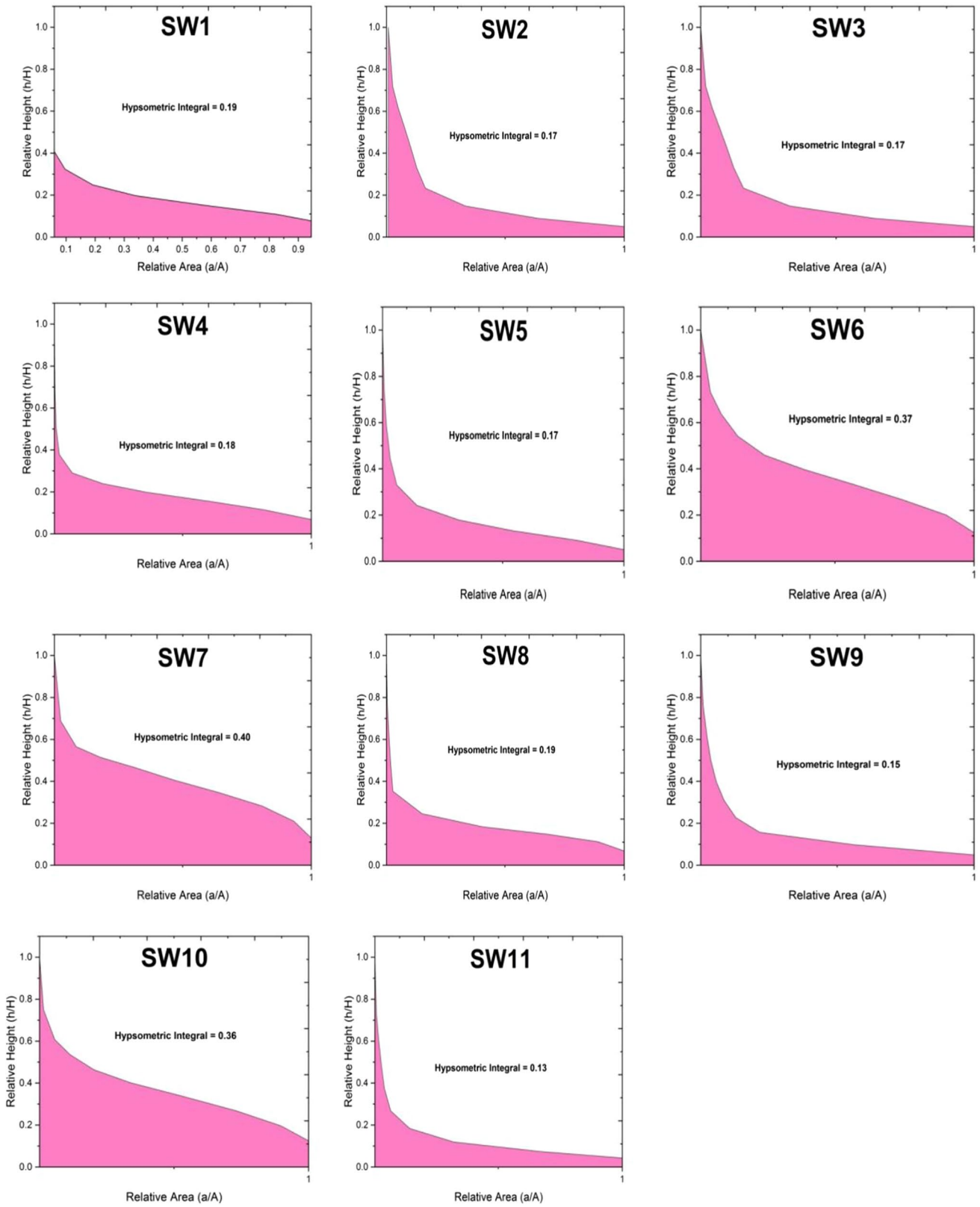
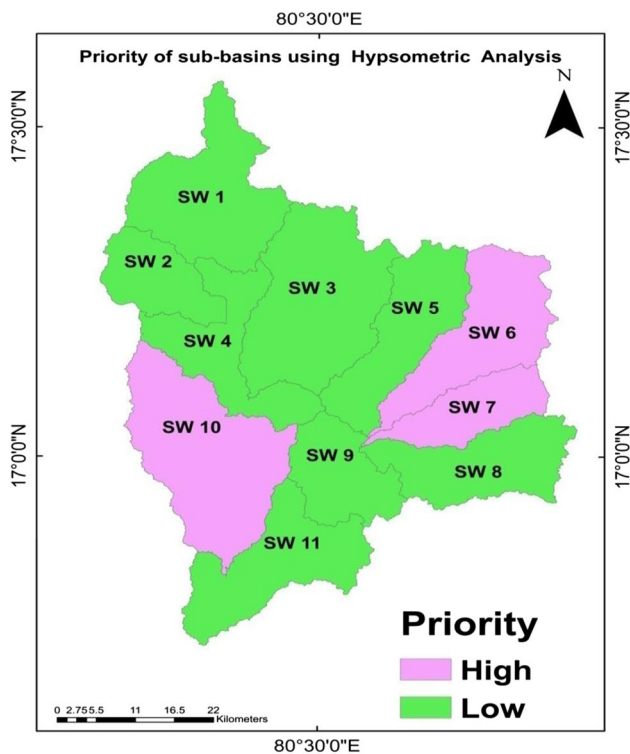


Fig. 12 The hypsometric integral values of each sub-watershed

**Table 11** Ranking and prioritization, and hypsometric integral: calculations

Parameters	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11
Hypsometric integral	0.1945	0.1732	0.1725	0.1847	0.1687	0.3721	0.4018	0.1896	0.1493	0.3641	0.1285
Ranking	8	5	4	6	3	10	11	7	2	9	1
Final priority	Low	Low	Low	Low	Low	High	High	Low	Low	High	Low



**Fig. 13** Priority of hypsometric analysis

erosion status but also the tectonic, climatic, and lithological elements that influence it (Sarp et al. 2011). The drainage network and watershed geometry have a big impact on hypsometry. The aspect ratio decreases, the stream system becomes more branched, and the bifurcation ratio increases. The toe height will then be of increasing elevation at the downstream part of the watershed for a low aspect ratio (Roy 2002).

### Prioritization of sub-watersheds based on hypsometric analysis

The hypsometric integral (HI) was obtained by using elevation–relief ratio (E) approach. HI in this study ranges from 0.1285 to 0.4018, as shown in Fig. 12. The ranking values for all eleven SWs were based on hypsometric integral values. High (0.311 to 0.402), medium (0.311 to 0.220), and low (0.220 to 0.128) were used to categorize the sub-watersheds (Farhan et al. 2016). As stated in Table 11, high-priority sub-watersheds are SW6, SW7, and SW10, there are no sub-watersheds of a medium priority, and low-priority sub-watersheds are SW1, SW4, SW2, SW9, SW5, SW11, and SW8. The hypsometric analysis’s final priority map is displayed in Fig. 13.

### Common sub-watersheds

The most common sub-watersheds were determined based on morphometric and hypsometric analysis. The most common watersheds are SW4 (low priority), as shown in Table 12. SW4 is identified as a low-priority sub-watershed in both the morphometric analysis-based PCA-WSA and hypsometric analysis-based prioritization, and it suggests that this sub-watershed is less susceptible to land degradation compared to other sub-watersheds in the Wyra River basin. Therefore, the implementation of management practices in SW4 may not be an immediate priority. However, it is still important to monitor the condition of SW4 to ensure that it remains stable and does not become more vulnerable to land degradation in the future.

### Conclusion

The most crucial aspect of organizing and implementing watershed improvement and management programs is prioritizing the watershed. To facilitate efficient planning

**Table 12** Common sub-watershed priority

Methods	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11
Morphometric analysis	Medium	High	Medium	Low	Medium	Low	Medium	Medium	High	Medium	Medium
Hypsometric analysis	Low	Low	Low	Low	Low	High	High	Low	Low	High	Low
Common priority	No	No	No	Low	No	No	No	No	No	No	No

for watershed management, this study employed geospatial techniques to conduct morphometric and hypsometric analyses of the sub-watersheds of the Wyra River basin. The prioritization of sub-watersheds based on morphometric analysis using PCA-WSA reveals that SW2 and SW9 are considered high-priority areas. However, when hypsometric analysis is used for prioritization, the high-priority areas are SW6, SW7, and SW10. The sub-watershed with the most common occurrence in both prioritization methods is SW4. To mitigate soil erosion, conservation measures such as artificial recharge structures (e.g. check dams and percolation tanks) can be implemented in the area. These measures have the potential to reduce erosion and can be effective tools for ensuring the long-term sustainability of the watershed. Moreover, the insights obtained from this study can be valuable for decision-makers in the Wyra watershed to implement effective management practices aimed at mitigating and preventing land degradation.

In future studies, it is recommended to consider incorporating social and economic factors could contribute to a more comprehensive understanding of the sub-watersheds and their priority for management interventions. Additionally, evaluating the effectiveness of management practices implemented based on sub-watershed prioritization could help refine and improve the process for future watershed management initiatives.

**Acknowledgements** We are thankful to the editors and potential reviewers.

**Author contributions** PRS contributed to conceptualization and supervision; PRS, AM, and HGA were involved in writing—review and editing; PRS and AM contributed to data curation and formal analysis; and PRS, AM, HGA, HA, AAA, and MM were involved in evidence collection, review, and editing.

**Funding** This project was funded by Princess Nourah Bint Abdulrahman University Research Supporting Project Number PNURSP2022R241 and Princess Nourah Bint Abdulrahman University, Riyadh, Saudi Arabia.

**Data availability** The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** On behalf of all authors, the corresponding author states that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Ethical approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

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