WATERSHED PRIORITISATION OF DRAINAGE BASINS BASED ON GEOMORPHOMETRIC PARAMETERS, NEYYAR WATERSHED, INDIA

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Abstract: Prioritisation of sub-watersheds (SWs) is becoming increasingly important in the conservation of natural resources, particularly in watershed planning. In this study, sub-watershed for the Neyyar basin was prioritised using three methods: morphometric analysis, principal component analysis (PCA) and hypsometric analysis. Morphometric analysis and hypsometric analysis were carried out using remote sensing (RS) and geographic information system (GIS) techniques, while PCA was performed for dimensionality reduction of morphometric parameters. The watershed was divided into 11 sub-watersheds (SW1–SW11), and each sub-watershed was given priority. To rank and prioritise SWs, 15 morphometric parameters were selected from the quantitative measures of morphometric analysis, including linear, relief, and areal. PCA was used to rank and prioritise SWs based on three highly correlated morphometric parameters. The hypsometric integral (HI) values were determined using the elevation relief ratio approach, and HI values were utilised to prioritise SWs. For both methods, such as morphometric analysis and PCA, a higher priority has been given to SW1. Using hypsometric analysis, higher priorities have been assigned to SW1, SW7, SW8, SW9, SW10 and SW11. The most common SWs that belong to the same priority of SWs and have a high correlation between them among the three methods are SW1, SW2, and SW5.The results of this analysis indicate that SW1 is a common high priority area with a significant risk of soil erosion, runoff and peak discharge. Therefore, decision-makers may utilise the high-priority sub-watershed to guide planning and development, measure conservation efforts and manage the land to prevent.

Key words: morphometric analysis, hypsometric analysis, PCA, Neyyar

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Introduction

Land and water are important elements on earth because both are required for life and a variety of development plans (Nookaratnam et al. 2005, Kudnar, Rajasekhar 2020). Any area where rainwater runoff is gathered and removed through a single outlet point is referred to as a watershed (Desta et al. 2005). Watershed research is necessary for any form of development as well as long-term management (Sangma, Guru 2020, Ditthakit et al. 2021).

A much more basic and reasonable approach is to study watershed morphometry (Imran et al. 2011). Morphometry is the science of evaluating and analysing the structure and scale of the planet's features, as well as the organisation of the planet's surface (Clarke 1996, Agarwal 1998, Obi et al. 2002). This analysis is extremely effective in situations where there is a scarcity of data and

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other resources, as well as a wide range of soil types (Rahmati et al. 2019, Meshram et al. 2020, Mathew et al. 2022). Sub-watersheds (SWs) can be classified without incurring high expenses or losing time using the morphometric method (Meshram et al. 2019). The morphometric method estimates quantitative landscape features such as a watershed's linear, areal or shape, and relief aspects (Dar et al. 2013). Watershed morphometric parameters are direct or inverse relationships between surface runoff and soil erosion (Nookaratnam et al. 2005, Gajbhiye, Sharma 2017) and are also used to find and prioritise the most important SWs. It is also necessary to establish SWs in order to handle environmental assets efficiently (Javed et al. 2009, Ayele et al. 2017, Manjare et al. 2018). Geomorphology, land use and land cover (LULC), and hydrological data are essential in determining a sub-watershed's river system (Bhattacharya et al. 2020, Shekar, Mathew 2022a, Vishwakarma et al. 2022).

Sub-watershed prioritisation is one of the most crucial principles for coordinated and effective watershed management. It can benefit in lowering sediment loads, floods and soil erosion in order to achieve sustainable development and identification of SWs that are critically endangered (Poongodi, Venkateswaran 2018, Sarkar et al. 2022). It will be possible if peak discharge and erosion risk assessment are taken into account while ranking SWs (Jain, Das 2010). Waiyasusri and Chotpantarat (2020) presented a thorough overview of the drainage watershed, which is particularly useful in studies such as watershed prioritisation, environmental management and hydrological modelling. In hydrology, drainage aspects are critical for understanding numerous hydrological processes (Khurana et al. 2020, Monteiro et al. 2022).

Compared to traditional data processing methods for prioritising SWs (Horton 1945, Schumm 1956, Strahler 1964), fast emerging spatial information technology has excellent instruments to overcome the difficulties of water and land resource managing and strategy (Rao et al. 2010). Satellite remote sensing (RS) is highly effective in analysing drainage morphometry since it can provide a synoptic view of a vast area (Esin et al. 2021, Kushwaha et al. 2022, Shekar, Mathew 2023). Image processing and analysis methods are quicker than ground surveys, and when used with a minimal number of field inspections, these methods yield useful data. Satellite data can be used for morphometric analysis and precise delineation of watersheds, SWs and other morphometric parameters or morphometric features (Ahmed et al. 2010, Singh et al. 2021). Numerous studies investigated the sub-watershed prioritisation based on morphometric analysis (López-Pérez, Fernández-Reynoso 2021, Bogale 2021, Magalhaes et al. 2022, Mathew, Shekar 2023).

Based on the principal component analysis (PCA), other researchers offered to minimise the dimension of morphometric parameters and discover variables that clarify the majority of the variance seen in a wide range of parameters (Arefn et al. 2020). For the study of information belonging to a wide range of aspects, the factor analysis approach is critical; it generates easily interpretable outcomes and has been effectively used in surface water and groundwater quality assessment using multi-component approaches (Praus 2005). Multivariate statistical methodologies such as PCA and factor analysis can be used to find fundamental components or factors that account for the majority of the fluctuations in a system (Shrestha, Kazama 2007). These methods decrease many variables into a small number of features while preserving the original information's relationships.

Furthermore, the hypsometric curve of the basin, a non-dimensional measure of the proportions of surface area of a catchment or watershed above a specific elevation, is used to analyse the geomorphic processes taking place inside basins and landforms (Langbein 1947, Willgoose, Hancock 1998, Hurtrez et al. 1999). The hypsometric integral (HI) also represents the erosive cycle (Strahler 1952a, Garg 1983). The complete period can be divided into three periods: the old or monadnock stage (HI is <0.30), wherein the watershed is completely controlled; the mature or equilibrium stage (between HI 0.30 and 0.60); and the young or in-equilibrium stage (HI >0.60), wherein the watershed is at high risk of erosion as the value of the integral increases (Strahler 1952a). According to Strahler (1952a), the youth stage of watersheds is marked by a convex-shaped hypsometric curve. On the contrary, old or peneplain watersheds have a concave hypsometric curve that is concave upwards at maximum elevations and concave downwards at minimum elevations, whereas mature watersheds have an S-shaped curve that is concave upwards at high elevations and concave downwards at low elevations. The hypsometric curve and HI are key predictors of the condition of the watershed because they show the degree of instability under the equal influences of tectonics and erosion (Weissel et al. 1994, Ritter et al. 2002, Shekar, Mathew 2022b). Estimating the level of erosion in a watershed is essential for prioritising watersheds for the recommendation of soil and water conservation measures (Ayele et al. 2021).

Recent studies have conducted an in-depth study on the prioritisation of SWs helpful for policies based on soil and water conservation. There has been limited research on the use of PCA to prioritise SWs. Finding the more efficient parameters for PCA-based watershed prioritisation is one of the major contributions of the study. On the contrary, the use of hypsometric analysis to prioritise SWs has not been studied before. Prior studies have not used the three methods, namely, morphometric analysis, PCA and hypsometric analysis, which were discussed earlier. This study was undertaken to examine the watershed parameters in the Neyyar river basin due to the significance of sub-watershed priority in the watershed management programmes. The current study objectives are to prioritise SWs based on different methods such as morphometric analysis, PCA

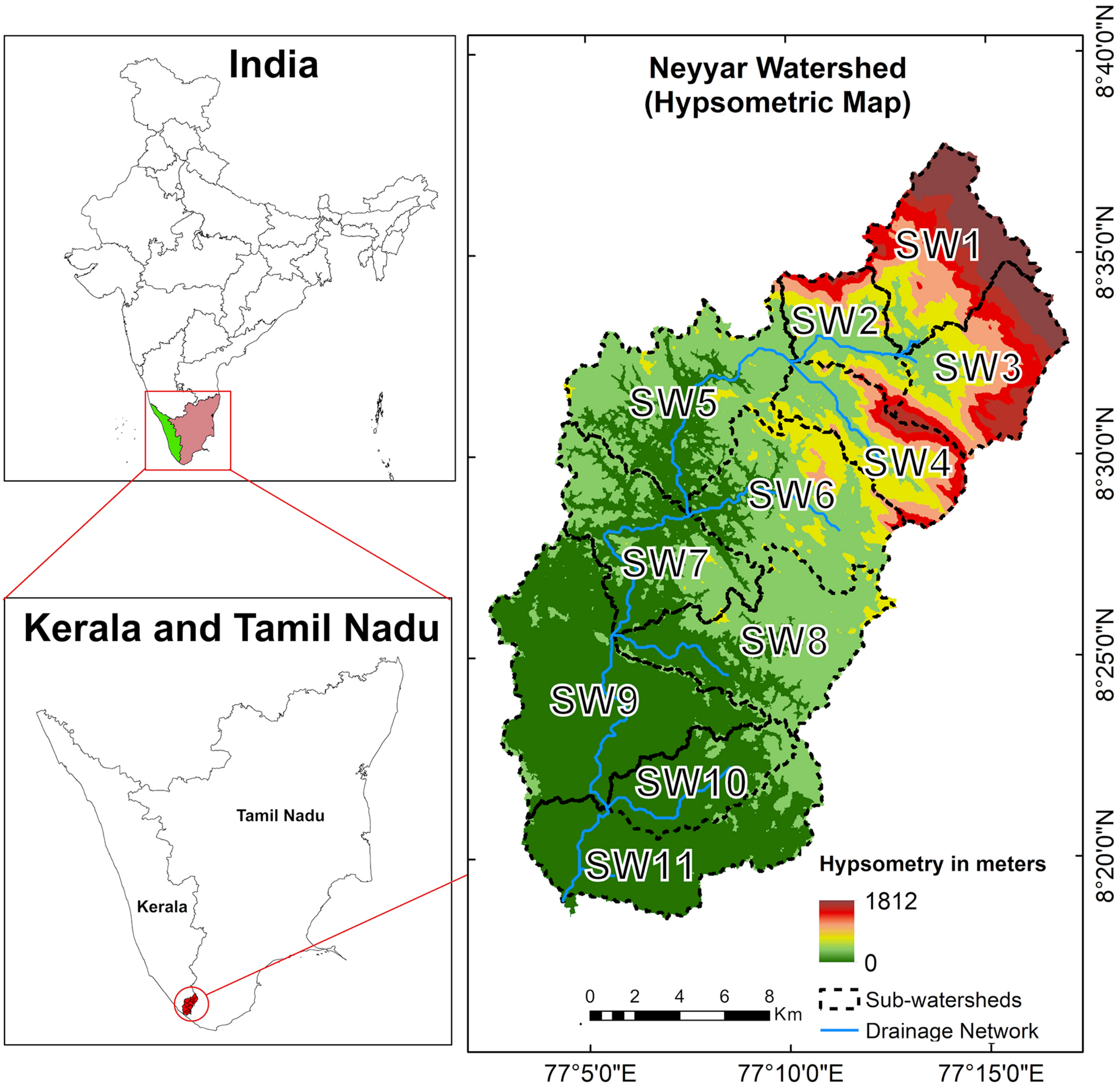

Fig. 1. Location map and hypsometric map of the study area, Neyyar watershed.

and hypsometric analysis. Additionally, the current study employs these three methods to locate the SWs associated with the common priority.

Study area

The Neyyar watershed includes Kerala and Tamil Nadu (Fig. 1). The latitude and longitude at the outlet of the Neyyar watershed are 8°18'56.6"N and 77°04'19.13"E, respectively. It has a total area of 474 km^2. According to the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM), the basin's elevation varies from 0 m to 1812 m above sea level. According to the U.S. Geological Survey (USGS) geologic classification (1998), the area's geologic classification is Neogene sedimentary rocks and undivided Precambrian rocks. Moreover, according to soil classification by the FAO (1988), the area's principal soil units are Plinthis Acrisols, Distric Nitosols and Dystric Regosols. Furthermore, Sentinel-2 data (ESRI 2021) classify the LULC as follows: trees (62.88%), built-up areas (31.64%), rangeland (2.45%), water (2.08%), crops (0.38%), bare ground (0.01%) and flooded vegetation (0.56%).

Data used

SRTM DEM products for the entire world, such as SRTM 1 arc-second (30 m). Only in the 1 arc-second DEM, where bigger stream channels are considerably more well described, are the small stream channels visible. A quick and affordable tool for regional geomorphological investigation is the SRTM DEM. The information was gathered from the USGS Earth Explorer (2021). SRTM-DEM is used to examine the drainage features of the river basin. Furthermore, ESRI (2021) Sentinel-2 data are utilised to comprehend the LULC (Karra et al. 2021). Additionally, the FAO (1988) system of soil categorisation was employed to identify the type of soil.

Methodology

The watershed delineation in this investigation was carried out using the SRTM-DEM. It is available for download from the USGS Earth Explorer website (2021). The DEM has a 30-m resolution. The Neyyar basin's 11 SWs were studied using quantitative morphometric characteristics.

Morphometric analysis

Figure 2 illustrates the process over DEM. Using ArcGIS 10.4.1, sub-watersheds (SW1–SW11) are categorised. Linear, shape and relief parameters were the three types of morphometric features analysed and classified. Table 1 shows the many empirical approaches used to determine these characteristics. The Neyyar River basin linear parameters were estimated and reported in Table 2. The highest value is ranked as 1, for the relief and linear features, and so on, while the lowest value is ranked as 1, for the areal or shape feature, and so on. The compound parameter (Cp) value was obtained by adding all the ranks in SW1, and the resultant sum was divided by the number of features. This was repeated for the remaining SWs. Based on their Cp values, the SWs were divided into three groups: high, medium and low.

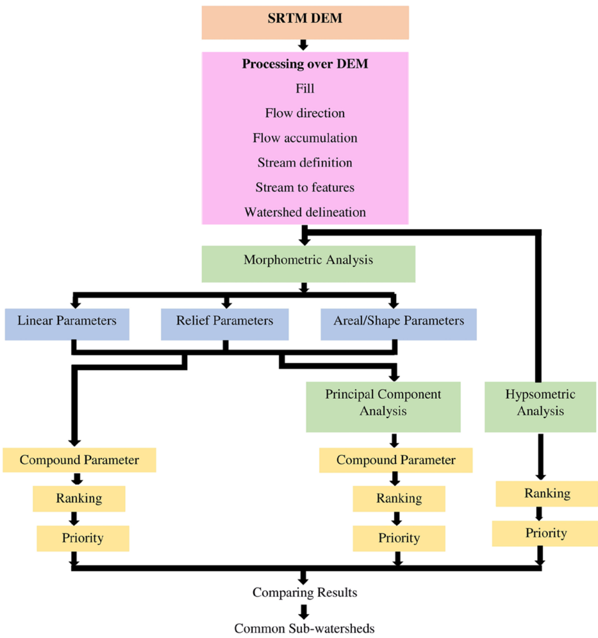

Fig. 2. Methodology used in the present study.

Principal Component Analysis

PCA is performed to reduce many variables into a small number of features while preserving the original information's relationships. In other

Table 1. Methods or formulae of parameters used in this study.

Parameter	Formulae or methods	References
Methods or formulae for linear parameters		
Stream order (U)	Hierarchical rank	Strahler (1964)
Stream number (N_u)	$N_u = N_{u1} + N_{u2} + \cdots + N_{un}$	Horton (1945)
Stream length (L_u)	$L_u = L_{u1} + L_{u2} + \cdots + L_{un}$	Horton (1945)
Mean bifurcation ratio (R_{bm})	Average of bifurcation ratio of all orders	Strahler (1957)
Bifurcation ratio (R_b)	$R_b = (N_u / N_{u+}1)$	Strahler (1964)
Mean stream length ratio (R_{lm})	Average of the steam length ratio of all orders	Strahler (1964)
Stream length ratio (R_l)	$R_l = (L_u / L_u{-}1)$	Horton (1945)
Drainage density (D_d)	$D_d = (\Sigma L_u) / A$	Schumm (1956)
Stream frequency (F_s)	$F_s = (\Sigma N_u) / A$	Schumm (1956)
Length of overland flow (L_o)	$L_o = (1 / (2Dd))$	Horton (1945)
Drainage texture (D_t)	$D_t = (\Sigma N_u) / P$	Schumm (1956)
Drainage intensity (D_i)	$D_i = (F_s / D_d)$	Faniran (1968)
RHO coefficient (ρ)	(R_{lm} / R_{bm})	Horton (1945)
Methods or formulae for relief parameters		
Maximum elevation (H)	GIS software	–
Minimum elevation (h)	GIS software	–
Relief (B_h)	$B_h = H–h$	Strahler (1952a)
Ruggedness number (R_n)	$R_n = B_h \times D_d$	Strahler (1952b)
Relative relief (R_{hp})	$R_{hp} = H \times 100 / P$	Melton (1957)
Methods or formulae for areal or shape parameters		
Perimeter of watershed (P)	GIS software	–
Area of watershed (A)	GIS software	–
Compactness coefficient (C_c)	$C_c = (P / 2(\pi A)^{0.5})$	Horton (1945)
Form factor (F_f)	$F_f = (A / Lb^2)$	Horton (1945)
Elongation ratio (R_e)	$R_e = (2 (A / \pi)^{0.5}) / (L_b)$	Schumm (1956)
Watershed length (L_b)	$L_b = 1.312 \times A^{0.568}$	Nookaratnam et al. (2005)
Circulatory ratio (R_c)	$R_c = 4\pi A / P^2$, where π = 3.14	Miller (1953)
Method or formula for hypsometric analysis		
Elevation-to-relief ratio (E)	E = (Mean elevation − minimum elevation / Maximum elevation − minimum elevation)	Pike and Wilson (1971)

Table 2. Neyyar basin linear parameters.

SW	Stream order (maximum)	Stream number (ΣN_u)	Stream length (ΣL_u)	Mean bifurcation ratio (ΣR_{bm})	Mean stream length ratio (ΣR_{lm})
SW 1	5	147	83	3.44	0.49
SW 2	5	99	51	3.07	0.62
SW 3	5	97	70	2.92	0.58
SW 4	4	74	56	3.78	0.80
SW 5	4	77	87	3.96	0.46
SW 6	4	92	77	4.11	0.77
SW 7	4	104	81	4.56	0.55
SW 8	4	102	79	4.49	0.66
SW 9	5	138	120	3.36	0.49
SW 10	4	90	54	4.24	0.86
SW 11	4	113	90	4.58	0.85

words, one of the crucial morphometric features for prioritising watersheds based on features that are strongly connected with components was assessed utilising PCA. In the current study, 15 morphometric factors were reduced to three crucial elements using Statistical Package for Social Sciences (SPSS) software version 22. Each component accounts for one highly associated feature, as seen by the rotated component matrix. Nookaratnam et al. (2005) stated that soil erosion has a direct impact on linear and relief features as well as an indirect impact on shape features. After obtaining three features, the sub-watershed with the highest value of relief and linear features has been ranked first, followed by the sub-watershed with the second highest value in the second rank, the third highest value in the third rank, and so on. The sub-watershed with the lowest value in the shape feature has been ranked first, followed by the sub-watershed with the second lowest value in the second rank, the third lowest value in the third rank, and so on (Nookaratnam et al. 2005). The Cp value was obtained by adding all the ranks in SW1, and the resultant sum was divided by the number of features. This was repeated for the remaining SWs. Based on their Cp values, the SWs were divided into three groups: high, medium and low. However, the PCA method of data handling has its requirements and limitations, and these have to be carefully observed.

Hypsometric analysis

The hypsometric curve and HI for the sub-watershed were also determined using the SRTM-DEM. The elevation-to-relief ratio technique was used in this study to estimate HI values. The HIs in this case study range from 0.146 to 0.388. After obtaining the HI values, the next step is to divide the HI values into three equal intervals in order to assign ranks as the SWs were classified into three groups: high, medium and low. The maximum interval values are treated as high priority, the next interval values are treated as medium priority and the minimum interval values are treated as low priority.

Results and discussion

The values obtained from 15 various parameters including linear, shape and relief parameters for 11 SWs of the Neyyar watershed are discussed below.

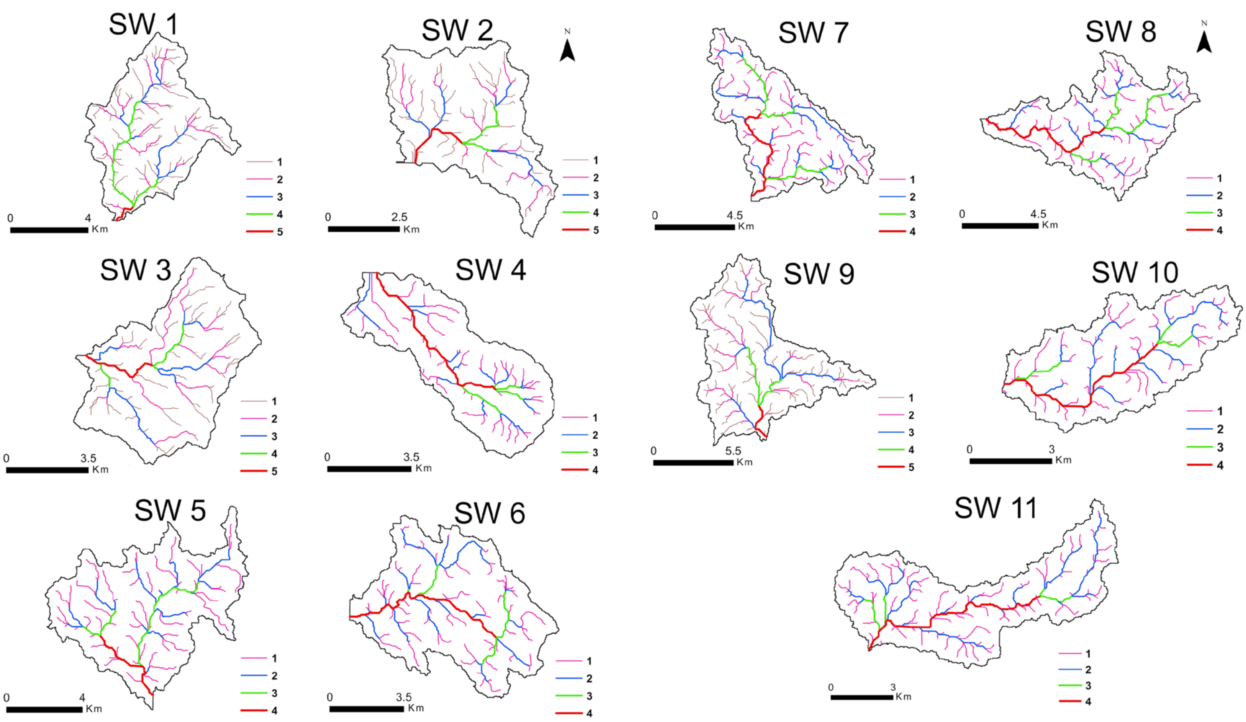

Fig. 3. Map of drainage networks and sub-watersheds.

Linear parameter

Stream order (U)

Every watershed evaluation includes a criterion for the order of stream, which is dependent on a typical organisational hierarchy of segments. Strahler's (1964) approach is used to assign the order to the streams. First stream orders are the smallest finger type and non-branched tributaries; second stream orders are formed when two first stream orders meet; third stream orders are formed when the second stream orders meet, and so on. SW1, SW2, SW3 and SW9 are in the fifth order, while SW4, SW5, SW6, SW7, SW8, SW10 and SW11 are in the fourth order in the Neyyar watershed (Fig. 3).

Stream number (N_u)

The number of stream segments with different orders is inversely proportional to the stream order. There is also a drop in first-order streams, which diminishes as the order of stream increases. SW1 and SW4 have the maximum and minimum N_u in this current study, respectively.

Stream length (L_u)

Stream length refers to the overall length of all stream segments in a given order in a watershed. Lu, which displays the watershed's sediment qualities, is one of the essential drainage properties. SW9 (120 km) and SW2 (52 km) are the lengths of the greatest and smallest streams, respectively, in this study.

Bifurcation ratio (R_b)

The bifurcation ratio was the ratio of the number of streams of one order to the number of streams of the next highest level, according to Strahler (1964). SW1 and SW11 have the highest bifurcation ratios in our study, whereas SW4 has the lowest.

Stream length ratio (R_l)

It is the proportion of one order's mean stream length to the following, smaller order mean stream length (Horton 1945). The maximum and minimum mean stream lengths in this study are SW10 and SW5, respectively.

Two fundamental laws, according to Horton (1945), link the number of distinct orders in a river basin to the length of the stream. The first is the law of stream numbers, which explains the relationship between N_u of a provided order and its order of stream using an inverted geometric

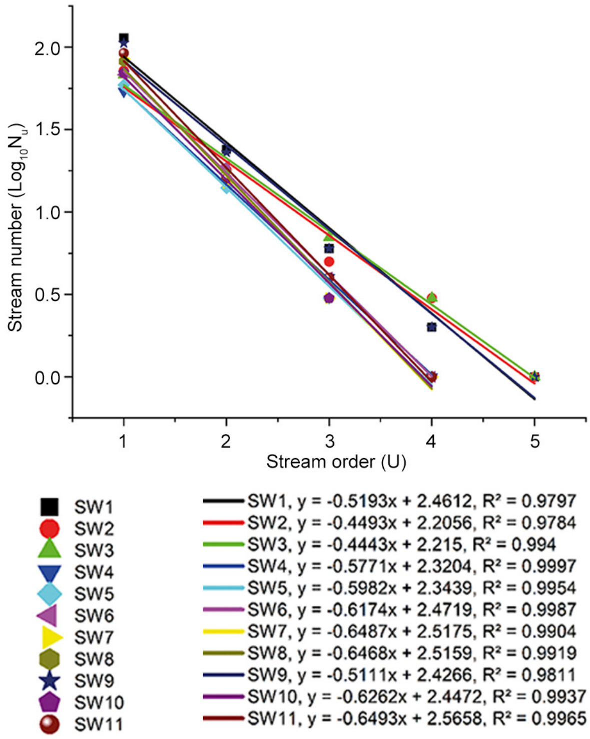

Fig. 4. Relationship between each sub-watershed's stream number and stream order.

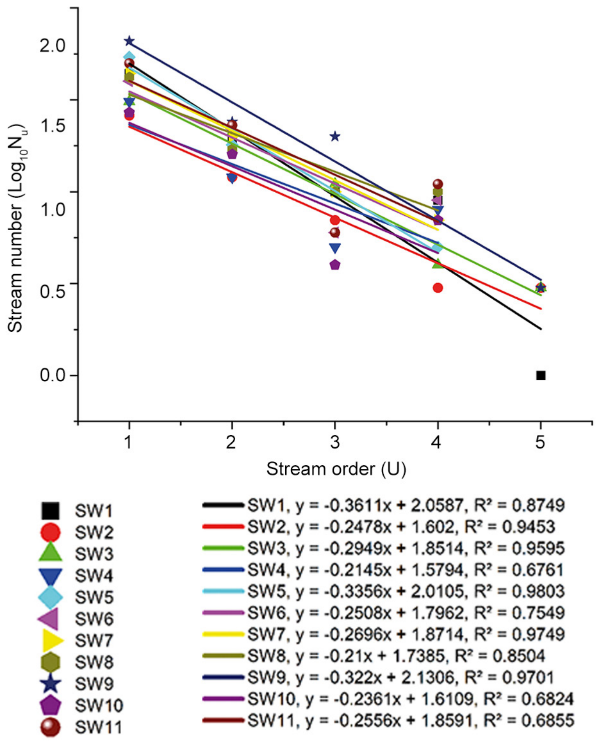

Fig. 5. Relationship between each sub-watersheds stream length and stream order.

series with the R_b as the base. The link between U and N_u is clearly shown with coefficients of determination ranging from SW2 (0.978) to SW4 (0.999) (Fig. 4).

The second is the law of L_u, which is defined as the mean length of a certain order when it comes to the stream length ratio, order of stream and average length of first-order streams. A direct geometric series is used to express this rule. With coefficients of determination ranging from SW4 (0.676) to SW5 (0.980), Figure 5 shows a substantial link between stream order and stream length.

Mean stream length (L_{sm})

It is a dimensional feature that indicates the normal size of drainage network components and their contributing catchment surfaces, according to Strahler (1964). The maximum (0.86) and minimum (0.46) mean stream lengths in this study are SW10 and SW5, respectively.

Mean bifurcation ratio (R_{bm})

Strahler (1957) used a weighted average ratio of bifurcation, which was calculated by multiplying the ratio of bifurcation for each additional set of patterns by the overall number of streams occupied in the ratio and taking the average of the combination of these results to arrive at a more representative bifurcation number. This method allowed for the calculation of a more precise bifurcation number. SW3 has the lowest value in this study, whereas SW11 has the highest value.

Stream frequency (F_s)

It is defined as the ratio of the overall number of streams in a watershed to the entire area of the watershed. In this study, SW2 has the highest value, while SW5 has the lowest.

Drainage density (D_d)

It refers to the ratio of the overall stream length to the watershed area. It depicts the progression of the stream and its spacing. Climate, relief, channel head and landscape change all have an impact. In this study, SW2 has the highest value, while SW5 has the lowest value.

Drainage texture (D_t)

It is defined as the ratio of the stream numbers to the watershed perimeter (P). In this study, SW1 has the highest value, while SW11 has the lowest value.

Length of the overland flow (L_o)

The reciprocal D_d is typically half the Lo (Horton 1945). In this study, SW5 has the highest value, while SW2 has the lowest value.

Drainage intensity (D_i)

Drainage intensity is the proportion of Fs to D_d (Faniran 1968). The D_i is maximum and minimum at SW2 and SW5, respectively, in the current study.

RHO coefficient (ρ)

It is the ratio of R_{lm} to R_{bm}. It is a critical feature that controls the stream network's storage capacity and drainage development. The RHO coefficient is maximum and minimum at SW5 and SW4, respectively, in this study.

Relief parameters

Relief (B_h)

It is quantitatively defined as the range between the maximum and minimum elevations of the watershed. SW1 has the maximum value in this study, whereas SW10 has the minimum value.

Relative relief (R_{hp})

It is the ratio of watershed relief to the watershed circumference. SW1 has the highest value in this study, while SW9 has the lowest value.

Ruggedness ratio (R_n)

It is the product of watershed relief and drainage density (Strahler 1952b). The greater and lower values have been discovered in this investigation at SW1 and SW9, respectively.

Areal parameters

Area of watershed (A)

The overall area enclosed by the basin boundary is referred to as the watershed area. The watershed covers 474.14 km^2 in total. The greatest and smallest sub-watershed regions in the current study are SW9 and SW2, respectively, as shown in Figure 6.

Perimeter of a watershed (P)

The full extent of a basin's boundaries is the watershed's perimeter. It has the equal size and shape as the watershed. The basin perimeter affects two parameters: the elongation ratio and the circulation ratio. The watershed has a total perimeter of 314 km. The largest and smallest sub-watershed perimeters of the 14 Neyyar basins are 69.93 km (SW 9) and 33.08 km (SW 2), respectively, as shown in Figure 7.

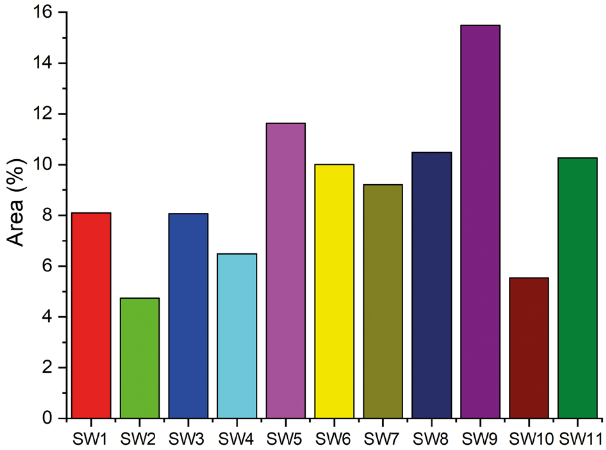

Fig. 6. Percentage of each sub-watersheds area.

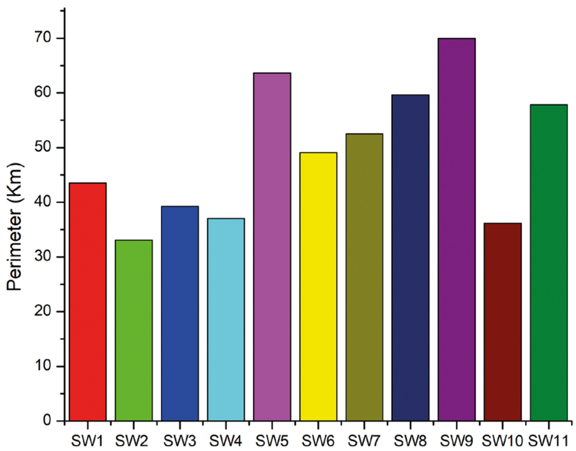

Fig. 7. Perimeter of each sub-watershed.

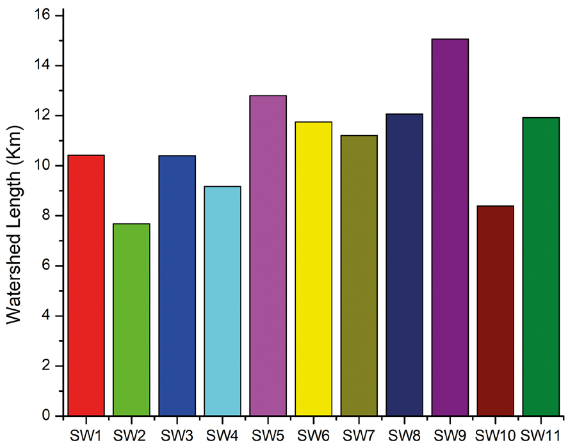

Fig. 8. Watershed length of each sub-watershed.

Watershed length (L_b)

The longest dimension of a watershed, according to Schumm (1956), is parallel to the major river channel. In the current research, SW9 (15.06 km) has the largest sub-watershed length, whereas SW2 has the shortest length (7.68 km), as shown in Figure 8.

Circulatory ratio (R_c)

It is the area of the watershed divided by the area of a circle with an equal circumference as the watershed's perimeter. SW3 has a higher circulatory ratio in this study, while SW5 has a lower circulatory ratio.

Elongation ratio (R_e)

It is the ratio of the diameter of a circle with an equal area as the catchment to the length of the catchment. SW2 has a higher elongation ratio in this study, while SW9 has a lower elongation ratio, as shown in Figure 9.

Form factor (F_f)

It is the ratio of the watershed area to the square of the watershed length. SW2 has a higher form factor in this current study, while SW9 has a lower form factor.

Compactness coefficient (C_c)

According to Horton (1945), it is the ratio of the watershed's perimeter to the circumference of its equivalent circular area. SW5 has a higher compactness coefficient in this study, while SW3 has a lower compactness coefficient.

Descriptive statistics of morphometric features

Table 3 displays the descriptive statistical analysis of all selected sub-watershed morphometric properties. Minimum, maximum, sum, mean, standard error, variance, standard deviation, median, 25th percentile, 75th percentile, skewness and kurtosis were calculated. The R_{bm} and L_o parameters have a left-skewed distribution, as shown in Table 3, R_{lm}, D_d, R_{hp}, R_c, R_e, F_f, F_s, D_t, C_c,

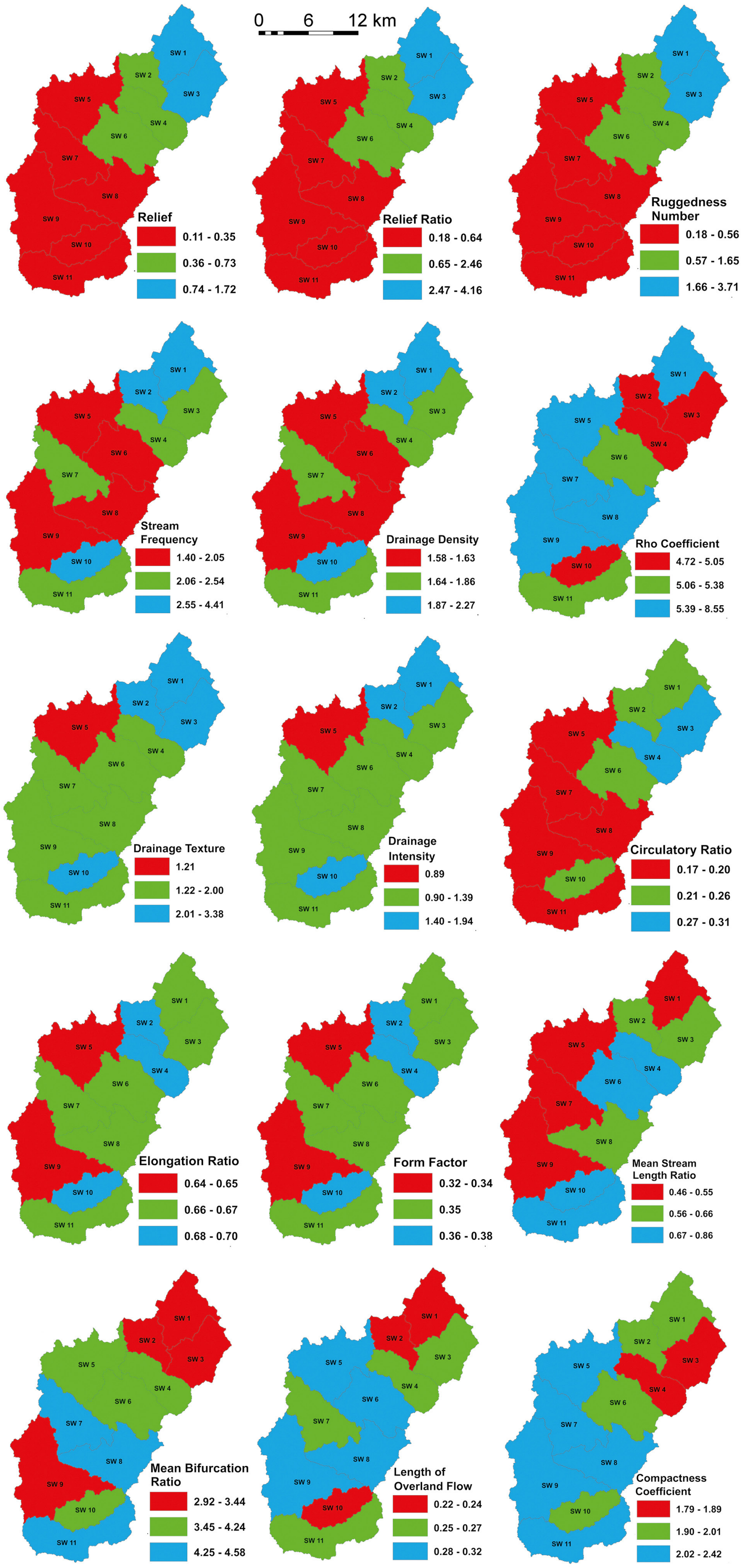

Fig. 9. Fifteen morphometric parameters of each sub-watersheds.

Table 3. Descriptive statistics of morphometric parameters.

Parameter	N	Minimum	Maximum	Sum	Mean	Standard error	Variance	Standard deviation	Median	25 percentiles	75 percentiles	Skewness	Kurtosis
R_{bm}	11	2.92	4.58	42.50	3.86	0.18	0.36	0.60	3.96	3.36	4.49	−0.31	−1.33
R_{lm}	11	0.46	0.86	7.15	0.65	0.05	0.02	0.15	0.62	0.49	0.80	0.27	−1.61
F_s	11	1.40	4.41	28.58	2.60	0.28	0.83	0.91	2.38	1.94	3.43	0.93	0.09
D_d	11	1.58	2.27	20.27	1.84	0.07	0.06	0.24	1.83	1.62	2.06	0.61	−0.68
D_t	11	1.21	3.38	24.03	2.18	0.18	0.37	0.61	1.98	1.88	2.49	0.64	0.45
L_o	11	0.22	0.32	3.03	0.28	0.01	0.00	0.03	0.27	0.24	0.31	−0.26	−1.13
ρ	11	4.72	8.55	67.67	6.15	0.42	1.92	1.39	5.38	4.96	6.98	0.70	−0.96
D_i	11	0.89	1.94	15.15	1.38	0.09	0.09	0.30	1.29	1.20	1.67	0.55	0.08
B_h	11	0.11	1.72	6.37	0.58	0.17	0.32	0.57	0.35	0.11	0.73	1.24	0.48
R_{hp}	11	0.18	4.17	16.46	1.50	0.46	2.32	1.52	0.64	0.34	2.46	0.99	−0.47
R_n	11	0.18	3.71	12.28	1.12	0.36	1.39	1.18	0.56	0.22	1.65	1.40	1.16
R_c	11	0.17	0.31	2.52	0.23	0.01	0.00	0.05	0.25	0.18	0.26	0.24	−1.24
R_e	11	0.64	0.70	7.35	0.67	0.00	0.00	0.02	0.67	0.66	0.68	0.29	−0.11
F_f	11	0.32	0.38	3.86	0.35	0.00	0.00	0.02	0.35	0.34	0.37	0.32	−0.13
C_c	11	1.79	2.42	23.32	2.12	0.07	0.05	0.22	2.01	1.97	2.34	0.07	−1.68

D_i, B_h and R_n parameters have a right-skewed distribution. With morphometric parameters' kurtosis values evaluated, it becomes evident that 10 of the parameters, namely, R_{bm}, R_{lm}, D_d, L_o, R_{hp}, R_c, R_e, F_f and C_c, exhibit platykurtic distribution. It indicates that the estimated kurtosis results were flat with thin tails, resulting in negative kurtosis results. Other morphometric features have positive kurtosis results, indicating that the distribution for these groupings of features is peaked and has thick tails, indicating that they are in the leptokurtic distribution (Redvan, Mustafa 2021). The whiskers box plots for the stated parameters are shown in Figure 10.

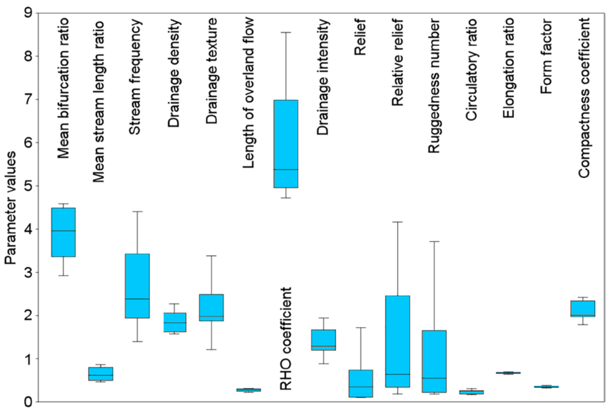

Fig. 10. Whiskers box plots of 15 morphometric parameters.

Morphometric sub-watershed prioritisation and ranking

To examine the features of the drainage system, morphometric analysis was performed for the SWs. To prioritise SWs for soil conservation, 15 morphometric factors representing linear, shape and relief features were used. Linear, shape and relief features are three different morphometric features that have been used to rank SWs in order of risk because they are either directly or inversely related to the risk of soil erosion, runoff and peak discharge. The relief and linear features are directly associated with risk of soil erosion, runoff and peak discharge, while the shape features are inversely associated with risk of soil erosion, runoff and peak discharge (Nookaratnam et al. 2005).

The highest value is ranked first for relief and linear features, and so on, while the lowest value is ranked first for the shape feature, and so on. Table 4 displays the ranking results for all 11 SWs. The compound parameter (Cp) value (4.47) was obtained by adding all the ranks in SW1 (67), and the resultant sum was divided by the number of features (15). This was repeated for the remaining SWs.

The SWs were classified into three classes after the compound value calculation: high (≥ 4.45 to < 7.33), medium (≥ 5.33 to < 6.20) and low (≥ 6.75

Table 4. Final ranking of morphometric analysis.

Parameter	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11
Mean bifurcation ratio	8	10	11	7	6	5	2	3	9	4	1
Mean steam length ratio	10	6	7	3	11	4	8	5	9	1	2
Stream frequency	2	1	4	5	11	9	6	8	10	3	7
Drainage density	2	1	6	7	11	9	4	10	8	3	5
Drainage texture	1	2	4	5	11	9	6	10	7	3	8
Length of overland flow	10	11	6	5	1	3	8	2	4	9	7
RHO coefficient	3	9	8	11	1	7	2	5	4	10	6
Drainage intensity	2	1	4	5	11	9	7	6	10	3	8
Relief	1	4	2	3	6	5	8	7	9	11	10
Relative ratio	1	3	2	4	6	5	8	7	11	9	10
Ruggedness number	1	3	2	4	6	5	8	7	11	9	10
Circulatory ratio	8	9	11	10	1	6	5	2	4	7	3
Elongation ratio	7	11	8	9	2	5	6	3	1	10	4
Form factor	7	11	8	9	2	5	6	3	1	10	4
Compactness coefficient	4	3	1	2	11	6	7	10	8	5	9
Sum of rankings (X)	67	85	84	89	97	92	91	88	106	97	94
Total number of parameters (Y)	15	15	15	15	15	15	15	15	15	15	15
Compound parameter (X/Y)	4.47	5.67	5.60	5.93	6.47	6.13	6.07	5.87	7.07	6.47	6.27
Ranking	1	3	2	5	9	7	6	4	11	10	8
Final priority	High	Medium	Medium	Medium	Low	Medium	Medium	Medium	Low	Low	Low

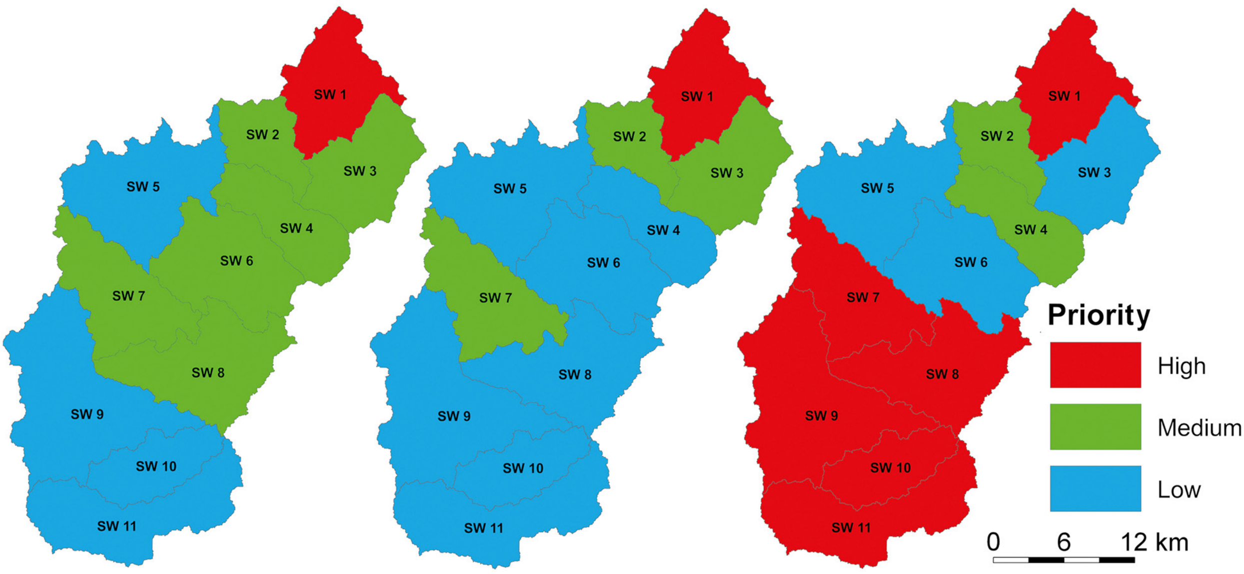

Fig. 11. Priority of SWs based on three methods (A is morphometric analysis, B is PCA and C is hypsometric analysis). PCA, principal component analysis; SWs, sub-watersheds.

to < 7.07). SW1 is a high-priority sub-watershed, while SW2, SW4, SW6, SW3, SW7 and SW8 are medium-priority SWs, and SW5, SW9, SW10 and SW11 are low-priority SWs. The final sub-watershed priority map for the Neyyar watershed is shown in Figure 11.

Prioritisation of SWs based on PCA

A statistical technique known as PCA can be used to find hidden elements that determine the pattern of correlations among several observable variables while preserving the original, accurate data. The correlation between each morphometric feature was identified using correlation analysis in SPSS version 22. It was evident from this investigation that F_f is very strongly correlated with Re. There was a strong correlation between D_d and F_s; between L_o, F_s and D_d; between D_i and F_s; between R_{hp} and B_h; between R_n, B_h and R_{hp}; and between C_c and R_c. On the contrary, D_t and

Table 5. Correlogram of 15 morphometric parameters.

	R_{bm}	R_{lm}	F_s	D_d	D_t	L_o	p	D_i	B_h	R_{hp}	R_n	R_c	R_e	F_f	C_c
R_{bm}	1														
R_{lm}	0.45	1													
F_s	−0.40	0.08	1												
D_d	−0.36	0.09	0.97	1											
D_t	−0.54	−0.06	0.92	0.89	1										
L_o	0.33	−0.13	−0.95	−0.99	−0.88	1									
p	0.27	−0.72	−0.41	−0.36	−0.37	0.39	1								
D_i	−0.39	0.13	0.99	0.93	0.92	−0.91	−0.47	1							
B_h	−0.68	−0.32	0.42	0.41	0.65	−0.40	−0.19	0.43	1						
R_{hp}	−0.73	−0.26	0.51	0.49	0.69	−0.49	−0.29	0.51	0.98	1					
R_n	−0.68	−0.33	0.52	0.50	0.73	−0.49	−0.17	0.51	0.99	0.98	1				
R_c	−0.62	0.20	0.51	0.49	0.61	−0.52	−0.68	0.54	0.71	0.79	0.68	1			
R_e	−0.24	0.39	0.81	0.80	0.61	−0.80	−0.59	0.80	0.29	0.41	0.33	0.66	1		
F_f	−0.25	0.39	0.81	0.80	0.61	−0.80	−0.59	0.80	0.29	0.41	0.33	0.66	1.00	1	
C_c	0.59	−0.23	−0.56	−0.54	−0.65	0.57	0.68	−0.59	−0.69	−0.76	−0.67	−0.99	−0.69	−0.68	1

■ – −1, □ – 0, ■ – 1

R_{lm} have a very weak correlation. Similarly, there is a weak correlation between Fs and R_{lm} and D_d and R_{lm}. In the given correlogram, as shown in Table 5, the blue cell with a value of 1 and the red cell with value of −1 represent the strongest positive (1) and negative correlation (−1) between two characteristics, respectively. In Table 6, the component loading matrix is displayed. The top three components, all of which have eigenvalues of more than 1, account for 91.53 percent of the overall variance in the actual information and are clearly important. According to the rotational component matrix, component 1 is strongly correlated with drainage density (as seen by the bold font, which indicates the number is very close to either +1 or −1), component 2 is strongly correlated with relief (as seen by the bold font) and component 3 is strongly correlated with the RHO coefficient (Table 7) (Meshram, Sharma 2017, Shekar, Mathew 2022c). The three important morphometric features deduced from PCA are drainage density, relief and the RHO coefficient. Therefore, the 11 SWs of the Neyyar watershed are prioritised using these characteristics.

Table 6. Total variance of the morphometric indices explained (15 morphometric parameters).

Component (15 morphometric parameters)	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	9.065	60.430	60.430	9.065	60.430	60.430	5.817	38.781	38.781
2	2.921	19.471	79.902	2.921	19.471	79.902	5.007	33.382	72.164
3	1.744	11.629	91.530	1.744	11.629	91.530	2.905	19.367	91.530
4	0.521	3.471	95.001						
5	0.461	3.076	98.076						
6	0.165	1.100	99.176						
7	0.109	0.724	99.900						
8	0.011	0.074	99.974						
9	0.003	0.018	99.992						
10	0.001	0.008	100.000						
11	2.101E-16	1.401E-15	100.000						
12	8.838E-17	5.892E-16	100.000						
13	2.866E-17	1.911E-16	100.000						
14	−3.703E-16	−2.468E-15	100.000						
15	−9.560E-16	−6.373E-15	100.000						

Table 7. Rotated component matrix (strong coefficients are marked by the bold font).

Parameter	Component		
	1	2	3
R_{bm}	−0.177	−0.814	0.031
R_{lm}	0.084	−0.414	0.855
F_s	0.951	0.256	0.125
D_d	**0.956**	0.229	0.106
D_t	0.802	0.515	0.039
L_o	−0.937	−0.227	−0.148
ρ	-0.232	−0.183	**−0.884**
D_i	0.918	0.263	0.185
B_h	0.200	**0.945**	−0.002
R_{hp}	0.277	0.937	0.087
R_n	0.311	0.911	−0.055
R_c	0.278	0.723	0.597
R_e	0.752	0.139	0.544
F_f	0.758	0.149	0.533
C_c	−0.336	−0.686	−0.599

According to the three morphometric features (drainage density, relief and RHO coefficient) obtained using the PCA technique, Table 8 displays the final priority ranks and Cp values. SWs were categorised as high (Cp values within ≥ 2 to < 4), medium (Cp values within ≥ 4 to < 6) and low (Cp values within 6 and 8). Among the 11 SWs, SW1 falls under a high priority; SW2, SW3 and SW7 fall under a medium priority; and SW4, SW5, SW6, SW8, SW9, SW10 and SW11 fall under a low priority. Figure 11 depicts the final sub-watershed priority map for the Neyyar watershed.

Prioritisation of SWs based on hypsometric analysis

The hypsometric curves capture the relief ratio and watershed volume, which are useful in providing excess rainfall and other hydrological processes (Keller, Pinter 1996, Vivoni et al. 2008). These graphs show not only the basin's erosion status but also the tectonic, climatic and lithological elements that influence it (Sarp et al. 2011). Roy (2002) claimed that as the aspect ratio decreases, the river system becomes more branched, resulting in a greater bifurcation ratio. The drainage network and basin geometry have a great impact on hypsometry.

The HI was determined using the elevation-to-relief ratio approach proposed by Pike and Wilson (1971). In the current research, HI varies from 0.146 to 0.388 (Fig. 12). Low-priority (≥ 0.146 to < 0.226), medium-priority (≥ 0.226 to < 0.307) and high-priority (≥ 0.307 to < 0.388) SWs were identified (Farhan et al. 2016). SW1, SW7, SW8, SW9, SW10 and SW11 are high-priority SWs, SW2 and SW4 are medium-priority SWs, while SW3, SW5 and SW6 are low-priority SWs, as shown in Table 9. The final sub-watershed priority map for the Neyyar basin is shown in Figure 11.

Common SWs

In the present study, compared with three methods, some SWs have a common priority such as SW1, SW2 and SW5, and there is good correlation among them. Other SWs like SW3, SW4, SW6, SW7, SW9, SW10 and SW11 have a minimum of two methods with the same priority. For example, SW3 is having medium, medium and low here; this could be suggested as medium because the majority of the methods show similar priorities. Finally, SW8 is different in all its methods because there is no correlation among them, as shown in Table 10.

Inferences

Traditionally, topographic maps or field surveys are used to determine the morphometric parameters. These variables are essential for

Table 8. Final ranking of principal component analysis.

Parameter	SW 1	SW2	SW 3	SW4	SW 5	SW6	SW7	SW8	SW 9	SW10	SW11
Drainage density	2	1	6	7	11	9	4	10	8	3	5
RHO coefficient	3	9	8	11	1	7	2	5	4	10	6
Relief	1	4	2	3	6	5	8	7	9	11	10
Sum of rankings (X)	6	14	16	21	18	21	14	22	21	24	21
Total number of parameters (Y)	3	3	3	3	3	3	3	3	3	3	3
Compound parameter (X/Y)	2	4.67	5.33	7	6	7	4.67	7.33	7	8	7
Ranking	1	2	4	6	5	7	3	10	8	11	9
Final priority	High	Medium	Medium	Low	Low	Low	Medium	Low	Low	Low	Low

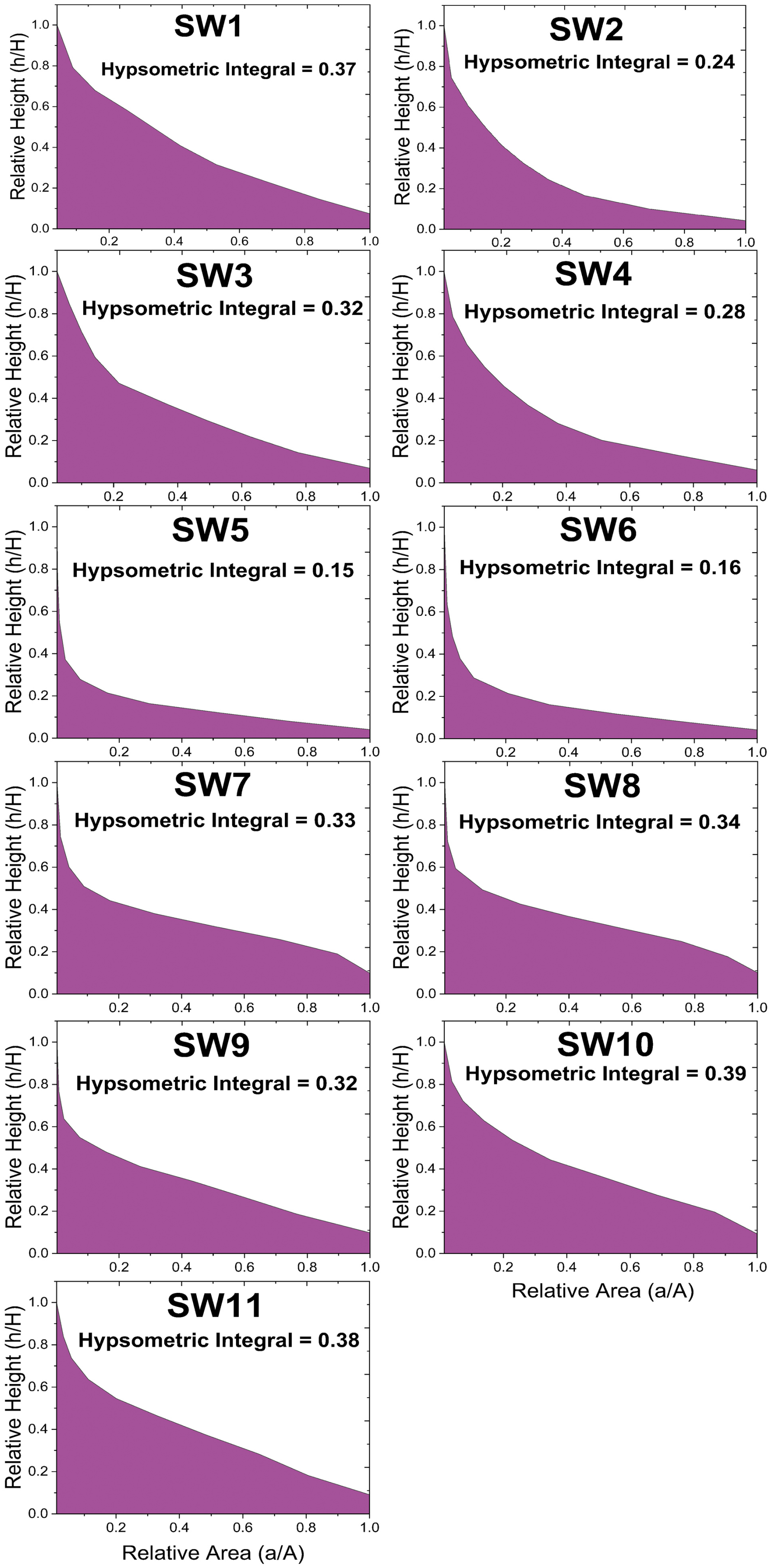

Fig. 12. Hypsometric curve and hypsometric integral HI.

Table 9. Final ranking of hypsometric analysis.

Parameter	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11
HI	0.37	0.24	0.32	0.28	0.15	0.16	0.33	0.34	0.32	0.39	0.38
Ranking	9	3	6	4	1	2	7	8	5	11	10
Final priority	High	Medium	Low	Medium	Low	Low	High	High	High	High	High

Table 10. Common priority of three methods (high = H, medium = M, low = L).

Method	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11
Morphometric analysis	H	M	M	M	L	M	M	M	L	L	L
PCA	H	M	M	L	L	L	M	L	L	L	L
Hypsometric analysis	H	M	L	M	L	L	H	H	H	H	H
Common priority	H	M	M	M	L	L	M	–	L	L	L

drainage analysis since they are readily available, straightforward and affordable. However, the extraction of channel networks and the delineation of watersheds from topographic maps are not only time-consuming but also use non-digital methods. So, in order to merge with RS and geographic information system data, these data are digitalised. For computerised mapping and spatial analysis, GIS is a powerful resource. GIS can be used to establish watershed priorities in a less expensive, less time-consuming and less labour-intensive manner. In this current research, three methods have been used for the Neyyar River basin prioritisation, wherein novel strategies are introduced to rank the priority of SWs based on PCA and hypsometric analysis. The results obtained from three methods indicate that SW1 is a common high priority area with a significant risk of soil erosion, runoff and peak discharge. Hence, high-priority SWs need immediate attention for soil and water conservation measures.

Conclusion

The current study uses PCA, morphometric analysis and hypsometric analysis to show how RS and GIS approaches can be used to prioritise SWs. A quantitative morphometric analysis was carried out in 11 SWs of the Neyyar River basin using GIS technology to determine the linear, shape and relief parameters. According to the outcomes of morphometric analysis-based prioritisation, the SW1 is of high priority. On the contrary, the PCA-based technique allows for more effective features for watershed prioritisation. According to the results of PCA-based prioritisation, SW1 is of high priority. According to the results of hypsometric analysis-based prioritisation, the SW1, SW7, SW8, SW9, SW10 and SW11 are of high priority. SW1 (high), SW2 (middle) and SW5 (low) are the most common SWs that have the same priority with good correlation among them. The study findings point to a useful tool for identifying locations (high priority, SW1) where strategies to control soil erosion and promote soil conservation may be implemented. This could involve both physical and biological solutions such as the construction of bunds and check dams, and the planting of multipurpose tree species, depending on the right location (high priority, SW1) and design requirements. The findings may be used by the decision-making bodies to organise and carry out watershed management operations to control soil erosion in high-priority areas. To further investigate the in-depth local study, micro-level watershed analysis will be carried out in the future.

Author Contribution

PRS: conceptualization, methodology, software, data curation, and writing—original draft preparation; AM: supervision, visualization, and investigation writing—reviewing and editing. The authors read and approved the final manuscript.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on responsible request.

Conflict of interest

The authors declare no competing interests.

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