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TOPSIS-BASED PRIORITISATION OF SUB-WATERSHEDS FOR EROSION AND FLOOD VULNERABILITY IN NAMBIYAR WATERSHED, SOUTH INDIA

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Abstract: Watershed management projects are undertaken to identify and prioritise regions with degradation problems to ensure effective development planning and conservation activities. This study prioritises sub-watersheds in the Nambiyar watershed, South India, to address degradation issues like soil erosion, runoff, and flood vulnerability for effective planning and conservation activities. Various reports stated that strong monsoons exacerbate flash floods in the Nambiyar watershed, generating substantial runoff and erosion. To rank the sub-watersheds, morphometric parameters, and Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS), a Multi-Criteria Decision Making (MCDM) technique was utilised. The results show that the sub-watersheds 1, 4, 2, and 3 are ranked 1, 2, 3, and 4, respectively, as the most vulnerable sub-watersheds for the occurrence of erosion, floods, etc., and hence categorised as 'Very High Priority' class with 57.01 sq. km (8%) of the total watershed area. The watersheds identified for 'high priority' cover an area of 199.19 sq. km, i.e., 29.93% of the area. High-ranked sub-watersheds are prioritised for resource conservation and management due to their susceptibility to flash floods, soil erosion, and excessive runoff. Similar studies combining geospatial and MCDM techniques in this watershed offer valuable insights for assessing physical characteristics and prioritising natural resource conservation and disasters.

Keywords: Drainage, morphometric analysis, TOPSIS, sub-watersheds, prioritisation.

Introduction

The quality of natural resources such as land and water in a watershed is inhibited when it confronts issues such as soil erosion, surface runoff, and flood vulnerability. Such problems can be identified by prioritising the area for taking suitable measures to prevent and manage the natural resources effectively. Morphometric properties of a drainage basin are quantitative landscape attributes derived from a drainage basin's terrain or elevation surface and drainage network (Biswas *et al.,* 2014). Quantitative analysis of the drainage basin is mainly accomplished to understand the evolution and structure of the basin. The inputs of the basin, like rainfall, lithology, geomorphology, soil, and land use, and the rate of stream flow vary from one basin to another (Ion, 1985; Aparna *et al.,* 2015). Morphometric analysis is the prime source for understanding the geomorphic characteristics of a basin. Hydrological and morphometric characteristics of a drainage basin help in the analysis of the general hydrological processes of the basin, examine flood vulnerability areas, study river regime, soil erosion and deposition, vegetation cover and changes; groundwater and water conservation among others (Rai *et al.,* 2014; Mishra *et al.,* 2016; Mayomi *et al.,* 2018; Kumar *et al.,* 2021).

Numerous studies have been carried out on morphometric analysis in various river basins for a specific purpose. The study conducted in a tropical mountain system in southern Western Ghats, India, revealed that analysing morphometric parameters helped to understand the tendency of soil erosion in the watershed and formulate a comprehensive watershed management plan (Thomas *et al.,* 2010; Singh *et al.,* 2021). Drainage morphometric parameters (linear, areal, and relief) were used for prioritising the sub-basin to map the groundwater potential zones in the Mulki-Pavanje basin in India (Avinash *et al.,* 2014). A study conducted in the Kanhar and lower Kosi River basins used Geographic Information System (GIS) based drainage morphometric analysis to comprehend the hydrological response behaviour in the basin (Rai *et al.,* 2017; 2018). The understanding of morphometric analysis to assess the form and process of the watershed is indispensable for watershed development, management, and conservation of resources (Najibi *et al.,* 2017; Prabhakaran *et al.,* 2018; Prasanna *et al.,* 2022). Comprehension of linear and relief morphometric parameters is a key element in examining and explaining the various processes responsible for the origin and development of drainage and landscape in a basin. Quantitative geomorphometric analysis of a basin also enables the understanding of tectonic activities that mould a landscape. This is evident from the studies conducted in two basins of Northern Borneo, which indicate the region has undergone a series of tectonic processes, like the upliftment of landscape in the past and also continues in the form of folding of thrust belts (Mathew *et al.,* 2016). Similar implications have been found in the landscape formation of the South Indian Peninsula, which is influenced by tectonic processes and climate forces. The movement of plates and related geomorphic processes affect the nature and course of drainage systems (Ramkumar *et al.,* 2019).

Prioritisation of sub-watersheds for resource management can be done by considering various morphometric parameters which induce flood, soil erosion, and surface runoff (Arabameri *et al.,* 2018; Nithershnirmal *et al.,* 2019; Bharath *et al.,* 2021; Tiwari *et al.,* 2021). Because of the accuracy and dependability of computed morphometric parameters, geospatial technology has emerged as a viable tool for quantitative research of drainage basins. Other than that, Multi-Criteria Decision Making (MCDM) was created as a more precise quantitative method for ranking and prioritising sub-watersheds based on morphometric criteria (Magesh *et al*., 2013; de Araújo *et al.,* 2022).

The past two decades witnessed tremendous changes in land use and land cover categories in the watershed, especially with the construction of the Kodumudiyar Dam in 2003 and the Nambiyar Dam in 2004. These dams serve as the main source of irrigation for more than 40 villages, which helped convert the scrubland to arable lands and increased the agricultural productivity in the watershed. Besides, the population density in these villages has also increased, thus accelerating stress on the quality of resources such as soil and water. The assessment of resource potential zones and cropping patterns carried out in the watershed shows that it is dominated by single crop 'paddy cultivation' utilising more amount of water which in time retarding the soil quality (Narmada *et al*., 2015). Various instances of flash flood occurrences have also been reported in the upper reaches of the River Nambiyar, i.e., in the foothills of the Western Ghats, affecting the livelihoods and infrastructure of people residing in the foothills (Times of India Report, 2018). To address these issues of maintaining the quality of land and water resources and supporting sustainable development, this study has been undertaken to identify the risk-prone areas to the occurrence of flash floods, runoff, and erosion.

Materials and Methods

Study Area

The Nambiyar watershed lies in the southern part of the Tirunelveli District of Tamil Nadu, India. It extends from 8°10'N to 8°32'N latitudes and 77°28'E to 77°50'E longitudes. The basin covers an area of 665.45 sq. km (66,545.98 ha). The source of the river is located in the Kalakkadu Reserved forest, which is a part of the Western Ghats with an altitude of 1800 m. The river flows towards the east, enters the plains at Thirukurangudi, and finally drains into the Bay of Bengal. Kodamadi Ar, Paratai

Ar, Tamarai Ar, Valliyurankal, and Kallanodai are the major tributaries of the Nambiyar River. The watershed has a unique locational setting that spans hilly terrain up to coastal plains. The dominant rock type found in this region is gneiss, which is composed of a variety of minerals. The most dominant formation observed in the watershed is metamorphic rocks of the Archean era, i.e., before 2.5 billion years ago. The drainage network in the watershed exhibits a dendritic pattern of drainage, which is also a sign of the uniformity of the underlying formation in the watershed. The dominant rock type found in this region is gneiss, which is composed of a variety of minerals. Many studies have noted that these rocks were formed from igneous rocks, the oldest of the peninsular region. Charnockites, also called black granites, occur in southern Tamil Nadu and extend up to Kanyakumari, Western Ghats, and Eastern Ghats. The lithology of coasts is composed of silt, clay, sand, clay sand alluvium, and calcareous sandstone, which are naturally soft unconsolidated sediments from the quaternary period. It is covered by red aeolian sand, locally known as 'teri' sand, and found along the coasts. Red garnet sand is also found along the coastal part of the Nambiyar watershed. The average slope of the Nambiyar watershed is 4° and ranges from 0° to 70°. The western portion of the watershed comprises highly dissected hills and valleys and has a moderate to steep slope of 7° to 70°. In the coastal plain region in the southeastern part of the watershed where the Nambiyar River debouches into the Bay of Bengal, the slope is very gentle, from 0° to 2°. Sandy clay loam is the dominant soil found in major parts of the watershed. It occupies 32% of the total watershed area (213.24 sq. km). Clay soil is the next predominant soil type found in the Nambiyar watershed, which covers an area of 150 sq. km (i.e., 21%). The average annual precipitation of the Nambiyar watershed is 1,027 mm, varying from 639.6 mm to 1,881.3 mm. Out of the four seasons, the Northeast Monsoon season has the greatest influence on rainfall distribution throughout the watershed, accounting for around 47% of total rainfall. The southwest monsoon contributed almost 30% of the total rainfall in the watershed. The location of the watershed and its physical and population characteristics are shown in Figure 1.

Analysis

The Survey of India Toposheets (No: 58H/06, 07, 10, 11, 15, 16) with a scale of 1:50,000 were used as the base map for delineating sub-watersheds and digitisation of the stream network. Google Earth images of the year 2023 and soil maps collected from Tamil Nadu Agricultural University were used to cross-reference the erosion-prone areas in the study area. The land use and land cover map of the watershed was prepared using the Landsat 8 satellite image downloaded from United States Geological Survey (USGS) Earth Explorer. Figure 2 depicts the flowchart of the methods used in the current study. The watershed was divided into 15 sub-watersheds designated as SW 1, 2, 3…, and 15, as shown in Figure 3, and morphometric parameters were calculated for these sub-watersheds. The selected parameters from linear, areal, and relief aspects were calculated using the formula given in Table 1. Further, in the Arc Soil and Water Assessment Tool (SWAT), the boundary and existing drainage network in the Nambiyar Watershed were validated using a Shuttle Radar Topography Mission – Digital Eleveation Model (SRTM-DEM) image.

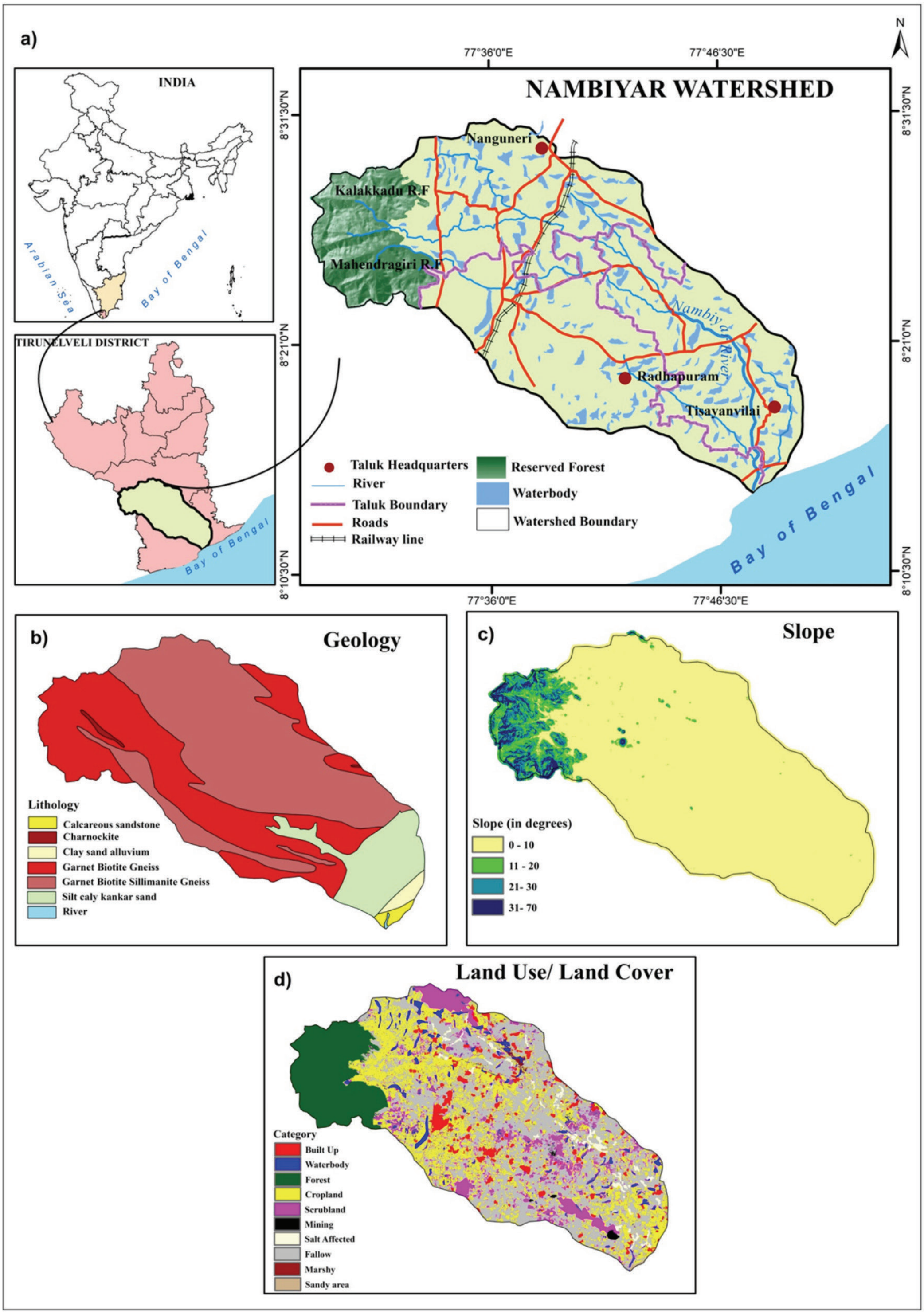


Figure 1: Location of the study area (a), geology map of the watershed (b), slope of the watershed (d), and landuse/land cover categories of the watershed (c)

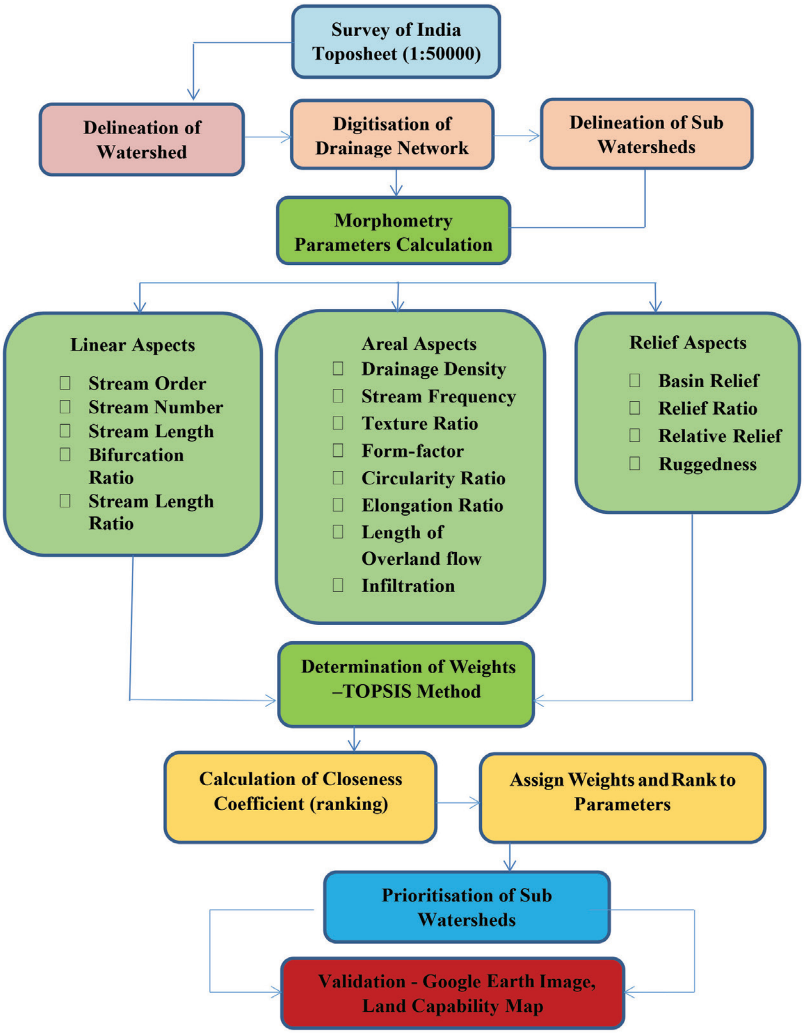


Figure 2: Flowchart of the methodology

Table 1: Morphometric Parameters and standard formula

	Morphometric Parameters	Formula	Reference
Linear Aspects	Streams Order (*Nu*)	Hierarchical Ordering of Streams	Strahler (1957)
	Stream Length (*Lu*)	Length of Stream	Horton (1945)
	Bifurcation Ratio (*Rb*)	*Nu*/(*Nu*+1) *Nu* is the length of streams in order in the given order, and (*Nu*+1) is the length of streams in the next higher order. *Nu* is any stream order	Horton (1945)
	Mean Stream Length (*Lum*)	*Lum* = *Lu*/Total no. of streams in an order (*Nu*)	Horton (1945)

	Stream Length Ratio (*Lur*)	*Lur* = *Lu*/(*Lu*-1) *Lu* is length of streams of a given order (*Lu*-1) is the length of streams previous lower order	Horton (1945)
	Rho coefficient (ρ)	ρ = *Lur*/*Rb*	Horton (1945)
Areal Aspects	Drainage Density (*DD*)	*DD* = L/A L-Total length of streams A- Area of the Watershed	Horton (1932)
	Stream Frequency (*Fs*)	*Fs* = N/A N- Total number of streams A-Area of the Watershed	Horton (1945)
	Texture Ratio (*Rt*)	*Rt* = N/P N-Total number of streams P-Perimeter of the Watershed	Horton (1945)
	Drainage Intensity (*DI*)	*DI* = *Fs*/*DD*	Faniran (1968)
	Drainage Texture (*DT*)	*DT* = *DD***Fs*	Smith (1950)
	Form-factor (*Ff*)	*Ff* = A/Lb2	Horton (1945)
	Circularity Ratio (Rc)	Rc = 4πA/P2 (π = 3.14)	Miller (1953)
	Elongation Ratio (Re)	Re = 2(√π/A)/Lb A-Area of the Watershed Lb-Length of the Watershed π = 3.14	Schumm (1956)
	Length of Overland Flow (*Lg*)	Lg = 1/2**DD*	Horton (1945)
	Constant Channel Maintenance (*c*)	1/*DD*	Schumm (1956)
	Infiltration Num (*If*)	*If* = *Fs***DD*	Faniran (1968)
	Compactness coefficient (*Cc*)	*Cc* = .2821*P/A2	Horton (1945)
	Leminscate's (*k*)	*k* = Lb2/A	Chorley (1957)
Relief Aspects	Basin Relief (*R*)	*R* = H-h H-Maximum Elevation h-Minimum Elevation	Schumm (1956)
	Relief Ratio (*Rr*)	*Rr* = *R*/Lb R-Basin Relief Lb- Length of basin	Schumm (1956)
	Ruggedness num (*Rn*)	*Rn* = *R***DD* *R*-Basin Relief *DD*-Drainage Density	Patton & Baker (1976)
	Melton ruggedness ratio (*MRn*)	*MRn* = *R*/√A	Melton (1957)
	Gradient Ratio (*Rg*)	*Rg* = H-h/Lb	Sreedevi *et al*. (2009)
	Relative relief (*Rhp*)	*Rhp* = H-h/P	Melton (1957)
	Dissection Index (*Di*)	*Di* = *R*/*Ra* *R*-Basin Relief *Ra*-Absolute Relief	Singh & Dubey (1994)

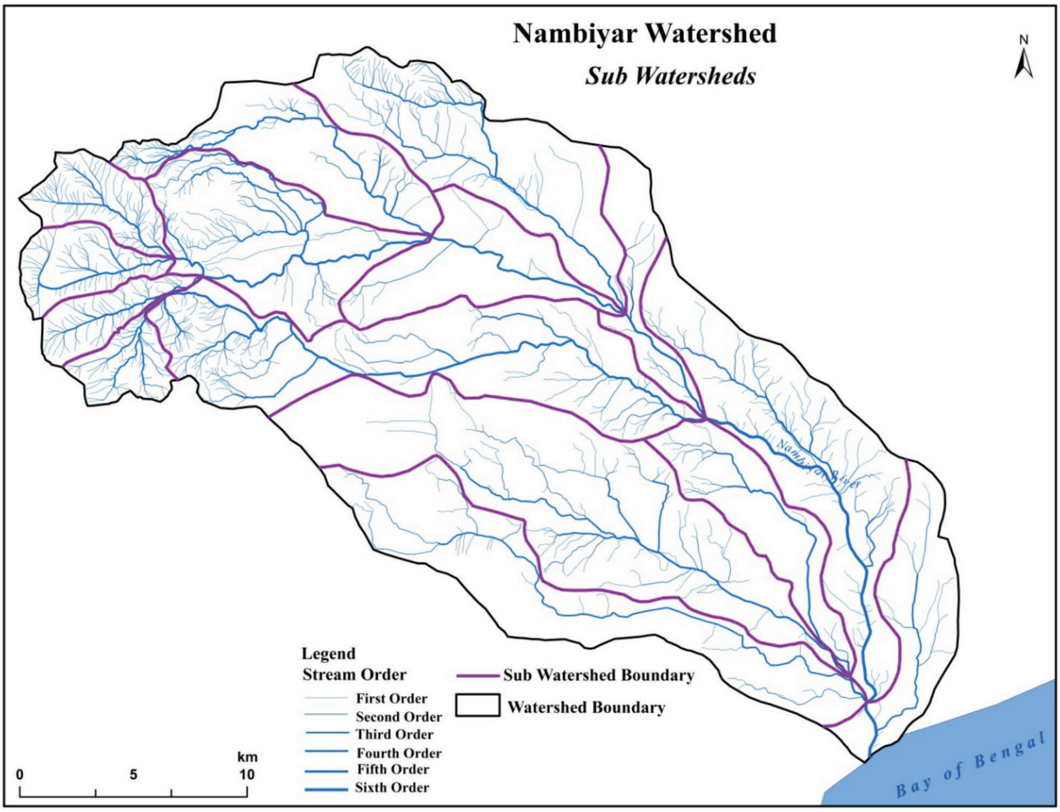


Figure 3: Delineated sub-watersheds of the Nambiyar Watershed

Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS)

In the present study, the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) technique is used for the prioritisation of sub-watersheds. It is a widely accepted MCDM technique in critical research developed by Yoon and Hwang in 1981 (Zavadskas, 2016). The best alternative is chosen based on the computation of the closeness coefficient and considers the distance of alternatives to deal with the worst solution. This method ranks the alternatives based on their proximity to the Positive Ideal Solution (PIS) and their distance from the Negative Ideal Solution (NIS) (Aouragh *et al.,* 2018).

Step 1: Calculation of the Normalised Matrix

Select all the morphometric parameters that directly and indirectly affect the flood and erosion vulnerability and prepare the matrix for ranking.

$$\begin{array}{cccc} & \boldsymbol{C_1} & \boldsymbol{C_2 \ldots} & \boldsymbol{C_n} \\ \boldsymbol{A_1} & \boldsymbol{X_{11}} & \boldsymbol{X_{12} \ldots} & \boldsymbol{X_{1n}} \\ \boldsymbol{A_2} & \boldsymbol{X_{21}} & \boldsymbol{X_{22} \ldots} & \boldsymbol{X_{2n'}} \\ \boldsymbol{A_n} & \boldsymbol{X_{n1}} & \boldsymbol{X_{n2} \ldots} & \boldsymbol{X_{nn}} \end{array}$$

where A_1, A_2, A_n are the possible 'alternatives' available that can be selected by a decision maker. Here 'A_1, A_2, A_n', or the 'alternatives' are 15 sub-watersheds of the Nambiyar Watershed.

C_1, $C_2 \ldots C_n$ is the criteria used for assessing performance among the 'alternatives'. Hence, criteria are used for each morphometric element selected for erosion and flood vulnerability. 'X_{ij}' is the ranking of alternatives A_i according to each criterion C_i:

$$N_{ij} = x_{ij} / \sqrt{\sum_{i=1}^{m} x_{ij}^2}, \quad (1)$$

where 'N_{ij}' is the normalised value and 'x_{ij}' is the morphometric parameters directly and indirectly related to erosion and flood vulnerability.

Step 2: Calculation of the Weighted Normalised matrix. The weighted normalised value 'Y_{ij}' is calculated below

$$Y_{ij} = w_j * n_{ij} \quad for\ i = 1, \ldots, m \quad j = 1, \ldots n \quad (2)$$

where w_j is the weight assigned to i[th] criterion,

$$\sum_{i=1}^{n} w_j = 1.$$

In the present study, an equal weight (0.07) has been given to each chosen criterion since the sum of weights is equal to 1, 1/14 = 0.07.

Step 3: Identification of Positive Ideal (A^+) and Negative Ideal (A^-) Solutions

$$A^+ = \{((max_i Y_{ij} / j \in J), (min_i Y_{ij} / j \in J')) \mid i = 1, 2, \ldots, m\} \quad (3)$$
$$\{= Y_1^+, Y_2^+, \ldots, Y_m^+\},$$

$$A^- = \{((max_i Y_{ij} / j \in J), (min_i Y_{ij} / j \in J')) \mid i = 1, 2, \ldots, m\} \quad (4)$$
$$\{= Y_1^-, Y_2^-, \ldots, Y_m^-\},$$

where J is related to positive criteria and J' is related to negative criteria. Here, the positive criteria are those that directly induce erosion and flood vulnerability, and the negative criteria are those that affect indirectly.

Step 4: Calculate the difference between each criterion from the Ideal Positive solution n. The difference from each criterion is given S_i^+ for the Ideal positive solution and S_i^- for an Ideal negative solution.

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (Y_i^+ - Y_{ij})^2} for\ i = 1, 2, \ldots m, \quad (5)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (Y_i^- - Y_{ij})^2} for\ i = 1, 2, \ldots m. \quad (6)$$

Step 5: Determination of how close to the ideal solution. The relative proximity of the alternative A_i to A^+ is defined as Closeness Coefficient (CCi) using the following equation:

$$CC_i = \frac{S_i^-}{S_i^+ + S_i} \ wher\ for\ i = 1, 2, \ldots m. \quad (7)$$

The alternative criteria can be ranked accordingly from high priority to low priority concerning the decreasing value of CC_i. Finally, assign a rank to the preference order. A high value of the closeness coefficient CC_i indicates that the alternative Ai is vulnerable to the selected problem. The best alternative is the one that comes closest to the ideal solution. Further, for cross reference of erosion-prone areas, the results were checked with land capability classes of the watershed prepared from the soil map collected from Tamil Nadu Agricultural University and Google Earth images.

Results

The morphometric analysis comprises the detailed examination of various linear, areal, and relief aspects which control the hydrological behaviour in a watershed. The linear aspect pertains to the number and length of streams in the watershed. Similarly, the area and perimeter aspects are useful for studying the response of a drainage system to its area. The relief aspects also correlate with the areal aspects by controlling the river's rate, direction, and discharge. Therefore, the morphometric analysis aids in comprehending the basic nature of the watershed and making inferences regarding the hydrological behaviour of the drainage. Hence, the selected parameters of linear, areal, and relief aspects have been analysed and prioritised in the sub-watersheds according to their significance for erosion flood vulnerability.

Linear Aspects

The numbers of Stream Order (Nu), Stream Length (Lu), Bifurcation Ratio (Rb), Stream Length Ratio (Lur), and Rho coefficient (ρ) are some parameters taken for analysis and the results of which are presented in Table 2 and Figure 4. Nambiyar watershed contains a total of 1,130 stream segments, with the sixth order being the highest 'Nu'. From the total of 1,130 streams, 841 streams (74%) are marked as 1st order, 219 streams (19.38%) are 2nd order, 52 streams (4.60%) are 3[rd] order, and 13 streams (1.15%), four streams (35%), one stream (0.09%) are assigned 4th, 5th and 6th order respectively. The total number of streams is higher in the sub-watersheds with hilly terrain where the river originates, i.e., SW 4, 5, 7, 9, and 12 have a total of 102, 106, 104, 181, and 127 streams, respectively. The Nambiyar watershed is designated as a 6th-order basin with 15 sub-watersheds.

The Rb is the ratio of stream number between a Nu and its immediate next higher order and indicates the dissection of streams. Generally, the ratio value decreases when the Nu increases. This is in accordance with the law of Nu, which states there is an inverse geometric sequence between the numbers of streams in each higher order (Horton, 1932). A higher value of Rb represents a matured basin in terms of landforms and drainage. In addition, a high value means high runoff and less chance for water to infiltrate the soil. The Mean Rb is calculated by finding the average Rb of all stream orders 'Nu'. It is observed that the majority of sub-watersheds exhibit a mean Rb of between 3 and 5. The mean Rb of SW 4, 6, and 7 ranges from 4 to 5. The SW 1, 2, 3, 5, 9, 10, and 14 located in the upper reaches of Nambiyar River exhibit a medium range of ratio 3.5 to 4. A low value of mean Rb is calculated in SW 8, 13, and 15, where the value lies between 2.5 and 3, respectively.

The total Lu in the Nambiyar Watershed is 1,086.29 km. Sub-watershed 9 has the longest streams with a total length of 169.12 km. It is one of the sub-watersheds with the largest number of streams in each order. Sub-watersheds 5, 7, 10, and 12 have the largest stream networks with lengths of 114.07 km, 102.85 km, 123.29 km, and 122.66 km, respectively. The average Lur of the Nambiyar Watershed is 0.53. The mean Lur varies among the sub-watersheds from 0.4 in SW1 to 1.45 in SW13. The coefficient of the watershed is 0.14, and it varies among each sub-watershed. Sub-watershed 11 has a high coefficient value of 1.48, indicating more discharge of water in this sub-watershed. Sub-watersheds 5,8,12, and 13 have ρ values of 0.3 to 0.5, indicating high storage during floods.

Table 2: Linear aspects calculated for Nambiyar Watershed

Stream Order	Nu	Nu (%)	Rb	Lu	Lu (%)	Lum	Lur	Rbm	Lurm	Rho Coefficient
SW1										
I	58	76.32	4.14	27.32	60.27	0.47				
II	14	18.42	4.67	8.61	18.99	0.62	0.32			
III	3	3.95	3.00	6.86	15.13	2.29	0.80			
IV	1	1.32		2.54	5.60	2.54	0.37			
	76			45.33				3.94	0.49	0.12
SW2										
I	53	76.81	4.1	30.11	68.14	0.57				
II	13	18.84	6.5	6.66	15.07	0.51	0.22			
III	2	2.90	2	2.16	4.89	1.08	0.32			
IV	1	1.45		5.26	11.90	5.26	2.44			
	69			44.19				4.20	0.99	0.24

SW3										
I	65	77.38	4.64	33.65	64.29	0.52				
II	14	16.67	3.5	8.54	16.32	0.61	0.25			
III	4	4.76	4	3.81	7.28	0.95	0.45			
IV	1	1.19		6.34	12.11	6.34	1.66			
	84			52.34				4.05	0.79	0.20
SW4										
I	83	81.37	5.53	46	70.80	0.55				
II	15	14.71	5	10.41	16.02	0.69	0.23			
III	3	2.94	3	4.3	6.62	1.43	0.41			
IV	1	0.98		4.26	6.56	4.26	0.99			
	102			64.97				4.51	0.54	0.12
SW5										
I	77	72.64	4.05	54.43	47.72	0.71				
II	19	17.92	2.4	21.17	18.56	1.11	0.39			
III	8	7.55	8	22.51	19.73	2.81	1.06			
IV	1	0.94	1	2.19	1.92	2.19	0.10			
V	1	0.94		13.77	12.07	13.77	6.29			
	106			114.1				3.86	1.96	0.51
SW6										
I	64	68.09	3.05	29.57	45.29	0.46				
II	21	22.34	3.0	12.07	18.49	0.57	0.41			
III	7	7.45	7	8.27	12.67	1.18	0.69			
IV	1	1.06		15.24	23.34	15.24	1.84			
	93			65.15				4.35	0.98	0.23
SW7										
I	79	75.96	3.76	58.26	56.65	0.74				
II	21	20.19	7.0	19.27	18.74	0.92	0.33			
III	3	2.88	3	11.78	11.45	3.93	0.61			
IV	1	0.96		13.54	13.16	13.54	1.15			
	104			102.9				4.59	0.70	0.15
SW8										
I	9	69.23	3.00	10.55	39.26	1.17				
II	3	23.08	3.0	6.17	22.96	2.06	0.58			
V	1	7.69		10.15	37.77	10.15	1.65			
	13			26.87				3.00	1.11	0.37

SW9										
I	131	72.38	3.45	80.96	47.87	0.62				
II	38	20.99	4.22	40.86	24.16	1.08	0.50			
III	9	4.97	4.50	15.26	9.02	1.70	0.37			
IV	2	1.10	2.00	3.99	2.36	2.00	0.26			
V	1	0.55		28.05	16.59	28.05				
	181			169.1				4.06	0.38	0.09
SW10										
I	63	74.12	3.71	61.23	52.83	0.97				
II	17	20.00	4.3	31.29	27.00	1.84	0.51			
III	4	4.71	4	18.11	15.62	4.53	0.58			
IV	1	1.18		12.66	10.92	12.66	0.70			
	85			123.3				3.99	0.60	0.15
SW11										
I	12	70.59	4.00	11.5	34.33	0.96				
II	3	17.65	3.00	4.29	12.81	1.43	0.37			
III	1	5.88	1.00	1.45	4.33	1.45	0.34			
V	1	5.88		16.26	48.54	16.26	11.21			
	17			33.5				2.67	3.97	1.5
SW12										
I	96	75.59	4.00	65.2	53.16	0.68				
II	24	18.90	6.0	24.12	19.66	1.01	0.37			
III	4	3.15	2.0	8.24	6.72	2.06	0.34			
IV	2	1.57	2.0	5.21	4.25	2.61	0.63			
VI	1	0.79		19.89	16.22	19.89	3.82			
	127			122.66				3.50	1.29	0.37
SW13										
I	16	64.00	2.67	12.37	35.64	0.77				
II	6	24.00	3.0	7.85	22.62	1.31	0.63			
III	2	8.00	2.0	3.39	9.77	1.70	0.43			
IV	1	4.00		11.1	31.98	11.10	3.27			
	25			34.71				2.56	1.45	0.57

SW14										
I	26	74.29	3.71	21.81	32.45	0.84				
II	7	20.00	7.00	21.39	31.83	3.06	0.98			
III	1	2.86	1	22.57	33.58	22.57	1.06			
V	1	2.86		1.44	2.14	1.44	0.06			
	35			67.21				3.90	0.70	0.18
SW15										
I	14	70.00	3.50	14.93	22.21	1.07				
II	4	20.00	4.00	7	10.42	1.75	0.47			
III	1	5.00	1	8.28	12.32	8.28	1.18			
VI	1	5.00		2.63	3.91	2.63	0.32			
	20			32.84				2.83	0.66	0.23
Nambiyar Watershed										
I	841	74.42	3.84	557.7	51.34	0.66				
II	219	19.38	4.21	229.8	21.15	1.05	0.41			
III	52	4.60	4.00	137.1	12.62	2.64	0.60			
IV	13	1.15	3.25	82.36	7.58	6.34	0.60			
V	4	0.35	4.00	59.54	5.48	14.89	0.72			
VI	1	0.09		19.89	1.83	19.89	0.33			
	1130			1086				3.86	0.53	0.14

Areal Aspects

The drainage basin area includes the Stream Frequency (*Fs*), Drainage Density (*DD*), Texture Ratio (*T*), Infiltration Num (*If*), Circularity Ratio (*Rc*), Elongation Ratio (*Re*), Form-factor (*Ff*), Length of Overland Flow (*Lg*), Constant Channel Maintenance (*c*), compactness coefficient, etc. The area and perimeter of the watershed are important criteria in determining all of the indices in a basin's morphometric study. The Nambiyar watershed has a total area of 665.5 sq. km and a perimeter of 124 km. Sub-watershed 10 has the largest area of all sub-watersheds at 110 sq. km, while sub-watershed 1 has the least at 11.77 sq. km. Table 3 shows the calculated areal characteristics of the current investigation, which are illustrated in Figure 4.

The ***Stream Frequency (Fs)*** indicates the number of streams per unit area (Horton, 1945). If the *Fs* is high in lower Nu, it implies a fine-textured stream network, whereas a low frequency in higher-order streams shows the river is maturing. (Strahler, 1957). *Fs* and runoff have a strong relationship. The higher the *Fs*, the greater the runoff, and vice versa. The value varies among the sub-watersheds from 0.38/sq. km in SW8 to 6.46/sq. km observed in SW1. SW1, 2, and 4 have the highest *Fs*, which can be directly correlated with the high *DD* found in these sub-watersheds.

Drainage Density (DD) is defined as the ratio of the total length of all orders' channels in the basin to the basin's drainage area (Strahler,

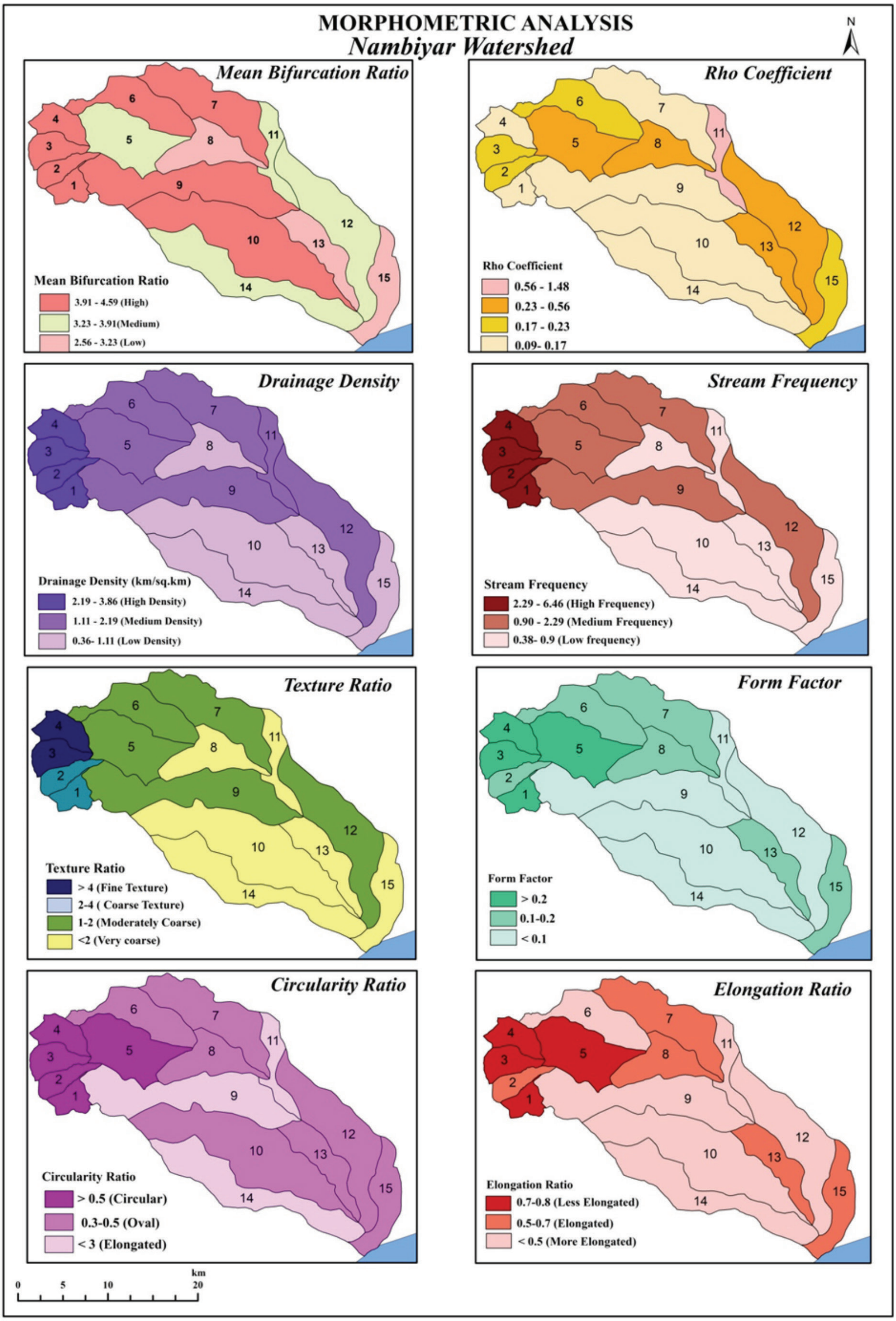


Figure 4: Morphometric Analysis (linear and areal aspects)

1957). It is influenced by components that regulate the feature length of the stream, such as weathering resistance, the permeability of rock formation, climate, and flora, among others. *Dd* is low in places underlain by highly resistant permeable material with vegetative cover and low relief. High *Dd* has been seen in areas with impermeable underlying material, low vegetation, and mountain relief (Rai *et al.,* 2014). The value of *Dd* in the watershed is 9.11, indicating the fine Drainage Texture (*DT*), and it varies from 0.4 in SW 8 to 5.28 in SW 4.

The ***Texture Ratio* (*Rt*)** depicts the texture of streams and is calculated by dividing the total number of first-order streams by the perimeter of the watershed. This ratio is determined by the watershed's lithology, infiltration capabilities, and relief (Avinash *et al.,* 2014). The Texture Ratio (*Rt)* of the Nambiyar watershed is 6.78, exhibiting moderate to fine texture. The ratio among the watershed varies from 0.28 to 3.54.

The ***Infiltration Num (If)*** is defined as the product of *DD* and *Fs*. This value is in negative correlation to the capacity of infiltration in a watershed, which means a high *If* value relates to low infiltration capacity, high runoff, and vice versa (Schumm,1965). For the Nambiyar watershed, the *If* value is 2.77, indicating medium runoff and high infiltration. Even while the overall figure is modest, it varies substantially between sub-watersheds, ranging from 0.29 to 24.87. SW1, 2, 3, and 4 had infiltration values of 24.87, 20.29, 16.9, and 23.45, indicating that these sub-watersheds have a high runoff rate but a low infiltration capacity.

The ***Circularity Ratio (Rc)*** is the ratio of the basin area to the area of a circle with the same perimeter as the river basin. The length and frequency of streams, geological formations, land use/cover, climate, relief, and slope of the basin all have a detrimental effect on the *Rc* (Strahler, 1957). The ratio values between 0.4 and 0.5 clearly indicate an elongated basin, and a value higher than this represents a more circular or rounded basin (Farhan *et al.,* 2017; Mahmood *et al.,* 2019). The *Rc* value of the Nambiyar watershed is 0.5, which shows that it is typically an elongated watershed. The ratio ranges from 0.24 in SW11 to 0.57 in SW14, indicating that all the sub-watersheds are elongated in shape.

Elongation Ratio (Re) is defined as the ratio of the diameter of a circle having the same area as the basin to the length of the basin. The value of the *Re* approaches 1 as the shape of the basin approaches a circle. A circular basin discharges runoff more efficiently than an elongated basin (Schumm, 1956; Strahler, 1957; Magesh *et al*., 2013). The *Re* of the watershed is 0.6, revealing that it is an elongated watershed. Sub watersheds 1, 3, 4, and 5 exhibit a ratio value between 0.7-0.8, indicating that these are less elongated watersheds prone to more runoff.

Form-factor (Ff) is defined as the ratio of basin area to basin length squared. For a perfectly circular basin, the *Ff* would always be smaller than 0.7854 (Horton, 1945). High-*Ff* basins have high peak flows with shorter durations, whereas extended sub-watersheds with low *Ffs* have lower peak flows with longer durations (Prabhakaran *et al.,* 2018). The *Ff* value of the Nambiyar watershed is 0.29, indicating there is less peak flow during normal rain conditions, and the watershed is long and narrow. Similarly, the *Ff* value does not vary much among the sub-watersheds, which ranges from 0.1 to 0.33.

The ***Length of Overland Flow (LG)*** is the distance that water travels overland before entering a waterway. The relationship between drainage density and overland flow is inverse. This element is inversely related to the average slope of the channel and is, to a considerable extent, synonymous with the length of sheet flow. The average *Lg* is around half the distance between stream channels, roughly equal to half the reciprocal of drainage density (Horton, 1945). The *Lg* value of the watershed is 0.3 km, indicating it is more exposed to channel erosion. The value ranges from 0.12 km in SW1 to 1.38 km in SW13. The high *Lg* in SW 13 is attributed to its low drainage density value, i.e., 0.36 km / sq.km.

The ***Constant of Channel Maintenance (c)*** is defined as the ratio of a drainage basin's area to the total lengths of all the channels given in sq. km per km. It is the reciprocal of the drainage density. This value specifies how many square metres of the watershed surface are needed to sustain one linear metre of the channel. The *c* is inversely proportional to the drainage density (Biswas *et al.,* 1999). The *c* value of the Nambiyar watershed is 0.61. The value varies among the sub-watersheds from 0.26 in SW1 and 4 to 2.79 in SW13.

The ***Compactness Coefficient (Cc)*** is the ratio of basin perimeter to which equals basin area. The *Cc* is unaffected by watershed size and is only affected by slope. For a perfect circle, the compactness constant is zero, increasing as the basin length increases. As a result, it is a direct indicator of the basin's elongated shape (Dikpal *et al.,* 2017; Rai *et al.,* 2018). The value of *Cc* ranges from 1.27 in SW3 to 2.03 in SW11, indicating that watersheds are elongated.

Relief Aspects

Along with linear and areal aspects, relief of the basin also has a significant role in determining the basin's shape and form. In other words, these three aspects are interconnected, and hence, it is essential to examine each in detail. Table 4 shows various relief aspects computed for the sub-watersheds, and the spatial variation is represented in Figure 5.

Basin Relief (R) is defined as the difference in maximum and minimum elevation in a drainage basin. *H* indicates the potential energy of a given basin about a specified datum available to move water and sediment downslope (Strahler, 1957; Avinash *et al.,* 2014). The highest elevation value in the watershed is 1,644 m above Mean Sea Level (MSL). The lowest elevation is 1 m, where the river drains into the Bay of Bengal. Hence, the

Table 3: Areal aspects calculated for Nambiyar Watershed

Sub-watershed	P	A	(Lb)	DD	Sf	Di	Dt	Rt	Ff	CR	ER	Lg	C	If	Cc
SW1	17.91	11.77	6	3.85	6.46	1.67	4.24	3.24	0.33	0.46	0.64	0.12	0.26	24.87	1.46
SW2	18.12	12.26	7.8	3.6	5.63	1.56	3.8	2.92	0.2	0.47	0.5	0.13	0.28	20.29	1.44
SW3	18.36	16.15	6.85	3.24	5.2	1.6	4.57	3.54	0.34	0.6	0.66	0.14	0.31	16.86	1.27
SW4	19.3	16.81	7.58	3.86	6.07	1.56	5.28	4.3	0.29	0.57	0.61	0.14	0.26	23.45	1.31
SW5	34.88	52.14	13.21	2.19	2.03	0.92	3.03	2.21	0.3	0.54	0.61	0.22	0.46	4.45	1.35
SW6	36.91	40.57	16	1.61	2.29	1.42	2.51	1.73	0.16	0.37	0.4	0.31	0.62	3.68	1.62
SW7	43.73	60.58	18.3	1.7	1.72	1.01	2.37	1.81	0.18	0.4	0.47	0.27	0.59	2.91	1.57
SW8	32.46	34.16	13.26	0.79	0.38	0.48	0.4	0.28	0.19	0.41	0.49	0.63	1.27	0.3	1.55
SW9	60.54	87.88	25.56	1.92	2.06	1.07	2.98	2.16	0.13	0.3	0.41	0.26	0.52	3.96	1.8
SW10	65.17	110.8	28.6	1.11	0.77	0.68	1.3	0.97	0.14	0.33	0.41	0.45	0.9	0.85	1.73
SW11	31.5	18.84	13.64	1.78	0.9	0.5	0.5	0.38	0.1	0.24	0.35	0.28	0.56	1.6	2.03
SW12	52.3	73.16	23.5	1.68	1.74	1.03	2.42	1.84	0.13	0.34	0.41	0.29	0.6	2.91	1.71
SW13	32.55	30.3	14.39	0.36	0.83	2.3	0.8	0.5	0.15	0.36	0.44	1.38	2.8	0.29	1.65
SW14	59.22	68.74	26.72	0.98	0.51	0.52	0.59	0.44	0.1	0.25	0.35	0.51	1.02	0.5	1.99
SW15	33.27	31.52	14.22	1.04	0.63	0.6	0.6	0.42	0.16	0.36	0.44	0.48	0.96	0.66	1.65
Nambiyar Watershed	124	665.5	48	1.63	1.4	9.11	1.7	6.78	0.29	0.54	0.6	0.3	0.61	2.77	1.34

H value of the watershed is 1,643 m. The relief of the sub-watershed ranges from 38 m in SW15 to 1436 m in SW1.

The ***Relief Ratio (Rr)*** is a dimensionless parameter defined as the ratio of basin relief to the length of the basin (Chorley, 1969). It is useful in the indication of the overall steepness of the basin. A low ratio value signifies it is composed of resistant formation, while a moderate to high value is attributed to steep and rugged topography. The *Rhl* of the watershed is 34.23, which represents moderate relief. The values vary greatly among the sub-watersheds, from 2.67 in SW 15, where the river drains into the sea, to a high ratio value of 239, noted in SW1, where the river originates. SW 7, 10, 11,12, 13, 14, and 15 are categorised as low relief, SW 5, 8, and 9 have moderate relief, SW 6 has a high relief ratio, and SW1, 2, 3, and 4 have a very high relief ratio.

Ruggedness Number (Rn) is the product of Basin relief and drainage density. This is a dimensionless index representing the steepness of the slope (Chandrashekar *et al.,* 2015). It is an important parameter considered in the vulnerability of the basin to the occurrence of flash floods. The Nambiyar watershed has an *Rn* value of 2.67, indicating moderate ruggedness of the terrain. The value ranges from 0.01 (SW 13) to 5.80 (SW4). It represents the general steepness of the watershed within the watershed.

The ***Relative Relief (Rhp)*** index is the ratio of basin relief to perimeter not dependent on the basin length (Schumm, 1965). It represents the general steepness of the watershed within the watershed. The *Rr* value of the study area is 13.25, varying from 1.14 in SW15 to 80.2 in SW1.

The ***Gradient Ratio (Rg)*** indicates channel slope and enables the assessment of runoff volume (Anil *et al.,* 2021). The high *Rg* represents hilly terrain and vice versa. The high *Rg* represents hilly terrain and vice versa. The *Rg* value of the watershed is 34.23, varying from 2.67 in SW15 to 239 in SW1.

Table 4: Relief aspects calculated for Nambiyar Watershed

Sub-watershed	Basin Relief	Relief Ratio	Rug Num	Gradient Ratio	Melton Rug Num	Relative relief	Leminscate's (k)
SW1	1436	239.33	5.52	239.33	419	80.18	3.06
SW2	1225	157.05	4.41	157.05	350	67.6	4.96
SW3	1298	189.48	4.2	189.48	323	70.7	2.91
SW4	1505	198.55	5.8	198.55	367	77.98	3.41
SW5	710	53.75	1.55	53.75	98	20.36	3.34
SW6	1151	71.94	1.85	71.94	181	31.18	6.31
SW7	253	13.83	0.43	13.83	32.51	5.97	5.52
SW8	406	30.62	0.32	30.62	69.5	12.51	5.14
SW9	1184	46.32	2.27	46.32	126	19.56	7.43
SW10	148	5.17	0.164	5.17	14	2.27	7.38
SW11	73	5.35	1.29	5.35	17	2.32	9.8
SW12	71	3.02	1.19	3.02	8	1.36	7.54
SW13	51	3.54	0.18	3.54	9	1.57	6.83
SW14	113	4.23	0.11	4.23	14	1.91	10.38
SW15	38	2.67	0.39	2.67	7	1.14	6.41
Nambiyar Watershed	1643	234.71	2.67	34.23	64.00	13.25	3.46

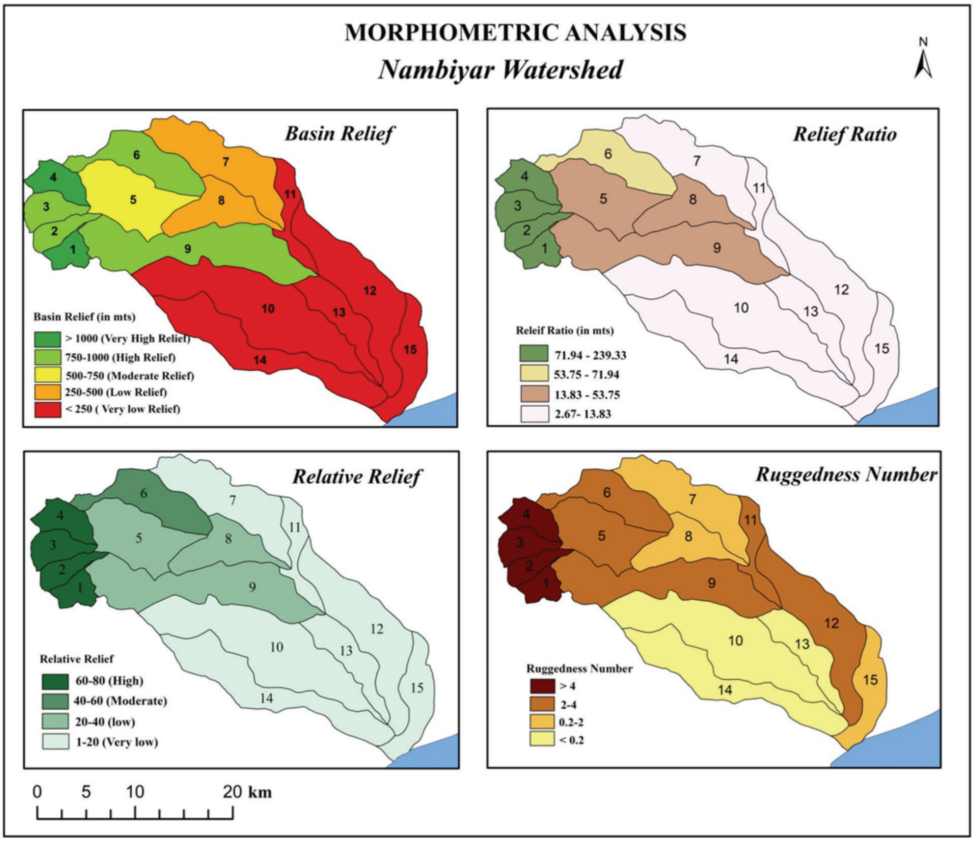


Figure 5: Morphometric analysis (relief aspects)

Prioritisation of Sub-watersheds

Many prior studies have shown that morphometric features, notably linear and relief factors, directly influence runoff, soil erosion, and flood conditions. Flood occurrence is directly related to *DD, Rb, Rt, Fs, Rr,* and *Rn*. As a result, in this study, *DD, Dt, Rb, Fs, Lg, If, Rhp,* and *Rn* are considered beneficiary or positive criteria that accelerate erosion, runoff, and flood. In contrast, areal parameters such as *Ff, Rc, Re, Cc,* and *C* are considered non-beneficiary or negative criteria that have an inverse effect on the rate of erosion and flood vulnerability. The TOPSIS technique is used in this study to prioritise the sub-watershed to identify flood- and erosion-prone areas and implement rapid conservation measures.

All sub-watersheds were prioritised based on their proximity to the optimal solution in the TOPSIS technique and their proportional importance to erosion and flood occurrence. Sub-watersheds 1, 2, 3, and 4 received the highest ranks of 1, 2, 3, and 4, respectively, in this method, indicating that they are highly prone to erosion and runoff and are thus categorised as a high priority for implementing conservation methods due to high drainage density, Fs, and If, all of which cause high runoff. The TOPSIS approach placed Sub Watershed 15 as 14th, indicating a low priority for erosion. It means that the upper portions of the river are vulnerable to flash floods, excessive runoff, and erosion, requiring careful land use planning to avoid natural hazards. Figure 6 depicts the final maps of prioritised sub-watersheds. Table 5 shows the Closeness coefficient value and rank assigned to each sub-watershed. The watershed's land

Table 5: Computed ranks of sub-watersheds using the TOPSIS method

Sub-watershed No.	Closeness Coefficient Value	Rank
SW1	0.5718	1
SW2	0.5364	3
SW3	0.5263	4
SW4	0.5661	2
SW5	0.3919	6
SW6	0.3677	8
SW7	0.3267	11
SW8	0.2773	15
SW9	0.3684	7
SW10	0.2880	12
SW11	0.4477	5
SW12	0.3451	9
SW13	0.3364	10
SW14	0.2840	13
SW15	0.2794	14

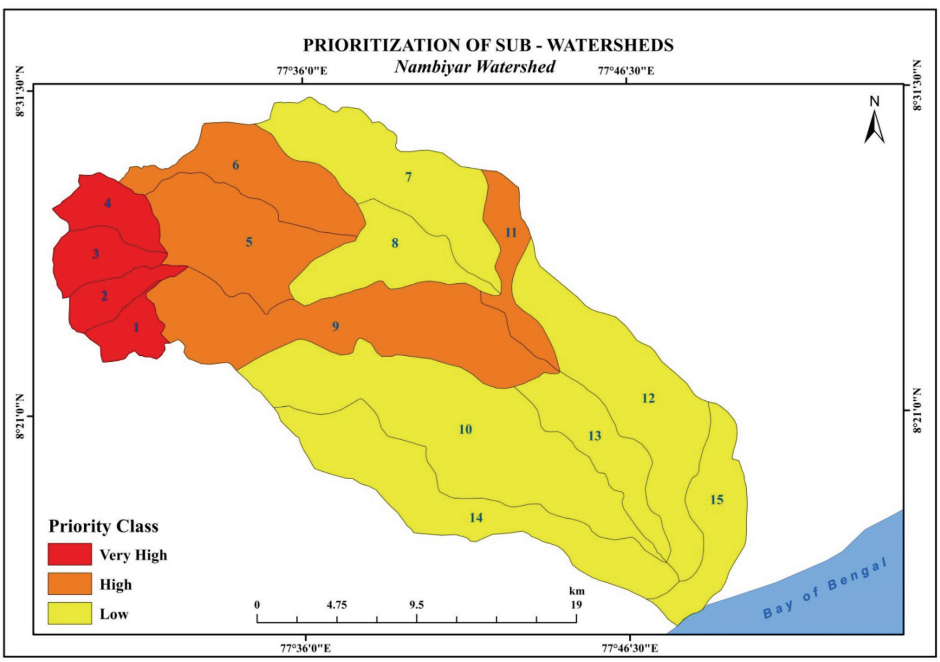


Figure 6: Prioritisation of sub-watersheds for erosion and flood vulnerability

capability classes show that cultivable land in the Nambiyar watershed falls into the moderately excellent and fairly good categories, with erosion and soil problems. The watershed's dominating land capability class is IIIe (162.28 sq. km) and IIIs (130.61 sq. km), the land that is moderately suitable for cultivation but has erosion and soil problems. This class is more common in the northern and central parts of the watershed, particularly in sub-watersheds 5, 6, 7, 8, 9, 10, 11, 12, 14, and 15. This region, which is heavily cultivated, must be managed to preserve the quality of land resources. Figures 7 (a) and (b) illustrate the land capability classifications and Google Earth images.

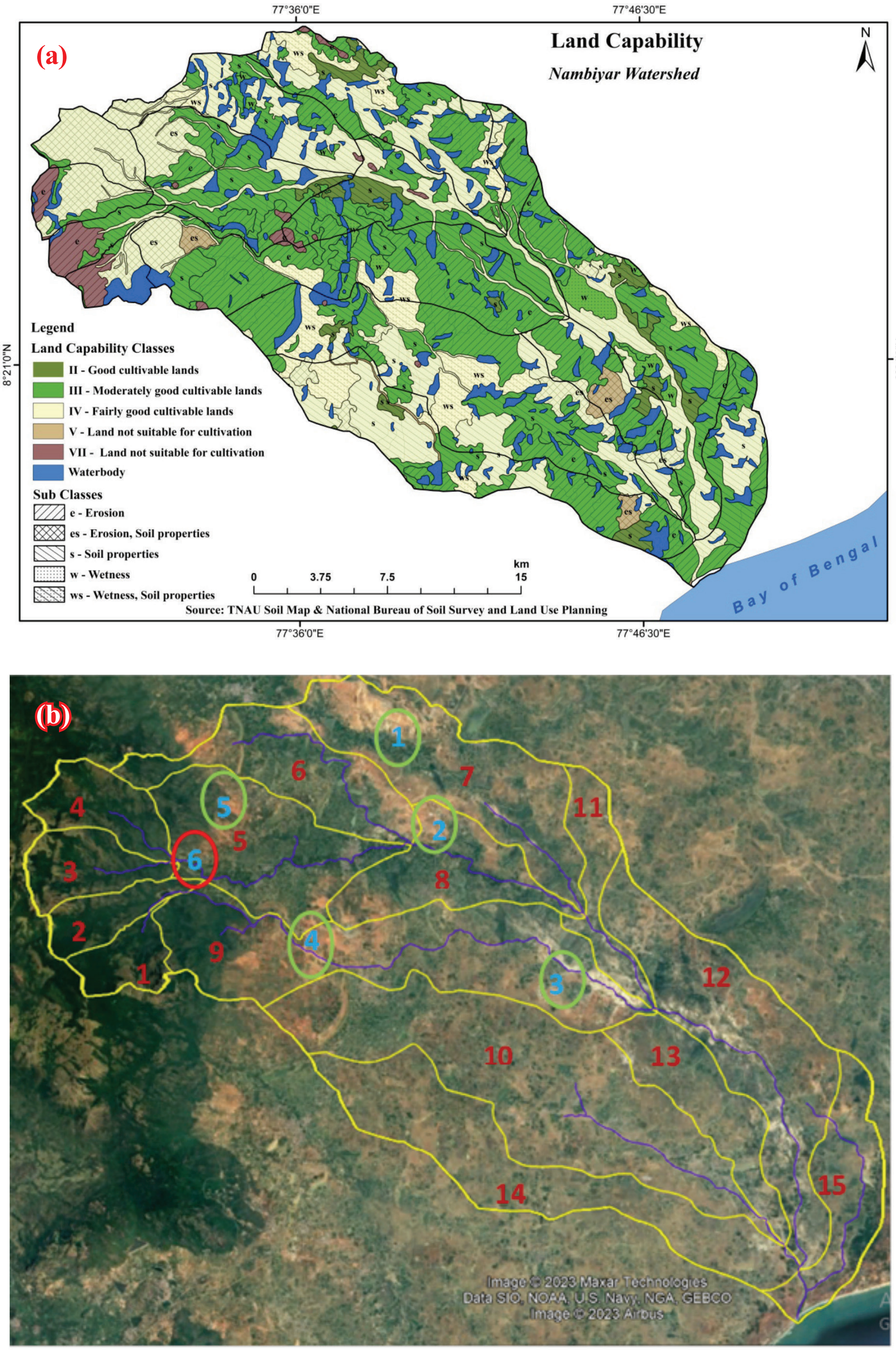
Discussions

High drainage density, Fs, and If are the morphometric parameters that induce flash floods leading to erosion in a watershed (Rai *et al.,* 2014; Abdul *et al.,* 2015; Ameri *et al.,* 2018; Singh *et al.,* 2021; Ghosh *et al.,* 2021). The linear parameters and relief parameters are directly related to the risk of erosion, such as drainage density, *Fs, Rb, DT, ρ, If,* Relief ratio, and *Rn* (Schumm, 1965; Wilford *et al.,*2004; Abdul *et al.,*2015; Tiwari *et al.,* 2021; Ghosh *et al.,* 2021). Meanwhile, areal aspects like *Rc*, constant of channel maintenance, compactness coefficient, and *Re* have an inverse relation with erosion and runoff (Aher *et al.,* 2013; Ameri *et al.,* 2018; Meshram *et al.,* 2020; Ghosh *et al.,* 2021). Likewise, *DD, Fs, Rr, Rn,* and *Rt* are directly related to the occurrence of the flood (Farhan *et al.,* 2017; Mahmood *et al.,* 2019; Akay *et al.,* 2020; Anil *et al.,* 2021). Therefore, in these studies, linear and relief parameters are taken as beneficiary or positive criteria, which accelerates erosion, runoff, and flood, while areal parameters are considered as non-beneficiary or negative criteria, which inversely affect the rate of erosion (Thomas *et al.,* 2010; Abdul *et al.,* 2015; Aouragh *et al.,* 2018; Makhdumi *et al.,* 2019; Singh *et al.,* 2021).

Apart from the morphometric elements, factors such as soil texture, rainfall, and land use categories correlate more, which determines the rate of erosion, runoff potential, and flood susceptibility in a region. Considering the soil texture, the Nambiyar watershed is covered by sand, sandy loam, loamy sand, sandy clay loam, sandy clay, clay, and clay loam. The northern and central part of the watershed is covered by clay and sandy clay, indicating low infiltration and high runoff. The spatial distribution of rainfall shows a decreasing trend from the interior near the Western Ghats towards the coastal region. The analysis of land use of the region indicated that settlements are distributed more in the central parts of the watershed. Other than that, land without scrubs occupies a significant area of the watershed, mainly in the northern and southern parts.

The Google Earth image of the Nambiyar watershed captured in the year 2021 has been extracted for validation, shown in Figure 7 (b). The sub-watershed boundaries are marked in the image as well, and circles denote the region of eroded lands. The regions or sub-watersheds have attained 'very high' and 'high' priority for risk of erosion, runoff, and soil problems by the TOPSIS method.

The Nambiyar is prone to flash floods, leading to erosion in the upper reaches of the river since the sub-watersheds 1, 2, 3, and 4 located here exhibit high drainage density, Fs, and If leading to high surface runoff (Times of India Report, 2018). These are twin problems that need main focus in the present since the parameters chosen are related to flood and erosion occurrence in the watershed. The population density is high in the central part of the watershed, especially in the sub-watersheds (Figure 1), where runoff is high, and frequent occurrence of floods is observed, which affects the lives of people residing in this region. Figure 8 shows some photographs of the River Nambiyar and the watershed taken during the field visits.


(a)
Land Capability
Nambiyar Watershed
N
77°36'0"E
77°46'30"E
8°21'0"N
Legend
Land Capability Classes
II - Good cultivable lands
III - Moderately good cultivable lands
IV - Fairly good cultivable lands
V - Land not suitable for cultivation
VII - Land not suitable for cultivation
Waterbody
Sub Classes
e - Erosion
es - Erosion, Soil properties
s - Soil properties
w - Wetness
ws - Wetness, Soil properties
0 3.75 7.5 15 km
Bay of Bengal
Source: TNAU Soil Map & National Bureau of Soil Survey and Land Use Planning
(b)
Image © 2023 Maxar Technologies
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2023 Airbus

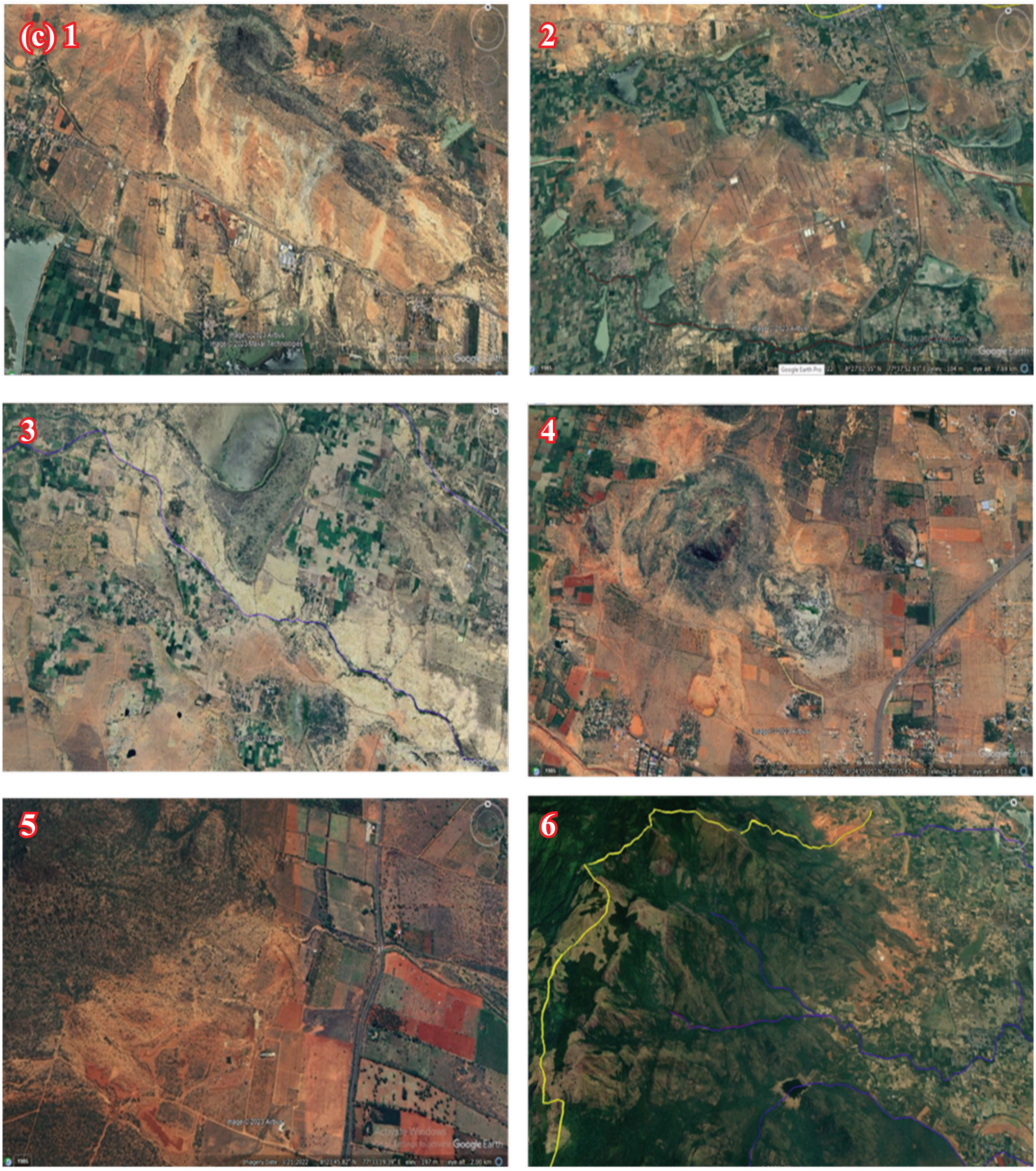


Figure 7: (a) Land capability classification of Nambiyar Watershed, (b) Google Earth images of the Nambiyar Watershed, erosion prone area, flood prone area, sub-watershed Id-1,2,3 , and (c) zoomed in Google images showing flood and erosion prone areas in the Nambiyar watershed

Figure 8: (a) Nambiyar River in its upper reaches, (b) barren hillocks in the watershed, (c) Nambiyar Dam located in Kotaikarungulam,(d) paddy and banana cultivation in the watershed, (e) scrublands with bushes in the watershed, and (f) River Nambiyar at its mouth

Conclusion

To implement appropriate land and water conservation measures, this study was carried out to prioritise the sub-watersheds in the Nambiyar watershed prone to flooding and erosion. TOPSIS, an MCDM technique, determined which sub-watersheds require high-priority conservation based on morphometric parameters. The findings show that flash floods are more likely in the upper reaches of the watersheds. According to the findings, the upper reaches of the watershed have a high drainage density, *Fs*, slope, and relief, indicating more runoff and erosion. The land use and land cover analysis show scrublands and salt-affected lands cover a significant area of the watershed. The morphometric analysis was performed in the Nambiyar Watershed to identify vulnerable areas for the occurrence of flash floods and erosion for land and water conservation. It is found that sub-watersheds 1, 2, 3, 4, and 5 are highly vulnerable to flash flood events and erosion, where conservation is needed to reduce peak water discharge during monsoon season. Morphometric analysis coupled with MCDM techniques like TOPSIS enabled the prioritisation of sub-watersheds by considering the relative significance of each morphometric parameter affecting various natural events and prioritising the same. Accordingly, the sub-watersheds of the Nambiyar watershed were ranked and prioritised for proposing and implementing various regulations and developmental activities. The Tamil Nadu Watershed Development Agency (TAWDEVA) has implemented various schemes, such as the Special Area Development Programme and the National Watershed Development Project for Rainfed Areas (NWDPRA), for restoration and conservation in this district using an integrated watershed approach. These programmes aim to maintain water harvesting structures as well as build gabion check dams, earthen check dams, and drainage line treatment works. However, based on the nature and severity of the problems in the Nambiyar watershed, this study recommends regulation in land utilisation patterns to convert the scrublands into arable lands in the northeastern part of the watershed. In the upper reaches of the watershed where there is flood occurrence, various measures such as check dams and rainwater harvesting systems should be implemented in each household to store the excess water from rainfall and runoff, which can be effectively used for agricultural and allied purposes. The Geospatial technique combined with Multi-Criteria decision-making methods offers a suitable solution for morphometric analysis and subsequently prioritising the sub-watersheds.

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Conflict of Interest Statement

The authors declared that they have no conflict of interest.

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