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Towards Sustainable Development: Ranking of Soil Erosion-Prone Areas Using Morphometric Analysis and Multi-Criteria Decision-Making Techniques

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Abstract: Sub-watershed prioritization using morphometric analysis and multi-criteria decision-making (MCDM) techniques is a systematic approach to identifying and ranking sub-watersheds based on their susceptibility to soil erosion. This helps in implementing targeted soil conservation measures. In this study, sub-watersheds in the Narangi basin are prioritized by employing morphometric analysis integrated with advanced MCDM techniques, including additive ratio assessment (ARAS), complicated proportional assessment (COPRAS), multi-objective optimization by ratio analysis (MOORA), and the technique for order preference by similarity to ideal solution (TOPSIS). Weights for various MCDM methods are determined using the criteria importance through an inter-criteria correlation approach (CRITIC: criteria importance through inter-criteria correlation method), while geospatial techniques ensure precise spatial analysis. The results provide a unified ranking of sub-watersheds, revealing that sub-watershed 3 (SW3) and SW9 are in the high-priority soil erosion category; SW1, SW2, SW5, and SW8 are medium-priority; and SW4, SW6, SW7, and SW10 are low-priority. This comprehensive and sustainability-oriented approach equips decision-makers with robust tools to identify and manage sub-watersheds at risk of soil erosion, ensuring the long-term sustainability of land and water resources. This study aligns with sustainable development goal 15 (life on land) and promotes sustainable land use practices to combat soil degradation.

Keywords: morphometric analysis; MOORA; COPRAS; TOPSIS; ARAS; sustainability

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1. Introduction

Watershed management, particularly through the study of watershed morphometry, is crucial for addressing challenges such as soil erosion, water scarcity, and land degradation. Morphometric analysis evaluates key parameters, which provide critical insights into the physical characteristics of a watershed. These parameters help identify erosion-prone areas. By understanding these characteristics, targeted soil conservation measures can be implemented. This not only reduces soil erosion but also enhances water retention,

improves land fertility, and ensures sustainable water resource management. Ultimately, integrating morphometric analysis into watershed management strategies is essential for mitigating the adverse impacts of soil erosion and promoting long-term environmental sustainability [1–14].

Morphology is something that can be defined as the mathematical description of the topographic reliefs that are found on the surface of the earth [15,16]. In their study, Rastogi and Sharma [17] found that the physiographic characteristics of watersheds can be connected to a variety of hydrological phenomena. The hydrologic response, which includes the generation of surface runoff, the capability of infiltration, and even the potential of groundwater, can be completely evaluated through the use of morphometric analytical techniques. According to Altaf et al., morphometric analysis is a method that helps forecast basin characteristics with more accuracy [18]. These characteristics include travel time, time to peak, and erosion severity. According to Puno and Puno, morphometric analysis is also helpful for ungauged watersheds that do not have much information regarding hydrology, geology, geomorphology, or soil [19]. Furthermore, the evaluation of drainage basins, the administration and preservation of natural resources, the measurement of the frequency of floods, and the control of erosion are all areas that could significantly benefit from the application of morphometric analysis [20]. The data that are gathered from the morphometric analysis of watersheds have the potential to be an important instrument for a variety of purposes, including the prevention of soil erosion, the mapping of landslide susceptibility, the prioritization of watersheds, the evaluation of groundwater potential, and the management of water resources [21–28].

River morphometric analysis used to need a significant amount of time and effort to be completed. Now, as a result of advancements in technology, the study of watershed features can be aided by satellite data such as digital elevation models (DEMs) in the event that topographic maps are unavailable. DEMs, on the other hand, provide continuous data and are easy to include in geographic information systems (GISs) [29]. This is in contrast to contours that are shown on topographic maps. DEMs have been utilized for morphometric analysis in a number of scholarly articles in the past several years [30,31]. Recent studies have used geospatial techniques and multi-criteria decision-making (MCDM) methods for soil erosion mapping and sub-watershed prioritization. Various approaches, including RUSLE, AHP, fuzzy MCDM, and GIS-based models, have been applied to assess erosion risk and conservation needs. These methods help identify erosion-prone areas and support effective watershed management [32–45]. Numerous studies worldwide have employed MCDM techniques in different works of research [46–50]. These studies, which aim to boost agricultural output and assure the sustainable use of natural resources, have placed a key emphasis on giving sub-watersheds a higher priority than other watersheds. By integrating these cutting-edge technologies and analytical methods, researchers have attempted to obtain a deeper comprehension of the characteristics of sub-watersheds, identify problem areas, and arrive at well-informed decisions in order to effectively manage resources and encourage sustainable land use practices [51].

A wide range of MCDM approaches have been utilized extensively in the research that has been published for the purpose of sub-watershed prioritization. These approaches evaluate and rank sub-watersheds according to a range of factors, thereby improving erosion management tactics and reducing susceptibility [52,53]. They accomplish this by identifying areas that are prone to erosion and efficiently distributing resources. Recent research has utilized MCDM methodologies on a GIS platform in order to prioritize sub-basins and develop effective management strategies for the prevention and protection of land degradation.

Integrating morphometric analysis with MCDM techniques, like multi-objective optimization by ratio analysis (MOORA), complicated proportional assessment (COPRAS), the technique for order preference by similarity to ideal solution (TOPSIS), and additive ratio assessment (ARAS), offers a novel, highly effective approach for prioritizing soil erosion-prone zones, such as sub-watersheds. Methods like MOORA, COPRAS, TOPSIS, and ARAS help in prioritizing sub-watersheds based on weighted criteria to determine their susceptibility to erosion. MOORA normalizes the decision matrix and calculates a performance index to rank sub-watersheds, while COPRAS evaluates alternatives by considering both the direct and inverse relationships of criteria. TOPSIS ranks sub-watersheds by measuring their geometric distance from an ideal and anti-ideal solution, identifying the most erosion-prone areas based on proximity to the worst-case scenario. ARAS, on the other hand, assigns utility values based on the sum of weighted criteria, comparing them with an ideal alternative to establish priority rankings. This combination enhances the accuracy and precision of identifying critical areas at risk of soil erosion compared to traditional methods. While morphometric analysis provides insights into the physical characteristics of the landscape, MCDM techniques enable the evaluation and ranking of these areas based on multiple factors, offering a comprehensive and robust decision-making framework. The novelty lies in combining spatially explicit morphometric data with decision-making models that are rarely used together in soil erosion studies, providing a clearer and more accurate delineation of high-priority erosion zones. This approach directly supports sustainable development goal 15 (life on land) by facilitating sustainable land management and conservation efforts, targeting areas most vulnerable to erosion, and promoting long-term environmental sustainability [54–58]. The primary goal of this study is to make use of SRTM-DEM data in order to conduct an analysis of the morphometric parameters of the sub-watersheds in the Narangi basin to gain an understanding of the hydrological characteristics of these watersheds. A further objective is to prioritize the sub-watersheds in accordance with their susceptibility to soil erosion by employing four different MCDM models, namely MOORA, COPRAS, TOPSIS, and ARAS. In addition, this research endeavors to ascertain the common priority of sub-watersheds according to morphometric analysis as well as MCDM techniques.

2. Materials and Methods

2.1. Study Area

An important hydrological system that has a total area of 1921 square kilometers is the Narangi watershed, which can be found in India between the states of Chhattisgarh and Odisha (Figure 1). This watershed is traversed by the Narangi River, which is a subtributary of the Godavari River. The physical coordinates of this location are as follows: 19°0′0″ north to 20°0′0″ north. Its longitude ranges from 81°30′0″ east to 82°15′0″ east. At the point where the Narangi River empties into the ocean, Ambabal can be found at the intersection of latitude 19°17′00″ north and longitude 81°47′20″ east. Within the Narangi River, the height can range anywhere from 537 to 787 m above sea level, as indicated by the DEM that was created by the shuttle radar topography mission (SRTM). The beginning of the monsoon season normally occurs in June and continues all the way through September.

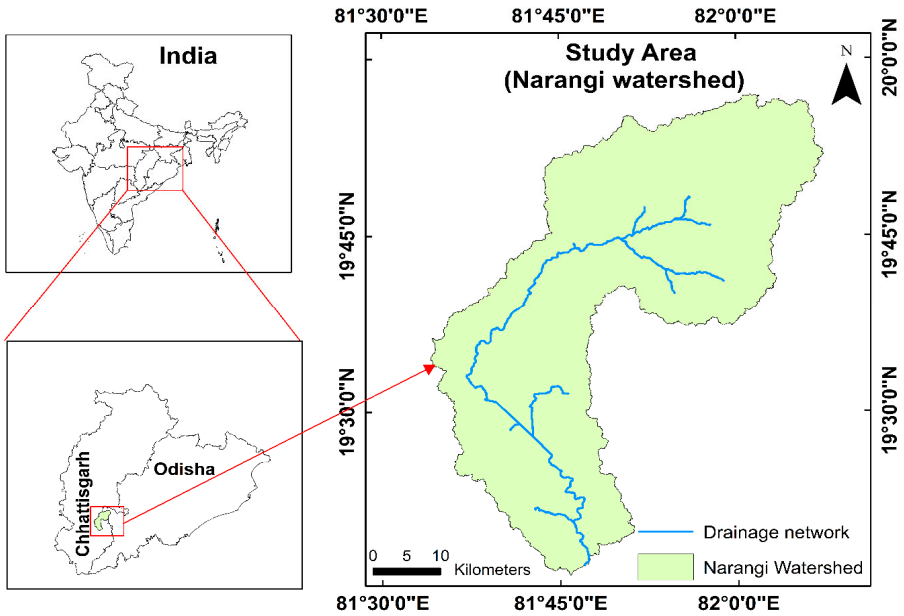


Figure 1. The study area of the Narangi watershed.

2.2. Methodology

The first step in the process of acquiring and preparing data is to collect a high-resolution DEM of the area under investigation from sources such as SRTM (30 m) (USGS EarthExplorer: https://earthexplorer.usgs.gov/, accessed on 1 February 2025). For the purpose of preparing the DEM for analysis, it passes through a number of pre-processing procedures. These phases involve filling sinks to eliminate depressions, calculating flow direction to establish water flow pathways, and accumulating flow to find regions with high flow concentration. All of these steps are necessary components of the process. The delineation of stream networks and their subsequent conversion into vector format for further analysis are accomplished through the application of a threshold value for flow accumulation. For the purpose of delineating sub-watersheds within the research area, the pre-processed DEM is then applied. This is accomplished by identifying drainage networks and splitting the region into smaller watersheds that are different from one another. Based on Horton's laws, the ten sub-watersheds were delineated. The law of stream numbers establishes a relationship between the number of streams and their respective orders, while the law of stream lengths defines the correlation between stream length and stream order. The study area was divided into 10 sub-watersheds to facilitate a more detailed hydrological analysis (Figure 2). After that, the sub-watersheds that were identified were subjected to morphometric analysis in order to calculate the numerous parameters that are characteristic of each sub-watershed. Sub-watersheds are rated according to these metrics, which include linear, relief, and shape parameters. The morphometric characteristics are used as input for MCDM. MCDM techniques play a vital role in ranking sub-watersheds for soil erosion assessment by systematically evaluating multiple influencing factors such as morphometric parameters. Methods like MOORA, COPRAS, TOPSIS, and ARAS help in prioritizing sub-watersheds based on weighted criteria to determine their susceptibility to erosion (Table 1; Table 2). MOORA evaluates multiple criteria by comparing beneficial and non-beneficial factors, providing a balanced ranking. COPRAS considers the significance of each criterion, ensuring a detailed prioritization process. TOPSIS ranks alternatives based on their geometric distance from an ideal best and worst solution, improving accuracy. ARAS determines performance scores, facilitating comparative evaluation. Within the framework of MCDM, weights are assigned to the parameters in accordance with their

relative relevance, and the findings are integrated in order to establish priority rankings. Establishing a common priority for all of the sub-watersheds is the final phase, which entails merging the rankings that were acquired via morphometric analysis and MCDM. In this study, a total of 10 sub-watersheds were analyzed, and their susceptibility to soil erosion was ranked using morphometric analysis and MCDM. Rank 1 indicates the sub-watershed with the highest erosion rate, requiring immediate attention for conservation measures, while the subsequent ranks represent progressively lower erosion susceptibility. This ranking system helps prioritize sub-watersheds for effective soil erosion management and mitigation strategies (Figure 3).

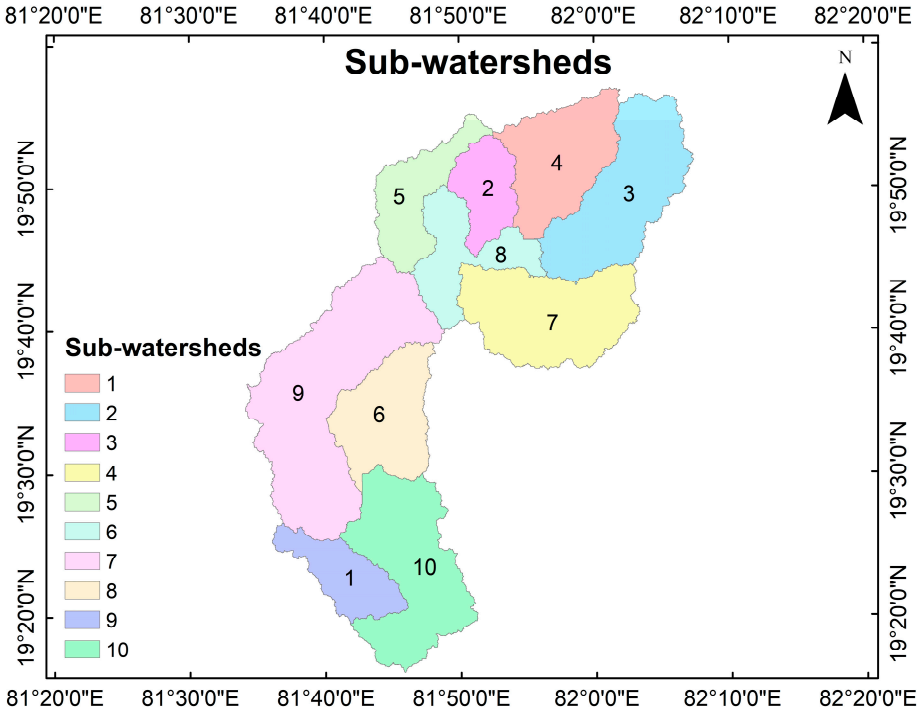


Figure 2. Narangi River basin and its sub-watersheds.

Table 1. MCDM equations.

Method	Formula	Equation Number
CRITIC	$X_{ij} = \frac{X_{ij} - X_j^{worst}}{X_j^{best} - X_j^{worst}}$	(1)
	$\sum_{k=1}^{m} \left(1 - r_{jk}\right)$	(2)
	$C_j = \sigma_j * \sum_{k=1}^{m} \left(1 - r_{jk}\right)$	(3)
	$W_j = \frac{C_j}{\sum_{k=1}^{m} C_j}$	(4)
MOORA	$x_{ij}^* = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$ (j = 1, 2, ….n)	(5)
	$y_i = \sum_{j=1}^{g} w_j x_{ij}^* - \sum_{j=g+1}^{n} w_j x_{ij}^*$ (j = 1, 2, ….n)	(6)
COPRAS	$R = (r_{ij})_{mxn} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}$	(7)
	$D = (y_{ij})_{mxn} = r_{ij} XW_j$ i = 1, 2, ….m and j = 1, 2, ……n	(8)
	$S+_i = \sum_{j=1}^{n} y_{+ij}$	(9)
	$S-_i = \sum_{j=1}^{n} y_{-ij}$	(10)

Table 1. *Cont.*

Method	Formula	Equation Number
COPRAS	$Q_i = S_{+i} + \frac{S_{-min}\sum_{i=1}^{m} S_{-i}}{S_{-i}\sum_{i=1}^{m}\frac{S_{-min}}{S_{-i}}}$ (i = 1, 2, ...m); where $S_{-min} = S_{-i}$	(11)
	$U_i = (\frac{Q_i}{Q_{max}}) \times 100\%$	(12)
	$X_{ij} = \frac{1}{x_{ij}^*}$	(13)
ARAS	$X_{ij} = \frac{x_{ij}}{\sum_{i=0}^{m} x_{ij}}$	(14)
	$X_{ij} = \frac{x_{ij}}{\sum_{i=0}^{m} x_{ij}}$; $\hat{x}_{ij} = X_{ij}\, w_j$	(15)
	$S_i = \sum_{j=1}^{n} \hat{x}_{ij}$; $I = \overline{0,\ m}$	(16)
	$K_i = \frac{S_i}{S_o}$	(17)
TOPSIS	$X_{ij} = \frac{X_{ij}}{\sqrt{\sum_{j=1}^{n} X_{ij}^2}}$	(18)
	$S_i^+ = \left[\sum_{j=1}^{m}\left(V_{ij} - V_j^+\right)^2\right]^{0.5}$	(19)
	$S_i^- = \left[\sum_{j=1}^{m}\left(V_{ij} - V_j^-\right)^2\right]^{0.5}$	(20)
	$P_i = \frac{S_i^-}{S_i^+ + S_i^-}$	(21)

Table 2. Morphometric parameters.

Parameters	Formulae or Methods	References
Linear Parameters		
Stream Length (L_u)	$L_u = L_{u1} + L_{u2} + \cdots + L_{un}$	[24]
Stream Length Ratio (R_l)	$R_l = L_u / L_u - 1$	[24]
Stream Number (N_u)	$N_u = N_{u1} + N_{u2} + \cdots + N_{un}$	[24]
Rho Coefficient (ρ)	R_{lm}/R_{bm}	[24]
Length of Overland Flow (L_o)	$L_o = (1/(2Dd))$	[24]
Mean Bifurcation Ratio (R_{bm})	Average of the Bifurcation Ratio of all orders	[27]
Bifurcation Ratio (R_b)	$R_b = N_u / N_u + 1$	[28]
Stream Order (U)	Hierarchical Rank	[28]
Mean Stream Length Ratio (R_{lm})	Average of the Steam Length Ratio of all orders	[28]
Drainage Density (D_d)	$D_d = (\sum L_u)/A$	[25]
Stream Frequency (F_s)	$F_s = (\sum N_u)/A$	[25]
Constant of Channel Maintenance (C_{cm})	$C = 1/D_d$	[25]
Drainage Texture (D_t)	$D_t = (\sum N_u)/P$	[25]
Drainage Intensity (D_i)	$D_i = F_s/D_d$	[59]
Infiltration Number (I_f)	$I_f = F_s \times D_d$	[59]
Relief Parameters		
Relief (B_h)	$B_h = H–h$	[26]
Relative Relief (R_{hp})	$R_{hp} = H \times 100/P$	[60]
Maximum Elevation (H)	GIS Software	-
Ruggedness Number (R_n)	$R_n = B_h \times D_d$	[61]
Minimum Elevation (h)	GIS Software	-

Table 2. *Cont.*

Parameters	Formulae or Methods	References
Areal/Shape Parameters		
Form Factor (F_f)	$F_f = (A/Lb^2)$	[62]
Shape Index (S_b)	$S_b = 1/F_f$	[62]
Compactness Coefficient (C_c)	$C_c = (P/2(\pi A)^{0.5})$	[24]
Area of Watershed (A)	GIS Software	-
Circulatory Ratio (R_c)	$R_c = (4\pi A/P^2)$; where $\pi = 3.14$	[23]
Watershed Length (L_b)	$L_b = 1.312 \times A^{0.568}$	[63]
Lemniscate Ratio (K)	$K = (Lb^2/4A)$	[64]
Perimeter of Watershed (P)	GIS Software	-
Elongation Ratio (R_e)	$R_e = (2*(A/\pi)^{0.5})/(L_b)$	[25]

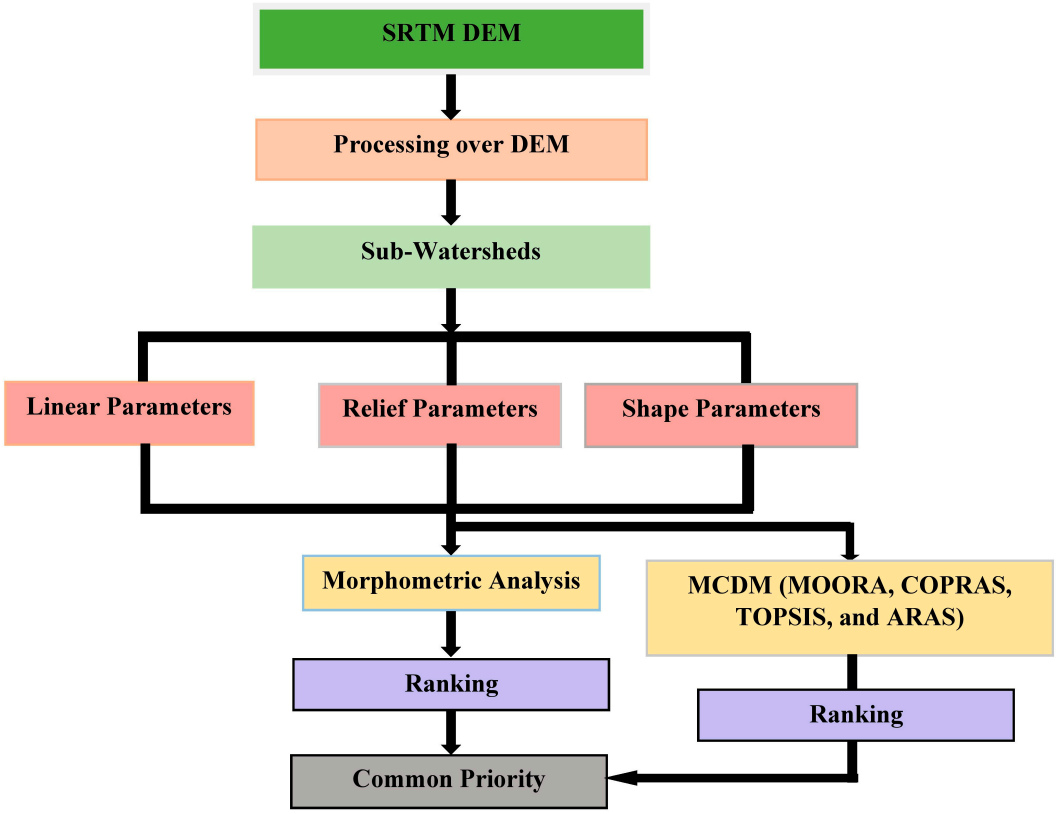


Figure 3. Flowchart for present research work.

3. Results

In order to gain an understanding of the flow of water through a watershed as well as its physical characteristics, such as its shape, size, and elevation, morphometric analysis is utilized. Within the scope of this research, sub-watersheds were assessed on the basis of these features in order to identify regions that may require additional attention for the sake of conservation or management. In order to rank the sub-watersheds, MCDM techniques such as MOORA, COPRAS, TOPSIS, and ARAS were utilized. These techniques took into consideration a variety of criteria. A final priority map was created by combining the findings from these methodologies with the findings from the morphometric study. This map assisted in determining which sub-watersheds require immediate attention. Here is a discussion of the specifics of the criteria that were utilized.

3.1. Linear Parameters

3.1.1. Stream Order (U)

The classification of the position of a stream within a hierarchy of tributaries is the first step in morphometric analysis. Stream order is a tool that assists in this classification. First-order tributaries are those that are the smallest and do not have any branches, which is defined by tributary junctions. The stream that is generated when two streams of the same order meet is of a higher order than the other stream. The order of these streams increases as they combine further downstream, with the main channel having the highest order to transmit the greatest quantity of flow, runoff, and sediment [65] (Figure 4).

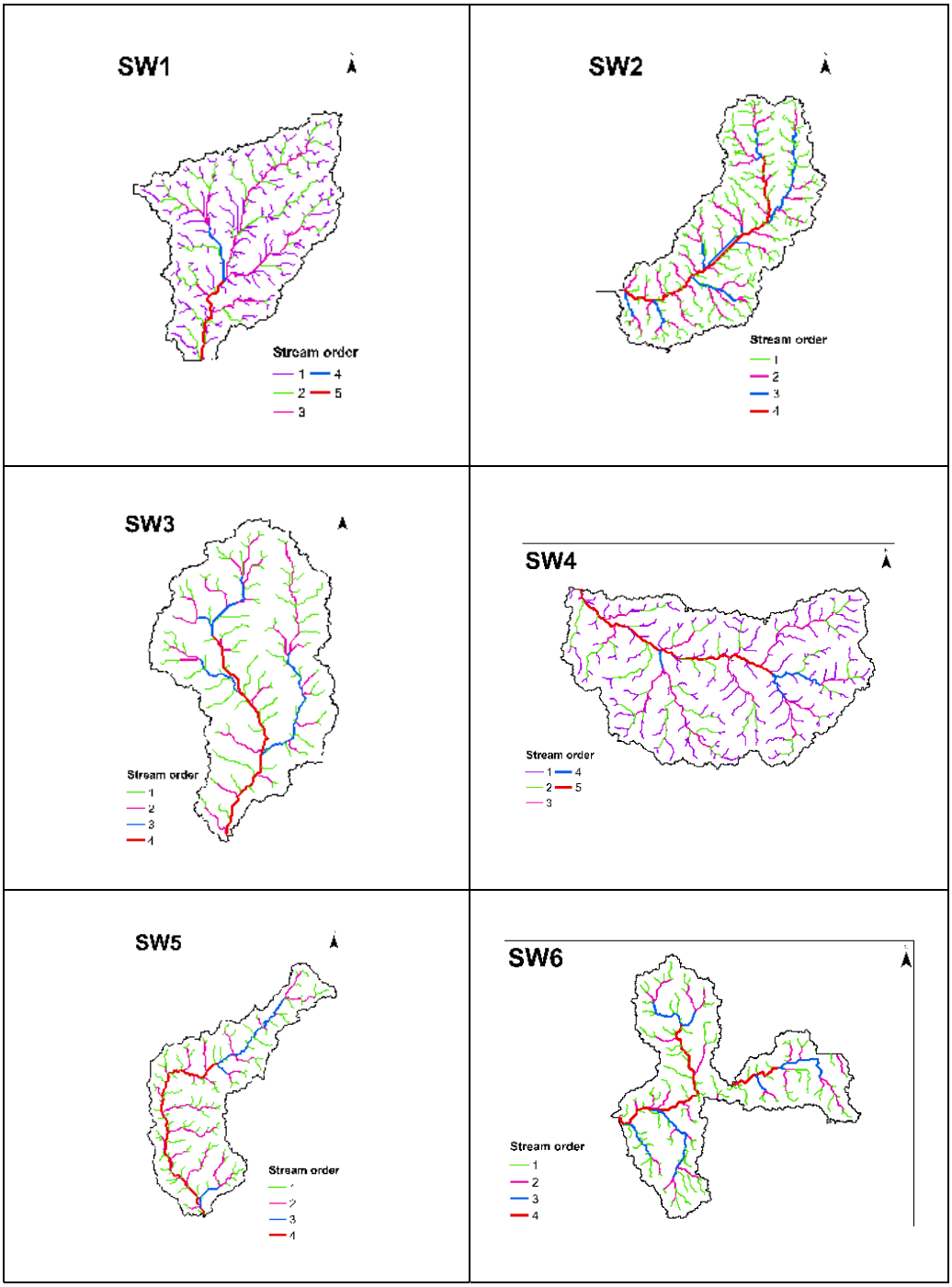


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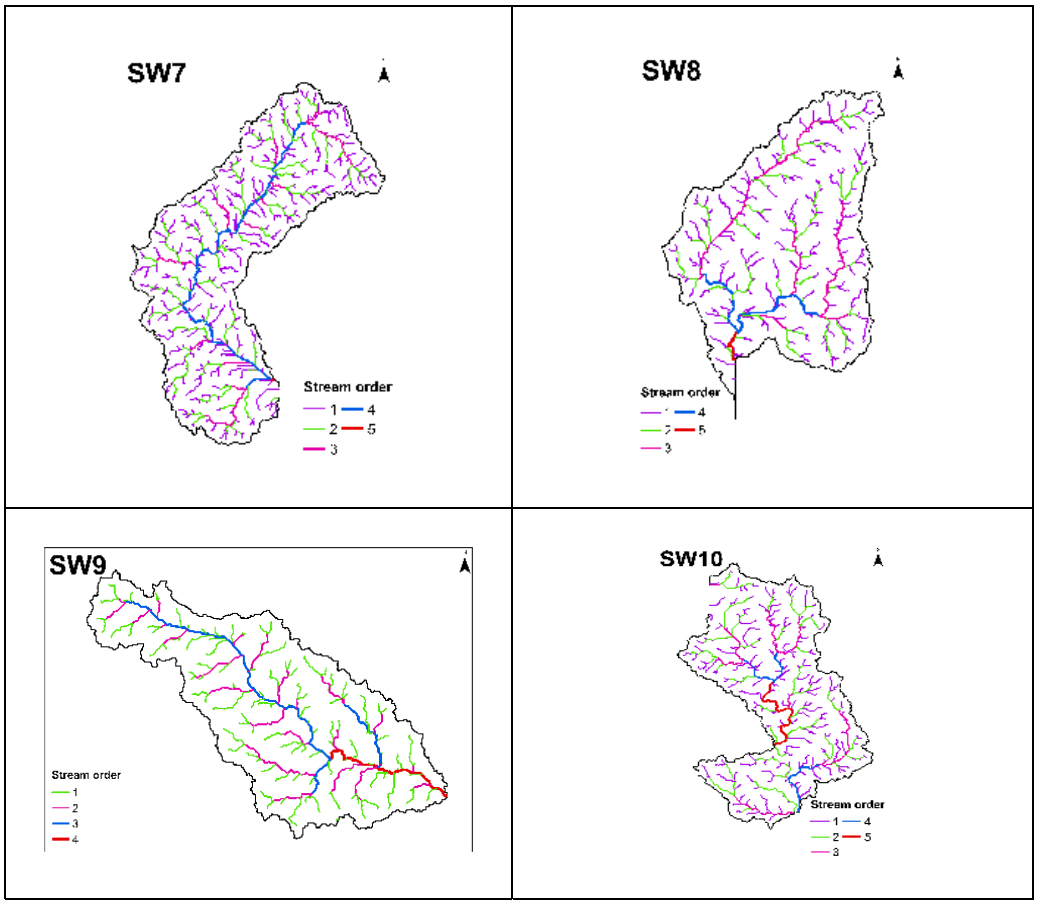


Figure 4. Sub-watersheds of Narangi River.

3.1.2. Stream Length Ratio (R_l)

The ratio of the mean length of streams at a particular order (L_u) to the mean length of streams at the next smaller order ($L_u - 1$) is the definition of the stream length ratio [24] (Table 2). There are two primary laws that characterize the correlations that exist between the number of streams and their lengths across the many orders that make up a drainage basin:

1. The law of stream numbers: This law provides an explanation for the relationship that exists between the number of streams that are present at a particular order and the stream order itself. This relationship conforms to an inverse geometric sequence, with the bifurcation ratio serving as the foundation. Along with the coefficients of determination, Figure 5 illustrates that there is a significant relationship between the order of the streams and the number of streams.
2. The law of stream lengths: This law describes the relationship between the average length of streams at each order, the average length of first-order streams, and the stream length ratio. It also describes how the average length of streams at each order relates to the stream order. A direct geometric series is formed by the relationship between the two. In a similar vein, Figure 6 illustrates a remarkable correlation between the order of the stream and the length of the stream, along with the coefficients of determination.

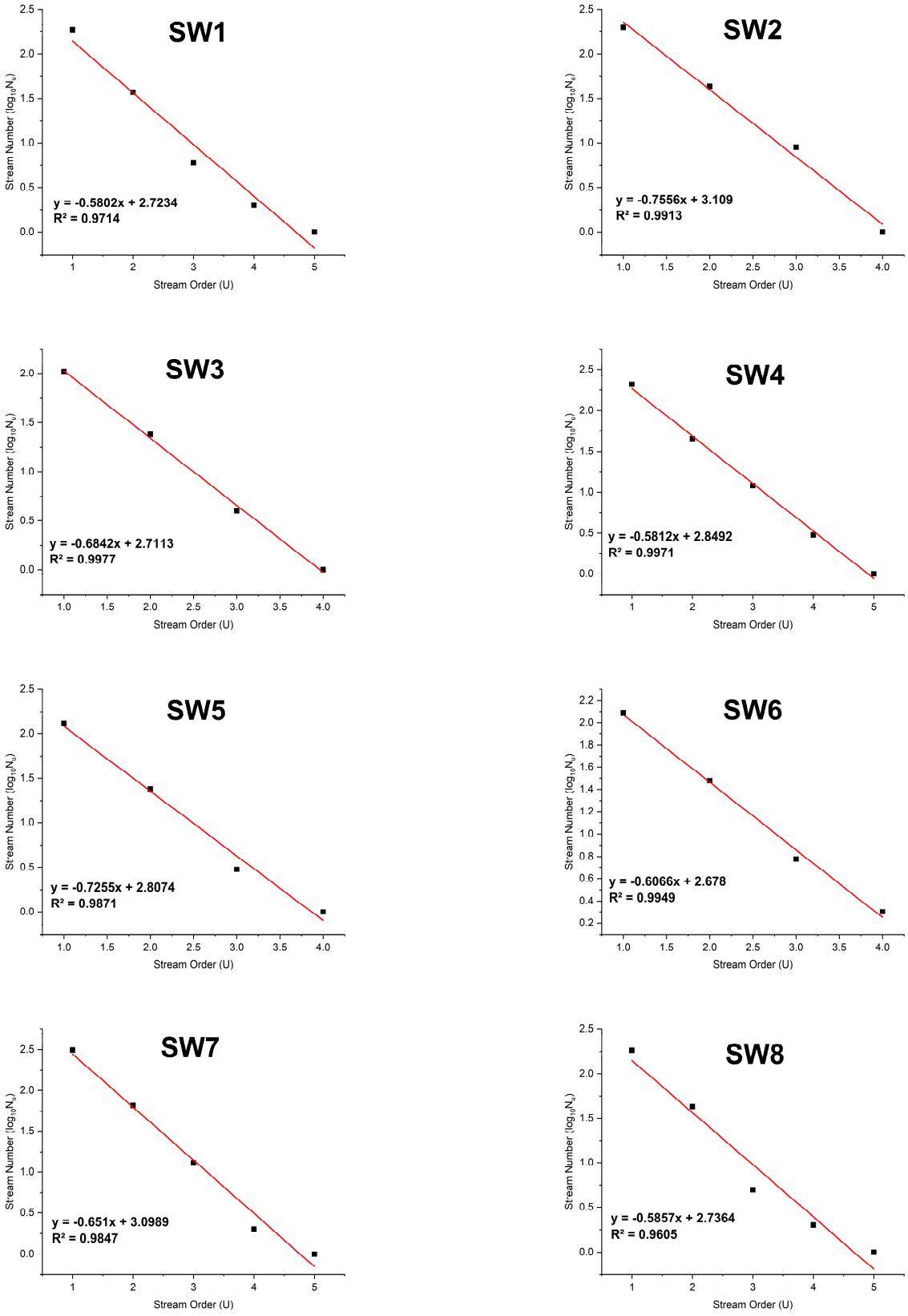


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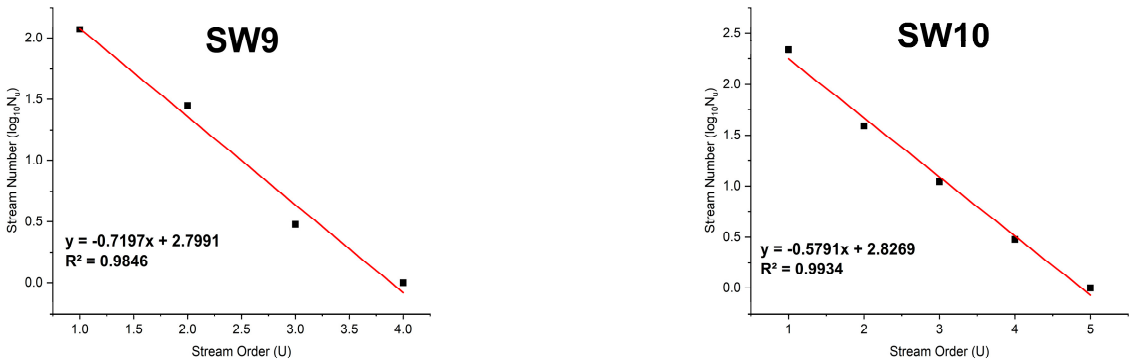


Figure 5. R^2 of stream number and stream order.

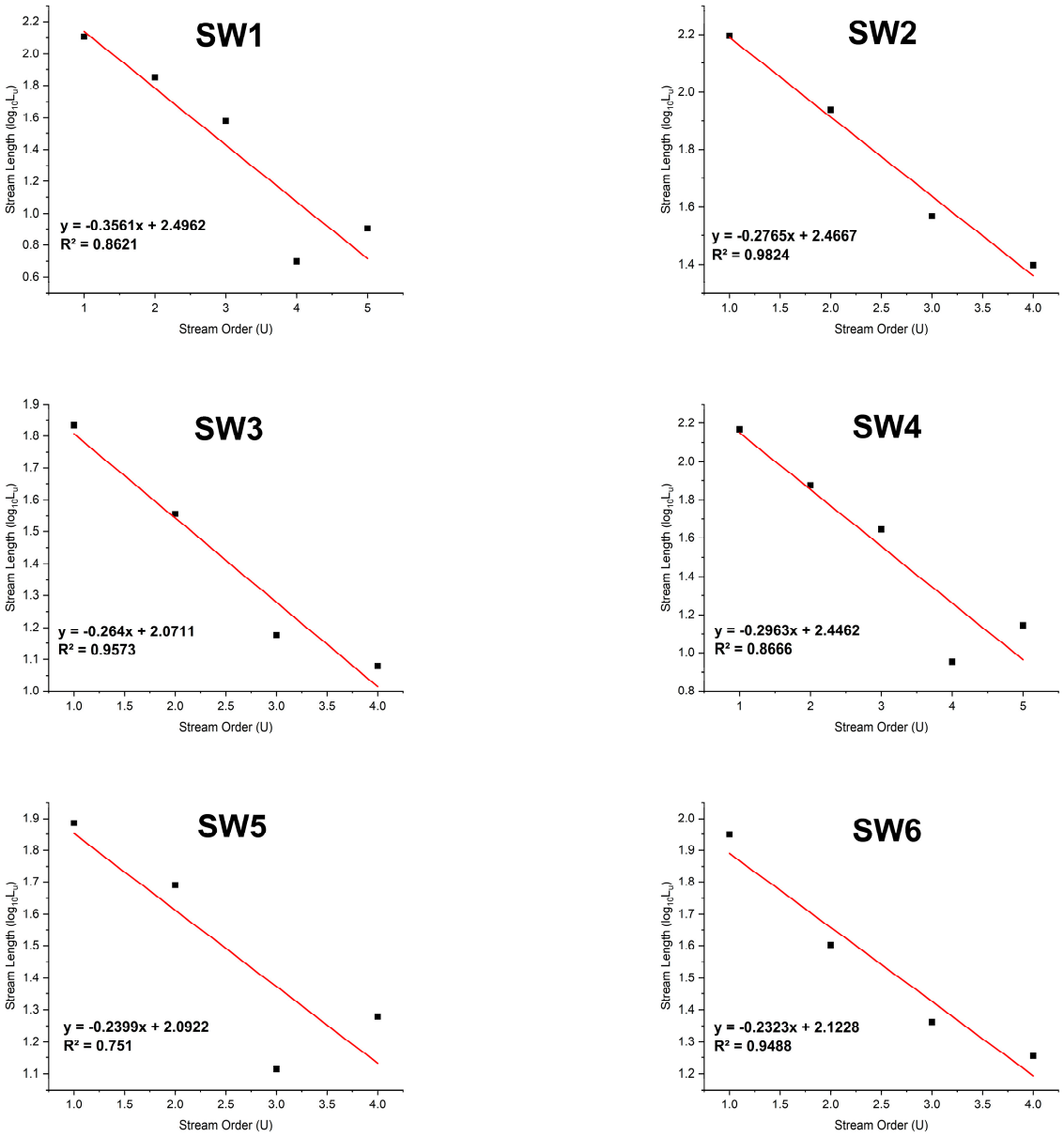


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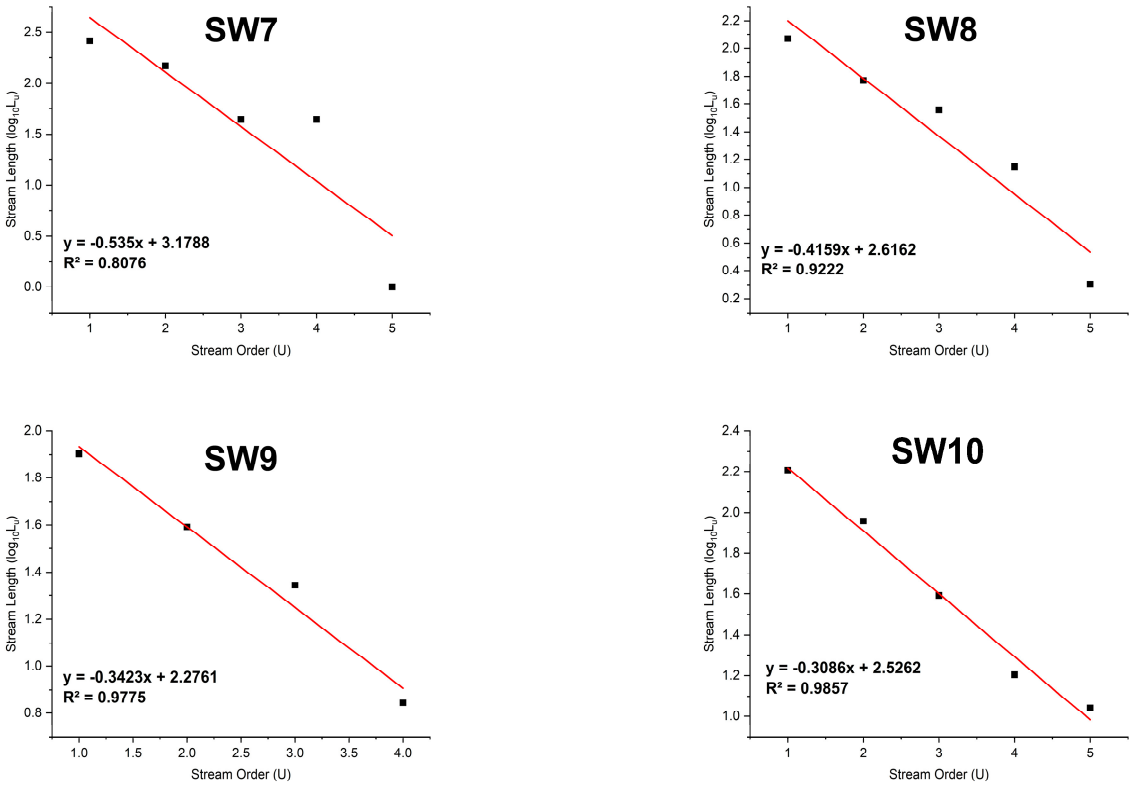


Figure 6. R^2 of stream length and stream order.

Stream frequency (F_s) represents the total number of stream segments per unit area. In this study, SW9 is ranked 1, while SW7 is ranked 10. Drainage density (D_d) is the total stream length within a specific area unit, with SW9 ranked 1 and SW4 ranked 10. Drainage texture (D_t) measures the total number of streams along the watershed perimeter; SW8 is ranked 1, and SW6 is ranked 10 in this study. The length of the overland flow (Lo), roughly calculated as half the inverse of D_d, assigns SW4 a rank of 1 and SW9 a rank of 10. Drainage intensity (D_i), the ratio of the number of streams per unit area to the total stream length per unit area, ranks SW8 as 1 and SW7 as 10 [59]. The Rho coefficient (ρ), derived by dividing the stream length ratio by the bifurcation ratio, assigns SW9 a rank of 1 and SW4 a rank of 10. Infiltration number (If) is calculated as the product of Dd and Fs, where higher values indicate lower infiltration rates and higher surface runoff; SW9 is ranked 1, while SW is ranked 10. Lastly, the constant of channel maintenance (C_{cm}), introduced as the inverse of D_d, assigns SW4 a rank of 1 and SW9 a rank of 10 in this study.

3.2. Relief Parameters

Relief (B_h) represents the difference in elevation between the maximum and minimum elevations within a watershed. In this study, SW2 is ranked 1, while SW8 is ranked 10. Relative relief (R_{hp}) [60] is calculated using the watershed relief in conjunction with its perimeter, with SW3 assigned a rank of 1 and SW7 a rank of 10. The ruggedness ratio (R_n), integrates slope steepness and length, calculated as the product of the maximum basin relief and drainage density. In this study, SW1 is ranked 1, while SW8 is ranked 10.

3.3. Areal Parameters

The circulatory ratio (R_c) is the ratio of the watershed area to the area of a circle with a circumference equal to the watershed's perimeter. In this study, SW6 is ranked 1, while SW3 is ranked 10. The elongation ratio (R_e) measures the ratio of the watershed area (A) to the square of the watershed length (L_b), with lower values indicating more elongated

watersheds. Here, SW7 is ranked 1, and SW3 is ranked 10. The form factor (F_f) is the ratio of the catchment area to the square of the catchment length; SW7 is ranked 1, while SW3 is ranked 10. The lemniscate ratio (K) is used to evaluate the watershed gradient [64], and SW3 is ranked 1, while SW7 is ranked 10. The compactness coefficient (C_c) represents the ratio of the watershed's perimeter to the circumference of a circle with the same area as the watershed. In this study, SW3 is ranked 1, and SW6 is ranked 10. Finally, the shape index (S_b), defined as the reciprocal of the form factor (F_f), assigns SW3 a rank of 1 and SW7 a rank of 10 (Table 3).

Table 3. Morphometric parameters of this study.

Parameters	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10
R_{bm}	4.04	6.11	4.79	3.84	5.49	4.03	4.58	4.34	5.53	3.95
R_{lm}	0.71	0.55	0.58	0.71	0.79	0.60	0.47	0.41	0.46	0.52
F_s	1.27	1.02	1.50	1.13	1.33	1.28	0.97	1.41	1.53	1.08
D_d	1.37	1.26	1.47	1.22	1.32	1.35	1.22	1.37	1.50	1.26
D_t	2.28	1.92	1.94	2.36	1.63	1.31	2.24	2.44	1.88	1.95
L_o	0.36	0.40	0.34	0.41	0.38	0.37	0.41	0.36	0.33	0.40
p	5.73	11.08	8.23	5.38	6.96	6.70	9.67	10.54	12.11	7.56
D_i	0.92	0.81	1.02	0.93	1.01	0.95	0.80	1.03	1.02	0.86
I_f	1.74	1.28	2.21	1.37	1.76	1.73	1.19	1.93	2.30	1.35
C_{cm}	0.73	0.80	0.68	0.82	0.76	0.74	0.82	0.73	0.67	0.80
B_h	0.18	0.18	0.13	0.15	0.11	0.14	0.14	0.10	0.16	0.14
R_{hp}	0.78	0.61	1.05	0.65	0.72	0.59	0.40	0.69	0.87	0.48
R_n	0.24	0.22	0.19	0.18	0.15	0.18	0.17	0.14	0.23	0.17
R_c	0.22	0.18	0.23	0.23	0.16	0.10	0.16	0.23	0.19	0.16
R_e	0.60	0.59	0.63	0.59	0.62	0.62	0.57	0.61	0.63	0.59
F_f	0.29	0.28	0.32	0.28	0.30	0.30	0.26	0.29	0.31	0.27
K	0.87	0.91	0.79	0.91	0.82	0.83	0.97	0.86	0.80	0.91
S_b	3.49	3.63	3.17	3.62	3.30	3.32	3.90	3.45	3.21	3.65
C_c	2.12	2.35	2.07	2.09	2.51	3.09	2.47	2.10	2.28	2.48

3.4. Morphometric Analysis

The analysis of morphometric sub-watershed prioritization is an essential component in gaining knowledge of the susceptibility of particular regions to soil erosion. By classifying morphometric data into linear, relief, and shape categories, this technique offers a methodical strategy to rank sub-watersheds from the most important to the least important. Erosion processes have a direct impact on the linear and relief dimensions of a landscape. Sub-watersheds that have greater values in these characteristics are more likely to have a higher vulnerability to erosion as a result of increased runoff, sediment transport, and stream network activity. Within the hierarchy of priorities for conservation initiatives, some regions are ranked far higher. In the other direction, form parameters provide an indirect indication of erosion potential. There is a correlation between lower values of form characteristics and higher erosion susceptibility, which leads to higher ranks for these sub-watersheds [63,66]. The calculation of the compound parameter, also known as Cp, is a comprehensive metric that is used to prioritize sub-watersheds (Figure 7). This is accomplished by combining the ranks of the separate factors under consideration. Ac-

cording to the information presented in Table 4, the sub-watersheds are divided into three priority categories: high, medium, and low significance. SW5, SW8, SW10, and SW13 are examples of sub-watersheds that are considered to have high priority, while SW5 and SW6 are considered to have medium priority. SW1, SW2, SW3, SW4, SW7, SW11, and SW12 are all sub-watersheds that are regarded as having low priority overall.

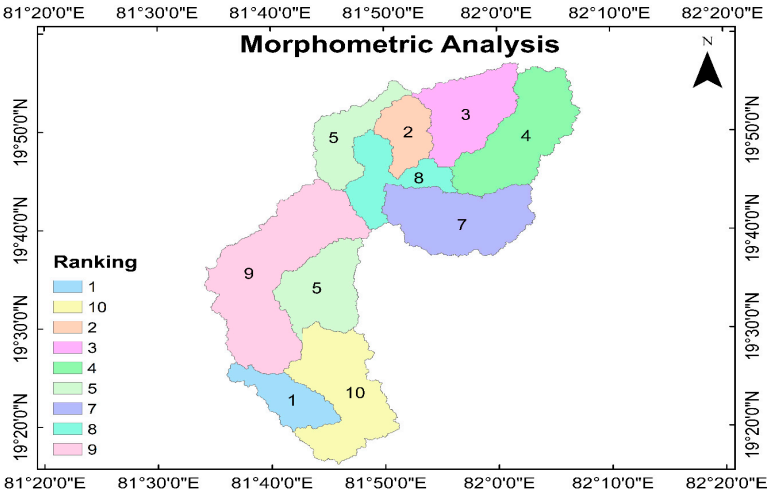


Figure 7. Ranking of Narangi sub-watersheds based on morphometric analysis.

Table 4. Ranking of ten sub-watersheds.

Parameters	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10
R_{bm}	7	1	4	10	3	8	5	6	2	9
R_{lm}	3	6	5	2	1	4	8	10	9	7
F_s	6	9	2	7	4	5	10	3	1	8
D_d	3	8	2	10	6	5	9	4	1	7
D_t	3	7	6	2	9	10	4	1	8	5
L_o	8	3	9	1	5	6	2	7	10	4
p	9	2	5	10	7	8	4	3	1	6
D_i	7	9	2	6	4	5	10	1	3	8
I_f	5	9	2	7	4	6	10	3	1	8
C_{cm}	8	3	9	1	5	6	2	7	10	4
B_h	2	1	8	4	9	6	5	10	3	6
R_{hp}	3	7	1	6	4	8	10	5	2	9
R_n	1	3	4	6	9	5	7	10	2	8
R_c	7	5	10	9	2	1	4	8	6	3
R_e	5	3	10	4	8	7	1	6	9	2
F_f	5	3	10	4	8	7	1	6	9	2
K	6	8	1	7	3	4	10	5	2	9
S_b	6	8	1	7	3	4	10	5	2	9
C_c	4	6	1	2	9	10	7	3	5	8
Sum of Rankings (x)	98	101	92	105	103	115	119	103	86	122
Total Number of Parameters (y)	19	19	19	19	19	19	19	19	19	19
Compound Parameter (x/y)	5.16	5.32	4.84	5.53	5.42	6.05	6.26	5.42	4.53	6.42
Ranking	3	4	2	7	5	8	9	5	1	10

3.5. Selection of Weights: CRITIC (Criteria Importance Through Inter-Criteria Correlation) Method

The CRITIC approach assigns values to alternatives without employing a decision matrix or relying on decision-makers. This approach resembles correlation. Employing a systematic approach to address various issues facilitates the formulation of precise and pragmatic decisions [67,68]. The CRITIC technique is used to calculate objective weights for criteria when decision-makers either disagree on weights or are unable to directly compare different criteria.

1. Normalize Data:

Start by standardizing (normalizing) the decision metrics to bring them to a comparable scale. This prepares the data for further analysis (Equation (1)). Xj best and Xj worst are the best and worst values for criterion j. Xij is the value of criterion j for option i, the normalized value.

2. Identify Best and Worst Values:

For beneficial criteria (where higher values are better, like linear and relief), the maximum value is the best, and the minimum is the worst. For non-beneficial criteria (where lower values are better, like shape), the minimum value is the best, and the maximum is the worst.

3. Calculate Standard Deviation (σ):

For each criterion, calculate the standard deviation of the normalized values. This shows the variation within each criterion.

4. Measure Conflict Between Criteria:

Create a matrix that compares each criterion against every other one. Find the correlation for each pair of criteria, then use the following equation (where rjk is the correlation coefficient) to measure how much each criterion conflicts with the others. Sum these values for each row to obtain the total "conflict" each criterion has with others (Equation (2)).

5. Calculate Information Content (Cj):

Multiply each criterion's standard deviation (σ) by its conflict measure. This gives a value that reflects the "information content" or importance of each criterion (Equation (3)). m is the number of criteria.

6. Determine Weights (Wj):

Divide each criterion's information content (Cj) by the total information content across all criteria to obtain the objective weight for each criterion (Equation (1)) (Table 5).

Table 5. Determining the objective weights.

Parameter	Sum	Sigma	Objective Weights	Weights
R_{bm}	16.97	0.35	5.91	0.05
R_{lm}	18.74	0.33	6.13	0.05
F_s	16.29	0.35	5.74	0.05
D_d	16.07	0.35	5.60	0.05
D_t	18.68	0.31	5.77	0.05
L_o	21.84	0.35	7.68	0.07

Table 5. *Cont.*

Parameter	Sum	Sigma	Objective Weights	Weights
p	17.76	0.35	6.17	0.05
D_i	16.81	0.38	6.42	0.06
I_f	16.14	0.35	5.60	0.05
C_{cm}	21.84	0.35	7.68	0.07
B_h	17.76	0.32	5.76	0.05
R_{hp}	15.58	0.29	4.50	0.04
R_n	16.64	0.34	5.62	0.05
R_c	16.76	0.32	5.40	0.05
R_e	16.46	0.32	5.24	0.05
F_f	16.48	0.32	5.27	0.05
K	21.52	0.32	6.79	0.06
S_b	21.52	0.32	6.79	0.06
C_c	21.16	0.30	6.45	0.06

3.6. MOORA-Based Sub-Watershed Prioritization and Ranking

As an MCDM tool, the MOORA method is used in order to resolve complex multi-objective privatization challenges in transition economies, which are frequently in conflict with one another [69]. The MOORA technique ranks the available alternatives by equating the performance of each alternative with regard to a criterion to a denominator that reflects all possibilities connected to that criterion [70]. This technique makes use of ratio systems to accomplish this and ranks the alternatives. The first thing that needs to be conducted is to make use of Equation (5) to perform normalization for both beneficial and non-beneficial parameters. Providing an estimate of the assessment values is the second step. When it comes to multi-object optimization, the normalized data must be multiplied by the weight criteria for each and every alternative use. In the case of advantageous traits, these normalized performances are added, and in the case of non-beneficial attributes, they are deducted, using Equation (6).

The ranking of soil erosion assessment values provides critical insights into the relative susceptibility of different sites (SW) to erosion. Based on the computed values of Yi (B + NB), SW9 ranks the highest (Yi = 0.462), indicating the most significant soil erosion risk among the assessed sites (Table 6). SW2 follows closely with a Yi value of 0.361, marking it as the second most vulnerable site. SW8 and SW3 rank third and fourth, with Yi values of 0.338 and 0.293, respectively, highlighting moderate to high erosion risks. SW7 and SW5 hold intermediate positions with values of 0.230 and 0.227, suggesting a moderate erosion threat. Meanwhile, SW1 (0.170), SW10 (0.151), SW4 (0.136), and SW6 (0.127) rank lower, indicating comparatively lesser erosion susceptibility. Meanwhile, SW1 (0.170), SW10 (0.151), SW4 (0.136), and SW6 (0.127) rank lower, indicating comparatively lesser erosion susceptibility (Figure 8). This ranking is crucial for prioritizing soil conservation strategies, ensuring that high-risk areas receive immediate mitigation efforts to prevent land degradation.

Table 6. Estimation of assessment values and ranking.

Parameters	Sum (Ben)	Sum (Non_Ben)	Yi (B + NB)	Rank
SW1	0.302	0.132	0.170	7
SW2	0.506	0.145	0.361	2
SW3	0.412	0.119	0.293	4
SW4	0.273	0.137	0.136	9
SW5	0.363	0.136	0.227	6
SW6	0.287	0.160	0.127	10
SW7	0.391	0.161	0.230	5
SW8	0.468	0.130	0.338	3
SW9	0.588	0.126	0.462	1
SW10	0.301	0.150	0.151	8

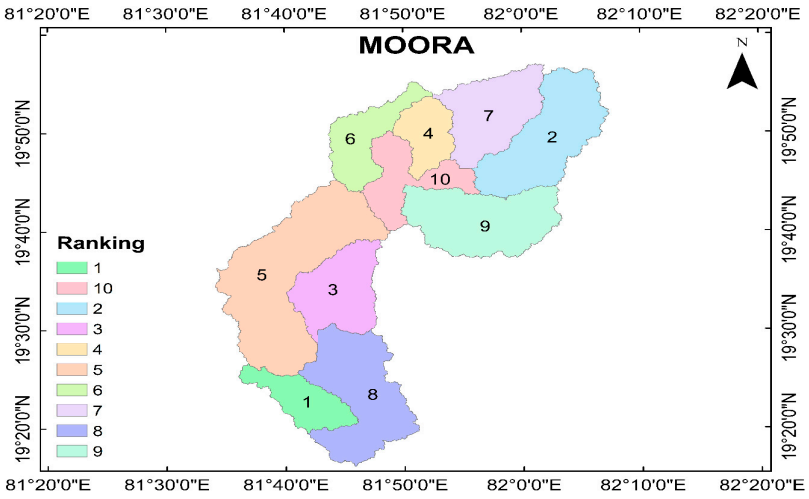


Figure 8. Ranking of Narangi sub-watersheds based on MOORA.

3.7. COPRAS-Based Sub-Watershed Prioritization and Ranking

Zavadskas et al. [71] developed COPRAS, which incorporates a direct and proportionate dependency on the significance and utility of the available alternatives when there are parameters that are in opposition to one another. COPRAS was developed in order to solve problems that involve a number of different parameters. COPRAS employs a step-by-step ranking method that takes into account the success of variants in terms of a variety of metrics and the weights that are associated with them. This is conducted in order to determine the system that will be used to select variants based on their relevance and degree of usefulness. According to Zavadskas et al., COPRAS provides a variety of dynamic decision-making challenges that can be utilized in engineering applications [72]. The first thing that needs to be conducted is to make use of Equation (7) to perform normalization for both beneficial and non-beneficial parameters.

The COPRAS method ranks the sites (SW) based on their relative significance in soil erosion assessment. This method considers both beneficial (S + i) and non-beneficial (S − i) attributes to determine the final utility value (Ui) for ranking. SW9 emerges as the highest-ranked site with a Ui value of 100.00, indicating that it has the most critical erosion susceptibility, requiring urgent intervention (Table 7) (Figure 9). SW5 (Ui = 99.91) and SW6 (Ui = 99.35) follow closely, highlighting their importance in erosion control efforts. SW3 (Ui = 98.23) and SW2 (Ui = 98.14) are next in the ranking, indicating high susceptibility but

slightly less than that of the top-ranked sites. SW10 (Ui = 97.80) holds the sixth position, while SW1 (Ui = 97.36) and SW8 (Ui = 97.11) rank seventh and eighth, respectively. SW7 (Ui = 96.68) and SW4 (Ui = 96.20) occupy the last two positions, suggesting relatively lower erosion risk. The ranking provided by the COPRAS method allows for a clear prioritization of sites, ensuring that mitigation measures focus first on the most erosion-prone areas while considering site-specific characteristics for sustainable watershed management.

Table 7. Calculation of quantitative utility and ranking.

Parameters	S + i	S − i	S−min/S − i	Qi	Ui	Rank
SW1	0.071	0.032	0.970	1.04	97.36	7
SW2	0.071	0.031	0.979	1.05	98.14	5
SW3	0.072	0.031	0.978	1.05	98.23	4
SW4	0.067	0.032	0.962	1.03	96.20	10
SW5	0.069	0.031	1.000	1.07	99.91	2
SW6	0.065	0.031	0.998	1.06	99.35	3
SW7	0.064	0.032	0.970	1.03	96.68	9
SW8	0.068	0.032	0.971	1.04	97.11	8
SW9	0.076	0.031	0.994	1.07	100.00	1
SW10	0.063	0.031	0.983	1.05	97.80	6
	S−min	**0.031**		1.07		

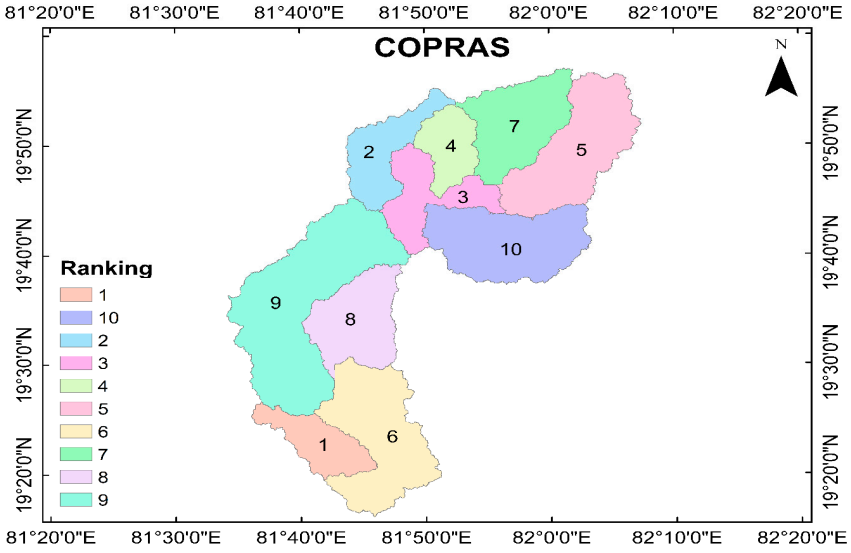


Figure 9. Ranking of Narangi sub-watersheds based on COPRAS.

3.8. ARAS-Based Sub-Watershed Prioritization and Ranking

The classic MCDM problem includes ranking a finite number of choice options, each of which is explicitly stated in terms of a variety of decision criteria that must be taken into consideration simultaneously. The challenge in this is based on the fact that these options must be taken into consideration simultaneously. According to the ARAS technique, the relative influence of the values and weights of the key criteria that are taken into consideration in a project is directly proportional to the utility function value that defines the complex relative efficiency of a feasible option [73]. This is the conclusion that can be drawn from the ARAS technique. In ARAS, the estimation of optimal values is of more

significance. The optimal value is essentially estimated in the same way as it is, for instance, in the case of linear and relief parameters; the maximum of that particular value will be the optimum value. This is because the value in question is a favorable quality. On the other hand, the least ideal value for the shape parameter is not useful. The value that is lower is therefore present. Currently, we have the best values available. Therefore, in order to determine the reciprocal of the non-beneficial characteristics themselves, Equation (13) should be used. A specific value is divided by a portion of this complete column using Equation (14), which is used to determine the advantageous feature. This entire column includes the value that offers the best results. Using Equation (15) results in the calculation of non-beneficial values. The next step is calculating the weighted normalized matrix using Equation (16). The next step is to calculate the optimal function for the ith alternate using Equation (17). The next step is to calculate the utility degree using Equation (14).

The ARAS method ranks the sites (SW) based on their relative utility degree (Ki), which indicates their significance in soil erosion susceptibility. In this method, the optimal value (1) serves as the benchmark for comparison. SW9 secures the highest rank with a Ki value of 0.874, indicating the most critical erosion-prone site (Table 8) (Figure 10). SW3 follows in second place with a Ki value of 0.846, highlighting its significant susceptibility to erosion. SW1 (Ki = 0.832) and SW2 (Ki = 0.830) rank third and fourth, respectively, showing moderate erosion risks. SW5 (Ki = 0.818) and SW8 (Ki = 0.807) are placed in the middle rankings, suggesting a need for erosion control measures but with less urgency than that of higher-ranked sites. SW6 and SW4 share the same Ki value of 0.798, ranking seventh and eighth, respectively. SW7 (Ki = 0.777) and SW10 (Ki = 0.769) hold the lowest ranks, indicating comparatively lower erosion risks. The ARAS method effectively provides a systematic ranking, ensuring that high-priority sites receive immediate conservation efforts, while lower-ranked sites may still require monitoring for potential changes in erosion dynamics.

Table 8. Calculation of utility degree and ranking.

Parameters	Si	Ki	Rank
Optimal Value	0.1093	1	
SW1	0.091	0.832	3
SW2	0.091	0.830	4
SW3	0.092	0.846	2
SW4	0.087	0.798	8
SW5	0.089	0.818	5
SW6	0.087	0.798	7
SW7	0.085	0.777	9
SW8	0.088	0.807	6
SW9	0.096	0.874	1
SW10	0.084	0.769	10
So = 0.1093			

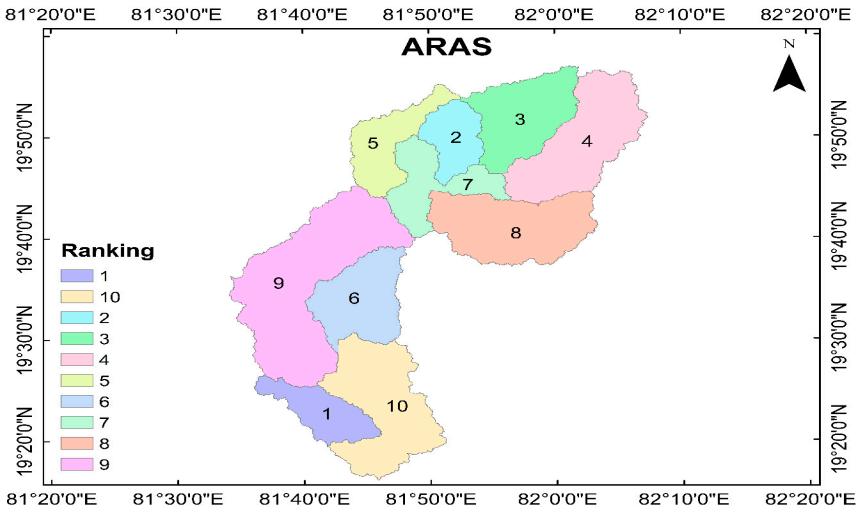


Figure 10. Ranking of Narangi sub-watersheds based on ARAS.

3.9. TOPSIS-Based Sub-Watershed Prioritization and Ranking

The TOPSIS method is a multi-criteria decision analysis technique designed to determine the alternative that is the closest to the positive ideal solution (and furthest from the negative ideal solution [74]. The TOPSIS method is an MCDM method originally introduced by Hwang et al. [75]. The procedures encompassed in the TOPSIS methodology can be delineated as follows. The first step is to conduct normalization using Equation (18). Subsequently, the weights of each criterion (Critic Method) are multiplied by the normalized performance value of each cell. This is a weighted normalized decision metric. Subsequently, the optimal best and the optimal worst values are determined for non-beneficial criteria, such as the shape parameter, where a lower value is preferred. The optimal best represents the least value, while the optimal worst denotes the largest value. However, for advantageous qualities such as linearity and alleviation, the maximum value is preferred. The optimal best represents the maximum value, while the optimal worst denotes the minimum value. This is the formula for computing the Euclidean distance from the ideal best (Vj+) to the ideal worst (Vj−). Initially, Equation (19) is employed to compute the Euclidean distance from the optimal ideal. Subsequently, the Euclidean distance is computed from the optimal worst utilizing Equation (20). These represent the Euclidean distances from the optimal best and the optimal worst. The performance score is then computed using Equation (21). It is represented by Pi.

The TOPSIS method ranks the soil erosion susceptibility of different sites (SW) based on their relative performance score (Pi). This method determines rankings by calculating the geometric distance of each site from the ideal best (Si+) and ideal worst (Si−) solutions. A higher Pi value indicates a higher priority for intervention due to greater erosion risk. SW9 ranks the highest with a Pi value of 0.630, identifying it as the most erosion-prone site requiring immediate attention. SW3 (Pi = 0.552) follows in second place, showing significant susceptibility. SW2 (Pi = 0.536) and SW1 (Pi = 0.515) are ranked third and fourth, respectively, emphasizing their high priority for soil conservation measures (Table 9) (Figure 11). SW5 (Pi = 0.492) holds the fifth rank, indicating a moderate erosion threat, while SW8 (Pi = 0.473) is in sixth place with a slightly lower risk. SW4 (Pi = 0.433) and SW6 (Pi = 0.418) rank seventh and eighth, showing relatively lower susceptibility compared to the top-ranked sites. SW7 (Pi = 0.410) and SW10 (Pi = 0.362) occupy the last two positions, indicating the least erosion vulnerability. The TOPSIS method effectively prioritizes sites based on their closeness to the ideal solution, ensuring that the most erosion-prone areas are targeted first for soil conservation and watershed management strategies.

Table 9. Performance score and ranking.

Parameters	Si+	Si−	Pi	Rank
SW1	0.020	0.021	0.515	4
SW2	0.018	0.021	0.536	3
SW3	0.018	0.022	0.552	2
SW4	0.023	0.018	0.433	7
SW5	0.019	0.019	0.492	5
SW6	0.022	0.016	0.418	8
SW7	0.023	0.016	0.410	9
SW8	0.022	0.020	0.473	6
SW9	0.015	0.026	0.630	1
SW10	0.023	0.013	0.362	10

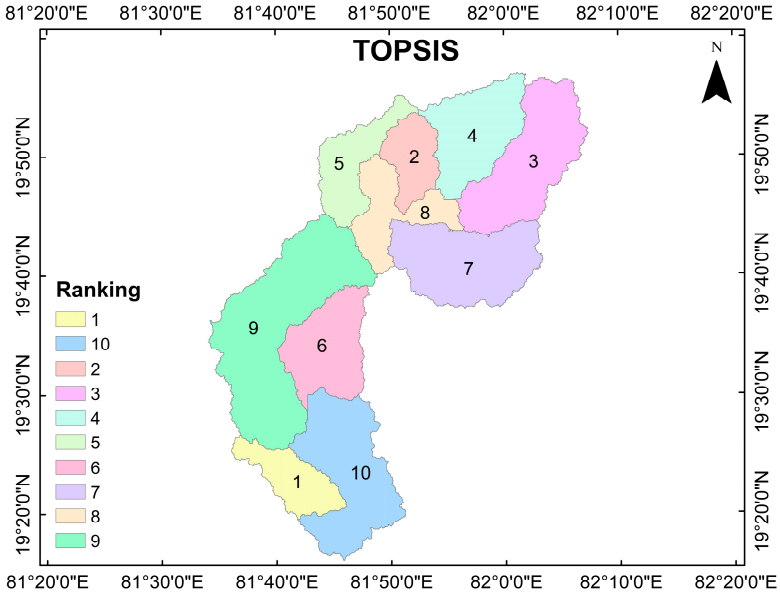


Figure 11. Ranking of Narangi sub-watersheds based on TOPSIS.

3.10. Common Prioritization

Combining morphometric analysis with MCDM tools like MOORA, COPRAS, TOPSIS, and ARAS enhances the accuracy of soil erosion ranking. This integrated approach effectively prioritizes sub-watersheds based on erosion susceptibility, ensuring precise classification into high-, medium-, and low-priority zones. By incorporating multiple analytical methods, the results become more reliable, facilitating better decision-making for soil conservation strategies. This research integrated morphometric analysis with MCDM tools, including MOORA, COPRAS, TOPSIS, and ARAS, to evaluate and rank the sub-watersheds of the Narangi watershed according to their sensitivity to erosion. The Cp values obtained from these methods were utilized to develop the final prioritization framework that categorized sub-watersheds into high-, medium-, and low-priority classifications. High-priority sub-watersheds, such as SW3 and SW9, are the most susceptible to erosion. Urgent intervention is required in these regions to avert any additional deterioration and depletion of arable soil. Proposed interventions encompass afforestation to provide vegetation cover, the installation of check dams to regulate runoff, and terracing to stabilize steep inclines. Medium-priority sub-watersheds, including SW1, SW2, SW5, and SW8, exhibited a mod-

erate risk of erosion. These regions necessitate proactive interventions, such as contour bunding and regulated land use policies, to avert further deterioration. Sub-watersheds of low priority, such as SW4, SW6, SW7, and SW10, exhibited rather steady conditions (Table 10). Regular monitoring and repair in these areas are crucial to maintaining stability and averting unexpected erosion concerns. The prioritizing map, integrating morphometric analysis and MCDM outcomes, visually represents erosion-susceptible areas within the Narangi watershed (Figure 12).

Table 10. Common priority of Narangi sub-watersheds.

Sub-Watershed	Morphometric Analysis	MOORA	COPRAS	ARAS	TOPSIS	Compound Parameter	Final Rank	Final Priority
SW1	3	7	7	3	4	4.8	5	Medium
SW2	4	2	5	4	3	3.6	3	Medium
SW3	2	4	4	2	2	2.8	2	High
SW4	7	9	10	8	7	8.2	8	Low
SW5	5	6	2	5	5	4.6	4	Medium
SW6	8	10	3	7	8	7.2	7	Low
SW7	9	5	9	9	9	8.2	8	Low
SW8	5	3	8	6	6	5.6	6	Medium
SW9	1	1	1	1	1	1	1	High
SW10	10	8	6	10	10	8.8	10	Low

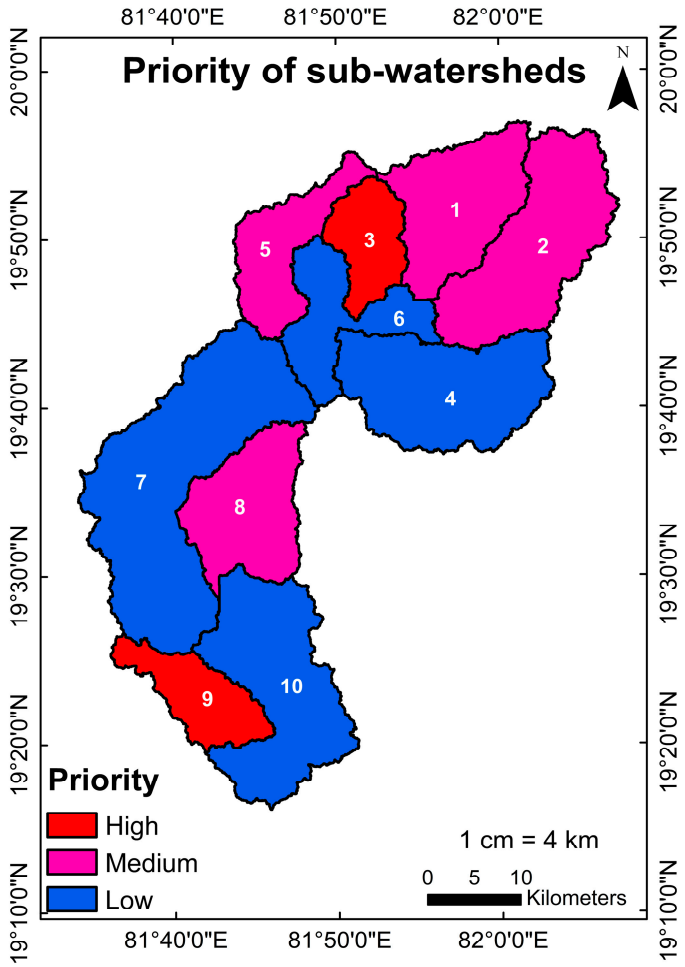


Figure 12. Common priority of Narangi sub-watersheds.

4. Discussion

The prioritization of sub-watersheds is essential for identifying regions most susceptible to soil erosion and for the effective implementation of conservation strategies. Studies illustrate the crucial importance of morphometric analysis and sophisticated methodologies in selecting sub-watersheds for sustainable watershed management in diverse settings. Abdeta et al. [76] employed morphometric analysis via ArcGIS to delineate erosion-prone regions in the Gidabo basin, Ethiopia, highlighting 18 characteristics to be prioritized. Rahaman et al. utilized GIS in conjunction with the fuzzy analytical hierarchy process (FAHP) in the Kallar watershed, Tamil Nadu, to categorize sub-watersheds into priority zones for enhanced resource planning [77]. Gezahegn and Mengistu enhanced this methodology by incorporating morphometric analysis with land use/land cover (LULC) evaluation in the Guder sub-basin, Ethiopia, utilizing SRTM DEM, ArcGIS, and the SWAT model [78]. Their research emphasizes the synergistic impact of land use and land cover changes with morphometric variables on hydrological dynamics, pinpointing critical watersheds for urgent conservation initiatives. Govarthanambikai and Sridhar employed PCA in conjunction with GIS methods to rank sub-watersheds in the Noyyal River basin, Tamil Nadu [79]. Their emphasis on associated morphometric characteristics through PCA highlights its significance in minimizing redundancy and improving prioritization precision. This connected research collectively underscores the adaptability of morphometric analysis in conjunction with sophisticated methodologies such as GIS, FAHP, PCA, and LULC modeling for the prioritization of watersheds aimed at efficient soil and water conservation. This method guarantees effective resource allocation and customized management strategies to reduce erosion and improve water resource sustainability.

The integration of morphometric analysis with MCDM approaches such as MOORA, COPRAS, and ARAS presents an innovative and efficient method for prioritizing areas susceptible to soil erosion, including sub-watersheds. This combination improves the accuracy and precision of identifying crucial regions susceptible to soil erosion relative to conventional techniques. The prioritizing map, developed through the integration of morphometric analysis and MCDM (including MOORA, COPRAS, TOPSIS, and ARAS) outcomes, provides a geographical depiction of erosion-susceptible areas within the Narangi watershed. This map functions as an essential instrument for decision-makers, facilitating appropriate resource allocation and directing interventions to areas of greatest need. The amalgamation of morphometric parameters, which emphasize physical and hydrological attributes, with the organized rankings derived from MCDM methodologies guarantees a rigorous and scientifically substantiated methodology. Soil and water conservation initiatives should first concentrate on high-priority sub-watersheds, whereas medium-priority areas necessitate specific techniques to mitigate potential threats. Low-priority zones, although stable, require ongoing monitoring to preserve their condition. Sub-watersheds 3 and 9 were designated as high-priority areas for soil erosion, largely attributable to a confluence of topographical, hydrological, and land use characteristics. Steeper slopes in these regions may expedite surface runoff, diminishing infiltration and augmenting water flow velocity, hence exacerbating soil displacement. Moreover, scant plant cover or alterations in land use may render soil more susceptible to erosive agents such as precipitation and surface water flow. Moreover, human activities may intensify the erosion process. Considering these reasons, it is essential to adopt efficient soil conservation practices, including afforestation, contour plowing, check dams, and other erosion control measures, to reduce soil loss and improve watershed sustainability. This extensive prioritizing approach greatly enhances sustainable watershed management. This strategy mitigates soil erosion, improves groundwater recharge, and promotes sustainable agriculture practices by targeting the most vulnerable locations. Moreover, it enhances water accessibility, diminishes

sedimentation in downstream aquatic systems, and promotes ecological equilibrium. These efforts not only safeguard the health of the Narangi watershed but also guarantee the socio-economic welfare of populations reliant on its resources. This prioritizing model demonstrates a proactive and cohesive method for watershed conservation, facilitating long-term sustainability, aligning with sustainable development goal 15 (life on land).

5. Conclusions

The investigation of soil erosion plays a crucial role in identifying sub-watersheds that require priority attention for sustainable conservation and mitigation efforts. By highlighting these critical areas, effective strategies can be implemented to control soil loss, enhance water resource management, and promote long-term environmental sustainability in the watershed. Conventional approaches for evaluating these factors can be expensive, laborious, and time-consuming. Nevertheless, geospatial technologies have revolutionized this procedure, rendering it more expedient and economical and less labor-intensive. Morphometric analysis was integrated with four MCDM methods—MOORA, COPRAS, TOPSIS, and ARAS—to prioritize the Narangi watershed, yielding a unified ranking for each sub-watershed. This study's findings indicate that SW3 and SW9 are classified under the high-priority soil erosion category; SW1, SW2, SW5, and SW8 are categorized as medium-priority; and SW4, SW6, SW7, and SW10 are designated as low-priority for soil erosion. This sustainability-focused method allows decision-makers to prioritize sub-watersheds with significant soil erosion risk for effective and sustainable development management, ensuring the long-term preservation of land and water resources, aligning with sustainable development goal 15 (life on land), which promotes the sustainable use of terrestrial ecosystems and combats land degradation.

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Abbreviations

The following abbreviations are used in this manuscript:

MCDM	Multi-criteria decision-making
SW	Sub-watershed
GIS	Geographic information system
SDG	Sustainable development goal

RS	Remote sensing
ARAS	Additive ratio assessment
COPRAS	Complicated proportional assessment
MOORA	Multi-objective optimization by ratio analysis
DEM	Digital elevation model

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