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Unveiling Soil Erosion Hotspots: Morphometric Analysis and Prioritization of Sub Watersheds in the Kumaradhara River Basin using AHP

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Abstract

Soil erosion poses a significant threat to the region of Southern Karnataka, demanding urgent attention from governmental bodies and urban planners. Extensive research has introduced various methodologies and models aimed at assessing soil erosion on a watershed scale. Among these approaches, morphometric characterization of rivers stands out as a natural indicator of watershed health, offering insights into soil erosion, sediment yield, and groundwater potential. In this study, we employ morphometric analysis to scrutinize the risk of soil erosion at the sub-watershed level, recognizing its pivotal role in natural resource planning and sustainable development. The utilization of the Analytic Hierarchy Process (AHP) method for prioritizing sub-watersheds underscores the growing importance of strategic decision-making in soil erosion conservation and management. By employing AHP, we can effectively rank sub-watersheds based on their urgency for conservation interventions. Our findings pinpoint the sub-watersheds situated in the eastern middle of the watershed as particularly vulnerable to soil erosion, necessitating immediate attention and tailored management practices to safeguard the overall health of the watershed. This critical analysis underscores the significance of integrating advanced methodologies such as morphometric analysis and AHP into watershed management strategies. By identifying high-risk areas and prioritizing conservation efforts, we can enhance the resilience of ecosystems and ensure the sustainable utilization of natural resources. The results of this study serve as a valuable foundation for informed decision-making and targeted interventions aimed at mitigating soil erosion and promoting long-term environmental sustainability in the Southern Karnataka region.

Keywords: Soil Erosion; Morphometry; Analytical Hierarchy Process; Prioritization

Introduction

Soil erosion poses a formidable challenge to the Indian economy, particularly affecting approximately 34% of its land situated in semi-arid regions. This pervasive issue demands careful consideration and strategic intervention to mitigate its adverse impacts. Ramarao et al., 2019). Many agricultural practices have deep historical roots and rely heavily on the natural rain cycle(1). Assessing and monitoring watersheds at the sub -

watershed (SWS) level can provide valuable insights into the state of vegetation health and its intricate connection with soil dynamics. This examination holds considerable significance for understanding and enhancing agricultural sustainability in the given context(1) .

Morphometric parameters provide crucial insights into soil characteristics within watersheds and sub-watershed (SWS) regions. Analyzing these parameters is pivotal for uncovering the nuanced soil properties, thereby advancing our comprehension of watershed dynamics and informing sustainable land management practices(2). Morphometric parameter values serve as invaluable resources for hydrological modeling and hold immense significance in natural resource management and watershed management endeavors. Their utilization plays a pivotal role in informing strategic decisions aimed at sustainable land and water resource management(3). Morphometric parameters are best for assessing flood risk mapping(4–6) and watershed management(1,7). This study emphasizes the analysis of morphometric parameters within the watershed, highlighting their substantial influence on large-scale soil erosion dynamics. This research holds significance for understanding the intricate relationship between morphometric characteristics and soil erosion processes, thus contributing to informed watershed management strategies.

Numerous researchers worldwide have developed various methodologies to identify a dependable approach for prioritizing sub-watersheds (SWS) in spatial decision-making. This endeavor is crucial for enhancing the effectiveness of watershed management strategies and ensuring optimal resource allocation(1,8). In recent times, the Analytical Hierarchy Process (AHP) has become a widely adopted and reliable multi-criteria decision-making system, garnering substantial trust among decision-makers(9). This study employs the AHP methodology to pinpoint sub-watersheds susceptible to soil erosion, with the objective of delineating erosion-prone zones. The findings demonstrate the effectiveness of AHP in generating reliable insights for watershed management and monitoring at the sub-watershed level.

Study Area

The Kumaradhara river, a tributary of the Nethravathi in Dakshina Kannada, spans from coordinates 12°29’4” to 12°58’33” N and 75°9’58” to 75°47’48” E, covering an area of 1776 sq. km. Originating in the central Western Ghats, its streams converge with the Nethravathi river near Uppinangadi town. The basin encompasses regions across Dakshina Kannada, Hassan, and Kodagu districts, hosting significant Hindu temples along its course. Agriculture serves as the primary livelihood in the region, though it faces substantial threats from soil erosion and sporadic flooding events.

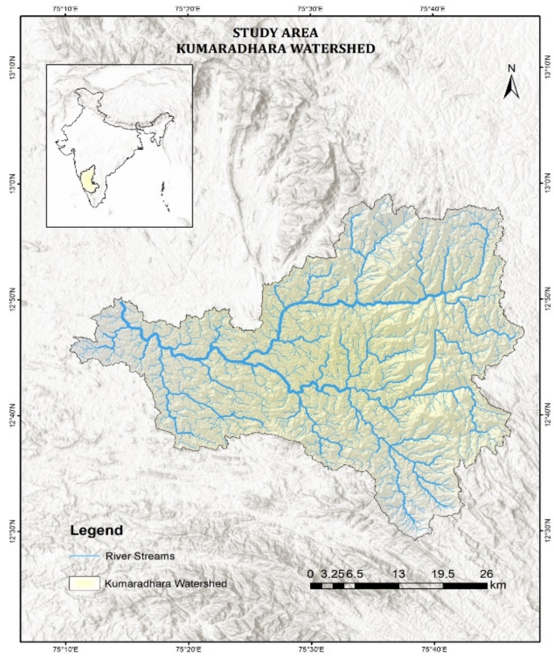

Fig. 1. Study area of Kumaradhara River

Materials & Methods

Linear parameters, aerial parameters, and relief factors are utilized for the analysis of morphometric parameters. The extraction of watershed, sub-watershed, and streams is performed using ArcGIS 10.8.2 software and Arc SWAT extensions. These factors are outlined in Table 1 and elaborated upon. The study incorporates ten morphometric parameters, contributing to its comprehensive analysis and interpretation.

Table 1. Morphometric metrics, formulas, and references to assess the Kumaradhara sub watersheds for assessing soil erosion

S. No.	Morphometric Parameters	Formula	
1	Drainage Texture (Dt)	Dt = Nu/P	(10)
2	Bifurcation Ratio (Rb)	Rb = Nu/Nu+1	(11)
3	Stream frequency (Fs)	Fs = Nu /A	(12)
4	Drainage Density (Dd)	Dd = Lu/A	(13)
5	Shape Factor (Sf)	Sf = Lb2/A	(13)
6	Circularity Ratio (Rc)	Rc = 4πA/P2	(14)
7	Form Factor (Ff)	Ff = A / Lb2	(11)
8	Elongation Ratio (Re)	Re = 1.129×P(A/Lb)	(12)
9	Compactness Coefficient (Cc)	Cc = 0.282 × P/PA	(15)
10	Avg. Length of Overland Flow	Lg = 1/2 × Dd	(10)

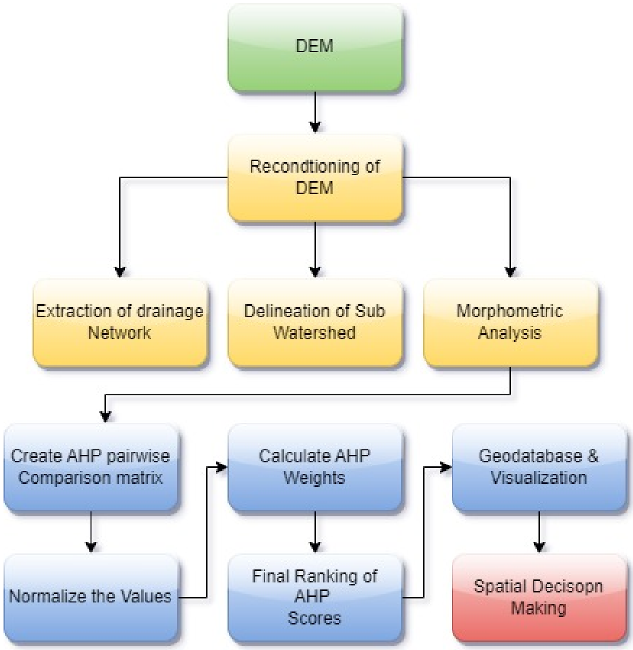

Fig. 2. Methodology of the Morphometric Analysis and AHP of Kumaradhara Sub-Watersheds

Drainage Texture (Dt)

The parameter Dt represents the ratio between the total number of drainage segments of all orders and the perimeter of the area under consideration. This metric holds significance in assessing the drainage efficiency and network complexity within the study area, contributing valuable insights to watershed analysis.

$Dt = Nu/P$ (1)

Where, Nu = Total number of stream segments of order u

P = Perimeter of the watershed or subwatershed

Bifurcation Ratio (Rb)

Rb signifies the relationship between the number of streams belonging to a specific order and those of the subsequent higher order. This metric offers crucial insights into the hierarchical structure and organization of the stream network within the study area, aiding in the understanding of watershed dynamics and drainage pattern analysis[13].

$Rb = Nu/Nu{+}1$ (2)

Where, Nu = Total number of stream segments of order u

Nu+1 = Total number of stream segments of the next higher order

Stream Frequency (FS)

FS represents the ratio of stream segments per unit area within the watershed. This metric serves as a fundamental indicator of the density and distribution of streams, offering valuable information for assessing hydrological processes and watershed characteristics[12].

$Fs = Nu/A$ (3)

Where Nu = Total number of stream segments of order u

A = Area of the Watershed or Subwatershed

Drainage Density (Dd)

Dd quantifies the stream channel length relative to the area of the drainage basin. This parameter is essential for evaluating the drainage network's spatial organization and efficiency, providing critical insights into watershed morphology and hydrological processes[12].

$Dd = Lu/A$ (4)

Where Lu = Total stream length of order u

A = Area of the Watershed or Subwatershed

Shape Factor (Sf)

The shape factor is determined by the ratio of the square of the basin length to its area. This parameter offers significant insights into the geometric characteristics of the basin, aiding in the assessment of basin morphology and hydrological behavior[10].

$Sf = Lb2/A$ (5)

Where Lb = Length of the basin

A = Area of the Watershed or Subwatershed

Circularity Ratio (Rc)

Rc represents the ratio of the basin area (A) to the area of a circle with an equivalent perimeter (P) as the basin. This parameter is crucial for assessing the basin's shape complexity and deviation from a circular form, providing valuable insights into hydrological processes and watershed dynamics[13].

$Rc = 4\pi A/P^2$ (6)

Where A = Area of the Watershed or Subwatershed

P = Perimeter of the watershed or subwatershed

Elongation Ratio (Re)

Re is defined as the ratio of the diameter of a circle with an equivalent area to that of the basin, to the maximum length of the basin. This parameter serves as a fundamental measure for evaluating the elongation and compactness of the basin shape, offering valuable insights into watershed morphology and hydrological processes[16].

$Re = 1.129 \times p(A/Lb)$ (7)

Where A = Area of the Watershed or Subwatershed

Lb = Length of the basin

Form Factor (Ff)

Ff represents the ratio of the basin area to the square of its length. This parameter provides essential information on the basin's elongation and compactness, aiding in the assessment of watershed morphology and hydrological characteristics (10).

$Ff = A / Lb^2$ (8)
Where A = Area of the Watershed or Subwatershed
Lb = Length of the basin

Compactness Coefficient (CC)

CC refers to the comparison of a basin's perimeter to that of a circular basin with equivalent area. This parameter offers insights into the basin's shape complexity and deviation from circularity, which is crucial for understanding hydrological processes and watershed characteristics (10).

$Cc = 0.282 \times P/\sqrt{A}$ (9)
Where A = Area of the Watershed or Subwatershed
P = Perimeter of the watershed or subwatershed

Average Length of Overland Flow (Lg)

The parameter Lg represents approximately half the average distance between stream channels, which is also roughly equivalent to half the reciprocal of drainage density. This metric holds significance in characterizing the spacing and arrangement of stream channels within the watershed, providing valuable insights into drainage network organization and hydrological processes (10).

$Lg = 1/2 \times Dd$ (10)
Where Dd = Drainage density

Table 2. AHP scale for pairwise comparision

Intensity	Definition
1	Equal Importance
3	Slightly More Important
5	Strongly Important
7	Very Strongly Important
9	Extremely Important
2, 4, 6, 8	Intermediate Values

The Analytic Hierarchy Process (AHP) is a well-known method for prioritizing demands. It was introduced by Saaty. This method is widely recognized for its effectiveness in decision-making processes, offering a structured approach to prioritization that considers various criteria and alternatives (9). In the Analytic Hierarchy Process (AHP), the initial step involves identifying all the total needs, followed by determining the criteria that will be used to prioritize these requirements. A pairwise analysis is then conducted between the most relevant pairs within the hierarchy. This systematic approach ensures thorough consideration of all factors and alternatives, facilitating informed decision-making processes (17). Following the identification of potential links between hierarchies, pairwise analysis is conducted, allowing users to express their preferences on a scale of 1 to 9. This step enables consumers to provide valuable input into the decision-making process, ensuring their preferences are duly considered within the prioritization framework (17). Table 2 outlines the scale used in the Analytic Hierarchy Process (AHP), which directs users to assign numerical values to elements within the hierarchy. To ensure the reliability of the prioritization process, the consistency ratio is calculated after completing the hierarchical analysis to detect any potential redundancies. AHP is applied to assess software needs and determine their relative importance, facilitating informed decision-making regarding top priorities and their respective degrees. The number of pairwise analyses required in AHP for evaluating n requirements is calculated as $n(n-1)/2$. This systematic approach ensures thorough consideration and prioritization of software needs based on user preferences and criteria (17).

Results & Discussion:

The streams within the Kumaradhara River basin are classified using the Strahler ordering technique, ranging from first to sixth order. Table 3 presents values associated with streams of different orders, including the total number of streams (Nu), stream length (Lu), mean stream length ratio (LSM), stream length ratio (RL), and bifurcation ratio (Rb). Analysis reveals that first-order streams exhibit the highest values, while sixth-order streams display the lowest. Additionally, Lu is greatest for first-order streams and least for sixth-order streams. Parameters such as LSM, RL, and Rb are notably smaller for sixth and second-order streams, with the highest values observed in second and first-order streams, respectively. This analysis offers insights into the spatial distribution and characteristics of streams within the basin, aiding in watershed management and hydrological studies.

Table 3. Values associated with streamsof different order

Steam order	Nu	Lu	LSM	RL	Rb
Order 1	1104	1000.247	0.906020833	2.192206876	2.23030303
Order 2	495	456.274	0.921765657	1.688159272	1.633663366
Order 3	303	270.279	0.892009901	2.032142374	1.761627907
Order 4	172	133.002	0.773267442	2.071424122	2.12345679
Order 5	81	64.208	0.792691358	2.181867609	1.928571429
Order 6	42	29.428	0.700666667	-	-
Total	2197	1953.438			

Table 4 displays relief and aerial parameters for 20 sub-watersheds (SWS). Sub-watershed 10 exhibits the highest drainage density, while sub-watershed 9 has the lowest. The

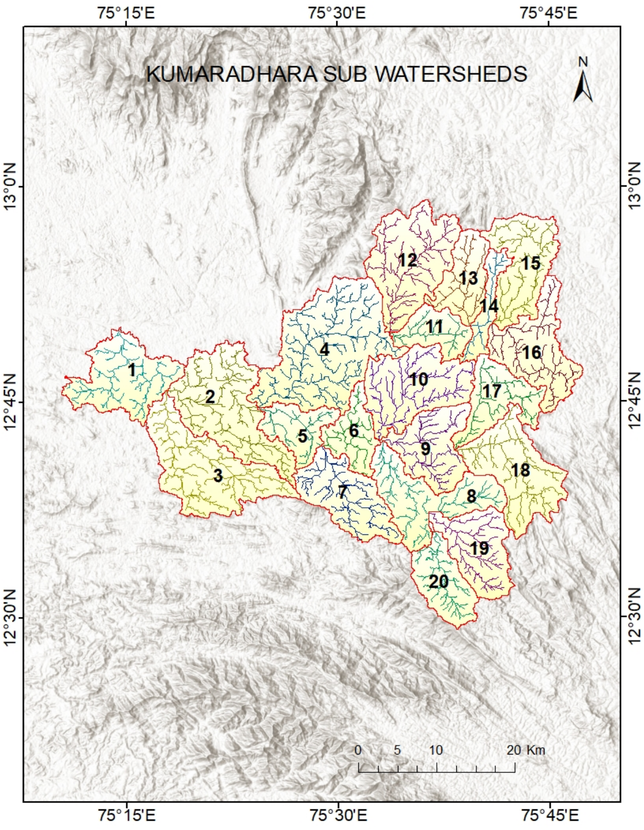

Fig. 3. 20 sub-watersheds of Kumaradhara River

mean bifurcation ratio is minimal in SWS 13 and maximal in SWS 5. SWS 13 has the lowest stream frequency at 0.886, whereas SWS 10 records the highest at 1.756. These findings offer crucial insights into the hydrological characteristics and variability among sub-watersheds, aiding in watershed management and planning endeavors. SWS 14 exhibits the lowest drainage texture value at 0.514, while SWS 4 has the highest. The average length of overland flow is minimal in SWS 9 and maximal in SWS 10. Form factor is lowest in SWS 14 and highest in SWS 10. SWS 10 has the lowest shape factor at 1.965, whereas it is highest at 7.353 in SWS 14. Circularity ratio is lowest in SWS 14 and highest in SWS 19. SWS 14 has the lowest elongation ratio, whereas SWS 10 records the highest. Circularity ratio is lowest in SWS 19 and highest in SWS 14. These observations provide valuable insights into the morphological characteristics and variability among the sub-watersheds, contributing to informed watershed management strategies and decision-making processes.

In Table 4, certain parameters have a direct impact on soil erosion, while others have an inverse relationship. Linear parameters such as drainage density, mean bifurcation ratio, stream frequency, and drainage texture directly influence soil erosion. Conversely, all shape factors and Lg inversely affect soil erosion. These insights are crucial for understanding the factors contributing to soil erosion within the watershed, informing effective erosion control and management strategies.

Table 5 comprises a pairwise comparison matrix for various parameters, with drainage density identified as the parameter most likely to significantly impact soil erosion, while Lg is expected to have the least influence. The remaining parameters fall between these extremes and are ranked accordingly based on their weightage. Subsequently, in Table 6, the values from the comparison matrix are normalized. Utilizing the eigenvector value of the matrix along with the total from the comparison matrix, the Maximum eigenvector is calculated. The consistency index (CI) is then determined with the help of the maximum eigenvector value, and the consistency ratio is computed using the random consistency index (RI) value, with the obtained ratio found to be less than 10%, indicating acceptable consistency. These calculations provide a robust basis for the prioritization and assessment of parameters influencing soil erosion within the watershed, facilitating informed decision-making in erosion control and management strategies.

A comparison matrix is formulated to evaluate each parameter's pairwise comparison across the sub-watersheds (SWS). Eigenvectors are computed subsequent to normalization. The resulting consistency ratio, well below 10%, indicates satisfactory consistency and validates further analysis. These steps provide a rigorous framework for assessing the relative importance of parameters and their impact on soil erosion within the watershed, facilitating informed decision-making in erosion control and management strategies.

Table 5. Pairwise comparison matrix for various parameters

SWS	DD	RBM	FS	DT	SF	RC	RE	FF	CC	LG
DD	1	2	2	3	4	4	5	5	7	6
RBM	0.5	1	2	2	3	3	4	5	6	6
FS	0.5	0.5	1	2	4	4	3	4	6	5
DT	0.33	0.5	0.5	1	4	4	6	6	7	7
SF	0.25	0.33	0.25	0.25	1	2	2	3	4	4
RC	0.25	0.33	0.25	0.25	0.5	1	1	3	4	3
RE	0.2	0.25	0.33	0.17	0.5	1	1	3	4	3
FF	0.2	0.2	0.25	0.17	0.33	0.33	0.33	1	2	1
CC	0.14	0.17	0.17	0.14	0.25	0.25	0.25	0.5	1	1
LG	0.17	0.17	0.2	0.14	0.25	0.33	0.33	1	1	1
Total	3.54	5.45	6.95	9.12	17.83	19.92	22.92	31.5	42	37

Eigenvector values are computed for all 20 sub-watersheds (SWS) across the ten parameters. The sum product of these eigenvectors from both the primary comparison matrix and the comparison matrix for each parameter is calculated. Results indicate that SWS 10, along with SWS 11, 8, and 14, are most susceptible to soil erosion. Conversely, SWS 18, 16, and 10 are identified as the least prone to soil erosion. These

Table 4. Relief and aerial parameters for 20 sub-watersheds

		Linear Parameters					Shape Parameters			
SWS	DD	RBM	Fs	Dt	Lg	Ff	Sf	Rc	Re	Cc
SWS1	0.999	1.634	1.151	1.326	0.499	0.374	2.674	0.167	0.69	2.445
SWS2	1.107	1.277	1.264	1.637	0.553	0.29	3.448	0.149	0.608	2.583
SWS3	1.118	0.974	1.221	1.583	0.558	0.272	3.676	0.15	0.588	2.574
SWS4	1.112	1.395	1.126	2.189	0.555	0.412	2.427	0.238	0.724	2.045
SWS5	0.974	2.716	1.24	1.016	0.486	0.405	2.469	0.174	0.718	2.392
SWS6	0.957	1.244	1.264	1.081	0.499	0.314	3.185	0.193	0.633	2.27
SWS7	1.161	1.056	1.321	1.736	0.58	0.374	2.674	0.245	0.691	2.018
SWS8	0.922	1.221	1.047	1.519	0.461	0.455	2.198	0.238	0.767	2.045
SWS9	0.841	2.656	0.925	1.041	0.42	0.316	3.165	0.16	0.635	2.498
SWS10	1.561	1.241	1.756	2.124	0.78	0.509	1.965	0.237	0.805	2.051
SWS11	0.945	0.629	1.163	1.095	0.472	0.386	2.591	0.254	0.701	1.982
SWS12	1.041	1.038	1.214	1.914	0.52	0.393	2.545	0.25	0.708	1.995
SWS13	0.957	0.616	0.886	0.954	0.478	0.367	2.725	0.252	0.684	1.986
SWS14	0.99	1.29	0.992	0.514	0.495	0.136	7.353	0.108	0.416	3.038
SWS15	1.034	2.23	1.287	1.511	0.517	0.342	2.924	0.193	0.66	2.27
SWS16	0.997	2.43	1.195	1.321	0.498	0.353	2.833	0.162	0.671	2.479
SWS17	0.972	793	1.141	1.046	0.486	0.212	4.717	0.158	0.52	2.509
SWS18	1.023	1.669	1.176	1.582	0.511	0.35	2.857	0.208	0.668	2.186
SWS19	1.05	1.205	1.232	1.682	0.525	0.366	2.732	0.3	0.682	1.823
SWS20	1.115	0.626	1.348	1.445	0.557	0.371	2.695	0.237	0.687	2.051
Total	20.875	820.147	23.949	28.316	10.45	6.997	61.852	4.073	13.256	45.24

Table 6. Normalized comparison matrix

SWS	DD	RBM	FS	DT	SF	RC	RE	FF	CC	LG	EV
DD	0.28	0.37	0.29	0.33	0.22	0.2	0.22	0.16	0.17	0.16	0.24
RBM	0.14	0.18	0.29	0.22	0.17	0.15	0.17	0.16	0.14	0.16	0.18
FS	0.14	0.09	0.14	0.22	0.22	0.2	0.13	0.13	0.14	0.14	0.16
DT	0.09	0.09	0.07	0.11	0.22	0.2	0.26	0.19	0.17	0.19	0.16
SF	0.07	0.06	0.04	0.03	0.06	0.1	0.09	0.1	0.1	0.11	0.07
RC	0.07	0.06	0.04	0.03	0.03	0.05	0.04	0.1	0.1	0.08	0.06
RE	0.06	0.05	0.05	0.02	0.03	0.05	0.04	0.1	0.1	0.08	0.06
FF	0.06	0.04	0.04	0.02	0.02	0.02	0.01	0.03	0.05	0.03	0.03
CC	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.03	0.02
LG	0.05	0.03	0.03	0.02	0.01	0.02	0.01	0.03	0.02	0.03	0.02
Total											1

findings offer valuable insights into the spatial variability of soil erosion susceptibility across the watershed, informing targeted erosion control and management efforts.

Figure 4 depicts the classification of the entire area into five zones based on soil erosion susceptibility: Shallow (<30%), Low (30% - 45%), Moderate (45% - 60%), High (60% - 75%), and Very High (>75%). The eastern middle region exhibits a higher susceptibility to soil erosion compared to other areas. These findings provide crucial spatial insights into soil erosion vulnerability across the study area, guiding targeted conservation and management strategies for sustainable land use.

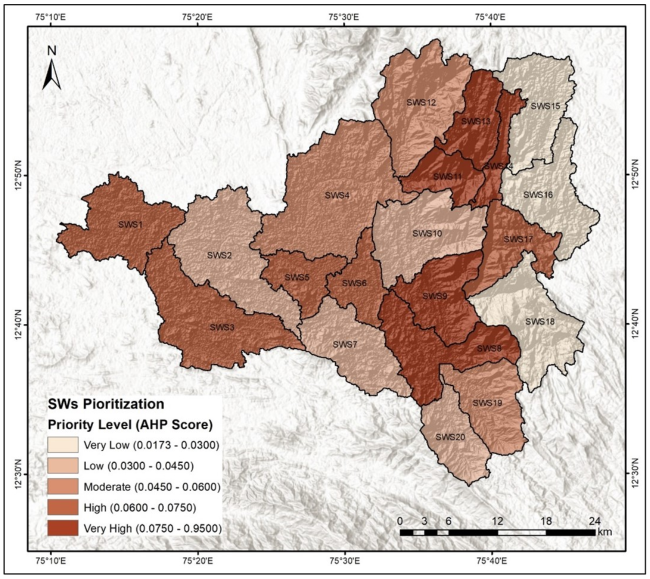

Fig. 4. Prioritization of Sub-watersheds, Kumaradhara River

Table 7. Weightage and priority assigned for 20 sub watersheds based on the comparison matrix

SWS	DD	RBM	FS	DT	SF	RC	RE	FF	CC	LG	Weightage	Priority
SWS1	0.06	0.03	0.09	0.07	0.02	0.02	0.06	0.05	0.06	0.02	0.05	5%
SWS2	0.03	0.05	0.03	0.03	0.09	0.01	0.01	0.01	0.11	0.07	0.04	4%
SWS3	0.02	0.13	0.04	0.03	0.11	0.01	0.01	0.01	0.11	0.11	0.06	6%
SWS4	0.02	0.03	0.07	0.01	0.01	0.06	0.11	0.11	0.02	0.08	0.04	4%
SWS5	0.07	0.01	0.03	0.11	0.01	0.02	0.09	0.09	0.05	0.02	0.05	5%
SWS6	0.07	0.04	0.02	0.08	0.07	0.03	0.02	0.04	0.05	0.04	0.05	5%
SWS7	0.02	0.07	0.02	0.01	0.02	0.08	0.06	0.07	0.01	0.11	0.04	4%
SWS8	0.12	0.05	0.07	0.03	0.01	0.07	0.12	0.11	0.02	0.01	0.07	7%
SWS9	0.10	0.01	0.11	0.10	0.07	0.01	0.02	0.01	0.08	0.01	0.07	7%
SWS10	0.01	0.04	0.01	0.01	0.01	0.04	0.15	0.15	0.02	0.15	0.03	3%
SWS11	0.10	0.08	0.07	0.07	0.01	0.12	0.07	0.07	0.01	0.01	0.08	8%
SWS12	0.03	0.07	0.04	0.01	0.01	0.09	0.08	0.08	0.01	0.05	0.04	4%
SWS13	0.09	0.10	0.11	0.11	0.03	0.11	0.04	0.04	0.01	0.01	0.09	9%
SWS14	0.05	0.02	0.10	0.13	0.15	0.01	0.01	0.01	0.15	0.02	0.07	7%
SWS15	0.03	0.01	0.01	0.04	0.06	0.03	0.02	0.02	0.04	0.04	0.03	3%
SWS16	0.04	0.01	0.04	0.04	0.04	0.01	0.03	0.03	0.07	0.02	0.03	3%
SWS17	0.06	0.09	0.06	0.06	0.14	0.01	0.01	0.01	0.11	0.01	0.06	6%
SWS18	0.03	0.01	0.04	0.02	0.05	0.03	0.02	0.02	0.03	0.03	0.03	3%
SWS19	0.02	0.04	0.03	0.01	0.05	0.20	0.04	0.04	0.01	0.09	0.04	4%
SWS20	0.01	0.10	0.01	0.03	0.02	0.05	0.04	0.04	0.02	0.11	0.04	4%
Weight	0.24	0.18	0.16	0.16	0.07	0.06	0.06	0.03	0.02	0.02	1.00	100%

Conclusion

In the Kumaradhara River watershed, soil erosion poses a significant threat, prompting the need for targeted attention from decision-makers and government authorities. This study employs the Analytic Hierarchy Process (AHP) to identify priority areas within the watershed requiring immediate intervention. Through this method, the watershed is classified into categories ranging from Very Low to Very High susceptibility to soil erosion. These findings hold critical importance for guiding effective resource allocation and management strategies to mitigate soil erosion impacts in the watershed.

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