Prioritization of Erosion Prone Micro-watersheds using Morphometric Analysis coupled with Multi-Criteria Decision Making

S. Nitheshnirmal [1,*], Ashutosh Bhardwaj [2], C. Dineshkumar [3] and S. Abdul Rahaman [1]

[1] Department of Geography, School of Earth Science, Bharathidasan University, Tiruchirappalli, Tamil Nadu, India; nirmalgsarath@gmail.com, abdulatgeo@gmail.com
[2] Photogrammetry and Remote Sensing Department, Indian Institute of Remote Sensing, ISRO, Dehradun, Uttarakhand, India; ashutosh@iirs.gov.in
[3] Department of Civil Engineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India; dineshchandrasekar.dk@gmail.com
* Correspondence: nirmalgsarath@gmail.com; Tel.: +91-8072859018
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Abstract: Soil erosion is a serious environmental threat amongst the prevailing major natural hazards which affects the livelihood of millions of people around the world. The deterioration of nutrient-rich topsoil can affect the sustainability of agriculture and various ecosystems by decreasing soil productivity. Conservation measures should be implemented in those regions which are critical to soil erosion. Identification of areas susceptible to soil erosion through prioritization of watershed can help in proper planning and implementation of suitable conservational measures. Therefore, in this study, prioritization of 23 micro-watersheds present in the Dnyanganga watershed of Tapti River basin is carried out based on morphometric parameters and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). TanDEM-X 90m openly accessible DEM generated from SAR interferometry, obtained through DLR is used for determining the morphometric parameters. These parameters are grouped into linear, areal and relief aspects. Initially, the relative weights of various morphometric parameters used in TOPSIS were determined using Saaty's Analytical Hierarchy Process (AHP). Thereafter, the MCDM package in R software was utilized to implement TOPSIS. The micro-watersheds were classified into very high (0.459 - 0.357), high (0.326 – 0.240), moderate (0.213 – 0.098), and low (0.096 – 0.088) prioritization levels based on the TOPSIS highest closeness (C_i^+) to ideal solution. It is evident from the results that micro-watersheds (MW10, MW18, MW19, MW2, MW11, and MW17) are highly susceptible to soil erosion and thus, conservation measures can be carried out in these micro-watersheds on priority to ensure the sustainability of future agriculture by preventing excessive soil loss through erosion.

Keywords: Soil Erosion, Prioritization of Micro-watersheds, TOPSIS, AHP, TanDEM-X, SAR Interferometry

1. Introduction

Soil erosion has been considered as one of the serious natural hazard which affects the sustainable development of a watershed worldwide in case of agriculture and natural resources management [1-3]. Accelerated erosion in a watershed can be slowed down by identifying and prioritising regions sensitive to soil erosion [4]. Morphometric analysis aids in the identification of sensitive regions which are vulnerable to soil erosion as the linear and shape parameters have a direct and indirect relationship with erodability [5]. There have been various studies which utilises morphometric

parameters for prioritization of watershed especially using MCDM [6-9]. In this study prioritization of 23 micro-watersheds present in the Dnyanganga watershed of Tapti River basin was carried out in order to identify the erosion prone micro-watersheds based on the morphometric parameters through Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method using R.

2. Study Area

The Dnyanganga watershed of Tapti River basin is situated in the north western part of Maharashtra covering the districts of Buldana and Akola (Figure 1). It comprises of Dnyanganga River which is a tributary of Purna River, which is the only river in upper Tapti basin having a perennial flow. The Dnyanganga River falls into Purna River near Yerli Taluk of Maharashtra, India. The watershed extends between the northern latitudes of 20° 25' 56.34" and 20° 55' 46.02" and between the eastern longitudes of 76° 13' 17.96" and 76° 45' 08.46". The Dnyanganga watershed covers a total area of about 1288.42 km2. The watershed has a tropical wet climate experiencing high rainfall in summer and low in winter. The average rainfall in the Dnyanganga watershed is about 830 mm and experiences an annual average temperature of 25° C.
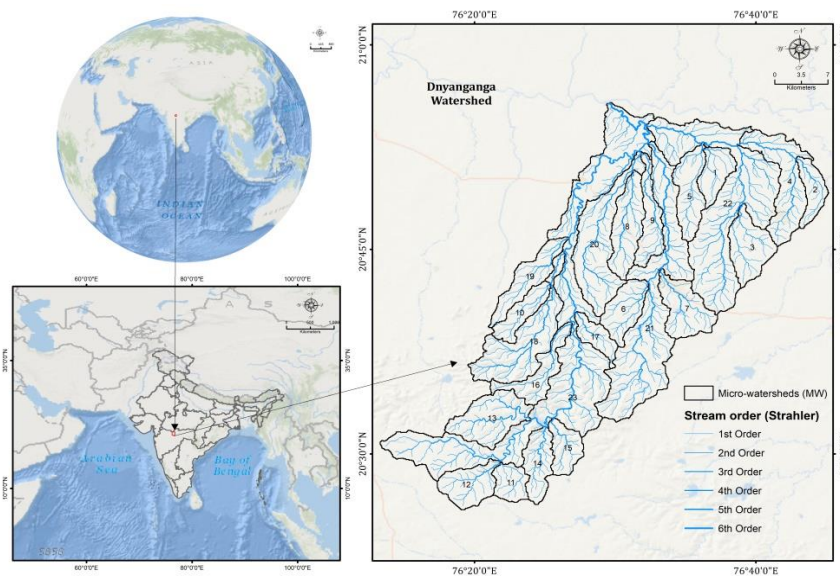
Figure 1. Geographical location of the study area

3. Dataset and Methodology

3.1. Dataset used

The present study utilises TanDEM-X (3 arcsec) data obtained from EOC GeoserviceTDM90 (https://download.geoservice.dlr.de/TDM90/) for the evaluation of morphometric indices and prioritization of the Dnyanganga micro-watersheds using TOPSIS MCDM.

3.2. Methodology

3.2.1. Morphometric Analysis

Firstly, the TanDEM-X data is projected and processed using watershed analysis tool in the TNTmips 2019 software by providing the inlet, outlet, basin and branch parameters required for delineating the micro-watersheds along with providing the critical threshold for the generation of stream networks which plays an important role in evaluation of morphometric parameters. The layout and map preparation were carried out using the ArcGIS 10.1.1. In the present study, eight morphometric parameters such as R_b, F_s, D_d, T, L_o, R_c, R_f and R_e were used to prioritize the 23

micro-watersheds of Dnyanganga watershed. The formulae present in the Table 1 is used to calculate the linear and shape morphometric parameters used in this study for prioritization of Dnyanganga micro-watersheds.

Table 1. Formulae for calculating morphometric parameters used in this study

Morphometric Parameters	Formula/Definition	Unit	References
Bifurcation Ratio (R_b)	$R_b = N_u / N_u + 1$	Dimensionless	[10]
Length of overland flow (L_o)	$L_o = 1 / 2D_d$	km	[11]
Drainage density (D_d)	$D_d = L / A$	km km^{-2}	[11]
Stream frequency (F_s)	$F_s = N_u / A$	km^{-2}	[11]
Drainage texture ratio (T)	$T = N_1 / P$	km^{-1}	[11]
Form factor (R_f)	$R_f = A / (Lb)^2$	Dimensionless	[11]
Circulatory ratio (R_c)	$R_c = 4\pi A / P^2$	Dimensionless	[10]
Elongation ratio (R_e)	$R_e = \sqrt{(A / \pi)} / Lb$	Dimensionless	[11]

3.2.2. TOPSIS

The TOPSIS model was introduced in 1981 [12], which ranks the alternative based on the closest distant to the ideal solution and the farthest distant to the negative-ideal solution. The steps of TOPSIS model is as follows,

Step 1. Establishing a decision matrix for ranking which is given in eqn (1).

$$D = \begin{bmatrix} a_{11} & a_{12} & ... & a_{1n} \\ a_{21} & a_{22} & ... & a_{2n} \\ . & . & ... & . \\ a_{m1} & a_{m2} & ... & a_{mn} \end{bmatrix} \quad (1)$$

Step 2. Determine the normalised decision matrix as follows

$$R_{ij} = \frac{a_{ij}}{\sqrt{\sum_1^m a_{ij}^2}} \quad (2)$$

where, R_{ij} is a normalized decision matrix element and a_{ij} is the i-th alternative performance in j-th criteria.

Step 3. Determine the weighted normalised decision matrix as follows

$$V_{ij} = R_{ij} \times w_j \quad (3)$$

where, V_{ij} is weighted normalized matrix element, R_{ij} is normalized matrix elements, and W_j is weight of criteria $_j$. The weights of the criteria were calculated using Saaty's Analytical Hierarchy Process [13].

Step 4. Determining and measuring the positive ideal solution (PIS) and negative ideal solution (NIS) as given in [11].

Step 5. The final step is to calculate closest coefficient of the alternatives to the ideal solution.

$$cl_i^+ = \frac{d_{i-}}{d_{i+} + d_{i-}}; 0 \le 1; i = 1, 2, ..., m \tag{4}$$

where, cl_i^+ is closeness coefficient, d_{i+} is positive ideal solution (PIS), and d_i^- is negative ideal solution (NIS).

4. Results and Discussion

The present study utilises eight morphometric parameters for the prioritization of Dnyanganga micro-watershed using TOPSIS MCDM approach performed through R statistical software. The five linear (R_b, F_s, D_d, T, L_o) and three shape (R_c, R_f, R_e) parameters of the each micro-watershed present in the study area has been calculated using the basic morphometric parameters such as area, perimeter, stream length, no. of streams, minimum and maximum elevation. Linear parameters have a direct relationship with soil erodability while shape parameters have an inverse relationship. Higher the values of linear parameters, greater will be the erosion whereas lower the values of shape parameters higher will be the erosion and vice versa [1-3]. Higher and lower values of linear (R_b, F_s, D_d, T & L_o) and shape (R_c, R_f & R_e) parameters indicating higher susceptibility to erosion are seen in the micro-watersheds of 11, 13, 13, 13, 12, 23, 23 and 17. In this study, the linear parameters were taken as positive criteria where the maximum values are favored for high erosion while the shape parameters were taken as negative criteria where the minimum values are favored for high erosion.

Table 2. Selected criteria along with its type and weights (AHP)

Criteria	R_b	F_s	D_d	T	L_o	R_c	R_f	R_e
Criteria Type	Positive	Positive	Positive	Positive	Positive	Negative	Negative	Negative
Criteria weights (AHP)	0.163	0.305	0.224	0.099	0.121	0.041	0.03	0.017

In this study, the relative weights of each criterion were determined through AHP (Table 2) using R statistical software (https://cran.r-project.org/web/packages/ahp/index.html) and the determined weights were given as input for determining best alternatives through TOPSIS using MCDM Package (https://cran.r-project.org/web/packages/MCDM/MCDM.pdf) in R.

Table 3. The values of morphometric parameters and closest coefficient (C_i^+) to the ideal solution with ranking (R^*) and priority index of Dnyanganga micro-watersheds

MSW	R_b	F_s	D_d	T	L_o	R_c	R_f	R_e	C_i^+	R^*	Priority Index
1	2.83	0.51	1.25	0.41	0.4	0.34	0.38	0.95	0.249	11	High
2	3.25	0.6	1.32	0.39	0.38	0.26	0.39	0.88	0.401	4	Very High
3	5.25	0.52	1.17	0.54	0.43	0.35	0.35	1.17	0.272	10	High
4	3.39	0.69	1.38	0.61	0.36	0.17	0.33	1.4	0.273	9	High
5	4.17	0.68	1.28	0.58	0.39	0.26	0.36	1.13	0.183	15	Moderate
6	4.17	0.65	1.3	0.61	0.38	0.36	0.36	1.06	0.098	18	Moderate
7	3	0.68	1.26	0.68	0.4	0.31	0.35	1.19	0.113	16	Moderate
8	5	0.6	1.3	0.57	0.38	0.27	0.35	1.22	0.096	21	Low
9	6.5	0.48	1.44	0.29	0.35	0.16	0.37	1.04	0.288	8	High
10	5	0.48	1.27	0.32	0.39	0.25	0.38	0.94	0.459	1	Very High
11	8	0.48	1.24	0.38	0.4	0.41	0.39	0.86	0.385	5	Very High

12	4	0.43	0.78	0.49	0.64	0.34	0.34	1.31	0.326	7	High
13	3.17	0.91	1.88	0.89	0.27	0.38	0.36	1.09	0.213	13	Moderate
14	4.17	0.69	1.42	0.58	0.35	0.3	0.37	1.04	0.096	19	Low
15	3.17	0.62	1.14	0.51	0.44	0.37	0.38	0.94	0.098	17	Moderate
16	4	0.62	1.4	0.35	0.36	0.13	0.36	1.06	0.096	20	Low
17	3	0.63	1.28	0.37	0.39	0.25	0.39	0.83	0.357	6	Very High
18	3.25	0.59	1.43	0.56	0.35	0.16	0.33	1.53	0.458	2	Very High
19	3.5	0.49	1.32	0.34	0.38	0.19	0.36	1.1	0.445	3	Very High
20	3.76	0.56	1.33	0.56	0.38	0.17	0.32	1.56	0.240	12	High
21	3.3	0.62	1.37	0.66	0.37	0.1	0.29	2.1	0.192	14	Moderate
22	4.06	0.59	1.38	0.72	0.36	0.11	0.29	2.2	0.088	23	Low
23	2.67	0.54	1.31	0.56	0.38	0.05	0.27	2.68	0.092	22	Low

Based on the results (Table 3), The micro-watersheds were classified into very high (0.459 - 0.357), high (0.326 – 0.240), moderate (0.213 – 0.098), and low (0.096 – 0.088) prioritization levels based on the TOPSIS highest closeness (C_i^+) to ideal solution (Figure 2).
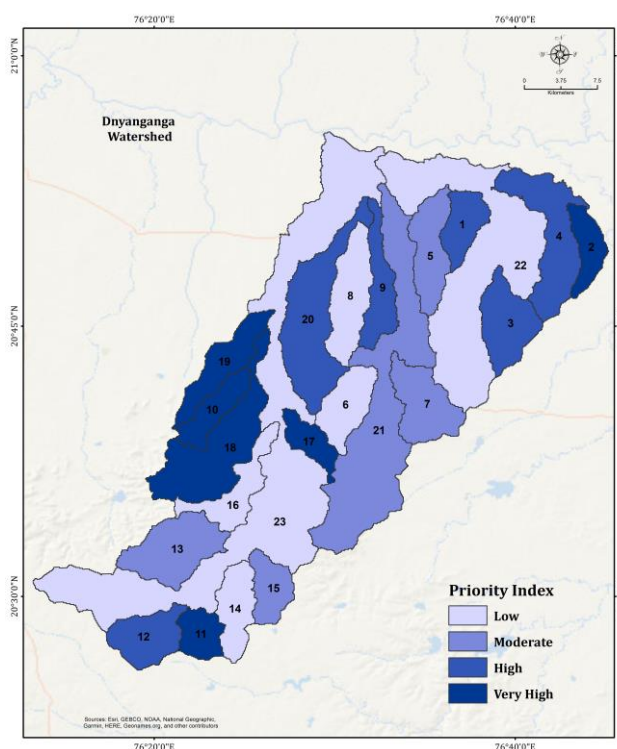

Figure 2. Soil erosion prioritization using TOPSIS model in Dnyanganga watershed

It is evident from the results that micro-watersheds (MW10, MW18, MW19, MW2, MW11, and MW17) are very highly susceptible to soil erosion and thus, conservation measures can be carried out in these micro-watersheds on priority to ensure the sustainability of future agriculture by preventing excessive soil loss through erosion.

5. Conclusion

The morphometric parameters have a great influence on the hydrological behavior of a river basin that identifies vulnerable regions to natural hazards such as soil erosion, which causes a huge

economic loss to human lives. Thus, in this study prioritization of 23 micro-watersheds was carried out in order to reduce and control the effects of soil erosion in the Dnyanganga watershed. The micro-watersheds having very high and high vulnerability to erosion should be taken care for soil and water conservation measures in order to ensure the sustainable development of agriculture and natural resources. This study establishes the usage of TOPSIS MCDM approach with the help of R which makes the calculation easy for the decision makers in formulating soil conservation plans at different levels.

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