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ORIGINAL PAPER

Prioritization of soil erosion-prone sub-watersheds using fuzzy-based multi-criteria decision-making methods in Narmada basin watershed, India

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Abstract

Every year, soil erosion causes significant damage to humans by reducing soil productivity and filling reservoirs from sediment deposition in the Manot watershed in the Narmada basin, India. Hence, it is important in this basin to recognize soil erosion-prone areas for preventive steps. In this research, prioritization of sub-watersheds of the Manot watershed has been done using fuzzy MCDM approaches such as Fuzzy-SAW, Fuzzy-VIKOR and Fuzzy-TOPSIS methods. For this purpose, the Shuttle Radar Topography Mission (SRTM)-generated Digital Elevation Model (DEM) was used to extract and analyze 12 morphometric parameters, including linear, aerial, and relief parameters. A fuzzy MCDM was successfully implemented for prioritizing watersheds in terms of soil erosion. Overall, the descending order in terms of susceptibility to erosion is found to be MN8 > MN7 > MN2 > MN10 > MN1 > MN9 > MN12 > MN4 > MN5 > MN6 > MN14 > MN3 > MN13 > MN11. The findings showed that morphometric parameters and the fuzzy MCDM approach have high efficiency in recognizing areas that are vulnerable to erosion.

Keywords MCDM · Prioritization technique · Soil conservation · Watershed management · Fuzzy MCDM

Introduction

Soil erosion is one of the major land loss problems on agricultural land and is regarded in modern times worldwide as a serious environmental hazard (Lu et al. 2003; Kim et al. 2005; Srinivasan et al. 2019; Meshram et al. 2021a, b, c; Silakhori et al. 2022; Benzougagh et al. 2022). Water erosion risk is an environmental, economic, and social issue that affects all countries. Soil degradation in India is estimated to be occurring on 147 million hectares (Mha) of land, including 94 Mha from water erosion, 16 Mha from acidification, 14 Mha from flooding, 9 Mha from wind erosion, 6 Mha from salinity, and 7 Mha from a combination of factors (Bhattacharyya et al. 2015). Therefore, the problem needs to be addressed prudently and a systematic solution to reduce the extent of the problem needs to be pursued. To exploit land and water resources efficiently and sustainably, one needs to try to find a sustainable unit so that such resources can be effectively handled and controlled.

Soil attrition or erosion, excess water flow or runoff, changes in rivers geometry, degradation of streams, and sediment accumulation in river and stream characteristics are related to morphometry (UNEP 1997). This suggests that the morphology of a basin's is fundamental to the basin hydrology. At present, geo-morphometric analysis using a new technique, i.e., RS and GIS is being utilized as this tool gives flexibility to analyze spatial data in new manner (Gajbhiye et al. 2014; Meshram and Sharma 2017).

In today's world, the majority of researchers use RS and GIS to evaluate natural disasters, prioritize watersheds, and

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determine various morphometric parameters in drainage basins (Gajbhiye et al. 2014; Khadse et al. 2015; Amani and Safaviyan 2015; Meshram and Sharma 2017). Watersheds were prioritized by Durbude et al. (2001) based on the percentage of agricultural land, drainage density, and percent slope. Javed et al. (2011) used an RS- and GIS-based approach for prioritization of watersheds. Based on an impact study of topography, climate, morphology, soil, land cover, management, and conservation factors, Jaiswal et al. (2015) proposed an effective multi-criteria decision support model (MCDSM) to prioritize vulnerable areas in a watershed for soil conservation steps. Mundetia et al. (2018) used a GIS approach to evaluate the morphometric characteristics of the Khari River basin and prioritize sub-watersheds based on ground water potentialities suggested by morphometric parameters.

To solve the problems of multifaceted situations, a technique has been evolved and is named MCDM (multi-criteria decision making) (Liu et al. 2006; Shih et al. 2007; Chang and Hsu 2009; Chang and Lin 2014; Salehi and Izadikhah 2014; Kobryń and Prystrom 2015; Nguyen et al. 2015; Mulliner et al. 2016; Mir et al. 2016; Malekian and Azarnivand 2016; Dong et al. 2017; Yu et al. 2017; Shojaie et al. 2017; Raju et al. 2017; Emovon and Aibuedefe 2020; Meshram et al. 2020a,b; Alvandi et al. 2021; Meshram et al. 2021a, b, c; Akbari et al. 2021; Meshram et al. 2022). Multiple-criteria decision-making (MCDM) is a sub-discipline of operations research that explicitly evaluates multiple conflicting criteria in decision making (both in daily life and in settings such as business, government and medicine). Multi-criteria decision-making (MCDM) methods provide a possibility to evaluate Options and other conflicting factors and to decide which alternative is the most suitable according to different criteria (Butkiene et al. 2020).

Multi-criteria decision-making (MCDM) is one of the well-known topics of decision making. Fuzzy logic provides a useful way to approach a MCDM problem. Very often in MCDM problems, data are imprecise and fuzzy. In a real-world decision situation, the application of the classic MCDM method may face serious practical constraints, because of the criteria containing imprecision or vagueness inherent in the information. For these cases, fuzzy multi-criteria decision-making (fuzzy MCDM) methods have been developed (Kahraman, 2008).

The Narmada basin, India has undergone extensive land use changes over the years, which has led to an increase in peak flood discharges and sediment production. Therefore, the study of flood and sedimentation of sub-basins in the Narmada basin, India and its prioritization is important to reduce the risk of floods through conservation and management operations. The aim of this study is to explore the application of morphometric parameters using fuzzy MCDM approaches to prioritize the erosion vulnerability of sub-watersheds of the Narmada basin, India. Soil erosion causes severe ecological problems that are close to rising soil development and basins filled by Narmada basin sedimentation. Our analysis will generate vast amount of information that will help water resource consultants detail more fertile soil and future water conservation designs in the basin (Meshram et al. 2019). To identify areas that should be vulnerable to erosion, the fuzzy MCDM approach in modeling and morphometry parameters plays an important role in developing new methodologies for controlling soil erosion with more competent solutions (Mekonnen et al. 2017). The understanding of the above-mentioned facts in the basin was still discussed, and no such scientific evaluations have been published for the basin so far. The results of this study are, therefore, novel and important in terms of water resources for the authorities concerned.

Materials and methods

Study area and data used

In this research, morphometric parameters of 14 sub-watersheds across the Manot watershed, Mandla, Madhya Pradesh State, India were studied. The Narmada River runs for about 269 km from its source to Manot, with a drainage area of 4884 square kilometers. The catchment is covered in forest and has hilly terrain. The catchment's elevation varies from 450 m near the Manot site to 1110 m above mean sea level in the upper reaches. It has a subtropical and sub-humid climate that is continental in nature, with average annual rainfall of 1596 mm. The major parts of the catchment, soils are red, yellow, and medium black with a shallow to very shallow depth. The catchment is covered by forest and its topography is hilly. The location map of the Manot watershed is shown in Fig. 1.

To do fuzzy MCDM analysis, we have taken the morphometric parameters for the 14 sub-watershed of the Manot watershed from the previous studies of Gajbhiye et al. (2014).

Fuzzy-based multi-criteria decision-making (fuzzy MCDM) techniques

In this section, we give a quick overview of three fuzzy MCDM techniques, namely Fuzzy-Simple Additive

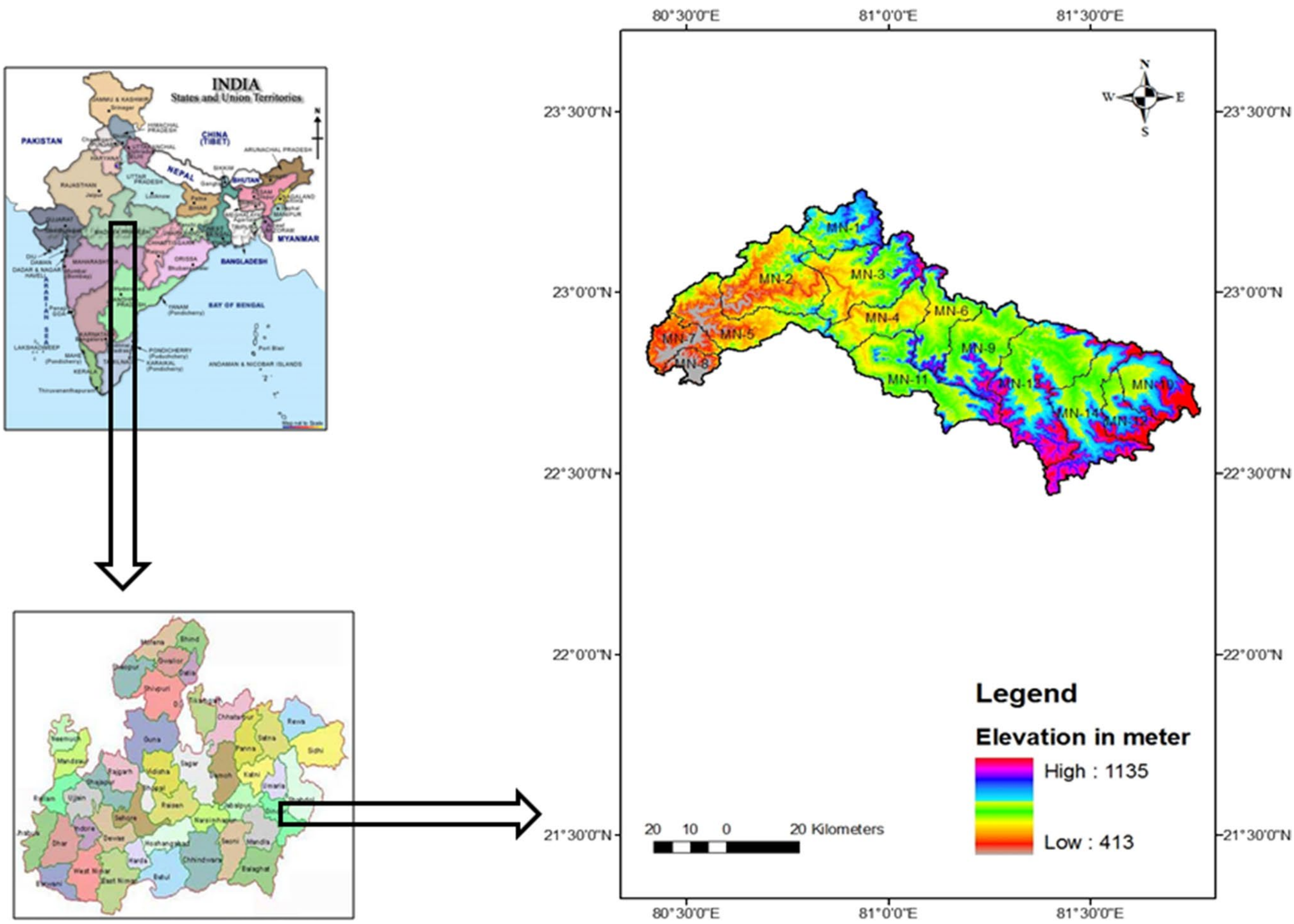

Fig. 1 Location map of the study area

Weighting (SAW), Fuzzy-The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Fuzzy-VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) that can be easily represented using fuzzy numbers.

Fuzzy-Simple Additive Weighting (Fuzzy-SAW)

This model is one of the most widely used multi-criteria decision-making methods. This approach is important because it enables the examination of options based on both quantitative and qualitative criteria. The steps of the Fuzzy-SAW method were performed as follows:

Step 1: Quantify the decision matrix.

Step 2: Normalize the decision matrix.

At this step, the linear descaling method was used for normalization**.** Therefore, we divide each value of the r_{ij} matrix by the maximum available r_{ij} matrix:

$$n_{ij} = \frac{r_{ij}}{Max(r_j)}. \quad (1)$$

Step 3: Weight the unscaled matrix.

The Analytical Hierarchy Method (AHP) method is used to weight each indicator in this analysis. The AHP was used to derive the indices' weights by referring to 10 experts in the corresponding weighting area for each of the indicators. Finally, using the following relationship, the final score for prioritization is determined:

$$A^* = \left\{ A^* | Max \sum_{j=1}^{n} w_j r_{ij} \right\}. \quad (2)$$

In this regard, w_j is the weight assigned to each of the indicators and $\mathcal{A}^*$ is the most appropriate option (sub-basin).

Fuzzy-The Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy-TOPSIS)

The Fuzzy-TOPSIS method is one of the most popular and widely used multi-criteria decision-making methods that is used to rank options in a fuzzy environment. This method was proposed by Huang and Eun in 1981. The steps of this method are similar to the TOPSIS method as follows (Patil and Kant 2014):

Step 1: Create a decision matrix.

Step 2: Normalize the decision matrix.

In this step, we convert the fuzzy decision matrix to a fuzzy matrix without scale. If the components are positive, we use Eq. 3, and if they are negative, we use Eq. 4:

$$n_{ij} = \left(\frac{\ell_{ij}}{u_j^*}, \frac{m_{ij}}{u_j^*}, \frac{u_{ij}}{u_j^*} \right), \tag{3}$$

$$u_j^* = \mathcal{M}ax u_{ij},$$

$$n_{ij} = \left(\frac{\ell_j^-}{u_{ij}}, \frac{\ell_j^-}{m_{ij}}, \frac{\ell_j^-}{\ell_{ij}} \right), \tag{4}$$

$$\ell_j^- = \mathcal{M}in \ell_{ij}.$$

Step 3: Weight the fuzzy unscaled matrix.

In this step, we weight the fuzzy unscaled matrix using Eq. 5:

$$v_{ij} = r_{ij} \times w_j. \tag{5}$$

Step 4: Determine the fuzzy ideal $\mathcal{A}^+$ and the anti-ideal fuzzy $\mathcal{A}^-$ for the components.

In this step, the positive ideal is equal to the largest value of each criterion column (Eq. 6). In addition, the negative ideal is equal to the smallest value of each criterion column (Eq. 7):

$$\begin{aligned} &\mathcal{A}^+ = \left(v_1^*, v_2^*, \ldots ..v_n^*\right) where, \\ &v_j^* = \left(c_j^*, c_j^*, c_j^*\right) \; and \; c_j^* = max\left\{c_{ij}\right\}, \end{aligned} \tag{6}$$

$$\begin{aligned} &\mathcal{A}^- = \left(v_1^-, v_2^-, \ldots ..v_n^-\right) where, \\ &v_j^- = \left(a_j^-, a_j^-, a_j^-\right) and \; a_j^- = min\left\{a_{ij}\right\}. \end{aligned} \tag{7}$$

Step 5: Calculate the sum of the distances of each component from the fuzzy positive ideal and the fuzzy negative ideal.

Then, the sum of the distances of each component from the fuzzy positive ideal and the fuzzy negative ideal is calculated using the following relationships:

$$d_i^+ = \sum_{j=1}^{n} dv\left(v_{ij}, v_j^+\right), (i = 1, 2, \ldots .m), \tag{8}$$

$$d_i^- = \sum_{j=1}^{n} dv\left(v_{ij}, v_j^-\right), (i = 1, 2, \ldots .m). \tag{9}$$

Step 6: Calculate the similarity index to the ideal option.

Finally, using the relationship of 10, the relative proximity of the sub-basins is the optimal solution, and the sub-basins are prioritized according to their distance:

$$c_i = \frac{d_i^-}{d_i^- + d_i^+}, (i = 1, 2, 3 \ldots \ldots m). \tag{10}$$

Fuzzy-VIsekriterijumska Optimizacija I Kompromisno Resenje (Fuzzy-VIKOR)

The Fuzzy-VIKOR method is a multi-criteria decision-making strategy that seeks to choose the best choice. The steps of this method are similar to the VIKOR method, which is described as follows (Eprycovik, 2011):

Step 1: Create a decision matrix.

Step 2: Determine the ideal values.

After forming the decision matrix, the best and worst values of each value in the decision matrix are determined using Eqs. 11 and 12:

$$f_i^- = min_j\left(f_{ij}\right), f_i^* = max_j\left(f_{ij}\right), \tag{11}$$

$$f_i^+ = max_j\left(f_{ij}\right), f_i^* = min_j\left(f_{ij}\right), \tag{12}$$

where f_i^+ are the best values and f_i^- are the worst values.

Step 3: Normalize the decision matrix.

In this step, normalization for positive and negative criteria is done based on the following relationships:

$$d_{jj} = \frac{\left(f_i^* - f_{ij}\right)}{\left(r_i^* - \ell_i^-\right)} for \rightarrow i\epsilon I^{b}, \tag{13}$$

$$d_{jj} = \frac{\left(f_i^* - f_{ij}\right)}{\left(r_i^* - \ell_{ij}\right)} for \rightarrow i\epsilon I^{c}. \tag{14}$$

Step 4: Determine the values of S and R:

At this stage, the maximum group utility values of the majority ($\mathcal{S}$) and individual regrets of the least of the opposite ($\mathcal{R}$) are calculated using Eqs. 15 and 16:

$$\mathcal{S}_j = \sum_{i=1}^{n} \left(w_i \times d_{ij} \right), \tag{15}$$

$$\mathcal{R}_j = max_i \left(w_i \times d_{ij} \right). \tag{16}$$

In these relations, w_i is the index weight.

Step 5: Calculate the VIKOR index ($\mathcal{Q}$):

Finally, the value of $\mathcal{Q}$, which is a hybrid function, is estimated using Eq. 17, which combines and $\mathcal{R}$ with weight as equations.

At the end, the sub-basins are classified and the final sub-basin is selected:

$$\mathcal{Q}_j = \frac{\mathcal{V}\left(\mathcal{S}_j + \mathcal{S}^+\right)}{\left(\mathcal{S}^- - \mathcal{S}^+\right)} + \frac{(1-\mathcal{V})\left(\mathcal{R}_j - \mathcal{R}^+\right)}{\left(\mathcal{R}^- - \mathcal{R}^+\right)}, \tag{17}$$

where $\mathcal{S}^+ = min_j \mathcal{S}_j$, $\mathcal{R}^+ = min_j \mathcal{R}_j$, $\mathcal{S}^- = max_j \mathcal{S}_j$, $\mathcal{R}^- = max_j \mathcal{R}_j$ and is the weight determined by the maximum agreement of the group.

Results and discussion

The Manot watershed is susceptible to high rates of erosion, with negative implications for soil productivity and water availability. However, because of spatially variable morphological characteristics, the different sub-basins within Manot are exposed to varying degrees of erosion. Erosion prone areas have been prioritized using basin dynamics guided by various morphometric parameters that influence erosion processes at the catchment scale. This will help in bringing forward localized prevention measures that are appropriate to each sub-basin and will enable an understanding of catchment dynamics. Four broad categories of the morphometric variables, consisting of shape parameters, drainage parameters, slope parameters and the hypsometric integral, were employed. Under each category, selected sub-categories were used (Table 1).

Prioritizing sub-basins in a watershed comprised of various dynamics and morphologies that can be highly uncertain and unachievable through simple analysis methods. At the same time, relying on perception can be very subjective and lack scientific objectivity. Therefore, the fuzzy MCDM technique has been applied in this study to minimize uncertainty by assigning weighted importance to the criteria applied in the study, followed by ranking of the criteria evaluation alternatives. Therefore, it can be said that multi-criteria decision-making techniques are a practical and appropriate approach for better decision-making based on mathematical sciences and optimization. Therefore, these types of low-cost and fast-track research can be prioritized to protect watersheds, which agrees to the findings of Khadse et al (2015), Gajbhiye et al (2014) and Thakkar et al. (2007). Given that all the morphological variables selected for this study are to some extent associated with erosion in the sub-basins, a triangular fuzzy function (Triangular Fuzzy Number (TFN), Fig. 2) has been used for this study to indicate the importance of each morphometric set of criteria. The resultant fuzzy decision matrix obtained from the aggregated triangular weights of criteria and fuzzy ratings of each of the sub-basins is presented in Table 2, while Table 3 shows the weighted decision matrix.

Integration of morphometric parameters is an efficient way to prioritize sub-basins to implement soil conservation practices (Gajbhiye et al. 2014; Meshram et al. 2019). Studies show the ability of GIS in prioritization of watersheds based on morphometric parameters (Pai et al. 2011) and the results of this research has proven this claim. In this study, a novel

Table 1 Morphometric parameters based on main categories and their sub-categories

Main category	Sub-categories	Symbol
Shape parameters	Form factor	R_f
	Elongation ratio	R_e
	Circularity ratio	R_c
	Compactness coefficient	C_c
Drainage parameters	Bifurcation ratio	R_b
	Drainage density	D_d
	Length of overland flow	L_o
	Drainage frequency	F_s
	Drainage texture	T
Slope parameters	Relief ratio	R_h
	Ruggedness number	RN
	Relative ratio	R_r
	Average slope of watershed	S_a
Hypsometric integral	Hypsometric index	HI

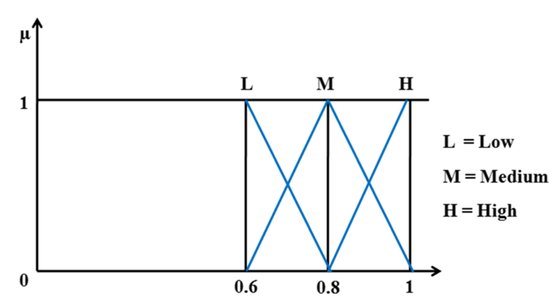

Fig. 2 Overview of fuzzy variables of the weight for each morphometric parameter

Table 2 Fuzzy decision matrix of criteria in different sub-basins

SW	Rh			Rr			RN			Rb			Dd			Fs			Rc		
	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
MN1	0.17	0.32	0.48	0.17	0.33	0.51	0.69	0.84	1	0.68	0.84	0.99	0.66	0.81	0.97	0	0.15	0.31	0.65	0.80	0.96
MN2	0.08	0.23	0.39	0.17	0.33	0.51	0.21	0.36	0.52	0.53	0.69	0.84	0.69	0.84	1	0.62	0.77	0.93	0.67	0.82	0.98
MN3	0.21	0.36	0.52	0.17	0.33	0.51	0	0.15	0.31	0.51	0.67	0.82	0.62	0.77	0.93	0.09	0.24	0.40	0.53	0.68	0.84
MN4	0.30	0.45	0.61	0.51	0.67	0.85	0.14	0.29	0.45	0.66	0.82	0.97	0.02	0.17	0.33	0.02	0.17	0.33	0.47	0.62	0.78
MN5	0.08	0.23	0.39	0.17	0.33	0.51	0.03	0.18	0.34	0.56	0.72	0.87	0.68	0.83	0.99	0.29	0.44	0.60	0.06	0.21	0.37
MN6	0.66	0.81	0.97	0.17	0.33	0.51	0.12	0.27	0.43	0.65	0.81	0.96	0.01	0.16	0.32	0.10	0.25	0.41	0.22	0.37	0.53
MN7	0.62	0.77	0.93	0.51	0.67	0.85	0.68	0.83	0.99	0.49	0.65	0.8	0.61	0.76	0.92	0.35	0.50	0.66	0.36	0.51	0.67
MN8	0.73	0.88	1	0.64	0.8	0.98	0.57	0.72	0.88	0.62	0.78	0.93	0.68	0.83	0.99	0.68	0.83	0.99	0.42	0.57	0.73
MN9	0.17	0.32	0.48	0.17	0.33	0.51	0.44	0.59	0.75	0.61	0.77	0.92	0.05	0.20	0.36	0.14	0.29	0.45	0.43	0.58	0.74
MN10	0.49	0.64	0.8	0.51	0.67	0.85	0.16	0.31	0.47	0.65	0.81	0.96	0	0.15	0.31	0.03	0.18	0.34	0.69	0.84	1
MN11	0	0.15	0.31	0.01	0.17	0.35	0.32	0.47	0.63	0.65	0.81	0.96	0.15	0.30	0.46	0.08	0.23	0.39	0.20	0.35	0.51
MN12	0.26	0.41	0.57	0.51	0.67	0.85	0.47	0.62	0.78	0.69	0.85	1	0.16	0.31	0.47	0.05	0.20	0.36	0.37	0.52	0.68
MN13	0.04	0.19	0.35	0.17	0.33	0.51	0.02	0.17	0.33	0.01	0.17	0.32	0.53	0.68	0.84	0.01	0.16	0.32	0.44	0.59	0.75
MN14	0.12	0.27	0.43	0.01	0.17	0.35	0.09	0.24	0.4	0.51	0.67	0.82	0.24	0.39	0.55	0.07	0.22	0.38	0.01	0.16	0.32
SW	Rf			Re			T			Lo			Cc			Sa			HI		
MN1	0.66	0.82	0.98	0.69	0.84	0.99	0.34	0.49	0.65	0.03	0.18	0.34	0.23	0.38	0.55	0.32	0.47	0.63	0.08	0.23	0.40
MN2	0.67	0.83	0.99	0.69	0.84	0.99	0.07	0.22	0.38	0.01	0.16	0.32	0.03	0.18	0.35	0.60	0.75	0.91	0.61	0.76	0.93
MN3	0.56	0.72	0.88	0.6	0.75	0.90	0.08	0.23	0.39	0.1	0.25	0.41	0.06	0.21	0.38	0.51	0.66	0.82	0	0.15	0.32
MN4	0.49	0.65	0.81	0.54	0.69	0.84	0.42	0.57	0.73	0.68	0.83	0.99	0.28	0.43	0.60	0.02	0.17	0.33	0.08	0.23	0.40
MN5	0.17	0.33	0.49	0.25	0.40	0.55	0.50	0.65	0.81	0.03	0.18	0.34	0.17	0.32	0.49	0.55	0.70	0.86	0.68	0.83	1
MN6	0.33	0.49	0.65	0.41	0.56	0.71	0.52	0.67	0.83	0.69	0.84	1	0.28	0.43	0.60	0.14	0.29	0.45	0.08	0.23	0.40
MN7	0.55	0.71	0.87	0.60	0.75	0.90	0.66	0.81	0.97	0.1	0.25	0.41	0.46	0.61	0.78	0.30	0.45	0.61	0.08	0.23	0.40
MN8	0.46	0.62	0.78	0.52	0.67	0.82	0.69	0.84	1	0.03	0.18	0.34	0.68	0.83	1	0.04	0.19	0.35	0.08	0.23	0.40
MN9	0.64	0.8	0.96	0.66	0.81	0.96	0.28	0.43	0.59	0.68	0.83	0.99	0.12	0.27	0.44	0.31	0.46	0.62	0.08	0.23	0.40
MN10	0.68	0.84	1	0.7	0.85	1	0.22	0.37	0.53	0.69	0.84	1	0.17	0.32	0.49	0.47	0.62	0.78	0.08	0.23	0.40
MN11	0	0.16	0.32	0.01	0.16	0.31	0.31	0.46	0.62	0.6	0.75	0.91	0.12	0.27	0.44	0.39	0.54	0.70	0.08	0.23	0.40
MN12	0.32	0.48	0.64	0.39	0.54	0.69	0.63	0.78	0.94	0.6	0.75	0.91	0.41	0.56	0.73	0.01	0.16	0.32	0.08	0.23	0.40
MN13	0.33	0.49	0.65	0.40	0.55	0.70	0.02	0.17	0.33	0.18	0.33	0.49	0	0.15	0.32	0.69	0.84	1	0.08	0.23	0.40
MN14	0.63	0.79	0.95	0.66	0.81	0.96	0.50	0.65	0.81	0.52	0.67	0.83	0.12	0.27	0.44	0.60	0.75	0.91	0.08	0.23	0.40

SW Sub-watershed, *L* low, *M* medium, *H* high

and logical approach of MCDM processes, i.e., Fuzzy-SAW, Fuzzy-VIKOR and Fuzzy-TOPSIS analysis-based prioritization was formulated successfully which plays an imperative role in illustrating the dilemma through integration of risk assessment factors causing natural resources' degradation. This may be one of the viable and efficient techniques, particularly over the data hungry conventional watershed prioritization approaches for designing and developing the efficient sustainable development and management practices, especially for the scarce/unavailable data conditions. For prioritization, this study employed fuzzy MCDM through the fuzzy analytic hierarchy process (AHP) to establish criteria weights while the different criteria were ranked using three prioritization approaches consisting of Fuzzy-VIKOR, Fuzzy-TOPSIS and Fuzzy-SAW. The VIKOR model prioritizes the alternative that is closest to the ideal solution while TOPSIS is based on the assumption that the best choice should be the one with the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution and the SAW model is based on a weighted average of how each alternative performs across all attributes, i.e., summing up the contributions of each attribute multiplied by its weight.

Table 3 Weighted decision matrix of criteria in different sub-basins (Manot watershed)

SW	Rh			Rr			RN			Rb			Dd			Fs			Rc		
	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
MN1	0.10	0.25	0.48	0.10	0.27	0.51	0.42	0.67	1	0.41	0.67	0.99	0.39	0.65	0.97	0	0.12	0.31	0.39	0.64	0.96
MN2	0.05	0.18	0.39	0.10	0.27	0.51	0.13	0.29	0.52	0.32	0.55	0.84	0.41	0.67	1	0.37	0.62	0.93	0.40	0.65	0.98
MN3	0.13	0.29	0.52	0.10	0.27	0.51	0	0.12	0.31	0.31	0.54	0.82	0.37	0.61	0.93	0.06	0.19	0.40	0.32	0.54	0.84
MN4	0.18	0.36	0.61	0.30	0.53	0.85	0.09	0.24	0.45	0.40	0.66	0.97	0.01	0.14	0.33	0.01	0.13	0.33	0.28	0.50	0.78
MN5	0.05	0.18	0.39	0.10	0.27	0.51	0.02	0.15	0.34	0.34	0.58	0.87	0.41	0.66	0.99	0.17	0.35	0.60	0.04	0.17	0.37
MN6	0.40	0.65	0.97	0.10	0.27	0.51	0.07	0.21	0.43	0.39	0.65	0.96	0.01	0.13	0.32	0.06	0.20	0.41	0.13	0.30	0.53
MN7	0.37	0.62	0.93	0.30	0.53	0.85	0.41	0.66	0.99	0.3	0.52	0.80	0.36	0.61	0.92	0.21	0.40	0.66	0.22	0.41	0.67
MN8	0.44	0.71	1	0.39	0.64	0.98	0.34	0.58	0.88	0.37	0.63	0.93	0.41	0.66	0.99	0.41	0.66	0.99	0.25	0.46	0.73
MN9	0.10	0.25	0.48	0.10	0.27	0.51	0.27	0.47	0.75	0.36	0.61	0.92	0.03	0.16	0.36	0.09	0.24	0.45	0.26	0.46	0.74
MN10	0.29	0.51	0.80	0.30	0.53	0.85	0.09	0.25	0.47	0.39	0.64	0.96	0	0.12	0.31	0.02	0.14	0.34	0.42	0.67	1
MN11	0	0.12	0.31	0	0.13	0.35	0.19	0.38	0.63	0.39	0.65	0.96	0.09	0.24	0.46	0.05	0.18	0.39	0.12	0.28	0.51
MN12	0.16	0.33	0.57	0.30	0.53	0.85	0.28	0.49	0.78	0.42	0.68	1	0.10	0.25	0.47	0.03	0.16	0.36	0.22	0.41	0.68
MN13	0.02	0.15	0.35	0.10	0.27	0.51	0.01	0.14	0.33	0	0.13	0.32	0.32	0.54	0.84	0.01	0.13	0.32	0.27	0.47	0.75
MN14	0.07	0.22	0.43	0	0.13	0.35	0.06	0.19	0.4	0.30	0.53	0.82	0.15	0.31	0.55	0.04	0.18	0.38	0.01	0.13	0.32

SW	Rf			Re			T			Lo			Cc			Sa			HI		
MN1	0.40	0.66	0.98	0.41	0.67	0.99	0.20	0.39	0.65	0.02	0.15	0.34	0.14	0.30	0.55	0.19	0.37	0.63	0.05	0.19	0.40
MN2	0.40	0.66	0.99	0.41	0.67	0.99	0.04	0.18	0.38	0.01	0.13	0.32	0.02	0.14	0.35	0.36	0.60	0.91	0.37	0.61	0.93
MN3	0.34	0.58	0.88	0.36	0.60	0.90	0.05	0.18	0.39	0.06	0.20	0.41	0.04	0.17	0.38	0.30	0.53	0.82	0	0.12	0.32
MN4	0.29	0.52	0.81	0.32	0.55	0.84	0.25	0.45	0.73	0.41	0.67	0.99	0.17	0.35	0.60	0.01	0.14	0.33	0.05	0.19	0.40
MN5	0.10	0.27	0.49	0.15	0.32	0.55	0.30	0.52	0.81	0.02	0.15	0.34	0.10	0.26	0.49	0.33	0.56	0.86	0.41	0.66	1
MN6	0.20	0.39	0.65	0.24	0.44	0.71	0.31	0.53	0.83	0.41	0.67	1	0.17	0.35	0.60	0.09	0.23	0.45	0.05	0.19	0.40
MN7	0.33	0.57	0.87	0.36	0.60	0.90	0.40	0.65	0.97	0.06	0.20	0.41	0.28	0.49	0.78	0.18	0.36	0.61	0.05	0.19	0.40
MN8	0.28	0.50	0.78	0.31	0.54	0.82	0.41	0.67	1	0.02	0.15	0.34	0.41	0.66	1	0.03	0.15	0.35	0.05	0.19	0.40
MN9	0.38	0.64	0.96	0.40	0.65	0.96	0.17	0.35	0.59	0.41	0.67	0.99	0.07	0.21	0.44	0.19	0.37	0.62	0.05	0.19	0.40
MN10	0.41	0.67	1	0.42	0.68	1	0.13	0.30	0.53	0.41	0.67	1.00	0.10	0.26	0.49	0.28	0.49	0.78	0.05	0.19	0.40
MN11	0	0.13	0.32	0.01	0.13	0.31	0.19	0.37	0.62	0.36	0.60	0.91	0.07	0.21	0.44	0.24	0.43	0.70	0.05	0.19	0.40
MN12	0.19	0.38	0.64	0.23	0.43	0.69	0.38	0.62	0.94	0.36	0.60	0.91	0.24	0.44	0.73	0	0.13	0.32	0.05	0.19	0.40
MN13	0.20	0.39	0.65	0.24	0.44	0.70	0.01	0.13	0.33	0.11	0.27	0.49	0	0.12	0.32	0.41	0.67	1	0.05	0.19	0.40
MN14	0.38	0.63	0.95	0.40	0.65	0.96	0.30	0.52	0.81	0.31	0.53	0.83	0.07	0.21	0.44	0.36	0.60	0.91	0.05	0.19	0.40

SW Sub-watershed, *L* low, *M* medium, *H* high

Table 4 Ideal positive option and ideal negative option (TOPSIS)

Criteria	Rh			Rr			RN			Rb			Dd			Fs			Rc		
	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Best value	0.44	0.71	1	0.39	0.64	0.98	0.42	0.67	1	0.42	0.68	1	0.41	0.67	1	0.41	0.66	0.99	0.42	0.67	1
Worst value	0	0.12	0.31	0	0.13	0.35	0	0.12	0.31	0	0.13	0.32	0	0.12	0.31	0	0.12	0.31	0.01	0.13	0.32

Criteria	Rf			Re			T			Lo			Cc			Sa			HI		
	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Best value	0.41	0.67	1	0.42	0.68	1	0.41	0.67	1	0.41	0.67	1	0.41	0.66	1	0.41	0.67	1	0.41	0.66	1
Worst value	0	0.13	0.32	0.01	0.13	0.31	0.01	0.13	0.33	0.01	0.13	0.32	0	0.12	0.32	0	0.13	0.32	0	0.12	0.32

L low, *M* medium, *H* high

Table 5 The distance from the ideal positive option (TOPSIS)

Sub-watershed	Rh	Rr	RN	Rb	Dd	Fs	Rc	Rf	Re	T	Lo	Cc	Sa	HI	S+
MN1	0.444	0.384	0.000	0.006	0.026	0.551	0.031	0.013	0.009	0.287	0.536	0.368	0.302	0.488	3.446
MN2	0.519	0.384	0.389	0.135	0.000	0.045	0.019	0.011	0.009	0.506	0.556	0.533	0.075	0.055	3.237
MN3	0.407	0.384	0.564	0.144	0.061	0.476	0.133	0.097	0.080	0.496	0.482	0.504	0.147	0.555	4.531
MN4	0.333	0.112	0.446	0.022	0.547	0.538	0.178	0.156	0.131	0.224	0.005	0.323	0.544	0.488	4.047
MN5	0.519	0.384	0.538	0.108	0.008	0.316	0.512	0.414	0.369	0.156	0.536	0.414	0.109	0.000	4.383
MN6	0.047	0.384	0.468	0.031	0.553	0.474	0.382	0.285	0.240	0.139	0.000	0.323	0.446	0.488	4.260
MN7	0.075	0.112	0.011	0.161	0.068	0.270	0.271	0.102	0.082	0.020	0.482	0.178	0.319	0.488	2.640
MN8	0.000	0.000	0.096	0.055	0.008	0.000	0.218	0.177	0.146	0.000	0.536	0.000	0.527	0.488	2.252
MN9	0.444	0.384	0.202	0.069	0.524	0.434	0.215	0.036	0.032	0.332	0.005	0.459	0.304	0.488	3.930
MN10	0.185	0.112	0.435	0.037	0.560	0.527	0.000	0.000	0.000	0.381	0.000	0.414	0.180	0.488	3.319
MN11	0.581	0.519	0.303	0.034	0.440	0.490	0.401	0.553	0.563	0.306	0.073	0.459	0.240	0.488	5.452
MN12	0.370	0.112	0.184	0.000	0.430	0.511	0.266	0.298	0.252	0.048	0.073	0.223	0.555	0.488	3.811
MN13	0.548	0.384	0.549	0.558	0.132	0.545	0.204	0.288	0.242	0.549	0.414	0.554	0.000	0.488	5.456
MN14	0.481	0.519	0.488	0.152	0.365	0.495	0.556	0.042	0.033	0.151	0.142	0.459	0.073	0.488	4.446

Table 6 The distance from the ideal negative option (TOPSIS)

Sub-watershed	Rh	Rr	RN	Rb	Dd	Fs	Rc	Rf	Re	T	Lo	Cc	Sa	HI	S^{-}
MN1	0.137	0.135	0.564	0.552	0.534	0.000	0.525	0.540	0.554	0.262	0.020	0.186	0.253	0.067	4.329
MN2	0.063	0.135	0.175	0.423	0.560	0.506	0.537	0.542	0.554	0.043	0.000	0.021	0.480	0.500	4.537
MN3	0.174	0.135	0.000	0.414	0.499	0.075	0.423	0.455	0.483	0.052	0.075	0.050	0.408	0.000	3.244
MN4	0.248	0.407	0.118	0.537	0.013	0.012	0.378	0.396	0.432	0.325	0.551	0.231	0.011	0.067	3.728
MN5	0.063	0.135	0.026	0.451	0.552	0.235	0.044	0.139	0.194	0.392	0.020	0.140	0.446	0.555	3.392
MN6	0.538	0.135	0.096	0.528	0.007	0.076	0.174	0.268	0.323	0.410	0.556	0.231	0.109	0.067	3.518
MN7	0.508	0.407	0.553	0.397	0.492	0.280	0.285	0.451	0.481	0.529	0.075	0.376	0.236	0.067	5.137
MN8	0.581	0.519	0.468	0.503	0.552	0.551	0.338	0.376	0.417	0.549	0.020	0.554	0.028	0.067	5.523
MN9	0.137	0.135	0.362	0.489	0.036	0.116	0.341	0.517	0.531	0.217	0.551	0.095	0.250	0.067	3.845
MN10	0.397	0.407	0.129	0.521	0.000	0.023	0.556	0.553	0.563	0.168	0.556	0.140	0.375	0.067	4.456
MN11	0.000	0.000	0.261	0.525	0.120	0.060	0.155	0.000	0.000	0.243	0.483	0.095	0.314	0.067	2.323
MN12	0.211	0.407	0.380	0.558	0.130	0.039	0.290	0.255	0.311	0.501	0.483	0.331	0.000	0.067	3.964
MN13	0.033	0.135	0.016	0.000	0.428	0.005	0.352	0.265	0.321	0.000	0.143	0.000	0.555	0.067	2.319
MN14	0.100	0.000	0.076	0.407	0.195	0.055	0.000	0.511	0.530	0.397	0.415	0.095	0.481	0.067	3.329

Based on the relative closeness values sub-basin MN8 displays the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution (Tables 4, 5 and 6), thus making it the optimum priority by TOPSIS. Conversely, MN13 is at the lowest priority, and therefore, the least affected by erosion of all the sub-basins. According to VIKOR (Table 7), the minimum Q value is the most preferred and this puts sub-basin MN7 at the highest priority followed by MN8, while MN11 is ranked the least affected by erosion. The Fuzzy-SAW ranking puts MN8 at the highest priority with MN11 being the least ranked.

The results in Table 8 show priority increasing with increasing rank number. Out of the 14 sub-basins, under-study in MN8 is the most vulnerable to erosion according to SAW and TOPSIS, while the same sub-basin is ranked second highest priority by VIKOR. On the other hand, MN7 is deemed to be the most susceptible by VIKOR and MN8 of second priority. Although not strictly equal, the rankings of

Table 7 The values of Q, R and S in the Fuzzy-VIKOR method (Manot watershed)

Sub-watershed	S	R	Q
MN1	0.445	0.071	0.68894
MN2	0.417	0.071	0.654615
MN3	0.584	0.071	0.857099
MN4	0.519	0.070	0.694598
MN5	0.563	0.069	0.680766
MN6	0.550	0.071	0.761868
MN7	0.340	0.063	0.061704
MN8	0.289	0.069	0.348945
MN9	0.507	0.067	0.495346
MN10	0.427	0.071	0.666796
MN11	0.702	0.071	1
MN12	0.489	0.071	0.741744
MN13	0.702	0.071	0.999694
MN14	0.573	0.071	0.843849

the three different prioritization methods are largely similar as shown by the radar chat (Fig. 3). Nonetheless, VIKOR seems to be out of range of Saw and TOPSIS for MN5 and MN9.

A strong positive correlation exists between the three prioritization approaches: SAW-TOPSIS (0.99), SAW-VIKOR (0.88) and TOPSIS-VIKOR (0.89). The close agreement between these prioritization methods is encouraging and provides confidence in the results obtained. According to

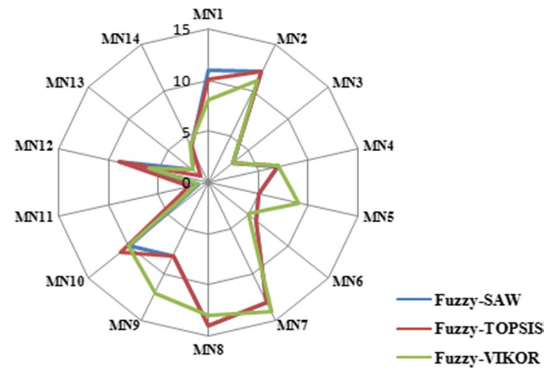

Fig. 3 Radar chart ranking the different sub-basins using Fuzzy-SAW, Fuzzy-TOPSIS and Fuzzy-VIKOR

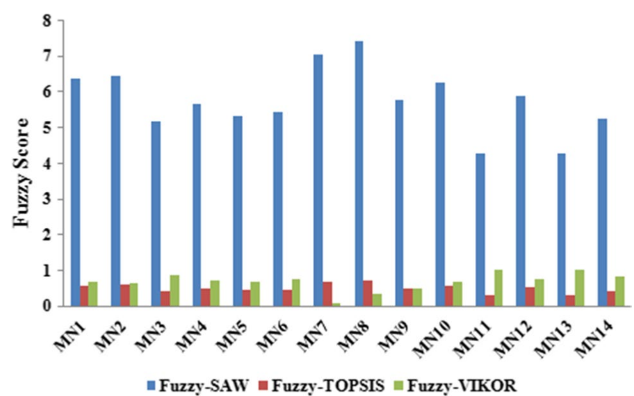

Fig. 4 Expounded overview of priority ranks for the sub-basins

Table 8 Priority ranking of the sub-basins

Sub-basin	Fuzzy-SAW		Fuzzy-TOPSIS		Fuzzy-VIKOR	
	Score	Prioritization ranks	Score	Prioritization ranks	Score	Prioritization ranks
MN1	6.379	11	0.557	10	0.689	8
MN2	6.458	12	0.584	12	0.655	11
MN3	5.190	3	0.417	3	0.857	3
MN4	5.665	7	0.479	7	0.695	7
MN5	5.336	5	0.436	5	0.681	9
MN6	5.459	6	0.452	6	0.762	5
MN7	7.046	13	0.661	13	0.062	14
MN8	7.430	14	0.710	14	0.349	13
MN9	5.780	8	0.495	8	0.495	12
MN10	6.255	10	0.573	11	0.667	10
MN11	4.284	1	0.299	2	1.000	1
MN12	5.897	9	0.510	9	0.742	6
MN13	4.288	2	0.298	1	1.000	2
MN14	5.274	4	0.428	4	0.844	4

Mulliner et al. (2016), using different methods to solve the same fuzzy multi-criteria problem provides more robust decision-making information. Further expounding on the results, Fig. 4 clearly shows that MN8 takes the highest priority. Overall, the descending order in terms of susceptibility to erosion is found to be MN8 > MN7 > MN2 > MN10 > MN 1 > MN9 > MN12 > MN4 > MN5 > MN6 > MN14 > MN3 > MN13 > MN11.

Given the results, the MCDM methods can be used as a suitable technique in prioritizing sub-basins, especially when the decision maker faces contradictory or even conflicting objectives and cannot decide on the best alternative(s). The MCDM process plays an imperative role when the complexity is involved due to several quantitative and qualitative criteria. MCDM and GIS techniques have displayed their capabilities in the prioritization of sub-basins. When used together, they compensate each other's shortcomings to better inform management planning. This is in agreement with the results Ghazvinei et al. (2016), Meshram et al. (2020a, b) and Alvandi et al. (2021).

Conclusion

There are many morphometric factors that are linked to erosion at the basin scale. Therefore, considering one or a few parameters when prioritizing the erosion-prone sub-basins may be fraught with uncertainty as each parameter, depending on its weight and magnitude of importance, stands a chance of providing conditions conducive to erosion. To deal with this kind of problem, the fuzzy logic framework becomes necessary. The focus of this study was to prioritize erosion-prone sub-basins of the Manot watershed. To solve the MCDM problem that exists in multi-parametered areas a novel approach that combines the fuzzy analytical hierarchy process (AHP) with the fuzzy ranking methods of TOPSIS, VIKOR and SAW was developed. Based on the fuzzy-weighted variables, the results of this study indicated that priority cannot be assigned based on the effect of one or two parameters, but rather a holistic consideration of the contributory weights of all morphometric variables is required so as to achieve some precision during the prioritization process. By considering all the contributing factors, fuzzy MCDM has, therefore, proved to be helpful in pinpointing the priority areas that are vulnerable to erosion. The results obtained by linking surface morphometry with erosion dynamics can provide useful information for basin management, with tailor made solutions for each sub-basin. An advantage of this study is that the three multi-criteria ranking techniques used largely agreed on the priority rankings, so the results obtained can be considered integrated and conclusive.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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