Erodibility prioritization and mapping of a Mid Himalayan watershed using Technique of order preference by similarity to ideal solution (TOPSIS)

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ABSTRACT

Soil erosion has a very intense impact on human activities through a decline in productivity of soils in the watershed of the Eastern Nayar watershed in Pauri district of Uttarakhand. Therefore, evaluation of these erodible areas is of utmost importance so that the preventive measures can be taken accordingly. It assessed the sub-basins in the basin using morphometric parameters and several multi-criteria decision-making models, such as Simple Additive Weighting (SAW) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), . Utilizing Advanced Space Thermal Emission Radiometer (ASTER) data and a 30 m Digital Elevation Model (DEM), morphometric parameters were extracted and analyzed. To test the MCDM methods, percent and intensity of change indices were adopted. The ranking results were such that sub-watershed 2 was ranked at top as the most susceptible to erosion for both TOPSIS and SAW models, where TOPSIS ranked into four-categories low, moderate, high, and very high, SAW model gave three categories as moderate, high and very high. In general, the morphometric parameters were effective for identifying erosion-prone areas. The TOPSIS approach was slightly better in terms of predictive accuracy than the other model.

Keywords: [Morphometry, GIS, prioritization, TOPSIS, }

1. INTRODUCTION

The hydrological response of a basin is significantly influenced by its morphological and climatic characteristics. Morphological attributes of a watershed are quantifiable features that play a crucial role in understanding its hydrological behavior. Therefore, linking these morphological parameters with hydrological characteristics can provide a valuable method to simulate the behavior of various basins, especially those that are not monitored.

Morphometric science involves the measurement, quantification, and mathematical analysis of the earth's surface, including its layout, shape, and landforms' dimensions. Analyzing the morphometry of a watershed offers a quantitative description of its drainage system, which is essential for watershed characterization. This analysis involves measuring linear features, area aspects, channel network gradients, and ground slopes contributing to the drainage basin. Remote sensing techniques, particularly satellite imagery, are convenient and effective methods for conducting morphometric analysis over large areas.

Various geomorphological parameters such as stream order, length, frequency, drainage density, texture ratio, farm factor, circulatory ratio, elongation ratio, bifurcation ratio, and compactness ratio are commonly used for sub-watershed prioritization within a watershed.

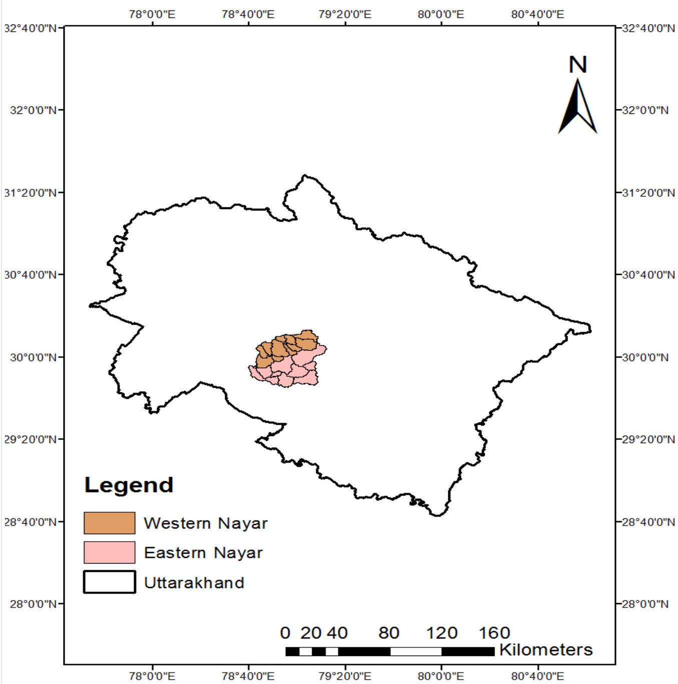
The prioritization of watersheds involves ranking sub-watersheds based on the level of conservation treatments they require. Once prioritized, assessing hydrological parameters like peak flow and runoff volume provides crucial information for implementing soil and water conservation measures. The physical characteristics of land use/land cover within the basin greatly influence these hydrological parameters, which are dynamic and subject to change.

Advancements in remote sensing technology have provided valuable tools for surveying, identifying, and classifying earth resources, aiding in watershed management decisions. GIS-based multi-criteria decision analysis (MCDA) combines geographical data and value judgments to assist decision-makers.. The present study utilizes GIS techniques and MCDM technique to identify critical sub-watersheds in the Western Nayar River watershed.

The study aims to prioritize sub-watersheds in the Western Nayar watershed within the fragile Mid-Himalayan ecosystem. It utilizes open-source GIS tools and remote sensing data to apply the TOPSIS approach.

2. MATERIAL AND METHODS

The analysis was conducted in the Nayar River, which is a non-glacial river located in the Uttarakhand state of India. Within this region, there are two main tributaries: Nayar East and Nayar West. The Western Nayar watershed is situated between 29°54'40"N - 30°12'80"N latitude and 78°43'40"E - 79°9'0"E longitude. The Nayar West tributary originates at an elevation of 2800 meters. The Western Nayar tributary is about 91 kilometers long.



For this study, Remote Sensing data such as Google Maps of the study area and Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) were utilized. Geospatial analysis was conducted using QGIS 2.16, an open-source software platform.

This research demonstrates the usefulness of the MCDM Technique approach for identifying sensitive zones in watersheds, which can guide land and water resource conservation practices for sustainable development.

2.1 Remote sensing and GIS techniques for watershed analysis:

Remote Sensing and Geographic Information System (GIS) are essential tools for watershed analysis. Remote sensing typically involves using satellite imagery and aerial photography. Satellite imagery, in particular, is highly advantageous for studying watershed behavior due to its multispectral capabilities and broad coverage. On the other hand, GIS focuses on analyzing different layers of data that contain spatial information linked to specific geographic locations. GIS allows for the integration of both machine-generated and user-generated spatial information, facilitating operations management, analysis, and decision-making processes. It encompasses all aspects of data acquisition and processing, making it a valuable tool for monitoring and assessing various phenomena.

GIS plays a crucial role in bringing together remotely sensed data and spatially referenced statistics, providing a comprehensive framework for analysis. Its ability to seamlessly merge data from diverse sources, including remotely sensed data, has significantly increased its use in applications such as mapping and change detection.

2.2 Delineation of watershed

The DEM from the Shuttle Radar Topography Mission (SRTM) is obtained through the Earth Explorer website (https://earthexplorer.usgs.gov/). This data will be utilized to create a drainage map using QGIS 2.6.0 software, utilizing the UTM projection. QGIS 2.6.0 provides spatial analysis tools that will be used to generate various thematic maps. For this study, the SRTM DEM will have resolutions ranging from 1 arc-second (30 meters) to as high as 30 arc-seconds (1 kilometer). Using QGIS 2.6.0 software, the study area will be delineated into sub-watersheds. This delineation process will enable a detailed analysis of the watershed structure and characteristics within the study area.

2.3 Drainage map:

The drainage networks for both the Western Nayar and Eastern Nayar watersheds are constructed using the Strahler approach. The Strahler method is chosen for its simplicity in stream ordering. The method follows these steps:

1. First-order streams originate directly from a source.
2. When two streams of order 'u' combine, they form a stream of order (u+1).
3. If two streams of different orders join, the stream of the higher order is maintained.

By employing the Strahler method, the drainage networks of the Western Nayar and Eastern Nayar watersheds are organized and classified according to stream order. This approach allows for a straightforward and systematic way to understand the flow patterns and hierarchy of streams within the watersheds.

table 1.**Morphometric Analysis:**

S. No.	**Morphometric parameter**	**Formula**	**Reference**
1	Stream order	Hierarchical rank	Strahler, (1964)
2	Stream length (Lu)	Length of the stream	Horton, (1945)
3	Mean stream Length (Lsm)	Lsm = Lu/Nu Where, Lu = total stream length of order 'u' Nu = total no. of stream segments of order 'u'	Strahler, (1964)
4	Stream frequency (Ns)	Ns = Nu / A where, Nu = total no. of streams of all orders A = area of basin (km^2)	Horton, (1932)
5	Bifurcation ratio (R_b)	R_b = Nu / Nu +1 Where, Nu = No. of stream segments of a given order Nu +1= No. of stream segments of next higher order.	Schumms, (1956)
6	Drainage density (D_d)	D_d = Lu /A where, Lu = total stream length of all orders A = area of basin (km^2)	Horton, (1932)
7	Drainage texture (T)	T= Nu / P where, Nu = total no. of streams of all orders P = perimeter (km)	Horton, (1945)
8	Length of overland flow (Lo)	Lo = 1/Dd*2 where, Dd = drainage density	Horton, (1945)
9	Elongation ratio (Re)	Re = 2 √(A / Pi)/ Lb where, A = area of basin (km^2) Lb = basin length Pi = Pi' value i.e. 3.14	Schumms, (1956)
10	Circulatory ratio (Rc)	Rc = $4*pi*A /P^2$ where, pi = pi' value i.e. 3.14 A = area of basin (km^2) P = perimeter (km)	Miller, (1953)
11	Form factor (R_f)	$R_f=A/Lb^2$ Where, A = area of basin (km^2) L_b^2 = square of basin length	Horton, (1932)
12	Compactness coefficient (Cc)	Cc= 0.2821 $P/A^{0.5}$ P = perimeter (km) A = area of basin (km^2)	Nooka Ratnam et al. (2005)

13	Shape Factor (Rs)	Rs= Lb^2/A Lb^2 = square of basin length A = area of basin (km^2)	Nooka Ratnam et al. (2005)

2.4 Watershed Prioritization:

Watershed prioritization, combined with morphometric parameters, has been a focus of research by various scholars in the field of watershed management. For the current study, the following morphometric parameters were selected: Mean Bifurcation Ratio, Drainage Density, Texture Ratio, Stream Frequency, Watershed Relief, Relief Ratio, Circulatory Ratio, Form Factor, Compactness Coefficient, Elongated Ratio, and Length of Overland Flow.

The choice of these parameters was based on recommendations from existing literature and previous research. Some parameters such as Mean Bifurcation Ratio, Drainage Density, Texture Ratio, Stream Frequency, Length of Overland Flow, and Relative Relief are positively correlated with erosion. This means that higher values of these parameters indicate higher erosion potential. Conversely, parameters like Circulatory Ratio, Elongated Ratio, Form Factor, and Compactness Coefficient are inversely proportional to erosion, as indicated by Nooka et al. (2005). Lower values of these parameters are associated with higher erosion potential.

This selection of morphometric parameters provides a comprehensive approach to assessing watershed characteristics related to erosion potential. By considering these parameters, the study aims to prioritize sub-watersheds within the Western Nayar watershed, taking into account their erosion susceptibility based on these established correlations.

2.5 Prioritization by TOPSIS Model

Morphometric analysis in drainage areas is helpful as sub-watersheds across various scales of priority (Biswas et al., 1999; Sureh et al., 2004. In this study, morphometric factors associated with the erosion hazard incorporated linear, shape and landscape properties of the watershed (Patel et al., 2013). The linear and landscape parameters are directly proportional to the erosion hazard whereas shape parameters have a negative correlation whereby lower values indicate higher vulnerability to erosion (Patel and Dholakia, 2010; Patel et al., 2012). For instance, higher ranked sub-watersheds presented higher values of drainage density whereas the low ranked possessed lower values of drainage density.

After calculating the linear, shape, and landscape morphometric parameters, as shown in Table 3, a decision matrix was structured in the first step of applying multi-criteria decision-making models. All the criteria used within the analysis, such as slope, drainage density, and stream frequency, had different units of measurement, which implies that normalization of data was needed to ensure comparability and applicability. The TOPSIS model was normalized using the vector approach assisted by the linear method of normalization.

TOPSIS, which stands for "Technique for Order of Preference by Similarity to Ideal Solution," is a multi-criteria decision-making (MCDM) method used for ranking a set of alternatives based on their proximity to the ideal solution. It was introduced by Hwang and Yoon in 1981 and is widely employed in decision analysis, operations research, and other fields. The TOPSIS method involves comparing alternatives to both the ideal and anti-ideal solutions to determine their relative closeness.

TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is a compensatory aggregation method used to compare a set of alternatives in multi-criteria decision-making. In TOPSIS, scores for each criterion are normalized, and the geometric distance between each alternative and the ideal alternative (the one with the best score in each criterion) is calculated. The method allows for trade-offs between criteria, accommodating situations where a poor result in one criterion can be compensated by a good result in another criterion.

3. RESULTS AND DISCUSSION

3.1Delineation of watersheds:

The Western Nayar watershed has been delineated utilizing QGIS 2.6.0 software. Specifically, the Western Nayar watershed has been partitioned into 11 distinct sub-watersheds, These delineations were made possible using digital elevation maps (DEMs) sourced from the Shuttle Radar Topography Mission (SRTM) with a resolution of 30 meters. The DEMs, depicted in [Fig. 1]for Western Nayar watersheds , provide detailed representations of the elevation and terrain characteristics of the regions. This information is instrumental in understanding the topographical layout and morphological features of the watersheds, supporting further analysis and the prioritization of sub-watersheds based on various parameters.

3.2 Drainage maps

Using QGIS 2.6.0 software, the drainage networks of the Western Nayar watershed have been established. Upon detailed examination of the drainage network map, it was observed that there are:

The Western Nayar watershed i classified as a 4th order watershed. Analysis of the drainage network map revealed the following:

i)163 first-order streams with a total length of 219.72 kilometers
ii)39 second-order streams covering 129.80 kilometers
iii)11 third-order streams with a combined length of 97.05 kilometers
iv) fourth-order stream with a length of 48.33 kilometers

These findings are summarized in Table. This detailed examination of the drainage network provides valuable insights into the stream order distribution and total stream lengths within each watershed.

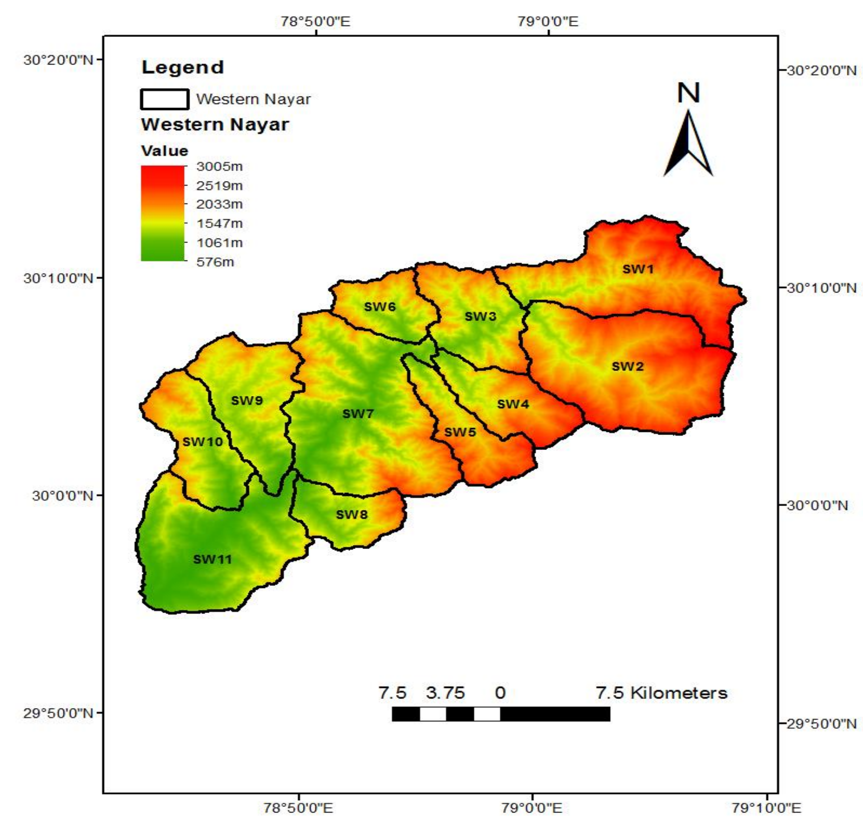


Fig 1:Digital Elevation Model (DEM) map of Western Nayar watersheds

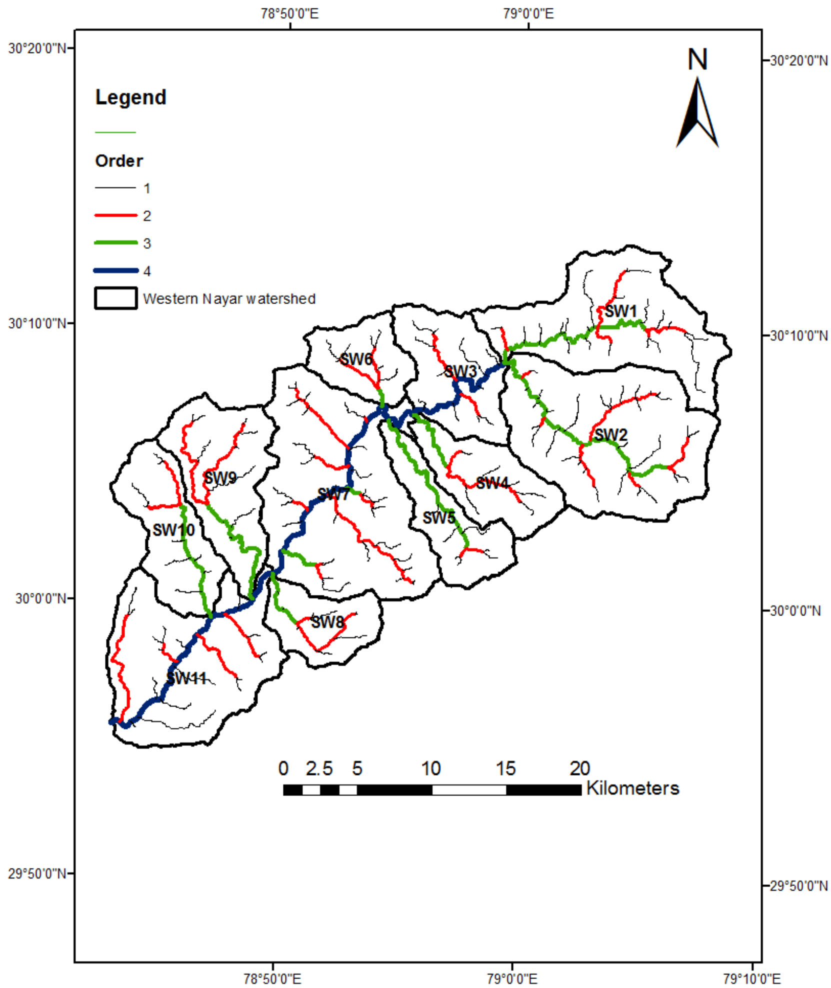


Fig 2.: Drainage network map of Western Nayar watershed

3.3 Prioritization by TOPSIS Model

In the TOPSIS model, the top three-ranked sub-watersheds have the highest scores, which are 0.740, 0.709, and 0.648, ranked 1 to 3, respectively. Thus, sub-watersheds ranked SW8, SW5, SW7 as described in fig 4.have been identified as being most susceptible to erosion. On the other end, the least sensitive to erosion are SW2,SW9,SW3 wih scores of 0.540,0.439 and 0.430 respectively. This area under study was then categorized into four classes: low (0–0.25), moderate (0.25–0.5), high (0.5–0.75), and very high (0.75–1).

Table 2:Sub Watershed wise analyzed morphometric parameters for Western Nayar watershed

	A	P	L_u	R_{bm}	D_d	N_f	R_c	R_f	C_c	R_e	R	L_o	T	R_h
SW1	93.55	68.9	20.88	4.62	0.65	0.28	0.25	0.21	2.01	0.52	1.75	0.77	0.30	84.13
SW2	118.6	68.2	19.68	5.64	0.60	0.32	0.41	0.31	1.56	0.62	1.68	0.82	0.50	85.71
SW3	50.15	42.7	9.50	4.62	0.75	0.52	0.34	0.56	1.70	0.84	1.31	0.66	0.49	137.89
SW4	42.37	41.5	12.97	2.50	0.64	0.54	0.31	0.25	1.80	0.57	1.58	0.77	0.14	122.48
SW5	37.88	46.45	13.23	2.75	0.62	0.26	0.22	0.22	2.13	0.53	1.58	0.80	0.15	121.53
SW6	30.74	32.03	6.44	2.75	0.57	0.33	0.38	0.74	1.63	0.97	1.17	0.87	0.22	182.81
SW7	134.62	79.99	18.34	3.87	0.77	0.30	0.26	0.40	1.94	0.71	1.70	0.64	0.38	92.89
SW8	31.63	32.75	10.60	2.75	0.65	0.32	0.37	0.28	1.64	0.60	1.69	0.77	0.21	169.00
SW9	60.94	51.59	17.45	3.25	0.68	0.2	0.29	0.20	1.86	0.50	0.78	0.73	0.17	44.59
SW10	48.51	44.38	12.42	3.25	0.56	0.25	0.31	0.31	1.80	0.63	1.24	0.89	0.20	103.33
SW11	100.61	8.144	16.54	4.00	0.64	0.21	0.27	0.37	1.92	0.68	1.34	0.78	0.23	81.21

Table 3: Weightage values for nine morphometric parameters

Morphometric parameters	**R**	**L_o**	**D_d**	**R_{bm}**	**N_f**	**T**	**R_e**	**R_c**	**R_f**
Weight (X_i)	0.24	0.18	0.19	0.13	0.08	0.05	0.05	0.05	0.03

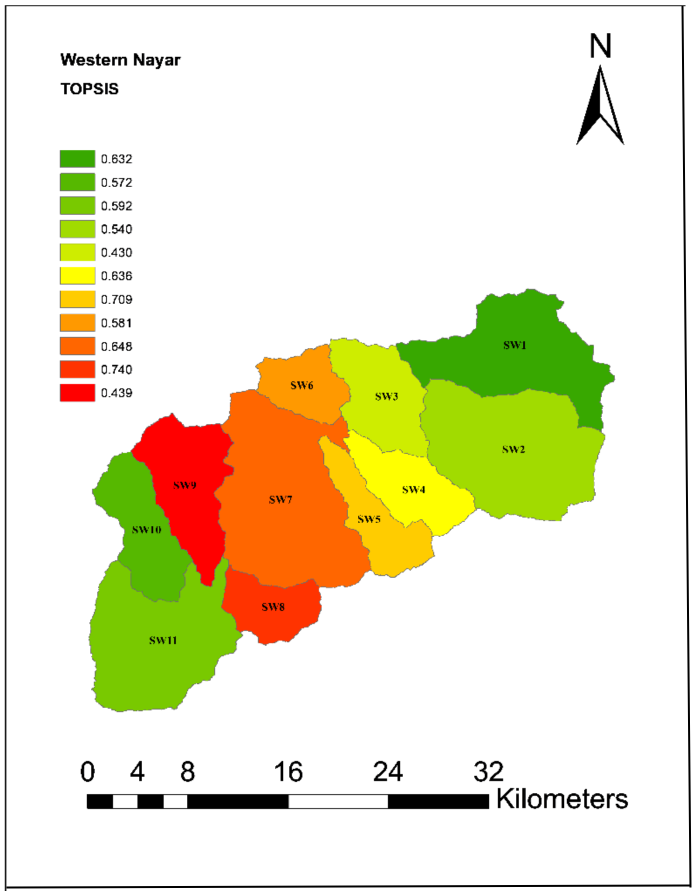


Fig 3.: Priority map of Western Nayar watershed based on TOPSIS

4. CONCLUSION

With the application of GIS techniques and ASTER DEM, this research demonstrated the current potential effectiveness of this tool in further geomorphometric analysis and identification of sub-watersheds for further morphometric characteristic extraction. The TOPSIS model provided four classes: very high, high, moderate, and low. TheHmalayan Basin is very highly prone to erosion, and hence, the necessity for proper conservation measures stands high in order to reduce soil erosion, decrease sedimentation in reservoirs, stabilize steep slopes so as not to cause landslides, and reduce the risk of flood hazards in the future. This study focuses on the applicability of GIS and remote sensing methods combined with MCDM, such as TOPSIS towards helping decision-makers and planners in soil and water resource management. Thus, the approach of prioritizing sub-watersheds itself is a viable method that may improve on watershed management and preservation of water resources.

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