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Research Article

Implementation of Morphometric Analysis in Prioritizing Sub-Watersheds: A Remote Sensing and GIS Aspect

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ABSTRACT

Sub-watershed prioritization has gained due importance in the recent time for management of natural resources at a watershed level especially in the perspective of planning and management of watersheds. Analysis of morphometric parameters (linear, areal, relief and shape aspects) is usually the core investigation outline for prioritization of sub-watersheds. The current study makes an effort to prioritize sub-watersheds of Kiknari nala watershed situated in Mandla district of Madhya Pradesh, India by executing morphometric analysis using the techniques of remote sensing and GIS. Different morphometric parameters such as bifurcation ratio (R_b), drainage density (D_d), stream frequency (F_s), texture ratio (R_t), relief ratio (R_h), form factor (F_f), circulatory ratio (R_c) and elongation ratio (R_e) for each sub-watershed was calculated using standard formulas and ranks were allocated so as to achieve values of compound parameter. In the present study, suitable soil and water conservation measures should be adopted primarily for SW – 2 having highest priority rank followed by SW – 1.

Keywords: *Morphometric analysis, sub-watershed prioritization, remote sensing, geographic information system, watershed.*

INTRODUCTION

Availability of utilizable natural resources (i.e. land and water) is declining progressively due to industrial expansion, growth of service sector and urbanization (Patil et al., 2016). Management and conservation of natural resources are critical and decisive to human well-being (Sharma et al., 2016). Their sensible utilization and supervision are supplementarily significant now than ever before to gratify the high demands of food production for the growing world (Sharma et al., 2010; Sharma & Seth, 2010).

In India, the available land resource is 326.06 million ha out of which 172 million ha of land is facing severe land degradation issues pivotally involving soil erosion with some extent of primary and secondary salinization (Sharma et al., 2008).

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Natural resources management at a watershed level plays a crucial role for overall development of the society (Patle et al. 2017; Patle, 2018; Patle & Awasthi 2019a, 2019b).

Watershed may be defined as a portion of earth surface with inclusion of topographically concentrating slopes in such a manner that they convert most part of precipitation into runoff incident on it so as to contribute runoff to a single outlet, positioned at a lower lying area (Sharma et al., 2012, Sharma et al., 2013). In the advancement of landforms, watershed holds a predominant role in geomorphic studies for land and water resources management (Rao, 2019; Rao et al., 2019)

A precise understanding of hydrological behavior of watershed is crucial for effective management necessitating thorough study of individual sub-watersheds for development of suitable management plan which needs enormous data (Tignath et al., 2014). Most of the watersheds in India are such that there is no proper facility of gauging site (Gajbhiye et al., 2015). The morphometric analysis of a watershed denotes its attributes and can be advantageous in synthesizing hydrological behavior (Meshram & Sharma, 2018). Development of management plan and its suitable implementation for large watersheds is challenging due to geo-environmental or cost-effective situations. (Bisen et al., 2019; Awasthi & Patle, 2019) Evaluation of morphometric parameters prerequisites in preparation of drainage map, ordering of numerous streams, measurement of basin area (A), basin perimeter (P), length of streams of different orders, highest and lowest elevations (H_{max}, H_{min}), watershed relief (H), bifurcation ratio (R_b), relief ratio (R_h), drainage density (D_d), stream frequency (F_s), texture ratio (R_t), form factor (F_f), circulatory ratio (R_c) and elongation ratio (R_e) which further aids in recognizing the nature of drainage basins (Sharma et al., 2010; Poongodi and Venkateswaran, 2018)

In the recent years, several studies has been executed for sub-watershed prioritization based on morphometric parameters (*i.e.*, linear, areal, relief and shape aspects) using remote sensing and GIS perspective such as Meshram and Sharma (2015), Sharma et al. (2015), Gaikwad and Bhagat (2018), Malik et al. (2019).

Meshram and Sharma (2015) applied remote sensing and GIS for successful execution of morphometric analysis by implementing Principal Component Analysis (PCA) and subsequent prioritization of the sub-watersheds of Shakkar river catchment, India. Balasubramanian et al. (2017) made analysis of morphometric characteristics of lower Bhavani basin, Tamil Nadu using mode of remote sensing and GIS, and prioritized the sub-watersheds based on relative values of compound parameter calculated for each sub-watershed. Poongodi and Venkateswaran (2018) prioritized micro-watersheds through morphometric analysis in the Vasishta Sub Basin of the Vellar river of Tamil Nadu in India. Arulbalaji and Padmalal (2020) performed morphometric analysis in order to prioritize sub-watersheds of Cauvery river basin of South India using simple compound parameter approach.

In the current study morphometric analysis and subsequent sub-watershed prioritization of Kiknari Nala watershed situated in Mandla district of Madhya Pradesh, India has been executed.

MATERIALS AND METHODS

A. Study area:-

The current investigation is carried out in Kiknari Nala watershed situated in Mandla district of Madhya Pradesh which is a tributary of Burhner river. The watershed is geographically located in between 80°50’42” E to & 80°56’57” E longitude and 22°33’59” N to 22°37’42”N latitude having an elevation ranging from 540 m to 910 m above mean sea level (MSL). The area of watershed is 38.61 km^2 having annual rainfall of ranging from 550 to 660 mm primarily intensive in midst of June to midst of September due to south-west monsoon. The watershed predominates in clay and loam soils. The location map of study area is depicted in Fig. 1.

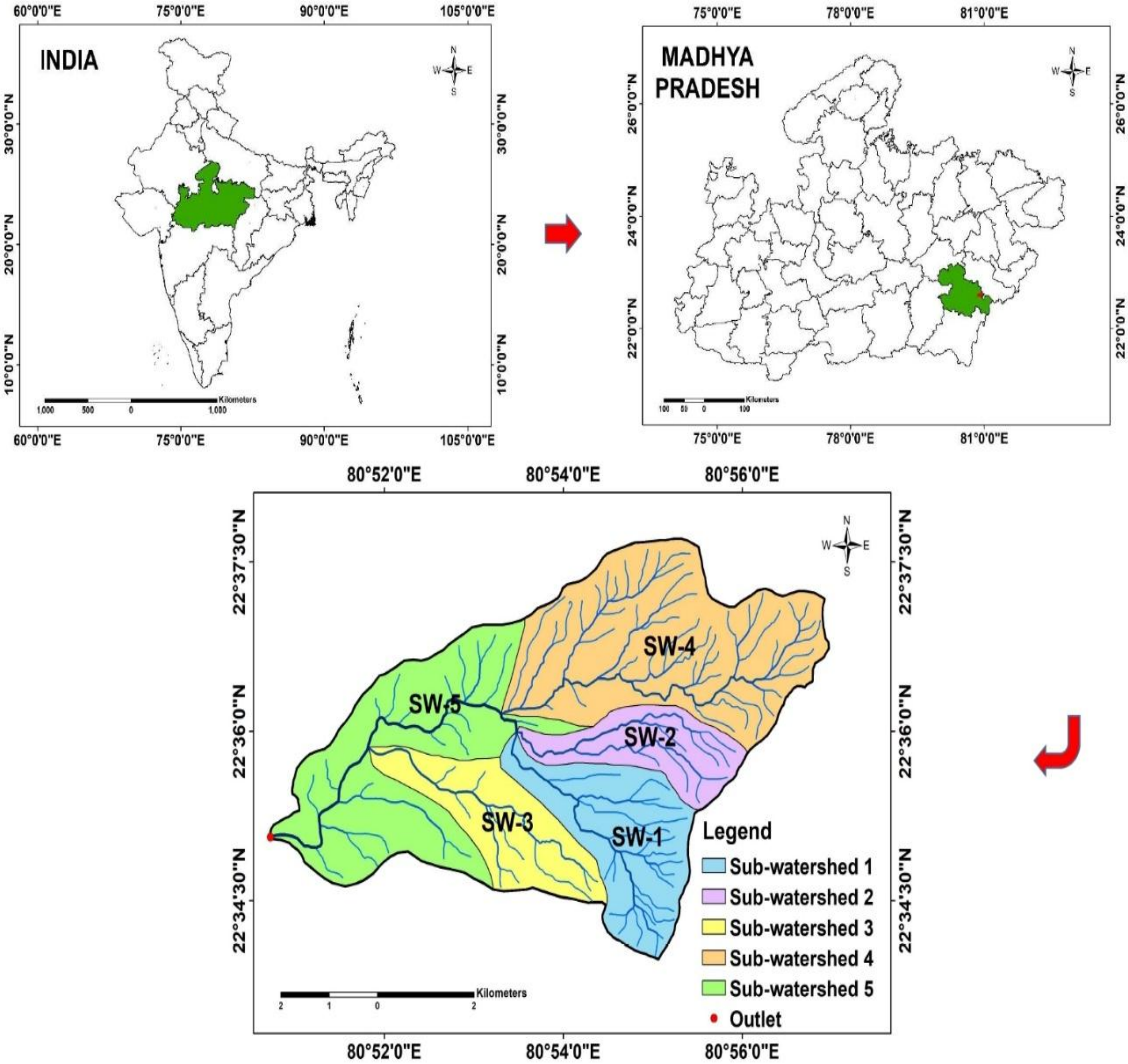

Fig. 1: Location map of study area

The base map of watershed was prepared using Survey of India (SOI) toposheet number F44/14 on 1:50000 scale. The toposheet was imported in ERDAS Imagine 10 software and consequently was georeferenced using WGS 1984 as geographic coordinate system. The further preparation of base map was executed in ArcGIS® 10.3 environment so as to acquire drainage and contour map of watershed. The sub-watersheds were delineated by taking third order streams as outlet of each sub-watershed while input parameters for morphometric analysis of each sub-watershed such as area, perimeter, stream length, highest and lowest elevations were obtained using calculate geometry option of ArcGIS®. Rather than the above discussed input parameters the secondary derived morphometric parameters were calculated in Microsoft® Excel® worksheet whose formulas are tabulated in Table 1. The False Color Composite (FCC) of Kiknari nala was prepared using AWiFS sensed satellite data of Resourcesat acquired on 17th December 2017. The Fig. 2, 3 and 4 illustrates the drainage map, contour map and FCC of Kiknari nala watershed with sub-watershed boundary.

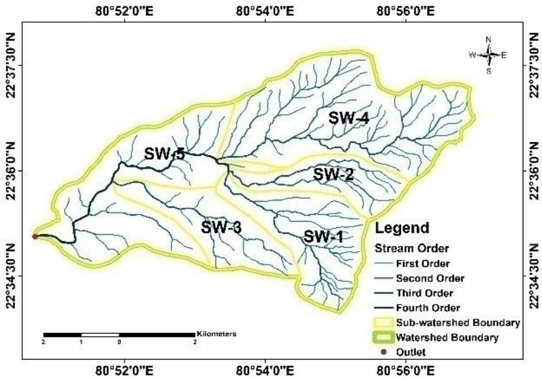

Fig. 2: Drainage map of Kiknari nala watershed with sub-watershed boundary

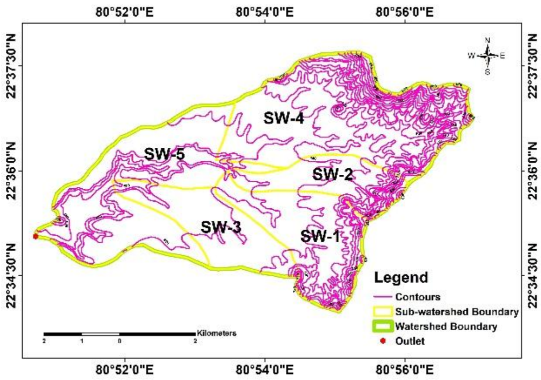

Fig. 3: Contour map of Kiknari nala watershed

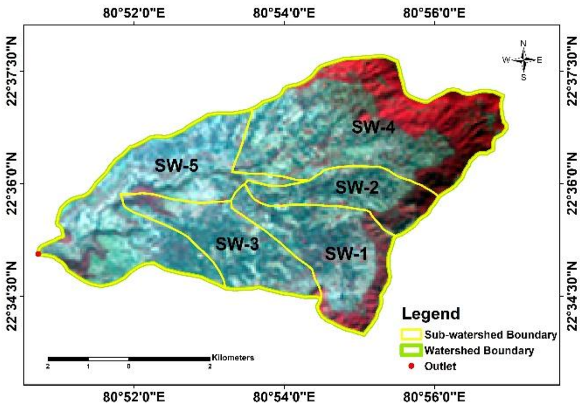

Fig. 4: FCC of Kiknari nala watershed

B. Morphometric analysis

A systematic narration of watershed geometry, stream, and its measurement to recognize the linear aspects of drainage network, areal aspects of watershed and relief aspects of stream network is referred to as morphometric analysis (Strahler, 1964). It is beneficial to implement quantitative analysis of shape parameters of a given basin as such parameters are in the form of dimensionless values which delivers an effective assessment irrespective of scale. The formulae adopted for calculation of different morphometric parameters is shown in Table 1.

a. Stream order (*u*)

Stream order is a type of classification that reflects a pattern of branches that unite to form the trunk stream leaving the catchment (Subramanya, 2013). It is a form of designation, allocated to the streams prevailing within the boundaries of the watershed and is a preliminary process in morphometric analysis. Horton (1945) and Strahler (1952) claimed a system, in which the network of streams is evidently demarcated on the topographic map of watershed along with identification of outlet. Strahler (1952) stream ordering system has been adopted in the study.

b. Stream number (N_u)

Stream number may be defined as number of stream segments of distinct order and is inversely proportional to stream order (*u*).

c. Stream length (L_u)

It denotes length of all the streams having stream order (*u*). It specifies the contributing area of the watershed of that order.

d. Basin perimeter (*P*)

It is the length of watershed boundary.

e. Basin length (L_b)

It is the distance between the outlet and most remote point of watershed.

f. Mean stream length ($\bar{L}_u$)

It is the ratio of length of stream of a specific order (L_u) to the total number of streams of that order (N_u).

g. Bifurcation ratio (R_b)

Bifurcation ratio may be defined as the ratio of number of streams of a given order (u) to the number of streams of higher order ($u+1$). The physical features of watershed that has underwent fewer structural disturbances and the arrangement of drainage network has not been deformed by structural differences is generally presented by lower values of R_b (Nag and Chakraborty, 2003). However, unusual higher values of R_b exist on steep sinking rocks. High values of R_b prevail for elongated watersheds while lower values of R_b exists for circular basins.

h. Drainage density (D_d)

Drainage density is one of the most important morphometric parameter indicating linear scale of landform in topographical areas that has been eroded by dominating streams. It is defined as the ratio of total length of streams of all orders ($\sum L_u$) to the area of watershed (A). D_d designates the closeness of streams, which delivers quantitative measure of mean length of stream channel for the whole basin. Furthermore, brief information about underlying rock can also be attained from D_d. Usually, areas with subsoil material which is permeable and highly resistant possess low D_d pertaining heavy vegetation and high relief whereas high D_d prevails in regions of weak, impermeable sub surface constituents which are sparsely vegetated with low reliefs. (Strahler, 1964).

i. Stream frequency (F_s)

Stream frequency also known as channel frequency or drainage frequency refers to the number of stream segments of all orders ($\sum N_u$) per unit of area of watershed (A). F_s predominantly rely upon lithology of the basin and reveal the texture of the drainage basin.

j. Texture ratio (R_t)

It is defined as the ratio of summation of stream segments of all orders ($\sum N_u$) to the perimeter of basin (P). It is sometimes also referred as drainage texture.

k. Relief (H)

Relief is the maximum vertical distance between the points of highest and lowest elevation in a watershed. For understanding the denudational characteristics of the basin, relief is a key factor (Sreedevi et al., 2009).

l. Relief ratio (R_h)

It is the ratio of total relief of watershed (H) and basin length (L_b). It implies the potential energy available to move water and sediments along the slope.

m. Form factor (F_f)

The ratio of area of basin (A) to the square of basin length (L_b) is referred to as Form factor.

n. Circulatory ratio (R_c)

It is a dimensionless morphometric parameter defined as the ratio of watershed area (A) to the area of circle having equal perimeter to that of basin (P). The basins which are circular in shape with low bifurcation ratio produces a sharp peak in their corresponding hydrograph.

o. Elongation ratio (R_e)

It is defined as the ratio of diameter of circle having same area to that of the watershed and basin length (L_b). The values of R_e varies from 0.6 to 1.0 for most of the climatic and geologic environments. Areas of low relief predominates in higher values of R_e which are close to 1 whereas values in the range of 0.6 to 0.8 relates to areas of high relief having steep slopes in land forms. Extended values in peak flows for the corresponding hydrographs is given by elongated basins with high values of bifurcation ratios.

C. Sub-watersheds prioritization

The considerations of resources for enactment of watershed development programs or various other reasons pertinent to administrative or political consideration limits the enactment to few sub-watersheds. Although, it is always better to start suitable control measures for the conservation and management of natural resources with available sub-watersheds having highest priority (Sharma et al., 2011). Sub-watershed prioritization is actually an approach of ranking of different sub-watersheds according to the order in which they have to be taken for treatment with appropriate soil conservation measures. Thus, it becomes essential to develop suitable approaches so as to prioritize sub-watersheds. Analysis of morphometric parameters is a significant approach for prioritization of micro-watersheds even without consideration of soil map (Biswas et al., 1999).

The morphometric parameters responsible for higher soil erosion *vulnerability are* D_d, F_f, R_c, R_e, R_b, R_h collectively known as erosion risk assessment parameters (Thakkar & Dhiman, 2007) which have been adopted in this study for sub-watershed prioritization. For prioritization of sub-watersheds, each watershed is allocated a rank based on their corresponding values of morphometric parameter. The averaging of rankings assigned for different morphometric parameters is termed as compound parameter. This compound parameter is the base criteria for final priority rankings of each sub-watersheds.

Table 1: Formulas adopted for calculation of linear, areal, relief and shape parameters

Morphometric parameters	Symbol	Formula/ Notations	Units	References
Linear parameters				
Basin Area	A	Area of watershed	(km^2)	
Basin perimeter	P	Perimeter of watershed	(km)	
Stream order	u	Hierarchical rank	-	Horton (1945) and Strahler (1952)
Stream length	L_u	Length of stream	(km)	Horton (1945)
Basin Length	L_b	Maximum length of watershed	(km)	
Mean stream length	$\bar{L}_u$	$\bar{L}_u = \frac{L_u}{N_u}$ where, $\bar{L}_u$= mean stream length (km) L_u= total length of stream of order *(u)* (km) N_u= total number of streams of order *(u)*	(km)	Strahler (1964)
Bifurcation ratio	R_b	where, N_u= total number of streams of order *(u + 1)*	(dimensionless)	Schumn (1956)
Areal parameters				
Drainage density	D_d	$D_d = \frac{\sum L_u}{A}$ where, $\sum L_u$= total length of streams of all orders (km)	(km/km^2) or (1/km)	Horton (1932)
Stream frequency	F_s	$F_s = \frac{\sum N_u}{A}$	(1/km^2)	Horton (1932)
Texture ratio	R_t	$R_t = \frac{\sum N_u}{P}$	(1/km)	Horton (1945)
Relief parameters				
Relief	H	$H = H_{max} - H_{min}$ where, H_{max} = maximum elevation of basin H_{min}= minimum elevation of basin	(m)	Hadley and Schumn (1961)
Relief ratio	R_h	$R_h = \frac{H}{L_b}$	(dimensionless)	Schumn (1963)
Shape parameters				
Form factor	F_f	$F_f = \frac{A}{L_b^2}$ (where $F_f < 1$)	(dimensionless)	Horton (1932)
Circulatory ratio	R_c	$R_c = \frac{12.57A}{P^2}$ (where $R_c \leq 1$)	(dimensionless)	Miller (1953)
Elongation ratio	R_e	$R_e = \frac{2}{L_b}\sqrt{\frac{A}{\pi}}$ (where $R_e \leq 1$)	(dimensionless)	Schumn (1956)

RESULTS AND DISCUSSION

Analysis of morphometric parameters of each sub-watershed of Kiknari Nala watershed was executed using GIS environment which are presented in tabular format in Table 2 and 3. The subsequent allocation of ranks to geomorphometric parameter is tabulated in Table 4.

The length of basin (L_b) for each sub-watershed was computed using the measure tool in ArcGIS® environment. Sub-watershed 5 has the maximum L_b *i.e.*7.03 km whereas sub-watershed 2 possess least L_b *i.e.* 4.45 km amongst all the five sub-watersheds.

Tectonic and watershed characteristics are generally revealed by R_b which was calculated for each sub-watershed that ranged from 3 to 7. Sub-watersheds with higher values of R_b specify mature topography of watershed with high runoff potential and less infiltration. Such characteristics are generally obtained in regions of steep sloping rock strata which predominate in narrow valleys surrounded by ridges. Low values of R_b lies in the regions with less structural control. The variations in numeric values of R_b among sub-watersheds are recognized to the differences in numerous phases of geomorphic development and topographic fluctuations.

The areal aspects of morphometric analysis comprised of D_d, F_s and R_t. D_d and F_s depicted a close correlation coefficient (0.931) for all the sub-watersheds designating an increase in F_s with respect to increase in D_d. Sub-watersheds with higher values of F_s produces more runoff as compared to the other sub-watersheds which is SW-1 followed by SW-4 in the current case. It has been minutely investigated over an extensive range of geologic and climatic considerations that low values of D_d is more probable to arise in regions with sub soil material of high permeability. These areas are predominant in dense vegetation cover with lower value of watershed relief. On the contrary, sub-watersheds with high D_d is expected in areas of weak or impermeable subsurface material having sparse vegetal cover and hilly relief. In the present analysis, SW- 3 possessed lower values of D_d specifying sub-soil material of high resistance and impermeability with thick vegetal cover and high watershed relief whereas high values of D_d in SW- 1 reflected streams of well-developed network, which is helpful in quick disposal of runoff resulting from intense flood conditions that can be characterized by a region of weak sub surface materials having a combination of sparse vegetation and high relief. R_t calculated for each sub-watershed varied from 1.033 km^{-1}for SW - 3 to 3.243km^{-1} for SW - 4.The values for R_h varied from 0.011 for SW - 5 to 0.072 for SW - 2 indicating that SW - 2 is severe from erosion point of view and should be provided with appropriate soil and water conservation structures.

In general, stream flow hydrographs and peak flows of a particular watershed is affected by shape of the watershed. The significant factors that are prominently responsible for defining the shape of the basin *i.e.* F_f, R_c and R_e were calculated for each sub-watershed of Kiknari nala. The values of F_f of 5 sub-watersheds of Kiknari nala is tabulated in table 3 that ranged from 0.178 to 0.245. The basins which are perfectly circular in shape should have the value of F_f equal to 0.7854 whereas basins with smaller values of F_f are elongated in shape. Higher values of F_f generate peak flows with shorter duration whereas lower values of F_f produces lower values of peak flows with longer duration. The values of F_f varied from 0.178 to 0.315 that showed that all sub-watersheds are elongated in shape generating flatter peak flows for longer duration of time. The factors prominently responsible for creating variations in the values of R_c are length of streams with its corresponding frequencies, geological structures, land use/land cover, climate, relief, and slope of the basin. R_c ranged from 0.250 to 0.574 specifying that inherent drainage system is structurally controlled. The value of R_e varied in between 0.476 and 0.633 reflecting the shape of watersheds to be elongated in shape with steep slopes and high reliefs.

Final priority ranks were allocated to each sub-watershed by initially assigning ranking to each sub-watershed for different linear, areal, relief and shape aspects of morphometric parameters. The allocation of initial priority rankings were strictly based on the relative relationship of different aspects of morphometric parameters with extent of susceptibility to erosion. Since, linear, areal and relief parameters are in direct relationship with soil erodibility (Biswas et al., 1999; Nooka Ratnam et al., 2005; Thakkar and Dhiman 2007; Sharma et al., 2010; Malik et al., 2019) designating larger values of these parameters having high extent of susceptibility to soil erosion with assigning higher ranks and subsequent gradual decrease in ranking with decreasing values of parameters. On the contrary, there exists an inverse relationship to soil erodibility for shape parameters in which the parameters with lower values are assigned higher ranks that gradually decreases for higher values of shape parameters. Thus final priority rankings were obtained by attaining average of allocated ranking to each aspect of morphometric parameter in which lowest value of compound parameter (2.50) was allotted highest rank (*i.e* 1) and highest value of compound parameter was allocated last rank (*i.e.* 5). Sub-watershed with highest priority rankings indicates greater degree of erosion and it becomes mandatorily important to implement appropriate soil and water conservation measures in the sub-watershed. The present study suggests, suitable soil and water conservation measures should be adopted principally for SW - 2 having highest priority rank followed by SW - 1. The final priority rank map of 5 sub-watersheds of Kiknari Nala watershed is shown in Fig. 5.

Table 2: Numeric details of linear parameters of 5 sub-watersheds of Kiknari Nala watershed

Name of Sub-watershed (SW)	Linear parameters									
	A	P	Stream order (u)				N_u	L_u	$\overline{L_u}$	L_b
	(km^2)	(km)	1	2	3	4		(km)		
SW-1	6.24	12.05	21	5	1	-	27	22.518	1.898	4.85
SW-2	3.70	10.21	9	3	1	-	13	13.326	1.656	4.45
SW-3	4.89	11.62	9	2	1	-	12	12.155	1.729	5.24
SW-4	13.13	16.96	45	9	1	-	55	46.099	2.696	6.46
SW-5	10.66	23.16	20	3	1	1	25	27.393	3.284	7.03

Table 3: Linear, areal, relief and shape parameters of 5 sub-watersheds of Kiknari Nala watershed

Name of Sub-watershed (SW)	Numeric values of morphometric parameters of each sub-watershed							
	Linear	Areal			Relief	Shape		
	R_b	D_d	F_s	R_t	R_h	F_f	R_c	R_e
	(dl)	(km/km^2) or (1/km)	(1/km^2)	(1/km)	(dl)	(dl)	(dl)	(dl)
SW-1	4.60	3.609	4.327	2.241	0.049	0.265	0.541	0.581
SW-2	3.00	3.604	3.515	1.273	0.072	0.187	0.446	0.488
SW-3	3.25	2.484	2.452	1.033	0.041	0.178	0.456	0.476
SW-4	7.00	3.512	4.190	3.243	0.052	0.315	0.574	0.633
SW-5	3.56	2.571	2.346	1.079	0.011	0.216	0.250	0.524

(dl) denotes dimensionless parameters

Table 4: Calculation of compound parameter values and allocation of final priority ranking of 5 sub-watersheds of Kiknari Nala watershed

Name of watershed	R_b	D_d	R_t	F_s	F_f	R_e	R_c	R_h	*CP*	Final Priority ranking
SW-1	2	1	2	1	4	4	4	3	**2.625**	**2**
SW-2	5	2	3	3	2	2	2	1	**2.500**	**1**
SW-3	4	5	5	4	1	1	3	4	**3.375**	**4**
SW-4	1	3	1	2	5	5	5	2	**3.000**	**3**
SW-5	3	4	4	5	3	3	1	5	**3.500**	**5**

CP – Compound parameter

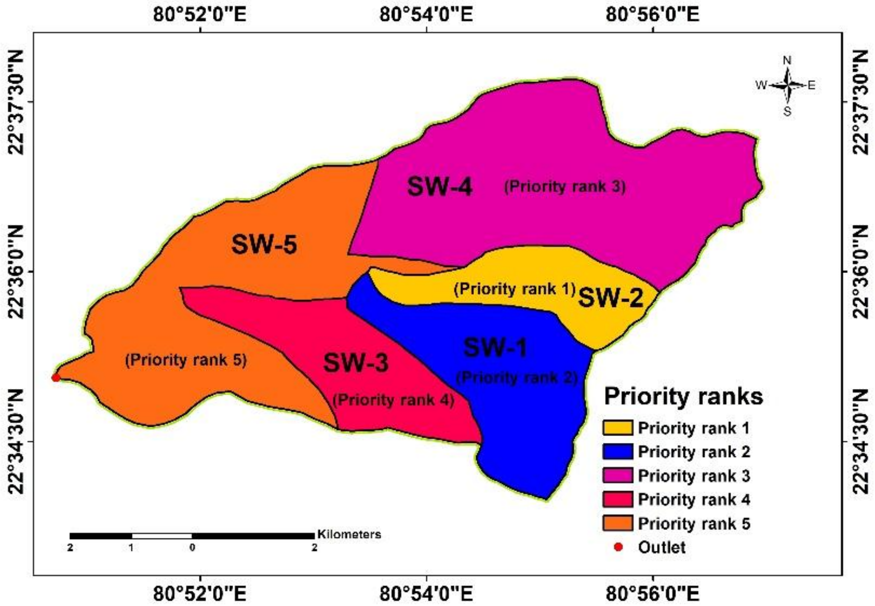

Fig. 5: Final priority rank map of 5 sub-watersheds of Kiknari Nala watershed

CONCLUSION

A quantitative analysis of sub-watersheds prioritization using morphometric parameters was executed in each sub-watersheds of Kiknari nala watershed by means of remote sensing and GIS. In the investigation linear, areal, relief and shape parameters of each sub-watershed of Kiknari nala watershed was assessed. The integration of remote sensing and GIS with morphometric analysis proved to be advantageous as the manual methods of analysis were extensively time consuming, tedious, cumbersome which ultimately created boredom in the investigation and was susceptible to human error. Prioritization of sub-watersheds with the assistance of morphometric parameters aids in exploring the relative characteristics with regard to hydrologic response of watershed. In the present study, thorough analysis of morphometric parameters depicted that sub-watershed - 2 of Kiknari nala watershed were most vulnerable to soil erosion and soil loss. Hence, appropriate control measures for mitigation of soil loss and erosion should be implemented in sub-watershed - 2 followed by relative sequence of sub-watersheds 1, 4, 3 and 5.

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