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Sub-Watershed Prioritization Using Compound Factor and Gis Analysis in A Semi-Arid Agricultural Watershed of Madhya Pradesh

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Abstract-- A comprehensive morphometric analysis and prioritization of the Khair watershed, located in the semi-arid region of Madhya Pradesh, was carried out using spatial information technology. The watershed was divided into ten sub-watersheds to analyze various morphometric parameters, which were subsequently incorporated into compound factor analysis to assess erosion susceptibility. The results indicate that the four sub-watersheds SW-1 to SW-4 fall under the high-priority category and require immediate conservation measures, whereas the remaining sub-watersheds are classified under moderate to low priority. The study highlights that the integration of remote sensing, GIS, and statistical techniques provides a reliable and efficient framework for watershed prioritization, offering significant insights for sustainable land and water resource management in semi-arid regions prone to soil erosion and land degradation.

Index Terms -- Morphometry, Prioritization, Khair watershed, Remote Sensing & GIS

I. INTRODUCTION

Watersheds serve as fundamental units for natural resource planning and management, as they represent natural hydrological systems in which water drains through a network of streams or water bodies, playing a crucial role in various developmental and ecological processes. Agriculture accounts for more than 70% of global freshwater withdrawals, followed by industrial and domestic uses, making these sectors the primary drivers of increasing water demand [10]. The accelerating pace of urbanization and industrialization, combined with rapid population growth, has intensified pressure on land and water resources, particularly in the arid and semi-arid regions of India. The watershed-based approach provides a practical and scientific framework for resource conservation, as it enables the division of larger basins into smaller sub-watersheds for effective prioritization and management, typically ranging from less than 5 sq. km to about 500 sq. km in area [5]. Geospatial technologies such as Remote Sensing, Geographic Information Systems (GIS), and Digital Elevation Models (DEM) have proven invaluable for planners and decision-makers, as these tools facilitate automated drainage extraction and watershed delineation even in remote and inaccessible terrains [9, 2]. A crucial aspect of watershed management is watershed prioritization, which involves ranking sub-watersheds within a larger basin based on their suitability for soil and water conservation measures.

The present study focuses on the Khair Watershed, located in the semi-arid region of Madhya Pradesh, India, where irregular and insufficient rainfall adversely affects agriculture and local livelihoods. The Khair watershed lies between 25°13′–25°40′ N latitudes and 77°53′–77°76′ E longitudes, covering an area of about 230 sq. km (Fig. 1). Physiographically, the region forms part of the Upper Vindhyan system, comprising the Rewa and Kaimur Groups. The watershed exhibits a dendritic drainage pattern, which is characteristic of homogeneous lithology and gentle relief. The area is mainly covered by lateritic, alluvial, and black soils. The topography is predominantly gentle, with elevations ranging from 388 m to 487 m above mean sea level. The average annual rainfall is approximately 959 mm, with most of the precipitation occurring during the southwest monsoon season.

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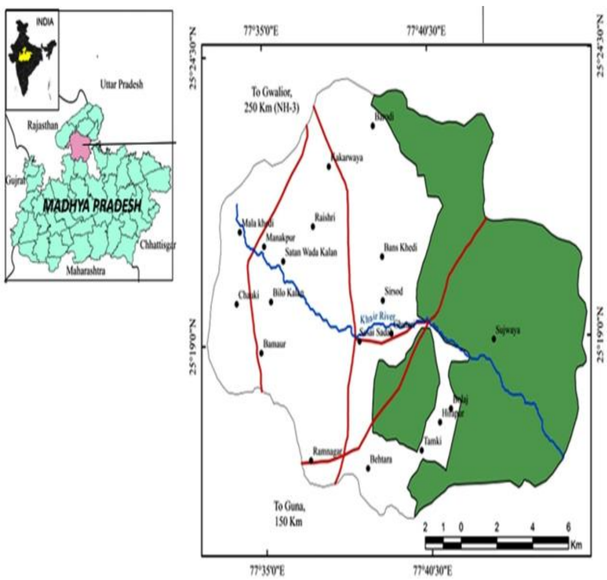

Figure 1 Location map of the watershed

II. MATERIALS AND METHODS

Landsat OLI (2022) imagery and the SRTM Digital Elevation Model (SRTM DEM) with a spatial resolution of 90 m were used to delineate the sub-watersheds and drainage network in the ArcGIS environment. The Khair watershed was subdivided into ten sub-watersheds for detailed analysis. Stream ordering was carried out using the Arthur Newell Strahler [7] stream ordering technique (Table 1). Standard methods and formulae were used to analyze various morphometric parameters covering linear, areal, and relief aspects of the watershed. Prioritization of the sub-watersheds, a crucial step in effective watershed management, was performed using the compound factor (Cf) method [8]. For sub-watershed prioritization, each parameter was assigned a rank based on its relationship with erosion susceptibility, where higher erosion potential corresponded to lower ranks, indicating higher priority (Table 2).

The computation was performed using the following equation.

$$\mathrm{Cf} = \frac{1}{n}\sum_{i=1}^{n} R$$

where *Cf* represents the compound factor, R ($R_1, R_2, \ldots, R_n$) are the ranks assigned to the individual morphometric parameters, and *n* is the total number of parameters. Further, all sub-watersheds were grouped into three priority categories based on the ranges of compound factor (Cf) values: high priority (< 4), medium priority (4–5), and low priority (> 5).

III. RESULTS AND DISCUSSION

Stream ordering is the first step in the analysis of a drainage basin. In the present study, Strahler's stream ordering technique was adopted due to its simplicity and wide applicability. The Khair Watershed is classified as a fifth-order basin. Among the sub-watersheds, SW-1, SW-3, SW-5, SW-8, and SW-9 are third-order basins; SW-2, SW-4, and SW-6 are fourth-order; while SW-7 and SW-10 are fifth-order basins). The watershed predominantly exhibits dendritic and sub-dendritic drainage patterns, indicating relatively homogeneous bedrock and limited structural control. Stream number refers to the total number of stream segments present in each stream order and is inversely proportional to stream order. A total of 405 stream channels were identified with a maximum of 1st order streams comprising 317 first-order. The number of streams in the other sub-watersheds is as follows: SW-1 (38), SW-2 (35), SW-4 (40), SW-5 (30), SW-6 (39), SW-7 (69), SW-8 (24), and SW-9 (29). The total stream length of the watershed is 361.9 km. Among the sub-watersheds, SW-3 has the minimum total stream length (14.48 km), while SW-10 has the maximum (71.7 km). The ratio between stream length and stream order remains relatively constant throughout successive orders of the basin which suggests that the watershed is underlain by homogeneous rock material and that geometric similarity is preserved across increasing stream orders. Higher Rb values indicate greater structural complexity and lower permeability of the subsurface strata. The Rb values ranging from 3.03 (SW-7) to 6.06 (SW-1) among the sub-watersheds suggesting moderate structural control. Drainage density is defined as the ratio of the total length of all stream segments of various orders to the total area of the drainage basin. It reflects the degree of channel spacing and serves as a numerical indicator of landform dissection and runoff potential.

The drainage density (Dd) of the watershed is 1.61 km/sq. km indicating moderate drainage texture. Most sub-watersheds exhibit moderate Dd values, which are associated with moderate vegetative cover and thin soil layers. The stream frequency (Fs) for the watershed is 1.80, with values ranging from 1.46 (SW-8) to 1.99 (SW-2) across the sub-watersheds. Higher Fs values are suggesting areas of steeper slopes and higher runoff potential. Sub-watersheds exhibiting higher texture ratio (T) values indicate areas characterized by hard subsurface materials, thin soil layers, and higher relief, whereas lower values correspond to regions with better vegetative cover and greater infiltration capacity. The circularity ratio (Rc) was introduced by Miller [4] as the ratio of the area of the basin to the area of a circle having the same circumference as the basin's perimeter. Sub-watersheds SW-3, SW-4, SW-7, and SW-10 have Rc values below 0.5, denoting elongated shapes, whereas the remaining sub-watersheds with Rc values above 0.5 are more circular in nature. Values of elongation ratio (Re) close to 1 indicate low-relief areas, while values deviating from 1 reflect steeper slopes and higher relief. The elongation ratio is found to be 0.67 in the study area. Majority of sub-watersheds fall within the 0.5–0.75 range, suggesting that the region has moderate relief and is moderately tectonically active. All sub-watersheds have form factor ratio (Rf) values below 0.5, the overall watershed is elongated in shape, which implies moderate runoff intensity and longer flood durations.

The overall basin shows the basin shape (Bs) value of 2.91, further confirming its elongated form. The length of overland flow (Lg) is defined as half of the reciprocal of drainage density and represents the distance water travels over the land surface before being concentrated into a defined stream channel [3]. Lg is 0.8, with sub-watershed values ranging from 0.71 to 0.89. Among sub-watersheds, SW-3 (1.68) has the highest compactness coefficient, while SW-1 (1.22) has the lowest. Since all sub-watersheds have compactness coefficient (Cc) values greater than 1.0, the drainage basins are generally elongated relative to circle, which suggests moderate peak flow response. Higher If values indicate lower infiltration capacity and consequently higher surface runoff. The relief ratio (Rh) is a dimensionless parameter defined as the ratio of the total relief of a basin—the difference in elevation between the highest and lowest points—to the longest dimension of the basin parallel to the principal drainage line [6]. Rh is 0.159. SW-10 (0.148) and SW-9 (0.13) exhibit the highest relief ratios, representing steeper areas. The ruggedness number (Rn) is 0.004, with the sub-watersheds having low values, indicating lower relief areas.

Table 1 Morphometric aspects of the drainage network in the study area

Watershed	u	Nu	Lu (km)	Log Nu	Log Lu	Rb (Mean)
Khair Watershed	1	317	187.58	2.501	2.273	4.61
	2	68	87.47	1.833	1.942	
	3	16	58.76	1.204	1.769	
	4	3	14.32	0.477	1.156	
	5	1	13.8	0.000	1.140	

Table 2 Compound factor results of the Khair sub-watersheds

Sub- watershed	Ranking of Morphometric Parameters													Compound Value
	Rb	*Dd*	*Fs*	*T*	*Lg*	*If*	*Re*	*Rf*	*Rc*	*Bs*	*Cc*	*Rn*	*Rr*	
SW1	1	2	4	3	2	2	8	8	10	3	1	8	9	4.69
SW2	9	4	1	5	4	3	6	6	5	5	6	7	10	5.46
SW3	4	5	2	10	5	4	1	1	1	10	10	5	8	5.08
SW4	8	3	9	8	3	8	3	3	4	8	7	9	5	6.00
SW5	3	6	7	7	6	6	5	5	6	6	5	3	6	5.46
SW6	7	8	5	4	8	7	9	9	7	2	4	4	7	6.23
SW7	10	1	6	2	1	1	4	4	2	7	9	10	4	4.69
SW8	5	10	10	9	10	10	10	10	8	1	3	2	3	7.00
SW9	2	9	8	6	9	9	7	7	9	4	2	1	2	5.77
SW10	6	7	3	1	7	5	2	2	3	9	8	6	1	4.62

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IV. PRIORITIZATION OF SUB-WATERSHEDS

Ranking of the morphometric parameters in the watershed analysis was performed based on their functional relationship with soil erodibility. The parameters considered include bifurcation ratio (Rb), drainage density (Dd), stream frequency (Fs), length of overland flow (Lo), texture ratio (T), infiltration factor (If), circularity ratio (Rc), elongation ratio (Re), form factor (Rf), shape factor (Bs), compactness coefficient (Cc), ruggedness number (Rn), and relief ratio (Rh) in the analysis. Soil erodibility is known to be directly associated with linear parameters such as Rb, Dd, Fs, Dt, Lo, and If, as well as relief parameters (Rn, Rh), because higher values of these indices reflect steeper slopes, more dissected terrain, and consequently higher erosion susceptibility. Conversely, erodibility is inversely related to aerial parameters (Re, Rf, Rc, Bs, Cc), where higher values typically indicate more stable, compact, and less erosion-prone basin geometries. Based on these relationships, higher ranks were assigned to sub-watersheds showing greater values of linear and relief parameters, and lower values of aerial parameters, since such characteristics infer greater soil erosion potential. In this ranking scheme, higher rank values indicate sub-watersheds with lower erosion risk, whereas lower ranks signify greater susceptibility to erosion [1].

After assigning ranks to each individual parameter, the total rank score for each sub-watershed was averaged by dividing it by the number of parameters to obtain the compound factor (Cf), representing the overall erosion susceptibility (Table 2). Based on the compound factor values ranging from 3.46 to 6.12, the ten sub-watersheds were classified into three priority categories: high (less than 4.35), moderate (4.35-5.25), and low (more than 5.25). Among them, SW- 1, 2, 3, 4 and 7 emerged as high-priority sub-watersheds, indicating greater susceptibility to degradation and a need for immediate conservation measures. Sub-watersheds SW-5, SW-8, SW-9, and SW-10 were categorized as moderate priority, while SW-6 was identified as low-priority areas (Fig. 2).

V. CONCLUSION

In this study, the compound factor approach was employed for sub-watershed prioritization. The analysis revealed a distinct spatial variation in the vulnerability of sub-watersheds within the basin. Sub-watersheds SW-1, SW-2, SW-3, SW-4, and SW-7 were identified as high-priority zones, indicating a greater susceptibility to soil erosion, rapid surface runoff, and reduced water retention capacity. These areas therefore require immediate intervention through appropriate soil conservation measures, construction of groundwater recharge structures, and the adoption of sustainable land management practices. The high-priority sub-watersheds exhibit comparatively deeper groundwater levels, highlighting their vulnerability to hydrological stress and reinforcing the effectiveness of the compound factor approach in identifying critical areas for watershed management.

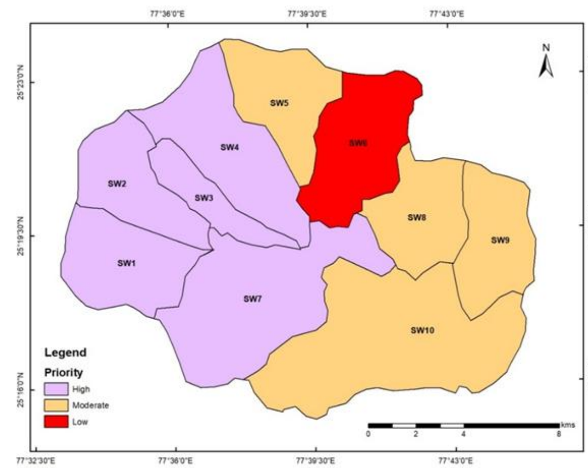

Figure 2 Prioritization of sub-watersheds in the study area

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