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An integrated analysis of morphometric characteristics and the prioritization of sub-watersheds of Kaljani River Basin in Sub-Himalayan North Bengal, India

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Abstract

This research uses geographic information system tools and techniques to statistically analyse the morphometric characteristics of the Kaljani River basin, an important sub-watershed in the North Bengal plain. In this study, the Fuzzy AHP is used to determine which sub-watersheds are most likely to experience erosion and rank them accordingly. For morphometric characterization, ten sub-watersheds were demarcated and their linear, areal, and relief characteristics calculated using SRTM-DEM data. The sub-watershed has been divided into five vulnerable zones based on the findings. In the Kaljani River basin, circular watersheds are quite effective in retaining precipitation. In addition, the soil in the watershed cannot hold water because of the surface roughness and predominance of sandstone foundation rock, permitting surface water to enter the drainage system. The fact that Sub-Watershed 1 was ranked first as a potential priority suggests that it is delicate, even if soil erodibility is utilised to plan and monitor development progress. Sub-watersheds 3, 6, and 10 displayed limited capacity to retain precipitation, quickly releasing large amounts of storm runoff. The downstream areas are most affected by this.

Keywords: *Basin morphometry, watershed, Fuzzy-AHP, Himalayan foreland, Kaljani River*

Introduction

Morphometric analysis of a drainage basin is essential for understanding topography, landform characteristics, and drainage networks. Generally, a drainage basin is a complex form of geomorphic and hydrological systems, contributing to landform evolution and shaping hydrological processes (Gajbhiye *et al.*, 2014). By examining drainage patterns, it is possible to infer regional geological history, landform processes, and basin geometry, all of which are crucial for basin management, including groundwater and surface water assessment, environmental planning, and evaluating land suitability. However, effective watershed management depends heavily on hydro-morphological understanding, underscoring the need for detailed micro-level analyses to support river hydrology and resource utilization efforts.

A key issue in morphometric studies is the inherent variability of drainage basin characteristics due to natural and anthropogenic influences, which can complicate measurements and limit the predictability of geomorphic behaviours (Hembram and Saha, 2020). Another challenge is the influence of spatial scale on morphometric parameters. For instance, smaller watersheds exhibit different morphometric relationships compared to larger basins, leading to potential discrepancies in regional analyses and management recommendations. Additionally, the morphometric approach often relies on geometric simplifications, potentially reducing accuracy in complex terrain, especially in mountainous regions like the Himalayan foothills, where variations in slope and relief are significant (Chakraborty *et al.*, 2023).

Abdo *et al.* (2023) completed an innovative work on sub-basin prioritization based on morphometric investigation using GIS platforms for the Baroda River from a conservation strategy point of view and classifying the sub-basins through this perspective. Contextually, Ghasemlounia & Utlu (2023) prioritized the sub-basins based on geo-morphometric properties relevant to flood analysis using the Principal Component Analysis (PCA) technique to explore flood control schemes. The comparative study of Redvan's Priority Ranking Method (RPRM), PCA and morphometric analysis (MA) method was used by them, which was not affordable in our study to reduce the methodological burden. Relying on the Analytical Hierarchy Process (AHP) technique was innovative, but in our case, we took the fuzzy logic method due to comparatively low topographic variability but dominance of the extensive flood plain catchment of Kaljani River. Reflection of technological advancement and steady endeavor is found in the works of Sarkar *et al.* (2022. Prioritizing Sub-basins using a multi-criteria decision-making (MCDM) approach on the basis of morphometric characteristics of a watershed was considered important in the context of soil erosion and stream displacements, taking the case of the Pinder River watershed of Uttarakhand. In order to suggest a suitable management plan, multiple techniques and the use of DEM data were one of the inspirations we took from their study for our case. Contextually, the study of Sharma & Mahajan (2020) is also noteworthy for considering Cartosat data for morphometric analysis while carrying out sub-watershed prioritization and finding the connection of Geomorphological evolution with morphometric exposure and the study of morphometric landscape. Sutradhar & Mondal (2023) worked on morphometric assessment for watershed prioritization towards flood management, taking some selected morphometric criteria for a rain-fed flashy channel like Ajay, displaying a similar nature of flood proneness like Kaljani. The work on hydromorphic characterization, along with sub-watershed prioritization done by Ghosh & Gope (2021) was directly linked to formulate concepts and ideas behind the methodological approach using Fuzzy Analytical Hierarchical Process (FAHP) for Upper Rihand watershed in Chhattisgarh. The study of Patel *et al.* (2022) on AHP and TOPSIS-based sub-watershed prioritization connecting tectonic analysis of a mountainous basin along with different geomorphological indices was conformal too to the present study. During the last few decades, eminent researchers (Singh *et al.*, 2013; Pande and Mohanir, 2017; Manjare *et al.*, 2021; Khan and ElKashouty, 2023) have been extensively using GIS tools and techniques for basin morphometric analysis as a powerful application in geomorphological studies.

The Kaljani River Basin (KRB) in the Bhutan Himalayan foothills has steep northern sides and tall peaks that descend to valleys and plains in the south. The varying geographical characteristics makes the river prone to all sorts of fluviatile actions encompassing high dissection, rigorous bifurcation, varying relief, highly corrugated ruggedness etc. for which the river is carrying enormous loads down-slope while descending to the foothill plain and subject to steady bed filling which in turn is deteriorating the river health in view of its decreasing cross sectional area. Reasonably, the flow dynamics is comparatively triggered over the neo-tectonically active Sub-Himalayan foothills and the phenomenon is quite unique compared to the neighboring rivers like Neora, Chel, Mal, Murti, Kurti, Mujnai, etc. The uniqueness of the morphometry of this river basin is its dynamism, especially floods and bed filling processes, almost throughout the year. Riparian inhabitants experience recurrent inundation, replenishment of bank bank-attached flood plain to a greater extent as observed during the field investigation. The repercussions of the 2016 flood (Roy & Das 2021) were studied through interpersonal investigation. In this context, morphometric analysis is inevitable to realize the channel behaviour and its erosion dynamics, which is the driving force for the present work. This study prioritizes basin sub-watersheds to identify flood and erosion-prone locations, enabling targeted flood mitigation and soil conservation initiatives. It also identifies human-modified regions, which are more susceptible to natural disasters.

Kaljani River basin

The Kaljani River, originating from the Himalayan foothills in Bhutan, serves as a vital watercourse in the North Bengal Dooars (NBD) region. Flowing southward through Bhutan and then India, it ultimately joins the Torsa River. Spanning over approximately 1487 km² with a length of about 97 km, the Kaljani supports a range of ecological systems and diverse landforms (Fig. 1). Numerous tributaries feed into it, including the *Bania, Buri*, and *Ghargharia* streams on the right, and the *Gadadhar, Cheko, Nonai, Dima, Gorom, Paro, Dhubijhora, Pana,* and *Kalijhora* on the left. These minor streams play a crucial role in maintaining the Kaljani's flow and contribute to its sediment load, which is particularly significant in the basin's lowlands and foothills.

The river course crosses the Indian state of West Bengal, particularly through the Alipurduar district in the Dooars region, an area rich in wetland ecosystems within the floodplain. This basin, especially in its lower and middle sections, exhibits extensive sedimentary deposits, contrasting with the upper reaches, which mirror the geological evolution typical of the Tertiary Himalayan formations. The upper course, with its hilly terrain, steep slopes, and high elevation, not only provides potential for hydro-energy but also contributes considerable sediment to the downstream areas, especially in the foothills and alluvial plains. A unique feature of the Kaljani River system is the presence of large alluvial fans in the foothills of the Himalayas, created by the river's steep slope transitions from higher elevations. The river's geomorphology reflects the interaction of tectonic uplift, sediment transport, and deposition processes. This dynamic interplay shapes the floodplain and contributes to the fertile, sediment-rich soils that support diverse agricultural and ecological functions in the basin.

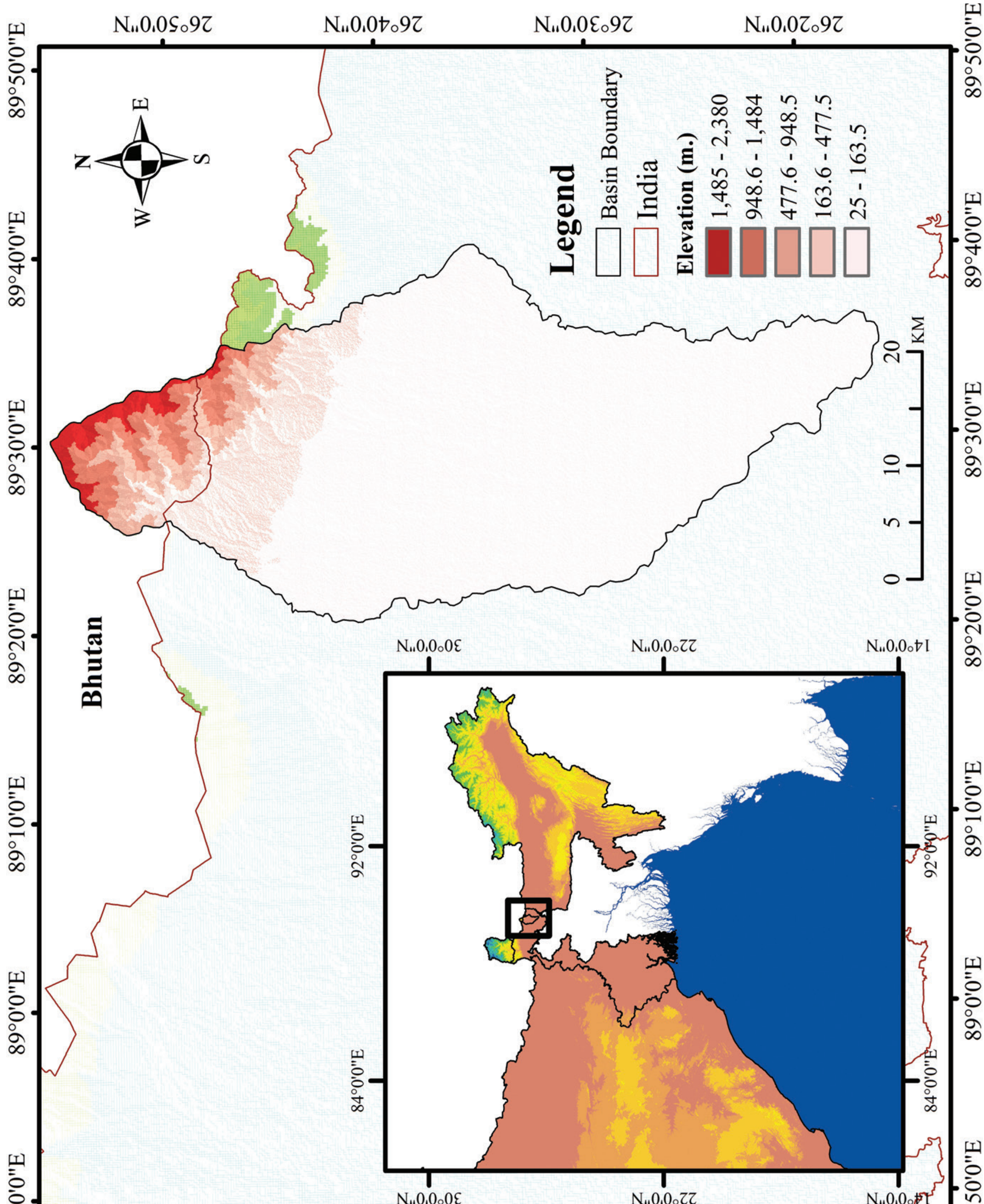

Fig. 1: Geographical settings of the Kaljani River Basin

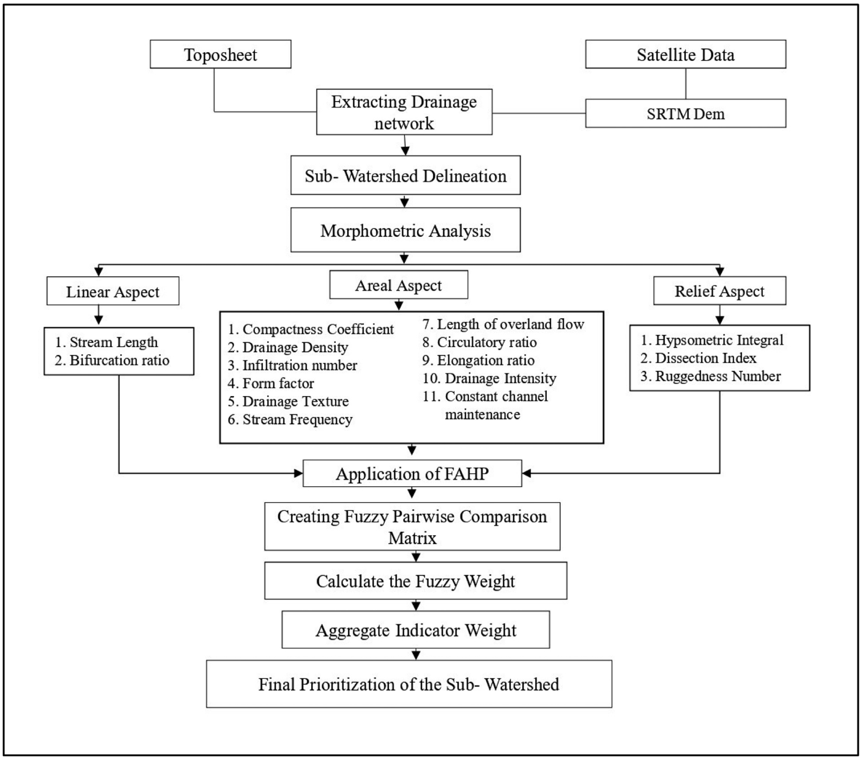

Fig. 2: Methodological flowchart

Database and methodology

The study evaluates quantitatively the drainage system characteristics to understand the hydrological phenomena. Key drainage metrics such as bifurcation ratio, length ratio, stream order, drainage density, drainage frequency, and stream frequency are also assessed. The SRTM-DEM with 30 metres spatial resolution is utilized to extract the drainage network, and the ArcGIS 10.4 software's Hydrology tool is employed to extract drainage lines and other parameters. The KRB watershed is defined using automated extraction methods. The morphometric analysis encompasses linear (stream order, mean bifurcation ratio, stream length, etc.), areal (stream frequency, texture ratio, drainage density, etc.), and relief aspects (relief ratio, ruggedness index, etc.). Ten significant sub-basins within the KRB are identified and delineated based on DEM-generated data and considering the catchment areas of the main tributaries of the Torsa River. Standard equations are used to determine all features for the drainage morphometric study. Further details on the methodology are provided in Figure 2.

Morphometric parameters

Following this, the sub-watershed database and drainage network underwent morphometric analysis using GIS. Stream order, area, perimeter, and basin length were computed. Utilizing these techniques, all extracted morphometric analysis data were used to determine the parameters (Table 2).

Table 1: Pair-wise comparison matrix of Fuzzy-AHP

	(Lu)			(Cc)			(Dd)			(Dt)			(Rbm)			(Rf)			(Rc)			(Di)		
(Lu)	1	1	1	0.33	0.50	1.00	0.33	0.50	1.00	0.25	0.33	0.50	0.25	0.33	0.50	0.20	0.25	0.33	0.20	0.25	0.33	0.20	0.25	0.33
(Cc)	1	2	3	1	1	1	0.33	0.50	1.00	0.33	0.50	1.00	0.25	0.33	0.50	0.25	0.33	0.50	0.20	0.25	0.33	0.20	0.25	0.33
(Dd)	1	2	3	1	2	3	1	1	1	0.33	0.50	1.00	0.33	0.50	1.00	0.25	0.33	0.50	0.20	0.25	0.33	0.20	0.25	0.33
(Dt)	2	3	4	1	2	3	1	2	3	1	1	1	0.33	0.50	1.00	0.33	0.50	1.00	0.33	0.50	1.00	0.25	0.33	0.50
(Rbm)	2	3	4	2	3	4	1	2	3	1	2	3	1	1	1	0.25	0.33	0.50	0.33	0.50	1.00	0.25	0.33	0.50
Rf	3	4	5	2	3	4	2	3	4	1	2	3	2	3	4	1	1	1	0.33	0.50	1.00	0.25	0.33	0.50
(Rc)	3	4	5	3	4	5	3	4	5	1	2	3	1	2	3	1	2	3	1	1	1	0.33	0.50	1.00
(Cm)	3	4	5	3	4	5	3	4	5	2	3	4	2	3	4	2	3	4	1	2	3	1	1	1
(Re)	4	5	6	3	4	5	3	4	5	2	3	4	2	3	4	2	3	4	2	3	4	1	2	3
(Olf)	4	5	6	4	5	6	4	5	6	2	3	4	2	3	4	2	3	4	1	2	3	1	2	3
(Fs)	5	6	7	4	5	6	4	5	6	3	4	5	3	4	5	3	4	5	1	2	3	2	3	4
(If)	5	6	7	5	6	7	5	6	7	4	5	6	3	4	5	4	5	6	1	2	3	2	3	4
(RR)	5	6	7	5	6	7	5	6	7	4	5	6	3	4	5	4	5	6	3	4	5	2	3	4
(Rn)	6	7	8	5	6	7	5	6	7	5	6	7	3	4	5	4	5	6	3	4	5	3	4	5
(DI)	6	7	8	6	7	8	6	7	8	6	7	8	4	5	6	5	6	7	3	4	5	4	5	6
HI	7	8	9	6	7	8	6	7	8	6	7	8	4	5	6	5	6	7	4	5	6	4	5	6

Continued……

(Re)			(Olf)			(Fs)			(If)			(Cm)			(Rn)			(DI)			HI			Normalized Weight
0.17	0.2	0.25	0.17	0.2	0.25	0.14	0.17	0.2	0.14	0.17	0.2	0.14	0.17	0.2	0.13	0.14	0.17	0.13	0.14	0.17	0.11	0.13	0.14	0.01389
0.2	0.25	0.33	0.17	0.2	0.25	0.17	0.2	0.25	0.14	0.17	0.2	0.14	0.17	0.2	0.14	0.17	0.2	0.13	0.14	0.17	0.13	0.14	0.17	0.01623
0.2	0.25	0.33	0.17	0.2	0.25	0.14	0.17	0.2	0.14	0.17	0.2	0.14	0.17	0.2	0.14	0.17	0.2	0.13	0.14	0.17	0.13	0.14	0.17	0.01765
0.25	0.33	0.5	0.25	0.33	0.5	0.2	0.25	0.33	0.17	0.2	0.25	0.17	0.2	0.25	0.14	0.17	0.2	0.13	0.14	0.17	0.13	0.14	0.17	0.02344
0.25	0.33	0.5	0.25	0.33	0.5	0.2	0.25	0.33	0.2	0.25	0.33	0.2	0.25	0.33	0.2	0.25	0.33	0.17	0.2	0.25	0.17	0.2	0.25	0.02724
0.25	0.33	0.5	0.25	0.33	0.5	0.2	0.25	0.33	0.17	0.2	0.25	0.14	0.17	0.2	0.17	0.2	0.25	0.14	0.17	0.2	0.14	0.17	0.2	0.02954
0.25	0.33	0.5	0.33	0.5	1	0.33	0.5	1	0.33	0.5	1	0.2	0.25	0.33	0.2	0.25	0.33	0.2	0.25	0.33	0.17	0.2	0.25	0.04066
0.33	0.5	1	0.33	0.5	1	0.25	0.33	0.5	0.25	0.33	0.5	0.25	0.33	0.5	0.2	0.25	0.33	0.17	0.2	0.25	0.17	0.2	0.25	0.04523
1	1	1	0.25	0.33	0.5	0.25	0.33	0.5	0.33	0.5	1	0.33	0.5	1	0.25	0.33	0.5	0.2	0.25	0.33	0.25	0.33	0.5	0.05496
2	3	4	1	1	1	0.33	0.5	1	0.33	0.5	1	0.25	0.33	0.5	0.2	0.25	0.33	0.2	0.25	0.33	0.17	0.2	0.25	0.05879
2	3	4	1	2	3	1	1	1	0.33	0.5	1	0.25	0.33	0.5	0.25	0.33	0.5	0.2	0.25	0.33	0.17	0.2	0.25	0.06915
1	2	3	1	2	3	1	2	3	1	1	1	0.33	0.5	1	0.25	0.33	0.5	0.33	0.5	1	0.33	0.5	1	0.08688
1	2	3	2	3	4	2	3	4	1	2	3	1	1	1	0.33	0.5	1	0.33	0.5	1	0.25	0.33	0.5	0.10059
2	3	4	3	4	5	2	3	4	2	3	4	1	2	3	1	1	1	0.33	0.5	1	0.25	0.33	0.5	0.11789
3	4	5	3	4	5	3	4	5	1	2	3	1	2	3	1	2	3	1	1	1	0.33	0.5	1	0.13867
2	3	4	4	5	6	4	5	6	1	2	3	2	3	4	2	3	4	1	2	3	1	1	1	0.1592

Fuzzy-AHP

Several studies (Das *et al.*, 2021; Withanage *et al.*, 2015; Rahaman *et al.*, 2022; Mangan *et al.*, 2019; Chakraborty *et al.*, 2023) have determined priority watersheds using methodologies such as Analytic Hierarchy Process (AHP), quantitative analysis, fuzzy logic, and statistical methodologies. AHP, when integrated with a GIS environment, proves highly effective for such situations. The present study also explored fuzzy modified AHP (F-AHP) within the context of expert decision-making after addressing fuzziness, uncertainty, and vagueness, discussing its advantages, disadvantages, and potential applications. Triangular fuzzy numbers employed in Fuzzy-AHP are suitable for comparing pair-wise matrices (Table 1). Conventional AHP is deemed inadequate for such cases, making Fuzzy-AHP widely utilized across various sectors. Its adaptability to different choices and problems makes it a valuable decision-making system.

Constructing Fuzzy Pairwise Comparison Matrices: Choosing the relative weights of each pair of elements within the same hierarchy is the first step of the fuzzy-AHP approach. The triangular fuzzy number ($\tilde{A} = \ddot{a}ij$), which is utilised for pair-wise comparison, is formed into the fuzzy evolution matrix of n criteria that is given below (Table 1),

$$A = \begin{matrix} 1 & \tilde{a}_{12} & \ldots & \tilde{a}_{ln} \\ \tilde{a}_{21} & 1 & & \tilde{a}_{2n} \\ \cdots & \cdots & \ddots & \cdots \\ \tilde{a}_{nl} & \tilde{a}_{n2} & \cdots & 1 \end{matrix}$$

Where $\tilde{a}_{ij}$ is a fuzzily defined triangular value, $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$, and $\tilde{a}_{ij}^{-1} = \frac{1}{\tilde{a}_{ij}}$. For each TFN, $\tilde{a}_{ij}$ or M= l, m, its membership function $\mu_{\breve{a}}(x)$ or $\mu_{\breve{a}}(x)$ is a continuous mapping of real numbers $-\propto \leq x \leq \propto$ to the closed interval [0, 1] and is estimated by the equation given below:

$$\mu_{\breve{a}}(x) = \begin{cases} \frac{(X-1)}{(m-1)} & (l \leq x \leq m) \\ \frac{(u-x)}{(u-m)} & (m \leq x \leq u) \\ 0, & < l\,x > l, \end{cases}$$

TFNs can be used for addition, multiplication, and inverse operations. If M_1 and M_2 are two TFNs with M_1 equal to (l_1, m_1, u_1) and M_2 equal to (l_2, m_2, u_2) respectively, then

Additional $M_1 \oplus M_2 = (l1 + l2, m1 + m2, u1 + u2)$

Multiplication $M1 \otimes M2 = (l1 \times l2, m1 \times m2, u1 \times u2)$

Inverse $M_1^{-1} = (l1, m1, u1)^{-1} = \frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}$

Calculation of the Weights: The criterion weights were calculated using Buckley's Fuzzy-AHP approach in the following steps. These matrices can be aggregated by utilising the fuzzy geometric mean methods (Buckley 1985) using the following formula after obtaining pair-wise comparison matrices from each decision maker.

$$l_i = \left[\prod_{j=1}^{n} l_{ij}\right]^{1/n} \quad \& \quad l = \left[\sum_{i=l}^{n} l_i\right]$$

$$m_i = \left[\prod_{j=1}^{n} m_{ij}\right]^{1/n} \quad \& \; m = \left[\sum_{i=1}^{n} m_1\right]$$

$$u_i = \left[\prod_{j=1}^{n} u_{ij}\right]^{1/n} \quad \& \quad u = \left[\sum_{i=1}^{n} u_i\right]$$

Step- 1: The following equation describes the fuzzy membership function that describes the weights of various parameters.

Using the geometric mean approach, a fuzzy geometric mean might be determined as follows:

$$\tilde{r}_i = [\tilde{a}_{i1}, \tilde{a}_{i2}, \ldots, \tilde{a}_{in}]^{1/n}$$

As a result, the formulation of the fuzzy geometric average values $\tilde{r}_i$ is as follows.

$$\tilde{r}_i = [lr_1, mr_1, ur_1] = \left[\left[\prod_{j=1}^{n} l_{ij}\right]^{1/n}, \left[\prod_{j=1}^{n} m_{ij}\right]^{1/n}, \left[\prod_{j=1}^{n} u_{ij}\right]^{1/n}\right]$$

The fuzzy geometric mean valuer $\tilde{r}_i$ of the criteria is represented by the letters lr_1, mr_1, and ur_1 which stand for lower, middle, and higher values.

Step 2: The second step involves employing the following formula to get the fuzzy weights of each parameter:

$$\widetilde{w}_i = \tilde{r}_1 \ddot{A} \, [\tilde{r}_1 \oplus \tilde{r}_2 \oplus \ldots \oplus \tilde{r}_n]^{-1}$$

The fuzzy weights $\widetilde{w}_i$ must be defuzzified as the last step in order to get the crisp weight w_i.

We used an equation to apply the Centre of Area (COA) method to get the precise numerical weights of each parameter.

$$w_i = \frac{l_{w1} + mw_i + uw_i}{3}$$

Table 2: Sub watershed-wise Morphometric Parameters of Kaljani River Basin

Parameters	SW-1	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7	SW-8	SW-9	SW-10
(R_{bm})	3.777	2.623	3.984	2.625	2.711	3.808	3.320	1.694	3.600	2.094
R_l	1.026	1.298	1.023	1.044	0.695	1.033	1.051	1.715	1.047	1.272
(R_{hO})	0.301	0.496	0.281	0.383	0.380	0.292	0.478	0.635	0.381	0.566
(R_c)	0.541	0.148	0.107	0.102	0.151	0.347	0.280	0.117	0.232	0.614
(R_e)	0.698	0.312	0.472	0.474	0.334	0.521	0.481	0.559	0.407	0.642
(D_t)	1.531	2.486	1.868	2.838	2.688	2.214	4.986	2.036	1.447	1.611
(C_m)	0.523	0.422	0.449	0.333	0.451	0.444	0.362	0.377	0.569	0.548
(F_s)	0.801	1.049	0.840	0.946	1.213	0.982	1.804	0.767	0.824	0.882
(D_d)	1.911	2.370	2.225	3.001	2.215	2.254	2.763	2.655	1.756	1.826
L_{of}	0.534	0.422	0.596	0.528	0.412	0.511	0.277	0.652	0.496	0.411
(R_t)	2.430	1.383	1.161	0.826	2.048	2.149	3.083	0.528	1.442	1.313
(I_f)	0.856	0.885	1.000	1.000	1.000	1.003	1.000	1.000	0.817	0.724
(R_f)	0.382	0.076	0.175	0.177	0.088	0.213	0.181	0.246	0.130	0.323
(C_c)	1.359	2.601	3.053	3.134	2.570	1.698	1.888	2.923	2.078	1.276
(R_r)	1370	184	544	218	72	378	38	25	27	148
(D_i)	0.797	0.523	0.661	0.534	0.428	0.626	0.418	0.413	0.369	0.523
(R_n)	5.526	1.301	4.170	0.813	0.339	3.111	0.221	0.143	0.125	0.148
(Hi)	0.293	0.103	0.108	0.220	0.261	0.071	0.223	0.230	0.238	0.328

Source: calculated by authors, 2023

R_{bm}= Mean Bifurcation Ratio, R_l= Stream length, R_{hO}= R_{ho} Coefficient, R_c= Circulatory ratio, R_e= Elongation ratio, D_t = Drainage texture, C_m = Constant of channel Maintenance, F_s= Stream frequency, D_d= Drainage density, L_{of}= Length of overland flow, R_t= Drainage texture ratio, I_f= Infiltration no, R_f= Form factor, C_c= Compactness Coefficient, R_r= Relative relief, D_i= Dissections index, *Rn*= Ruggedness number, *Hi*= Hypsometric integral

Finally, the following equation has been used to normalize the obtained weights:

$$w_i = \frac{w_1}{\sum_{j=1}^{n} w_1}$$

Where, w_i is the normalized weight.

Results

Topographical characteristics significantly influence infiltration capacity, runoff, soil erosion, and flooding. Tectonic activity in the watershed results in severe floods and erosion, particularly evident in the northern part of the basin. The basin topography is characterized by steep inclines in the lower Himalayas to the north and gentler slopes in the flood plains of the Brahmaputra River to the south. Drainage systems on flatter terrain often exhibit winding or serpentine patterns across floodplains.

Characteristics of the watersheds

Linear Aspect

Key linear morphometric parameters measured for the basin include Stream Order, bifurcation ratio, stream lengths ratio and

Rho (ρ) coefficient ratio for each stream order.

Stream order: Stream order is a geomorphological measure indicating the degree of branching within river systems, typically denoted as a positive whole integer. According to Horton's rule, the number of stream segments decreases as the stream order increases. Based on research findings, the river in question is classified as a 6^{th}-order stream (Fig. 3a). Figure 3a displays the stream order of the KRB, with Sub-Watershed 5 having the highest order and Sub-Watershed 10 having the lowest.

Bifurcation ratio (R_{bm}): Horton defined R_{bm} as the proportion of streams of a given order to those of one order below it. Sub-Watershed 3 has the highest R_{bm} of 3.984, while SW-8 has the lowest at 1.69 (Table 2). Lower R_{bm} indicates a well-developed drainage system with limited surface flow and minimal risk of erosion or floods. Higher R_{bm} suggests increased risk of overland flow, erosion, and flooding. SW 8 is more vulnerable to flooding and erosion compared to SW 6, 9, and 1. Uneven R_{bm} values in Sub-watershed 5 indicate geological unconformities and heightened flooding risk, with R_{bm} decreasing rapidly with increasing order.

Stream length ratio (R_l): R_l is the proportion of a stream segment's total length shared between lower and higher orders. A rising R_l indicates a fully developed geomorphic stage. Comparison of stream lengths reveals the permeability of basin rocks. SW-8 has the highest average R_l (1.715), while SW-5 has the lowest (0.695) among sub-watersheds.

RhO coefficient (RhO): The Rho coefficient, determined by dividing stream length ratio by bifurcation ratio, reflects the storage capacity of the drainage network. A coefficient above 0.50 enhances hydrologic storage during flooding. SW 8 exhibits the highest Rho coefficient, while SW 10 has the lowest. Table 2 refers to the Rho values of each sub-watershed.

Areal aspect

Circularity ratio (R_c): The R_c is a dimensionless quantitative measure of the basin shape, representing the ratio of the basin area to that of a circle with equal perimetric length to the basin border. R_c Values indicate the basin's phase of development, with low, medium, and high values representing early, mature, and ancient phases, respectively. Each sub-watershed in the Kaljani watershed has R_c values ranging from 0.102 to 0.61. Sub-watersheds 2, 3, 4 and 8 exhibit low R_c values while 1, 6, 7 and 10 show higher values. High R_c values suggest long basins with moderate runoff flows and high subsurface permeability, while low values indicate flatter, longer-lasting flow peaks near the watershed. R_c Values are influenced by various factors such as stream length, geological formations, topography, climate, and land use/land cover dynamics. Refer to Table 2 for R_c values of the KRB sub-watersheds.

Elongation ratio (R_e): R_e, a defining geographical feature of a basin, is the ratio of a circle's diameter to the maximum length of the basin (Schumm, 1956). Within the KRB's sub-watersheds, R_e values range from 0.31 to 0.698 percent. Higher R_e values indicate elongated basins, where precipitation-fed water travels longer distances before reaching the basin outflow, affecting hydrological dynamics. Watersheds 1, 6, 8, and 10 with high R_e scores imply shorter concentration times and a greater flood risk, while the second, third, and fifth watersheds have smaller elongation ratios. Values closer to 1 suggest lower elevations, while those closer to 0.6 indicate steeper slopes at comparatively higher elevations. Table 2 shows the R_e values for each of the watersheds.

Constant of channel maintenance (C_m): The C_m reflects the drainage area needed to sustain one unit of channel length, indicating watershed erodibility (Schumm, 1956). Higher C_m values suggest greater groundwater potential and recharge. In the Kaljani watersheds, sub-watershed 9 has the highest C_m value (0.569) and sub-watershed 10 has the lowest (0.333). C_m values indicate moderate slopes, strong surface runoff, and permeable subsoil. Watersheds 1, 9, and 10 exhibit somewhat higher C_m values, indicating steep slopes and limited permeability, while watersheds 4, 7, and 8 have low C_m values, suggesting weak rock types or sparse vegetation.

Stream frequency (F_s): F_s, the ratio of a watershed's total stream segments to its surface area that controls the stream network, bedrock properties and basin size. In the KRB, sub-watersheds 7 and 8 have the highest and lowest frequencies, respectively (Fig. 3g & Table 2). Stream frequency is influenced by infiltration capacity, permeability, and basin relief. Higher F_s values indicate increased runoff due to factors like less vegetation, higher relief, reduced infiltration capacity, and impermeable subsurface materials.

Drainage density (D_d): The D_d measures the level of channelization in a basin, influenced by lithology, structure, and climate. It is the proportion of the basin's area to the sum of all stream lengths (Horton, 1945). In the Kaljani watershed, D_d ranges from 3.001 to 1.756, with sub-watershed 4 having the highest and sub-watershed 9 having the lowest D_d values (Table 2, Fig. 3b). High D_d is linked to increased sediment production, flood peaks, steep slopes, and reduced agricultural suitability. Sub-watershed 8 exhibits high potential for sediment yield, floods, and erosion. D_d reflects physiographic features, runoff potential, rock type, basin shape, land cover, and climate, with higher values indicating increased risks of these issues.

Length of overland flow (L_{of}): L_{of}, half of drainage density, indicates the time water spends on the ground before entering streams, affecting basin hydrology and physiography (Horton, 1932). It reflects surface runoff occurrence when rainfall intensity exceeds soil absorption capacity, more effective on gentle slopes. Sub-watershed 8 exhibits a higher L_{of} (0.652) than sub-watershed 7 (0.277), influencing surface runoff. Lower L_{of} values correspond to increased surface runoff contribution to stream discharge, especially in uniform terrain. Higher L_{of} indicates limited surface runoff, as seen in watersheds 1, 3, and 8, while lower L_{of} suggests strong surface runoff and channel erosion, observed in sub-watersheds 5, 7, and 10 (Table 2).

Drainage texture ratio: The R_t, a critical morphometric variable, reflects basin lithology, slope, relief, and climatic factors, influencing soil erosion and infiltration (Smith, 1950). It measures the proximity of stream segments within a basin, defined as the ratio of watershed perimeter to the number of first-order streams. Sub-watershed 7 exhibits the highest R_t value (3.083), while sub-watershed 3 has the lowest (1.161) (Table 2). Higher R_t values indicate increased drainage texture, suggesting potential erosion and dissection in the future.

Table 3: Prioritization values and rank

Sub-Watershed	SW-1	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7	SW-8	SW-9	SW-10
Prioritization Score	0.193	0.076	0.101	0.083	0.082	0.109	0.090	0.068	0.087	0.111
Rank	1	7	4	7	8	3	5	10	6	2

Infiltration number (I_f): The I_f value, a key morphometric index, reflects topsoil permeability and erosion incidence. It inversely correlates with erosion, depending on relief, slope, lithology, and vegetation cover. Higher I_f values indicate impermeable surfaces resistant to erosion, while lower values denote erosive watersheds. Sub-watershed 10 has the lowest value (0.724), indicating high erosion risk, while sub-watershed 6 has the highest resistance (1.003). High I_f values imply less permeable basins, low infiltration, high runoff, and frequent flooding, as seen in sub-watersheds 4, 5, and 6. Lower values suggest vulnerability to flash floods, observed in sub-watersheds 1, 9, and 10 and Refer to Figure 3d for the infiltration Index of each sub-watershed.

Form factor (R_f): Horton (1945) introduced the form factor, a dimensionless ratio of basin area to the square of basin length, reflecting drainage-basin outline shape and providing insights into slope, topography, soil quality, runoff, and flood potential. Sub-watershed 1 exhibits the highest R_f value (0.382), while sub-watershed 2 has the lowest (0.076). R_f predicts flood formation, erosion levels, and sediment transport capacity. Higher R_f values in watersheds 1, 6, 8, and 10 indicate heavy runoff and susceptibility to flooding, while lower values in watersheds 2, 5, and 9 suggest reduced runoff and longer duration (Table 3).

Compactness Coefficient (C_c): The C_c, comparing a watershed's perimeter to that of an equivalent circular region, reflects the basin's shape relationship. Values range from 3.134 to 1.276, with sub-watershed 4 having the highest and sub-watershed 10 the lowest (Table 3). Higher values indicate less vulnerability to erosion (greater compactness), while lower values suggest greater elongation and vulnerability to erosion.

Relief aspects

Relative relief (R_r): R_r measures the difference in height between a region's highest and lowest points compared to its local base level. In the KRB, with 10 sub-watersheds, relative relief varies from 13.71 m in SW-8 to 2275.21 m in SW-10 (Figure 3e). This metric influences terrain dissection and morphological evaluations, indicating erosion magnitude and temporal patterns.

D$_i$ssection index (D_i): The D_i reveals the depth of vertical erosion within a region, indicating landform history variations. Values range from 0 to 1, with higher values indicating greater vertical cutting. In the KRB, D_i varies from 0.369 to 0.797, with SW-9 and SW-1 exhibiting the extremes (Fig. 3c). This metric aids understanding of relief segmentation, geomorphological mapping, and environmental vulnerability assessment. Lower D_i values suggest minimal riverbed erosion and a move toward flat surfaces. SW-9, 8, and 7 have lower D_i values compared to SW-1, 3, and 6.

Ruggedness number (R_n): The R_n, combining slope steepness and basin length, is calculated by multiplying basin relief by drainage

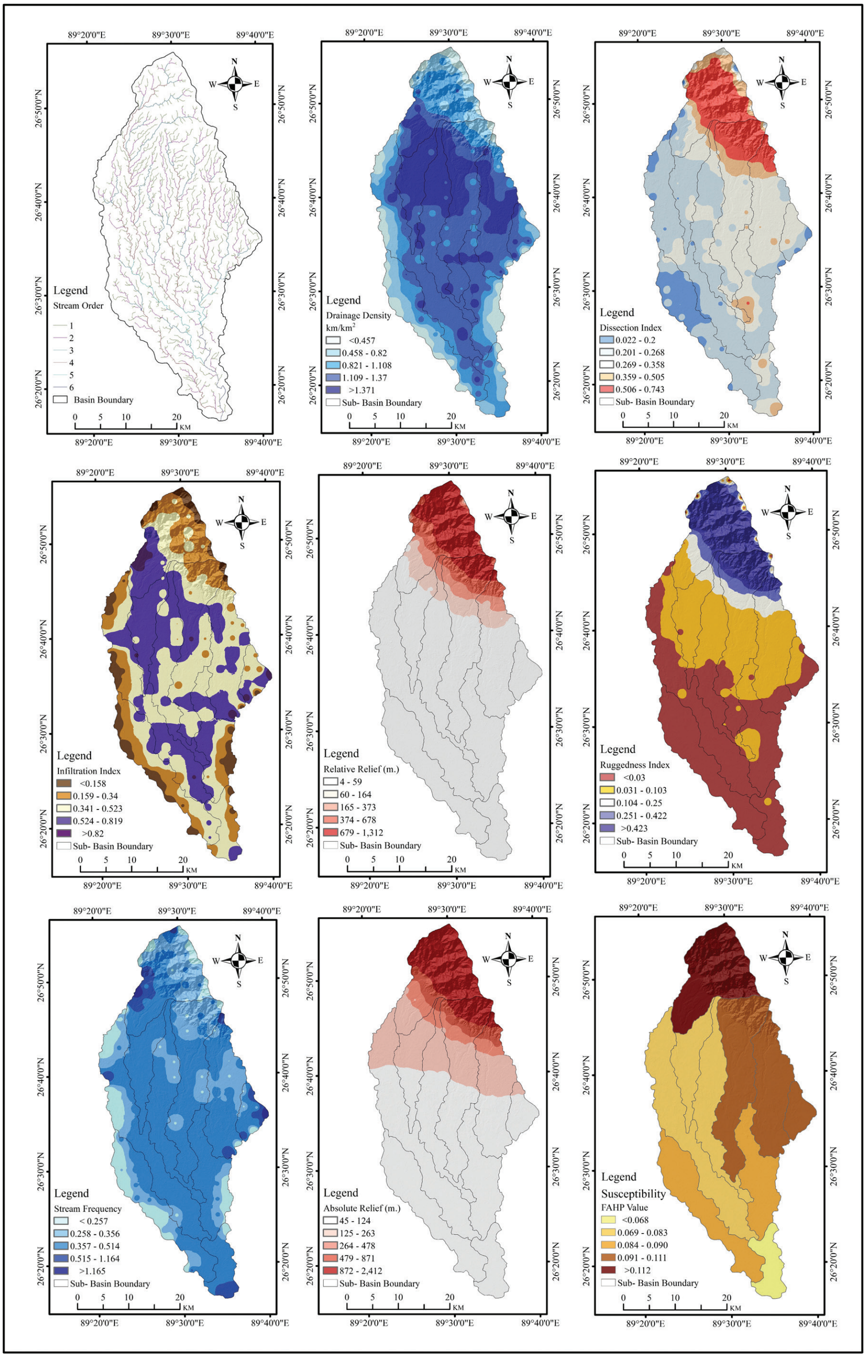

Fig. 3: (a) Stream order (b) Drainage density (c) Dissection index (d) Infiltration rate (e) Relative relief (f) Ruggedness index (g) Stream frequency (h) Absolute relief (i) Prioritization map of Sub Watershed of Kaljani river basin based on Fuzzy-AHP Value

density (Strahler, 1957). R_n values range from 0.028 in SW-8 to 5.526 in SW-1. High R_n values indicate steep slopes and lengthy basins, increasing erosion likelihood. SW-1, 6, and 2, situated on higher terrain, are more prone to erosion, while SW-8, 9, and 10 show lower erosion susceptibility due to moderate relief and smaller R_n values (Fig. 3f).

Hypsometric integral (H_i): The H_i quantifies the relationship between area size and elevation, indicating geological activity and watershed development level. H_i values for the Kaljani watershed range from 0.071% to 0.333%. $H_i$gher values suggest younger, less degraded topography with deep gorges, while lower values indicate older, more deteriorated topography or regularly spaced drainage basins (Pike & Wilson 1971). The lowest and highest H_i values are found in watersheds 6 and 10, respectively, indicating varying erosion risks, with the 10th basin showing a higher risk.

Discussion

In developing plans for watershed restoration, prioritizing sub-watersheds is crucial. The Kaljani River sub-watersheds underwent a comprehensive morphometric assessment to understand their characteristics, hydrological processes, and erosional mechanisms. This research integrates various spatial aspects, including runoff estimation and soil characteristics, to plan conservation measures effectively. Subsequently, prioritizing critical sub-watersheds is essential for efficient watershed management and development planning. The research utilizes multi-criteria decision-making (MCDM), particularly Chang's fuzzy analysis, to prioritize sub-watersheds based on their unique morphometric features and hydrological reactions. MCDM, facilitated by fuzzy analysis, simplifies decision-making by displaying choice criteria as maps and assigning weights to relevant characteristics. Through fuzzy pair-wise comparison matrices, morphometric criteria are evaluated, and weights are normalized using the F-AHP. This approach allows for the ranking of sub-watersheds based on their importance and risk levels, providing a solid foundation for watershed conservation efforts and management planning.

To enhance the implementation of conservation measures, an integrated risk assessment map was created by overlaying morphological feature criteria and rankings from different weights within a GIS framework. Each category was independently ranked based on FAHP analysis values, with higher values indicating greater danger and priority. The process continued until the ranking of each hydrological unit was established.

Using FAHP analysis results ranging from 0.068 to 0.193, the importance of each variable was determined. Subsequently, sub-watersheds were ranked based on their analysis values, with SW-1 having the highest and SW-8 the lowest (Fig. 3i). This analysis highlighted SW-1 as a prime for optimal management strategies due to its higher resource degradation. Watersheds 3, 6, and 10 were prioritized with levels ranging from 0.0878 to 0.1160 (Table 3), while watersheds 4 and 9 fell into the medium priority range with ratings between 0.0865 and 0.0877. Watersheds 2 and 5 were assigned lower priority levels.

Conclusion

The investigation of erosional challenges within the Kaljani watershed and its sub-watersheds is crucial for understanding key aspects such as linear, areal, and relief characteristics, and for devising effective solutions. Utilizing a combined approach of remote sensing, GIS, and topographical mapping, this study identified SW1 as highly vulnerable, requiring immediate attention for planning and development purposes. Sub-Watersheds 3, 6, and 10 also exhibit significant vulnerability, while SW 7 and 9 are moderately vulnerable. Sub-watersheds 2, 4, 5, and 8 show low vulnerability but contribute to localized flooding along downstream due to their inability to retain high precipitation flash. Overall, the morphometric characteristics highlight diverse morpho-climatic patterns across sub-watersheds, emphasizing the need for tailored conservation strategies to mitigate soil erosion and downstream flooding from spatio-temporal perspectives.

Competing interest

The corresponding author declares that they have no conflict of interest.

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