

Geospatial morphometric parameter assessment for hydrological prioritization of sub watershed in the Upper Yamuna River basin, Western Himalaya, India

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Abstract

Watershed characterization and prioritization play an important role in sustainable watershed management particularly in regions experiencing soil erosion, land degradation and water resource depletion. In this present study, remote sensing, and Geographic Information System (GIS) were used for watershed characterization, identification of suitable water harvesting and recharge structure through morphometric analysis and evaluate sub watershed prioritization. Spatial resolution of 12.5 m of ALOS PALSAR DEM was utilized to delineate drainage networks and derive key linear, areal and relief morphometric parameters for Upper Yamuna River basin (UYRB) and classified thirteen sub watersheds. Compound parameter ranking method were adopted to classify ranking and prioritize the sub watershed SW2, SW8, SW5 and WS6 as very high to high categories whereas SW 9 at lowest prioritize categories. The medium priority categories SW1, WS3, WS7, WS11, WS12 and SW 13 constitute the largest portion covering of 46.48% of the total watershed area. The very high priority categories SW2 and WS8 account only for 23.82% of the total watershed area. These sub watersheds require water resource conservation and sustainable management practices. This study recommended water conservation measure including contour bund, check dam, and plantation of multipurpose tree species to mitigate runoff and soil erosion in priority sub watershed. And it can also support decision maker in optimizing the investment allocation by ensuring the economically viable and socially acceptable watershed management practices.

1. INTRODUCTION

Natural resources worldwide are subjected to escalating stress driven by rapid population growth, expanding urbanization and the impact of ongoing climate variability and change. These pressure have significantly altered environmental stability, resulting in interconnected challenges such as soil degradation, deterioration of water quality, and overexploitation of groundwater systems.(Reddy 2003; Wani and Javed 2013; Dempsey et al., 2018). In particular, the increasing strain on water resources is widely recognized as a critical factor contributing to regional instability and potential conflict (Richey et al., 2015). Such challenges are particularly evident in countries like India, where high population density and a substantial dependence on land and water resources amplify the risks and consequences of resource depletion. Watershed and sub-watershed scale planning is essential for the sustainable management of natural resources. A watershed encompasses natural system which include water, soil, vegetation, and human systems that interact with these resources through socioeconomic activities. Consequently, watershed integrate hydrological, biological, and socioeconomic components. The degree of the maturity of the fluvial system and spatial and temporal characteristics of the drainage system are governed by geomorphological and geological control as well as soil properties and vegetation cover (Nikolova, Kamburov and Rizova, 2021). A watershed constitutes a fundamental unit for morphometric analysis, as it defines the natural boundary within which hydrodynamic and geomorphic processes operate. It is within the basin where both aggradation and denudation processes shapes landscape transformation over time (Luo and Howard 2005).

Morphometric assessment serves as a quantitative approach to evaluate watershed physiography by systematically analyzing terrain and drainage characteristics, including slope, channel network geometry, drainage divide location and stream length. It involves the estimation of key indices such as relative relief, form factor, circulatory ratio, and bifurcation ratio and drainage density. These morphometric indices provide critical insight into watershed behavior and are widely utilized for prioritizing sub watershed and supporting the design and implementation of effective soil and water conservation strategies (Kumar et al., 2020; Bagwan, 2021). Morphometric parameters have widely adopted in geomorphological investigations to analyze diverse hydrological and terrain related processes, including runoff generation, morphotectonic and neotectonics controls, flash floods susceptibility (Syed et al., 2017; Pant et al., 2020), soil erosion risk (Thakur et al., 2012; Jothimani et al., 2020), groundwater potential assessment (Doke et al., 2020; Rawat et al., 2021), and watershed prioritization for sustainable management (Ahmed et al., 2018; Arulbalaji and Padmalal, 2020). Among the governing factor, drainage gradient and channel slope play a critical role in shaping the morphometric response of a watershed, as they regulate flow velocity, erosional processes, and sediment transport, thereby influencing the overall geomorphic evolution of fluvial systems (Strahler 1964 ; Nautiyal, 1994).

Geomorphology, examines the physical and chemical processes that shape and modify Earth's surface features, producing characteristic landform patterns. Morphology offers a quantitative basis for describing the landform with detailed measurement and evaluations of their properties (Horton, 1945). Morphometry advance this by applying mathematical and statistical methods to quantitatively depict terrain relief and its component, while revealing links to key environmental factors like soil characteristics, erosion dynamics, and land surface processes (Hadji et al., 2024, Hassan, 2025). Analyzing a river basin morphometrically provides a through characterization of its drainage system which is a key foundation for effective environmental management. These morphometric traits strongly influence hydrological behaviors, such as runoff production, infiltration capacity, and the intensity and occurrence of flood (Almada et al., 2019). At the basin level, interactions between morphometric attributes and local climate govern the hydrological cycle within running water ecosystems (Soni, 2017).

Moreover, morphometric analysis has been widely applied to prioritize and evaluate sub watershed (Kumar et al., 2015). It provides a quantitative basis for interpreting drainage network, hydro-geomorphological attributes, and natural hazard of the basin for sustainable watershed management and planning (Gunjan et al., 2019). Quantitative morphometric analysis constitutes a fundamental framework for understanding watershed dynamics and apprising hydrological decision making but its application in Upper Yamuna River basin (UYRB) remains notably limited. In this present study, it delivers morphometric assessment of sub watershed of the UYRB with the explicit objective of prioritizing sub watersheds for strategic water resource management. An analytical framework was employed to evaluate key morphometric parameters governing drainage architecture, basin geometry and hydrological response. Geographical Information system (GIS) and remote sensing (RS) techniques were used for this present study. Derived indices were systematically integrated to classify and rank sub watershed based on the hydrological response and susceptibility to degradation. By situating the findings within the broader body of watershed research, this study provides actionable insight for scholar, policy maker and local stakeholders. The outcomes support evidence driven decision making enhance the design of the integrated watershed management strategies and contribute to the upscaling of sustainable land and water management practice in data scarce regions of the Himalaya.

2. Data and Methods

2.1 Study area:

The UYRB is in the western Himalayan region of northern India and represents one of the most important headwater catchments of the Yamuna River, a major tributary of the Ganga River system. The basin originates from the Yamunotri Glacier, situated on the southwestern slopes of the Bandarpunch Massif in the state of Uttarakhand. The Yamuna River flows from the glacier at an elevation of approximately 6,200 m above mean sea level, descending through rugged mountainous terrain before entering the Indo-Gangetic plains. The study area generally encompasses the upstream region of the Yamuna River up to the Dakpathar Barrage, which serves as a hydrological control point for water regulation and irrigation. Geographically, the UYRB extends approximately between Latitude: 30°26' N to 31°25' N and Longitude: 77°36' E to 78°38' E (Fig. 1). The basin covers parts of the districts of Uttarkashi, Dehradun, and Shimla of Uttarakhand and Himachal Pradesh state. It drains a mountainous terrain characterized by steep slopes, deep valleys, and complex geological structures typical of the Himalayan orogenic belt. The total area of the Upper Yamuna Basin upto Dakpathar is approximately 7473 km². The UYRB is characterized by highly rugged terrain and pronounced altitudinal variation. Elevation within the basin ranges from about 466 m above sea level in the foothill regions to more than 6,000 m in the glaciated zones near the source of the Yamuna River. The physiography of the basin can broadly be divided into the following zones: (a). High Himalayan Zone: The northernmost part of the basin consists of glaciated peaks and snow-covered mountains associated with the Greater Himalaya. This zone includes the source region of the Yamuna River and several snow-fed tributaries. The terrain is dominated by steep slopes, cirques, glacial valleys, and moraines. Prominent peaks in this region include the Bandarpunch Peak acts as an important snow accumulation zone. (b). Middle Himalayan Zone: South of the Greater Himalayan range lies the Middle Himalayan region, characterized by moderately high mountain ranges and deep river valleys. Elevations in this zone generally range between 2,000 and 4,000 m. The landscape includes forested slopes, narrow valleys, and numerous tributary streams that contribute to the Yamuna River. (c) Lesser Himalayan and Foothill Zone: The southern part of the basin transitions into the Lesser Himalaya and Siwalik ranges, where elevations decrease to around 466–1,000 m. This region marks the transition from mountainous terrain to the alluvial plains of northern India. The overall drainage pattern of the basin is largely dendritic to sub-parallel, reflecting the influence of geological structures and tectonic activity in the region. The climate of the UYRB is strongly influenced by altitude, monsoon circulation, and western disturbances. Due to the large elevation gradient within the basin, the climate varies from subtropical conditions in the lower elevations to alpine and nival climates in the higher reaches.

2.2 Morphometric parameter and methodology

Digital Elevation Model (DEM) has been widely used for hydrological investigation and topographic assessment. ALOS PALSAR of spatial resolution 12.5 m obtained from Alaska Satellite Facility (ASF) Distributed Active Archive Center (DAAC) was used to derive morphometric parameters due to its relatively high spatial resolution, which is suitable for capturing fine scale topographic variations and drainage features in mountainous terrain. The DEM was pre-processed in a GIS environment using spatial analyst extension tool of ArcGIS 10.3 software to remove spurious depression. A threshold of 10,000 values was applied to delineate the drainage network of the UYRB. This threshold was selected through visual calibration on google earth pro to represent the observed channel initiation points and drainage density of the present study area while minimizing over and under representation of the first order stream. It is observed that the drainage network extraction in sub watershed boundaries resulted in modification of stream order due to dependence of the stream hierarchy. So, stream order was performed using Strahler method at the basin scale to preserve upstream and downstream connectivity prior to sub watershed delineation. The Arc SWAT tool extension in ArcGIS 10.3 was employed to delineate watershed boundaries based on defined pour points. The present study area is divided into 13 sub watersheds, which have been number SW1 to SW13. Morphometric parameters such as linear, areal and relief were calculated based on the mathematical formulae and methods which have been already developed and summarized in Table 1.

3. Morphometric parameters

After delineation of watershed boundary and drainage networks, morphometric analysis was divided into three main categories: **1) Linear aspects:** It defined the hierarchical and structural characteristics of the drainage network which include stream order, stream length and connectivity of the stream and rivers within the watershed. **2) Areal aspect:** It describes the spatial configuration of the basin, encompassing watershed area, the watershed's shape and how water flows across the surface; and **3) Relief aspects:** It quantifies the vertical structure of the watershed, including elevation range, slope, and terrain ruggedness. Collectively, these metrics provide an integrated framework for assessing hydrological processes, including runoff generation, erosional susceptibility, and sediment transport behavior.

3.1 Linear aspects:

Watershed area (A)

It refers to the total planimetric extent of the drainage area and is a primary morphometric control on hydrological response. It regulates rainfall input volume and significantly influences runoff generation and peak discharge. While larger watershed area generally yields higher runoff due to increase catchment area, smaller watershed may also experience high flood peaks and sediment yield depending on drainage network structure, basin morphology, and relief characteristics. In the present study, watershed area varied from 123.47 to 1436.49 km², with SW11 and SW3 representing the minimum and maximum extents respectively (Table 2).

Watershed Perimeter (P)

It defines the outer boundary of the drainage watershed along the drainage divide that separates adjacent catchments and directs surface runoff towards a common outlet. Variation in perimeter among the watershed reflect difference in watershed size and geometric complexity, which exert a strong control on hydrological response. In the present study SW3 exhibits the largest perimeter (261.23 km), indicating a comparatively large and geometrically complex watershed, which influences runoff generation, drainage network development and sediment transport process. Watershed with larger perimeter such as

SW3 (261.23 km), SW2 (232.73 km), and SW12 (206.33 km) and SW8 (204.25 km) are generally characterized by elongated boundary configuration that result in longer flow paths, increase spatial heterogeneity in hydrological forcing and greater variability in runoff generation. Such watershed may also exhibit enhance hydrological connectivity and increase travel times, thereby influencing flow attenuation and peak discharge characteristics. In contrast, watershed with smaller perimeter such as SW10 (92.88 km) and SW11 (88.13 km), tend to display more compact shapes, shorter flow paths, and relatively homogenous hydrological responses, often resulting in faster concentration times and more pronounce flash flood behavior. Among the studied sub watershed, SW 11 exhibits smallest perimeter (88.13 km), whereas SW5 shows an intermediate value (149.75 km). Although watershed perimeter generally increases with drainage area as observe in SW1 (162.38 km), SW2 (232.7 km) and SW3 (261.23 km), the relationship is not strictly proportional. Notable deviation such as SW4 (140.08 km) and SW12 (206.33 km) suggest the influence of watershed boundary irregularity and geomorphic controls on catchment geometry (Fig. 1). These variations highlight the role of watershed shape complexity in modulating hydrological response and drainage organization.

Watershed length (L_b)

It defined the longest dimension of drainage watershed measured along the principal flow path form the outlet to the farthest point on the watershed divide. It plays a crucial role for determining the time of concentration and flow travel time within the watershed. L_b strongly influences runoff response, peak discharge, and timing of flood events (Beven 2020), making a critical parameter for hydrological modelling, flood forecasting and watershed management and affect channel flow dynamic, erosion intensity and sediment transport processes by controlling flow velocity and the extent of the drainage network. In the present study the maximum L_b attained by SW3 (81.53 km) whereas minimum was recorded in SW11 (20.23 km).

Stream order (U)

It represents the hierarchical position of a stream within a watershed and is a fundamental component of morphometric analysis. Stream order is based on the number and arrangement of tributary junctions and is commonly determined using the Strahler (1964) method. In this classification, the smallest fingertip and unbranched channels are designated as first order streams. When two first order streams converge, they form a second order stream; similarly, the confluence of the two second order stream produces a third order stream, and the hierarchy continues in this manner (Fig. 2). Stream order increases progressively at channel junctions toward the downstream directions as tributaries merge and the drainage system become more integrated. The highest order stream within the watershed represents the main channel stream, watershed (Kumar and Lal, 2017). In this present study, SW6 and SW12 are classified as sixth order stream, SW2, SW3, SW4, SW9 and WSW11 as fifth order watershed, SW1, SW5, SW7, SW8 and SW13 as fourth order watershed, and SW10 as third order watershed. Generally, higher stream order indicates a more complex and well-integrated drainage network capable of conveying greater water and sediment fluxes, which may influence flood magnitude and basin scale geomorphic evolution.

Stream number (Nu)

It refers to the total number of stream segment within each stream order and represents a fundamental component of drainage system analysis. According to Horton (1945), the relationship between stream number and stream order follows an inverse

Table 1
Mathematical expression used for morphometric parameter analysis.

Parameters	Formula/Methods	Unit	Reference
Watershed Area(A)	GIS software analysis	km ²	Schumm (1956)
Watershed Perimeter(P)	GIS software analysis	km	Schumm (1956)
Watershed Length (L _b)	GIS software analysis	km	---
Maximum Elevation (H _{max})	GIS software analysis	km	---
Minimum Elevation (H _{min})	GIS software analysis	km	---
Linear Aspects			
Stream order (U)	Hierarchical rank	Dimensionless	Strahler (1964)
Stream number (N _u)	$N_u = N_{u1} + N_{u2} + \dots + N_{un}$	Dimensionless	Horton (1945)
Stream length (L _u)	$L_u = L_{u1} + L_{u2} + \dots + L_{un}$	km	Horton (1945)
Mean stream length (L _{sm})	$L_{sm} = \frac{\sum_{u=1}^n L_u}{N_u}$	km	Horton (1945)
Stream length ratio (R _L)	$R_L = \frac{L_{sm}}{L_{sm-1}}$	Dimensionless	Horton (1945)
Bifurcation ratio (R _b)	$R_b = \frac{N_u}{N_{u+1}}$	Dimensionless	Schumm (1956)
Mean Bifurcation ratio (R _{bm})	Average of bifurcation ratios of all orders	Dimensionless	Schumm (1956)
Rho coefficient (ρ)	$\rho = \frac{R_b}{R_L}$	Dimensionless	Horton (1945)
Areal Aspects			
Drainage density (D _d)	$D_d = \frac{L_u}{A_u}$	km/km ²	Schumm (1956)
Stream frequency (F _s)	$F_s = \frac{N_u}{A_u}$	km ⁻²	Schumm (1956)
Drainage intensity (D _i)	$D_i = \frac{L_u}{A_u}$	km ⁻¹	Faniran (1968)
Drainage texture (D _T)	$D_T = \frac{L_u}{A_u}$	km ⁻¹	Schumm (1956)
Length of overland flow (L _g)	$L_g = \frac{1}{2} D_d$	km	Schumm (1956)
Form factor (F _f)	$F_f = \frac{A_u^2}{L_u^2}$	Dimensionless	Horton (1945)
Elongation ratio (R _e)	$R_e = \frac{L_u}{\sqrt{A_u}}$	Dimensionless	Schumm (1956)
Circulatory ratio (R _c)	$R_c = \frac{L_u^2}{A_u}$	Dimensionless	Miller (1953)
Compactness coefficient (Cc)	$C_c = \frac{L_u}{\sqrt{\pi A_u}}$	Dimensionless	Horton (1945)
Lemniscate's ratio (K)	$K = \frac{L_u^2}{A_u^2}$	Dimensionless	Chorley et al. (1957)
Relief Aspects			
Relief (R)	$R = H_{max} - H_{min}$	km	Strahler (1952)
Relative relief (R _{hp})	$R_{hp} = \frac{R}{H_{max}}$	Dimensionless	Melton (1957)
Relief ratio (R _r)	$R_r = \frac{R}{H_{min}}$	Dimensionless	Schumm (1956)

Parameters	Formula/Methods	Unit	Reference
Ruggedness number (R_n)	$R_n = R \times D_d$	Dimensionless	Strahler (1964)
Constant of channel maintenance (C)	$C = b_d$	km	Schumm (1956)
Infiltration number (I_f)	$I_f = D_d \times F_s$	km^{-3}	Faniran (1968)
Dissection index (DI)	$DI = \frac{R_{hp}}{R_{max}}$	Dimensionless	Nir (1957)

geometric progression, reflecting systematic reduction in channel frequency with increasing order (Fig. 3). This parameter provides important insights into watershed hydrological behavior, particularly surface runoff features and infiltration capacity. A watershed with high numbers of first order stream indicates highest infiltration and permeability, often indicative of dissected terrain drainage networks with many streams across multiple orders may reflect lithological controls such as soft sedimentary formation including shale and slate which promote dense drainage networks (Biswas, 2016). In the present study, first order stream is most abundant, with the highest count observed at SW3 (240) and the lowest at SW10 (20) indicating spatial variability in drainage density and surface runoff response across the sub watershed.

Stream length (Lu)

Stream length is defined as the distance between the source and outlet of a stream, which is fundamental morphometric parameter controlling drainage development and runoff dynamics. The analysis of the 13 sub watershed (Table 2) demonstrate that SW3 exhibits the maximum total stream length 740.77 km while minimum stream length exhibits by SW10 (70.41 km). Typically stream length increase with stream order, while shorter length are associated with steep slope and fine texture and longer length occur in areas of lower slope (Strahler 1964). This parameter also measure the hydrological behavior and lithological characteristics of the watershed. Permeable and well drained watershed have fewer and longer stream length whereas impermeable bedrock is characterized by shorter stream length (Sethupathi et al., 2011)

Stream length ratio (R_L): It is defined as the ratio of mean stream length of the given order to that of the next lower order (Horton, 1945), generally increases with stream order, reflecting progressive stream development and providing insights into basin evolution and lithological controls (Fig. 4). Stream length ratio shows lower values at SW10 (1.387), SW5 (1.636) and SW5 (1.636) but significant variability with higher values in SW4 (9.99), SW11 (10.71) and SW12 (63.12). The exceptional higher value of R_L in SW12 is resulted from the stream order truncation caused by clipping from the basin during sub watershed delineation. The coefficient of determination (R^2) indicates the degree of correlation between stream order and stream number (Fig. 3) and between stream order and stream length (Fig. 4). Higher R^2 value as shown by SW1, SW2 and SW5 have strong conformity with Horton's law and well-organized drainage network but lower values (SW11, SW12 and SW13) suggest weak relationships and deviate from the theoretical model. These deviations indicate strong geometric, geomorphic, and structural controls, including sub basin confluence effects and lithological heterogeneity. High R_L values suggest large stream extension and erosion potential whereas low values reflect constrained stream development. As R_L is sensitive to the stream length of the preceding order, local anomalies strongly influence its magnitude. The drainage system in UYRB exhibits only partial conformity to Horton's law with pronounced spatial variability.

Bifurcation ratio (R_b)

It is the ratio of the number of streams of a given order (N_u) to the number streams of the next higher order (N_{u+1}) (Schumm 1956). It quantifies the branching pattern of a drainage network within the watershed, providing the hierarchical structure and geological control. Low values of R_b shows that the watershed has less structurally disturbed without any distortion in drainage network. The mean calculates R_b value of the sub watershed range from 1.56 to 4.50 which commonly report for natural drainage network. The values suggest that the drainage networks are generally dendritic and developed under relatively homogenous lithological and geomorphological controls with some structural disturbances. SW4 exhibited the highest mean R_{bm} ratio (4.5), followed by SW11 (2.80) and SW 2 (2.37) indicating well developed and mature drainage network with elongated basin geometry and moderate geological control. SW9 (2.07) show slightly lower R_{bm} suggesting less branching and possible lithological variation. From the hydrological perspective, R_{bm} values range from 1.56 to 4.50 is consistent in our analysis and suggesting the structure might not dominate the drainage network (Dikpal et al., 2017). But value varies significantly depending on local topography, geology, and climatic conditions. Higher value of R_{bm} generally correspond to elongated watershed with slower runoff concentration and reduced peak discharge whereas lower R_{bm} values are associated with rapid flow concentration thereby increasing flood potential. Spatial variation of R_{bm} reflect the combined influence of topography, lithology, tectonic setting and erosion on watershed morphology and hydrological behavior.

Rho coefficient (ρ)

It defined the ratio of stream length (RL) to bifurcation ratio (R_b), is an important dimensionless parameter used to evaluate drainage development and the storage capacity of the watershed. It also tells the relationship between drainage density and basin physiographic characteristics. The calculated ρ coefficient values show variation among the studied sub watershed (Table 2). Here, ρ coefficient is higher at SW11 (27.521), SW4 (4.948) and SW9 (1.312) while lower at SW6 (0.431), SW12 (0.467) and SW10 (0.53). The exceptional high value of ρ observed at SW11 (27.52) is consequence of the stream order truncation caused by clipping from the basin during sub watershed delineation. It suggests the highest storage capacity during floods and greater hydrological buffering capacity within the sub watershed.

Table 2
Computed morphometric parameter of the delineated sub watershed of the UYRB.

Sl No.	Parameter	Morphometric parameter computed for the delineated sub watershed											
		SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
1	Area (A)	535.158	973.646	1436.795	478.895	526.572	325.823	218.020	806.168	758.087	130.243	123.475	85.475
2	Perimeter (P)	162.375	232.725	261.225	140.075	149.750	120.475	103.275	204.250	190.600	92.875	88.125	20.475
3	Length (Lb)	46.528	65.365	81.533	43.683	46.102	35.100	27.938	58.720	56.704	20.850	20.228	60.475
4	Maximum elevation (H)	5419	6284	5210	3772	3409	3109	3146	6241	3017	2666	2218	35.475
5	Minimum elevation (h)	1229	1230	878	880	752	731	1006	1002	632	438	418	41.475
6	Highest stream order (U)	4	5	5	5	4	6	4	4	5	3	5	6.475
7	No. of Streams (Nu)	165	343	478	153	187	117	81	267	247	39	49	29.475
8	Length of streams (Lu)	261.712	513.103	740.769	260.159	277.007	185.658	120.667	409.385	409.052	70.413	85.451	46.475
9	Mean stream length (Lsm)	6.175	6.988	7.444	10.810	5.722	9.969	5.797	6.258	8.190	5.510	10.836	6.475
10	Stream length ratio (R _L)	1.840	1.898	3.037	9.986	1.636	6.958	1.847	1.806	5.411	1.387	10.714	6.475
11	Bifurcation Ratio (Rb)	5.268	9.481	7.194	17.994	5.160	9.925	5.163	4.951	8.286	3.111	11.198	7.475
12	Mean Bifurcation Ratio (Rbm)	1.756	2.370	1.799	4.498	1.720	1.985	1.721	1.650	2.072	1.556	2.800	1.475
13	RHO Coefficient (ρ)	0.604	0.880	0.989	4.948	0.686	0.431	0.621	0.939	1.312	0.530	27.521	0.475
14	Mean stream length ratio (R _{lm})	0.920	0.759	1.215	3.994	0.654	1.392	0.924	0.903	2.164	0.925	4.286	2.475
15	Drainage density (Dd)	0.489	0.527	0.516	0.543	0.526	1.541	0.553	0.508	0.540	0.541	0.692	0.475
16	Stream frequency (Fs)	0.308	0.352	0.333	0.319	0.355	0.971	0.372	0.331	0.326	0.299	0.397	0.475
17	Drainage intensity (Di)	0.630	0.668	0.645	0.588	0.675	0.630	0.671	0.652	0.604	0.554	0.573	0.475
18	Drainage texture (T)	1.016	1.474	1.830	1.092	1.249	3.333	0.784	1.307	1.296	0.420	0.556	1.475
19	Length of overland flow (Lg)	1.022	0.949	0.970	0.920	0.950	0.324	0.903	0.985	0.927	0.925	0.722	0.475
20	Form factor (Ff)	0.247	0.228	0.216	0.251	0.248	0.264	0.279	0.234	0.236	0.300	0.302	0.475
21	Elongation ratio (Re)	0.561	0.539	0.525	0.565	0.562	0.580	0.597	0.546	0.548	0.618	0.620	0.475
22	Circulatory ratio (Rc)	0.255	0.226	0.264	0.307	0.295	0.282	0.257	0.243	0.262	0.190	0.200	0.475
23	Compactness coefficient (Cc)	1.981	2.104	1.945	1.806	1.841	1.883	1.974	2.030	1.953	2.296	2.238	1.475
24	Relief (R)	4.190	5.054	4.332	2.892	2.657	2.378	2.140	5.239	2.385	2.228	1.800	3.475
25	Relative relief (Rhp)	2.580	2.172	1.658	2.065	1.774	1.974	0.982	2.565	1.251	2.399	2.043	1.475
26	Relief ratio (Rr)	0.090	0.077	0.053	0.066	0.058	0.068	0.077	0.089	0.042	0.107	0.089	0.475

SI No.	Parameter	Morphometric parameter computed for the delineated sub watershed											
		SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
27	Ruggedness number (Rn)	2.049	2.663	2.233	1.571	1.398	3.665	1.184	2.660	1.287	1.205	1.246	1.184
28	Constant of channel maintenance (C)	2.045	1.898	1.940	1.841	1.901	0.649	1.807	1.969	1.853	1.850	1.445	1.184
29	Infiltration number (If)	0.151	0.186	0.172	0.174	0.187	1.497	0.206	0.168	0.176	0.162	0.275	0.151
30	Dissection index (Di)	0.476	0.346	0.318	0.547	0.520	0.635	0.312	0.411	0.415	0.900	0.921	0.476
31	Lemniscate ratio (K)	1.011	1.097	1.157	0.996	1.009	0.945	0.895	1.069	1.060	0.834	0.828	1.011

3.2 Areal aspect:

Drainage density (D_d)

It defined as the total stream length per unit watershed area (Horton 1945) reflects the degree of channel development and drainage network dissection within the watershed. In the present study, higher D_d values in SW6 (1.54 km/km^2), indicate closely space channel, higher runoff potential and lower infiltration capacity whereas lower values in SW1 (0.49 km/km^2), SW8 (0.51 km/km^2) and SW3 (0.52 km/km^2) suggesting permeable terrain, reduced drainage dissection and greater infiltration potential.

Stream frequency (F_s)

It defined as the number of stream segment per unit watershed area (Horton 1945), reflecting the drainage texture and runoff potential within a watershed. F_s show a positive relation with drainage density, indicating increased stream population with greater drainage development (Suji et al., 2015). In the present study, higher F_s value observed in SW6 (0.97 km^{-2}) indicating intense drainage dissection, higher runoff generation and lower infiltration capacity while lower values at SW10 (0.3 km^{-2}), SW 1(0.31 km^{-2}) and SW4 (0.32 km^{-2}) suggest relatively permeable terrain, reduce surface runoff and higher infiltration potential.

Drainage intensity (D_i)

It is defined as the dimensionless ratio between of stream frequency to drainage density (Faniran 1968), which represents the efficiency of drainage network in conveying surface runoff. In the present study, sub watershed SW5 (0.68 km^{-1}), SW2 (0.67 km^{-1}) and SW7 (0.67 km^{-1}) exhibit higher D_i values, indicating relatively better drainage efficiency and lower susceptibility to geomorphic hazards. But SW10 (0.55 km^{-1}) and SW11 (0.57 km^{-1}) show low D_i suggesting a greater potential for flood generation, erosion processes and slope instability, thereby reflecting a higher geomorphic impact and environmental sensitivity. SW4 (0.59 km^{-1}) and SW9 (0.60 km^{-1}) have intermediate D_i values suggesting a balance interaction between infiltration and surface runoff processes.

Drainage texture (D_t)

It defines as the number of stream segment per unit watershed perimeter (Horton 1945). It is an important indicator of drainage dissection and terrain characteristics. Higher D_t values observed in SW6 (3.33 km/km^2), SW3 (1.83 km/km^2) and SW12 (1.45 km/km^2) suggest finer drainage texture, closed space channel, higher runoff response and greater susceptibility to erosion. In contrast, lower D_t values in SW10 (0.42 km/km^2), SW11 (0.56 km/km^2), SW7 (0.78 km/km^2) and SW13 (0.90 km/km^2) suggesting a sparsely distributed drainage network, greater infiltration capacity and lower runoff and sediment transport potential.

Length of overland flow (L_g)

It is defined as the half of the reciprocal of drainage density (Horton 1945), representing the average distance travelled by surface runoff before it is connected into defined stream channel. In the study area, higher L_g values observed in SW1 (1.02 km^{-1}), SW8 (0.98 km^{-1}), SW3 (0.97 km^{-1}) and SW13 (0.94 km^{-1}) indicate comparatively longer runoff travel path, lower drainage dissection and higher infiltration potential and delayed hydrological response. Conversely, lower L_g values in SW6 (0.36 km^{-1}) and SW11 (0.72 km^{-1}) suggest closely spaced drainage channels, rapid flow concentration, reduced infiltration opportunity and greater surface runoff potential. These variations imply difference in terrain characteristics, slope conditions, permeability, and drainage development among the sub watersheds.

Figure 4: Relationship between stream order and stream length.

Form factor (F_f)

It is defined as the ratio of watershed area to the square of the watershed length (Strahler 1964) and is used to evaluate watershed shape and runoff characteristics. Higher values of F_f represent more circular watershed and produce higher peak flow within a shorter duration whereas lower F_f values indicate elongated watershed with delayed runoff and lower peak discharge (Horton 1945). In the present study, the F_f value range from 0.22 to 0.30 suggesting elongated watershed geometry and slower runoff concentration.

Elongation ratio (R_e)

It is defined as the ratio between the diameter of a circle having the same area as the watershed and the maximum watershed length (Schumm 1956). Generally, R_e values close to 1 indicate nearly circular watershed with rapid runoff concentration and higher flood potential whereas lower values represent elongated watershed with slower runoff movement and delayed peak discharge. In the present study, the R_e range from 0.52 to 0.62 which represent elongated watershed showing delayed hydrological response.

Circulatory ratio (R_c)

It is the ratio of watershed area to the area of a circle having the same perimeter as the watershed (Miller 1953). It is an important geomorphological parameter that describes the shape and compactness of a watershed area. Lower R_c values indicate elongated watershed with longer runoff travel times and delayed peak flow whereas higher R_c values represent more circular watershed and concentrate runoff and prone to flooding. Lower, moderate, and higher values of R_c represent young, mature, and old stages of watershed development respectively. Among the analysed sub watershed, SW4 (0.31), SW5 (0.29) and SW6 (0.28) have higher R_c values suggesting compact watershed with faster runoff response and greater flood susceptibility whereas SW10 (0.19) show lower value of R_c indicating elongated watershed and slower runoff concentration.

Compactness coefficient (C_c)

It is defined as the ratio of the watershed perimeter to the circumference of the circle having the same area as the watershed. It reflects watershed shape and compactness and is largely independent of watershed size, though influence by slope characteristics. In the present study, SW10 (2.296), SW11 (2.238), SW2 (2.104), and SW8 (2.03) exhibit higher C_c values, indicating elongated watershed with delayed runoff response whereas SW4 (1.81), SW5 (1.84) and SW6 (1.88) have lower compactness coefficient values, suggesting relatively compact watershed geometry and rapid runoff generation.

Lemniscate's ratio (K)

It is used to evaluate watershed shape and slope characteristics (Chorley et al., 1957). Lower K values indicate relatively compact watershed with steeper gradients and faster runoff concentration whereas higher values represent elongated watershed with gentle slope and delayed runoff response. In the present study, higher K values exhibit by SW3 (1.157), SW2 (1.097), and SW12 (1.078) suggesting slower runoff movement extended flow duration whereas SW11 (0.828), SW12 (0.834) and SW7 (0.895) have lower K values suggesting rapid runoff movement.

3.3 Relief Aspect:

Relative relief (R_{hp})

It is important morphometric parameter that represents the elevation disparity within a watershed. It is calculated by dividing watershed relief by the watershed perimeter (Melton 1957). In this present study, sub watershed SW1 (2.58), SW8 (2.565) and SW10 (2.399) represents the higher value SW7 (0.982) and SW9 (1.251) have lower values in relative relief. Sub watershed wise relative relief value is shown in the Table 2.

Relief ratio (R_r)

It is the ratio of maximum watershed relief to the watershed length measure along the main river channel (Schumm 1956). It tells overall watershed steepness and the intensity of the erosional processes. In the present study, SW10 (0.107) and SW1 (0.09) exhibit higher R_r values representing steep terrain and active erosion while SW 9 (0.042), SW 12 (0.052) and SW 3 (0.053) values represent gentle slope and reduce erosion intensity.

Ruggedness Number (R_n)

It is the combined effect of watershed relief and drainage density (Strahler 1964). It represents terrain ruggedness, slope steepness and erosion susceptibility within the watershed. In the present study, SW6 (3.665), SW2 (2.663) and SW8 (2.66) have higher value of R_n indicating steep and highly dissected terrain while SW7 (1.184), SW10 (1.205) and WS 11(1.246) have lower R_n values representing gentle and stable topography.

Infiltration number (I_f)

It is defined as the product of drainage density and frequency (Faniran 1968) reflecting the runoff and infiltration characteristics of a watershed. In the present study SW 6 (1.5 km) and SW11 (0.27 km) have higher value of infiltration number suggesting rapid runoff generation and greater susceptibility to erosion and flash floods. In contrast, SW1 (0.15 km) and SW10 (0.16 km) show lower I_f values, indicating better reduced runoff response and relatively stable hydrological conditions.

Dissection index (D_i)

It measures the degree of landscape incision and erosional development within a watershed (Pal et al., 2012). The sub watershed SW11 (0.92) and SW 10 (0.90) have higher D_i values which indicate dissected terrain with steep valley and intense erosion while SW7 (0.31), SW3 (0.32), and SW 8 (0.41) and SW9 (0.41) exhibit lower D_i values representing smoother, slower runoff response and less eroded surfaces.

3.4 Statistical analysis: It identifies the interrelationship of parameter and provide insight into topographical characteristic of a watershed for its management, planning and development of the area. In this present study, the relationship among different morphometric parameters were evaluated using Pearson's correlation and relation among them were analyzed. The correlation matrix reveals strong structural coherence among morphometric parameters (Table 3). Basin size parameter such as area (A), perimeter (P), stream number (Nu) and stream length (Lu) is highly correlated ($r = 0.984$ to 0.998) which indicate scale control drainage development. Drainage density (D_d) and stream frequency (F_s) show near perfect correlation ($r = 0.992$) and strong positive association with infiltration number (I_f) $r = 0.995$ highlighting their dominant control on runoff generation, reduced infiltration and enhanced runoff indicating of susceptibility to erosion and flash flooding. Length of overland flow (L_g) is strongly negatively correlated with D_d ($r = -0.975$) and F_s ($r = -0.953$), confirming that increased drainage density shortens flow paths and accelerates hydrological response. Moderate negative correlation between basin shape parameter (elongation and compactness coefficient) and drainage variables, suggest that more compact watershed tend to have slightly higher runoff efficiently although, this relationship is less pronounced. D_i shows strong negative correlation with watershed size variables ($r = -0.71$ to -0.73) indicating that less extensive watershed is relatively more hydrologically active and responsive to rainfall events. Overall drainage network parameter emerges as primary controls on runoff and erosion susceptibility, providing a reliable basis for sub watershed prioritization.

Table 3
Correlation matrix representing the interrelationship among the different morphometric parameters

A	A	P	Nu	Lu	Lsm	Dd	Fs	Lg	Cc	C	If	DI
	1	0.984	0.997	0.998	-0.119	-0.273	-0.222	0.364	-0.247	0.364	-0.226	-0.714
P	0.984	1	0.984	0.982	-0.165	-0.293	-0.237	0.391	-0.215	0.391	-0.242	-0.735
Nu	0.997	0.984	1	0.998	-0.122	-0.256	-0.2	0.341	-0.241	0.341	-0.21	-0.717
Lu	0.998	0.982	0.998	1	-0.089	-0.255	-0.205	0.338	-0.247	0.338	-0.211	-0.707
Lsm	-0.119	-0.165	-0.122	-0.089	1	0.49	0.426	-0.583	-0.104	-0.583	0.434	0.297
Dd	-0.273	-0.293	-0.256	-0.255	0.49	1	0.992	-0.975	-0.157	-0.975	0.995	0.258
Fs	-0.222	-0.237	-0.2	-0.205	0.426	0.992	1	-0.953	-0.223	-0.953	0.997	0.163
Lg	0.364	0.391	0.341	0.338	-0.583	-0.975	-0.953	1	0.053	1	-0.95	-0.37
Cc	-0.247	-0.215	-0.241	-0.247	-0.104	-0.157	-0.223	0.053	1	0.053	-0.211	0.52
C	0.364	0.391	0.341	0.338	-0.583	-0.975	-0.953	1	0.053	1	-0.950	-0.37
If	-0.226	-0.242	-0.21	-0.211	0.434	0.995	0.997	-0.95	-0.211	-0.95	1	0.189
DI	-0.714	-0.735	-0.717	-0.707	0.297	0.258	0.163	-0.37	0.52	-0.37	0.189	1

4. Morphometric Ranking and Prioritization of sub watershed:

Watershed prioritization based on morphometric parameters was analysed for the sub watersheds (SW1, SW2, SW3, SW4, SW5, SW6, SW7, SW8, SW9, SW10, SW11, SW12 and SW13) of the UYRB. Linear and relief morphometric parameter show a direct relationship with soil erodibility, where higher values indicate greater susceptibility to soil erosion within a watershed (Sujatha et al., 2015). Therefore, sub watershed with highest values of linear and relief parameter were rated as first rank, second higher as second rank and followed the subsequent lower values. But areal and shape parameter have an inverse relationship with soil erodibility (Raja et al., 2017), where lowest value indicates higher erosion susceptibility. Hence, sub watershed with the lowest areal/shape parameter values were rated as higher priority ranks. The compound parameter method was used for prioritization, assuming equal importance for all morphometric parameters (Farhan 2017). After ranking all thirteen-sub watershed for each parameter, the ranking values were summed and divided by the total number of parameters, in this case, it has divided by twenty and obtain the compound value. So, the sub watershed with the lowest value of compounded value was assigned the highest priority and denoted by number 1, the next higher value denoted by number 2 and so on, then the sub watershed with highest compounded value received the lowest priority rank (Ayele et al., 2017). The prioritization result implies that higher priority sub watershed is vulnerable to runoff generation, peak discharge, and soil erosion. Thus, suitable land and water management practices should be implemented based on their priority ranks. Twenty morphometric parameters were selected for ranking and prioritization of the sub watersheds based on the values obtained from the calculation (Table 4).

Figure 5 shows that the final priority map of the sub watersheds. In this present study, the medium priority categories constitute the largest portion covering of 46.48% of the total watershed area. The very high priority zone account for 23.82% while 11.41% for high priority zone. The low priority zone covers only 18.29% of the total watershed area. The sub watershed SW2, SW8, WS5 and WS6 are four sub watersheds which occupies the very high to high category of prioritization, so they are relatively more susceptible to land degradation, water retention ability and soil erosion due to their geomorphometric characteristics. Hence, these sub watersheds require immediate attention of appropriate soil and water conservation measures based on the final priority ranking.

Table 4
Detailed of the prioritized zone of the Upper Yamuna River Basin sub watersheds.

Sl No	Parameter	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11
1	Rbm	1.756[5]	2.37[11]	1.799[7]	4.498[13]	1.72[3]	1.985[9]	1.721[4]	1.65[2]	2.072[10]	1.556[1]	2.8[12]
2	ρ	0.604[10]	0.88[6]	0.989[4]	4.948[2]	0.686[8]	0.431[13]	0.621[9]	0.939[5]	1.312[3]	0.53[11]	27.521
3	Rlm	0.92[4]	0.759[2]	1.215[7]	3.994[11]	0.654[1]	1.392[8]	0.924[5]	0.903[3]	2.164[10]	0.925[6]	4.286[1]
4	Dd	0.489[13]	0.527[9]	0.516[11]	0.543[5]	0.526[10]	1.541[1]	0.553[3]	0.508[12]	0.54[7]	0.541[6]	0.692[2]
5	Fs	0.308[12]	0.352[5]	0.333[8]	0.319[11]	0.355[4]	0.971[1]	0.372[3]	0.331[9]	0.326[10]	0.299[13]	0.397[2]
6	Di	0.63[8]	0.668[3]	0.645[6]	0.588[11]	0.675[1]	0.63[8]	0.671[2]	0.652[5]	0.604[10]	0.554[13]	0.573[1]
7	T	1.016[9]	1.474[3]	1.83[2]	1.092[8]	1.249[7]	3.333[1]	0.784[11]	1.307[5]	1.296[6]	0.42[13]	0.556[1]
8	Lg	1.022[1]	0.949[5]	0.97[3]	0.92[9]	0.95[4]	0.324[13]	0.903[11]	0.985[2]	0.927[7]	0.925[8]	0.722[1]
9	Ff	0.247[6]	0.228[2]	0.216[1]	0.251[8]	0.248[7]	0.264[9]	0.279[11]	0.234[4]	0.236[5]	0.3[12]	0.302[1]
10	Re	0.561[6]	0.539[2]	0.525[1]	0.565[8]	0.562[7]	0.58[9]	0.597[11]	0.546[4]	0.548[5]	0.618[12]	0.62[13]
11	Rc	0.255[6]	0.226[3]	0.264[9]	0.307[13]	0.295[12]	0.282[11]	0.257[7]	0.243[4]	0.262[8]	0.19[1]	0.2[2]
12	Cc	1.981[8]	2.104[11]	1.945[5]	1.806[1]	1.841[2]	1.883[3]	1.974[7]	2.03[10]	1.953[6]	2.296[13]	2.238[1]
13	R	4.19[4]	5.054[2]	4.332[3]	2.892[6]	2.657[7]	2.378[9]	2.14[12]	5.239[1]	2.385[8]	2.228[11]	1.8[13]
14	Rhp	2.58[1]	2.172[4]	1.658[10]	2.065[5]	1.774[9]	1.974[7]	0.982[13]	2.565[2]	1.251[12]	2.399[3]	2.043[6]
15	Rr	0.09[2]	0.077[5]	0.053[11]	0.066[9]	0.058[10]	0.068[8]	0.077[5]	0.089[3]	0.042[13]	0.107[1]	0.089[3]
16	Rn	2.049[5]	2.663[2]	2.233[4]	1.571[7]	1.398[8]	3.665[1]	1.184[13]	2.66[3]	1.287[9]	1.205[12]	1.246[1]
17	C	2.045[13]	1.898[9]	1.94[11]	1.841[5]	1.901[10]	0.649[1]	1.807[3]	1.969[12]	1.853[7]	1.85[6]	1.445[2]
18	If	0.151[13]	0.186[6]	0.172[10]	0.174[9]	0.187[5]	1.497[1]	0.206[3]	0.168[11]	0.176[8]	0.162[12]	0.275[2]
19	DI	0.476[7]	0.346[11]	0.318[12]	0.547[5]	0.52[6]	0.635[4]	0.312[13]	0.411[10]	0.415[9]	0.9[2]	0.921[1]
20	K	1.011[8]	1.097[12]	1.157[13]	0.996[6]	1.009[7]	0.945[5]	0.895[3]	1.069[10]	1.06[9]	0.834[2]	0.828[1]
Compounded parameter (Cp)		7.05	5.65	6.9	7.6	6.4	6.1	7.45	5.85	8.1	7.9	7.2
Ranking		6	1	5	11	4	3	10	2	13	12	7
Final Priority		Medium	Very high	Medium	Low	High	High	Medium	Very high	Low	Low	Medium
% of area		7.16	13.03	19.23	6.41	7.05	4.36	2.92	10.79	10.14	1.74	1.65

4.1 Groundwater recharge potential:

The groundwater recharge is controlled by morphometric parameters such as drainage density, stream frequency and length of the overland flow which reflect infiltration capacity of the surface and surface runoff (Diksha et al., 2019). SW1, SW12 and SW3 have low drainage density indicating highly permeable subsurface dense vegetation cover favoring groundwater infiltration (Strahler 1964). The study reveals that the sub watersheds SW1, SW3, SW4, SW5, SW6 and SW8 exhibit favorable condition for groundwater recharge.

5. Conclusion

The integrated application of geospatial techniques and statistical analysis for morphometric parameters has proven effective in deciding the watershed prioritization. Geospatial analysis offers a dynamic, efficient, and reliable alternative to conventional methods by enabling the integration of multiple morphometric parameters for solving complex watershed management problems. In the present study, sub watershed SW2, SW8, WS5 and WS6 require to harness to meet regional water demand. These sub watersheds require immediate attention for water resource conservation and sustainable management. However, morphometric analysis alone is insufficient for watershed characterization and prioritization of sub watershed, it should be integrated with land use and land cover analysis, runoff estimation and sediment yield assessment. The methodology employed in this study provides a useful framework for identifying erosion prone area, runoff, flash flood and planning suitable soil and water conservation strategies. The geospatial analysis can be effectively applied for watershed protection, restoration planning and sustainable natural resource management, particularly in data scarce regions.

5.1 Recommendation practice for policy maker to achieve SDG's.

To ensure water management of sub watershed in UYRB, the policy maker should adopt the holistic and climate responsive approach to meet the United Nation SDG's. The following recommendations may be considered:

1. Sub watershed that falls in highest priority zone may be targeted for rainwater harvesting and recharge structure (Check dam, bund and plantation of multipurpose tree species based on appropriate site conditions) to increase the groundwater resources for the purposes of meeting SDG 6 –Clean water and sanitation.
2. Sub watershed that falls in medium priority zone may be targeted to adopt sustainable agriculture techniques and efficient irrigation, which would help to build resilience against climate change (SDG-13).
3. Regular monitoring of groundwater quality and community education programs will be important in safeguarding public health and wellbeing (SDG – 3). The conservation of natural recharge zone, river and wetlands is recommended in the water management process to sustain stability and biodiversity (SDG – 15).

Declarations

Disclosure

statement: No potential conflict of interest was reported by the author (s).

Author Contribution

RSA: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing; NPM: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Validation; Visualization; Writing – original draft; Writing – review & editing; SPR : Project administration; Resources; Supervision; Validation; Visualization; Writing – review & editing; MO: Conceptualization; Formal analysis; Investigation; Methodology; Resources; Validation; Visualization; Writing – review & editing; AM: Conceptualization; Formal analysis; Investigation; Methodology; Resources; Validation; Visualization; Writing – review & editing; RS: Conceptualization; Formal analysis; Investigation; Methodology; Resources; Validation; Visualization; Writing – review & editing.

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Data Availability

The morphometric data were derived from the Alos Palsar DEM using GIS technique. The derived data are available from the corresponding author upon reasonable request.

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Figures

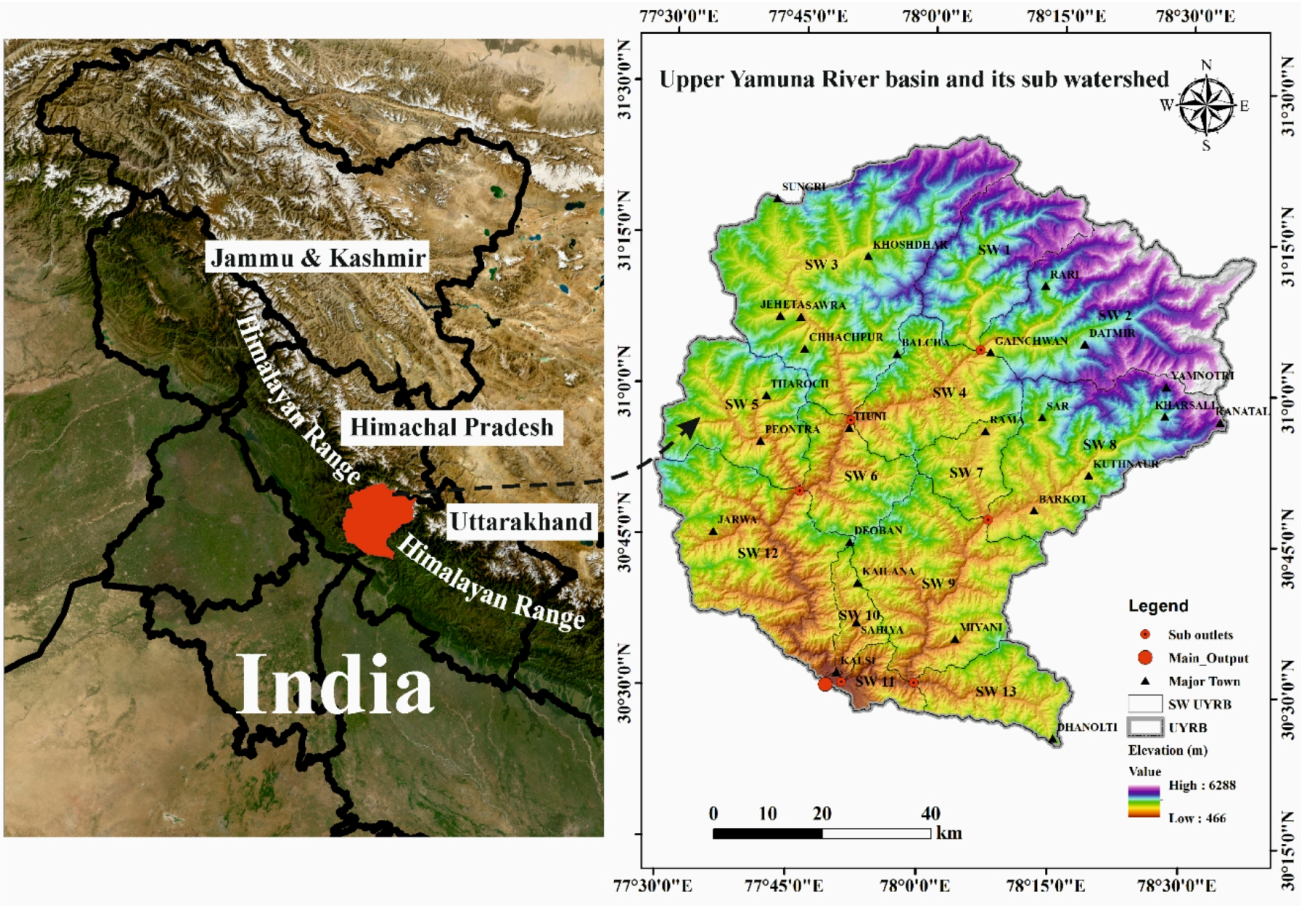


Figure 1
Location of the study area.

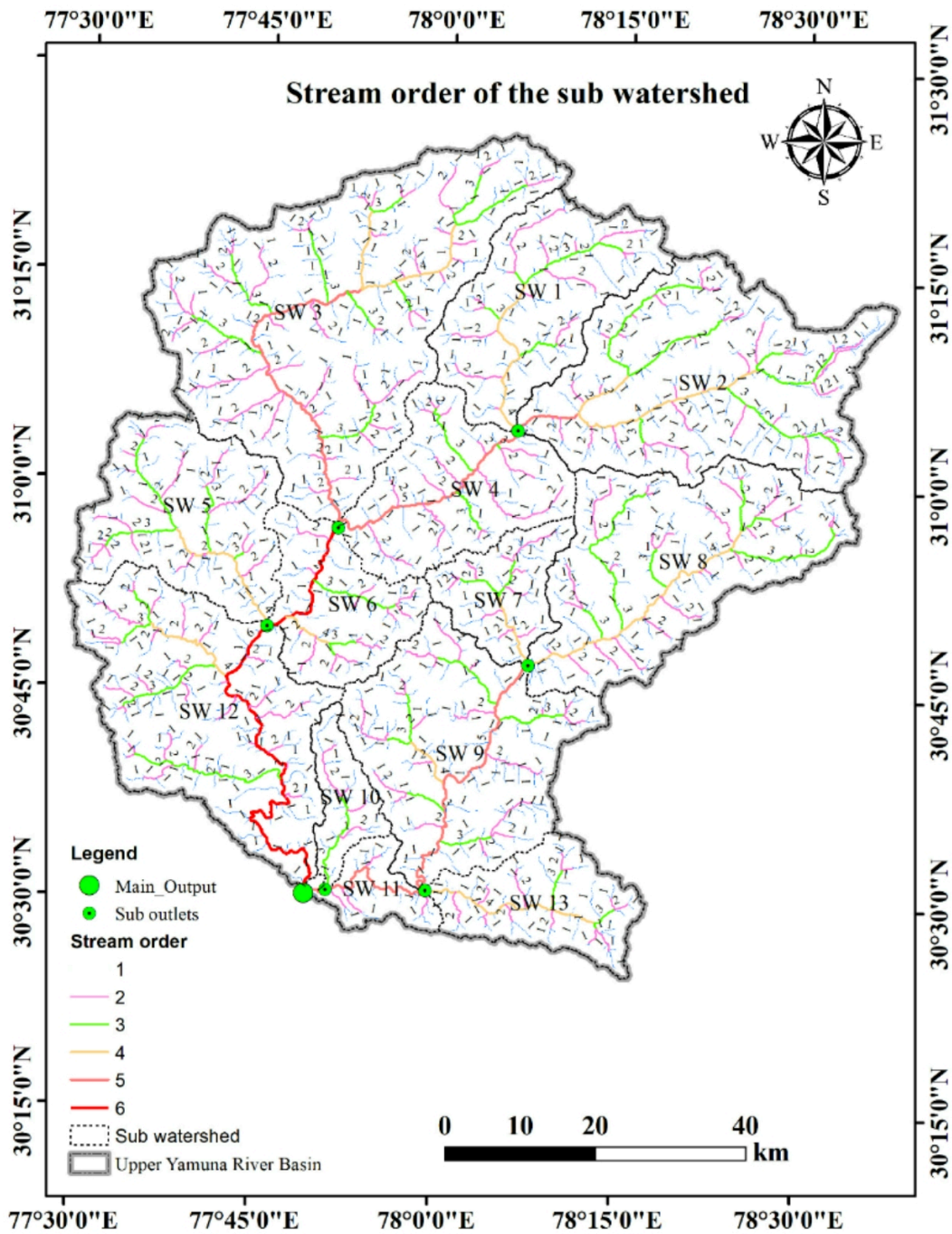


Figure 2

Drainage network and associated stream orders of the UYRB.

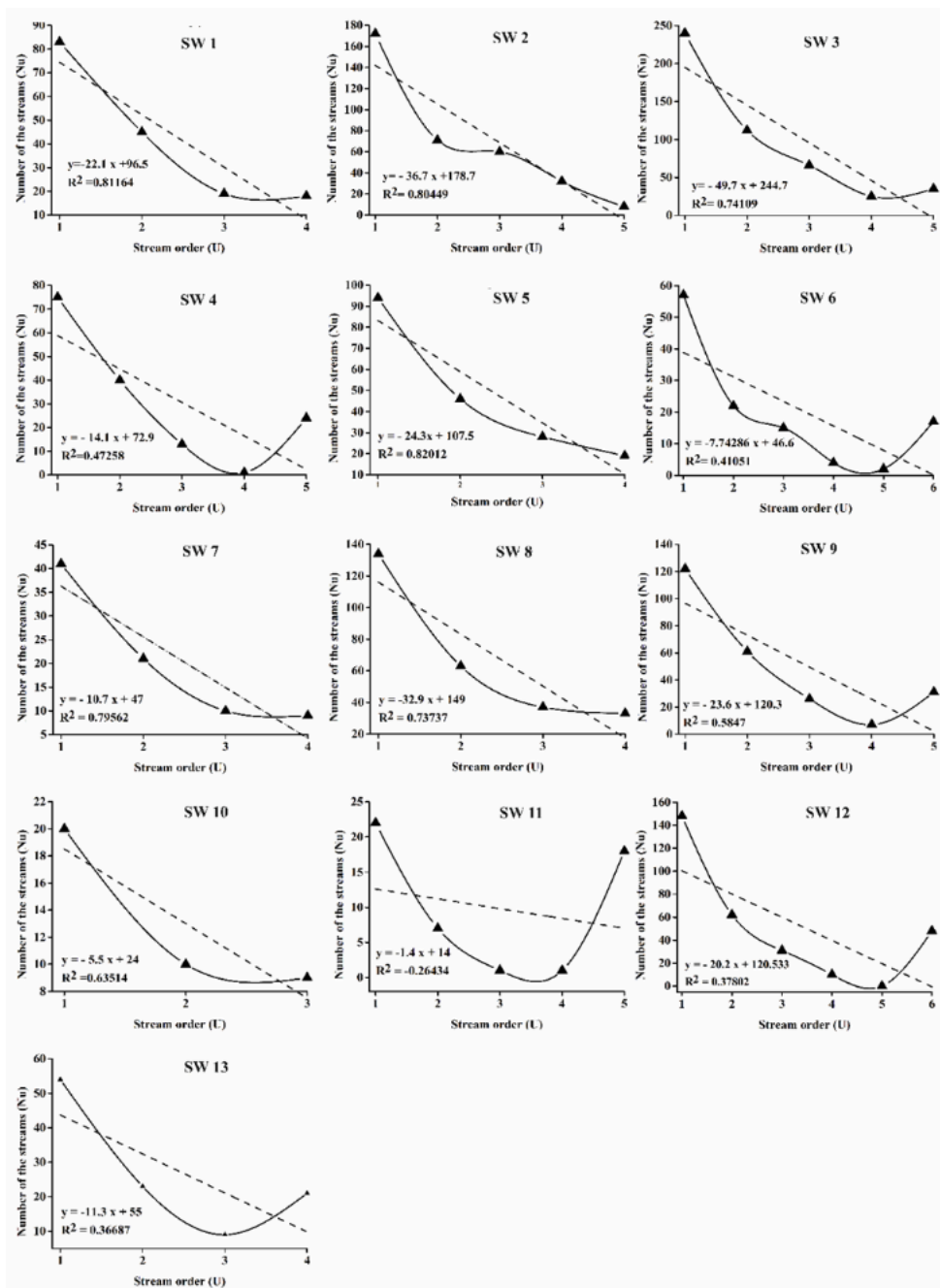


Figure 3

Relationship between stream order and stream number.

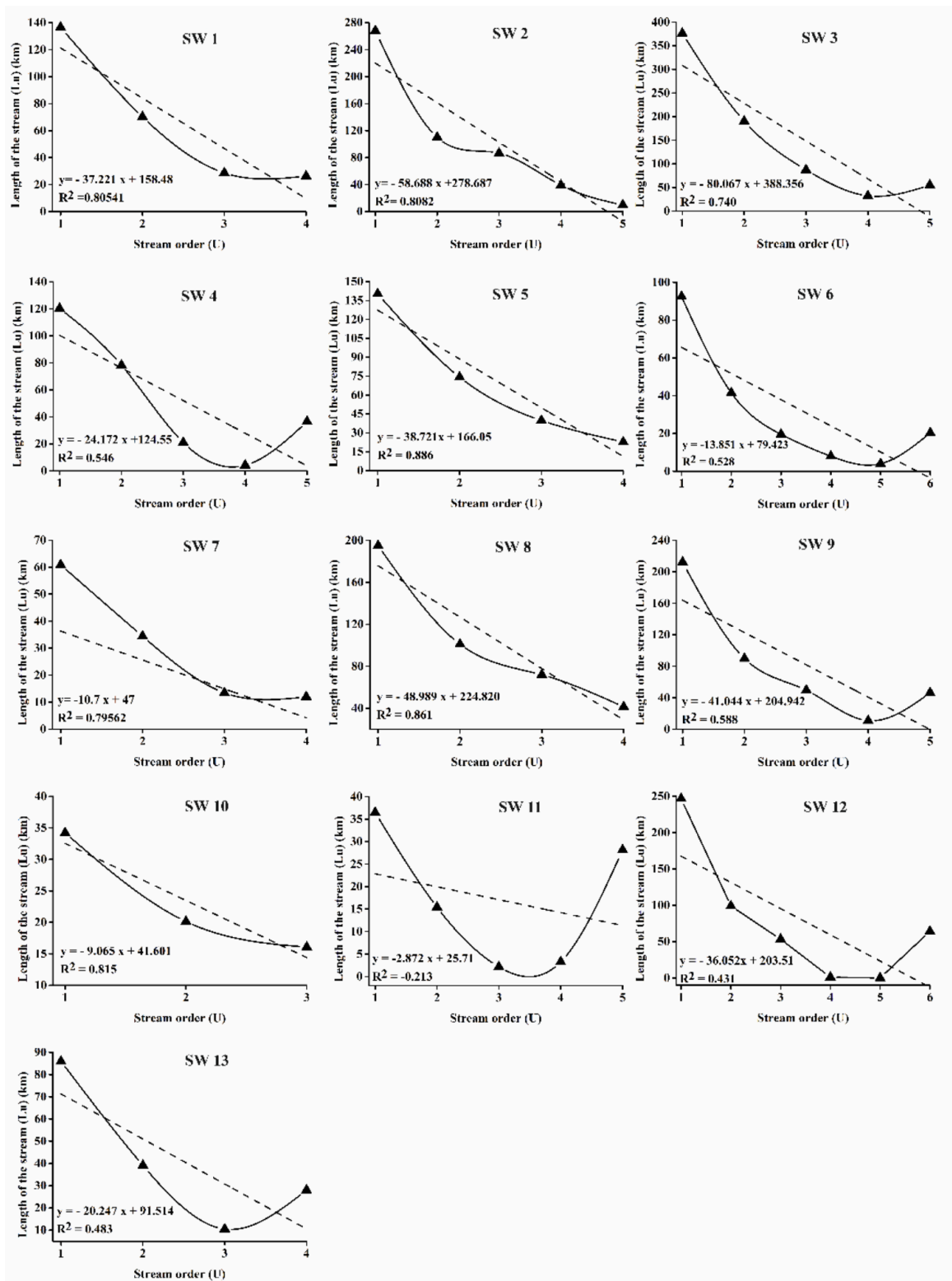


Figure 4

Relationship between stream order and stream length.

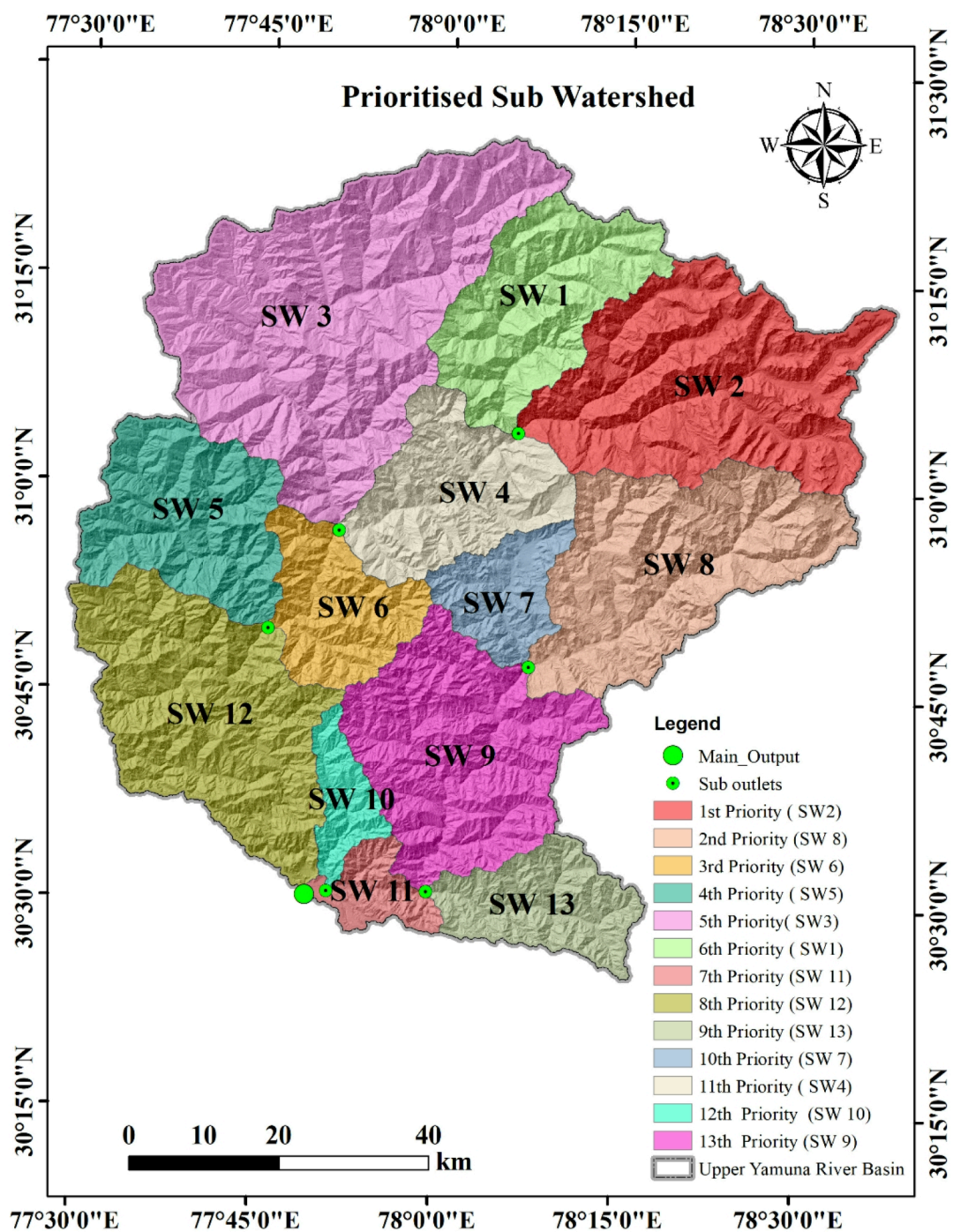


Figure 5

Prioritization of sub watersheds in the UYRB based on integrated morphometric analysis.

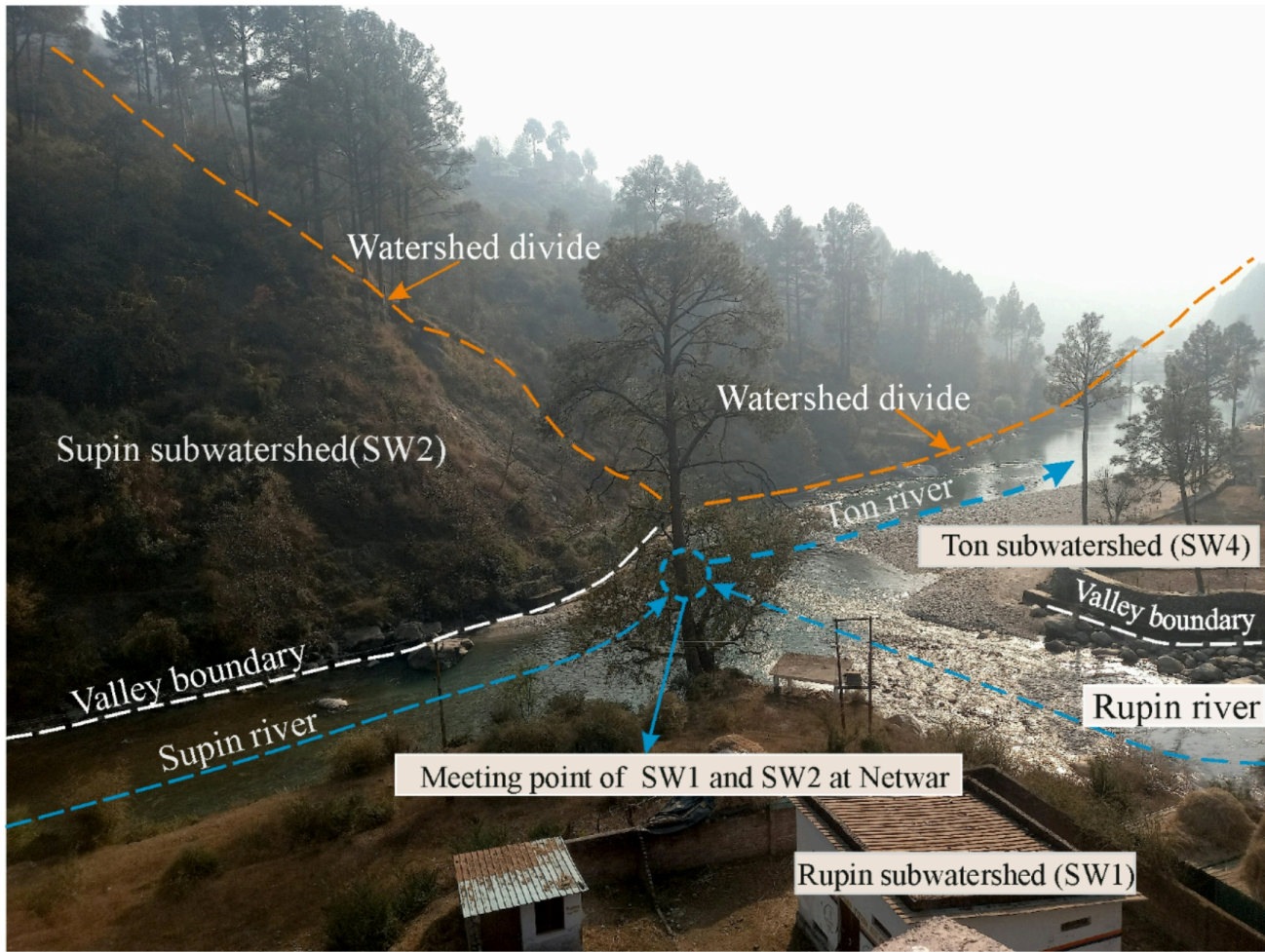


Figure 6

Meeting point of the subwatershed SW1 and SW2 at Netwar.