



GIS-based sub-watershed prioritization through morphometric analysis in the outer Himalayan region of India

Swati Sharma¹ · Mahajan A. K.¹

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Abstract

The study indicates the viability of geographic information system and remote sensing data for the analysis as well as estimation of the stage and the rate of erosional processes in a Himalayan watershed for improved planning and management. The Gaj watershed lies in the outer Himalayan region of Himachal Pradesh, India, which has been characterized in to nine sub-watersheds for studying the geomorphological evolution of each separately for comparative assessment irrespective of any scale issue. The method involves the use of 30 m Cartosat (digital elevation model) for operative and time-saving data extraction of morphometric and hypsometric parameters. The estimated hypsometric integral values and the shape of the hypsometric curves reveal varying degree of erosional stages of the sub-watersheds demanding attention over the denudation activities. The results have helped in the qualitative discussions and prioritizing the sub-watershed for sustainable soil–water conservation and management, which can be useful for controlling the erosional activities at right locations in the study area.

Keywords GIS · DEM · Himalayan watershed · Hypsometry · Sub-watershed prioritization

Introduction

Hypsometric analysis is the study of distribution of the cross-sectional areas of ground surface with respect to its elevations (Strahler 1952), and it is used to characterize the erosional landforms at their different stages of erosion (Schumn 1956). Concept of hypsometry was first introduced by Langbein (1947) which has helped in generating parameters, i.e., hypsometric curve and hypsometric integral (HI) (Ritter et al. 2002). These dimensionless parameters permit the comparisons of various watersheds without considering any scale issues (Dowling et al. 1998). The hypsometric curve allows to evaluate the incision rate of rocks in a basin as compared to the original rock mass (Hurtrez et al. 1999). It also indicates the stage of erosional cycle for landforms in a watershed where the convex upward hypsometric curve is reflected for a young basin, S-shaped curve for mature basin

and concave upward curve for peneplains (Strahler 1952). The other parameter, i.e., the hypsometric integral represents inequilibrium between the erosion and tectonic forces within a basin which can help to find out the surface runoff and sediment yield (Weissel et al. 1994; Pike and Wilson 1971; Garg 1983; Sarangi and Bhattacharya 2000; Jain et al. 2001).

The watershed management and monitoring of the water resources are important for their micro-prioritization which is useful in the sustainable development and for choosing a proper land use pattern. The drainage patterns and drainage parameters provide surface and subsurface information to understand the influence of drainage morphology (Strahler 1964; Clarke 1996; Aggrawal 1998; Obi Reddy et al. 2004). The hypsometric analysis has been used by various researchers for studying the basin parameters (linear, relief and areal) and in watershed prioritization in order to analyze the erosional stages of the respective basins (Ohmori 1993; Rao et al. 1994; Willgoose and Hancock 1998; Pradhan and Senapati 2002; Dabral 2003; Pandey et al. 2004; Shukla et al. 2014; Gajbhiye et al. 2014; Babu et al. 2016; Fenta et al. 2017; Rai et al. 2017). The hypsometric studies for the Himalayan watersheds such as Sainj and Tirthan sub-watersheds of the river Beas in Himachal Pradesh (H.P.), India, watersheds of the Siwalik hills of Central Nepal have been accomplished by Singh and Sarangi (2008), Singh (2009),

✉ Swati Sharma
swati.9238@gmail.com

Mahajan A. K.
akmahajan@rediffmail.com

¹ Department of Environment Science, School of Earth and Environmental Sciences, Central University of Himachal Pradesh, Dharamshala, H.P. 176206, India

Awasthi et al. (2002), respectively, to analyze the erosional cycles and their impacts on the basin morphology.

The Beas River is situated in the Punjab Himalaya originating from the Rohtang Pass near Manali, H.P., and finally it enters the Pong Dam's reservoir in district Kangra, which is mostly active for the irrigation practices in the state of Punjab. This river has many tributaries such as Baner, Neugal and Gaj out of which Gaj tributary forms a major watershed with its provenance area in the Dhauladhar range of Kangra valley, H.P. The basin characteristics of Baner and Neugal watershed of H.P. have been evaluated by Dhar et al. (2005) for studying their geo-environmental impacts. The morphometric analysis of the Neugal watershed of Beas River has been performed by Guleria et al. (2014) to understand the role of erosional processes, whereas the Gaj watershed cutting across the rocks of Lesser Himalaya (Granite, Gneisses, Panjal volcanic slates and phyllites), outer Himalaya [(Upper Siwalik Conglomerates and Feldspathic Sandstones of Siwaliks Group) and the Dharamshala Group of rocks (Sandstone, shale, mudstone and claystone)] remains untouched in context of morphometric and hypsometric studies. The Gaj watershed hosts a number of Hydel projects, wide flood plains and developing towns in its proximity. The present study involves the hypsometric analysis of nine sub-watersheds of overall Gaj watershed area which has allowed to understand their landform evolution process, structural settings and the present stages of erosional cycle. Also, the interpretation of the remnant rock mass by estimating the hypsometric integrals for the sub-watersheds has been carried out which has indicated the priority for sustainable soil and water conservation management measures. The study also brings in to light the reason of slope instability throughout the basin, especially at the higher elevation areas which are prone to neo-tectonic activities.

Study area

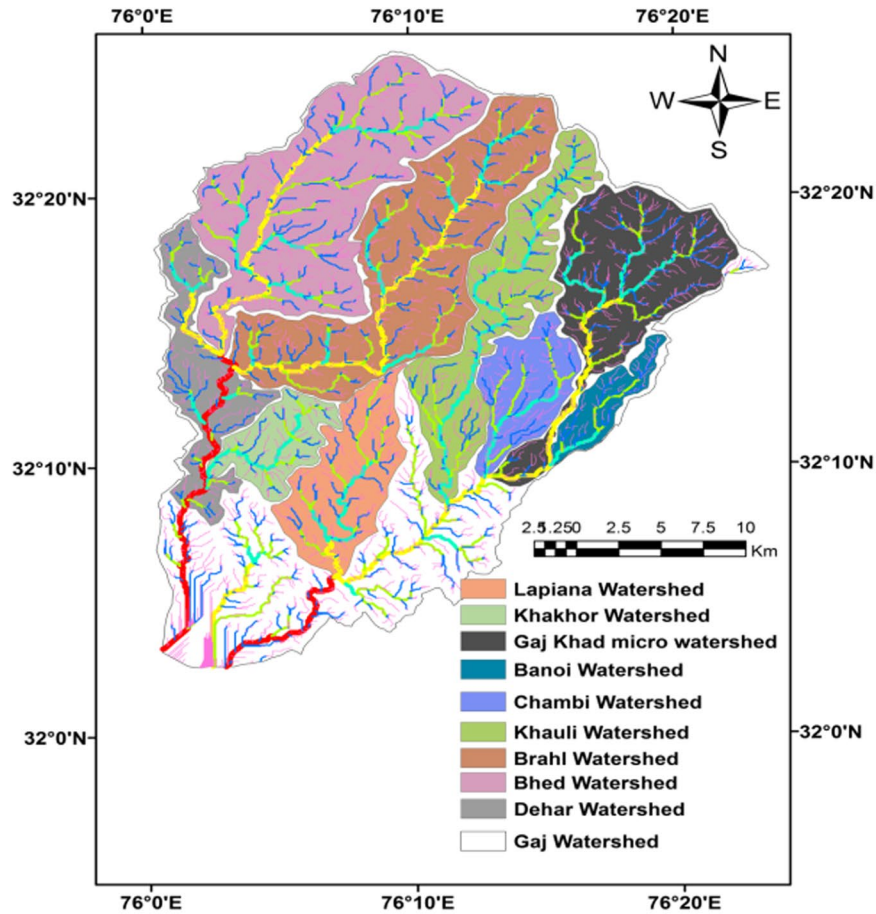
The Gaj watershed extends from 32°0'N-32°25' N latitudes to 76°0'E-76°25'E longitude in District Kangra, Himachal Pradesh, with total catchment area of 929 Km² (Fig. 1). The elevation of the watershed ranges between 3269 and 4500 m a. m. s. l. The Gaj is one of the main tributaries of river Beas which originates from Rohtang pass located in the Higher Himalaya and has a number of contributing tributaries flowing from the Kullu Valley (in the east) to Kangra Valley (in the west) and in the middle dissecting the slopes of district Mandi of Himachal Pradesh. The climate of the Gaj watershed is semi-temperate to sub-humid where the higher reaches have semi-temperate climate receiving heavy snow fall in winters, whereas the sub-humid climate toward the southern slopes of the watershed leads to heavy rainfall during the monsoon season. The annual precipitation rate

reaches up to 2600 mm and along the existing steep slopes, high rainfall events lead to a number of landslide events which finally feed the drainage segments causing increased sediment load. The watershed area has a thick vegetation cover instead of which it is prone to erosional processes due to the neo-tectonic activities and high precipitation. The study area falls in the Zone V (high hazard) as per the earthquake zonation map of India. The anthropogenic activities such as mining of the slopes for road widening, hydel projects and the construction activities add up the erosion. This watershed includes high elevation ranges with steep slopes to moderately incline hillocks to planes with indecisive drainage patterns. The lithology of the Gaj watershed (Fig. 2) shows alluvium sediments at the southern most parts of the study area. The Outer Himalayan rock exposures in the central parts and the Lesser Himalayan rocks near to the northern edge comprise the overall lithology of the study area. Tectonically, the study area comprises major thrusts, viz., Main Boundary Thrust (MBT), Jawalmukhi Thrust, Drini Thrust, Panjal Thrust and the Chail Thrust. The presence of these weakness planes has lead to the dynamic reworking of litho-units in time which is earmarked by the crushed and weathered rock exposures.

Material and method

The 30 m DEM (digital elevation model) (source- NRSC, Hyderabad) has been used to delineate the nine sub-watersheds of the Gaj Basin, i.e., Dehar (55.3 Km²), Bhed (161 Km²), Brahl (156.4 Km²), Khauli (83.8 Km²), Gaj sub-watershed (96.8 Km²), Chambhi (39.3 Km²), Banoi (19.3 Km²), Lapiana (57.6 Km²) and Khakhhor (30.2 Km²). Figure 3 represents the flow of methodology used in the hypsometric analysis that led to the prioritization of the sub-watersheds in the study area. The elevations points for various sub-watersheds were extracted from their respective digital elevation models (Fig. 4) which were then used to evaluate the hypsometric integrals and plot the hypsometric curves. The stream network for each of the sub-basin was extracted (Fig. 5) using the hydrology tool in GIS platform which has the Strahler's stream ordering scheme. The stream networks have helped to find out the stream orders, length of various stream segments, area and perimeter of the sub-basins for calculation of the main morphometric parameters (Table 1) (drainage density, bifurcation ratio, texture ratio, relief ratio, etc.). These parameters have helped to understand the linear, relief and aerial aspects which control the geomorphology of a watershed. The calculation of the morphometric parameters has lead to perform the hypsometric analysis for each sub-watershed to know its stage of erosional cycle and to estimate the amount of the remaining original rock mass. The elevation points and the cumulative

Fig. 1 Location map of Gaj watershed and its nine sub-watersheds



percentage of the relative surface areas (Km^2) were used for plotting the hypsometric curves, and then, their respective hypsometric integrals were estimated using the altitudinal statistics, i.e., the elevation-to-relief ratio.

Morphometry and estimation of hypsometric integrals

The drainage network can be defined as a set of tributaries which join together to form the main drainage system, and the total area these tributaries cover is known

as a watershed. In other words, the drainage pattern is the geometry that all the tributaries follow to merge with each other and modify the basin’s shape and geomorphology (Nag and Chakraborty 2003). The drainage pattern is dependent on the lithology (loose or compact), permeability of the rock units, slope angle, structural and tectonic history of the basin. The channel flow patterns are the surface expressions of the variables influencing river dynamics (Kuhni and Pfiffner 2001). The sub-watersheds of the Gaj Basin have been investigated for linear, relief and aerial aspects (Table 2), and the quantitative parameters derived are the stream order (U), stream length (Lu),

Fig. 2 Lithological map of Gaj watershed of district Kangra, Himachal Pradesh, India

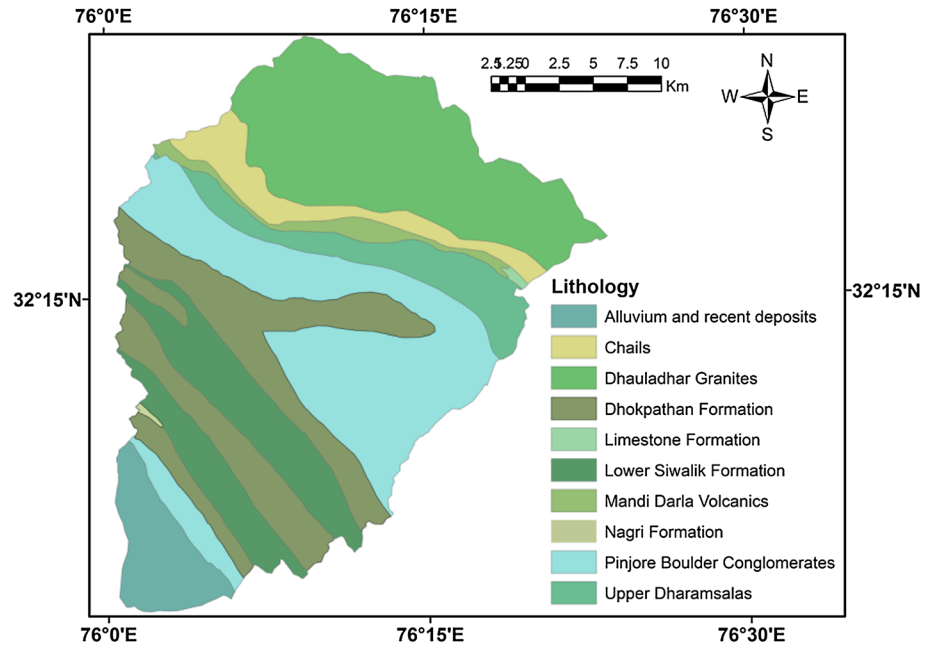
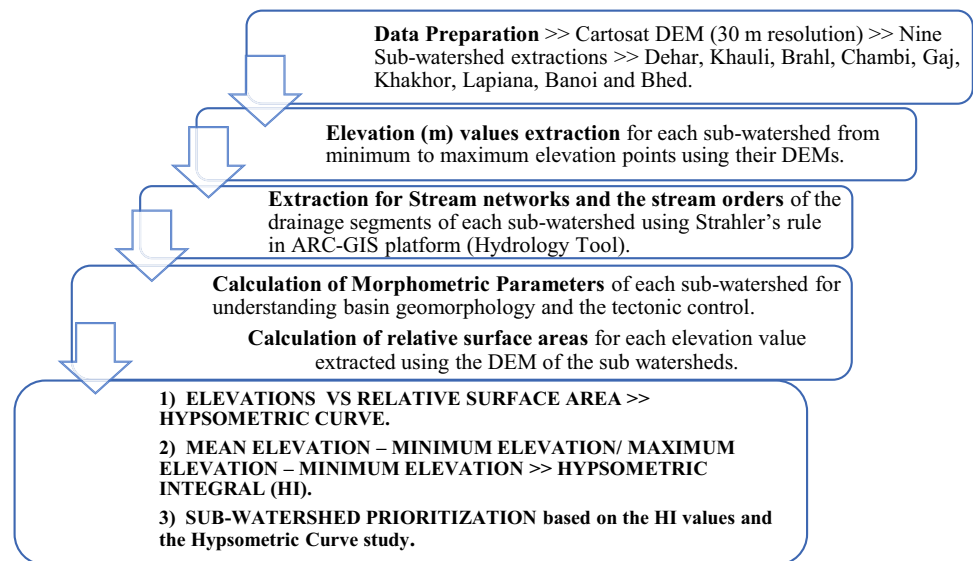


Fig. 3 Flowchart representing different steps of morphometric and hypsometric analysis of the sub-watersheds in the study area



bifurcation ratio (R_b), $\sum R_b$, basin relief (B_h), drainage density (D_d), texture ratio (T), constant channel maintenance (c) and stream frequency (F_s). These parameters have led to understand the dynamic changes in the configuration of the landforms due to the geological and geomorphological processes over time. The hypsometric analysis aims at establishing relationship between the elevation points of a basin and the associated surface areas which is indicated by the hypsometric curves. For the present study area, the elevations and the respective relative surface area values for each sub-watershed were extracted from their respective DEMs. Considering the elevations and relative surface area, Ritter et al. (2002) have given the model of

hypsometric curves interpretation as shown in Fig. 6. The hypsometric curve with convex upward shape indicates a young basin, whereas the 'S'-shaped hypsometric curve indicates the mature stage of a basin and the concave curve indicates an old or eroded basin. The calculated values of surface areas and the extracted relative elevations for various sub-watersheds have been plotted in the form of graphs as shown in Fig. 7a–i. The maximum, mean and minimum elevations of various DEMs helped to give the quantitative assessment of hypsometric integral (HI) or the elevation-to-relief ratio of rock mass which has sustained the erosional processes. The derived HI values have been tabulated and are shown in Table 3.

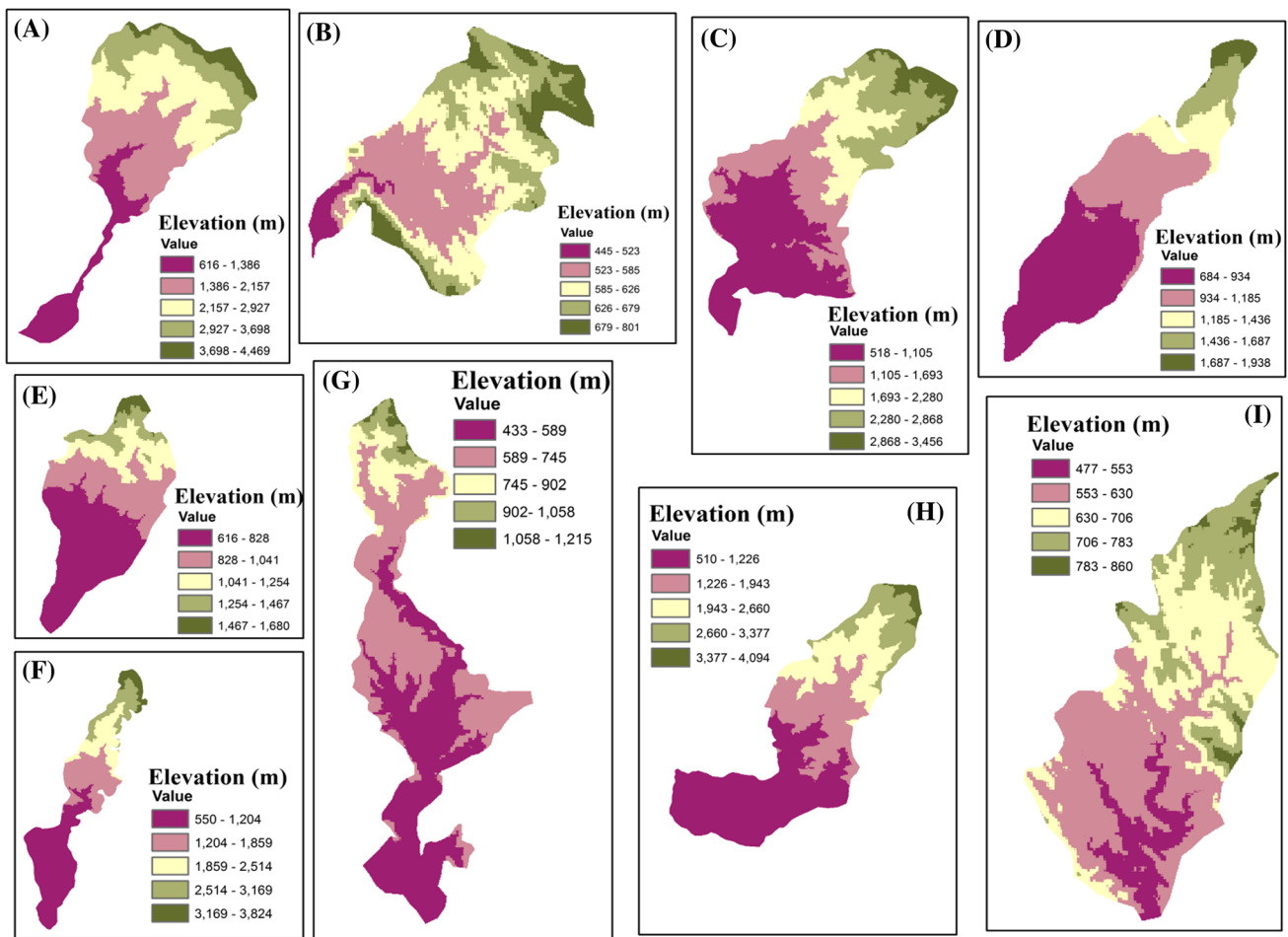


Fig. 4 Digital elevation model of **a** Gaj sub-watershed, **b** Khakhor sub-watershed, **c** Bhed sub-watershed, **d** Banoi sub-watershed, **e** Chambi sub-watershed, **f** Khauli sub-watershed, **g** Dehar sub-watershed, **h** Brahl sub-watershed and **i** Lapiana sub-watershed

Results and discussion

The Gaj watershed covers an area of 929 Km² and its drainage segments originate from an altitude of 4500 m. In the present study, the morphometric analysis using the established mathematical equations has been performed for the quantitative calculation of linear, relief and aerial aspects (stream order (U), stream length (Lu), bifurcation ratio (Rb), mean Rb, basin relief (Bh), drainage density (Dd), texture ratio (T) and constant channel maintenance (c) as shown in Table 2) of the nine delineated sub-watersheds. The linear parameters have helped to calculate the mean bifurcation ratio ($\sum Rb$) of each sub-watershed, which is considered as the index of lithological and geological control and its value generally ranges between 3 and 5 (Strahler 1964). The lower the 'Rb' value, less is the structural control on the basin. The study reflects that the mean Rb ranges between 1.65 and 2.31 for all the nine sub-watersheds which indicates a moderate structural control on their landforms. The sub-watersheds, viz.,

Gaj, Banoi, Brahl and Lapiana, are more influenced by structural disturbances as compared to the other sub-watersheds. The relief aspects of the watershed have helped to calculate the relief ratio (Rh) which is the ratio of the basin relief (Bh) and the maximum basin length (Lb) (Schumn 1956). Rh indicates the overall steepness of basin's slope and vulnerability of the area toward erosion. The overall Rh value ranges between 0.03 and 0.17 for the sub-watersheds, and the highest value has been calculated for the Gaj sub-watershed (0.17). Likewise, the other high elevation basins like Brahl, Khauli and Bhed have a high value of relief ratio indicating steep slopes and more proneness to the erosional activities. The drainage density (Dd) is the numerical measurement of the landscape dissection and the runoff potential. It is the stream length per unit area (Horton 1945). The overall Dd value for the study area ranges from 2.19 to 2.53 which indicates a moderate control of lithological permeability in all the sub-watersheds. It can be inferred that at the higher altitudes, the slopes are steep and the lithology is hard

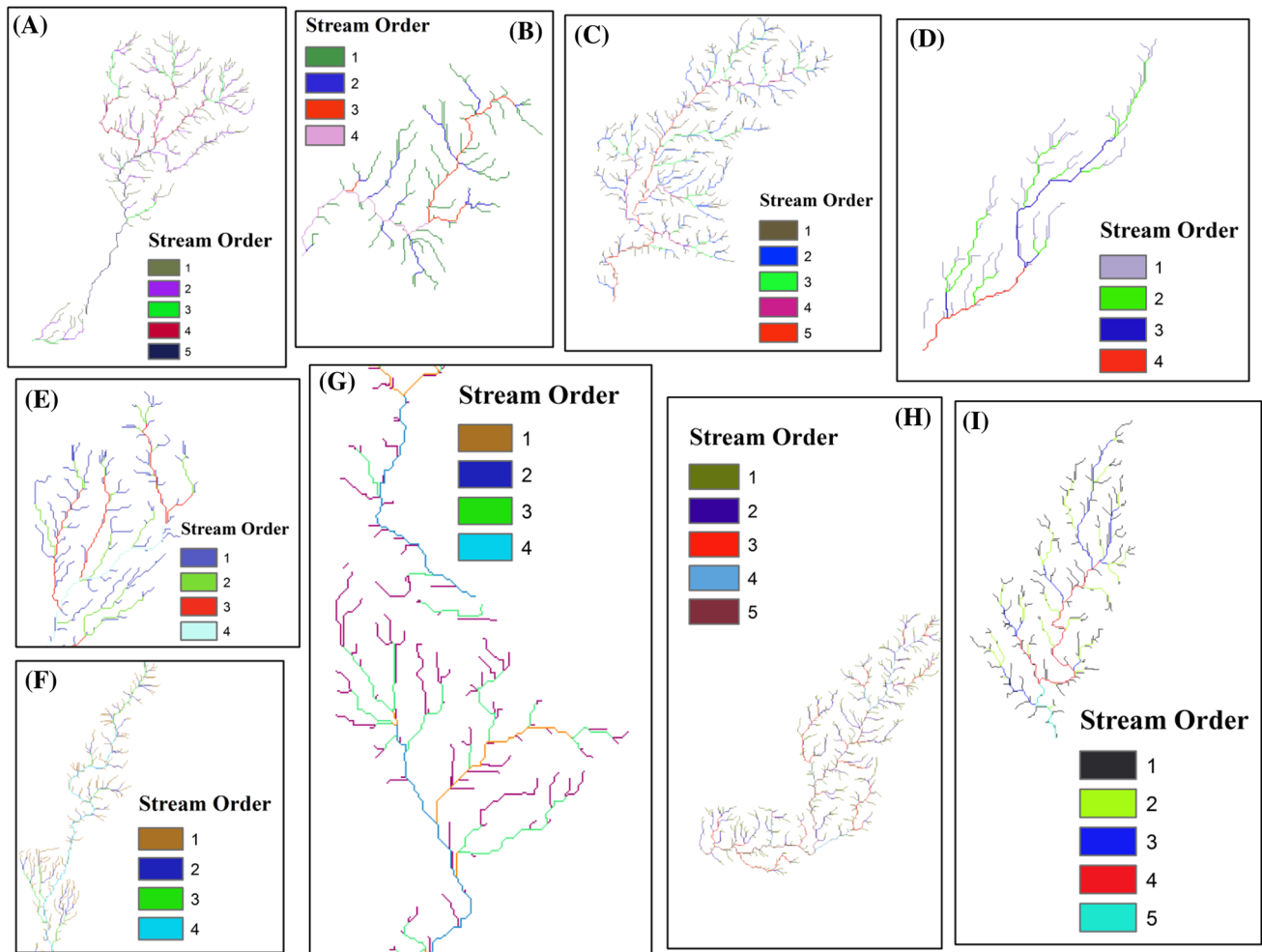


Fig. 5 Stream networks and their stream orders for **a** Gaj sub-watershed, **b** Khakhor sub-watershed, **c** Bhed sub-watershed, **d** Banoi sub-watershed, **e** Chambi sub-watershed, **f** Khauli sub-watershed, **g** Dehar sub-watershed, **h** Brahl sub-watershed and **i** Lapiana sub-watershed

Table 1 Morphometric parameters calculated for sub-basins of Gaj watershed

S.no	Parameter	Formula	References
1	Stream order (U)	Hierarchical rank	Strahler (1964)
2	Stream length (Lu)	Length of the stream	Horton (1945)
3	Bifurcation ratio (Rb)	$R_b = N_u / N_{u+1}$	Strahler (1964)
4	Mean bifurcation ratio (Rbm)	$R_{bm} = \sum R_b$	Strahler (1957)
5	Drainage density (Dd)	$D_d = L/A$	Horton (1945)
6	Stream frequency (Fs)	$F_s = N/A \text{ (Km}^2\text{)}$	Horton (1932)
7	Texture ratio (T)	$T = N/P$	Horton (1945)
8	Constant channel maintenance (c)	$C = 1/D_d$	Schumm (1956)
9	Basin length(lb)	$L_b \text{ (Km)}$	Schumm (1956)
10	Basin relief Bh	Bh	Schumm (1956)
11	Relief ratio Rh	$R_h = B_h/L_b$	Schumm (1963)

and impervious (Dhauladhar Granites) due to which the overland flow (runoff) is high as compared to the low lying area where the lithology is more pervious (Chails, Dharamsala and Siwaliks); therefore, the drainage density falls

under moderate values for the sub-watersheds. Schumm (1956) has defined constant channel maintenance (C) as inverse of the drainage density (Dd), which depends on the rock type, its permeability, the duration of the erosion

Table 2 Estimated morphometric parameters for sub-basins

Sr no. (Basin)	U	Nu (Number of stream segments)	Lu (m)	Rb	$\sum Rb$	Dd	C	T	Fs	Bh	Lb	Rh
1) Bhed	1	480	184,152.7	2.08	1.73	2.23	0.45	6.58	5.84	2.9	23	0.13
	2	231	93,480.4	2.26								
	3	102	36,713.1	1.65								
	4	62	22,116.6	0.94								
	5	66	22,616.9									
2) Brahl	1	504	181,999.3	2.31	1.80	2.21	0.45	6.95	6.27	3.6	23.4	0.15
	2	218	77,586.8	1.63								
	3	134	41,861.6	2.53								
	4	53	18,900.4	0.74								
	5	72	25,807.8									
3) Khauli	1	251	115,841.4	2.49	1.65	2.46	0.41	3.35	5.85	3.3	26.6	0.12
	2	101	41,580.3	1.77								
	3	57	21,700.4	0.70								
	4	81	27,577.8									
4) Chambi	1	109	51,633.3	2.53	1.77	2.48	0.40	3.53	5.39	1.06	11.5	0.09
	2	43	19,954.9	1.16								
	3	37	16,643.4	1.61								
	4	23	9077.7									
5) Banoi	1	54	25,160.7	1.86	1.87	2.53	0.40	2.01	5.39	1.2	11	0.11
	2	29	12,972.3	2.42								
	3	12	6593.8	1.33								
	4	9	4068.4									
6) Gaj Sub	1	293	121,531	2.01	1.94	2.28	0.44	4.74	5.84	3.65	21.1	0.17
	2	146	50,721.1	2.92								
	3	50	17,180.6	1.02								
	4	49	16,822.8	1.81								
	5	27	14,290.8									
7) Khakhor	1	80	38,913.8	2.29	1.75	2.20	0.45	2.66	5.03	0.35	7.8	0.04
	2	35	12,276.4	1.67								
	3	21	8449.3	1.31								
	4	16	6867.7									
8) Lapiana	1	159	67,582.5	2.48	2.31	2.28	0.44	3.97	5.36	0.38	15.15	0.03
	2	64	27,959.3	1.36								
	3	47	17,833.3	1.52								
	4	31	12,295	3.88								
	5	8	3472.4									
9) Dehar	1	157	62,105.7	2.28	1.78	2.19	0.46	2.50	5.35	0.78	20.9	0.04
	2	69	31,161.6	1.73								
	3	40	14,367.7	1.33								
	4	30	13,491.2									

and the climatic history of the watershed. The value of ‘C’ for nine sub-basins falls between 0.40 and 0.46 which also indicates high runoff potential and low permeability of the rocks. The texture ratio (T) in a watershed relates to factors such as vegetation, climate and relief. It is defined as the ratio of the total number of stream segments to the perimeter of the watershed (Horton 1945). The texture ratio calculated for Brahl sub-watershed is 6.95 which is highest

among all followed by the Bhed sub-watershed (6.58), Gaj micro-sub-watershed (4.74) and rest sub-watersheds show lower values for example Khauli (3.35), Chambi (3.53), Lapiana (3.97), Banoi (2.01) and Khakhor (2.66). The sub-watersheds such as Brahl, Bhed and Gaj receive higher precipitation as compared to the lower elevation sub-watersheds that lead to more erosional activities. The ratio of total number of stream to the area of the watershed

Fig. 6 Hypsometric curve model proposed by Ritter et al. (2002), showing the relation between elevation of a basin and the relative surface area and their resultant curves depicting erosional stages of a basin

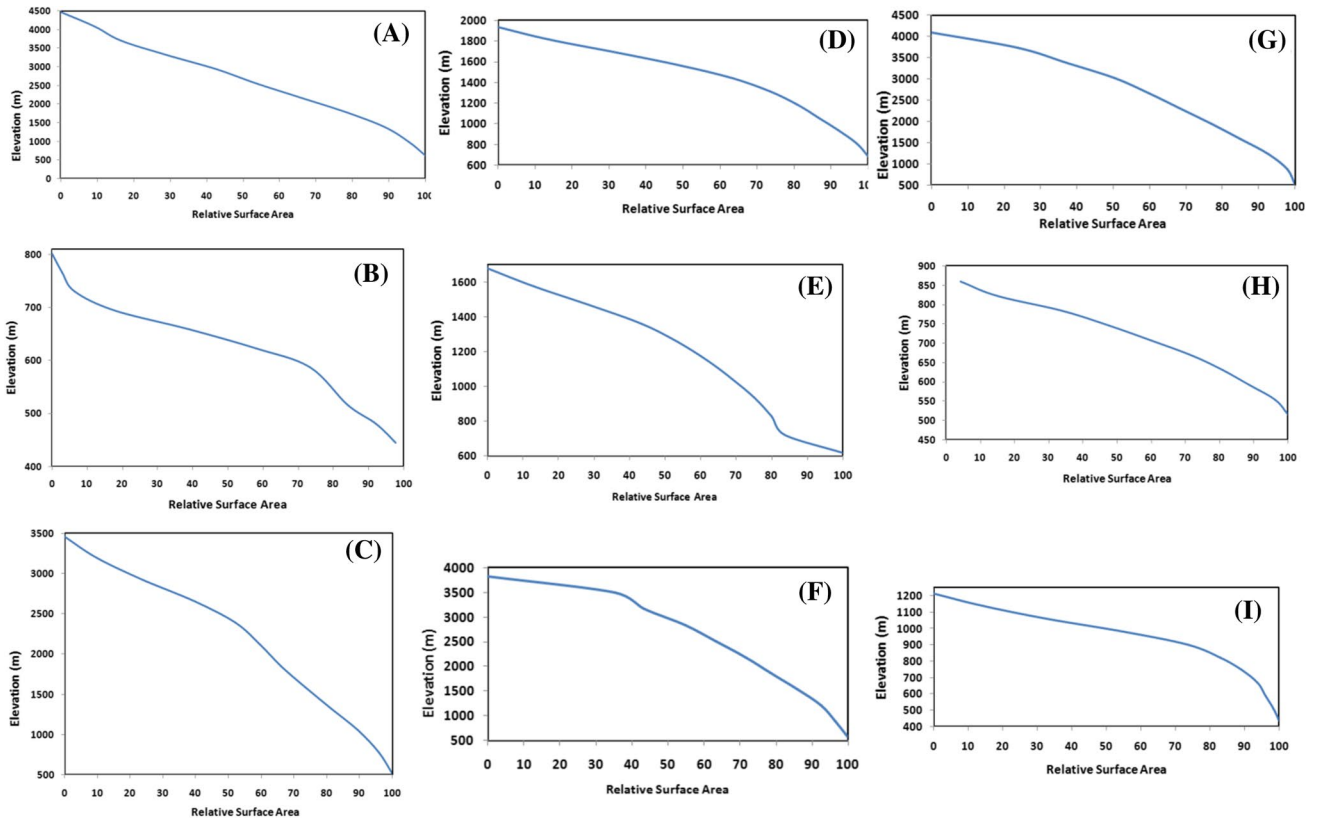
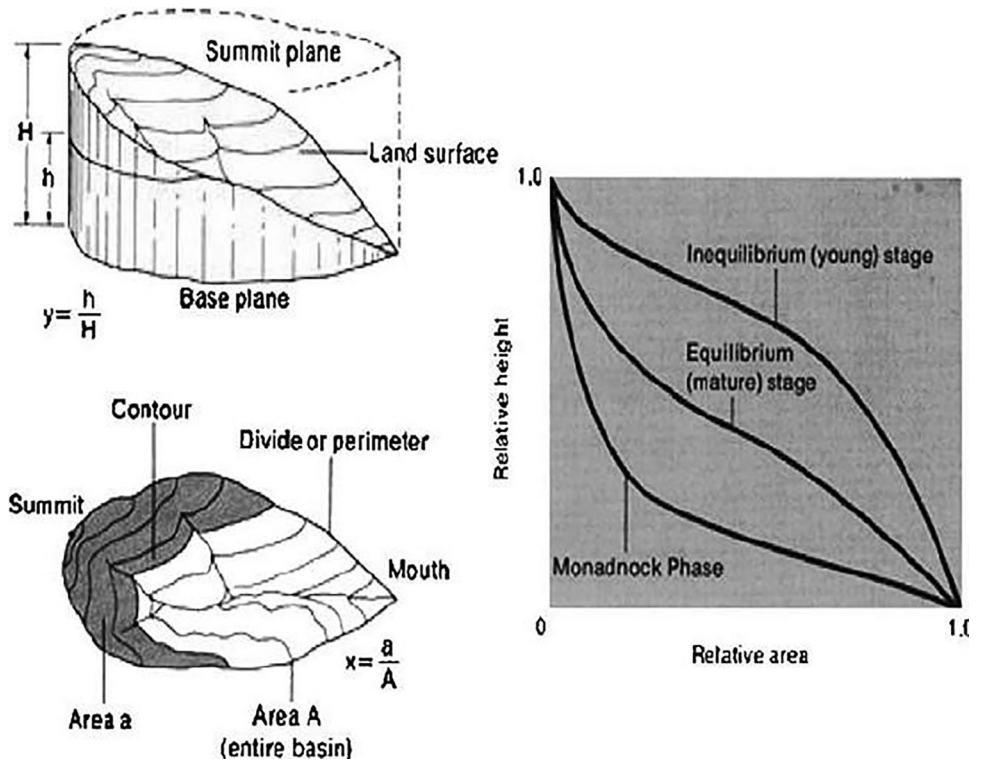


Fig. 7 Hypsometric curve of sub-basins **a** Gaj sub-watershed, **b** Khakhor sub-watershed, **c** Bhed sub-watershed, **d** Banoi sub-watershed, **e** Chambi sub-watershed, **f** Khauli sub-watershed, **g** Dehar sub-

watershed, **h** Brahl sub-watershed and **i** Lapiana sub-watershed plotted between relative surface area on abscissa and elevations on the ordinate

Table 3 Estimated hypsometric integral of sub-basins

S. no	Sub-basin	Hypsometric integral (HI) (%)
1	Dehar	50
2	Bhed	55
3	Brahl	50
4	Khauli	50
5	Gaj sub-basin	50
6	Banoi	50
7	Chambi	50
8	Lapiana	50
9	Khakhhor	52

is defined as the stream frequency (F_s) (Horton 1932). The F_s depends on the lithology and texture of the drainage area and is derived maximum for the Brahl sub-watershed which has the maximum area of 156.4 Km² and also the highest number of stream segments as compared to other sub-watersheds.

Pike and Wilson (1971), proposed the method for calculating the elevation-to-relief ratio (E) (Eq. 1) that has been used to find out the value of hypsometric integral (HI) for the present study areas (Table 3).

Equation 1:

$$E = \frac{\text{Mean Elevation} - \text{Minimum Elevation}}{\text{Maximum Elevation} - \text{Minimum Elevation}} \quad (1)$$

where E is the elevation relief ratio.

For the delineated sub-watersheds, the hypsometric curves have been plotted between the cumulative percentage of the surface areas with respect to the elevation points (Fig. 7a–i). The hypsometric curve for the Dehar sub-watershed (Fig. 7g) is convex upward indicating inequilibrium or more erosional activity, whereas the Bhed, Brahl and Banoi sub-watersheds represent convex hypsometric curves (Fig. 7c,d,h). These results indicate the impact of the steep slopes in the high elevation areas which also indicates sediment removal from the landforms while the heavy rainfall episodes or by the local drainages. The hypsometric curve for Gaj sub-watershed is almost ‘S’ shaped with concave upward shaped for higher elevation points, whereas convex upward for the lower elevation points. This marks the presence of mature and youthful landforms, respectively, in the Gaj sub-watershed area. Same pattern can be seen for Chambi (Fig. 7e), Lapiana (Fig. 7i) and Khakhhor (Fig. 7b) sub-watersheds indicating their mature stage of erosional cycle. The hypsometric curve for the Khauli sub-watershed (Fig. 7f) is complex as the middle

elevation areas have a concave depression which represents more denudation of its landforms.

The HI values vary between 50 and 55% (Table 3) for the delineated sub-watersheds making it evident that the erosional activities are enormous in all the sub-watersheds which are denudating the landforms actively and achieving equilibrium. The Bhed sub-watershed falls in the late youthful stage with the highest HI value, i.e., 55%. The morphometric parameters such as ‘Dd’ and ‘C’ also confirm the erosional proneness of these sub-watersheds. The high elevation areas of the Bhed, Brahl, Khauli and Gaj sub-watersheds have steep slopes and are located near the discharge points, which increases the runoff potential. Thus, the capability of bringing large sediment load also increases which ultimately contributes toward high siltation. The highly dissected sub-watersheds due to the presence of transverse and longitudinal faults along with the high frequency of streams contribute to large erosional and slope instability events. These results revealed that the Bhed, Brahl, Khauli and Gaj sub-watersheds are more susceptible to erosion as compared to rest of the sub-watersheds. The direct impact of the increasing sediment yield is obvious on the Pong Dam’s reservoir at the tail end of the study area which will decrease the reservoir’s capacity and its utility for various irrigation and power generation purposes. Each sub-watershed with HI value of 50% indicates an onset of the mature stage of their erosional cycle where the landforms are experiencing active denudation and are near to the stage of denudating, i.e., the erosion of elevated landmasses. But, due to the presence of transverse and longitudinal faults (Main Boundary Thrust, Murree Thrust and Jwalamukhi Thrust) in the vicinity of these sub-watersheds, along with the high frequency of streams contribute to the number of slope instability events. Therefore, the results and the evaluations from the hypsometric study based on the erosional proneness of sub-watersheds have helped in their micro-prioritization, indicating the requirement of water-soil conservation measures and mapping the mass movements.

Conclusion

The present study outlines the application of GIS and remote sensing data (DEM) in delineating watersheds for morphometric and hypsometric study which is useful for the sub-watershed prioritization, rather than practicing manual approach for each sub-watershed separately. The study shows that the morphometric analysis is essential for studying the drainage behavior and its impact on the prevailing rock units in a watershed area. It also assesses the effects of tectonics and geological parameters in modifying the watershed’s morphology. It has helped to study the risk potentials of the various sub-watersheds toward large erosional and

slope instability events, whereas the hypsometric study has allowed to express the denudation rates of the landforms. This analysis has helped to visualize the erosional stages of the selected sub-watersheds by quantitative interpretations, i.e., HI estimation. The results of the study indicate the necessity of micro-watershed study for planning the mitigation with applicability of the aftermath for micro-level planning. The morphometric and hypsometric analysis results indicated that the low elevation sub-watersheds (Khakhor, Lapiana and Chambi) fall under the lowest priority due to their gentle to moderate slopes (0° to 25°) and their land use is mainly for the cultivation practices. The Dehar and the Banoi sub-watersheds were assigned moderate priority due to their moderate slope (15° – 25°), less forest cover and high anthropogenic interferences. The Bhed, Brahl, Khauli and Gaj sub-watersheds fall under high prioritization category as they belong to the higher elevation areas with steep to very steep slopes (30° – 45°) and weak lithology in their middle and lower parts. The mining and development activities with immense pressure of tourism are the major causes of landform denudation in the overall study area as some of the fast developing towns such as Dharamshala and Mcleodganj belong to this region. These results can be useful for controlling the erosional activities at right locations and defining a strategy for proper land use planning by the public work departments.

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