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ORIGINAL ARTICLE

Flood hazard assessment of upper Jhelum basin using morphometric parameters

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Abstract

Morphometric parameters can be useful tools to provide general understanding of physical characteristics of drainage basin with respect to floods. To evaluate the flood influencing factors in the upper Jhelum basin, we delineate the upper Jhelum basin into ten sub-basins, followed by extraction of drainage network and morphometric parameters using Advanced Spaceborne Thermal Emission and Reflection Radiometer digital elevation model and topographic maps in Geographic Information System. The overall flood potential was determined on the basis of compound value obtained for all morphometric parameters of each sub-basin. The analysis reveals that, in general, the northeastern segment of the upper Jhelum basin reveals comparative higher flood potential than the southwestern segment. The tributaries, such as Lidder, Veshav, Arapal, Arapat, and Bring, exhibit greater potential to produce peak flows during rainfall events, while the tributaries like Dudhganga, Rambiara, Sandran, Romushi, and Sasara express moderate-to-low flood potential, respectively. The results of this study are likely to be very useful for effective flood hazard mitigation in upper Jhelum floodplain.

Keywords Flood hazard evaluation · Morphometric parameters · Upper Jhelum basin · Kashmir valley

Introduction

Floods account for one-third of all geophysical hazards in the world (Adhikari et al. 2010), causing highest deaths and property damage (CEOS 2003). The flood potential of the drainage basins is significantly affected by their morphological properties. Morphometry provides an understanding of general geomorphic setup, hydrologic conditions, erosion, and mass movement characteristics of the drainage basins (e.g., Baumgardner 1987; Eze and Efiong 2010). Morphometric analysis is a quantitative measurement of landscape shape, and is carried out through the mathematical analysis of linear, aerial, and relief aspects of the basin (Clark 1966; Keller and Pinter 1996). Several studies have used morphometric analysis to understand the hydrological characteristics of the basin (Nag and Chakraborty 2003; Esper Angillieri 2008; Sreedevi et al. 2009). The approach helps to derive the overall attributes of the landscape terrain or elevation surface and drainage network within a drainage basin. Moreover, peak hydrograph time, travel time discharge in a basin, and intensity of erosional processes operating at catchment scale can be predicted with a better insight and accuracy from morphometric analysis (Patton and Baker 1976; Ozdemir and Bird 2009; Eze and Efiong 2010). Many authors (Horton 1945; Smith 1950; Miller 1953; Schumm 1956; Strahler 1957; Chow 1964; Raza et al. 1978; Chow et al. 1988; Ward and Robinson 2000) have utilized specific morphometric parameters such as stream order, basin area and perimeter, stream length, basin length, drainage density, stream frequency, bifurcation ratio, drainage texture, relief ratio, ruggedness number, form factor, circulatory ratio, compactness index, and lemniscate ratio to understand the behavior of surface drainage networks and characteristic of the basin. In addition, these parameters have been used to develop a primary hydrological diagnosis and prioritize the sub-basins according to their flood potential (Boulton 1968; Patton and Baker 1976; Gardiner and Park 1978; Costa 1987; Patton 1988; Sreedevi et al. 2005; Roughani et al. 2007; Esper Angillieri 2008; Javed et al. 2009; Ozdemir and Bird 2009; Youssef et al. 2011; Patel et al. 2012; Masoud

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2016). The process of prioritization identifies basins contributing maximum discharge during rainfall events (Patel et al. 2012).

The traditional methods were usually adopted for morphometric characterization of basins in the past (Horton 1945; Smith 1950; Strahler 1957; Magesh et al. 2011). However, with the advent of Geographic Information System (GIS), high-resolution digital elevation models (DEMs), and remote-sensing techniques, the assessment of basin morphometry has been more accurate, rapid, and cost-effective (Bertolo 2000; Ahmed et al. 2010). The extraction of drainage networks from DEMs is based on gravity, i.e., water is flowing from higher to lower elevation using the steepest descent, and it is assumed that there is no interception, evapo-transpiration and loss to groundwater (Ozdemir and Bird 2009). Automated extraction methods are the most efficient approach when DEM cell size is significantly smaller than the sub-basin dimensions.

Flooding is influenced by number of factors such as climate, land use and land cover, lithology, geomorphology, and many other hydrologic and hydraulic conditions. Frequency of flooding seems to have greatly increased in recent decades because of deforestation, land-use change, population growth, urbanization, inhabitation in the high slope zones, loss of wetlands, and climatological factors associated with an increase in extreme rainfall events (Vincent 1997; Berz et al. 2001; McBean 2004; Peduzzi et al. 2009; Pradhan 2010; Pradhan and Lee 2010; Bhat et al. 2018). While recognizing the considerable impact of various factors on flood frequency and magnitude, the present study focuses primarily on assessing flood hazard potential of various sub-basins in upper Jhelum (Fig. 1) according to their morphometric properties. The study area is spread over six administrative districts (Anantnag, Shopian, Pulwama, Kulgam, Budgam, and Srinagar) of Kashmir region, located in Jammu and Kashmir State of India.

Flooding scenario of the Kashmir valley

The Kashmir valley is one of the most vulnerable flood hazard prone regions in India (Sen 2010), where records of extreme floods and associated loss date back to 883 AD (Khoihami 1885; Lawrence 1895; Koul 1925; Dev 1983; Raza et al. 1978; Bilham et al. 2010; Singh and Kumar 2013; Bilham and Bali 2013). Kashmir valley has witnessed series of floods; a few notable events are 879 AD, 1841, 1893, 1903, 1929, 1948, 1950, 1957, 1959, 1992, 1996, 2002, 2006, 2010, and 2014. The extreme flood event of 2014—the highest ever recorded on the trunk river Jhelum, resulting in colossal loss of assets and human life—is the recent example of Kashmir basin's exposure to flood hazard (Mishra 2015; Bhatt et al. 2016; Kumar and Acharya 2016). The low-level convergence of southeasterlies and northwesterlies coupled

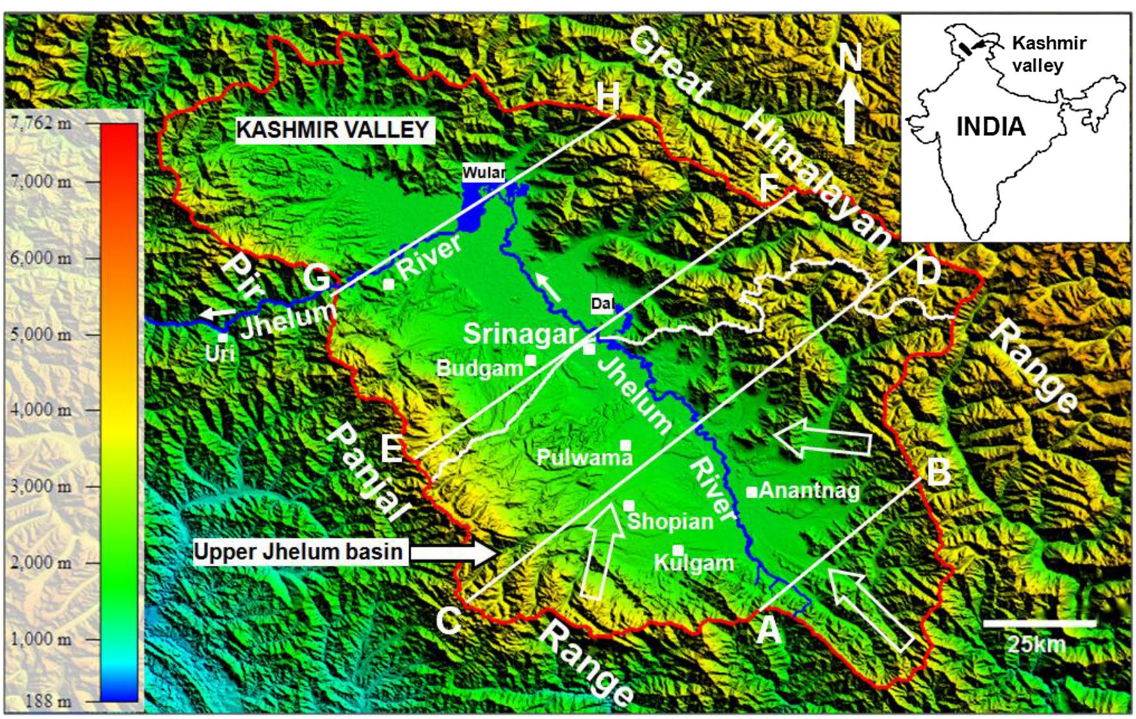

Fig. 1 DEM of Kashmir valley showing location of upper Jhelum basin. Blank white arrows show flow direction of the Jhelum tributaries. Section lines A–B, C–D, E–F, and G–H show surface topography with underlying geology in Fig. 3

with orographic uplift result in heavy rainfall (Mishra 2015) and a prolonged rainfall event often triggers a flood in the basin. Moreover, the distinct geomorphic disposition (bowl shape) of the basin is considered as another factor responsible for water logging or recurrent inundation in the Kashmir basin (Tabish and Nabil 2014; Meraj et al. 2015; Alam et al. 2018). In addition, human settlement expansion, modification of the floodplain (land filling, encroachment, and road/railway construction), erosion/degradation by the perennial tributaries, and subsequent alluvial deposition in the water bodies leading to the extinction of wetlands and waterways are other few intensifying factors of the flood hazard in the valley. No scientific investigation has been carried out to estimate the flood hazard potential of the Kashmir basin based on morphometric parameters, except a few micro-watershed studies (e.g., Romshoo et al. 2012; Altaf et al. 2013; Meraj et al. 2015).

Drainage characteristics

The Kashmir valley is an elongated NW–SE Graben-type basin evolved in late Miocene or pull-apart sedimentary trough (Bhat 1982; Burbank 1983; Alam et al. 2015, 2017), spread over an area of 15,220 km^2. It is bounded by two major mountain ranges, i.e., Pir Panjal in the south–southwest and great Himalaya in the east–northeast. The bordering mountain ranges are drained by 22 tributaries: 11 from Pir Panjal range and 11 from great Himalaya range, which confluence the Jhelum River (trunk channel) in a general radial pattern (Fig. 2). The tributaries have different length ranging from ~23 km of Sasara (smallest stream) to ~100 km of Sind (largest stream). Originating from the Verinag in the south, the Jhelum river drains most of the length of Kashmir valley, flowing in northwest direction up to Wular lake. However, after exit from the Wular lake, Jhelum river cuts across the Pir Panjal in a single drainage outlet commonly known as 'Baramulla-Uri gorge'. The tributaries flow over heterogeneous rock types such as Panjal trap, quartzite inclusions, Agglomeratic slate, shale, gneissose granite, limestone, Karewa, and river alluvium (Lydekker 1876; Middlemiss 1911; Wadia 1975; Krishnan 1982; Bhatt 1989). Furthermore, the great Himalayan tributaries are mostly flowing over hard-rock terrain with steep gradient and concave shape compared to Pir Panjal tributaries, which have soft-rock terrain with gentle gradient and general convex shape (Ahmad and Bhat 2012; Ahmad 2014; Ahmad et al. 2013, 2015, 2017). The topographic profiles drawn in SW–NE direction along the entire NW–SE length of the Kashmir valley suggest that the NE flank of Kashmir is dominated by Paleozoic–Mesozoic basement compared to SW flank, which comprises of unconsolidated Plio-Pleistocene Karewa sediments (Fig. 3).

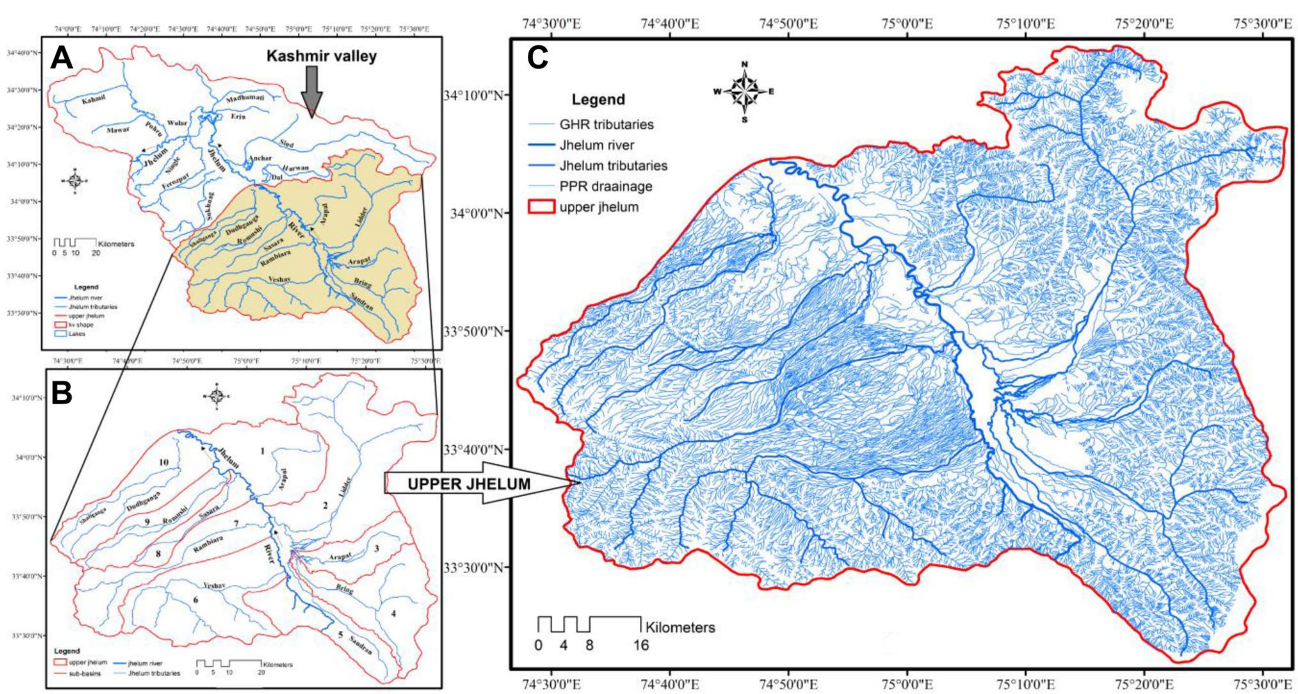

Fig. 2 Drainage characteristics of the upper Jhelum basin: **a** major drainage network of the Jhelum River in Kashmir valley; **b** sub-basins of the upper Jhelum: 1 = Arapal, 2 = Lidder, 3 = Arapat, 4 = Bring, 5 = Sandran, 6 = Veshav, 7 = Rambiara, 8 = Sasara, 9 = Romushi, and 10 = Dudhganga–Shaliganga; **c** drainage map of the upper Jhelum (study area)

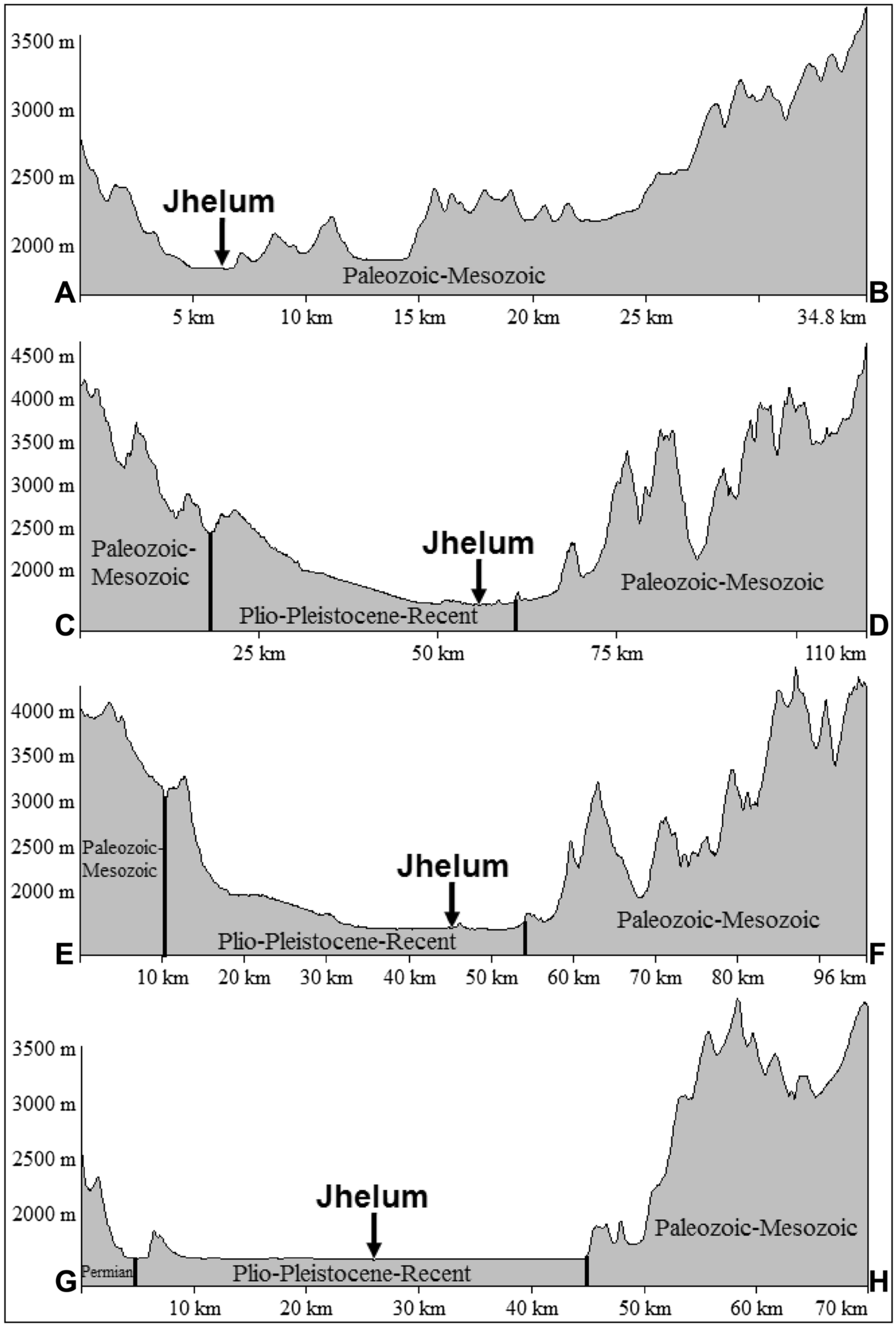

Fig. 3 Topographic profiles show gentle and convex slope on the Pir Panjal flank compared to steep and concave slope on the Great Himalayan flank in Kashmir valley. The convexity and gentle slope may be the effect of the Balapur fault, exerted on the Pir Panjal range (e.g., Ahmad et al. 2015). Profile section lines are shown in Fig. 1

Geological setting

The Kashmir valley is situated within the crystalline complex in the northwest Himalaya and contains diverse lithological Formations ranging from Precambrian to Recent (Lydekker 1876; Middlemiss 1911; Wadia 1975; Bhatt 1989; Krishnan 1982). The basal part contains oldest stratigraphic basement floor known as Salkhala Series (Precambrian) overlain by Dogra Slates (lower Cambrian) (Wadia 1975). In addition, it contains more or less full sequence of fossiliferous Paleozoic such as Panjal Volcanic Series (Panjal Trap and Agglomeratic Slate), Gneissose granite, Gondwana Shale, Fenestella Shale, Syringothyris Limestone, Permo-Triassic rocks, Conglomerate Beds, and inclusions of Varved Clays in various parts of Kashmir (Lydekker 1876; Middlemiss 1911; Wadia 1975; Krishnan 1982).

Among the hard-rock varieties, the study area (upper Jhelum) consists of Panjal Volcanic Series (Panjal Trap and Agglomeratic Slate), gneissose granite, Muth Quartzite, Fenestella Shale, metamorphic schists, and Zewan and Syringothyris limestone varieties (Fig. 4). However, maximum area is covered by lacustrine and fluvio-glacial sediments, collectively known as the Karewa deposits (Plio-Pleistocene) (Farooqi and Desai 1974; Singh 1982; Bhatt 1989). With ~1300 m thickness, the Karewa deposits consist of unconsolidated clays, sands, and conglomerates with lignite beds unconformably lying on the bedrock, and is overlain by the recent river alluvium (Wadia 1975; Singh 1982; Bhatt 1989). These deposits (Karewa) have been subdivided into lower or Hirpur, and upper or Nagum and Dilpur Formations, respectively (Bhatt 1989). The older lower Karewa/Hirpur Formation consists of layers of gray to bluish-gray clays, light-gray sandy clays, fine-to-coarse-grained green to purple sands, conglomerates, lignite, and lignitic clays. The younger upper Karewa or Nagum Formation contains fine-to-coarse-grained greenish-to-purplish sands, gray and ochre sandy clays, ochre, and cream colored marls and gravels. The youngest upper Karewa or Dilpur Formation mostly contains brown silt known as loess, which has aeolian origin (Pant et al. 1978; Bronger et al. 1987). The loess is characterized by the presence of interbedded profiles of paleosols. The perennial tributaries (left and right bank) of the river Jhelum have carved out and exposed major geological part in the region besides newly developed road cuts.

Materials and methods

We use Survey of India (SoI) topographic maps (1:50,000) and freely available Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model (DEM) to delineate various sub-basins of the Upper Jhelum basin for evaluating their comparative flood hazard potential. The ASTER DEM with an accuracy of 4.7 m (elevation) and 7.3 m (horizontal) in flat terrains and ~7 m (elevation) and 14 m (horizontal) in hilly terrains (e.g., Muralikrishnan et al. 2013) is very useful to derive meaningful inferences regarding morphometric parameters. ASTER DEM has been used in numerous studies with different topographic settings (e.g., Ahmed et al. 2010; Gichamo et al.

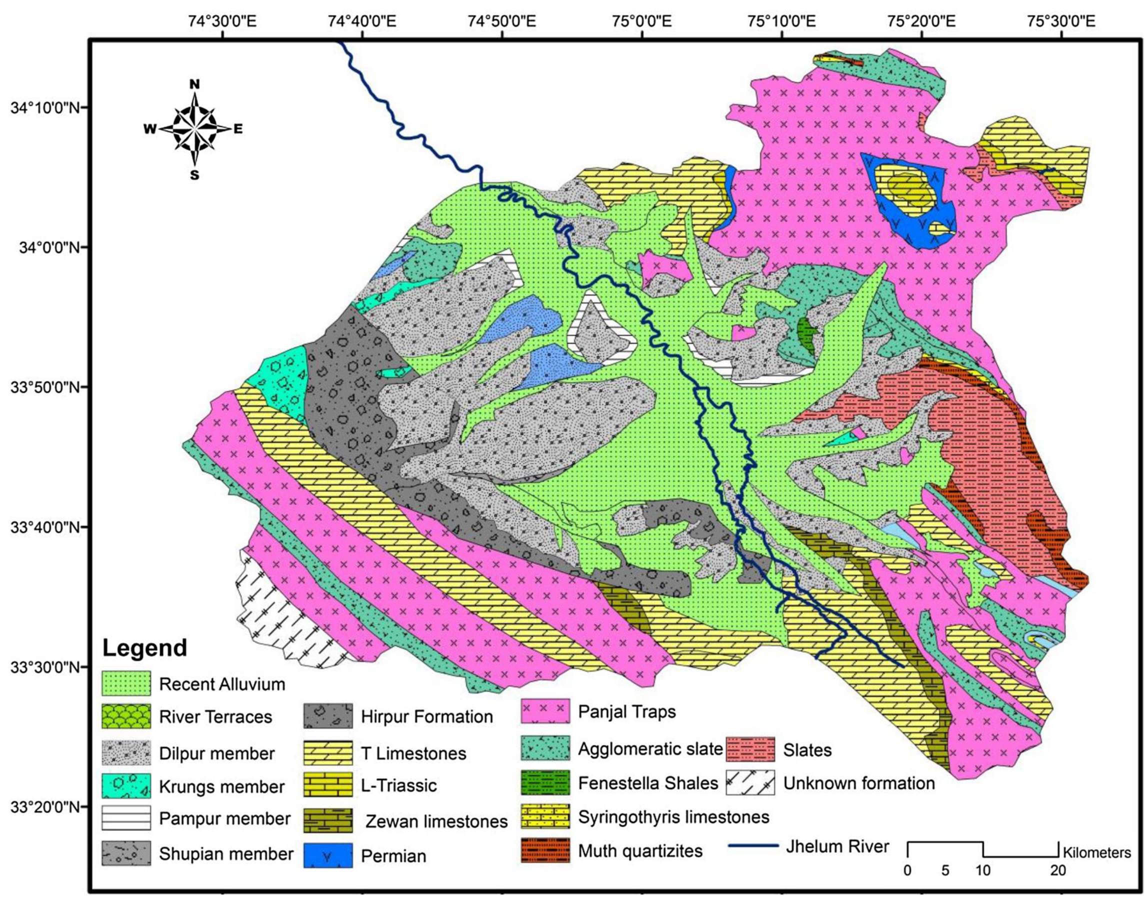

Fig. 4 Geology of the upper Jhelum (compiled after Middlemiss 1911; Thakur and Rawat 1992; Bhatt 1989)

2012; Sharma et al. 2014) and the validity of the DEM has also been tested successfully on the earth's lowest elevation in the Dead Sea (Jordan) (Al-Fugara 2015). In the present study, complementary use of the two data sets (ASTER DEM and SOI Topographic maps) in GIS environment (Arc GIS 9.3) assisted in delineating sub-basin boundaries, drainage network and various morphometric parameters (e.g., Maidment 2002; Ozdemir and Bird 2009). Moreover, we use Spatial Analyst extension and Arc hydro tool of ArcMap 10.2 to understand the general topographic characteristics of the Upper Jhelum basin like drainage, flow direction, flow accumulation, slope, aspect, and hill shade (Fig. 5).

The main stream length (L) and basin length (l_b) were prepared after Schumm (1956), whereas Strahler's (1957) scheme was adopted for stream ordering. The morphometric parameters were divided into basic types: area (A), perimeter (P), length (l_b), stream order (S_u), maximum and minimum heights (H, h), total stream length (Ltc), total stream length of a given order (l_n), and number of stream segments of a given order (N_n). The parameters were obtained using mathematical expressions (Table 1). The upper Jhelum consists of ten major sub-basins: Veshav, Rambiara, Sasara, Romushi, Dudhganga, Sandran, Bring, Arapat, Lidder, and Arapal.

Results and discussion

The upper Jhelum river basin covers an area (A) of 5946 km^2, with a perimeter (P) of 398.6 km, total length (l_b) of 92.6 km, highest elevation of 5138 m (H), lowest elevation of 1392 m (h), and mean width (W_m) of 62.9 km. In general, the upper Jhelum basin exhibits a dendritic, trellis, and parallel-to-sub-parallel drainage patterns. The trunk river (upper Jhelum) of the study area is seventh order stream; having ten sub-basins, five from Pir Panjal, and five from great Himalayan ranges. The basic parameters such as stream numbers, stream length, sub-basin area, sub-basin perimeter, basin length, and maximum and minimum elevation of the sub-basin are presented in Tables 2 and 3, whereas derived parameters computed through the measurement of linear, aerial, and relief aspects are shown in Table 4.

Stream order (S_u)

To understand the drainage basin characteristics, the preliminary step is to delineate stream orders followed by the calculation of stream numbers and stream lengths (Horton 1945; Strahler 1957). It is generally believed that, with increasing stream order, the discharge and flow velocity of the stream increases (Costa 1987). In the study area, all the sub-basins are having sixth-order streams with exception of Veshav, which has seventh order. Hence, all the tributaries are having potential to produce a significant discharge and develop flooding scenario in the downstream areas of the Jhelum, whereas Veshav and Lidder streams produce maximum discharge of water during rain storm events or flood periods.

Stream number (N_u)

The count of stream channels derived from stream orders is known as stream number (Strahler 1957). The basin with high stream numbers usually reflects high discharge and causes rapid peak flow during rain storm events than the low stream numbers. In the upper Jhelum basin, the number of stream segments decreases as the order increases (Tables 2, 3). The upper Jhelum basin is characterized by high relief, varied lithology, and structural discontinuities, which seems to be responsible for inequalities in stream frequencies of each order. The stream numbers are relatively high (10280) for SE sub-basins than the SW sub-basins (5932), indicating rapid peak flow during rain–storm events from SE. Moreover, SE sub-basins are mostly covered by hard-rock terrain, which causes less permeability and infiltration, therefore, contributes instant discharge to the trunk river (Jhelum).

Bifurcation ratio (R_b)

R_b is an important parameter to affect peak of the runoff hydrograph (Chorley 1969; Jain and Sinha 2003). High R_b values indicate instantaneous discharge and possibility of flash flooding during extended rainy hours (Howard 1990; Rakesh et al. 2000). However, R_b does not precisely remain constant between stream orders because of variations in basin geometry, lithology, and tectonics. The flat terrains have R_b 2, whereas mountainous or highly dissected terrains have values from 3 to 4 (Horton 1945; Strahler 1957). In the present study, R_b values vary from 3.1 to 4.7, indicating higher values of R_b (Table 4). The higher value of R_b indicates highly dissected terrain, mature topography with a higher degree of drainage integration, and higher discharge potential (Horton 1945; Eze and Efiong 2010). In particular, high R_b value of Sandran and Dudhganga sub-basins suggests the early hydrograph peak with high potential for flash flooding during the storm events among all the sub-basins. Hence, these sub-basins are more vulnerable to flooding and contribute maximum discharge to the Jhelum river. The low R_b for Sasara suggests delayed hydrograph peak.

Drainage density (D_d)

It indicates the closeness of spacing of channels and is very useful to understand the landscape dissection, runoff potential or travel time of water in a basin, infiltration capacity of the land, relief, underlying lithology, climatic conditions, and vegetation cover of the basin (Horton 1932; Gardiner and Park 1978; Patton 1988; Reddy et al. 2004).

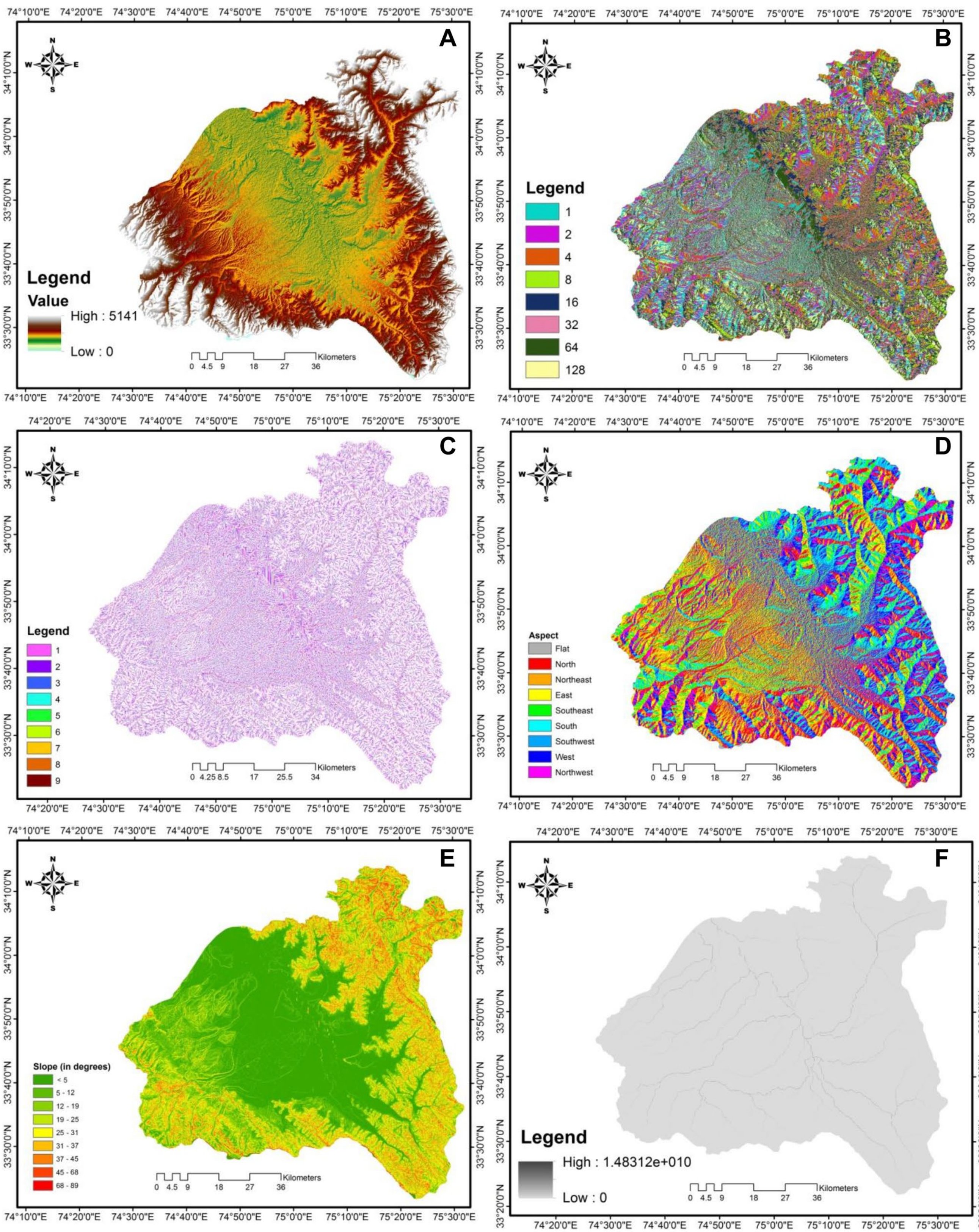

Fig. 5 General morphological attributes of the upper Jhelum extracted from ASTER DEM. **a** DEM, **b** flow direction, **c** drainage map along with stream order, **d** aspect map, **e** slope map, and **f** flow accumulation

Table 1 Morphometric parameters and their mathematical expressions

S. no.	Morphometric parameters	Formula	References
1	Stream order (S_u)	Hierarchical	Horton (1945), Strahler (1957)
2	Stream number (N_u)	$N_u = N_1 + N_2 + \ldots + N_n$	Horton (1945)
3	Stream length (L_u)	$L_u = L_1 + L_2 + \ldots + L_n$	Horton (1945)
4	Bifurcation ratio (R_b)	$R_b = N_n - 1/N_n$	Schumm (1956)
5	Form factor (F)	$F = A/L^2$	Horton (1932)
6	Elongation ratio (E_b)	$E_b = \frac{\sqrt[2]{A_b/\pi}}{l_b}$	Schumm (1956)
7	Circularity ratio (C)	$C = 4\pi A/P^2$	Miller (1953)
8	Drainage texture (T_d)	$T_d = \sum N_n/P$	Horton (1945)
9	Compactness index (c)	$c = P/2\sqrt{pA}$	Gravelius (1914)
10	Stream frequency (F_s)	$F_s = \sum N_n/A$	Horton (1932)
11	Drainage density (D_d)	$D_d = \mathrm{Ltc}/A$	Horton (1932)
12	Lemniscate ratio (K)	$K = l^2/4A$	Chorley et al. (1957)
13	Basin relief (H_r)	$H_r = H - h$	Hadley and Schumm (1961)
14	Relief ratio (R_r)	$R_r = H_r/L$	Schumm (1956)
15	Ruggedness number (R_n)	$R_n = H_r \times D_d$	Melton (1957)

It is measured as the total length of streams of all orders per unit area divided by the area of drainage basin. D_d is a significant controlling factor of surface runoff influencing the flood peak discharges (Pallard et al. 2009). High and low D_d values are obtained due to sub-surface material (impermeable/permeable), vegetation (sparse/good), relief (high/low), runoff/infiltration (high/low), and flood volumes (high/low) (Pallard et al. 2009). In the present analysis, high D_d values are observed in Arapat, Bring, Liddar, Veshav, and Arapal sub-basins ($D_d > 2$ km/km^2) due to high relief and impermeable sub-surface material, and hence, these sub-basins contribute more runoff in a short time. The Sasara and Dudhganga have lowest D_d values ($D_d < 1$ km/km^2) because of low relief, which imply the influence of low runoff during the flood period. The Rambiara, Romushi, and Sandran sub-basins have medium D_d values which, therefore, contribute average discharge of water during flood periods.

Stream frequency (F_s)

F_s is the count of all stream segments per unit area of a basin. It describes the texture of a stream network, and is associated with permeability, infiltration capacity, and relief of watersheds to produce discharge (Patton and Baker 1976; Montgomery and Dietrich 1989; Eze and Efiong 2010). F_s is also useful to compare basins that are underlain by different bedrock terrains. High F_s values are obtained for impermeable sub-surface material, sparse vegetation, high relief conditions, and low infiltration capacity (Reddy et al. 2004; Bhatt and Ahmed 2014). In the present analysis, F_s values vary from 1.2 to 4.6 per km^2 (Table 4). In general, the mean F_s is high for great Himalayan sub-basins indicating impermeable sub-surface material, high runoff potential, low infiltration capacity, and early peak discharge compared to low F_s values for Pir Panjal sub-basins (e.g., Patton and Baker 1976). The Bring sub-basin has the highest F_s value followed by Sandran, Arapat, and Lidder, since these streams and their adjacent tributaries are flowing mostly over hard-rock terrain with least permeability of soil which, therefore, causes more discharge in less period of time during high intensity rainfall. The Sasara sub-basin has lowest F_s value because of low relief and leading cover of soft sediments, which causes low runoff during rainfall. The results of F_s indicate that Bring, Sandran, Arapat, and Lidder sub-basins produce the early peak discharges to the Jhelum River and, thus, have higher flood potential, whereas Veshav, Arapal, and Dudhganga sub-basins take longer time period to generate peak discharge to the Jhelum River because of low runoff.

Drainage texture (T_d)

T_d is the ratio between total numbers of stream segments of all orders to the perimeter of the basin (Horton 1945). T_d depends on several factors such as climate, rainfall, vegetation, rock and soil type, infiltration capacity, relief, drainage density, and stage of development (Smith 1950). The unconsolidated formations (soft terrain) covered by vegetation free topographic surface produce fine texture, whereas consolidated formations (hard-rock terrain) have coarse texture (Sreedevi et al. 2009). T_d is classified into four categories: coarse (< 4 per km), intermediate (4–10 per km), fine (10–15 per km), and very fine (> 15 per km) (Smith 1950). In the study area, the drainage texture varies from 2.9 to 17.3 indicating range of textures from coarse to very fine (Table 4). In general, the combined T_d of great Himalayan

Table 2 Basic morphometric parameters of the upper Jhelum basin (Pir Panjal flank)

Sub-basin	A (km^2)	P (km)	l_b (km)	H (m asl)	h (m asl)	Stream order	Stream no.	Total orders	Stream length	Total length
Pir Panjal sub-basins										
Veshav	1014.8	161.4	44.1	4564	1559	1	2005	2643	1301.1	2205.1
						2	482		465.3	
						3	113		204.1	
						4	28		98.8	
						5	11		64.6	
						6	3		32.7	
						7	1		38.5	
Rambiara	872.63	167.7	58.7	4625	1527	1	1074	1330	726.02	1209.2
						2	200		243.3	
						3	44		124.1	
						4	8		38	
						5	3		77	
						6	1		0.79	
Sasara	256	108	37.2	2418	1579	1	241	313	241	441.2
						2	52		82.1	
						3	13		47.4	
						4	4		19.1	
						5	2		27.9	
						6	1		23.7	
Romushi	365	122	47.3	4651	1577	1	437	572	350	659.6
						2	93		143.5	
						3	30		96.7	
						4	9		40.5	
						5	2		5.1	
						6	1		23.8	
Dudhganga	649.7	129.2	47.8	4617	1563	1	866	1074	528.6	872.0
						2	160		141.1	
						3	37		76.9	
						4	8		46.3	
						5	2		62.1	
						6	1		17.07	

sub-basins is high ($T_d = 15.08$) compared to Pir Panjal sub-basins ($T_d = 8.04$). Moreover, coarse texture drainage basins have large basin lag time followed by intermediate, fine, and very fine texture classes (Esper Angillieri 2008), which suggest that the great Himalayan sub-basins have higher water yielding capacity and shorter catchment response time than the Pir Panjal sub-basins. In particular, Bring, Lidder, Arapal, and Veshav sub-basins have the highest T_d values.

Relief ratio (R_r)

R_r is an important indicator for determining the overall slope of a drainage basin along with the intensity of flow of water. It is measured between total relief of a basin and the longest basin length parallel to the principal drainage line (Schumm 1956). Moreover, surface flow is generally associated with steeper hill slopes, higher stream gradients, and increasing relief (Patton 1988). Drainage basins with high R_r indicate short basin lag time, instant flow velocity, high peak discharge, high erosion, and sediment yield (Bhatt and Ahmed 2014). In the upper Jhelum river basin, the R_r varies from 1.5 to 3.2 (Table 4). The Lidder and Rambiara sub-basins having high R_r values suggest that their underlying terrain is characterized by steep slopes, and, thus, attain higher peak flows with greater velocities (Altin and Altin 2011). Therefore, these sub-basins contribute maximum water in short period of time and cause floods in the lower part of the Jhelum basin. In addition, these sub-basins are highly susceptible to erosion. The Arapat, Dudhganga, Romushi, Sandran, and Arapal sub-basins having the moderate R_r values thereby cause moderate influence on flooding. The Sasara sub-basin has lowest R_r value, indicating that nearly flat terrain, longer

Table 3 Basic morphometric parameters of the upper Jhelum basin (great Himalayan flank)

Sub-basin	A (km^2)	P (km)	l_b (km)	H (m asl)	h (m asl)	Stream order	Stream no.	Total orders	Stream length	Total length
Great Himalayan sub-basins										
Sandran	365.23	118.3	47.1	4065	1583	1	1028	1463	64.1	99.7
						2	294		14.3	
						3	120		10.3	
						4	18		5	
						5	2		1.5	
						6	1		4.5	
Arapat	304	86.2	30.2	4400	1582	1	886	1129	464.7	758.9
						2	187		133	
						3	42		75.5	
						4	9		46	
						5	3		17.3	
						6	2		22.4	
Bring	505.36	135.2	40.6	4351	1582	1	1866	2342	1121.9	1741.1
						2	359		314.1	
						3	82		137	
						4	20		81.4	
						5	10		38.3	
						6	5		48.4	
Lidder	1267.2	222.6	53.8	5047	1535	1	3094	3858	1954.5	2949
						2	606		524.3	
						3	127		253.1	
						4	25		103.1	
						5	5		37.4	
						6	1		76.6	
Arapal	539	96.7	30.8	4239	1495	1	986	1488	666.2	1094.4
						2	398		195.1	
						3	69		89.2	
						4	18		43.7	
						5	10		32.4	
						6	7		67.8	

basin length, therefore, has least flood influence on Jhelum river.

Ruggedness number (R_n)

Slope is another important indicator of runoff, which provides general representation of relief ruggedness within the drainage basin (Melton 1957; Masoud 2016). Basins with gentle slope produce less runoff and small peaks of runoff, because they provide maximum time for water to infiltrate due to low flow velocity, whereas steep slope basins have greater flow velocity or faster surface runoff, therefore, shorter concentration times to peak of hydrograph (Masoud 2016). High R_n occur in those basins which have steep and long slopes and fine texture, thus, is highly susceptible to erosion and increased peak discharge (Patton and Baker 1976; Ozdemir and Bird 2009; Masoud 2016). Moreover, peak discharge would increase in basins due to increasing relief and drainage density (Patton 1988). In the upper Jhelum basin, Bring, Lidder, and Veshav sub-basins have highest R_n values, indicating that they have high relief, fine texture, and possibilities of high surface flow (Table 4). Moreover, these sub-basins are susceptible to erosion and producing increased peak discharge. The Sandran and Sasara have the lowest R_n values because of low relief and lesser degree of terrain complexity causing less water flow. The Arapat, Arapal, Romushi, Rambiara, and Dudhganga sub-basins have moderate R_n values indicating medium runoff due to partly covering of flat top surfaces or valley-type topography and moderate degree of dissection.

Table 4 Derived parameters of the upper Jhelum river basin

Sub-basins	Bifurcation ratio (R_b)	Stream frequency (F_s)	Drainage density (D_d)	Drainage texture (T_d)	Compactness index (c)	Form factor (F)	Circulatory ratio (C)	Elongation ratio (E_b)	Lemniscate ratio (K)	Basin relief (H_r)	Ruggedness number (R_n)	Relief ratio (R_r)
Veshav	3.734	2.604	2.172	16.375	1.429	0.521	0.489	0.814	0.479	3005	6.361	2.927
Rambiara	3.500	1.500	1.700	7.900	1.601	0.252	0.387	0.567	0.989	3098	4.196	3.028
Sasara	3.176	1.222	1.723	2.898	1.904	0.184	0.275	0.485	1.352	839	2.639	1.531
Romushi	3.526	1.567	1.807	4.688	1.801	0.163	0.308	0.455	1.533	3074	5.329	2.949
Dudhganga	4.072	1.653	1.342	8.312	1.429	0.284	0.489	0.601	0.879	3054	3.965	2.953
Sandran	4.722	4.005	0.273	12.366	1.746	0.164	0.327	0.458	1.518	2482	0.701	2.567
Arapat	3.500	3.700	3.400	13.090	1.395	0.333	0.513	0.651	0.750	2818	6.943	2.781
Bring	3.535	4.634	3.445	17.322	1.697	0.306	0.347	0.624	0.815	2769	9.475	2.750
Lidder	4.991	3.044	2.327	17.331	1.764	0.437	0.321	0.746	0.571	3512	7.651	3.287
Arapal	3.061	2.760	2.030	15.387	1.175	0.568	0.724	0.815	0.440	2744	5.757	2.835

Form factor (*F*)

F represents the shape or outline of a basin, and is a ratio between the area of the basin and the square of the basin length (Horton 1932). It is a useful parameter to obtain a relationship of flow intensity of drainage basins along with their peak discharge (Horton 1945; Gregory and Walling 1973). High *F* values occur in the basins having potential to produce high peak flows in short duration and low *F* values are vice versa (Kochel 1988; Howard 1990; Reddy et al. 2004; Youssef et al. 2011). In the upper Jhelum River basin, the *F* values are ranging from 0.2 to 0.6. In general, most of the SW sub-basins have low *F* values indicating elongated nature with low peak runoff of longer duration; whereas, Veshav, Liddar, and Arapal sub-basins have highest *F* values indicating circular nature with high peak runoff flow of short duration, thereby influencing discharge and flooding situation of lower Jhelum river.

Elongation ratio (E_b)

Like form factor E_b also represents the shape of a river basin. It is defined as the ratio of diameter of a circle with the same area as that of the basin to the maximum basin length (Schumm 1956). It helps to provide understanding about the hydrological character of a drainage basin. The E_b values vary from 1 for circular basins and 0 for elongate basins. High E_b values occur for circular basins, considered as highly hazardous, because they yield peak flow in short period of time compared to low E_b in elongated basins (Potter and Faulkner 1987; Singh and Singh 1997; Masoud 2016). In the upper Jhelum river basin, E_b varies from 0.5 to 0.9 (Table 4), indicating elongated characters of most of the sub-basins with high relief and steep slope except that of Arapal and Veshav; hence, the sub-basins are prone to erosion with less infiltration capacity which, however, suggests delayed time to peak flow. On the other hand, Arapal and Veshav sub-basins have highest E_b value indicating low relief, gentle slope, and oval-to-circular landscape. Therefore, the basins are prone to flood peak discharge having shorter lag time and higher peak flows than the elongated basins (e.g., Singh and Singh 1997).

Compactness index (*c*)

It is defined as the ratio between the length of the drainage basin boundary and the perimeter of a circle with the same area (Gravelius 1914). It provides numerical representation of degree of deviation of a basin shape from a standard circle (Wentz 2000). The *c* of a drainage basin is the product of lithology, vegetation, and climate regime, and gives an idea about the infiltration characteristics of the basin. The circular basins ($c = 1$) yield shortest time of concentration before peak flow occurs in the basin, whereas deviations from circular basins ($c > 1$) reflect vice versa (Altaf et al. 2013). In the present analysis, Arapal, Arapat, Dudhganga, and Veshav sub-basins have lowest c (Table 4) which indicates low infiltration capacity or high runoff, whereas the Sasara sub-basin has highest c indicating high infiltration capacity or lowest runoff among all the sub-basins and Liddar, Bring, and Romushi sub-basins fall in intermediate category.

Lemniscate ratio (*K*)

K is used to determine the shape and slope of a drainage basin (Chorley et al. 1957). According to Lykoudi and Zanis (2004), the lemniscate values for elongate basins vary from 0.5 to 1.8. If the values are <0.5, then the shape of the basin tends to be circular, and if the values are >2, then the basin shape is fully elongated. The circular basins tend to have low values of lemniscate ratio and are more hazardous to erosion than the elongate basins because of short time of concentration from the remotest point in the basin to reach the outlet compared to that in elongated ones (Chorley et al. 1957; Morgan 2005). In the upper Jhelum river basin, Arapal, Veshav, and Lidder sub-basins have low K (Table 4), indicating circular character with shortest basin lag time. Therefore, these sub-basins are most vulnerable to flooding compared to Sasara, Romushi, and Sandran sub-basins.

Circulatory ratio (*C*)

C is a quantitative measure and is defined as the ratio of the basin area to the area of a circle having the same circumference as the perimeter of the basin (Miller 1953). Drainage basins characteristics such as length and frequency of streams, geological structures, land-use land-cover, climate, relief, and slope of the basin have significant influence on C (Altaf et al. 2013). Moreover, basin hydrological response is controlled by basin shape and the arrangement of stream segments, which provide a general influence of magnitude and shape of flood peaks (Ward and Robinson 2000). The high C suggests that the basin has circular shape with moderate-to-high relief and permeable surface causing peak flows in shorter duration, whereas low C indicates elongated basin with low relief and impermeable surface resulting in lower peak flow for longer duration (Sreedevi et al. 2005; Altaf et al. 2013). In the upper Jhelum river basin, highest C value was observed in the sub-basins of Arapal, Arapat, Dudhganga, and Veshav (Table 4), indicating that these sub-basins attain peak flows in short duration of time; whereas Rambiara, Sasara, Romushi, Sandran, Bring, and Liddar sub-basins have moderate C values, indicating that these sub-basins have longer duration of flow discharges, good groundwater recharge potential, and larger basin lag times.

Basin relief (H_r)

H_r is defined as the difference in elevation between the highest and lowest points in the basin (Schumm 1956). It is a significant factor to understand the denudational characteristics of a drainage basin, landforms and drainage network development, runoff conditions, and erosional properties of the terrain (Patton 1988). Instant runoff response and high flood peaks are also due to steep hill slopes and higher stream gradient (Patton 1988). Moreover, basin relief and measures of channel gradient and basin slope have long been recognized as parameters having relation with river discharge (Sherman 1932; Benson 1964; Murphey et al. 1977). In the present analysis, highest H_r value observed in Liddar sub-basin, intermediate values in Sandran, Arapat, Bring, and Arapal sub-basins, and lowest value in Sasara sub-basin. The high H_r ($H_r > 3000$) values in Lidder along with Veshav, Dudhganga, Rambiara, and Romushi sub-basins indicate the gravity of low infiltration and high runoff or quick hydrological basin response (Ozdemir and Bird 2009) during rain–storm events.

Compound value (C_v)

Single or limited parameters cannot present the comprehensive picture of the flood hazard potential of any sub-basin, and hence, each of the linear, aerial, and relief morphometric parameters is taken into consideration for assessing the flood influencing characteristics among ten sub-basins of the upper Jhelum basin. The morphometric parameters, i.e., stream order, stream number, mean bifurcation ratio, drainage density, stream frequency, drainage texture, relief ratio, ruggedness number, form factor, basin relief, compact index, lemniscate ratio elongation ratio, and circulatory ratio, have a direct but variable relationship with flood runoff. Therefore, influencing value (highest weightage 10 and least 1) is given to each selected parameter as per its nature (Table 5) (e.g., Bhatt and Ahmed 2014; Altaf et al. 2014). C_v is derived by calculating the average of ranks assigned to the individual parameters. The sub-basin with highest C_v is most susceptible to flood as a result needs highest priority for flood mitigation measures, whereas lowest C_v basins are least susceptible to flood thereby needs lower priority. Hence, C_v analysis indicate that the southeast sub-basins (Great Himalaya) have greater discharge influence on the main Jhelum river than the southwest sub-basins (Pir Panjal) (Fig. 6). Among all the tributaries of upper Jhelum, Lidder has greater potential to generate maximum discharge during the rainy season because of runoff generating characteristics (high values of R_b, D_d, T_d, F, E_b, K, H_r, R_n, and R_r). Similarly, Arapal and Veshav indicate high runoff due to high values of F, C, R_b, T_d, and D_d, and low values of c and K. The Dudhganga and Rambiara reveal the moderate values

Table 5 Ordering of sub-basin influence on the main Jhelum River

Sub-basins	Bifurcation ratio (R_b)	Stream frequency (F_s)	Drainage density (D_d)	Drainage texture (T_d)	Compactness index (c)	Form factor (F)	Circulatory ratio (C)	Elongation ratio (E_b)	Lemniscate ratio (K)	Basin relief (H_r)	Ruggedness number (R_n)	Relief ratio (R_r)	Compound value (C_v)	Priority
Veshav	7	5	7	8	8	9	8	9	9	6	7	6	7.42	High
Rambiara	4	2	3	3	7	4	7	4	4	9	4	9	5.0	Medium
Sasara	2	1	4	1	2	3	2	3	3	1	2	1	2.08	Low
Romushi	5	3	5	2	3	1	3	1	1	8	5	7	3.67	Low
Dudhganga	8	4	2	4	8	5	8	5	5	7	3	8	5.75	Medium
Sandran	9	9	1	5	5	2	5	2	2	2	1	2	3.75	Low
Arapat	4	8	9	6	9	7	9	7	7	5	8	4	6.92	High
Bring	6	10	10	9	6	6	6	6	6	4	10	3	6.83	High
Lidder	10	7	8	10	4	8	4	8	8	10	9	10	8.0	High
Arapal	3	6	6	7	10	10	10	10	10	3	6	5	7.17	High

of F_s, D_d, T_d, F, E_b, K, and R_n, and moderate-to-high R_b, c, and C thereby contribute moderate runoff or have comparatively average influence on upper Jhelum River. The Sasara, Romushi, and Sandran tributaries contribute least runoff to the main Jhelum River because of lower values of all the runoff influencing parameters (Table 4).

Conclusions

The morphometric parameters derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model (DEM) and topographic maps helped to understand the hydrological behavior of various sub-basins of upper Jhelum. Based on the integration of each discharge influencing morphometric parameter, the sub-basins of upper Jhelum have been categorized into three flood hazard potential zones: high hazard (6.0–8.0), moderate hazard (5.0–6.0), and low hazard (2.0–5.0). The morphometric results show exceptional corroboration from two different geomorphic settings in the present such as southeastern sub-basins (Great Himalaya) which are mostly covered by steep slopes of underlying dominant Palaeozoic massif, and, as a result, have low permeability, less infiltration capacity, and greater runoff (flood) influence on the main Jhelum river than the southwestern sub-basins (Pir Panjal), which consists of gentle slopes of underlying late Quaternary unconsolidated Karewa sediments. To reduce floods, we suggest that there is dire need to construct flood spill channel, which can take one-third of the total flow of the Jhelum River and more significantly the existing river levees should be made strong to prevent overtopping or failure that would cause significant flood damages impacting vulnerable communities along the Jhelum River. However, during heavy rain–storm events, tremendous volume of adjacent tributary discharge is mostly responsible for flooding scenario, because these tributaries carry enormous quantity of silt, and, as a result, it was drastically reduced the carrying capacity of Jhelum River. Hence, prevention measures would not only be taken to prevent floods in the floodplain of the downstream agricultural crops and settlements, but mitigation measures should be taken in the upper tributary streams, as well; for instance, early flood warning system, stability of levees/embankments, flood walls, flood gates, introduction of water storage areas (check dams), protect wetlands, strategic cultivation, production of flood risk maps, prevent further development in flood prone areas, adaptation of advanced flood forecasting techniques, and specifically desiltation/dredging at impressive rate for the Jhelum river.

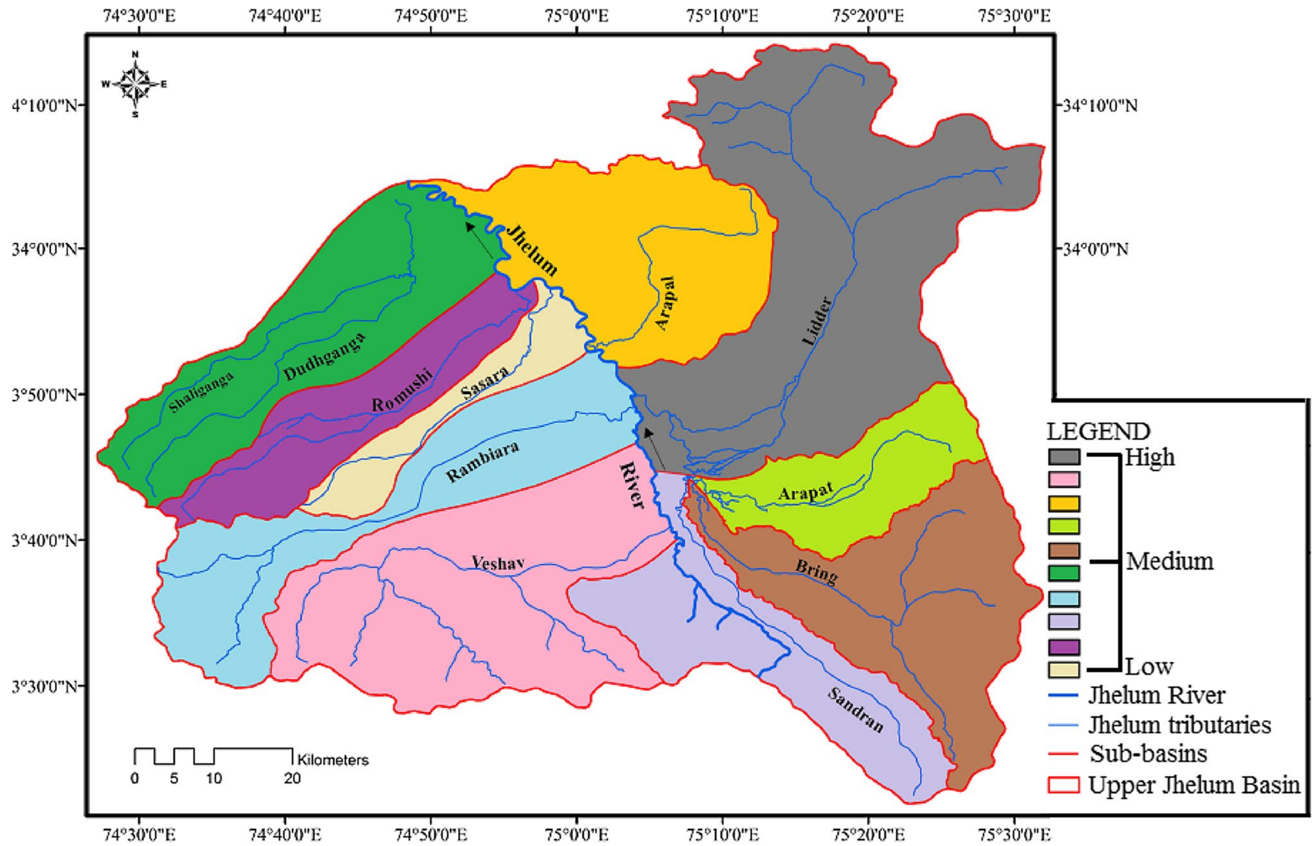

Fig. 6 Flood hazard map of the upper Jhelum. The maximum flood influence of sub-basins in the main Jhelum River is from east–northeast, Kashmir valley

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References

Adhikari P, Hong Y, Douglas KR, Kirschbaum DB, Gourley J, Adler R, Brakenridge GR (2010) A digitized global flood inventory (1998–2008): compilation and preliminary results. Nat Hazards 55:405–422. https://doi.org/10.1007/s11069-010-9537-2

Ahmad S (2014) Extension of out-of-sequence Balapur Fault and identification of other active faults on the eastern front of the Pir Panjal range, Kashmir valley, Ph.D. thesis. Department of Earth Sciences, University of Kashmir, p 174

Ahmad S, Bhat MI (2012) Tectonic geomorphology of the Rambiara basin, SW Kashmir Valley reveals emergent out-of-sequence active fault system. Himal Geol 33(2):162–172

Ahmad S, Bhat MI, Madden C, Bali BS (2013) Geomorphic analysis reveals active tectonic deformation on the eastern flank of the Pir Panjal Range, Kashmir Valley, India. Arab J Geosci. https://doi.org/10.1007/s12517-013-0900-y

Ahmad S, Alam A, Ahmad B, Bhat MI, Bhat MS (2015) Geomorphic evidence of unrecognized Balapur fault segment in the southwest Kashmir basin of northwest Himalayas. Geomorphology 250:159–172

Ahmad S, Alam A, Ahmad B, Afzal A, Bhat MI, Bhat MS, Ahmad FA (2017) Tectono-geomorphic indices of the Erin basin, NE Kashmir valley, India. J Asian Earth Sci 151:16–30

Ahmed SA, Chandrashekarappa KN, Raj SK, Nischitha V, Kavitha G (2010) Evaluation of morphometric parameters derived from ASTER and SRTM DEM—a study on Bandihole sub-watershed basin in Karnataka. J Indian Soc Remote Sens 38:227–238

Alam A, Ahmad S, Bhat MS, Ahmad B (2015) Tectonic evolution of Kashmir basin in northwest Himalayas. Geomorphology 239:114–126

Alam A, Bhat MS, Kotlia BS, Ahmad B. Ahmad S. Taloor AK, Ahmad HF (2017) Coexistent pre-existing extensional and subsequent compressional tectonic deformation in the Kashmir basin, NW Himalaya. Quat Int 444:201–208

Alam A, Bhat MS, Farooq H, Ahmad B, Ahmad S, Sheikh AH (2018) Flood risk assessment of Srinagar city in Jammu and Kashmir, India. Int J Disaster Resil Built Environ 9(2):114–129. https://doi.org/10.1108/IJDRBE-02-2017-0012

Al-Fugara A (2015) Comparison and validation of the recent freely available DEMs over part of the earth's lowest elevation area: Dead Sea, Jordan. Int J Geosci 6:1221–1232. https://doi.org/10.4236/ijg.2015.611096

Altaf F, Meraj G, Romshoo SA (2013) Morphometric analysis to infer hydrological behaviour of Lidder Watershed, Western Himalaya,

India. Hindawi Publishing Corporation. Geogr J. https://doi.org/10.1155/2013/178021
Altaf S, Meraj G, Romshoo SA (2014) Morphometry and land cover based multi-criteria analysis for assessing the soil erosion susceptibility of the western Himalayan watershed. Environ Monit Assess. https://doi.org/10.1007/s10661-014-4012-2
Altin TB, Altin BN (2011) Drainage morphometry and its influence on landforms in volcanic terrain, Central Anatolia, Turkey. Procedia Soc Behav Sci 19:732–740
Baumgardner R (1987) Morphometric studies of sub-humid and semiarid drainage basin. In: Texas Panhandle and Northeastern New Mexico. University of Texas Bureau of Economic Geology, Austin, Report of Investigations, 163
Benson MA (1964) Factors affecting the occurrence of floods in the Southwest. USGS water supply paper, 1580-D, pp 1–72
Bertolo F (2000) Catchment delineation and characterisation, catchment characterisation and modelling Euro landscape project. Space Application Institute, Joint Research Center, Ispra
Berz G, Kron W, Loster T, Rauch E, Schimetschek J, Schmieder J et al (2001) World map of natural hazards—a global view of the distribution and intensity of significant exposures. Nat Hazards 23(2–3):443–465
Bhat MI (1982) Thermal and tectonic evolution of Kashmir basin vis-à-vis petroleum prospects. Tectonophysics 88:117–132
Bhat MS, Alam A, Ahmad B, Kotlia BS, Farooq H, Taloor AK, Ahmad S (2018) Flood frequency analysis of river Jhelum in Kashmir basin. Quat Int. https://doi.org/10.1016/j.quaint.2018.09.039
Bhatt DK (1989) Lithostratigraphy of the Karewa Group, Kashmir valley, India and a critical review of its fossil record. Mem Geol Surv India 122:1–85
Bhatt S, Ahmed SA (2014) Morphometric analysis to determine floods in the Upper Krishna basin using Cartosat DEM. Geocarto Int 29(8):878–894. https://doi.org/10.1080/10106049.2013.868042
Bhatt CM, Rao GS, Farooq M, Manjusree P, Shukla A, Sharma SVSP, Kulkarni SS, Begum A, Bhanumurthy V, Diwakar PG, Dadhwal VK (2016) Satellite-based assessment of the catastrophic Jhelum floods of September 2014, Jammu & Kashmir, India. Geomat Nat Hazards Risk. https://doi.org/10.1080/19475705.2016.1218943
Bilham R, Bali BS (2013) A ninth century earthquake-induced landslide and flood in the Kashmir Valley, and earthquake damage to Kashmir's Medieval temples. Bull Earthq Eng 12:79–109. https://doi.org/10.1007/s10518-013-9504-x
Bilham R, Singh B, Bhat I, Hough S, 2010, Historical earthquakes in Srinagar, Kashmir: clues from the Shiva Temple at Pandrethan. In: Sintubin M, Stewart IS, Niemi TM, Altunel E (eds) Ancient earthquakes, Geological Society of America Special Paper, vol 471, pp 107–117
Boulton AG (1968) Morphometric analysis of river basin characteristics. J Hydrol 6(2):227
Bronger A, Pant RK, Singhvi AK (1987) Pleistocene climatic changes and landscape evolution in the Kashmir Basin, India: Paleopedologic and Chronostratigraphic studies. Quat Res 27:167–181
Burbank DW (1983) The chronology of intermontane-basin development in the northwest Himalaya and the evolution of the Northwest Syntaxis. Earth Planet Sci Lett 64:77–92
CEOS (2003) The use of earth observing satellites for hazard support: assessments and scenarios. Final report of the CEOS Disaster Management Support Group (DMSG)
Chorley RJ (1969) Introduction to fluvial processes. Methuen and Co. Limited, London, p 588
Chorley RJ, Malm DEG, Pogorzelski HA (1957) A new standard for estimating basin shape. Am J Sci 255:138–141
Chow VT (1964) Handbook of applied hydrology: a compendium of water-resources technology. McGraw-Hill, New York
Chow VT, Maidment DR, Mays LW (1988) Applied hydrology. McGraw-Hill, New York
Clark JJ (1966) Morphometry from map, essays in geomorphology. Elsevier, New York, pp 235–274
Costa JE (1987) Hydraulics and basin morphometry of the largest flash floods in the conterminous United States. J Hydrol 93:313–338
Dev JS (1983) Natural calamities of Jammu and Kashmir state. Ariana Publishing House, New Delhi
Esper Angillieri MY (2008) Morphometric analysis of Colanguil river basin and flash flood hazard, San Juan, Argentina. Environ Geol 55:107–111
Eze BE, Efiong J (2010) Morphometric parameters of the Calabar River basin: implication for hydrologic processes. J Geogr Geol 2:18–26
Farooqi IA, Desai RN (1974) Stratigraphy of Karewas, India. J Geol Surv India 15(3):299–305
Gardiner V, Park CC (1978) Drainage basin morphometry: review and assessment. Prog Phys Geogr 2(1):1–35. https://doi.org/10.1177/030913337800200102
Gichamo TZ, Popescu I, Jonoski A, Solomatine D (2012) River cross-section extraction from the ASTER global DEM for flood modelling. Environ Model Softw. https://doi.org/10.1016/j.envsoft.2011.12.003
Gravelius H (1914) Flusskunde. Goschen Verlagshan dlug Berlin. En Zavoianu, I. 1985. In: Morphometry of drainage basins. Elsevier, Amsterdam
Gregory KJ, Walling DE (1973) Drainage basin form and process: a geomorphological approach. Wiley, New York, p 456
Hadley RF, Schumm SA (1961) Sediment sources and drainage basin characteristics in upper Cheyenne River Basin. USGS Water Suppl 1531-B:198
Horton RE (1932) Drainage basin characteristics. Trans Am Geophys Union 13:350–361
Horton RE (1945) Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Geol Soc Am Bull 56:275–370
Howard AD (1990) Role of hypsometry and planform in basin hydrologic response. Hydrol Process 4(4):373–385
Jain V, Sinha R (2003) Evaluation of geomorphic control on flood hazard through geomorphic instantaneous unit hydrograph. Curr Sci 85:1596–1600
Javed A, Khanday MY, Ahmed R (2009) Prioritization of subwatersheds based on morphometric and land use analysis using remote sensing and GIS techniques. J Indian Soc Remote Sens 37:261–274
Keller EA, Pinter N (1996) Active tectonics: earthquakes, uplift, and landscape. Prentice Hall, New Jersey
Khoihami PGH (1885) Tarikh-i-Hassan, vols. I and II, Folios 511 and 263 **(in Persian)**
Kochel RC (1988) Geomorphic impact of large floods: review and new perspectives on magnitude and frequency. In: Flood geomorphology. Wiley, New York, pp 169–187
Koul PA (1925) Geography of Jammu and Kashmir State. Thacker Spink, Calcutta
Krishnan MS (1982) Geology of India and Burma. Higginbotham, Madras, p 536
Kumar R, Acharya P (2016) Flood hazard and risk assessment of 2014 floods in Kashmir Valley: a space-based multisensor approach. Nat Hazards 84:437–464. https://doi.org/10.1007/s11069-016-2428-4
Lawrence WR (1895) The Valley of Kashmir (reprint), Kesar Publishers, Srinagar **(reprint 1884)**
Lydekker R (1876) Notes on the geology of the Pir Panjal and neighbouring districts. Rec Geol Surv India 9:155–183
Lykoudi E, Zanis D (2004) The influence of drainage network formation and characteristics over a catchment's sediment yield. In: Proceedings of second international conference on fluvial

hydraulics-river flow. University of Napoli-Federico II, Naples, pp 793–800
Magesh NS, Chandrasekar N, Soundranayagam JP (2011) Morphometric evaluation of Papanasam and Manimuthar watersheds, parts of Western Ghats, Tirunelveli district, Tamil Nadu, India: a GIS approach. Environ Earth Sci 64(2):373–381
Maidment DR (ed) (2002) Arc Hydro: GIS for water resources. ESRI Press, Redlands
Masoud MH (2016) Geoinformatics application for assessing the morphometric characteristics' effect on hydrological response at watershed (case study of Wadi Qanunah, Saudi Arabia). Arab J Geosci 9:280. https://doi.org/10.1007/s12517-015-2300-y
McBean G (2004) Climate change and extreme weather: a basis for action. Nat Hazards 31(1):177–190
Melton MA (1957) An analysis of the relations among elements of climate, surface properties, and geomorphology, Technical Report No. 11, Office of Naval Research Project NR 389-042. Department of Geology, Columbia University, New York
Meraj G, Romshoo SA, Yousuf AR, Altaf S, Altaf F (2015) Assessing the influence of watershed characteristics on the flood vulnerability of Jhelum basin in Kashmir Himalaya. Nat Hazards 77:153–175. https://doi.org/10.1007/s11069-015-1605-1
Middlemiss CS (1911) Sections in Pir Panjal and Sindh valley. Kashmir Rec Geol Surv India 41:115–144
Miller VC (1953) A quantitative geomorphic study of drainage basin characteristics in Clinch Mountains Area, Virginia and Tennessee. Technical report, 3 Office of the Naval Research. Department of Geology, Columbia University, New York
Mishra AK (2015) A study on the occurrence of flood events over Jammu and Kashmir during September 2014 using satellite remote sensing. Nat Hazards 78:1463–1467. https://doi.org/10.1007/s11069-015-1768-9
Montgomery DR, Dietrich WE (1989) Source areas, drainage density and channel initiation. Water Resour Res 25:1907–1918
Morgan RPC (2005) Soil erosion and conservation. Blackwell Publishing, New York
Muralikrishnan S, Pillai A, Narender B, Reddy S, Venkataraman VR, Dadhwal VK (2013) Validation of Indian national DEM from Cartosat-1 data. J Indian Soc Remote Sens 41:1–13
Murphey JB, Wallace DE, Lane LJ (1977) Geomorphic parameters predict hydrograph characteristics in the Southwest. Water Resour Bull 13:25–38
Nag SK, Chakraborty S (2003) Influence of rock types and structures in the development of drainage network in hard rock area. J Indian Soc Remote Sens 31(1):25–35
Ozdemir H, Bird D (2009) Evaluation of morphometric parameters of drainage networks derived from topographic maps and DEM in point floods. Environ Geol 56:1405–1415
Pallard B, Castellarin A, Montanar A (2009) A look at the links between drainage density and flood statistics. Hydrol Earth Syst Sci 13:1019–1029
Pant RK, Agrawal DP, Krishnamurthy KV (1978) Scanning electron microscopic and other studies on Karewa beds of Kashmir, India. In: Whalley WB (ed) Scanning electron microscopy in the study of sediments. Geoabstracts, Norwich, pp 275–282
Patel DP, Dholakia MB, Naresh N, Srivastava PK (2012) Water harvesting structure positioning by using geo-visualization concept and prioritization of mini-watersheds through morphometric analysis in the lower Tapi basin. J Indian Soc Remote Sens 40:299–312
Patton PC (1988) Drainage basin morphometry and floods. In: Baker VR, Kochel RC, Patton PC (eds) Flood geomorphology. Wiley, USA, pp 51–65
Patton PC, Baker VR (1976) Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls. Water Resour Res 12:941–952
Peduzzi P, Dao H, Herold C, Mouton F (2009) Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index. Nat Hazards Earth Syst Sci 9(4):1149–1159
Potter KW, Faulkner EB (1987) Catchment response time as a predictor of flood quantiles. J Am Water Resour Assoc 23(5):857–861
Pradhan B (2010) Remote sensing and GIS-based landslide hazard analysis and cross-validation using multivariate logistic regression model on three test areas in Malaysia. Adv Space Res 45(10):1244–1256
Pradhan B, Lee S (2010) Delineation of landslide hazard areas on Penang Island, Malaysia, by using frequency ratio, logistic regression, and artificial neural network models. Environ Earth Sci 60(5):1037–1054
Rakesh K, Lohani AK, Sanjay CC, Nema RK (2000) GIS based morphometric analysis of Ajay river basin up to Sararath gauging site of south Bihar. J Appl Hydrol 14(4):45–54
Raza M, Ahmad A, Mohammad A (1978) The Valley of Kashmir: geographical interpretation, vol 1. The Land, Vikas Publishing House Pvt. Ltd., New Delhi, pp 1–59
Reddy GPO, Maji AK, Gajbhiye KS (2004) Drainage morphometry and its influence on landform characteristics in a basaltic terrain, Central India—a remote sencing and GIS approach. Int J Appl Earth Observ Geoinf 6(1):1–16
Romshoo SA, Bhat SA, Rashid I (2012) Geoinformatics for assessing the morphometric control on hydrological response at watershed scale in the Upper Indus Basin. J Earth Syst Sci 121(3):659–686
Roughani M, Ghafouri M, Tabatabaei M (2007) An innovative methodology for the prioritization of sub-catchments for flood control. Int J Appl Earth Obs Geoinf 9:79–87
Schumm SA (1956) Evolution of drainage system and slope in badlands of Perth Amboy, vol 67. Geological Society of America Bulletin, New Jersey, p 597
Sen D (2010) Flood hazards in India and management strategies. In: Jha MK (ed) Natural and anthropogenic. Springer, Dordrecht
Sharma CS, Mishra A, Panda SN (2014) Assessing impact of flood on river dynamics and susceptible regions: geomorphometric analysis. Water Resour Manag 28:2615–2638. https://doi.org/10.1007/s11269-014-0630-2
Sherman LK (1932) The relation of hydrographs of runoff to size and character of drainage basin. Trans Am Geophys Union 13:332–339
Singh IB (1982) Sedimentation pattern in the Karewa basin, Kashmir valley, India and its geological significance. J Palaeontol Soc India 27:71–110
Singh O, Kumar M (2013) Flood events, fatalities and damages in India from 1978 to 2006. Nat Hazards 69(3):1815–1834
Singh S, Singh MC (1997) Morphometric analysis of Kanhar river basin. Natl Geogr J India 43(1):31–43
Smith KG (1950) Standards for grading texture of erosional topography. Am J Sci 248:655–668
Sreedevi PD, Subrahmanyam K, Ahmed S (2005) The significance of morphometric analysis for obtaining groundwater potential zones in a structurally controlled terrain. Environ Geol 47:412–420
Sreedevi PD, Owais S, Khan H, Ahmed S (2009) Morphometric analysis of a watershed of South India using SRTM data and GIS. J Geol Soc India 73:543–552
Strahler AN (1957) Quantitative analysis of watershed geomorphology. Trans Am Geophys Union 38:913–920
Tabish SA, Nabil S (2014) Epic tragedy: Jammu and Kashmir floods: a clarion call. Emerg Med 5:1–8. https://doi.org/10.4172/2165-7548.1000233
Thakur VC, Rawat BS (1992) Geologic map of Western Himalaya. Wadia Institute of Himalayan Geology, Dehra Dun

Vincent RK (1997) Fundamentals of geological and environmental remote sensing. Prentice-Hall Inc., Upper Saddle River

Wadia DN (1975) Geology of India, 4th edn. Tata McGraw-Hill, New Delhi

Ward RC, Robinson M (2000) Principles of hydrology, 4th edn. McGraw-Hill, New York

Wentz EA (2000) A shape definition for geographic applications based on edge, elongation, and perforation. Geogr Anal 32(1):95–112

Youssef AM, Pradhan B, Hassan AM (2011) Flash flood risk estimation along the St. Katherine road, southern Sinai, Egypt using GIS based morphometry and satellite imagery. Environ Earth Sci 62(3):611–623