Variability of Geomorphological Characteristics and the Altered Hydrological Regime of the Upper Indus Basin, Pakistan

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The administration of watersheds holds significant relevance in the field of water resources engineering and management. The main objective of this research is to assess the geomorphological attributes of the Upper Indus Basin (UIB) in Pakistan, with a particular emphasis on its hydrological phenomena. The demarcation of the boundaries of the 21 sub-basins within the UIB was achieved by employing ArcGIS software. The findings indicate that the subbasins demonstrate a range of drainage patterns, varying from sub-dendritic to dendritic. This suggests that there is a consistent texture and absence of structural influence within the subbasins. The research identified a range of stream orders, extending from 3.76 to 365.73 km, indicating a diversity in bifurcation ratios that spans from 3.00 to 5.40. The findings of this investigation suggest the presence of geologic formations that offer favorable conditions. The total length of streams and the number of stream segments demonstrate an upward trend in first-order streams, whereas they decline as the stream order advances. The Drainage Density (DD) of all sub-watersheds has a variation ranging from 0.170 to 0.231 km^{-1}, indicating the presence of regions characterized by materials with notable resistance and porosity. The observed low drainage intensity in these watersheds suggested that the capacity to remove surface runoff is insufficient, rendering them susceptible to the occurrence of flooding, gully erosion, and landslides. Greater infiltration capacity and less runoff are correlated with higher elongation ratios. The findings derived from our study are intended to provide a significant contribution to the development of a sustainable water management strategy for the UIB in the upcoming years. The main focus of this work is to analyze the geomorphological characteristics of mountainous watersheds located in the UIB of Pakistan and assess their influence on hydrologic processes.

Keywords: Upper Indus Basin, Hydrological process, Drainage Density, Erosion, Geomorphological characters.

Introduction:

In the realm of academic discourse, the recognition of watersheds as pivotal entities for strategic planning and effective land and water resource governance is well-established. This paper sets out to delve into the subject of climate change and its profound implications for the natural world, highlighting the integral role of watersheds in this critical context. This is employed to mitigate the effects of natural disasters and facilitate the attainment of goals pertaining to sustainable development. The term watershed is employed to signify a naturally transpiring physiographic or ecological entity that is comprised of interconnected components and operates as a cohesive system [1]. This research unveiled that it is imperative to possess a comprehensive awareness of the hydrologic cycle to get thorough knowledge of a watershed. Hydrologic processes encompass the inherent progression by which water experiences a metamorphosis into water vapor, subsequently precipitates onto the Earth's surface, and ultimately reenters the atmosphere via evaporation. The procedures outlined here govern the ingress and egress of water within the watershed [2]. The response of a particular watershed to various hydrological processes depends on a multitude of physiographic, hydrological, and geomorphological attributes. The classification of a watershed yields significant insights into its attributes; nonetheless, it is crucial to recognize that these criteria are distinct and particular to each single watershed.

The administration of a watershed necessitates the planned allocation of water and land resources within the designated region to achieve maximum productivity while minimizing the detrimental impacts on the natural surroundings. A comprehensive watershed management program encompasses various objectives, including the regulation of detrimental runoff, the management and utilization of runoff for advantageous purposes, erosion control, sediment production reduction, groundwater storage augmentation, and appropriate land resource utilization within the watershed [3]. The current scrutiny showed that it is crucial to conduct a comprehensive and thorough analysis of its various characteristics to optimize the management of a watershed. The information acquired through this investigation should be efficiently utilized during the development stage, with a particular emphasis on the smooth incorporation of various planning elements. The proper execution of this methodology is crucial in ensuring the efficient management of the watershed [4].

The interconnection between land planning and natural resource management is closely tied to the geomorphological attributes of watersheds. Every watershed displays distinct attributes including its dimensions, configuration, incline, patterns of water flow, plant life, geological composition, soil makeup, topographical elements, climatic conditions, and land utilization. The hydrologic and geomorphic cycles take place within the confines of the watershed. Through the analysis of geomorphometric attributes on a watershed level, scholars can acquire significant insights into the genesis and evolution of land surface phenomena. Watershed characterization involves the systematic application of methodologies to evaluate and comprehend the diverse array of activities occurring within a specific watershed [5]. The utilization of remote sensing and Geographic Information System (GIS) methodologies has become increasingly prominent in the realm of watershed characterization, hence facilitating the effective execution of watershed management initiatives. The hydrological characteristics of several river basins and sub-basins in different geographical regions worldwide have been investigated using conventional approaches [5].

Unfortunately, a significant portion of the nation's watersheds is considered degraded. Hydrologists face a multitude of difficulties while endeavoring to understand the fundamental principles governing hydrological processes within a watershed. This is especially true when working with ungauged catchments, where there is a lack of hydrological data available. The response of a watershed to different hydrological processes depends on several physiographic, hydrogeological, and geomorphological properties. The objective of this statement is to underscore the uniqueness of the research being conducted. [6].

The UIB suffers from a lack of monitoring in several watersheds due to inadequate financial resources, human resources, equipment, and limited accessibility to gauge stations. The persistent absence of essential information has consistently resulted in the ineffectiveness of numerous planning attempts by the government, occasionally rendering the attainment of planning objectives exceedingly difficult [7]. Considering these circumstances, it will be imperative for research and development plans related to mountain resources in Pakistan to heavily rely on the analysis of watershed elements and the use of fundamental coefficients as the primary methodology for offering hydrological explanations. The examination of watershed characteristics is a potentially effective method for developing a framework to plan and implement efforts. The quantitative evaluation of characteristics about mountainous watersheds holds considerable importance in the field of hydrological research. This includes the examination of groundwater capacity, management of groundwater resources, assessment of flood and water resources potential, basin governance, and environmental assessment [8]. The assessment of quantitative geomorphometric attributes of sub-watersheds in the UIB facilitates an enhanced comprehension of the hydrological impacts resulting from spatial and temporal variations, hence offering valuable insights into the geomorphological factors involved. The data and expertise utilized in this study were acquired through the analysis of geomorphometric characteristics. It is recommended to effectively utilize this knowledge within the integrated watershed management program, a program that is specifically designed to promote the progress and governance of water resources in the UIB in the future [9].

The primary objective of this project is to investigate the influence of geomorphological characteristics on hydrological processes in various mountainous watersheds situated in the UIB. The research objectives are achieved through the utilization of remote sensing and GIS techniques, to improve the implementation of integrated watershed management. The objectives that were explicitly mentioned were as follows:

To assess the geomorphological attributes of mountainous watersheds within the UIB, it is imperative to estimate specific parameters. The parameters consist of many linear properties, including stream order, stream number, stream length, basin length, basin size, basin perimeter, stream frequency, length of overland flow, drainage density, texture ratio, drainage texture, drainage intensity, and infiltration number. Moreover, it is crucial to consider numerous aerial attributes, such as form factor, elongation ratio, circularity ratio, and compactness coefficient. Furthermore, it is imperative to duly consider relief factors such as basin relief and relief ratio. The main focus of this study is to investigate the influence and response of geomorphological attributes on the hydrological phenomenon. [10] .

Study Site

The Indus Basin is situated within the geopolitical boundaries of four nations. The majority of its geographic expanse is situated within the territorial confines of Pakistan, with significant upstream portions extending to India, China, and Afghanistan. The hydrographic basin, encompassing a total size of 1,137,819 km^2, is distributed among several nations. The conducted research illustrates that the drainage basin encompasses a total area of approximately 9.7 x 105 km^2, positioning it as the twelfth largest among river systems globally [11]. The measured area of the deltaic zone in this specific site is 3 x 104 km^2 making it the seventh largest globally in terms of its size. The yearly water output is slightly below 2×10^{11} m^3, positioning it as the ninth biggest basin on a worldwide scale. In addition, it is worth noting that the river has an annual sediment discharge of 2×10^{11} kg, so positioning it as the sixth highest in terms of global sediment discharge. The Indus River is formed through the confluence of five prominent rivers that originate from the eastern direction, namely the Jhelum, Chenab, Ravi, Beas, and Sutlej. This research specifically focuses on the catchment area located within the geopolitical boundaries of Pakistan. The basin being examined is situated within the geographical coordinates of latitude 33º, 40′ to 37º, 12′ N, and longitude 70º, 30′ to 77º, 30′ E. The boundaries of the UIB were determined through the application of a Digital Elevation Model (DEM), as depicted in Figure 1 **(See at the end of Paper)**. The range of elevation extends from 254 m to 8570 m above the Mean Sea Level (MSL). Over 40% of the geographic area is situated at an elevation of over 2000 meters above the MSL [12]. The study site is composed of numerous principal subbasins, such as Chitral, Swat, Panjkora, Kunar, Bara, Kabul, Shyok, Shigar, Hunza, Gilgit, Astore, Gorband, Brandu, Haro, Siran, Soan, Kunhar, Neelum, Kanshi, Poonch, and more subbasins. The basin is supplied with water from several sources, such as seasonal snowmelt, continual glacier melt, and direct runoff caused by precipitation in both the winter and summer monsoon seasons. The basin exhibits a range of moisture levels throughout the aridity index, encompassing a spectrum from humid to hyper-arid conditions [13].

Material and Method:

The current study employs an extensive methodology that combines remote sensing techniques with (GIS) tools to conduct a comprehensive analysis of landforms and establish a prioritization system for basins. The process of defining and marking the boundaries of the 21 subwatersheds in the UIB in Pakistan, including Chitral, Swat, Panjkora, Kunar, Bara, Kabul, Shyok, Shigar, Hunza, Gilgit, Astore, Gorband, Brandu, Haro, Siran, Soan, Kunhar, Neelum, Kanshi, Poonch, and others, was accomplished by utilizing a 90-meter DEM and employing the Arc Hydro extension within the ArcGIS 10.2 software. This research aims at identifying and addressing the DEM sinks to improve the accuracy of flow direction and flow accumulation calculations. The delineation of the boundaries of the 21 subwatersheds was accomplished through the establishment of a pour point for each individual subwatershed as seen in Figure 1 **(See at the end of Paper)**. The pour point refers to the specific geographical position at which water originating from the entire watershed is discharged into the primary river. The methods employed to create the stream network in both watersheds depended on a cumulative count of upstream cells that contribute flow to each cell. A crucial threshold of 2000 cell counts was employed to demarcate streams within each of the 21 sub watersheds in order to conduct a comparative analysis of the various watersheds, [14].

The assessment of the watershed's scope involved determining the geometric properties of the polygons representing the generated watershed. Furthermore, the calculation of the watershed's length was accomplished by combining the total length of the mainstream channel with the distance from the farthest point of the main channel to the outer boundary of the watershed.

The calculation of the aggregate stream length required the summation of the individual lengths of stream segments within each specific subwatershed. The primary geomorphological characteristics, particularly those that display a linear arrangement, include stream order, stream number, stream length, and basin length. A thorough assessment has been carried out on many factors about relief, including basin relief, relief ratio, and roughness numbers, for all 21 sub-watersheds. The examination was conducted utilizing recognized mathematical methodologies, as outlined in Table 1. In addition, the process of obtaining elevation maps that illustrate the topography of the subbasins' basins was carried out using the reclassification tool within the ArcGIS spatial analyst module as indicated in Figure: 6.

Table 1: Method of calculating geomorphological parameters of drainage basin. [15].

Sr. No.	Parameter	Formula/Definition	References
1	Maximum Elevation (m)	Highest point of basin	[8]
2	Minimum Elevation (m)	Lowest point of basin	[8]
3	Basin Area, A (Km^2)	Area that enclosed basin boundary	[8]
4	Basin Perimeter, P (km)	Outer boundary of the basin that enclosed its area	[8]
5	Basin Length, L_b (km)	The longest dimension of the basin parallel to the principal drainage line.	[8]
6	Stream Order, U	Hierarchical rank (Strahler Scheme)	[16]
7	Total Number of Streams, N_u	Total number of stream segment of all orders	[17]
8	Stream Length, L_u	Length of the stream	[17]
9	Stream Length Ratio, RL_s	$RL_s = Lu/Lu_{-1}$; Where, Lu=The total stream length of order "u"; Lu_{-1} =The total stream length of its next lower order	[17]
10	Bifurcation Ratio, R_b	$R_b = N_u/N_{u+1}$; Where N_u = Total no. of stream segments of order "u"; N_{u+1} = Number of segments of the next higher order	[8]
11	Mean Bifurcation Ratio, R_{bm}	Average of bifurcation ratios of all orders	[8]
12	Mean Stream Length, L_{sm} (Km)	$Lsm=L_u/N_u$; Where, L_u= Stream length of a given order (km), N_u=Total number of stream segment.	[8]
13	Length of Overland Flow, LoF (Km)	$A/2*L_u$; Where, L_u=Total stream length of all order (km), A= Area of basin	[8]
14	Stream Frequency, S_f	$S_f = N_u/A$ Where, N_u=Total number of stream segment; A=Area of basin	[17]
15	Drainage Density, D_d	$D_d=L/A$ Where, L=Total length of stream, A= Area of basin (Km^2)	[17]
16	Texture Ratio, R_t	$T=N_1/P$ Where, N_1=Total number of first order stream, P=Perimeter of basin.	[8]
17	Drainage Texture, D_t	$D_t = N_u/P$; Where, N_u = Total no. of streams of all orders; P = Perimeter (km)	[17]
18	Drainage Intensity, D_i	$Di = S_f / D_d$; Where, S_f = Stream frequency; D_d = Drainage density	[7]
19	Infiltration Number, I_f	$If = S_f * Dd$; Where, S_f = Stream frequency; Dd = Drainage density	[7]
20	Form Factor, R_f	$Rf = A / L_b^2$; Where, L_b = Basin Length (km); A= Area of basin (Km^2)	[17]
21	Circularity Ratio, R_c	$R_c = 12.57*(A/P^2)$; Where, A= Area of basin (Km^2); P = Basin Perimeter (km)	[6]
22	Elongation Ratio, R_e	$R_e = 2/Lb *(A/\pi)^{0.5}$; Where, L_b = Basin Length (km); A= Area of basin (Km^2)	[8]
23	Compactness Coefficient, C_c	$C_c = 0.2841*P/A^{0.5}$; Where, A= Area of basin (Km^2); P = Basin Perimeter (km)	[6]

24	Constant Channel Maintenance, C	$C = 1/D_d$; Where, D_d = Drainage density	[17]
25	Shape index, S_w	$S_w = L_b^2/A$; Where, L_b = Basin length; A = Area of basin	[17]
26	Basin Relief, B_h (m)	Vertical distance between the lowest and highest points of basin.	[8]
27	Relief Ratio, R_h	$R_h = B_h / L_b$ Where, B_h=Basin relief, L_b=Basin length	[8]
28	Relative relief, Rr (%)	$Rr = B_h/P*100$; Where, B_h=Basin relief, P = Basin Perimeter	
29	Ruggedness Numbers, R_n (Km)	$R_n=B_h \times D_d$; Where, B_h= Basin relief, D_d = Drainage density	[8]

Results:

This section provides an overview of the findings and analyses related to features including stream order, stream length, mean stream length, stream length ratio, bifurcation ratio, length of overland flow, basin length, and perimeter, constitutes the morphometric examination of a basin.

The comprehension of stream order and stream numbers is of great significance within the discipline of fluvial geomorphology. The drainage network is of paramount importance in facilitating the conveyance of water and sediments from a specific basin via a solitary outlet. The greatest rank of the basin is attributed to this distinctive outlet, therefore signifying its classification as the basin's order. The dimensions of rivers and basins exhibit significant variety by the hierarchical structure of the basin. The first step in basin analysis involves the arrangement and structure of stream networks. To conduct a thorough examination of basin characteristics, it is essential to undertake a rigorous investigation of the many aspects associated with stream networks [18]. This study has conducted a stream rating assessment using the suggested methodologies. The assessment of stream order was carried out in a comprehensive set of 21 subbasins, wherein the observed stream orders exhibited a range spanning from 3 to 7. The subbasins where the highest stream order, specifically defined as 7, is seen encompass the Shyok River and the Gilgit River basin. This phenomenon occurs near the confluence where the Indus River crosses with the Alam Bridge. In contrast, the Gorband basin exhibits the minimum stream order, which is designated as 3. Table 2 presents the quantitative data about the streams linked to each stream order within the 21 subbasins of the Indus basin. Although most basins have a drainage pattern of the fourth order, the five studied basins had streams of the fifth order. The streams located in the Hunza, Gilgit, and Kabul basins demonstrated a classification of the 6th order. The prevailing drainage patterns observed in all basins of the stream network are commonly described as sub-dendritic to dendritic. The observation noted above suggests that there is a uniform texture and a lack of structural influence, as depicted in Figure 2. The prevalence of first-order streams is observed to be the highest among all stream orders. Furthermore, Figure 3 **(See at the end of Paper)** illustrates a decrease in the overall number of stream segments as the stream order increases. The discovery cited above suggests that the entire region has a consistent lithological composition. Furthermore, from a geological perspective, there are no observable signs of uplift occurring inside the basin. The Kabul basin exhibits the highest number of streams, totaling 2,254.

The measurement of stream Length has been carried out utilizing the methodologies proposed by Horton, which is a significant hydrological metric in a basin since it offers useful insights on the characteristics of surface runoff. Watersheds characterized by effective drainage often demonstrate the presence of permeable bedrock and formations, as seen by a scarcity of elongated streams. Conversely, watersheds characterized by bedrock and formations with limited permeability display a higher prevalence of shorter streams. This claim is substantiated by prior scholarly investigations. Typically, stream segments demonstrate a higher overall length in streams of first order, followed by a drop in length as stream order increases. The research entailed the quantification of stream networks of varying orders within a certain watershed, together with the computation of their respective lengths from the discharge point to the point of drainage split. The accomplishment was achieved by the application of GIS software. Table 3 presents the findings about the lengths of streams in each of the 21 subbasins, arranged sequentially. The data depicted in Figure 2 provides compelling and incontrovertible evidence of a positive association between stream order and cumulative stream length. A positive link has been observed between stream order and the characteristics displayed by first-order streams. As the order of a stream increases, there is a tendency for these values to gradually decrease [19]. The Shyok basin displayed a notable discrepancy in the lengths of its streams of different orders, specifically between the first-order and seventh-order streams. The former had a remarkable span of 8400 km, and the latter possessed a relatively shorter extent of 320 km. The Kabul basin demonstrated the highest aggregate stream length, reaching a total of 17,528 km.

Table 2: Stream order and stream number of mountainous watersheds of UIB, Pakistan.

Sr. No.	Watershed/ Basin	Stream Order, U	Stream Number, N_U							Total Streams, Nu
			I	II	III	IV	V	VI	VII	
1	Kunhar	4	51	12	2	1				66
2	Neelum	4	148	33	7	1				189
3	Poonch	4	78	22	7	1				108
4	Kanshi	4	24	6	2	1				33
5	Shyok	7	1507	361	94	20	6	2	1	1991
6	Shigar	5	150	38	11	2	1			202
7	Gilgit	6	231	56	18	5	2	1		313
8	Hunza	6	257	65	15	6	2	1		346
9	Gilgit at Alam	7	506	133	30	11	4	2	1	687
10	Astore	4	69	15	3	1				88
11	Gorband	3	15	2	1					18
12	Brandu	4	30	8	2	1				41
13	Siran	4	31	8	3	1				43
14	Haro	4	59	15	4	1				79
15	Soan	5	206	47	11	2	1			267
16	Chitral	5	233	54	11	4	1			303
17	Kunar	5	502	107	19	5	1			634
18	Swat	4	115	26	5	1				147
19	Panjkora	5	110	22	5	2	1			140
20	Bara	4	31	5	2	1				39
21	Kabul	6	1718	425	86	19	5	1		2254

The Mean Stream Length (SLm) is an essential attribute that is linked to the drainage network and the landforms it contains (15). The SLm values for all 21 subbasins demonstrate a range of 3.76 to 365.73 km, with variances seen within various stream orders. The Soan basin exhibits the most elevated SLm, at 9.49 km. Table 4 presents a comprehensive comparative analysis of the Land Surface Models (LSMs) about each subbasin. A positive association has been shown between stream order and the average length of streams, suggesting that a rise in stream order is associated with a corresponding increase in the average length of streams. Previous studies have noted that the SLm value of a stream order consistently displays a greater magnitude in comparison to that of a lower order. Conversely, the SLm value of a lower order consistently exhibits a smaller magnitude when compared to that of a higher order. The variety observed in the SLm values across various subbasins can be attributed to their close correlation with the size and terrain of these subbasins [20].

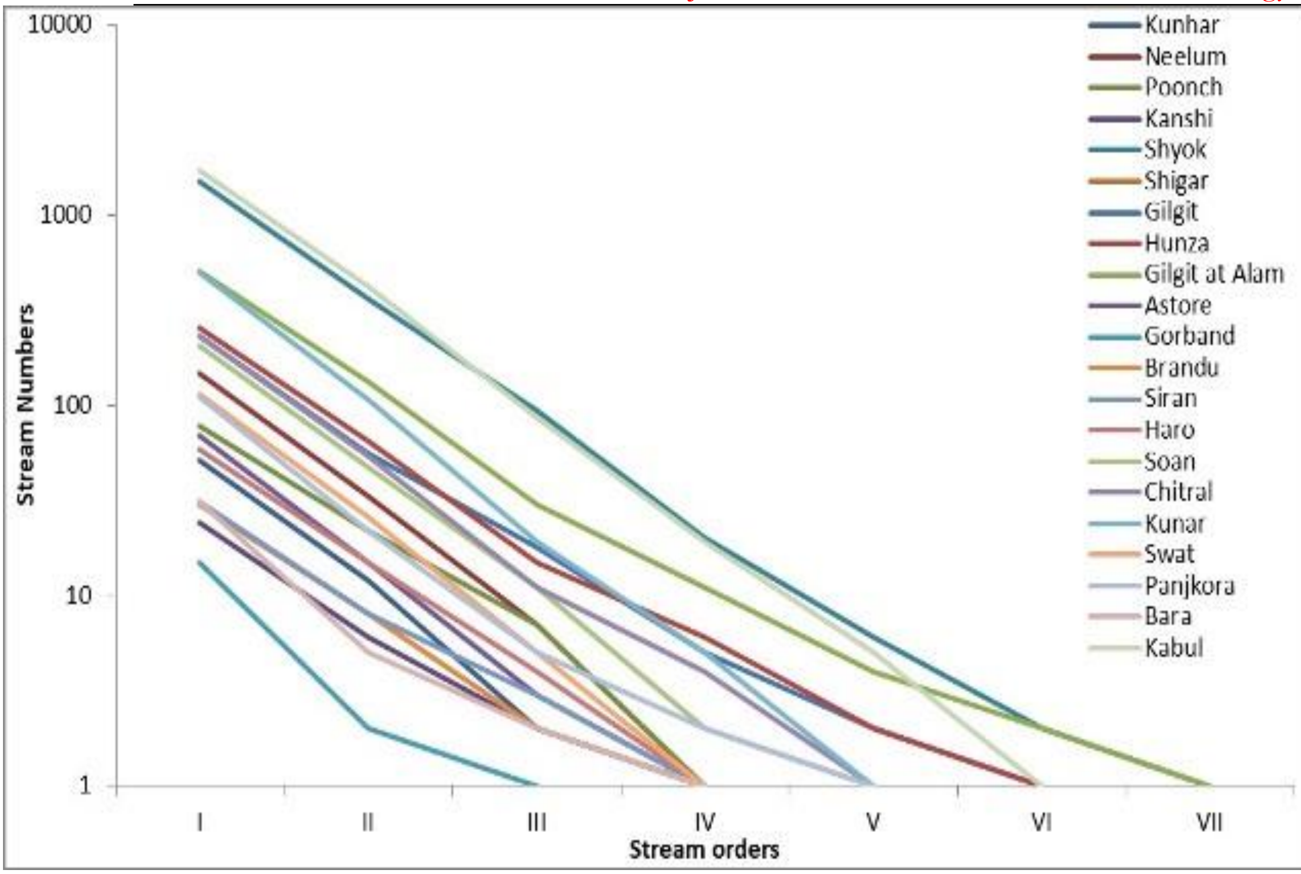

Figure 2: Relationship between stream order and number of streams for 21 sub-watersheds.

Table 3: Stream lengths of mountainous watersheds of UIB, Pakistan.

Sr. No.	Watershed/ Basin	Stream Order, U	Stream Length, L_U (Km) I	II	III	IV	V	VI	VII	Total Stream Length, Lu (Km)
1	Kunhar	4	238	94	21	138				491
2	Neelum	4	655	326	119	244				1344
3	Poonch	4	378	238	131	116				863
4	Kanshi	4	156	81	20	41				298
5	Shyok	7	8400	3565	1811	734	401	434	320	15666
6	Shigar	5	736	323	216	146	62			1483
7	Gilgit	6	1182	542	232	95	117	80		2248
8	Hunza	6	1307	719	276	190	91	87		2670
9	Gilgit at Alam	7	2648	1331	558	296	218	174	40	5266
10	Astore	4	414	176	83	58				731
11	Gorband	3	56	43	13					113
12	Brandu	4	149	90	62	10				311
13	Siran	4	137	72	75	54				338
14	Haro	4	330	149	133	61				673
15	Soan	5	1259	636	404	117	117			2533
16	Chitral	5	1140	441	379	155	99			2213
17	Kunar	5	2445	1031	633	242	366			4716
18	Swat	4	557	262	79	138				1036
19	Panjkora	5	579	262	78	126	17			1062
20	Bara	4	146	68	117	12				342
21	Kabul	6	9155	4146	2039	1044	779	365		17528

Table 4: SLm of mountainous watersheds of UIB, Pakistan.

Sr. No.	Watershed/ Basin	Stream Order, U	Mean Stream Length, L_{sm} (Km)							Mean Stream Length, L_{sm} (Km)
			I	II	III	IV	V	VI	VII	
1	Kunhar	4	4.67	7.83	10.31	137.71				7.43
2	Neelum	4	4.43	9.87	16.97	244.39				7.11
3	Poonch	4	4.85	10.81	18.66	116.31				7.99
4	Kanshi	4	6.49	13.56	9.91	40.83				9.03
5	Shyok	7	5.57	9.87	19.27	36.70	66.90	217.18	320.39	7.87
6	Shigar	5	4.90	8.51	19.67	72.83	62.35			7.34
7	Gilgit	6	5.12	9.67	12.88	18.91	58.67	79.97		7.18
8	Hunza	6	5.09	11.07	18.39	31.75	45.62	86.66		7.72
9	Gilgit at Alam	7	5.23	10.01	18.59	26.93	54.41	87.15	40.30	7.66
10	Astore	4	6.01	11.73	27.66	58.17				8.31
11	Gorband	3	3.76	21.71	13.49					6.29
12	Brandu	4	4.97	11.20	31.05	10.11				7.58
13	Siran	4	4.42	9.06	25.15	53.58				7.87
14	Haro	4	5.60	9.94	33.18	61.17				8.52
15	Soan	5	6.11	13.54	36.77	58.42	117.50			9.49
16	Chitral	5	4.89	8.17	34.41	38.65	98.84			7.30
17	Kunar	5	4.87	9.63	33.29	48.38	365.73			7.44
18	Swat	4	4.84	10.09	15.90	137.75				7.05
19	Panjkora	5	5.26	11.93	15.53	62.96	17.44			7.59
20	Bara	4	4.72	13.54	58.35	11.68				8.78
21	Kabul	6	5.33	9.76	23.71	54.93	155.89	364.73		7.78

The Stream Length Ratio (SLR) is a statistical measure used to objectively evaluate the relationship between the lengths of different streams. The SLR values are displayed in Table 5. The variability in stream lengths across streams of varying orders within each subbasin is observed within each specific subwatershed. The observed alteration can be ascribed to fluctuations in the incline and topography, suggesting that the streams are presently in a phase of advanced youth with regards to geomorphic evolution [21].

The Bifurcation Ratio, denoted as BR, is a quantitative measure utilized in several academic disciplines to assess the branching pattern of a certain system. The dimensionless quantity under consideration functions as a measure of the level of connectivity between streams of different orders within a certain drainage basin. The data reported in Table 6 demonstrates that the Rb values observed in all 21 subbasins display a variation ranging from 2.00 to 6.20. The Mean Bifurcation Ratio (MBR) displays a spectrum of values ranging from 3.00 to 5.40. The Neelum watershed demonstrates the highest values of MBR, specifically 5.40, indicating an early peak in the hydrograph and a reduced lag time within the basin. The aforementioned observation suggests that the structural variables have a substantial impact on the establishment of drainage patterns within this watershed. The regions of Kanshi and Shigar exhibit the lowest MBR levels, specifically at 3.0 and 3.07, respectively. The aforementioned numerical values suggest a delayed occurrence of the peak in the hydrograph. Based on the research conducted by Strahler in 1964, it was observed that the bifurcation ratio often falls within the range of 3.0 to 5.0 in drainage basins that have not undergone any geological alterations [22]. All subbasins encompassed within this range exhibit geologically favorable formations that do not exert any discernible impact on the drainage pattern. The provided MBR values presented in Table 6 illustrate an immediate peak observed in the hydrograph, indicating a relatively shorter lag period for the basin.

Table 5: Stream length ratios of mountainous watersheds of UIB, Pakistan

Sr. No.	Watershed/ Basin	Stream Order, U	Stream Length Ratio, RL						Mean Stream Length Ratio, RLsm
			I-II	II-III	III-IV	IV-V	V-VI	VI-VII	
1	Kunhar	4	0.39	0.22	6.68				2.43
2	Neelum	4	0.50	0.36	2.06				0.97
3	Poonch	4	0.63	0.55	0.89				0.69
4	Kanshi	4	0.52	0.24	2.06				0.94
5	Shyok	7	0.42	0.51	0.41	0.55	1.08	0.74	0.62
6	Shigar	5	0.44	0.67	0.67	0.43			0.55
7	Gilgit	6	0.46	0.43	0.41	1.24	0.68		0.64
8	Hunza	6	0.55	0.38	0.69	0.48	0.95		0.61
9	Gilgit at Alam	7	0.50	0.42	0.53	0.73	0.80	0.23	0.54
9	Astore	4	0.42	0.47	0.70				0.53
10	Gorband	3	0.77	0.31					0.54
11	Brandu	4	0.60	0.69	0.16				0.49
12	Siran	4	0.53	1.04	0.71				0.76
13	Haro	4	0.45	0.89	0.46				0.60
14	Soan	5	0.51	0.64	0.29	1.01			0.61
15	Chitral	5	0.39	0.86	0.41	0.64			0.57
16	Kunar	5	0.42	0.61	0.38	1.51			0.73
17	Swat	4	0.47	0.30	1.73				0.84
18	Panjkora	5	0.45	0.30	1.62	0.14			0.63
19	Bara	4	0.46	1.72	0.10				0.76
20	Kabul	6	0.45	0.49	0.51	0.75	0.47		0.53

Table 6: BR of mountainous watersheds of UIB, Pakistan.

Sr. No.	Watershed/ Basin	Stream Order, U	Bifurcation Ratio, R_b						Mean Bifurcation Ratio, R_{bm}
			I-II	II-III	III-IV	IV-V	V-VI	VI-VII	
1	Kunhar	4	4.25	6.00	2.00				4.08
2	Neelum	4	4.48	4.71	7.00				5.40
3	Poonch	4	3.55	3.14	7.00				4.56
4	Kanshi	4	4.00	3.00	2.00				3.00
5	Shyok	7	4.17	3.84	4.70	3.33	3.00	2.00	3.51
6	Shigar	5	3.95	3.45	5.50	2.00			3.73
7	Gilgit	6	4.13	3.11	3.60	2.50	2.00		3.07
8	Hunza	6	3.95	4.33	2.50	3.00	2.00		3.16
9	Gilgit at Alam	7	3.80	4.43	2.73	2.75	2.00	2.00	2.95
10	Astore	4	4.60	5.00	3.00				4.20
11	Gorband	3	7.50	2.00					4.75
12	Brandu	4	3.75	4.00	2.00				3.25
13	Siran	4	3.88	2.67	3.00				3.18
14	Haro	4	3.93	3.75	4.00				3.89
15	Soan	5	4.38	4.27	5.50	2.00			4.04
16	Chitral	5	4.31	4.91	2.75	4.00			3.99
17	Kunar	5	4.69	5.63	3.80	5.00			4.78
18	Swat	4	4.42	5.20	5.00				4.87
19	Panjkora	5	5.00	4.40	2.50	2.00			3.48
20	Bara	4	6.20	2.50	2.00				3.57
21	Kabul	6	4.04	4.94	4.53	3.80	5.00		4.46

The determination of the perimeter of a basin, denoted as P, is achieved through the measurement of the cumulative length along the boundaries that delineate separate watersheds. The aforementioned metric possesses the capacity to serve as an evaluative tool for analyzing the many aspects and structures of a particular watershed. The various perimeters of the subbasins within the UIB are presented in Table 7, ranging from 180 km to 3138 km. The Kabul basin exhibits the largest diameter, measuring 3138 km in length [23].

The Length of Overland Flow (LOF) refers to the distance that water travels across the land surface before it converges into a well-defined stream channel. The Landform variable, often known as LOF, plays a significant role in shaping the hydrologic and physiographic characteristics of drainage basins. The estimation of length of overland flow can be estimated as approximately 0.5 times the inverse of DD [24]. The aforementioned element demonstrates a negative link with the average gradient of the channel and displays a significant association with the magnitude of sheet flow. The research domain exhibits a range of LOF values, varying from 2.16 to 2.95 km, as illustrated in Table 7.

Table 7: Area, perimeter, longest flow path, and length of overland flow of mountainous watersheds of UIB, Pakistan.

Sr. No.	Watershed/ Basin	Basin Area, A (Km^2)	Basin Perimeter, P (km)	Longest Flow Path, L_b (km)	Length of Overland Flow, LoF (Km)
1	Kunhar	2631	499	180	2.68
2	Neelum	7416	921	269	2.76
3	Poonch	4232	508	175	2.45
4	Kanshi	1288	270	99	2.16
5	Shyok	79646	3105	905	2.54
6	Shigar	7023	771	227	2.37
7	Gilgit	12703	964	240	2.83
8	Hunza	13732	908	262	2.57
9	Gilgit at Alam	27273	1475	310	2.59
10	Astore	3989	446	120	2.73
11	Gorband	668	180	51	2.95
12	Brandu	1448	240	74	2.33
13	Siran	1737	324	120	2.57
14	Haro	3092	491	155	2.30
15	Soan	11212	877	295	2.21
16	Chitral	12390	1057	294	2.80
17	Kunar	25939	1652	569	2.75
18	Swat	5741	635	226	2.77
19	Panjkora	5923	594	186	2.79
20	Bara	1833	324	101	2.68
21	Kabul	87962	3138	782	2.51

Table 7 illustrates the considerable disparity in the Longest Flow Path (LFP) among the subbasins of the UIB, with a range of values spanning from 51 km to 905 km. The Shyok basin exhibits a considerable perimeter, measuring 905 km [25].

Key Attributes of Aerial Phenomena:

The morphometric analysis of a basin revealed that a positive correlation has been seen between the size of a watershed and the rates of runoff volume [26]. The evaluation of the maximum rate at which runoff occurs holds substantial significance in the development of erosion control structures and channels designed to accept the highest possible volume of runoff. The drainage areas of the subbasins within UIB exhibit significant variation, with values ranging from 668 km^2 to 87,962 km^2, as documented in Table 7. The Kabul basin exhibits a substantial extent in terms of its geographical dimensions. All 21 subbasins have been classified into four distinct groups based on their respective sizes. The classification of these groups is as follows: the watershed group, which contains areas up to 1,000 km^2; the sub-catchment group, which ranges from 1,000 to 7,000 km^2; the catchment group, spanning from 7,000 to 30,000 km^2; and the basin group, which includes territories between 30,000 and 95,000 km^2. Based on the aforementioned criteria, it is apparent that two basins have been identified within the watershed, whilst ten basins have been classified as sub-catchments. Moreover, a comprehensive analysis has revealed a total of eight basins as catchments, with two basins being explicitly designated as basins, as depicted in Figure 4. The Shyok and Kabul River basins are situated within the encompassing basin [27].

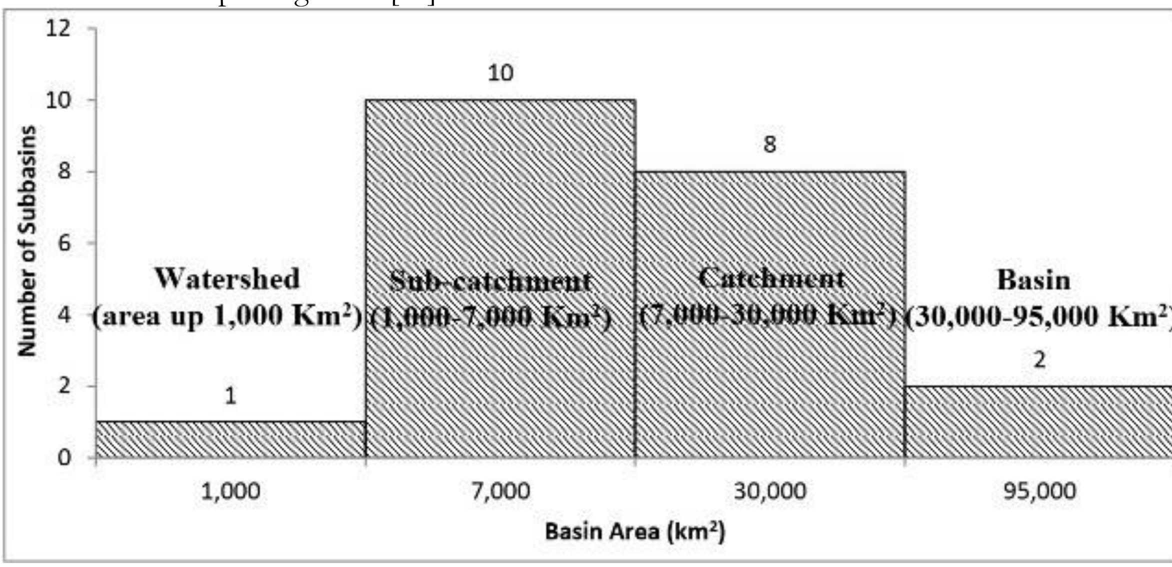

Figure 4: Number of basins by drainage basin area.

The concept of DD pertains to the proximity of channel spacing and serves as a quantitative measure of landscape fragmentation and the probability of surface runoff. The density factor is subject to the influence of multiple factors, such as climate, rock composition, topography, infiltration capacity, vegetation density, and run-off intensity index. The computed values of DD within the UIB region is shown in Table 8, which demonstrates a variation ranging from 0.170 to 0.231 km^{-1}. The numbers given above are indicative of the presence of regions characterized by the existence of resilient permeable material, abundant vegetation, and minimal topographic variation. Consequently, these areas exhibit a greater propensity for infiltration and might be considered favorable sites for groundwater recharge when compared to watersheds characterized by high DD values. Based on the variable DD, it can be inferred that Gilgit will exhibit the longest basin lag time, while Soan will have the smallest lag time [28].

A positive association has been observed between the Frequency of Streams (FS) and the DD within the watershed. This suggested that an increase in DD is associated with a greater number of streams. The recorded values of Fs in each subbasin are displayed in Table 8, exhibiting a range spanning from 0.021 to 0.029. The data demonstrated suggests a noteworthy occurrence of markedly low Fs values. The analysis of stream frequency data revealed a very sparse distribution of streams inside the subbasins. Furthermore, this observation implied that the basin exhibits a restricted quantity of drainage outlets or conduits. The rationale behind this phenomenon can be attributed to the sedimentary geology of the particular study site. This suggested that there are constraints on the availability of storm runoff, which could potentially lead to the occurrence of a devastating flood event. The probability of flooding escalates when the capacity of a limited number of water outlets is rapidly surpassed, both during and following a storm event.

The importance of the Texture Ratio (TR) in evaluating drainage morphometrics has been highlighted. The significance of Drainage Texture (DT) is highly relevant in the field of geomorphology as it pertains to the spatial organization of drainage lines. The attributes of drainage are subject to the effect of lithology, infiltration capacity, and topographic characteristics of the terrain. This study presents a taxonomy for characterizing DT, which encompasses five distinct classifications: very coarse (less than 2), coarse (2 to 4), moderate (4 to 6), fine (6 to 8), and very fine (more than 8). The findings of the study are presented in Table 8, indicating that the values for all basins are below 2. This suggested that the drainage texture of these basins can be classified as very coarse [18].

The concept of Drainage Intensity (DI) suggests that when the DI value is low, the impact of DD and stream frequency on the degree of surface erosion caused by denudation agents is minimal or negligible. The findings shown in Table 8 demonstrate a correlation between the values of DI and a decrease in DD, stream frequency, and drainage intensity. These factors, when combined, work together to result in a reduced rate of surface runoff removal within the watershed. Consequently, this particular situation renders the watershed more vulnerable to the incidence of flooding, gully erosion, and landslides [13].

Table 8: SF, DD, TR, DT, DI, and IN of Mountain Watersheds in Pakistan's UIB.

Sr. No.	Watershed/ Basin	Stream Frequency, S_f	Drainage Density, D_d	Texture Ratio, R_t	Drainage Texture, D_t	Drainage Intensity, D_i	Infiltration Number, I_f
1	Kunhar	0.025	0.186	0.102	0.132	0.135	0.005
2	Neelum	0.025	0.181	0.161	0.205	0.141	0.005
3	Poonch	0.026	0.204	0.154	0.213	0.125	0.005
4	Kanshi	0.026	0.231	0.089	0.122	0.111	0.006
5	Shyok	0.025	0.197	0.485	0.641	0.127	0.005
6	Shigar	0.029	0.211	0.195	0.262	0.136	0.006
7	Gilgit	0.025	0.177	0.240	0.325	0.139	0.004
8	Hunza	0.025	0.194	0.283	0.381	0.130	0.005
9	Gilgit at Alam	0.025	0.193	0.343	0.466	0.130	0.005
10	Astore	0.022	0.183	0.155	0.197	0.120	0.004
11	Gorband	0.027	0.170	0.084	0.100	0.159	0.005
12	Brandu	0.028	0.215	0.125	0.171	0.132	0.006
13	Siran	0.025	0.195	0.096	0.133	0.127	0.005
14	Haro	0.026	0.218	0.120	0.161	0.117	0.006
15	Soan	0.024	0.226	0.235	0.305	0.105	0.005
16	Chitral	0.024	0.179	0.220	0.287	0.137	0.004
17	Kunar	0.024	0.182	0.304	0.384	0.134	0.004
18	Swat	0.026	0.180	0.181	0.231	0.142	0.005
19	Panjkora	0.024	0.179	0.185	0.236	0.132	0.004
20	Bara	0.021	0.187	0.096	0.120	0.114	0.004
21	Kabul	0.026	0.199	0.547	0.718	0.129	0.005

The Infiltration Number (IN) is seen to vary within the range of 0.004 and 0.006, as reported in Table 8 of the current research. Within the specific environment being considered, the presence of low values may indicate a heightened level of infiltration and a diminished level of run-off. The present analysis provides significant insights into the infiltration features of the watershed. The Form Factor (FF) is a numerical metric that regularly exhibits values below 0.754, indicating the existence of a watershed with a perfectly circular morphology. Basins characterized by high FF are correlated with elevated peak flows of relatively shorter periods, while extended subwatersheds with low form factors exhibit reduced peak flow rates that persist for longer durations. The FF values for each of the 21 subbasins are displayed in Table 8. These values indicate elongated shapes and imply the existence of prolonged periods with flat hydrograph peaks.

The Circularity Ratio (CR) has been shown in Table 8 which displays the range of Rc values for various sub-watersheds located within the UIB, with a variability ranging from 0.10 to 0.32. The Elongation Ratio, denoted as ER, is a quantitative measure used to evaluate the extent of elongation or deformation experienced by a material under external stress. According to Strahler, the aforementioned ratio has a range of values spanning from 0.6 to 1.0 across different climatic and geologic categorizations. The improvement of watershed slope classification can be achieved through the utilization of the elongation ratio index. The current index categorizes slopes based on their elongation values, including circular slopes (0.9-0.10), oval slopes (0.8-0.9), less elongated slopes (0.7-0.8), elongated slopes (0.5-0.7), and very elongated slopes (< 0.5). Table 9 contains the statistical data regarding the elongation ratio. The Reynolds Number (RN) of the subbasins in Gilgit, Hunza, Gorband, Brandu, Panjkora, and Bara is less than 0.7. This observation suggested that the subbasins being studied exhibit an elongated shape with significant differences in elevation and steep slopes. The research findings indicate that there will be a reduction in travel time, enhanced concentration levels, decreased setbacks, and a decrease in the frequency of flood peaks. The subbasins that remain exhibit values below 0.5, indicating their elongated nature and vulnerability to erosion and the accumulation of silt.

The Compactness Coefficient, denoted as C, is a quantitative measure employed to assess the circularity of a basin. The observation of a circular basin exhibiting the minimum time of concentration before the initiation of peak flow within the basin has been documented. A Coefficient of Circularity (CC) equal to 1 signifies that the basin exhibits optimal circular attributes. A credit card number that exceeds 1 signifies an increased degree of departure from the circular characteristics of the basin. The assigned values for each subwatershed exhibit variation, ranging from 1.79 for Brandu to 3.13 for Shyok, as illustrated in Table 9. Consequently, it may be inferred that the Shyok subbasin exhibits the most pronounced departure from a circular morphology, suggesting that it will experience a more prolonged duration of concentration before attaining its maximum flow rate in comparison to the remaining subbasins.

The mathematical definition of the constant denoting channel maintenance, sometimes written as C, is the reciprocal of the Drainage Density (DD). This statistical measure calculates the necessary extent of the drainage area to sustain a predetermined length of a canal. The results of the current investigation demonstrated that variable C exhibits a variety of values, specifically ranging from 4.32 for Kanshi to 5.65 for Gilgit, as depicted in Table 9. The Kanshi, Soan, and Haro subbasins exhibit distinct features such as the presence of soils with poor resistivity, little vegetation, and rugged topography.

The shape index, denoted as Sw, is a quantitative metric employed to evaluate the shape characteristics of an object. The arrangement of a drainage basin is a significant factor in influencing the extent of water and sediment flow, as well as the size and topographic variations of the basin. The form index values for the sub-watersheds within the research region exhibit a notable disparity, with Gilgit recording a value of 3.52 and Kunar registering a value of 12.50, as depicted in Table 9. Within the context of surface water, it is apparent that Gilgit demonstrates a comparatively lower basin lag time, whereas Kunar exhibits a greater basin lag time.

Table 9: Shape characteristics (areal aspects) of mountainous watersheds of UIB, Pakistan.

Sr. No.	Watershed/ Basin	Form Factor, R_f	Circularity Ratio, R_c	Elongation Ratio, R_e	Compactness Coefficient, C_c	Constant Channel Maintenance, C	Shape index, S_w
1	Kunhar	0.08	0.13	0.32	2.76	5.36	12.31
2	Neelum	0.10	0.11	0.36	3.04	5.52	9.77
3	Poonch	0.14	0.21	0.42	2.22	4.90	7.25
4	Kanshi	0.13	0.22	0.41	2.14	4.32	7.57
5	Shyok	0.10	0.10	0.35	3.13	5.08	10.29
6	Shigar	0.14	0.15	0.42	2.61	4.73	7.31
7	Gilgit	0.22	0.17	0.53	2.43	5.65	4.53
8	Hunza	0.20	0.21	0.51	2.20	5.14	4.98
9	Gilgit at Alam	0.28	0.16	0.60	2.54	5.18	3.52
10	Astore	0.28	0.25	0.59	2.01	5.45	3.61
11	Gorband	0.26	0.26	0.57	1.97	5.90	3.89
12	Brandu	0.26	0.32	0.58	1.79	4.66	3.79
13	Siran	0.12	0.21	0.39	2.21	5.13	8.36
14	Haro	0.13	0.16	0.40	2.51	4.59	7.82
15	Soan	0.13	0.18	0.40	2.35	4.43	7.77
16	Chitral	0.14	0.14	0.43	2.70	5.60	6.97
17	Kunar	0.08	0.12	0.32	2.91	5.50	12.50
18	Swat	0.11	0.18	0.38	2.38	5.54	8.89
19	Panjkora	0.17	0.21	0.47	2.19	5.58	5.82
20	Bara	0.18	0.22	0.48	2.15	5.35	5.52
21	Kabul	0.14	0.11	0.43	3.01	5.02	6.95

Relief Dimensions:

The morphometric examination of a basin encompasses the evaluation of several relief characteristics, such as topography, relief ratio, relative relief, and roughness number. Table 10 displays the relief characteristics of each subbasin. The subject matter under consideration refers to the discipline of topography. The UIB exhibits an elevation variation spanning from 215m to 8566m above Mean Sea Level (MSL). The influence of altitude on meteorological variables, particularly temperature and snow accumulation, is widely acknowledged in scholarly discussions. The impact of changes in elevation on the processes of snowmelt and snow accumulation within mountainous watersheds has considerable importance. One potential strategy for enhancing simulation efficiency involves the subdivision of watersheds into distinct height bands, particularly in cases where there are notable changes in elevation and complex topographical features. The assessment of the distribution of the basin's area across different elevation classes among the 21 sub-basins was conducted and visually depicted in Figure 5. Figure 6 **(See at the end of Paper)** illustrates the geographical attributes of each subbasin.

The RR is a quantitative measure that assesses the vertical disparity between the maximum elevation observed inside a specific hydrological basin and the minimum height situated on the valley bottom. The topographic variation of the river basin, ranging from 0.53 km to 7.22 km, is a crucial factor to consider in this particular situation. The concept pertains to the quantitative assessment of the collective magnitude of incline shown by a hydrological basin. Moreover, it serves as a dependable indicator of the magnitude of erosion phenomena taking place on the inclines of the basin. There is typically a positive relationship between the Hydraulic Radius (HR) and the decrease in drainage area and size of a given drainage basin. The results of the current investigation indicate that the Rh values, as presented in Table 10, display variation across different geographic regions. In the Shyok region, the least observed value of HR is recorded as 0.01, while the highest reported value is documented as 0.074 in Gorband. Elevated levels of HR values indicate the existence of significant erosion processes. The findings of this study suggest that Gorband and Astore exhibit a higher vulnerability to erosion relative to Shyok, based on a single criterion used to assess erosion severity in the subwatersheds of the studied area.

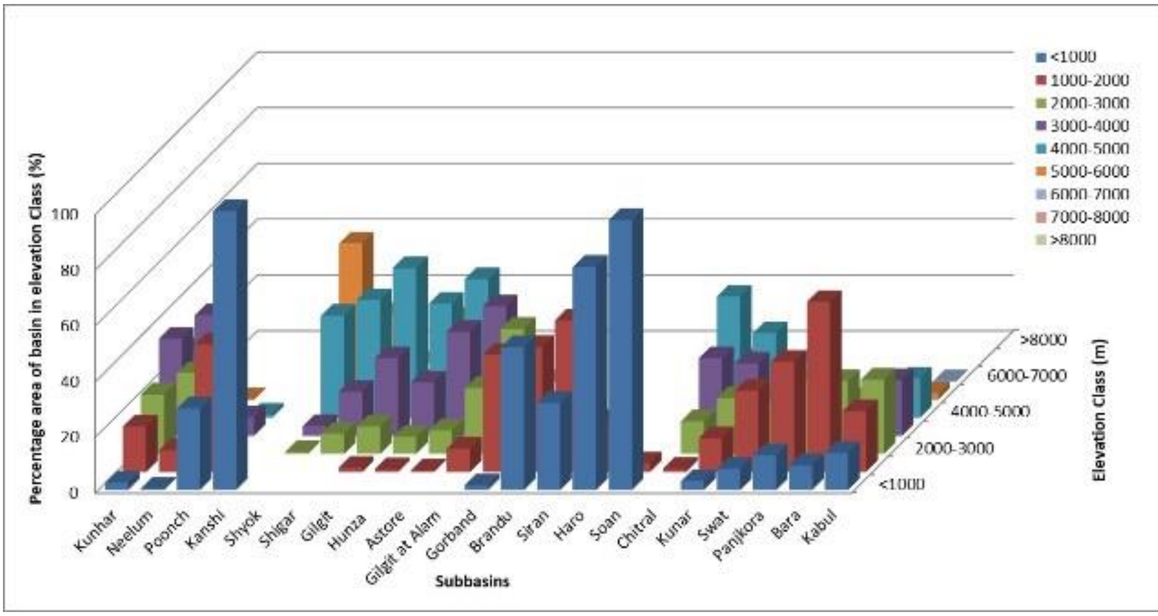

Figure 5: Percentage area of subbasins in various elevation classes.

Table 10: Maximum & minimum elevation, basin relief, relief ratio, relative relief, and ruggedness numbers of mountainous watersheds of UIB, Pakistan.

Sr. No.	Watershed/ Basin	Maximum Elevation (Km)	Minimum Elevation (Km)	Basin Relief, H (Km)	Relief Ratio	Relative Relief, Rr (%)	Ruggedness Numbers, Rn (Km)
1	Kunhar	5.11	0.63	4.47	0.02	0.90	0.83
2	Neelum	6.29	0.67	5.61	0.02	0.61	1.02
3	Poonch	4.70	0.33	4.37	0.02	0.86	0.89
4	Kanshi	0.87	0.33	0.53	0.01	0.20	0.12
5	Shyok	7.80	2.29	5.51	0.01	0.18	1.08
6	Shigar	8.57	2.18	6.39	0.03	0.83	1.35
7	Gilgit	7.06	1.42	5.64	0.02	0.59	1.00
8	Hunza	7.70	1.43	6.27	0.02	0.69	1.22
9	Gilgit at Alam	7.81	1.25	6.56	0.02	0.44	1.27
10	Astore	7.80	1.22	6.58	0.05	1.48	1.21
11	Gorband	4.42	0.62	3.80	0.07	2.12	0.64
12	Brandu	2.87	0.45	2.43	0.03	1.01	0.52
13	Siran	4.24	0.45	3.80	0.03	1.17	0.74
14	Haro	2.79	0.27	2.52	0.02	0.51	0.55
15	Soan	2.26	0.22	2.05	0.01	0.23	0.46
16	Chitral	7.60	1.48	6.12	0.02	0.58	1.09
17	Kunar	7.60	0.54	7.07	0.01	0.43	1.28
18	Swat	5.82	0.68	5.14	0.02	0.81	0.93
19	Panjkora	5.75	0.64	5.11	0.03	0.86	0.92
20	Bara	3.74	0.51	3.22	0.03	0.99	0.60
21	Kabul	7.51	0.28	7.22	0.01	0.23	1.44

The Ruggedness Number (Rn) is a quantitative metric employed to evaluate the level of structural complexity exhibited by a specific topography, taking into account factors such as variations in elevation and the density of water channels. Furthermore, this suggested that the region is prone to soil erosion. The results reported in Table 10 of the current study revealed that Kanshi and Soan display the lowest roughness values (Rn = 0.12 and 0.46, respectively), while Kabul exhibits the highest roughness value (Rn = 1.44). The findings suggest that the subwatershed of Soan exhibits the lowest susceptibility to erosion, whereas the subwatershed of Kabul demonstrates the highest vulnerability relative to all other sub-watersheds within the examined region.

Discussion:

The analysis of geomorphometric characteristics associated with the drainage network is an essential requirement for conducting hydrological investigations. Hence, the analysis of the dynamics and interrelationships of stream networks plays a crucial role in many water resources-related research endeavors. The utilization of remote sensing satellite data and (GIS methodologies have the potential to enhance the efficiency of drainage delineation. Through the integration of recently updated datasets with pre-existing ones, geomorphologists can attain positive outcomes that facilitate the formulation of decisive findings about the drainage basin. The current study involves doing a geomorphometric analysis on 21 subbasins situated in the mountainous area of the UIB in Pakistan. The current study is based on several drainage characteristics and utilizes satellite data from remote sensing, along with advanced GIS methodologies. It can be deduced that subbasins characterized by challenging topography are classified as seventh-order basins. The primary distinguishing feature of subbasins is the predominance of streams with lower orders. The morphometric analysis involved the quantification and evaluation of many characteristics of basins, including linear, areal, and relief properties. A thorough examination of the morphometric characteristics of all sub-watersheds uncovers the existence of dendritic to sub-dendritic drainage patterns. These patterns suggest a significant level of lithological uniformity within the designated study region. Moreover, the variations in Rb values seen throughout the sub-watersheds can be ascribed to differences in topography and the geometric attributes of each specific sub-watershed. The frequency of stream order occurrence is highest in first-order streams, followed by second-order streams. The available empirical evidence about stream frequency reveals a noteworthy association between sub-basins and the proliferation of stream population, particularly about the increase in DD.

The DD values of the subbasins are less than five, indicating that the subsurface area exhibits permeability, which is a prominent characteristic of coarse drainage. The observed variations in stream length ratios can be attributed to the variety in slope and topographic characteristics of the region. The available empirical data about stream frequency values suggested a direct relationship between the number of stream segments and the DD in all subwatersheds. A notable fraction of subbasins exhibited a greater degree of elongation, while the remaining subbasins also displayed elongation. Greater elongation ratio measurements indicated a heightened capacity for infiltration and a diminished inclination for runoff. Conversely, lower Reynolds numbers indicated a heightened vulnerability to erosion and silt deposition. The database information and knowledge generated from the study possess the potential to make a valuable contribution towards the effective implementation of the integrated watershed project. The primary objective of this project is to enhance the facilitation of water resource development and management in the UIB region in the foreseeable future.

Conclusion:

In conclusion, it can be inferred that the presented evidence substantiates the stated hypothesis. The findings from this investigation have resulted in the formulation of specific conclusions.

- It may be deduced that subbasins characterized by rugged topography are consistently classified as basins of the seventh order. The primary distinguishing feature of subbasins is the prevalence of lower-order streams.
- The available empirical data on stream frequency suggests that there is a positive relationship between the number of streams and the density of drainage within all sub-basins.

- The DD values of the subbasins are found to be less than five, indicating that the subsurface area exhibits permeability, a trait commonly associated with coarse drainage.
- A considerable fraction of subbasins display elongated configurations, characterized by notable variations in elevation and severe gradients. As a result, the subbasins undergo reduced trip durations, increased levels of concentration, prolonged lag times, and extended periods of flood peaks.
- Higher values of the elongation ratio are indicative of a greater infiltration potential and a reduced amount of runoff. Conversely, lower Reynolds (Re) values exhibit a positive correlation with an augmented vulnerability to erosion and the accumulation of silt.

References:

[1] K. J. Gregory, "Drainage networks and climate. Chapter 10 in Geomorphology and Climate (E, Derbyshire ed.).," *London John Wiley*, 1976.

[2] P. H. Pinchmel, "Densities de drainage et densities et densities des Valles.," *Tijol ker Ned Ard-Kun. Genoots*, pp. 373-376., 1957.

[3] R. P. C. Morgan, "The role of climate in the denudation system: A case study from west Malaysia. Chapter II in Geomorphology and Climate (Derbyshire, E ed.).," *London John Wiley Sons*, 1976.

[4] S. DE Chorley RJ, Schumm SA, "Geomorphology. Methuen, London. GIS techniques.," *Int. J. Eng. Sci. Technol.*, vol. 2, no. 12, pp. 7763–7770, 1984.

[5] S. S, "Quantitative analysis of watershed geomorphology using remote sensing techniques.," *Ann Arid Zo.*, vol. 34, no. 4, pp. 243–251, 1995.

[6] P. E. Potter, " A Quantitative Geomorphic Study of Drainage Basin Characteristics in the Clinch Mountain Area, Virginia and Tennessee. V. C. Miller ," *https://doi.org/10.1086/626413*, vol. 65, no. 1, pp. 112–113, Jan. 1957, doi: 10.1086/626413.

[7] "Faniran, A. (1968) The Index of Drainage Intensity—A Provisional New Drainage Factor. Australian Journal of Science, 31, 328-330. - References - Scientific Research Publishing." https://www.scirp.org/(S(351jmbntvnsjt1aadkposzje))/reference/ReferencesPapers.aspx?ReferenceID=1845498 (accessed Oct. 10, 2023).

[8] "Schumm, S.A. (1956) Evolution of Drainage Systems and Slopes in Badlands at Perth Amboy, New Jersey. Geological Society of America Bulletin, 67, 597-646. - References - Scientific Research Publishing." https://www.scirp.org/(S(351jmbntvnsjt1aadkposzje))/reference/ReferencesPapers.aspx?ReferenceID=1768382 (accessed Oct. 10, 2023).

[9] R. Chorley, "Horton, R.E. 1945: Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. Bulletin of the Geological Society of America 56, 2 75-370," *Prog. Phys. Geogr.*, vol. 19, no. 4, pp. 533–554, Dec. 1995, doi: 10.1177/030913339501900406/ASSET/030913339501900406.FP.PNG_V03.

[10] "Melton, M. (1957) An Analysis of the Relations Among Elements of Climate, Surface Properties and Geomorphology. Department of Geology, Columbia University, Technical Report, 11, Project NR 389-042. Office of Navy Research, New York. - References - Scientific Research Publishing." https://www.scirp.org/(S(i43dyn45teexjx455qlt3d2q))/reference/ReferencesPapers.aspx?ReferenceID=2029733 (accessed Oct. 10, 2023).

[11] W. Liu and C. Shi, "Analysis of University Science Research Capability Elements and Evaluation Based on BP Neural Network," *J. Serv. Sci. Manag.*, vol. 01, no. 03, pp. 266–271, 2008, doi: 10.4236/JSSM.2008.13030.

[12] B. Víg *et al.*, "Morphometric analysis of low mountains for mapping flash flood susceptibility in headwaters," *Nat. Hazards*, vol. 114, no. 3, pp. 3235–3254, Dec. 2022, doi: 10.1007/S11069-022-05513-6/FIGURES/11.

[13] A. Al-Hurban, F. Al-Ruwaih, and A. Al-Dughairi, "Quantitative Geomorphological and Hydromorphometric Analysis of Drainage Basins of As Sabriyah (Kuwait) Using GIS

Techniques," *J. Geogr. Inf. Syst.*, vol. 13, no. 02, pp. 166–193, 2021, doi: 10.4236/JGIS.2021.132010.

[14] N. Hadadin, Z. Tarawneh, K. Shatanawi, Q. Banihani, and M. R. Hamdi, "Hydrological Analysis for Floodplain Hazard of Jeddah's Drainage Basin, Saudi Arabia," *Arab. J. Sci. Eng.*, vol. 38, no. 12, pp. 3275–3287, Oct. 2013, doi: 10.1007/S13369-013-0812-X/METRICS.

[15] C. I. Ikhile, "Geomorphology and Hydrology of the Benin Region, Edo State, Nigeria," *Int. J. Geosci.*, vol. 07, no. 02, pp. 144–157, 2016, doi: 10.4236/IJG.2016.72012.

[16] A. N. Strahler, "Quantitative Gemorphology of Drainage Basin and chanel Networks Chapter 4 in Tech. Mem. 66/5.," *Handb. Appl. Hydrol. (e V. T. Chow (ed)). New York MC Graw Hill.*, 1964.

[17] R. E. Horton, "Erosional Development of Streams and their Drainage Basins, Bulletin of the Geological Society of America," vol. 56, pp. 275–370, 1945.

[18] J. Krishnamurthy, G. Srinivas, V. Jayaraman, and M. Chandrasekhar, "Influence of rock types and structures in the development of drainage networks in typical hardrock terrain," 1996.

[19] O. YILDIZ, "An investigation of the effect of drainage density on hydrologic response," *Turkish J. Eng. Environ. Sci.*, vol. 28, no. 2, pp. 85–94, 2004, Accessed: Oct. 10, 2023. [Online]. Available: http://search/yayin/detay/1268

[20] "Singh, S. (1992) Quantitative Geomorphology of the Drainage Basin. In Chouhan T.S., and Joshi, K.N., Eds., Readings on Remote Sensing Applications, Scientific Publishers, Jodhpur. - References - Scientific Research Publishing." https://www.scirp.org/(S(lz5mqp453edsnp55rrgjct55.))/reference/referencespapers.aspx?referenceid=2163426 (accessed Oct. 10, 2023).

[21] R. V. Ruhe, "Topographic discontinuities of the Des Moines lobe [Iowa-Minnesota]," *Am. J. Sci.*, vol. 250, no. 1, pp. 46–56, Jan. 1952, doi: 10.2475/AJS.250.1.46.

[22] R. E. Horton, "Drainage-basin characteristics," *Eos, Trans. Am. Geophys. Union*, vol. 13, no. 1, pp. 350–361, Jun. 1932, doi: 10.1029/TR013I001P00350.

[23] P. K. Rai, K. Mohan, S. Mishra, A. Ahmad, and V. N. Mishra, "A GIS-based approach in drainage morphometric analysis of Kanhar River Basin, India," *Appl. Water Sci.*, vol. 7, no. 1, pp. 217–232, Mar. 2017, doi: 10.1007/S13201-014-0238-Y/FIGURES/7.

[24] I. RodrÍguez-Iturbe and L. A. Escobar, "The dependence of drainage density on climate and geomorphology," *Hydrol. Sci. J.*, vol. 27, no. 2, pp. 129–137, 1982, doi: 10.1080/02626668209491095.

[25] Z. R. Ansari, L. A. K. Rao, and A. Yusuf, "Gis based morphometric analysis of yamuna drainage network in parts of fatehabad area of agra district, Uttar Pradesh," *J. Geol. Soc. India*, vol. 79, no. 5, pp. 505–514, May 2012, doi: 10.1007/S12594-012-0075-2/METRICS.

[26] K. P. Berger and D. Entekhabi, "Basin hydrologic response relations to distributed physiographic descriptors and climate," *J. Hydrol.*, vol. 247, no. 3–4, pp. 169–182, Jul. 2001, doi: 10.1016/S0022-1694(01)00383-3.

[27] R. A. Dar, R. Chandra, and S. A. Romshoo, "Morphotectonic and lithostratigraphic analysis of intermontane Karewa Basin of Kashmir Himalayas, India," *J. Mt. Sci.*, vol. 10, no. 1, pp. 1–15, Feb. 2013, doi: 10.1007/S11629-013-2494-Y/METRICS.

[28] D. Sindhu, Sadashivappa, A. S. Ravikumar, and B. L. Shivakumar, "Quantitative Analysis of Catchment Using Remote Sensing and Geographic Information System," *Aquat. Procedia*, vol. 4, pp. 1421–1428, Jan. 2015, doi: 10.1016/J.AQPRO.2015.02.184.

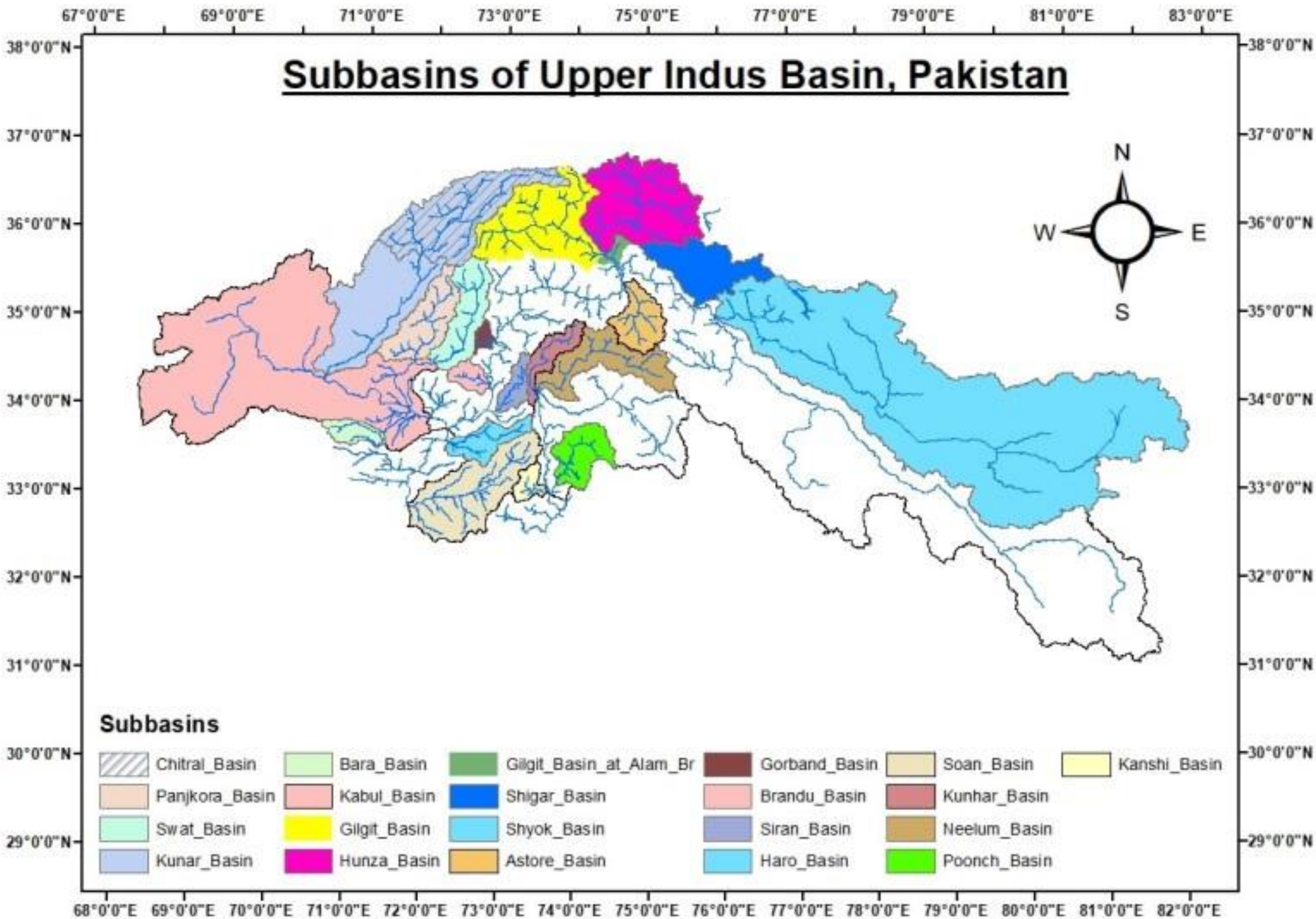

Figure 1. Subbasins of UIB, Pakistan.

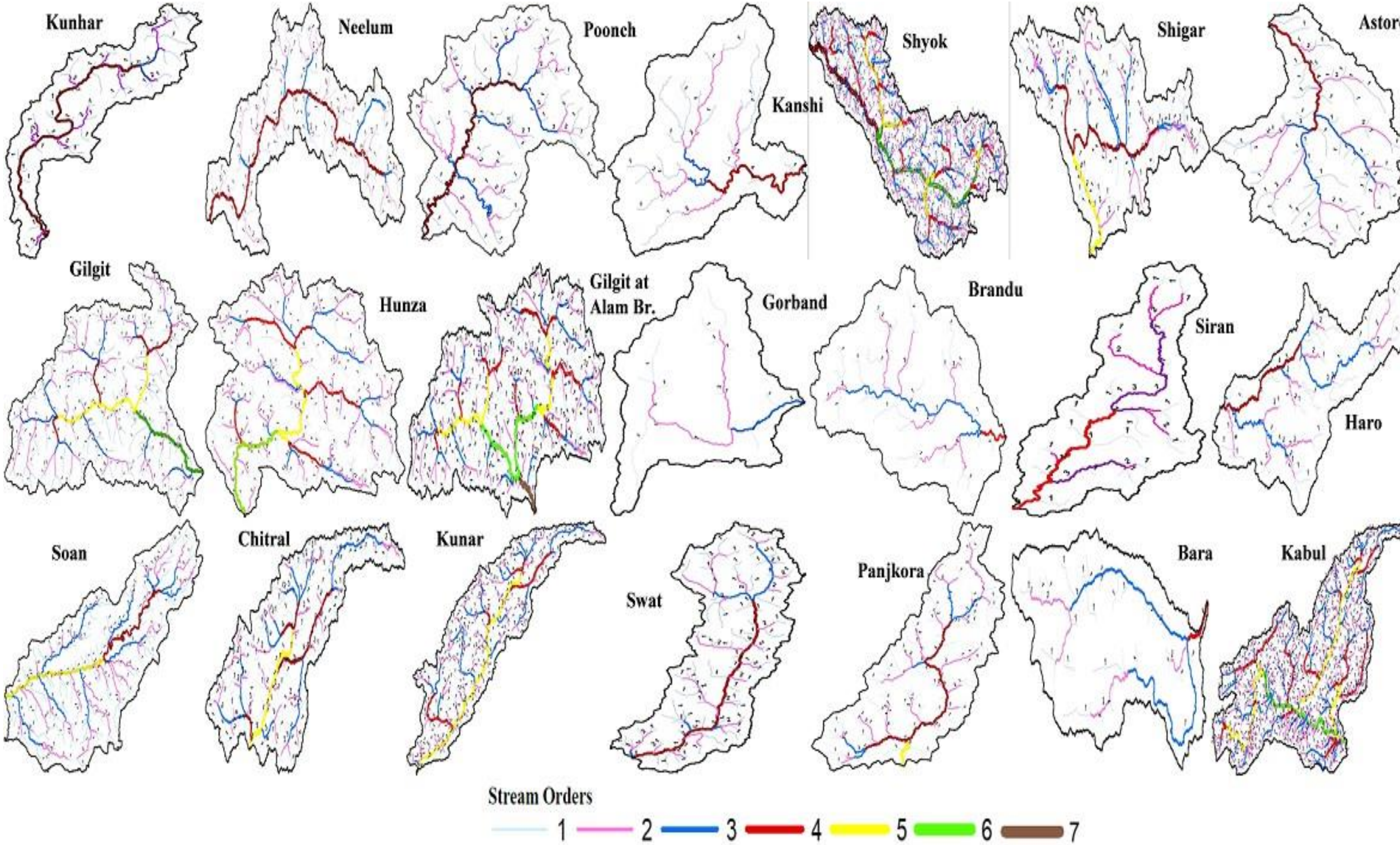

Figure 3: Stream order of sub-watersheds of UIB, Pakistan.

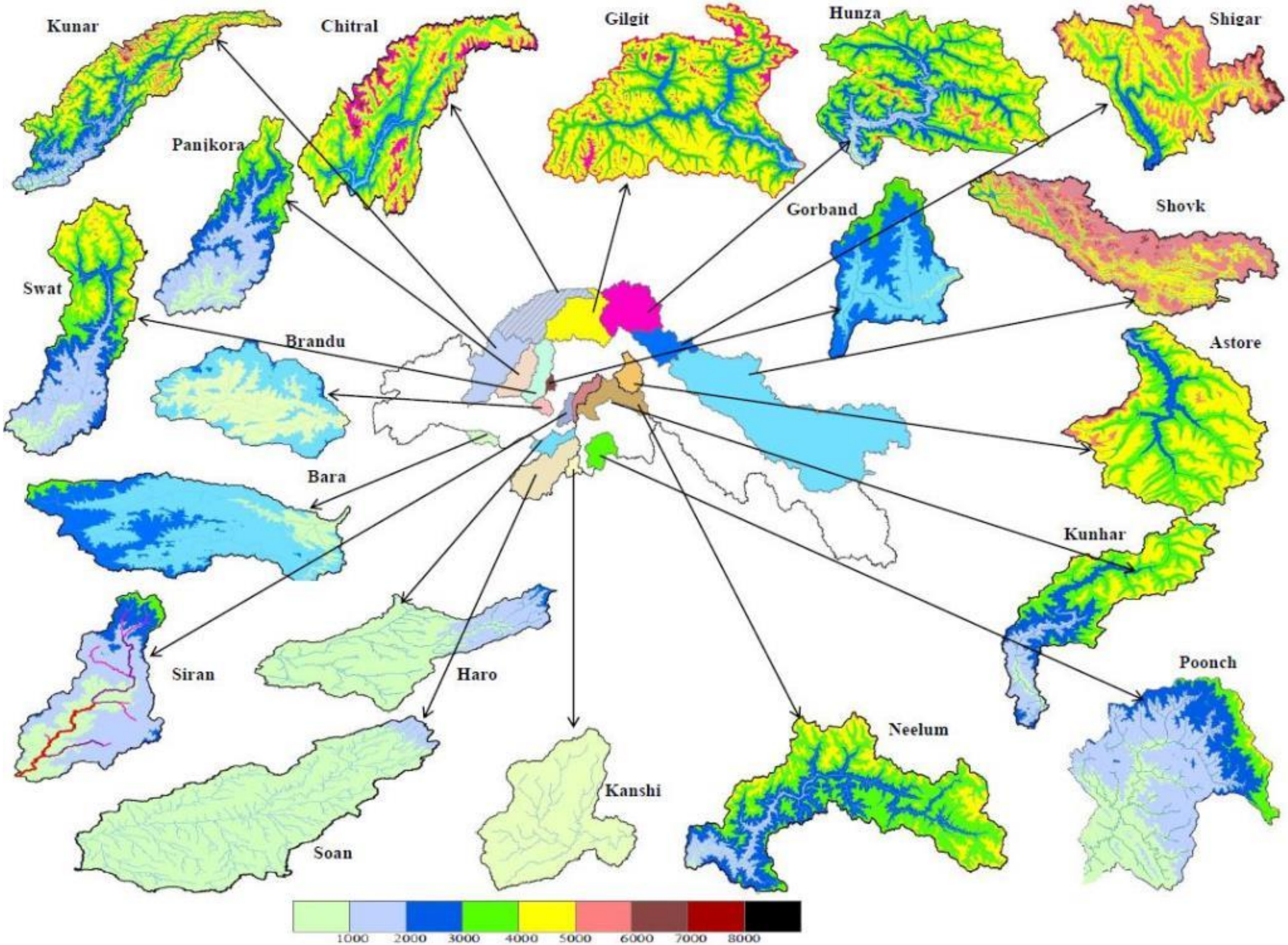

Figure 6: Topography of subbasins of Indus Bain Basin (IBB), Pakistan. (Elevation is in meter unit from above MSL)