Soil Erosion Susceptibility Mapping And Sediment Yield Estimation Using Gis Based Compound Factor Approach: A Study Of Chitral River Basin, Pakistan

Nazia Noureen[1], Dr. Jamal Nasir[2], Zohaib Akhtar[3], Sana Malik[4], Muhammad Nouman Aslam[5], Rehan Khan[6], MD Abu Syed[7], Noor Muhammad[8]

1. Ph.D. Scholar, Department of Geography and Geomatics, University of Peshawar
Email: nnoureen15@gmail.com
2. Associate Professor, Department of Geography and Geomatics, University of Peshawar
Email: drjamal@uop.edu.pk
3. School of Civil Engineering, Tianjin University, Tianjin, China
Email: zohaibak@tju.edu.cn
4. Lecturer Geography, FGDC PAC, Kamra Cantt Attock
Email: sanamalik0299@gmail.com
5. Senior Geotechnical Engineer, NESPAK, Lahore, Pakistan
Email: nouman.aslam@nespak.com.pk
6. Quaid-i-Azam University, Islamabad, Pakistan
Email: rkgeo7262@gmail.com
7. MSc Scholar, Department of Civil Engineering, Chongqing University, Chongqing, China
Email: L2300072@stu.cqu.edu.cn
8. Senior Engineer, Earthtech Engineering Services, Islamabad, Pakistan
Email: noorm1255@gmail.com

Abstract

Chitral River Basin (CRB), having its source from glaciers and snowfields of the Hindu Kush mountain range, is extremely soil erosion prone because of its very rugged topography and hydrological characteristics. The overall objective of this study is to identify sub-watersheds vulnerable to soil erosion through prioritizing the sub-watersheds using geospatial approach with the morphometric analysis and the Compound Factor (CF) method. The main data source is the ASTER Global Digital Elevation Model (DEM) at 30 m resolution that was used to generate 25 morphometric parameters using ArcMap 10.8 software. These parameters were grouped into two types according to literature available; those that have direct relationship with soil erosion and those that have inverse relationship with the susceptibility of the soil to erosion.

There are 19 sub-basins in the Chitral River Basin, which have a wide range of morphometric characteristics including basin area, stream number, stream length and drainage density. The CF method was used to incorporate the influence of all the morphometric parameters and to rank sub-basins based on their erosion susceptibility. The results show that 37 % of the sub-basins are highly susceptible to soil erosion, 31 % of the sub-basins are very highly susceptible, 16 % of the sub-basins are moderately susceptible and 16 % are less susceptible. The study findings suggest that focused implementation of soil conservation and sustainable watershed management practices is needed to reduce soil erosion hazards in the watershed of Chitral River.

Keywords: Chitral River Basin (CRB), Morphometric Ranking Approach (MRA), Drainage Density (D_d), Circulatory Ratio (R_c), Soil Erosion Susceptibility, Compactness Coefficient (C_c)

Introduction

Land and water are the two most critical natural resources necessary for life, ecosystem stability and food security. Recent studies reveal that they are very interrelated via the hydrological cycle and their utilization is becoming more and more endangered by climate change, land degradation, soil erosion, deforestation and unsustainable use of resources. Hence, the need for integrated land and water resource

management approaches with the help of GIS, remote sensing and sustainable watershed planning is seen as critical for environmental sustainability, production and sustainable human well-being (Grigg, 2024). Water and land resources are critical for sustaining agricultural productivity and food security because the good health of water and land resources is closely linked to sustainable agricultural production and the ecosystem's stability. Water and wind erosion have been found to remove the fertile top soil and organic matter from the soil, thereby reducing the soil fertility, farm productivity and degrading environment. Hence, sustainable land management practices like conservation agriculture, watershed management and soil conservation practices are recommended more and more to avoid deterioration of soil health and ecological sustainability in the long term (Quinton & Fiener, 2024).

The common issue that harms the ecosystem and depletes natural resources is soil and land degradation. One of the biggest issues is soil erosion, which lowers soil productivity by losing the top layer of soil. An estimated 15.5 billion metric tons of erogenous sediment are transported to the oceans annually by global rivers. Due to severe soil erosion, around 30% of the world's agricultural land has already been destroyed and transformed into unproductive land. Climate change is predicted to make soil loss worse in places where it is already happening. Water and wind are the two main variables that contribute to land deterioration (Bado & Bationo 2018).

A significant issue that lowers soil productivity is soil erosion, which replaces the topmost layer of soil (Pham et al., 2018). Water has been found to be responsible for about 45.5% of land erosion in steep slope locations in Nepal (Chalise et al. 2019). According to Berihun et al. (2020), soil loss in Ethiopia due to fluvial erosion in highlands ranges from 20 to 80 t hae1 yre1.Researchers, planners, and decision makers are very concerned about land degradation caused by improper management and overuse of natural resources (Kulimushi et al., 2021; Kolekar, 2021). Natural resources are lost as a result of land degradation, and the ecosystem deteriorates (Wang et al., 2020). The process of soil erosion and various modeling techniques aid in comprehending ecosystem dynamics and stability (Alewell et al., 2019). Since the 1930s, land degradation has received a lot of attention since it prevents sustainable agricultural development and the protection of natural resources (Arabameri et al., 2018). Maintaining soil fertility and protecting socioeconomic, environmental, and biophysical resources depend on the assessment of soil loss susceptibility (Kulimushi et al., 2021). In the past, a number of methods were taken into consideration to assess the vulnerability to soil loss; some of them included rainfall intensity, soil characteristics, and physiography as primary determinants (Rushema et al., 2020). Drainage systems and watershed priority are studied using a number of GIS-based models. The Soil Disintegration Model (Pham et al., 2018), Weighted Aggregate Investigation Method (Rahmati et al., 2019), Multivariate Approach (Farhan et al., 2018), and Compound Factor Approach (Nitheshnirmal et al., 2019) are a few notable examples.

Watershed morphometry, which is particularly crucial for identifying watersheds vulnerable to soil erosion, offers a thorough understanding of the watershed's geo-hydrological behavior and expresses the watershed primary climatic, geological, geomorphic, and morphological properties. One of the most popular Multi Criteria Decision Making (MCDM) techniques is watershed morphometry, which offers a comparable approximation based on scientific knowledge and perception of a qualitative phenomenon. Because of the Chitral River Basin's high hydro climatic conditions, fragile soils, and steep hilly terrain, soil erosion is a significant environmental hazard. The basin, which is situated in the Hindu Kush region, has very steep slopes and high terrain. A substantial amount of the land has slope gradients greater than 60°, which greatly increases runoff velocity and soil detachment processes (Khan et al., 2021; Ali et al., 2020).

The primary causes of soil erosion in this area are snowmelt, heavy rainfall, and surface runoff. As a result, fertile topsoil is continuously removed, degrading land resources. While the transported sediments contribute to river siltation and reservoir sedimentation, which ultimately degrades water quality and aquatic ecosystems, the loss of soil fertility immediately lowers agricultural production (Hussain et al., 2019). Due to its extremely erodible slopes, poor lithology, and scant vegetation cover, the Chitral River, a significant tributary of the Kabul River system, transports significant sediment loads (Ullah et al., 2018). High rates of soil erosion and sediment production in the basin have been documented in earlier

research, suggesting significant land degradation in higher catchment areas (Rehman et al., 2020). The region's ability to manage its land and water resources sustainably is severely hampered by this high sediment production. Therefore, in order to promote efficient soil conservation and watershed management techniques in the Chitral River Basin, it is crucial to identify and prioritize erosion-prone sub-watersheds using geospatial and morphometric approaches.

Material and Methods

Study Area

The Chitral River Basin (CRB) roughly follows the district boundary of Upper and Lower Chitral. CRB is located between 35° 18′ 15″ to 36° 49′ 50″ N latitudes and 71°22′ 15″ to 73° 54′ 45″ E longitudes. CRB is characterized by its high elevation; the height of the basin varies between 1063 meters to 7025 meters. The Chitral River originates from the Chiantar Glacier in the extreme northeast of the district at Baroghil and flows through the middle of the valley until it enters Afghanistan's Kunar province. It reenters the Peshawar valley in Khyber district flows along the boundary of district Khyber and Mohmand, and flows through district Charsadda, Nowshera until it joins the River Indus near Khairabad. The river is nourished by the snow and melting glaciers of the Hindukush Mountains, ensuring a continuous flow throughout the year. The important tributaries of the Chitral River are Mastuj River, Thorkhow River, Lutkoh River (Garam Chasma River), Golen Gol, Chitral Gol, and Shishi Gol. Figure 1 illustrates the location map of the study area, Chitral River Basin.

Data Collection

The Digital Elevation Model (DEM) provides an accurate representation of a region's landscape. DEM-based geospatial drainage network extraction and watershed delineation enable rapid morphometry (Kacem et al., 2014). According to Buccolini et al. (2012), DEM could be utilized to identify numerous basic and secondary morphometric features of the watershed. The main source of data was ASTERG DEM (V3), which was obtained from NASA Earth data (ASTER Global Digital Elevation Map, NASA.gov) and had a spatial resolution of 30 meters.

Using the Horton (1945), Smith (1957), and Strahler (1964) outlined approach, the fundamental and secondary morphometric parameters were derived in the Arc GIS 10.8 software environment. A maximum of eighteen (18) morphometric parameters were utilized in the current research, of which seven (7) were the basic parameters and the remaining were derived parameters. Basin geometry, drainage texture, and topographic parameters make up these derived parameters. Figures 2 show the methodological approach that was used for soil erosion susceptibility analysis utilizing Compound Factor Approach.

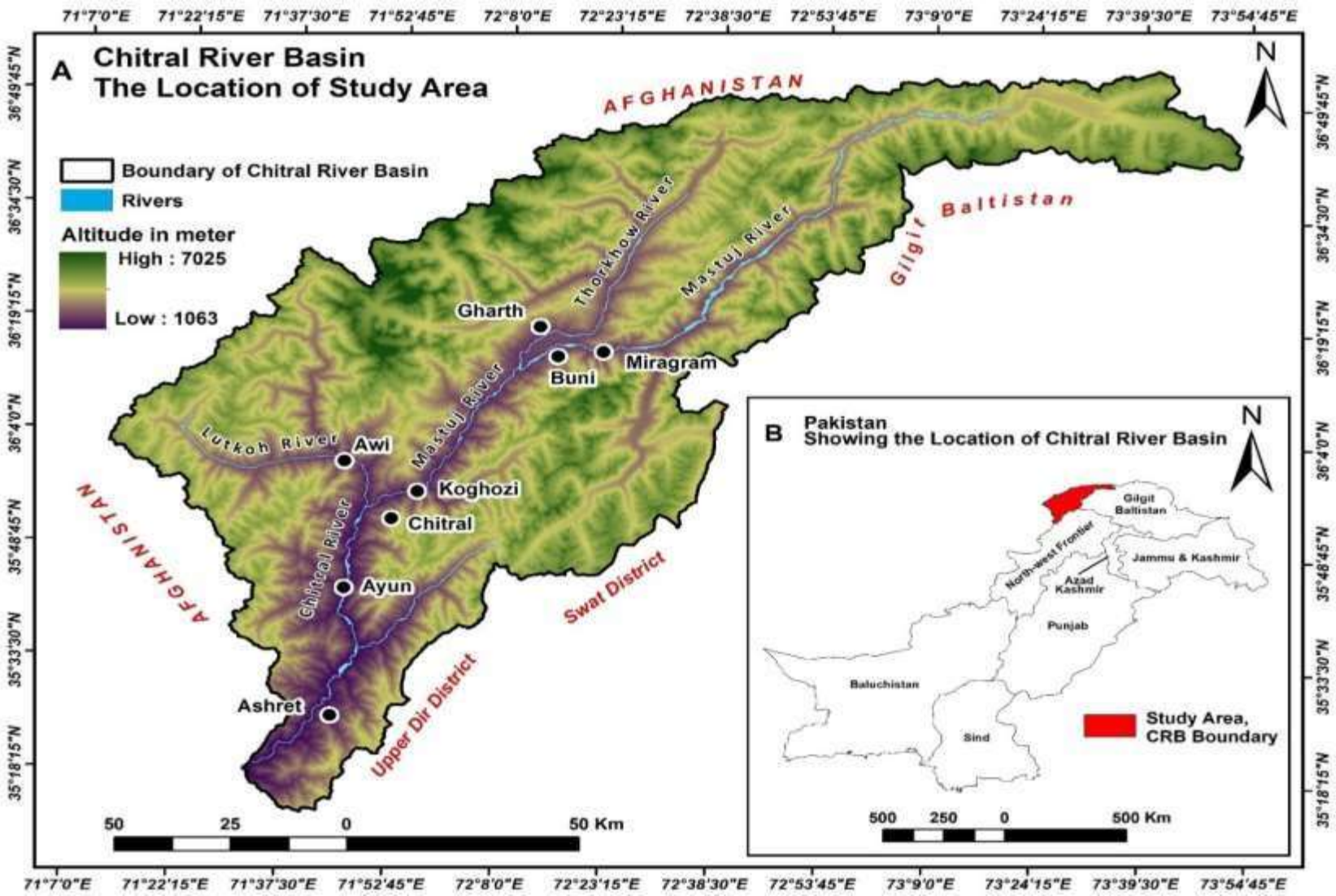


Figure 1.1 A. Illustrating the study area Chitral River Basin B. Pakistan Administrative Units showing the location of the Study area

Data Analysis

The obtained morphometric parameters will be grouped according to the literature study that is currently available. The variables in the first category will have a direct bearing on the probability of soil loss. The members of this group were A, Bh, Fs, Dd, Dt, Di, If, Lu, Nu, P, Rb, Rn, Rh, and R/W. The second group consists of variables that have an inverse relationship with the likelihood of soil erosion; that is, the higher the value of these variables, the lower the likelihood of soil loss. Among them are the Lg, Re, Rc, and Cc.

Compound Factor Approach (CFA):

This method was developed using knowledge-driven modeling by Todorovski and Dzeroski (2006). Because the CF technique transforms a subjective judgment of a phenomenon supported by verifiable facts into a quantitative evaluation that provides equal weight to all criteria, it can only be used in comparative investigations. This approach is widely used to assess erosion risk at the sub-watershed level (Akhtar et al., 2024; Nasir et al., 2023).

According to Altaf et al. (2014), the Compound Factor Approach (CFA) evaluates the compound factor's (CF) significance based on the total number of SWs. The number of sub watersheds in the Chitral River Basin (CRB) was used to rank the SWs based on each of the characteristics that were examined. First place went to the Sub-watershed with the highest Group 1 variables score, and nth place went to the SW with the lowest. On the other hand, the SW with the highest value was placed nth, while the SWs with the lowest Group 2 variable score were ranked first.

Following the Sub-Watershed ranking, final rankings were determined by adding together all of the variables' rank values and dividing the result by the total number of variables to produce the composite value, also known as the Compound Factor. The CF displays the total effect of all factors (morphometric traits) on the likelihood of soil erosion in that particular SW.

Equation…3.1 empirically expresses the compound factor (Hembram and Saha, 2023); Benzougagh et al., 2022; Ganie et al., 2023; Nasir et al., 2023).

$$CF = \frac{1}{x}\sum_{i=1}^{x} R \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots Eq.1$$

Where x represents the number of utilized morphometric parameters and R represents the ranking.

Which is derived by the ranking of selected parameters for every sub watershed and subsequently adding all the sub parameters ranks into a single rank value.

Figure 3.1 depicts the methodology adapted to prioritized erosion susceptible sub-watersheds using compound factor approach.

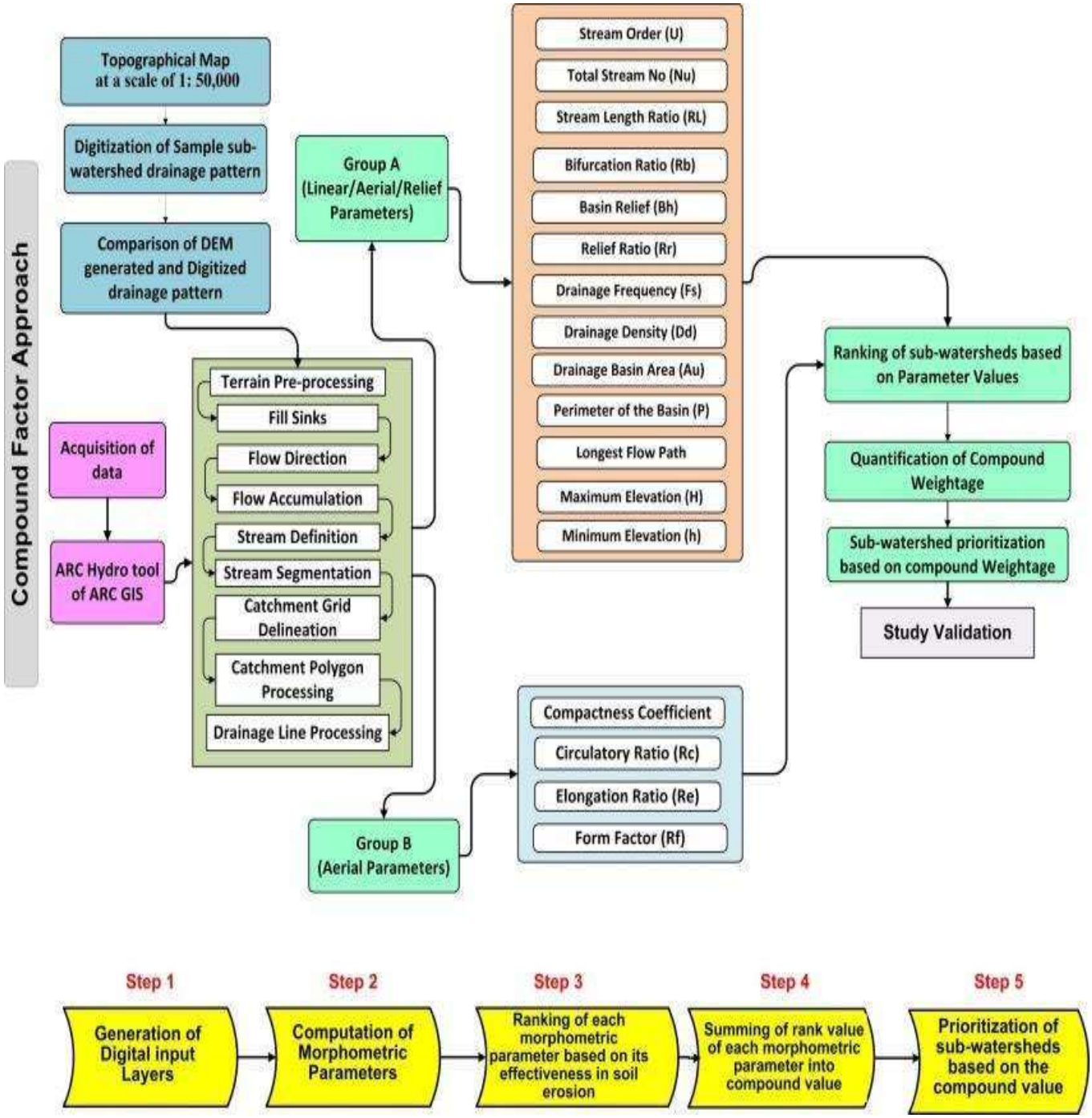


Figure 3.1. Compound Factor Approach Research Methodology Flow Chart

Results and Discussion

Based on the existing literature research, the generated morphometric parameters were split into two groups. The morphometric characteristics that are directly associated with the probability of soil loss are included in the first group. The members of this group were: A, Bh, Fs, Dd, Dt, Di, If, L, Lb, Lu, L2, Nu, P, Rb, Rc, Rh, Rl, R/W, U, W. The second group comprises the chosen morphometric characteristics that are inversely correlated with the likelihood of soil erosion; that is, the higher the value of these variables, the lower the likelihood of soil loss. They include the B_s, R_e, R_n, and the C_e. The analysis results were summarized in table 1 and 2. Table 1 shows group 1 morphometric parameters, their Sub-basin value while table 4.2 shows group 2 morphometric parameters, their Sub-basin value.

The Chitral River Basin comprises 19 sub-basins with substantial spatial variability. Basin area ranges from 128.05 km² (SB-17) to 1272.97 km² (SB-9). Stream number varies between 21 (SB-19) and 175 (SB-15), while total stream length ranges from 57.23 km (SB-17) to 586.68 km (SB-15). Basin perimeter also shows strong variation from 51.45 km (SB-4) to 192.75 km (SB-15), with an average of 106.4 km. Basin length varies between 18.39 km and 66.27 km, whereas basin width ranges from 8.27 km to 31.48 km. The length–width ratio varies from 1.62 to 5.31, indicating diverse basin shapes from elongated to moderately compact forms.

Areal morphometric analysis indicates that drainage density varies from 0.39 to 0.57 km/km², while stream frequency ranges from 0.12 to 0.21 streams/km². Drainage texture ranges from 0.20 to 0.78, and infiltration number varies from 0.0507 to 0.1197, indicating spatial differences in runoff generation potential. Form factor (0.0592–0.4606), circularity ratio (0.36–0.65), and elongation ratio (0.36–0.99) further indicate that most sub-basins are elongated in shape, which generally enhances runoff concentration. Compactness coefficient varies between 1.2409 and 1.6714, indicating differences in basin compactness and runoff behavior.

Sub-basin prioritization shows that 37% of sub-basins fall under high erosion susceptibility, 31% under very high susceptibility, 16% under moderate susceptibility, and 16% under low susceptibility. Sub-basins with higher erosion risk are characterized by higher values of Group 1 parameters (stream length, drainage density, stream frequency, bifurcation ratio) and lower values of Group 2 parameters (form factor, circularity ratio, elongation ratio), indicating enhanced runoff and reduced infiltration capacity.

Stream Number

The hydrological features and drainage pattern of a region are determined by this parameter, which is crucial to the study of stream networks. In hydrology and geomorphology, the number of streams is often combined with other morphometric parameters to characterize the landscape and drainage patterns, assess watershed characteristics, model hydrological processes, and investigate sediment transport and erosion (Chaithong, 2022). Table 1 displays the number of streams for the sub-basins of the Chitral basin. Figure 2A shows the spatial distribution of stream number across CRB. The analysis found that each CRB sub-watershed has an average of 79 streams. SW-19 (21) has the fewest stream numbers, whereas SW-15 (175) has the most.

Stream Length

In morphometric analysis, stream length refers to the total length of each individual stream segment within a certain region, such as a river network or watershed (Alarifi et al., 2022). It is an essential statistic for describing an area's hydrological characteristics and drainage pattern. The hydrologic behavior of a river basin or watershed is significantly influenced by stream length (Tola and Shetty, 2022). It affects the stream network's sediment movement, water retention, and flow dynamics.

A range of morphometric computations and hydrological models that consider both the total length of the stream and the length of its component sections are used to assess a location's drainage patterns, erosion potential, and flood threat. By examining stream length in conjunction with other morphometric variables, researchers and hydrologists can get a great lot of insight into the hydrological and geomorphological processes influencing the landscape and water behavior of the studied area. Table 1 depicts the stream length of 19 Sub-basin of CRB. Figure 2B illustrate the spatial distribution of various stream lengths

across the Sub-basins of CRB. The analysis reveals that the average streams length per sub-watershed of CRB is 227.57km. The highest stream length is computed for SW-15 (586.68 km) and lowest for SW-17 (57.23km).

Table 1. Selected Group 1 Morphometric Parameters values at Sub-basins across Chitral River Basin

Sub Basins	Linear Parameters (One Dimension)						Relief Parameters (Three Dimension		
	N_u	L_u	R_b	R/W	P	B_h	R_h	R_n	L_g
SB-1	86	228.34	2.58	1.73	98.5	2501	85.42	4387.72	0.17
SB-2	25	66.02	2.63	5.31	61.03	3061	69.73	6512.77	0.24
SB-3	34	82.83	3.03	2.71	57.05	3493	104.55	6849.02	0.25
SB-4	24	58.07	2.75	3.69	51.45	3709	83.37	8625.58	0.22
SB-5	116	375.61	3.21	2.16	135.78	4015	83.52	8193.88	0.25
SB-6	77	194.64	3.84	2.31	102.33	4541	88.95	9082	0.26
SB-7	83	193.23	3.98	3.93	100.57	4719	91.33	10040.43	0.24
SB-8	37	86.65	3.2	2.82	68.25	3008	118.05	6138.78	0.25
SB-9	173	499.64	3.37	1.89	186.45	5281	90.09	13541.03	0.19
SB-10	50	135.11	3.62	4.1	71.19	5861	93.42	11492.16	0.26
SB-11	33	91.31	5.25	4.72	64.08	4359	75.57	9476.09	0.23
SB-12	153	426.63	3.37	1.62	168.33	5151	101.3	12264.29	0.21
SB-13	164	499.45	3.55	1.74	167.14	3620	73.67	7702.13	0.24
SB-14	70	198.63	3.8	1.84	110.68	3975	117.67	9695.12	0.21
SB-15	175	586.68	3.51	3.04	192.75	4240	63.98	8153.85	0.26
SB-16	85	236.99	4.09	2.52	126.9	4415	92.75	10267.44	0.22
SB-17	22	57.23	4.12	1.8	58.54	4116	223.82	9354.55	0.22
SB-18	69	241.56	4.37	2.51	138.4	4337	92.24	9856.82	0.22
SB-19	21	65.39	5.5	2.68	63	3104	112.5	7218.6	0.22

N_u	Stream No	L_u	Stream Length	R_b	Bifurcation Ratio
P	SB Perimeter	R/W	Length Width Ratio	B_h	Basin Relief
R_h	Relief Ratio	R_n	Ruggedness Number	L_g	Length of Overland Flow

Source: DEM analysis in Arc Hydro tool, ArcMap 10.8

Table 2. Selected Group 1. Morphometric Parameters Values at Sub-basins, across CRB

Source: DEM analysis in Arc Hydro tool, ArcMap 10.8

Sub Basins	Areal Parameters (Two Dimension)										
	D_i	I_f	D_t	A	F_s	D_d	R_c	R_e	C_c	Bs	Ff
SB-1	0.3684	0.1197	0.7	394.92	0.21	0.57	0.51	0.96	1.3985	2.17	0.4606
SB-2	0.3617	0.0799	0.34	140.43	0.17	0.47	0.47	0.42	1.4531	13.72	0.072
SB-3	0.3921	0.102	0.49	164.58	0.2	0.51	0.64	0.53	1.2547	6.78	0.147
SB-4	0.3953	0.0731	0.35	133.94	0.17	0.43	0.64	0.36	1.2543	14.78	0.067
SB-5	0.3061	0.0735	0.7	762.51	0.15	0.49	0.52	0.98	1.3874	3.03	0.329
SB-6	0.4	0.1	0.53	384.14	0.2	0.5	0.46	0.58	1.4732	6.78	0.147
SB-7	0.4255	0.094	0.52	407.25	0.2	0.47	0.51	0.63	1.4061	6.56	0.152
SB-8	0.4285	0.1029	0.44	174.27	0.21	0.49	0.47	0.91	1.4588	3.73	0.268
SB-9	0.3333	0.0507	0.64	1272.97	0.13	0.39	0.46	0.98	1.4745	2.7	0.370
SB-10	0.3725	0.0969	0.56	262.01	0.19	0.51	0.65	0.36	1.2409	15.02	0.066
SB-11	0.3478	0.0736	0.41	197.18	0.16	0.46	0.6	0.37	1.2876	16.87	0.059
SB-12	0.3478	0.063	0.74	1001.2	0.15	0.42	0.44	0.98	1.501	2.58	0.387
SB-13	0.3478	0.0705	0.66	1061.72	0.15	0.47	0.48	0.97	1.4473	2.27	0.439
SB-14	0.3478	0.0574	0.5	474.08	0.14	0.41	0.49	0.92	1.4343	2.41	0.415
SB-15	0.3478	0.078	0.78	1123.93	0.15	0.52	0.38	0.98	1.6222	3.91	0.255
SB-16	0.3478	0.0645	0.5	538.79	0.15	0.43	0.42	0.88	1.5426	4.21	0.237
SB-17	0.3478	0.0748	0.2	128.05	0.17	0.44	0.47	0.94	1.4597	2.64	0.378
SB-18	0.3478	0.0528	0.38	545.87	0.12	0.44	0.36	0.99	1.6714	4.05	0.246
SB-19	0.3478	0.0559	0.29	150.32	0.13	0.43	0.48	0.68	1.4498	5.06	0.197

Bifurcation Ratio (Rb)

The bifurcation ratio (Rb) is a geometric metric that describes the branching pattern of a network or tree-like structure (Ramadan et al., 2022). It is often used to describe the branching complexity of systems like as blood veins, river networks, brain networks, and computer algorithms in hydrology, biology, geomorphology, and computer science. The mathematical expression for the bifurcation ratio (Rb) with

D_i	Drainage Intensity	I_f	Infiltration No	D_t	Drainage Texture Ratio
A	Sub-basin Area	F_s	Stream Frequency	D_d	Stream Density
R_c	Circulatory Ratio	R_e	Elongation Ratio	C_c	Compactness Coefficient
Bs	Shape Factor	Ff	Form Factor		

respect to river networks or stream channels is as follows:

$$\boldsymbol{Rb} = \frac{\boldsymbol{Nn+1}}{\boldsymbol{Nn}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Eq.1.1}$$

$$Where:$$
$$Rb\ is\ the\ bifurcation\ ratio.$$
$$Nn+1\ is\ the\ number\ of\ branches\ at\ a\ higher\ hierarchical\ level\ (the\ next\ level).$$
$$Nn\ is\ the\ number\ of\ branches\ at\ the\ current\ hierarchical\ level.$$

The sub-basin BR are shown in table 1. Figure 2C shows the spatial distribution of BR of various Sub-basin of CRB. The examination shows that the average Rb ratio for CRB is 3.67. The highest Rb ratio is computed for SW-19 (5.5) and lowest for SW-01 (2.58).

Sub-Basin Perimeter (P)

Determining the watershed's limits is a prerequisite to measuring its perimeter. The division where water flows to a common outflow point is indicated by the watershed border. The line that surrounds a watershed is its perimeter, according to Chandniha and Kansal (2017). It can be used to ascertain the SW's size and shape and is computed along the lines that divide each SW. The CRB sub-basin perimeter is shown in Table 1, and Figure 2D shows the spatial distribution of the sub-basin perimeter across CRB. SWS-09 and SWS-4 had the largest and smallest perimeter areas, respectively, with perimeter values of 186.45 km2 and 51.45 km2.

Sub-basin Length-Width Ratio (R/W)

The length-width ratio illustrates the relationship between a watershed's width and length. A watershed is the region of land where all water flows to a single outlet, such as a lake, river, or stream. Sing et al. (2013). The physical shape, hydrological activity, and response to rainfall events of a watershed can all be explained by this ratio. The length-width ratio is calculated by dividing the maximum width of the main river or watershed by its length. Nasir et al. (2020).

$$\boldsymbol{Rlw} = \frac{\boldsymbol{L}}{\boldsymbol{W}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Eq.1.2}$$

A watershed topography, land usage, and underlying geology can all have a big impact on the length-width ratio. A watershed with a high length-to-width ratio (long and narrow) reacts to rainfall events faster because water may move downstream more quickly down a smaller channel. However, watersheds with low length-to-width ratios (short and wide) usually react more slowly because water travels across a larger area more slowly.

Table 1. summarizes the Sub-Basins Length Width Ratio (L/W) of CRB, Figure 2E illustrates the spatial distribution of Sub-Basin Length Width Ratio across the CRB. The analysis reveals that SW-02 has the largest watershed length to width ratio (05.31m), while SW-012 has the smallest watershed width (1.62).

Basin Relief (Bh)

Basin relief is the elevation difference between the watershed's discharge point and the highest point of the drainage divide (Youssef et al., 2011). It is represented by the letter R. A basin relief map shows the elevation fluctuations and features of a specific geographic location, usually a valley or basin. By showing variations in height and depth throughout the region, the basin relief allows viewers to view the world in three dimensions.

The basin relief, which depicts the overall steepness of the watershed and the volume and velocity of the water flow, helps explain the erosional process occurring inside the basin (Schumm, 1956). Basin relief data is useful for applications including geological research, urban development, environmental

assessment, and flash flood susceptibility modeling. They support decision-making and provide a comprehensive understanding of topography.

$$\boldsymbol{Basin\ Relief(Bh) = H - h} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Eq.1.3}$$
$$\boldsymbol{R = Maximum\ Relief - Minimum\ Relief}$$

Table 1 summarizes the sub-basin relief and figure 2F illustrates the spatial distribution of sub-basin relief across the CRB. The data shows that the basin relief varies significantly throughout the CRB. SW-01 has the lowest basin relief (2501 m), whereas SW-10 has the highest (5861 m). In contrast to those identified in the southern part of the basin, the analysis shows that the majority of the sub-watershed located in the northeast river of the Chitral region has considerable basin relief.

Relief Ratio (R_h)

The relief ratio (Rh), which shows the overall steepness and erosional potential of a watershed, is an important relief metric in morphometric study. It is calculated by dividing the overall relief of the basin by its length. Higher relief ratio values indicate steeper topography, higher runoff velocity, stronger stream erosive force, and increased susceptibility to soil erosion and flooding. Recent research indicates that relief features significantly influence sediment transport, conservation planning prioritization, and watershed hydrological responses. According to Singh et al. (2021), Shekar & Mathew (2022), and Attar et al. (2025), morphometric analysis in conjunction with remote sensing and GIS has proven to be an effective technique for identifying significant sub-watersheds and encouraging sustainable watershed management. Table 1 shows the sub-basin relief ratio of CRB and figure 4A illustrate the spatial distribution of sub-basin relief ratio of CRB. The analysis reveals that SW-15 has the lowest relief ratio (63.98) and SW-17 has the greatest (223.82). The high relief ratio indicates that the slope between the highest and lowest altitudes has changed dramatically. Higher relief ratios are linked to higher stream flow and the possibility of substantial runoff.

Ruggedness Number (R_n)

The Ruggedness Number is a terrain analysis statistic used by hydrological, geographical, and geomorphological areas to quantify how rugged or hard a region is. It determines the variation in elevation or relief within a certain area, typically a watershed or a portion of the land. Whether utilized in hydrological modeling, landform analysis, or environmental research, the Ruggedness Number which is calculated using elevation data for a specific location is useful for understanding terrain features (Strahler, 1964). Ruggedness is a dimensionless metric that is calculated by dividing drainage density by basin relief, or the difference between the highest and lowest altitudes in sub-watersheds. Table 1 shows the sub-basins ruggedness number (R_n) of CRB. Figure 4B illustrate the spatial distribution of sub-basin ruggedness number across the CRB. The analysis reveals that great variation exist among the ruggedness number across the CRB sub-watersheds. The highest ruggedness number (13541.03) is computed for SW-09 and lowest (4387.72) for SW-01.

Length of Overland Flow (L_g)

The length of overland flow in different locations is estimated and studied by hydrologists and watershed managers using a variety of techniques, such as hydrological models and remote sensing technology. For efficient management of water resources, flood control, and erosion prevention, an understanding of overland flow is crucial. In hydrological research, the length of overland flow is crucial, especially for modeling watersheds and forecasting floods. It influences how long it takes for water to enter a channel, which can have an impact on the hydrograph of a watershed as a whole as well as peak flow rates during a downpour. Roads, homes, and pavement are examples of man-made constructions that can modify water flow pathways and increase runoff, which can impact overland flow in natural environments (Danino et al., 2021). Table 1 depicts the length of overland flow values of 21 sub-basins of CRB. Figure 4C illustrates the Sub-basins L_g of CRB. The analysis reveals that the average length of overland flow per

sub-watershed of CRB is 0.22. The highest length of overland flow is recorded for SW 06 and 15 (0.26) and lowest for SW-01 (0.17).

Drainage Intensity (D_i)

In morphometric analysis, drainage intensity (Di) is a statistic used to assess the efficiency of drainage systems in a watershed or drainage basin. According to Fan Iran (1968), it is the ratio of stream frequency to stream density. An empirical representation of it is an equation;

$$\boldsymbol{Drainage\ Intensity}(\boldsymbol{D}_{\boldsymbol{i}}) = \frac{\boldsymbol{F_s}}{\boldsymbol{D_d}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Eq.1.4}$$

$$Where\ F_S\ is\ the\ stream\ frequency\ and\ D_d\ is\ the\ stream\ density$$

Table 1 summarizes the sub- D_i of the CRB, while Figure 4D shows the spatial distribution of sub-basin drainage intensities of the CRB. The analysis reveals that the drainage intensity varies from 0.3061 to 0.4285. The highest drainage intensity was computed for SB-8 (0.4285) and the lowest was recorded for SB-5 (0.3061). The average drainage intensity computed for the Chitral river basin was 0.363.

Infiltration Number (I_f)

Drainage density (Dd) and stream frequency (Fs) are used to calculate a basin or watershed's infiltration number (If). The permeability of the basin is revealed. According to Romshoo et al. (2012), the permeability potential of the basin is negatively correlated with the infiltration number. Higher runoff and a slower rate of infiltration into the basin are indicated by a larger infiltration value. The quantity of infiltrations causes drainage densities to rise. In addition to highlighting high-relief regions and impermeable lithology within the basin/watershed, the infiltration number offers information on the rate of infiltration in the basin. Equation 4.10 (Faniran, 1968) represents it mathematically.

$$Infiltration\ Number\ (If) = F_s \times D_d \ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq.\ 1.5$$

$$Where\ F_s\ is\ the\ stream\ frequency\ and\ D_d\ is\ the\ stream\ density$$

Table 2 shows the sub-basins-wise infiltration number of the CRB. Figure 4E illustrates the spatial distribution of the sub-basin infiltration number for CRB. The infiltration number for the Chitral River sub-basins ranges from 0.0507 to 0.1197, according to the study. SB-9 had the lowest infiltration number (0.0507), while SB-1 had the highest (0.1197). The average number of sub-basin infiltration is 0.078.

Drainage Texture Ratio (D_t)

Drainage texture is described as the consistency or pattern of the distribution of drainage lines (stream segments) over a landscape by Horton (1945) and Li et al. (2022). Plant cover, soil infiltration capability, underlying lithology (kind of rock), and the landscape's overall relief all have an impact. However, drainage texture can be measured using the drainage texture ratio. To calculate this, divide the total number of stream segments across all orders at that location by the circumference of the area. It may be computed numerically using equation 4:

$$\boldsymbol{Dt} = \frac{\boldsymbol{Nu}}{\boldsymbol{P}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Eq.1.6}$$

$$Where\ Nu\ is\ the\ total\ number\ of\ stream\ segments\ and\ P\ is\ the\ perimeter\ of\ the\ basin$$

Table 2 depicts the drainage texture ratios for 21 Sub-basins of CRB, Figure 4F shows the spatial distribution of D_t across the CRB. The analysis shows that that SW-13 has a high Dt ratio of 0.98 and

SW-17 has a lowest Dt ratio of 0.38. According to Smith (1950) the SW 1,5,7,9,12,13,15 has a very fine texture, SW 3, 6, 10, 14 and 16 has fine texture, Similarly SW 2, 4, 8, 11 and 18 has moderate texture and SW 17 and 19 has a coarse texture. Table 4.17 show the texture ratio of 19 sub-watersheds of Chitral river basin.

Sub-basin Area (A)

The area of land that provides water flow to a certain point in a drainage system is known as the basin area, catchment area, or watershed area. Watershed area delineation and area computation, represented by the letter A, aid in comprehending a region's hydrological features (Schumm, 1956).

Table 2 depicts the sub-basin area across the CRB, Figure 5A shows the spatial distribution of sub-basin area across the CRB. The analysis of Table 4.15 and Figures 4.16 and 4.16 reveals that the sub-basin area of the Chitral River Basin is quite diverse, ranging from 128.05 to 1272.97 km^2.The SB-9 has the largest area 1272 Km^2 while SB-17 has the smallest area i.e. only 128.05 km^2. The average sub-basin area of the Chitral River basin is 490.42 km^2.

Stream Frequency (F_s)

Drainage frequency is a good indicator of how many stream channel connections there are in a given region. The total number of Stream segments for each Order in a Unit Area is called the Stream frequency, according to Horton (1932). Horton (1932, 1945) states that high stream frequency values indicate steep terrain surfaces and higher surface runoff. Given its significant link with the watershed's drainage density, it suggests that the number of streams increases in response to higher drainage densities. The frequency of streams indicates a high, steep slope, increasing surface flow and the risk of flooding. Stream frequency, which is mostly determined by the lithology of the basin, represents the structure of the drainage network. It provides helpful details on the complexity of drainage networks and can be used to better understand topographical characteristics and hydrodynamic behavior in a variety of disciplines, such as geomorphology, hydrology, and environmental science. The stream frequency can be computed using equation 1.7:

$$\boldsymbol{Fs = \frac{Nu}{Au}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Eq.1.7}$$

$$Where\ Nu = total\ number\ of\ stream\ and\ Au = drainage\ basin\ area$$

Table 2 summarizes the sub-basin F_s of CRB, while Figure 5B shows the spatial distribution of sub-basin stream frequencies of the CRB.The examination indicates that the average stream frequency of Chitral River Sub-watersheds is 0.16. The highest stream frequency is computed for SW-08 (0.21km/km^2) and lowest for SW-18 (0.12 21km/km^2).

Stream Density (D_d)

Drainage density (DD) can be computed by dividing the entire area of the area, which is typically expressed in square kilometers or square miles, by the total length of all streams or channels, which is typically expressed in kilometers or miles. This geomorphological metric provides information on the quantity of waterways or channels that are present in a specific landscape or watershed by estimating the number of stream channels or a drainage network that exist within a given region of land or specifically a watershed (Tariq et al., 2022).

$$\boldsymbol{Drainage\ Density = \frac{TotalLengthofStreams(in\ km)}{TotalArea(in\ Km^2)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Eq.1.8}$$

Table 2 depicts the stream densities for various sub-basins of the Chitral River basin, while Figure 5C illustrates the sub-basin stream densities across the 19 sub-basins of the CRB. The analysis reveals that some insignificant variation exist within the drainage density of the study region. The drainage density

with the greatest value is computed for SW-01 (0.57) while the smallest drainage density is recorded for SW-09 (0.39). The average computed drainage density of Chitral River Sub-watersheds is 0.46.

Circulatory Ratio (R_c)

The watershed's circulatory ratio (Rc) is a geographic metric that characterizes the intricacy of a watershed's form (Miller, 1953). It quantifies the degree to which a river or stream winds and flows inside a watershed. The main channel's sinuosity is measured using this ratio in proportion to the watershed's valley length. According to Parkash et al. (2019), the formula for determining the watershed circulatory ratio (Rc) is:

$$Rc = 4\pi \frac{A}{P2} \quad \text{Eq. 1.9}$$

$$Where\ A = Area\ of\ the\ basin, \pi = 3.14\ and\ P = Perimeter\ of\ the\ basin$$

The circulatory ratio of sub-basins of the CRB is shown in Table 2, while Figure 5D illustrates its spatial distribution. The analysis reveals that SW-10 has the highest circulatory ratio (0.48), while SWS-18 has the smallest RC ratio (0.36).

Elongation Ratio (R_e)

The elongation ratio is a morphometric statistic used to define the aspect ratio and shape of a landform or item. In several scientific domains, including geology, geography, and image analysis, it is frequently employed to quantify the elongatedness of features and assess their geometric characteristics. The longest dimension of an elongation ratio is the ratio of an item to its shortest dimension (Miller, 1953). The ratio of the longest basin length to the diameter of a circle with the same size as the catchment area is known as the elongation ratio in morphometric analysis (Schumm, 1956).

An extended basin seems to be just as effective in releasing runoff as a circular basin, according to Singh et al. (2020). Despite a wide range of climatic and geographic factors, the ratio's continuous range is between 0.6 and 1.0. The region typically has very little relief when the elongation ratio is around 1; it typically has large relief and a high earth slope when it is between 0.6 and 0.8 (Strahler, 1964). Alternatively, these values can be classified as (a) less elongated (0.7), (b) oval (0.9-0.8), and (c) circular (>0.9). The formula used to calculate it is Equation 1.10.

$$Elongation\ ratio\ (Re) = \frac{Dc}{Lb} \ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq.\ 1.10$$

$$Where\ Dc = diameter\ of\ the\ circle$$
$$Lb = length\ of\ the\ drainage\ basin$$

The Elongation ratio computed for 19 sub-basins of the Chitral River basin is shown in Table 2 and Figure 5E illustrates its spatial distribution across CRB. The analysis reveals that SW-18 has the highest elongation ratio (0.99), while SW-10 has the smallest elongation ratio (0.36).

Compactness coefficient (C_c)

In morphometric analysis, the compactness coefficient is used to quantify a basin's degree of circularity or compactness. It is computed by dividing the basin's area by its perimeter or circumference. It is computed by dividing the watershed's perimeter by the radius of a comparable circular area. The compactness coefficient is represented quantitatively by Equation 1.11 (Horton, 1945).

$$Compactness\ Coefficient\ (C_c) = (P/2(\pi A))0.5 \ldots\ldots\ldots\ldots Eq.\ 1.11$$

$$Where\ P\ is\ the\ sub-basin\ perimeter\ and\ A\ is\ the\ area\ of\ the\ watershed$$

Table 2 depicts the Sub-Basins C_c of the CRB. Figure 5F illustrates the compactness coefficient of 19 sub-basins of CRB. The Chitral River basin's average Cc value, according to the analysis, ranges from 0.0592 to 0.4606. SB-1 has the greatest Cc value (0.4606), while SB-11 has the lowest (0.0592). The greater Cc value indicates that the basin is more susceptible to soil erosion due to increased runoff and decreased infiltration capacity. Given that SB-1, SB-13, SB-14, and SB-9 have greater Cc values, soil erosion is more likely to occur.

Shape Factor (Bs)

The Shape Factor, often called the Form Factor (Rf), is a dimensionless morphometric parameter that describes the general geometry and shape of a drainage basin. Understanding the hydrological behavior of the basin, particularly its runoff response, flood potential, and erosion susceptibility, is crucial. Horton (1932) introduced the form factor, which Strahler (1957) subsequently improved. It can be stated numerically as:

$Rf=A/L^2b$.....Eq1.12

Where:
Rf = Form Factor
A = Area of the basin (km²)
Lb = Basin length (km), measured along the main drainage line from the outlet to the basin divide

Table 2 depicts the Sub-basins Bs of the CRB. Figure 5F illustrates the Shape factor of 19 sub-basins of CRB. The analysis reveals that the highest value is computed for SB-11 (16.87) and the lowest for SB-1 (2.17).

Form Factor (Ff)

Morphometric analysis uses a geometric parameter known as the "form factor" to describe the geometry of a drainage basin. The basin's area (A) divided by the square of its length (Lb2) yields this dimensionless ratio. The following is the mathematical expression for the form factor (Ff) (Strahler, 1964):

$$Form\ Factor = \frac{A}{Lb^2} \ldots\ldots\ldots\ldots\ldots Eq.1.13$$

Where A is the basin area and Lb2 is the square of the basin length

Important information about how compact or extended the basin shape is can be found in the form factor. It is particularly useful for understanding basin shape, stream flow characteristics, sediment transport, and erosion processes in hydrological and geomorphological study.

Table 2 depicts the Sub-basins Ff of the CRB. Figure 5F illustrates the Form factor of 19 sub-basins of CRB. The sub-basin form factor, according to the research, ranges from 0.0592 to 0.4606. SB-11 is the more elongated basin with a form factor value of 0.0592, while SB-1 is the more circular basin with a form factor value of 0.4606, according to the consideration of the form factor values. The sub-basins of the Chitral River have an average form factor of 0.247.

Sub-basin Soil Erosion Susceptibility Assessment

Soil erosion processes are influenced by a number of elements other than morphometric parameters, such as soil type and texture, rainfall characteristics like intensity, length, quantity, and erosivity, and anthropogenic activities. However, these characteristics are greatly influenced by the morphometric parameters of the basin, including basin area, stream number, stream length, drainage density frequency and intensity, shape factors, circulatory ratio, elongation ratio, and so forth (Benzougagh et al., 2022). To evaluate soil erosion risk and more precisely estimate erosion rates, the Compound Factor Approach integrates these variables into a thorough framework.

In order to analyze and assess soil erosion, the "Compound Factor Approach" considers a number of morphometric parameters related to the erosion processes. Instead of concentrating just on individual factors, this approach considers the combined effects of multiple morphometric parameters on soil erosion (Ali et al., 2024). The impact of each morphometric parameter on soil erosion is ascertained using empirical models in this manner. These factors are aggregated and graded to predict soil erosion rates or vulnerability in a particular basin. By taking into account the combined effects of numerous factors, the Compound Factor Approach finds effective basin-level erosion control and management strategies tailored to particular environmental circumstances and land use patterns (Roy and Chintalacheruvu, 2024).

Tables 3 and 4 provide a summary of the selected group 1 morphometric characteristics, their Sub-basin values, and corresponding ranks. Table 5 summarizes the selected group 2 morphometric parameters, their Sub-basin values, and ranks. Tables 6 summarize analysis results for the specified morphometric parameters in groups 1 and 2, as well as their compound factor ranks. Table 6 shows the selected group 1 & 2 morphometric parameters ranking and sub-basin compound factor value of 19 sub-basins of CRB. Figure 6 illustrates the Compound Factor Approach based sub-basin soil erosion susceptibility of CRB. Figure 7 showing the percentage area under various soil erosion susceptibility classes.

Table .3 Selected Group 1 Morphometric Parameters, their Sub-Basin value and Corresponding Rank

S-basin	Group One Morphometric Parameters													
	Stream No		Stream Length		Bifurcation Ratio		Sub-basin Perimeter		Length Width Ratio		Basin Relief		Relief Ratio	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
SB-1	86	14	228.3	12	2.58	1	98.5	9	1.73	2	2501	1	85.42	7
SB-2	25	4	66.0	4	2.63	2	61.03	4	5.31	19	3061	3	69.73	2
SB-3	34	6	82.8	5	3.03	4	57.05	2	2.71	12	3493	7	104.55	15
SB-4	24	3	58.0	2	2.75	3	51.45	1	3.69	15	3709	9	83.37	5
SB-5	116	15	375.6	15	3.21	6	135.78	14	2.16	7	4015	9	83.52	6
SB-6	77	11	194.6	10	3.84	13	102.33	11	2.31	8	4541	15	88.95	8
SB-7	83	12	193.2	9	3.98	14	100.57	10	3.93	16	4719	16	91.33	10
SB-8	37	7	86.6	6	3.2	5	68.25	7	2.82	13	3008	2	118.05	18
SB-9	173	18	499.6	18	3.37	8	186.45	18	1.89	6	5281	18	90.09	9
SB-10	50	8	135.1	8	3.62	11	71.19	8	4.1	17	5861	19	93.42	13
SB-11	33	5	91.31	7	5.25	18	64.08	6	4.72	18	4359	13	75.57	4
SB-12	153	16	426.6	16	3.37	7	168.33	17	1.62	1	5151	17	101.3	14
SB-13	164	17	499.4	17	3.55	10	167.14	16	1.74	3	3620	6	73.67	3
SB-14	70	10	198.6	11	3.8	12	110.68	12	1.84	5	3975	8	117.67	17
SB-15	175	19	586.6	19	3.51	9	192.75	19	3.04	14	4240	11	63.98	1
SB-16	85	13	236.9	13	4.09	15	126.9	13	2.52	10	4415	14	92.75	12
SB-17	22	2	57.2	1	4.12	16	58.54	3	1.8	4	4116	10	223.82	14
SB-18	69	9	241.5	14	4.37	17	138.4	15	2.51	9	4337	12	92.24	11
SB-19	21	1	65.3	3	5.5	19	63	5	2.68	11	3104	4	112.5	16

Source: DEM analysis in Arc Hydro tool, ArcMap 10.8

Table 4. Selected Group 1 Morphometric Parameters, their Sub-Basin value and corresponding Ranks

Sub-Basins	Group One Morphometric Parameters													
	Drainage Intensity		Infiltration No		Drainage Texture Ratio		Sub-basin Area		Stream Frequency		Stream Density		Ruggedness Number	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
SB-1	0.36	13	0.11	19	0.7	17	394.92	10	0.21	19	0.57	19	4387.72	1
SB-2	0.36	12	0.07	13	0.34	3	140.43	3	0.17	13	0.47	12	6512.77	3
SB-3	0.39	15	0.10	17	0.49	8	164.58	5	0.2	17	0.51	17	6849.02	4
SB-4	0.39	16	0.07	8	0.35	4	133.94	2	0.17	12	0.43	6	8625.58	9
SB-5	0.30	1	0.07	9	0.7	16	762.51	15	0.15	9	0.49	14	8193.88	8
SB-6	0.4	17	0.1	16	0.53	12	384.14	9	0.2	16	0.5	15	9082	10
SB-7	0.42	18	0.09	14	0.52	11	407.25	11	0.2	15	0.47	11	10040.43	15
SB-8	0.42	19	0.10	18	0.44	7	174.27	6	0.21	18	0.49	13	6138.78	2
SB-9	0.33	2	0.05	1	0.64	14	1272.97	19	0.13	3	0.39	1	13541.03	19
SB-10	0.37	14	0.09	15	0.56	13	262.01	8	0.19	14	0.51	16	11492.16	17
SB-11	0.34	3	0.07	10	0.41	6	197.18	7	0.16	10	0.46	9	9476.09	12
SB-12	0.34	4	0.06	5	0.74	18	1001.2	16	0.15	8	0.42	3	12264.29	18
SB-13	0.34	5	0.07	7	0.66	15	1061.72	17	0.15	7	0.47	10	7702.13	6
SB-14	0.34	6	0.05	4	0.5	10	474.08	12	0.14	4	0.41	2	9695.12	13
SB-15	0.34	7	0.07	12	0.78	19	1123.93	18	0.15	6	0.52	18	8153.85	7
SB-16	0.34	8	0.06	6	0.5	9	538.79	13	0.15	5	0.43	5	10267.44	16
SB-17	0.34	9	0.07	11	0.2	1	128.05	1	0.17	11	0.44	8	9354.55	11
SB-18	0.34	10	0.05	2	0.38	5	545.87	14	0.12	1	0.44	7	9856.82	14
SB-19	0.34	11	0.05	3	0.29	2	150.32	4	0.13	2	0.43	4	7218.6	5

Source: DEM analysis in Arc Hydro tool, ArcMap 10.8

Table 5 Selected Group 2 Morphometric Parameters, their Sub-watershed value and corresponding Ranks

Sub-Basins	Group Two Morphometric Parameters											
	Circulatory Ratio		Elongation Ratio		Compactness coefficient		Length of Overland Flow		Shape Factor		Form Factor	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
SB-1	0.51	14	0.96	13	1.39	6	**0.17**	**1**	2.17	1	0.46	19
SB-2	0.47	9	0.42	4	1.45	11	**0.24**	**13**	13.72	16	0.07	4

SB-3	0.64	18	0.53	5	1.25	3	**0.25**	**16**	6.78	15	0.14	6
SB-4	0.64	17	0.36	2	1.25	2	**0.22**	**9**	14.78	17	0.06	3
SB-5	0.52	15	0.98	18	1.38	5	**0.25**	**15**	3.03	7	0.32	13
SB-6	0.46	6	0.58	6	1.47	14	**0.26**	**19**	6.78	14	0.14	5
SB-7	0.51	13	0.63	7	1.40	7	**0.24**	**12**	6.56	13	0.15	7
SB-8	0.47	8	0.91	10	1.45	12	**0.25**	**14**	3.73	8	0.26	12
SB-9	0.46	5	0.98	17	1.47	15	**0.19**	**2**	2.7	6	0.37	14
SB-10	0.65	19	0.36	1	1.24	1	**0.26**	**18**	15.02	18	0.06	2
SB-11	0.6	16	0.37	3	1.28	4	**0.23**	**10**	16.87	19	0.05	1
SB-12	0.44	4	0.98	16	1.50	16	**0.21**	**4**	2.58	4	0.38	16
SB-13	0.48	11	0.97	14	1.44	9	**0.24**	**11**	2.27	2	0.43	18
SB-14	0.49	12	0.92	11	1.43	8	**0.21**	**3**	2.41	3	0.41	17
SB-15	0.38	2	0.98	15	1.62	18	**0.26**	**17**	3.91	9	0.25	11
SB-16	0.42	3	0.88	9	1.54	17	**0.22**	**8**	4.21	11	0.23	9
SB-17	0.47	7	0.94	12	1.45	13	**0.22**	**7**	2.64	5	0.37	15
SB-18	0.36	1	0.99	19	1.67	19	**0.22**	**6**	4.05	10	0.24	10
SB-19	0.48	10	0.68	8	1.44	**10**	**0.22**	**5**	5.06	12	0.19	8

Source: DEM analysis in Arc Hydro tool, ArcMap 10.8

Table 6. Selected Group 1 & 2 Morphometric Parameters ranking and Sub-Basin Compound Factor Value

Sub-Basins	Morphometric Parameters																					al	CF A
	Group one														Group Two								
	Nu	Lu	R_b	P	L/W	B_h	R_h	R_n	D_i	I_f	D_t	A	F_s	D_d	L_g	R_c	R_e	Cc	Bs	Fs		
SB-1	14	12	1	9	2	1	7	1	13	19	17	10	19	19	1	14	13	6	1	19	239	9.96
SB-2	4	4	2	4	19	3	2	3	12	13	3	3	13	12	13	9	4	11	16	13	193	8.04
SB-3	6	5	4	2	12	7	15	4	15	17	8	5	17	17	16	18	5	3	15	17	237	9.88
SB-4	3	2	3	1	15	9	5	9	16	8	4	2	12	6	9	17	2	2	17	12	178	7.42
SB-5	15	15	6	14	7	9	6	8	1	9	16	15	9	14	15	15	18	5	7	9	282	11.75
SB-6	11	10	13	11	8	15	8	10	17	16	12	9	16	15	19	6	6	14	14	16	280	11.67
SB-7	12	9	14	10	16	16	10	15	18	14	11	11	15	11	12	13	7	7	13	15	275	11.46
SB-8	7	6	5	7	13	2	18	2	19	18	7	6	18	13	14	8	10	12	8	18	224	9.33
SB-9	18	18	8	18	6	18	9	19	2	1	14	19	3	1	2	5	17	15	6	3	271	11.29
SB-10	8	8	11	8	17	19	13	17	14	15	13	8	14	16	18	19	1	1	18	14	291	12.13
SB-11	5	7	18	6	18	13	4	12	3	10	6	7	10	9	10	16	3	4	19	10	210	8.75
SB-12	16	16	7	17	1	17	14	18	4	5	18	16	8	3	4	4	16	16	4	8	279	11.63
SB-13	17	17	10	16	3	6	3	6	5	7	15	17	7	10	11	11	14	9	2	7	260	10.83

SB-14	10	11	12	12	5	8	17	13	6	4	10	12	4	2	3	12	11	8	3	4	206	8.58
SB-15	19	19	9	19	14	11	1	7	7	12	19	18	6	18	17	2	15	18	9	6	311	12.96
SB-16	13	13	15	13	10	14	12	16	8	6	9	13	5	5	8	3	9	17	11	5	245	10.21
SB-17	2	1	16	3	4	10	14	11	9	11	1	1	11	8	7	7	12	13	5	11	182	7.58
SB-18	9	14	17	15	9	12	11	14	10	2	5	14	1	7	6	1	19	19	10	1	244	10.17
SB-19	1	3	19	5	11	4	16	5	11	3	2	4	2	4	5	10	8	10	12	2	152	6.33

Source: DEM analysis in Arc Hydro tool, ArcMap 10.8

N_u	Total Stream No.	**L_u**	Total Stream Length	**R_b**	Bifurcation Ratio
P	Perimeter	**L/W**	Length Width Ratio	**B_h**	Basin Relief
R_h	Relief Ratio	**R_n**	Ruggedness Number	**D_i**	Drainage intensity
I_f	Infiltration Number	**D_t**	Drainage Texture Ratio	**A**	Basin Area
D_d	Drainage Density	**F_s**	Stream Frequency	**L_g**	Length of Overland Flow
R_c	Circulatory Ratio	**R_e**	Elongation Ratio	**Cc**	Compactness Coefficient
Bs	Shape Factor	**Ff**	Form Factor		

	Very High Erosion		**High Erosion**		**Moderate Erosion**		**Low Erosion**

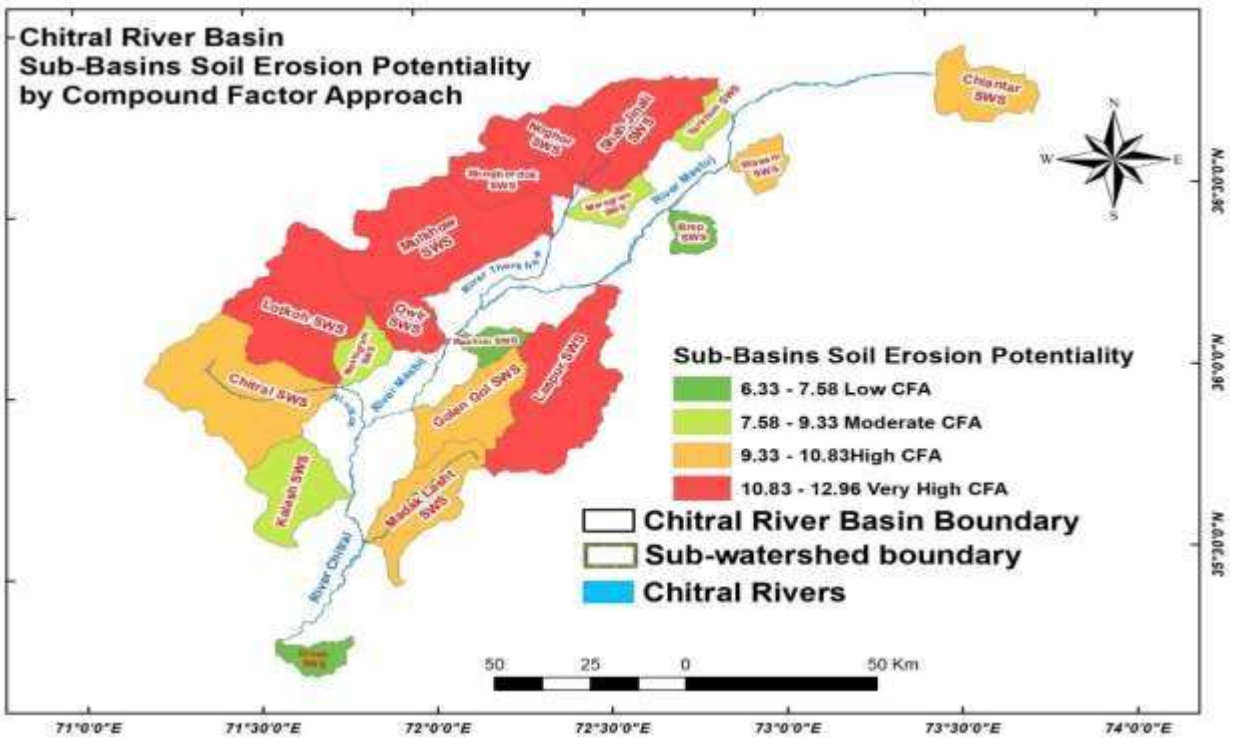


Figure 1.2 Illustrating the compound factor approach based soil erosion susceptibility ranking of sub-basins of Chitral river basin

Discussion

The analysis of figure 4.29 reveals that 7 sub-basins (37% of the total sub-basins of Chitral river basin) i.e. SB-5. SB-6, SB-7, SB-9, SB-10, SB-12, and SB-15 have the highest susceptibility to soil erosion. Similarly, 6 sub-basins (31% of the total sub-basins of the Chitral river basin), i.e. SB-1, SB-3, SB-8, SB-13, SB-16, and SB-18 are highly susceptible to soil erosion. The 3 sub-basins (16 % of the total sub-basins) i.e. SB-2, SB-11, and SB-14 are moderately susceptible to soil erosion. While remaining 3 sub-basins (16 % of the total sub-basins of Chitral river basin) i.e. SB-4, SB-17 and SB-19 have an overall lower susceptibility to soil erosion.

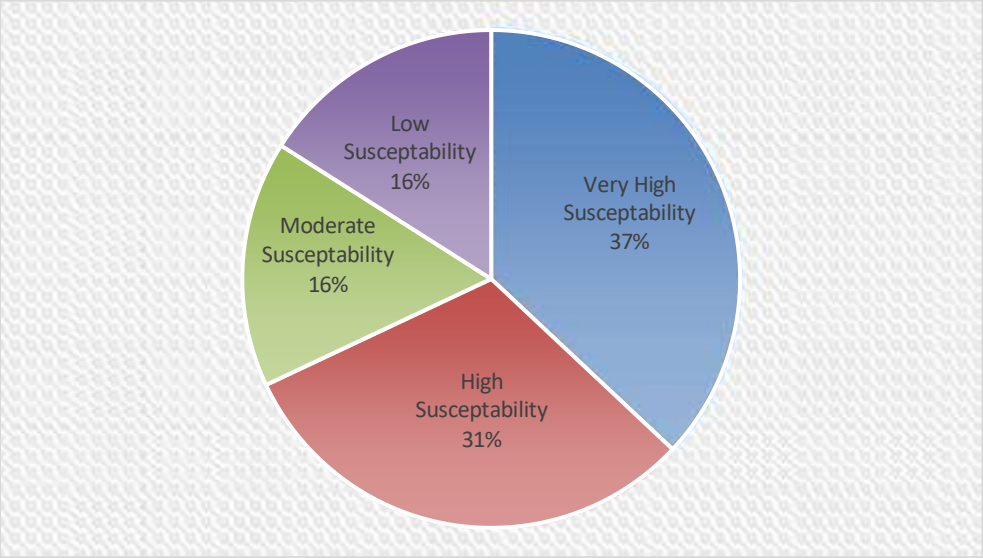


Figure 1.3. Showing Compound Factor approach based soil erosion Susceptibility of Chitral river Sub-basins

The analysis reveals that the majority of the area-wise larger sub-basins report very high to high soil erosion susceptibility, while smaller sub-basins have moderate to low soil erosion susceptibility table 6.

The analysis of sub-basins with very high soil erosion susceptibility reveals that these basins have higher stream number, stream length, larger basin area higher bifurcation ratio, lower form factor, shape factor, and circulatory ratio (lower value higher soil erosion susceptibility). Overall the sub-basin with very high to high soil erosion susceptibility has very high to high group one morphometric parameter value and low to very low group two morphometric parameter values.

Conclusion

The morphometric analysis of Chitral River Basin sub-basins, clearly shows that there are marked variations in the susceptibility to soil erosion among different sub-basins. Based on the results it can be concluded that most of the sub basins are at very high and high susceptible category, which shows the high susceptibility of the basin to the soil erosion processes of acceleration. In this regard, sub-basins SB-5, SB-6, SB-7, SB-9, SB-10, SB-12, and SB-15 are very highly susceptible to soil erosion, and SB-1, SB-3, SB-8, SB-13, SB-16, and SB-18 are highly susceptible to soil erosion. Contrastingly, only a few sub-basins were classified as moderate to low susceptibility zones, where the geomorphic conditions are relatively stable.

Additionally, the study shows that larger sub-basins are more susceptible to severe soil erosion because of their larger bifurcation ratio, mean stream number, stream length, and basin size. Lower form factor, shape factor, and circulation ratio values also show an extended basin shape in highly sensitive sub-basins, which indicates concentrated runoff and enhanced erosion. The combination of group one morphometric parameters, which are directly correlated with erosion risk, and group two morphometric parameters, which are inversely correlated with erosion risk, has a substantial impact on the pattern of erosion susceptibility across the basin.

Overall, the results indicate that morphometric parameters are a good and reliable indicator for identifying areas prone to erosion in the Chitral River Basin. The study highlights the need for good watershed management, soil conservation measures, afforestation, slope stabilization, and sustainable land-use planning especially in the very high and high susceptibility sub-basins to combat environmental hazards in the region and reduce land degradation in the future.

References

1. Achu, A. L., & Thomas, J. (2023). Soil erosion and sediment yield modeling in a tropical mountain watershed of the southern Western Ghats, India using RUSLE and Geospatial tools. Total Environment Research Themes, 8, 100072.
2. Akbar, H., &Gheewala, S. H. (2020).Changes in hydroclimatic trends in the Kunhar River Watershed. Journal of Sustainable Energy & Environment, 11, 31-41.
3. Ali, R., Sajjad, H., Masroor, M., Saha, T. K., Roshani, & Rahaman, M. H. (2024). Morphometric parameters based prioritization of watersheds for soil erosion risk in Upper Jhelum Sub-catchment, India. Environmental Monitoring and Assessment, 196(1), 82.
4. Alewell, C., Borrelli, P., Meusburger, K., & Panagos, P. (2019). Using the USLE: Chances, challenges and limitations of soil erosion modelling. International soil and water conservation research, 7(3), 203-225.
5. Alekseevskiy, N. I., Berkovich, K. M., & Chalov, R. S. (2008). Erosion, sediment transportation and accumulation in rivers. International Journal of Sediment Research, 23(2), 93-105.
6. Altaf, S., Meraj, G., & Romshoo, S. A. (2014). Morphometry and land cover based multi-criteria analysis for assessing the soil erosion susceptibility of the western Himalayan watershed. Environmental monitoring and assessment, 186, 8391-8412.
7. Arabameri, A., Pradhan, B., Rezaei, K., Yamani, M., Pourghasemi, H. R., & Lombardo, L. (2018).Spatial modelling of gully erosion using evidential belief function, logistic regression, and a new ensemble of evidential belief function–logistic regression algorithm. Land Degradation & Development, 29(11), 4035-4049.
8. Bado, V. B., & Bationo, A. (2018). Integrated management of soil fertility and land resources in Sub-Saharan Africa: involving local communities. Advances in Agronomy, 150, 1-33.
9. Balasubramanian, A., Duraisamy, K., Thirumalaisamy, S., Krishnaraj, S., & Yatheendradasan, R. K. (2017). Prioritization of subwatersheds based on quantitative morphometric analysis in lower Bhavani basin, Tamil Nadu, India using DEM and GIS techniques. Arabian Journal of Geosciences, 10, 1-18.
10. Benzougagh, B., Meshram, S. G., Dridri, A., Boudad, L., Baamar, B., Sadkaoui, D., &Khedher, K. M. (2022).Identification of critical watershed at risk of soil erosion using morphometric and geographic information system analysis. Applied Water Science, 12, 1-20.
11. Berihun, M. L., Tsunekawa, A., Haregeweyn, N., Dile, Y. T., Tsubo, M., Fenta, A. A., ... & Srinivasan, R. (2020). Evaluating runoff and sediment responses to soil and water conservation practices by employing alternative modeling approaches. Science of the Total Environment, 747, 141118
12. Bettoni, M., Maerker, M., Bosino, A., Conedera, M., Simoncelli, L., & Vogel, S. (2023). Land use effects on surface runoff and soil erosion in a southern Alpine valley. Geoderma, 435, 116505.
13. Bharath, A., Kumar, K. K., Maddamsetty, R., Manjunatha, M., Tangadagi, R. B., & Preethi, S. (2021). Drainage morphometry based sub-watershed prioritization of Kalinadi basin using geospatial technology. Environmental Challenges, 5, 100277.
14. Bishop, M. P., Shroder Jr, J. F., & Colby, J. D. (2003). Remote sensing and geomorphometry for studying relief production in high mountains. Geomorphology, 55(1-4), 345-361.
15. Borkar, V. S., Gokhale, N. B., More, S. S., Wahane, M. R., &Khobragade, N. H. (2018). Mapping land use/cover using remote sensing and GIS techniques: A case study of rahat micro watershed of Nagpur district India. International Journal of Chemical Studies, 6(1), 15-18.
16. Chalise, D., Kumar, L., Spalevic, V., & Skataric, G. (2019). Estimation of sediment yield and maximum outflow using the IntErO model in the Sarada river basin of Nepal. Water, 11(5), 952.
17. Chaithong, T. (2022). Flash flood susceptibility assessment based on morphometric aspects and hydrological approaches in the Pai River Basin, Mae Hong Son, Thailand. Water, 14(19), 3174.
18. Chandrashekar, H., Lokesh, K. V., Sameena, M., & Ranganna, G. (2015). GIS–based morphometric analysis of two reservoir catchments of Arkavati River, Ramanagaram District, Karnataka. Aquatic Procedia, 4, 1345-1353.
19. Chorley, R. J. (2019). The drainage basin as the fundamental geomorphic unit. In Introduction to physical hydrology (pp. 37-59). Routledge.
20. Faniran, A. (1968). The index of drainage intensity: a provisional new drainage factor. The Australian journal of science, 31(9), 326-330.
21. Farhan, Y., Anbar, A., Al-Shaikh, N., Almohammad, H., Alshawamreh, S., & Barghouthi, M. (2018). Prioritization of sub-watersheds in a large semi-arid drainage basin (Southern Jordan) using morphometric analysis, GIS, and multivariate statistics. Agricultural Sciences, 9(04), 437.
22. Farhan, Y., & Anaba, O. (2016). A remote sensing and GIS approach for prioritization of Wadi Shueib Mini-Watersheds (Central Jordan) based on morphometric and Soil erosion susceptibility analysis. Journal of Geographic Information System, 8(1), 1-19.

23. Ganie, P. A., Posti, R., Kunal, K., Kunal, G., Bharti, V. S., Sehgal, V. K., ... & Pandey, P. K. (2023). Modelling of the Himalayan Mountain river basin through hydro-morphological and compound factor-based approaches using geoinformatics tools. Modeling Earth Systems and Environment, 9,3053–3084.
24. Grigg, N. S. (2024). Framework and function of integrated water resources management in support of sustainable development. Sustainability, 16(13), 5441.
25. Khan, H. (2022). Soil Erosion Susceptibility and Soil Loss Estimation, Kunhar River Watershed, District Mansehra, Pakistan. Unpublished M.Phil thesis submitted to Department of Geography & Geomatics, University of Peshawar.
26. Haokip, P., Khan, M. A., Choudhari, P., Kulimushi, L. C., &Qaraev, I. (2022). Identification of erosion-prone areas using morphometric parameters, land use land cover and multi-criteria decision-making method: geo-informatics approach. Environment, Development and Sustainability, 24(1), 527-557.
27. Hembram, T. K., & Saha, S. (2020). Prioritization of sub-watersheds for soil erosion based on morphometric attributes using fuzzy AHP and compound factor in Jainti River basin, Jharkhand, Eastern India. Environment, Development and Sustainability, 22(2), 1241-1268.
28. Horton, R. E. (1932). Drainage-basin characteristics. Eos, transactions american geophysical union, 13(1), 350-361.
29. Horton, R. E. (1945). Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geological society of America bulletin, 56(3), 275-370.
30. Kacem, L., Igmoullan, B., Mokhtari, S., Amar, H., & Agoussine, M. B. (2014). Morphometric characterization of upstream mountainous watershed using geographic information system GIS: high valley of Tifnoute High Moroccan Atlas. Journal of Biodiversity and Environmental Sciences, 5(6), 62-66.
31. Miller, V. C. (1953). A quantitative geomorphic study of drainage basin characteristics in the Clinch Mountain area, Virginia and Tennessee (Vol. 3). New York: Columbia University.
32. Kolekar, S. S., Mishra, A., Choudhari, P., & Choudhari, N. R. (2021). Identification of specific areas for water conservation measures using Geoinformatics approach. Arabian Journal of Geosciences, 14, 1-13
33. Kulimushi, L. C., Choudhari, P., Maniragaba, A., Elbeltagi, A., Mugabowindekwe, M., Rwanyiziri, G., ...& Singh, S. K. (2021). Erosion risk assessment through prioritization of sub-watersheds in Nyabarongo River catchment, Rwanda. Environmental Challenges, 5, 100260.
34. Mahmood, R., Jia, S., & Babel, M. S. (2016). Potential impacts of climate change on water resources in the Kunhar River Basin, Pakistan. Water, 8(1), 23.
35. Mahmood, R., Babel, M. S., & Shaofeng, J. I. A. (2015). Assessment of temporal and spatial changes of future climate in the Jhelum river basin, Pakistan and India. Weather and Climate Extremes, 10, 40-55.
36. Malik, A., Kumar, A., Kushwaha, D. P., Kisi, O., Salih, S. Q., Al-Ansari, N., & Yaseen, Z. M. (2019). The implementation of a hybrid model for hilly sub-watershed prioritization using morphometric variables: Case study in India. Water, 11(6), 1138.
37. Meshram, S. G., Singh, V. P., Kahya, E., Alvandi, E., Meshram, C., & Sharma, S. K. (2020). The feasibility of multi-criteria decision making approach for prioritization of sensitive area at risk of water erosion. Water Resources Management, 34, 4665-4685.
38. Michael, D., Meena, R. S., Kumar, B., & Nobert, J. (2024). Identification of erosion-prone areas using morphometric, hypsometric, and compound factor approaches in the Ruvu River Basin, Tanzania. Modeling Earth Systems and Environment, 10(1), 1375-1394.
39. Mohammed, K. M. (2023). Assessment of Morphometric and Hypsometric Analysis of the Ruste Basin Using Remote Sensing and Geographical Information System Techniques. Kirkuk University Journal For Agricultural Sciences, 14(4), 1-19.
40. Mukherjee, J., & Patel, P. P. (2022). Landscape characterization using geomorphometric parameters for a small sub-humid river basin of the Chota Nagpur Plateau, Eastern India. Drainage Basin Dynamics: An Introduction to Morphology, Landscape and Modelling, 127-152.
41. Muthukrishnan et al., (2013). Drainage morphometry evaluation for Kodavanar sub basin to understand the interrelationships in morphological systems and in process-response systems. International Journal of Geomatics and Geosciences, 3(4), 692-707.
42. Nasir, M. J., Ahmad, W., Jun, C., Iqbal, J., & Bateni, S. M. (2023). Soil erosion susceptibility assessment of Swat River sub-watersheds using the morphometry-based compound factor approach and GIS. Environmental Earth Sciences, 82(12), 315.
43. Nitheshnirmal, S., Thilagaraj, P., Rahaman, S. A., & Jegankumar, R. (2019). Erosion risk assessment through morphometric indices for prioritisation of Arjuna watershed using ALOS-PALSAR DEM. Modeling Earth Systems and Environment, 5, 907-924.

44. Panagos, P., Standardi, G., Borrelli, P., Lugato, E., Montanarella, L., &Bosello, F. (2018). Cost of agricultural productivity loss due to soil erosion in the European Union: From direct cost evaluation approaches to the use of macroeconomic models. Land Degradation & Development, 29(3), 471-484.
45. Pande, C., Moharir, K., & Pande, R. (2021). Assessment of morphometric and hypsometric study for watershed development using spatial technology–a case study of Wardha river basin in Maharashtra, India. International Journal of River Basin Management, 19(1), 43-53.
46. Pareta, K., & Pareta, U. (2011). Quantitative morphometric analysis of a watershed of Yamuna basin, India using ASTER (DEM) data and GIS. International journal of Geomatics and Geosciences, 2(1), 248-269.
47. Prakash, K., Rawat, D., Singh, S., Chaubey, K., Kanhaiya, S., & Mohanty, T. (2019). Morphometric analysis using SRTM and GIS in synergy with depiction: a case study of the Karmanasa River basin, North central India. Applied Water Science, 9(1), 13-23.
48. Pham, T. G., Degener, J., &Kappas, M. (2018). Integrated universal soil loss equation (USLE)and Geographical Information System (GIS) for soil erosion estimation in A Sap basin: Central Vietnam. International Soil and Water Conservation Research, 6(2), 99-110.
49. Quinton, J. N., & Fiener, P. (2024). Soil erosion on arable land: An unresolved global environmental threat. Progress in Physical Geography, 48(1), 3–30.
50. Rahmati, O., Falah, F., Naghibi, S. A., Biggs, T., Soltani, M., Deo, R. C., ... & Bui, D. T. (2019). Land subsidence modelling using tree-based machine learning algorithms. Science of the total environment, 672, 239-252.
51. Ramadan, A.A.,Elmahdy,S.I.,&Ahmed,M.S.(2022).Morphometric analysis of drainage basins using GIS techniques for hydrological assessment. Arabian Journal of Geosciences, 15, 1–18.
52. Rai, P. K., Mishra, V. N., & Mohan, K. (2017). A study of morphometric evaluation of the Son basin, India using geospatial approach. Remote Sensing Applications: Society and Environment, 7, 9-20.
53. Rai, P. K., Chandel, R. S., Mishra, V. N., & Singh, P. (2018). Hydrological inferences through morphometric analysis of lower Kosi river basin of India for water resource management based on remote sensing data. Applied water science, 8, 1-16.
54. Rai, P. K., Singh, P., Mishra, V. N., Singh, A., Sajan, B., & Shahi, A. P. (2019). Geospatial approach for quantitative drainage morphometric analysis of varuna river basin, India. Journal of Landscape Ecology, 12(2), 1-25.
55. Roy, S., & Chintalacheruvu, M. R. (2024). Google Earth Engine-based morphometric parameter evaluation and comparative analysis of soil erosion susceptibility using statistical and machine learning algorithms in large river basins. Earth Science Informatics, 17(1), 75-97.
56. Romshoo, S. A., Bhat, S. A., & Rashid, I. (2012). Geoinformatics for assessing the morphometric control on hydrological response at watershed scale in the Upper Indus Basin. Journal of Earth System Science, 121, 659-686.
57. Sabir, M. A., Shafiq-Ur-Rehman, S., Umar, M., Waseem, A., Farooq, M., & Khan, A. R. (2013). The impact of suspended sediment load on reservoir siltation and energy production: a case study of the Indus River and its tributaries. Pol. J. Environ. Stud, 22(1), 219-225.
58. Schumm, S. A. (1956). Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geological society of America bulletin, 67(5), 597-646.
59. Singh, A. P., Arya, A. K., & Singh, D. S. (2020). Morphometric analysis of Ghaghara River Basin, India, using SRTM data and GIS. Journal of the Geological Society of India, 95, 169-178.
60. Singh, O., & Singh, J. (2018). Soil erosion susceptibility assessment of the lower Himachal Himalayan Watershed. Journal of the Geological Society of India, 92, 157-165
61. Singh, D., Karan, K., Singh, S. K., Chauhan, P., & Berndtsson, R. (2023). Fusing morphometric characteristics with extreme precipitation indices for identifying the most vulnerable sub-basin at risk of flooding. Journal of Hydro-environment Research, 50, 44-56.
62. Smith, K. G. (1950). Standards for grading texture of erosional topography. American journal of Science, 248(9), 655-668.
63. Smith, D. D., & Wischmeier, W. H. (1957). Factors affecting sheet and rill erosion. Eos, Transactions American Geophysical Union, 38(6), 889-896.
64. Strahler, A. N. (1956). Quantitative slope analysis. Geological Society of America Bulletin, 67(5), 571-596.
65. Strahler, A. N. (1964). Part II. Quantitative geomorphology of drainage basins and channel networks. Handbook of Applied Hydrology: McGraw-Hill, New York, 4-39.
66. Todorovski, L., & Džeroski, S. (2006). Integrating knowledge-driven and data-driven approaches to modeling. ecological modelling, 194(1-3), 3-13.

67. van Beek, R., Cammeraat, E., Andreu, V., Mickovski, S. B., & Dorren, L. (2008). Hillslope processes: Mass wasting, slope stability and erosion. Slope stability and erosion control: Ecotechnological solutions, 17-64.
68. Wang, J., Wei, H., Cheng, K., Ochir, A., Davaasuren, D., Li, P &Nasanbat, E. (2020).Spatio-temporal pattern of land degradation from 1990 to 2015 in Mongolia. Environmental Development, 34, 100497.
69. Wilson, J. J., Chandrasekar, N., & Magesh, N. S. (2012). Morphometric analysis of major sub-watersheds in Aiyar & Karai Pottanar Basin, Central Tamil Nadu, India using remote sensing & GIS techniques. Bonfring International Journal of Industrial Engineering and Management Science, 2(1), 8-15.
70. Xu, Q., Chen, W., Zhao, K., Zhou, X., Du, P., Guo, C., ... & Pu, C. (2021). Effects of land-use management on soil erosion: A case study in a typical watershed of the hilly and gully region on the Loess Plateau of China. Catena, 206, 105551.
71. Akhtar, Z,, Nasir, M. J., Ali, Z., Zahid, S.M.H., Iqbal, S., & Khan, Z. (2024). Sediment Yield Estimation Using GIS-Based Sediment Production Rate (SPR) Approach: A Study of Kunhar River Basin, Pakistan. Migration Letters, 21(S11) 111-134
72. Zhang, Q., Wang, Z., Wang, X., Luo, H., & Zhang, J. (2024). Relationship among runoff, soil erosion, and rill morphology on slopes of overburdened stockpiles under simulated rainfall. Journal of Hydrology, 633, 130991.
73. Zhao, Q., Li, D., Zhuo, M., Guo, T., Liao, Y., & Xie, Z. (2015). Effects of rainfall intensity and slope gradient on erosion characteristics of the red soil slope. Stochastic environmental research and risk assessment, 29, 609-621.