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Morphometric Analysis of Panjhara River Basin With Use of GIS for Development of Watershed Plan

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Abstract

Objectives: Geomorphological changes that occur within a watershed have an influence on the availability and scarcity of water. As a consequence, a quantitative analysis of the watershed geometry is necessary to ascertain the impact of geomorphological processes on the catchment's hydrology. **Methods:** Remote sensing (RS) and geographic information systems (GIS)-based strategies have gained in popularity recently because they help strategists and decision-makers make precise and effective decisions. The Panjhara River basin, tributary of Tapi River was selected for this study. The research demonstrates that, for improved planning and maintenance, GIS and RS data may be utilized to analyze and approximatively measure the duration and pace of erosional activities in a Panjhara River basin. The technique uses a 30-meter shuttle radar topography mission digital elevation model (SRTM-DEM) and Survey of India toposheet for efficient and quick extraction of morphometric data and hypsometric analysis**. Findings:** The linear, areal, and relief aspects of the Panjhara River catchment were subjected to the twenty-six morphometric criteria. The Re, Rc, and Ff all imply an elongated basin form. According to statistical study, there is a strong correlation between stream order and stream number as well as between stream order and stream length. The shape of the hypsometric curves and the findings of the computed hypsometric integrals represent the erosive phases of the Panjhara River basin. **Novelty:** The research finds that stakeholders involved in watershed development and management initiatives may find the results of morphometric and hypsometric analyses valuable.

Keywords: Morphometric Analysis; Hypsometric Analysis; Stream; GIS

1 Introduction

A river basin is a key geomorphic and hydrological unit that develops as a result of the complex interplay of the earth's surface topography, climate, and hydrological processes. It is a strategic geographic unit that can be micro basin (Few Hectares) to macro basin (Millions of Hectors)[1–3] and its network depicts the entire three-dimensional geometry and evolutionary processes[4,5]. The study of measuring and analyzing the size, shape, and configuration of the Earth's surface characteristics is known as morphometric analysis. It's a quantitative tool for estimating the many aspects of the drainage system, including the number and length of the streams, the drainage density, the ratio of bifurcations, the slope, the form, and the relief of the basin[6–8]. It offers important information on the geology and hydrology of the basin as well. Morphological factors are critical in mitigating a drainage basin's hydrological issue, environmental change, drainage characteristics, flood risk and unsustainable water consumption[9–11].

Traditional sources for the morphometric analysis include topographic maps and field surveys which were popular methods for drainage evaluation and Numerous scholars have looked at various catchment aspects using traditional methods[12–17]. Nowadays Rapidly developing spatial information technology, RS, and GIS provide excellent and widely tools for addressing the bulk of issues with water resource planning and management, compared to conventional data processing techniques. Assessing drainage morphometry benefits greatly from the synoptic image over a large region that satellite remote sensing can provide. Watershed analyses which rely on the shuttle radar topography mission (SRTM) digital elevation model (DEM) have seen a surge in popularity, accuracy, efficiency, and cost-effectiveness. Water shortage and surplus may be affected by geomorphological changes within a watershed. To thereby determine the effect of geomorphological processes on the hydrology of the catchment, a quantitative examination of the watershed geometry is essential[18–20].

Watersheds are dynamic units that exhibit temporal and spatial alterations, such as runoff characteristics that transform basin input and output, which can be seen in the form of variation in discharge, sediment load, and other watershed characteristics[18]. To understand the characteristics of the watershed a systematic investigation is required, includes analysis of linear, aerial and relief aspect of the watershed. Stream length, number of streams, bifurcation ratio, mean stream length ratio, frequency of streams, stream length ratio, stream density, drainage texture, drainage intensity, length of overland flow, and Rho coefficient are all linear variables. Watershed relief, relief ratio, relief relative, ruggedness number, maximum elevation, and minimum elevation are all forms of relief variables. Circulatory ratio, basin area, length, perimeter, form factor, elongation ratio, lemniscate ratio, and compactness coefficient are aerial variables. Most of the geomorphic characteristics about a catchment can be obtained in the hypsometric curve, which also represents the entire basin slope and shows what percentage of the basin is above a certain elevation. By limiting erosion via rock characteristics, hypsometric curves aid in the study of basin erosional phases and give crucial details on basin slope and geomorphology, which are important for catchment treatment, basin planning, and the location of infrastructure for collecting rainwater[21–23] .

Morphometric analysis of the basin plays crucial role in planning and development of the watershed as well as for achieving sustainable land and water resource use and provides platform for planners and policymakers to build management plans for catchment area. The goal of the present study is to determine morphometric parameters for the Panjhara River basin in India, including linear, relief, and areal aspects. The study also seeks to determine the hypsometric analysis of the basin.

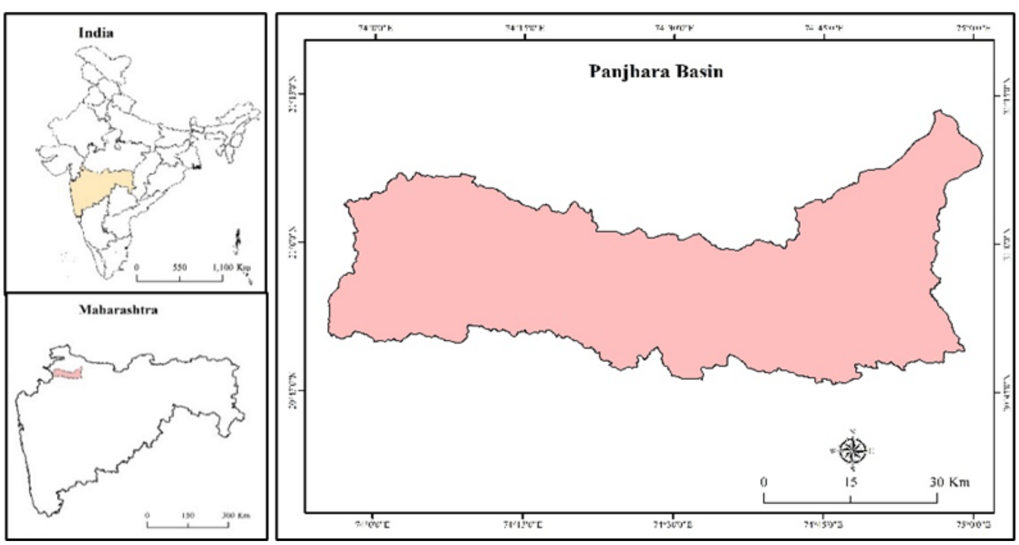

Fig 1. Location of the Study Area

The Panjhara basin defined by coordinate, 20°49'22.78" North to 21°11'23.86" North latitude and 73°43'43.46" East to 74°58'41.89" East longitude as shown in Figure 1 . It occupies total area of 2994.95 sq.km. The average elevation of the basin is 385 meters with maximum of 1221 meters and minimum of 125 meters. The basin is part of upper Tapi River basin, a west flowing river of Peninsular region. The slope of the basin ranges from 0° to 72.41°. The basin bounded by Salbari-Dolbari range on south serving water divide between Girna basin and Panjhara basin, while on north it is bounded by Burai Basin. The basin is part of Deccan plateau and from complex geomorphological characteristics.

2 Methodology

Quantitative morphometric characteristics have been employed in the present study to examine the watershed using RS and GIS methodologies. The Panjhara River basin has been defined using the SRTM-DEM (30 meter) and Survey of India toposheet (1:50000). The processing of the DEM and SOI toposheet was done using ArcGIS 10.8 software, and the watershed is classified based on morphometric analysis. The analysis of morphometric properties has led to the classification of these traits into three aspects: linear, relief, and areal. There is a plethora of empirical techniques for assessing these three aspects.RS and GIS techniques are used to analyses the hypsometric analysis for the Panjhara river basin region. The line feature class in ArcGIS 10.8 was used to produce the contours, which were then subjected to the hydrology tool's processing. The attribute tables of the geo-referenced feature classes that represented the contours and their enclosed area with the catchment boundary were used to record the contours' height and length as well as their area and perimeter values. The hypsometric curve for the catchment was plotted out by using these numbers, with the help of attribute feature classes. In this study, the HI was determined using the elevation-relief-ratio technique.

Table 1. Formulae for morphometric parameters

Aspect	Parameter	Formulae	
Linear	Stream Order (U)	Hierarchical Rank	Strahler (1964)
	Stream Number (N_u)	N_u=N_{u1}+N_{u2}+N_{u3}+……N_{un}	Horton (1945)
	Stream Length (L_u)	L_u=L_{u1} + L_{u2}+L_{u3}……+L_{un}	Horton (1945)
	Stream length Ratio (R_L)	R_L =L_u/L_{u-1}	Horton (1945)
	Bifurcation ratio (R_b)	R_b=N_u/N_{u+1}	Schumm (1956)
	Mean Bifurcation Ratio (Rbm)	R_{bm}=R_{b1}+R_{b2}+R_{b3}….R_{bn}/n	Schumm (1956)
	Rho coefficient	Rho Coefficient= R_L/R_b	Horton (1945)
Areal	Stream Frequency (Fs)	Fs= $(\sum Nu)/A$	Horton (1945)
	Drainage Density (Dd)	D_d = $(\sum Lu)/A$	Horton (1945)
	Drainage Texture (Dt)	Dt = $\sum Nu)/P$	Horton (1945)
	Texture Ratio (T)	T=$\sum Nu1)/D$	Horton (1945)
	Drainage Intensity (Di)	Di = Fs/Dd	Schumm (1956)
	Infiltration number (If)	If = Fs*Dd	Schumm (1956)
	Length of overland flow (Lo)	Lo = (1/(2Dd))	Horton, 1945
	Constant of Channel Maintenance (Ccm)	Ccm = 1/Dd	Schumm (1956)
	Form Factor	Ff = A/L_b^2	
	Circulatory Ratio (Rc)	Rc =4πA/P^2	Strahler (1964)
	Elongation Ratio (Re)	Re=$(2(A/\pi)^{0.5})/L_b$	Schumm (1956)
	Sinuosity Index (SI)	SI=AL/EL Where, AL= Actual length of stream, EL= Expectedstraight path of the stream	Schumm (1956)
Relief	Basin Relief (Bh)	Bh =H-h	Schumm (1956)
	Relative Relief		Melton (1957)
	Relief Ratio (Rh)	Rh =Bh/Lb	Schumm (1956)
	Maximum Elevation (H)	GIS Analysis	Schumm (1956)
	Minimum Elevation (h)	GIS Analysis	Schumm (1956)
	Ruggedness Number (Rn)	Rn = Bh*Dd	Miller (1953)
	HI (Hypsometric Integration)	Emean – Emin / Emax –Emin	Pike and Wilson (1971)

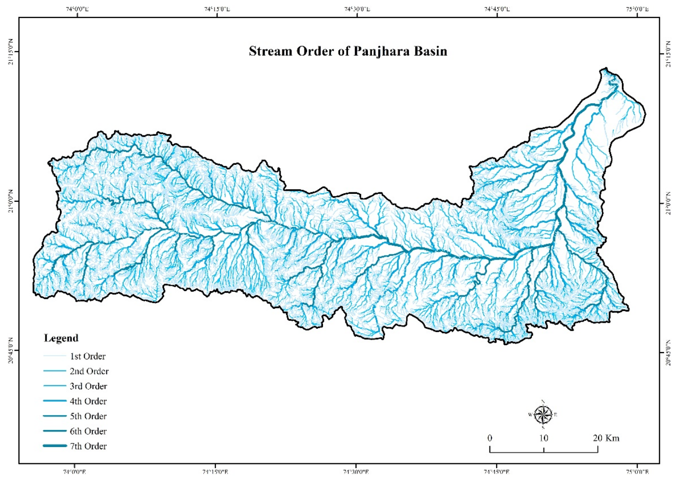

Fig 2. Stream order of Panjhara basin

Table 2. Stream details for Panjhara river basin

Stream Order	Stream Number ($N\mu$)	Stream Length ($L\mu$)	Mean Stream Length	Bifurcation Ratio (RL)	Stream Length Ratio (R_L)
1	7331	4495.8	0.61	-	
2	1807	1699.5	0.94	4.06	0.38
3	446	931.3	2.94	4.05	0.55
4	117	472.7	4.04	3.81	0.51
5	23	216.0	9.39	5.09	0.46
6	3	75.8	25.26	7.7	0.35
7	1	102.3	102.30	3	1.3
	$\sum N\mu$ 9728	**$\sum L\mu$ 7993.3**	**0.82**	**∑Rbm 4.61**	**∑Rlm 0.6**

Table 3. Results of morphometric analysis

Sr.No.	Parameters	Results
1	Perimeter (P)	400.20 m
2	Basin Length	107.25m
3	Stream Order	7
4	Drainage Density (Dd)	2.67
5	Stream Frequency (Fs)	3.25
6	Drainage Texture (Rt)	24.31
7	Drainage Intensity (Di)	1.22
8	Texture Ratio (T)	8.21
9	Constant Channel Maintenance	0.37
10	Form Factor (Rf)	0.26
11	Circulatory Ratio (Rc)	0.23
12	Elongation Ratio (Re)	0.58
13	Length of overland Flow	0.19
14	Basin Relief	160
15	Relief Ratio	0.0015
16	Relative Relief	1096 m
17	Ruggedness Number	2.93
18	Rho Coefficient	0.13
19	Infiltration Number	8.67‘
20	Sinuosity index	1.35

3 Result and Discussion

The geomorphological characteristics, geological circumstances, and behavior of river basins over different hydrological cycles are all better understood when combined with the quantitative description of the geometrical conditions provided by the morphometric properties of the Panjhara catchment. The results of various parameters discussed as follows.

3.1 Linear aspects

3.1.1 Stream order (U)

Strahler's Stream ordering scheme, which is a slightly modified version of Horton's scheme with the least unbranched fingertip streams chosen as the first order, the confluence of two first sequence streams forming second order streams, the joining of two second order streams to create a third order stream, and other features have led to its acceptance [24,25]. The stream order of the Panjhara basin is shown in the Figure 2, which points that the seventh order is the highest order in the present study.

3.1.2 Stream length (Lu)

The length of the stream was determined by applying the suggested legislation by Horton. The length of a stream is one of the most important hydrologic characteristics of a watershed since it reveals runoff characteristics [3]. Streams having a shorter length may be found in areas with greater slopes and less pronounced textures. Longer streams have a more gradual gradient because of their greater length. In most cases, the distance between individual stretches of a stream is greatest in the first streams and shrinks in subsequent streams as the orders of the stream increase [23]. Distances from the catchment's outlets to their respective drainage splits are recorded and logged using a GIS program. Total length of all orders in the Panjhara basin is 7993.3 km, in which the total length of first order is 4495.8 km, 1699.5 km for second order, 931.3 km for third order, 472.7 km for fourth order, 216.0 km for fifth order, 75.8 km for sixth order and 102.3 km for seventh order.

3.1.3 Stream number (Nu)

In this context, "Stream number" indicates the total number of stream subsections included in each sequence. Horton claims that the number of stream segments in an order generates a geometric series in reverse proportion to the order [18]. The trunk stream is the most important part of a stream. The Panjhara river system is 7^{th} order system with total of 9728 stream segments. Out of which 7331 are first order streams, 1807 are second order streams, 446 are third order stream, 117 are fourth order stream, 23 are fifth order streams, 3 are sixth order streams and a seventh order stream.

3.1.4 Mean stream length

The average length of a stream is a defining feature of the watershed and the surfaces to which it drains [16]. Calculating the average stream length required dividing the average stream length for a certain stream order by the total number of stream segments. The average stream length of the Panjhara basin is 0.82.

3.1.5 Bifurcation ratio (Rb)

The extent to which a drainage system branches is measured by the bifurcation ratio. It is the proportion of a drainage basin's first-order stream segments to its second-order stream segments [17]. Except in areas where geology is predominated, Strahler, found that the bifurcation ratio varies only slightly across locations and environments. It has been seen that does not have a constant value as one goes up in sequence. The mean bifurcation ratio of the Panjhara basin is 4.61. The bifurcation ratio ranging between 3 and 5 indicate the natural drainage system within a homogenous rock. A high bifurcation ratio indicates a strong structural control over the drainage pattern and well-dissected drainage basins, whereas a low bifurcation ratio characterizes a watershed with a flat or gently undulating topography. The higher bifurcation ratio leads to less chances of risk of flooding.

3.1.6 Stream length ratio (R_L)

The ratio of the average stream length of one order to that of the next lower order is a key factor in surface flow and runoff, as stated by Horton [18]. The symbol for this is Rl. The average stream length ratio for the Panjhara basin is 0.6.

3.1.7 Stream frequency (Fs)

The stream frequency (Fs) of a basin is the number of stream segments in the basin expressed as a fraction of the basin's total area. There is a positive association between stream frequency and drainage density within the watershed, suggesting that there will be more streams as the drainage density increases. Many factors, including climate, plant cover, rock and soil type, rainfall amount, infiltration capacity, relief, run-off intensity, permeability of topography, and slope, have all been crucial in determining drainage frequency and density. Basin Fs is calculated to be 3.25. When there is a lot of drainage and streams in a basin, the runoff is rapid, increasing the likelihood of floods[21]

3.1.8 Drainage density (Dd)

It is the ratio of the total length of all orders of stream segments to the total area of the catchment, as stated by Schumm. If you want to know how closely spaced channels are, you may use the drainage density, which gives you a quantitative assessment of the mean distance of a stream path throughout the whole catchment[23]. Dimensions of catchment density collected throughout a wide range of geology and environmental types suggest that areas that mostly oppose very porous sub-surface material beneath dense vegetative regions and when relief is least are likely to have minimal catchment density. Maximum catchment density is a result of a combination of factors, including impermeable underlying material, sparse vegetation, and steep terrain. The catchment texture becomes coarser at lower densities and finer at higher ones. Dd is the notation for this value. The Dd for this basin is 3.25.

3.1.9 Rho Coefficient (ρ)

As the ratio of stream length to bifurcation, it is a key measure in assessing a basin's potential for water storage by measuring the relationship between drainage density and physiographic development[21]. Watersheds with higher values have a greater ability to store water, whereas those with lower values have a smaller reservoir. Changing environmental, geological, geomorphological, biological, and anthropogenic influences all have significant effects on this parameter. The rho coefficient value for the Panjhara basin is 0.13.

3.1.10 Drainage texture (Dt)

According to Horton, it is the total number of segments across all orders divided by the total perimeter of the stream. It's represented by the letter Rt. In this basin, Rt equals 24.31.

3.1.11 Texture ratio (T)

Texture ratio is an important factor in the drainage morphometric analysis which is depending on the underlying lithology, infiltration capacity, and relief aspect of theterrain[19]. The texture ratio is expressed as the ratio between the first-order streams and the perimeter of the basin. The texture ratio in the study area is 8.21km-1.

3.1.12 Form Factor (Rf)

The form factor denoted by the symbol "Rf," is the dimensionless ratio of the basin area to the square of the basin length[14]. A basin's flow strength is indicated by this parameter. In the case of a circular watershed, the form factor would always be smaller than 0.754. The basin will be more elongated if the form factor has a lower value, and it will be more circular if the form factor has a larger value. Larger peak flows of shorter duration are typical of basins with high form factors, whereas flatter peak flows typical of extended watersheds with low form factors are seen. The study region has a Rf value of 0.26, which is more consistent with elongated basin shape than circular one.

3.1.13 Elongation ratio (Re)

The elongation ratio (Re) is the maximum length of a drainage basin divided by the diameter of the outermost circle inside that basin[17]. Values for ratio ranges from around 0.6 to about 1.0 over a broad range of climate and geologic conditions. Circular (0.9–0.10), oval (0.8–0.9), less elongated (0.7–0.8), elongated (0.5–0.7), and more elongated (0.5) describe the range of values for the index of elongation ratio. Runoff is discharged more efficiently from a circular basin than from an elongated one. Values around 1.0 indicate very low relief in the form of a perfect circle, whereas values between 0.6 and 0.8 indicate somewhat moderate relief[2]. With a Re of 0.58, the research area is narrower, has steeper slopes, and a higher relief than average indicates elongated basin.

3.1.14 Circulatory ratio (Rc)

It is the ratio between the area of the basin and the area of the circle where diameter is the same as the perimeter of the basin that is defined as the Circulatory Ratio[19]. When the basin is circular in form, the ratio equals 1, but when it is severely elongated and filled with homogenous geologic materials, the ratio is in the range of 0.4 and 0.5. The slope, relief, geologic structure, temperature, and land use/cover of the basin all have an effect on Rc. The Rc value of 0.23 for the basin demonstrates its elongated form, modest runoff flow, and excellent permeability of the subsoil. Unlike other quantities, Rc has no units of measurement. Values in the low, middle, and high ranges represent the adolescent, adult, and senile phases of the tributary basins' life cycles, respectively[21].

3.1.15 Length of overland flow (Lg)

The hydrologic and physiographic evolution of a drainage basin is affected by the length of overland flow (Lg), which is the distance water travels before it becomes concentrated into mainstream. Infiltration (exfiltration) and percolation through the soil, which change over time and place, have a major impact on Lg[16]. The longer distance that rainfall had to flow before it was condensed into streams is indicated by a larger Lg number[22]. The shorter runoff distances in this research are supported by the shorter value of the overland flow length, which is 0.19 km.

3.1.16 Constant of Channel Maintenance (Ccm)

The inverse drainage density in length, as defined by Schumm (1956) [17], has been utilized as a characteristic called constant of channel maintenance. This length-based constant (expressed as square feet per foot) becomes larger as the size of the land-form unit gets bigger. The cost of the basin's 0.37 channel upkeep is minimal. This equates to an average of 0.37 square feet of basin area required to cut a 1.0-foot-long channel for the stream.

3.1.17 Infiltration number (If)

The infiltration number is a watershed's infiltration potential as calculated by multiplying the drainage density by the stream frequency[19]. Higher infiltration and less runoff are indicated by lower infiltration numbers. The infiltration number of the Panjhara basin is 8.67, which implies low infiltration number.

3.1.18 Relative relief

Relative relief is a ratio between the watershed's relief and its perimeter[19]. The benefit it offers over the relief ratio is that it does not rely on the basin length, which may be a problematic quantity for watersheds with non-standard shapes. The relative relief of the basin is 2.74.

3.1.19 Relief ratio (Rh)

The relief ratio is the quotient of the elevation difference between a basin's lowest and highest points (the total relief) and the basin's longest dimension parallel to its primary drainage line[17]. In other words, it is a ratio that can't be expressed in any one unit of measurement. A high Rh value is an indication of a steep slope and a high relief, while a low Rh value is the opposite. Steeper basins have quicker runoff, resulting in higher peak basin flows and more erosive force[23]. Since the Rh value in the basin is 0.0015, it has both a high relief and a steep slope[25]. Google Earth and a 1:50,000 scale topographical map is used for visual interpretation and calculation.

3.1.20 Hypsometric analysis

The river system and catchment shape have a significant influence on hypsometry. For instance, the width to length ratio of the catchment, also known as the "aspect ratio," has a significant impact on the shape of the hypsometric curve. Representation of hypsometric curves based on heights and relative surface area. A convex ascending hypsometric curve indicates a juvenile basin, a mature basin has S-shaped hypsometric curve, and old or eroded basin has concave hypsometric curve. The hypsometric curves for the Panjhara River basin are shown inFigure 3, which found to have a mix of convex and concave and S shapes, which could be attributed to soil erosion caused by washout of the soil mass, and stream cutting. The Hypsometric Integral value of the basin is 0.34 indicating mature stage of landform development.

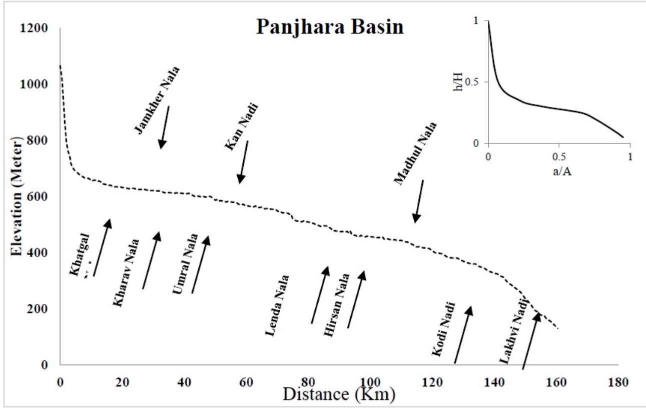

Fig 3. Hypsometric analysis of Panjhara basin

3.1.21 Sinuosity index (SI)

A channel's sinuosity index (SI) is a measure of its degree of tortuousness that also reveals the effect of topography on sinuosity and the effect of hydraulics on relatively unstable and readily trans locatable sediment deposits inside the channel. The average sinuosity index for the Panjhara basin is 1.35.

4 Conclusion

GIS and Remote Sensing techniques were used to conduct the morphometric study of the Panjhara basin. In this study, twenty-six morphometric parameters were computed and scientifically analyzed. Topography, slope, lithology, surface runoff, infiltration capacity, and hydrological characteristics are all comprehended with the morphometric parameter. The Panjhara basin exhibited complex physiographic and geological characteristics, contributed by presence of the Sahyadri ranges, mafic dyke's swarms and Tapi fault. The Panjhara river is part of west flowing river system flow in dendritic drainage pattern in an elongated basin, the morphometric and hypsometric studies point mature stage of landform development with low relief, low structural control, sparse vegetation and low infiltration rate. Implementation of necessary steps to preserve water and soil resources for the long-term development of the watershed will be facilitated by this study.

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