



Morphometric analysis of a drainage basin: A study of some part of Painganga river sub-basin, district Chandrapur, Maharashtra

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Abstract

Present study aims to understand the morphometric characteristics of Painganga River sub basin using remote sensing and geographic information system (GIS). The drainage pattern of the study area is dendritic to sub dendritic with stream orders ranging from I to V orders. Drainage density ranges from 1.42 km/km² to 1.57 km/km² suggesting low drainage density. The change in stream length ratio from one order to another order indicates their late youthful stage of geomorphic development. SW-3 and SW-5 shows high bifurcation and mean bifurcation ratio suggesting strong geological and lithological controls on the basin. The values of form factor and circulatory ratio, suggest that all the five sub watersheds are elongated in shape. Elongation ratio of all the five sub watersheds ranges from 0.58 to 0.79 which indicates all the five sub watersheds are elongated and the basin is usually associated with high relief and steep ground slope.

Keywords: Painganga river, morphometry, remote sensing and GIS

Introduction

According to (Clarke 1966) ^[10], Drainage morphometry is defined as a measurement of linear, areal and relief characteristics of any drainage basin. (Horton, 1945) ^[15] introduced the quantitative analysis of drainage basins. The drainage of the watershed framed by the main stream and their tributaries is influence by geological setting and the lithological control of the area (Lone A, 2017) ^[20]. Morphometric parameters is used to prepare drainage map, ordering of the various streams, measurement of catchment area, length, perimeter of drainage channels, drainage density, drainage frequency, bifurcation ratio, texture ratio and circulatory ratio (Kumar *et al.*, 2000; Reddy *et al.*, 2002, Reddy *et. al.*, 2003 Manjare, 2017) ^[42, 42, 39, 25]. The basin geomorphic characteristics have long been believed to be important indices of surface processes (Engelhardt *et al.* 2012; Forzieri *et al.* 2008) ^[12, 13]. Human induced alteration of the natural landscape since long time by means of urbanization, agriculture and natural vegetation has resulted in removal and replacement of natural vegetation and land cover with numerous human-induced practices of altered structure. As a result of which there is visible difference between old and new land-use & land-cover patterns which are composed of both the natural and human-induced environments (Shrivatra *et al.*, 2021a; Reddy *et. al.*, 2004; Manjare, *et al.*, 2018) ^[45, 40, 26]. The relationship between drainage morphometric parameters to its underlain geology, geomorphology and hydrological characteristics is established through the work of different geologist and geomorphologist (Strahler 1952; Chorley *et al.*, 1985) ^[49, 9]. The different morphometric characteristics like linear parameters, areal or basin parameters and relief parameters are important for any river basin management and the variations in linear, areal, relief parameters within drainage were examined by computing and assessing morphometric parameters which outline the topographical, geological and hydrological states of watershed (Angillieri, 2012; Kabite and Gessesse, 2018; Manjare *et al.*, 2014a; Reddy, *et al.*

2018; Manjare, *et al.* 2020; Shrivatra *et al.* 2021b) ^[2, 17, 23, 41, 27, 46] by analysing CARTOSAT DEM and topographical maps. The geomorphological stages of evolution with its erosional characteristics can also be best understood through the different drainage morphometric parameters (Strahler 1952) ^[49].

Remotely sensed high spatial resolution data together with topographical data based analysis procedures, have come out as highly effective tool to understand and manage the natural resources. It provides the near real time and accurate information related to distinct geological formation, landforms and helps in identification of drainage channels, which are altered by natural forces and human activities. GIS is an effective tool to analyze spatial and non-spatial data on drainage, geology, landforms parameters to understand their interrelationship (Manjare *et al.*, 2014b) ^[24]. Many authors found remote sensing and GIS as an efficient tool to understand the morphometric behaviour of any plain topographical area, groundwater delineation (Sreedevi *et al.*, 2005; Ansari *et al.*, 2012; Bali *et al.*, 2011; Pareta and Pareta, 2012; Parveen *et al.*, 2012; Reddy, 2018; Manjare *et al.* 2020) ^[3,4, 4, 35, 14, 27].

Morphometric analysis of streams is an important aspect for characterization of watershed. Proper planning and management of watershed is very necessary for sustainable development (Chandniha and Kansal, 2017; A. Bera *et al.*, 2018; Reddy, *et al.*, 2018 Manjare *et al.*, 2018) ^[8, 5, 41, 26]. GIS technique are effectively used in recent times in determining quantitative description of basin geometry i.e., morphometric analysis. GIS provides an excellent means of storing, retrieving, manipulating and analysing geo-referenced drainage information (Reddy *et al.*, 2002; Manjare *et al.* 2020) ^[38, 27].

Study Area

The study area falls in Chandrapur district of Maharashtra which is located in Survey of India 1:50,000 scale toposheet no. 56 M/1, 56 M/2, 56 I/13 and 56 I/14 bounded by latitude

and longitude 19°48'56"N and 79°03'43"E, 19°48'21"N and 79°02'E and 19°44'43"N and 78°52'59"E is in the Korpana taluka in Chandrapur district, Maharashtra. The Painganga River originates from Ajantha ranges in Aurangabad district

in Maharashtra. The river enters in Korpana taluka at Kodsi village and it converging into Wardha River near a small village called Wadha in Chandrapur taluka of Chandrapur district and forms the small sub watershed (Fig. 1).

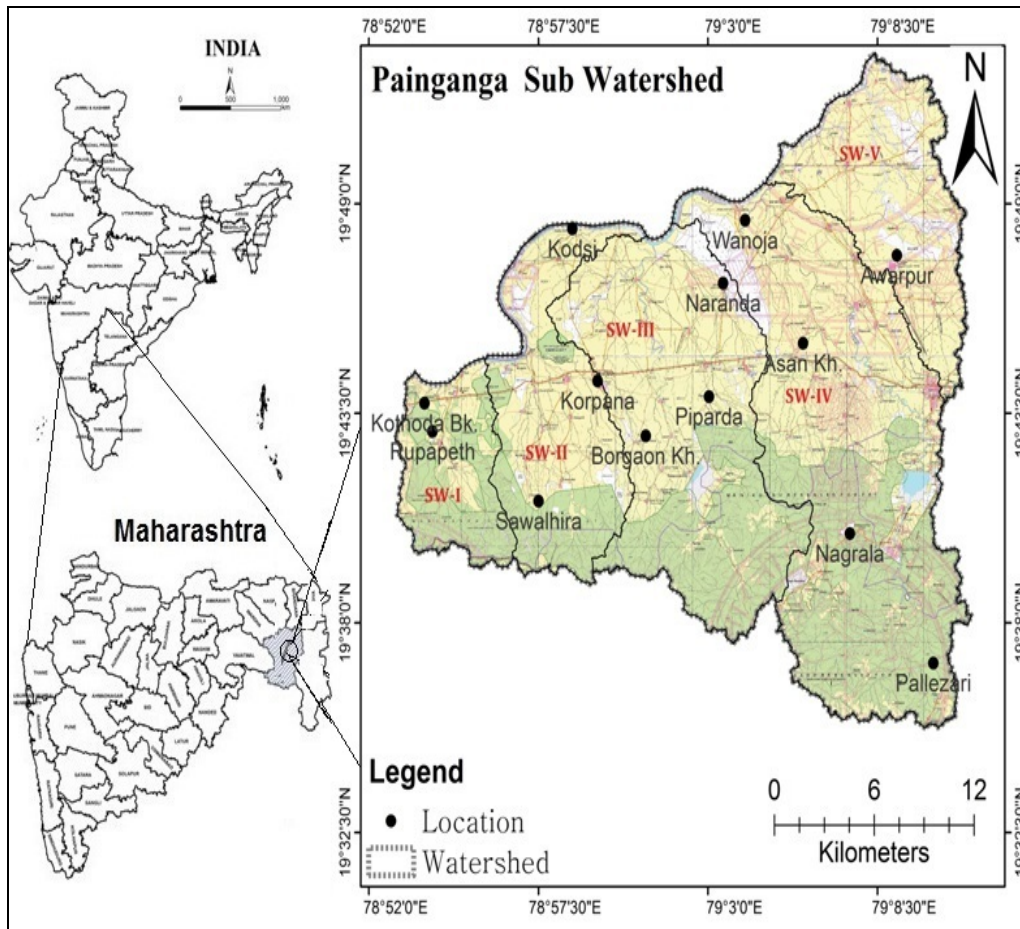


Fig 1: Topomosaic and location map of the study area

General Geology

The Vindhyan sediments, Lower Gondwana sediments, Deccan Traps, Alluvium and soil mainly constitute the geology of the area. The Geological map is been prepared from satellite data and DRM followed by field checks (Fig. 2). Geologically, the study area is underlain by Limestones of Penganga Group along the western extremity of the study area with dissected out crops along central, northern and eastern parts of watershed. Limestone-Shale sequence of Penganga Group is noticed in the remaining parts of watershed unconformably followed by Deccan basalts (A.P. Dharshivkar *et al.*, 2014).

Geology of the Study Area

Laterite

Laterite is rich in iron and aluminium oxides, formed by weathering. Laterites are commonly seen as over Deccan Traps. It is generally Reddish brown in colour and hard, thickness varies from a few cm. to 8 m. Laterite in the study area are seen in small patches towards southern part (Fig. 2).

Basaltic lava flow

The igneous activity during upper cretaceous period released tremendous outburst of volcanic energy resulting in the eruption of thick series of lava and associated pyroclastic materials. The basalt rock is solidified lava flow

of upper Cretaceous to Eocene period. The Penganga group of rocks are overlain by the Deccan trap basaltic lava flows of Sahyadri Group with some patches of laterite (Upper Cretaceous to Paleogene age), which cover Nagrala and southern part of the study area. The Basaltic rock in the study area shows porphyritic to sub porphyritic in texture, compact and weathered (Fig. 2).

Sandstone/ shale

Sandstone is a sedimentary rock mainly made of sand or quartz grains while shale is a finely stratified sedimentary rock of silt and clay-size mineral particles. The colour of sandstone varies depending on its composition. Sandstone usually has a light colour since they are made of light-coloured minerals. Like sandstone, shale is also a very common type of sedimentary rock. It's typically grey in colour, but this colour can change depending on the presence of other minerals. In study area sandstone/shale can be seen in northern part (Fig. 2). In some area feldspathic arenites are sandstones are also observed which contain less than 90% quartz, and more feldspar than unstable lithic fragments, and minor accessory minerals. Feldspathic sandstones are commonly immature or sub-mature. In study area feldspathic sandstone can be seen in northern part (Fig. 2).

Limestone/ shale

Limestone and shale with bands of limestone and shale are seen in the study area. In the study area the Penganga Limestone is greyish black, fine-grained, non-crystalline and moderate to highly indurated in nature. The shales are of white to grey in colour and soft in nature and can be seen northern, western and small portion of eastern part of the study area. Limestone is exposed around Sawalhira, Awarpur and Kodsi etc. villages. Limestone-Shale with Limestone Bands, which is exposed in Piparda, Korpana, Bargaon Kh. villages of the study area (Fig. 2).

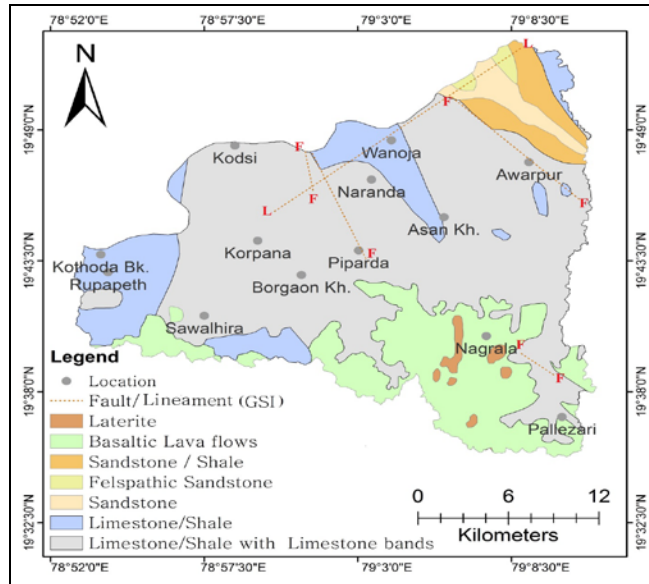


Fig 2: Geological map of study area (modified after GSI, 2000)

Geomorphology

The geomorphology map has been prepared by visual interpretation and field studies. In the study area, five major geomorphic units are present viz., denudational hills, plateau, pediments, pediplain, and alluvial plain.

Denudational hills

Denudational landforms are formed as a result of active processes of weathering, mass wasting and erosion due to the action of exogenic agents upon the exposed rocks. During these processes, the rocks on the land surface are worn away and the result is an overall lowering of the land surface. In the study area it covers southern and western part of watershed. It covers the area near Pallezari and Nagrala village (Fig. 3).

Plateau

A plateau is a flat, elevated landform that rises sharply above the surrounding area on at least one side. Plateaus occur on every continent and take up a third of the Earth's land. They are one of the four major landforms, along with mountains, plains, and hills. In the study area it covers southern and western part of watershed. It is located in the area near Kusumbi, Dhanakdevi and Jiwati village (Fig. 3).

Pediments

A pediment is a gently sloping erosion surface or plain of low relief formed by running water in arid or semiarid region at the base of a receding mountain front. A pediment is underlain by bedrock that is typically covered by a thin, discontinuous veneer of soil and alluvium derived

from upland areas. In the study area it is situated between hilly terrain/plateau and plains. It is located in the area near Nokari Bk., Sawalhira village (Fig. 3).

Pedi plain

Pedi plain is the broad, relatively flat rock surface formed by the joining of several pediments. Pediplains are usually formed in arid or semi-arid climates and may have a thin veneer of sediments. It is postulated that the pediplain may be the last stage of landform evolution, the final result of the processes of erosion. It covers central part of watershed and it is located in the near Bargaon Kh., Piparda village (Fig. 3).

Alluvial plain

An alluvial plain is a largely flat landform created by the deposition of sediment over a long period of time by one or more rivers coming from highland regions, from which alluvial soil forms. As the highlands erode due to weathering and water flow, the sediment from the hills is transported to the lower plain. In the study area it covers northern part of watershed. It is located in the area near Kodsi, Wanoja, Awarpur village (Fig. 3).

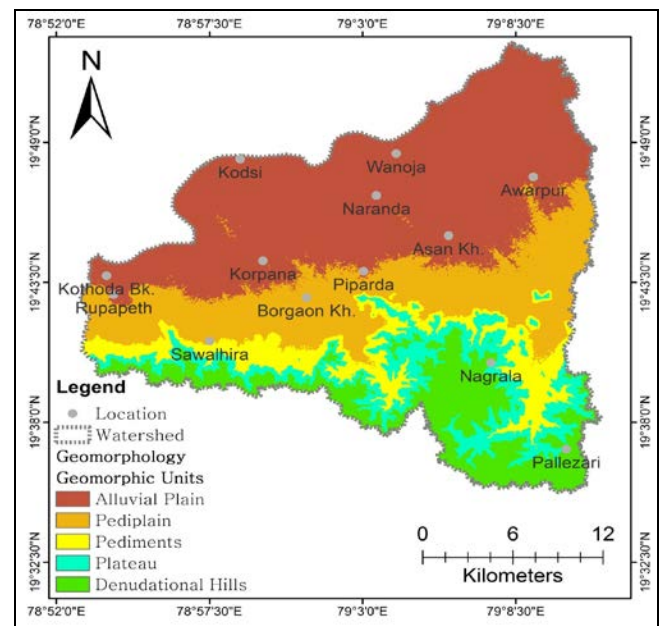


Fig 3: Geomorphological map of the study area

Data used

The study area falls in Chandrapur district of Maharashtra which is located in Survey of India 1:50,000 scale toposheet no. 56 M/1, 56 M/2, 56 I/13 and 56 I/14 which were rectified through the software Arc-GIS 10.3.1 version. The Indian Remote Sensing Satellite IRS 1C Linear Imaging Self Scanner (LISS-III) image with 23.5m spatial resolution down loaded from the website BHUVAN (Fig. 4) and the Shuttle Radar Topography Mission (SRTM) digital data taken from the website United States Geological Survey (USGS) (Fig 5). The District Resource Map (DRM) have been procured from Geological Survey of India are used to delineate geology and geomorphology of the study area.

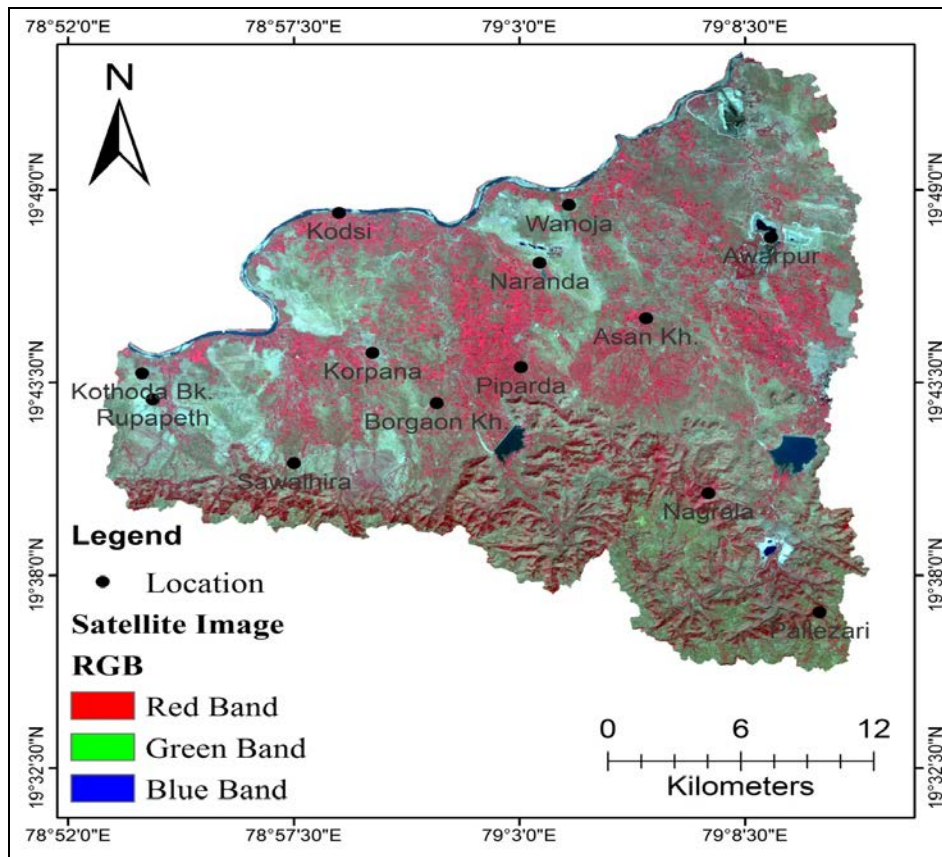


Fig 4: IRS LISS III satellite image of 23.5.mt. spatial resolution of the study area

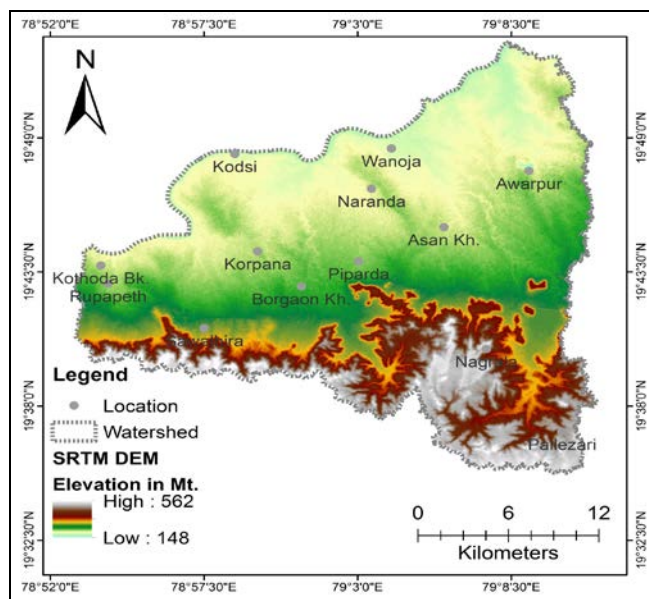


Fig 5: SRTM DEM of 30 mt. resolution map of the study area

Methodology

The toposheet taken from SOI has been rectified and mosaic using the software Arc GIS 10.3.1 version. Morphometric parameters are calculated namely; stream length, bifurcation ratio, drainage density, stream frequency, form factor, texture ratio, elongation ratio, circularity ratio and constant of channel maintenance are calculated based on the formulae (Table No. 1) suggested by (Horton, 1945, Miller, 1953, Schumn, 1956, Strahler, 1964) [15, 29, 51]. Morphometric analysis of river basin is carried out to understand the relationships among different aspects of drainage parameters and resources distribution (Reddy *et al.*, 2002)

[38]. IRS LISS -3 satellite data of 19 January 2019, and SOI toposheets were used to delineate geomorphic maps and geomorphic units were extracted from the satellite image by Digital Elevation Model (DEM) and incorporated into GIS database. The geological map was then used to delineate different types of rocks present in the area. The final layout of drainage and lithological map was prepared using the software Arc-GIS 10.3.1 version.

Morphometric Analysis

Morphometry is simply the measurement of features present on the surface of earth formed due to endogenetic as well as exogenetic processes and their mathematical analysis (Lone A, 2017) [20]. The morphometric analysis is carried out through measurement of linear, areal and relief aspects of the basin (Nag and Chakraborty, 2003) [32]. The watershed characteristics, regional topography, drainage pattern, basin geometry, nature of bedrock and groundwater potential zones can be studied using morphometric analysis of watershed. Morphometric analysis is used in watershed prioritization and conservation of natural resources at watershed level. The landform processes, soil physical properties and erosional characteristics can be studied using drainage morphometry (Horton, 1945; Strahler, 1957) [15, 50]. Remote sensing and GIS techniques play an important role in providing spatial information needed for computation of morphometric parameters of drainage basins. Morphometric parameters provide information on various terrain factors such as denudation characteristics, nature of bedrock, etc. The morphometric analysis is carried out by three aspects, namely linear, aerial and relief (Table No. 1).

Table 1: Formulae adopted for computations of morphometric parameters

	Sr. no	Parameter	Symbol	Formula	Reference
Linear	1.	Stream Order	S_u	Hierarchical rank	Strahler (1952) [49]
	2.	Stream number	N_u	$N_u = S_1 + S_2 + S_3 \dots L_n$	Horton (1945) [15]
	3.	Stream Length	L_u	Length of the stream (kilometres)	Strahler (1964) [51]
	4.	Mean stream length	L_{sm}	$L_{sm} = L_u / N_u$ where, L_u = Total stream length of order 'u' N_u = Total no. of stream segments of order 'u'	Strahler (1964) [51]
	5.	Stream length Ratio	R_L	$R_L = L_{sm} / L_{sm-1}$ L_{sm} = Mean stream length of a given order and L_{sm-1} = Mean stream length of next lower order	Strahler (1964) [51]
	6.	Bifurcation Ratio	R_b	$R_b = N_u / N_{u+1}$ where, N_u = Total no. of stream segments of order 'u' N_{u+1} = Number of stream segments of the next higher order	Schumm (1956) [43]
	7.	Mean bifurcation ratio	R_{bm}	R_{bm} = Average of bifurcation ratio of all orders	Strahler (1964) [51]
	8.	Rho coefficient	ρ	$\rho = L_u / R_b$	Horton (1945) [15]
Areal	9.	Basin perimeter (km)	P	P = Outer boundary of drainage basin measured in kilometres	Schumm (1956) [43]
	10.	Basin length (km)	L_b	$L_b = 1.312 \times A^{0.568}$ where, A = Area of the basin	Schumm (1956) [43]
	11.	Basin area (km ²)	A	Area from which water drains to a common stream and boundary is determined by opposite ridges	Schumm (1956) [43]
	12.	Form factor ($R_f < 1$)	R_f	$R_f = A / L_b^2$ where, A = area of the basin (km ²) and L_b = basin length, km	Horton (1932) [14]
	14.	Drainage density	D_d	$D_d = L_u / A$ measured in (km/ km ²) where, L_u = Total length of the stream (km) and A = Area of the basin in (km ²)	Horton (1932) [14]
	15.	Stream frequency	F_s	$F_s = N_u / A$ where, N_u = Total no. of stream segments of all orders and A = area of the basin (km ²)	Horton (1945) [15]
	16.	Drainage texture	D_t	$D_t = N_u / P$ where, N_u = Total no. of stream of all orders and P = basin perimeter measured in km	Horton (1945) [15]
	17.	Circulatory ratio ($R_c \leq 1$)	R_c	$R_c = 4\pi A / P^2$ where, A = area of the basin (km ²) and P = basin perimeter measured in km	Miller (1953) [29]
	18.	Elongation ratio	R_e	$R_e = 2\sqrt{A/\pi} / L_b$, Where, A = Basin area, L = Basin length	Bull & Mc Fadden (1977) [6]
	19.	Constant of channel maintenance (km ² /km)	CCM	CCM = $1 / D_d$ Where, D_d = drainage density	Schumm (1956) [43]
Relief	20.	Maximum height of the basin	Z	GIS analysis/DEM	
	21.	Height of basin mouth	z	GIS analysis/DEM	
	22.	Basin relief/ Relative relief (m)	H	$H = Z - z$ where, Z = Maximum elevation of the basin (m) and Z = Minimum elevation of the basin (m)	Strahler (1952) [42]
	22.	Relief ratio	R_r	$R_r = H / L_b$ where, H = Basin relief and L_b = Length of basin	Schumm (1956) [43]
	23.	Ruggedness number	R_n	$R_n = D_d * H$ where D_d = Drainage density and H = Basin relief (m)	Patton & Baker (1976) [36]

Linear Aspect of River Basin Morphometry

The linear aspects of morphometric analysis of basin include stream order, stream number, stream length, mean stream length, stream length ratio, rho coefficient and bifurcation ratio.

Stream Order (N_u)

The stream order designation is the first step in drainage basin analysis and is based on hierarchical rank. Stream has proven to be useful indicator of stream size, discharge, and drainage area (Strahler, 1957) [50]. Painganga River is allocated as 5th order stream. It is observed that number of streams decreases as the stream order increases. The stream order and stream number is presented in (Table 2). Out of five sub watersheds, SW-2 and SW-4 have 5th order stream, SW-1 have 3rd order stream while remaining SW-3 and SW-4 have 4th order stream.

Stream Length (L_u)

According to law proposed by (Horton, 1945) [15], stream length is calculated. Streams having short lengths indicate area with steep slopes and finer texture, whereas longer stream length indicates low gradients (Strahler, 1964) [51]. The irregular trend in stream length indicates discrepancies in lithology. The stream length for all the five sub watersheds has been calculated (Table 2). In SW-3, 1st order (120.06km), 2nd order (87.48), 3rd order (17.22), 4th order (27.58) and in SW-4, 1st order (158.02 km), 2nd order (106.10), 3rd order (36.53), 4th order (12.82), 5th order (29.80). The irregularities of stream length in SW-3 between 3rd order and 4th order same for SW-4 between 4th order and 5th order indicates geological and morphological controls on river basin.

Table 2: Calculation of different Linear Morphometric Parameters of all five Sub Watersheds from the Study Area

Sr. No.	Sub Watershed Code	Basin Area (km ²)	Stream Order (S _u)	Stream Number (N _u)	Stream Length (L _u) (km)	Log N _u	Log L _u
1.	SW1	47.35	I				
			II	38	41.45	1.57	1.61
			III	9	21.22	0.95	1.32
			IV	2	5.77	0.30	0.76
			V				
2.	SW2	91.77	I	97	66.99	1.98	1.82
			II	22	46.79	1.34	1.67
			III	8	21.08	0.90	1.32
			IV	4	5.60	0.60	0.74
			V	1	4.15	0	0.61
3.	SW3	165.15	I	315	120.06	2.49	2.07
			II	38	87.48	1.57	1.94
			III	7	17.22	0.84	1.23
			IV	2	27.58	0.30	1.44
			V				
4.	SW4	230.15	I	199	158.02	2.29	2.19
			II	53	106.10	1.72	2.02
			III	10	36.53	1	1.56
			IV	3	12.82	0.47	1.10
			V	1	29.80	0	1.47
5.	SW5	85.28	I	153	71.92	2.18	1.85
			II	20	28.49	1.30	1.45
			III	7	11.35	0.84	1.05
			IV	2	9.95	0.30	0.99
			V				

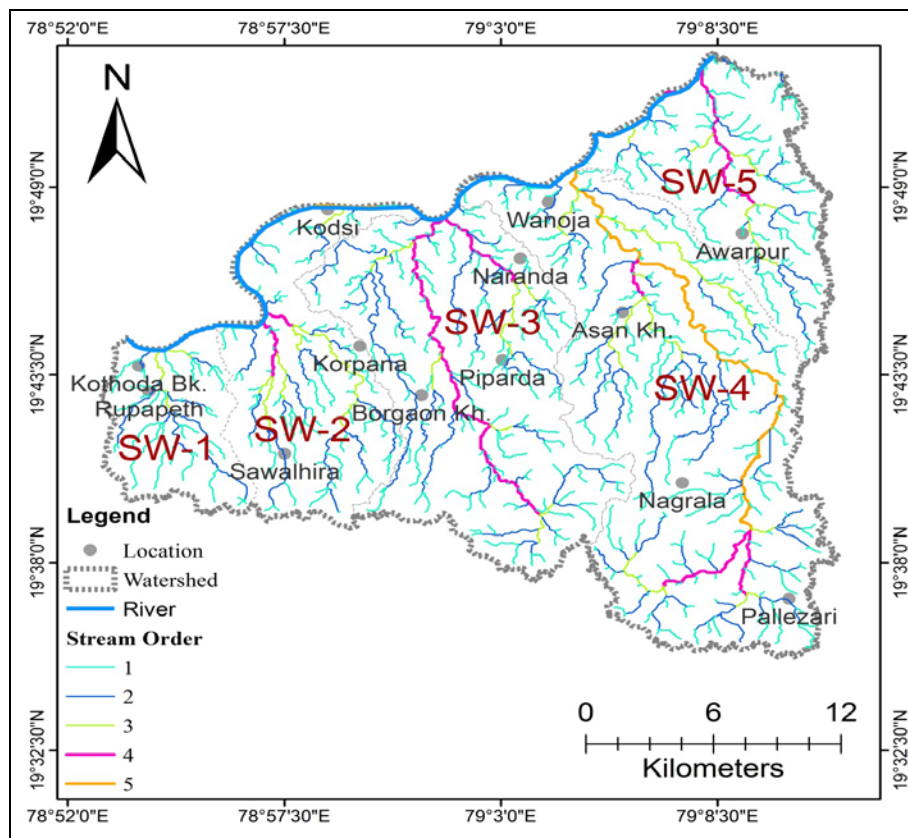


Fig 6: Drainage map of the study area

Mean Stream Length (L_{sm})

According to (Strahler, 1964), mean stream length is the characteristic property of drainage network and associated surface. It is calculated by dividing the total length of streams of given order (L_u) to the total number of streams (N_u) (Mahala, A., 2019) [22]. The mean stream length for all five sub watersheds has been calculated (Table 3). Low

values in the upper reaches of sub watershed indicate young morphological development and high erosion potentiality. The L_{sm} in the study area for SW-1 vary from 1.09 km to 2.88 km, SW-2 varies from 0.69 km to 4.15 km, SW-3 varies from 0.38 km to 13.79 km, SW-4 varies from 0.79 km to 29.80 km, and SW-5 varies from 0.47 km to 4.97 km. In SW-2, 1st order (0.69 km), 2nd order (2.12 km), 3rd order

(2.63 km), 4th order (1.4 km), 5th order (4.15 km). The low value of L_{sm} for high order stream i.e., 1.4 km for 4th order in SW-2 is due to the fact that the streams fall within this order has stopped their channel lengthening much before than the lower order streams.

Stream Length Ratio (R_L)

According to (Horton, 1945) [15], stream length ratio is the ratio between mean stream length of one order to next lower order of the stream. Areas having mountain–plain front river basin have irregular tendency of stream-length ratio than regular plateau fringe river basin (Magesh and Chandrasekhar, 2014) [21]. The R_L value is calculated for all five sub watersheds (Table 3). The R_L in the study area for SW-1 starts with 2.15 for 1st to 2nd order and 1.22 for 2nd to 3rd order, for SW-2 starts with 3.07 for 1st to 2nd order, 1.24 for 2nd to 3rd order, 0.53 for 3rd to 4th order and 2.96 for 4th to 5th order, for SW-3 starts with 6.05 for 1st to 2nd order, 1.06 for 2nd to 3rd order and 5.60 for 3rd to 4th order, for SW-4 starts with 2.53 for 1st to 2nd order, 1.82 for 2nd to 3rd order, 1.16 for 3rd to 4th order and 6.97 for 4th to 5th order, for SW-5 starts with 3.02 for 1st to 2nd order, 1.14 for 2nd to 3rd order and 3.06 for 3rd to 4th order. The changes in the R_L between successive stream orders of the basin varies due to the differences in slope and topographic conditions (Adhikari, S., 2020).

Table 3: Calculations of mean stream length (l_{sm}) and stream length ratio (r_l) for all five sub watersheds from the study area

Sr. No.	Sub Watershed Code	Mean Stream Length (L_{sm}) (km)					Stream Length Ratio (R_L)			
		I	II	III	IV	V	II/I	III/II	IV/III	V/IV
1.	SW1	1.09	2.35	2.88			2.15	1.22		
2.	SW2	0.69	2.12	2.63	1.4	4.15	3.07	1.24	0.53	2.96
3.	SW3	0.38	2.30	2.46	13.79		6.05	1.06	5.60	
4.	SW4	0.79	2.00	3.65	4.27	29.80	2.53	1.82	1.16	6.97
5.	SW5	0.47	1.42	1.62	4.97		3.02	1.14	3.06	

Bifurcation Ratio (R_b)

According to (Horton, 1945) [15], the bifurcation ratio is defined as the ratio between the total numbers of stream segments of one order (N_u) to that of next higher order (N_{u+1}). The low R_b value indicates reduction in structural influence while high R_b value indicates elongated basins (Nag, 1998). The importance of this parameter is, it denotes the water carrying capacity and related flood potentiality of any basin. The value normally ranges between 2 to 5 (Joji et al., 2013) [16]. Studies identified that mountain-plain areas have high R_b value than plateau-plain fringe areas due to its young morphological adjustment and high water pressure (Kim and Jung, 2015) [18]. The bifurcation ratio is calculated for all five sub watersheds (Table 4). The R_b value for SW-1 is 4.22 for 1st to 2nd order and 4.5 for 2nd to 3rd order, for SW-2 is 4.40 for 1st to 2nd order, 2.75 for 2nd to 3rd order, 2.00 for 3rd to 4th order and 4.00 for 4th to 5th order, for SW-3 is 8.28 for 1st to 2nd order, 5.42 for 2nd to 3rd order and 3.5 for 3rd to 4th order, for SW-4 is 3.75 for 1st to 2nd order, 5.3 for 2nd to 3rd order, 3.33 for 3rd to 4th order and 3.00 for 4th to 5th order, for SW-5 is 7.65 for 1st to 2nd order, 2.85 for 2nd to 3rd order and 3.5 for 3rd to 4th order. Based on R_b values, SW-3 and SW-5 have high values whereas remaining SW-1, SW-2 and SW-4 have low values. The irregularities in R_b values is due to strong geological and lithological controls of the basin and high bifurcation ratio in higher order streams indicates large amount of water received in upper

basin area. But low R_b and related lower number streams in lower reaches increase water pressure (Mahala, A., 2019) [22]. The mean bifurcation ratio is also calculated for all five sub watersheds (Table 4), the R_{bm} is 4.36 for SW-1, 3.28 for SW-2, 5.73 for SW-3, 3.84 for SW-4 and 4.67 for SW-5.

Table 4: Calculations of bifurcation ratio (r_b) and mean bifurcation ratio (rb_m) for all five sub watersheds from the study area

Sr. No.	Sub Watershed Code	Bifurcation Ratio (R_b)				Mean Bifurcation Ratio (R_{bm})
		I/II	II/III	III/IV	IV/V	
1.	SW1	4.22	4.5			4.36
2.	SW2	4.40	2.75	2.00	4.00	3.28
3.	SW3	8.28	5.42	3.5		5.73
4.	SW4	3.75	5.3	3.33	3.00	3.84
5.	SW5	7.65	2.85	3.5		4.67

Rho Coefficient (ρ)

Rho coefficient (ρ) is the ratio of stream length ratio to bifurcation ratio and it determines the relationship between the drainage density and the physiographic development of the basin, and allows the evaluation of the storage capacity of the drainage network (Horton 1945) [15]. According to (Mesa, 2009), it is influenced by climatic, geological, biological, geomorphological and anthropogenic factors. The ρ is calculated for all five sub watersheds (Table 5), for SW-1 the ρ for 1st order is 0.50 and 0.27 for 2nd order, for SW-2 the ρ for 1st order is 0.69, 0.45 for 2nd order, 0.26 for 3rd order and 0.74 for 4th order, for SW-3 the ρ for 1st order is 0.73, 0.19 for 2nd order and 1.6 for 3rd order, for SW-4 the ρ for 1st order is 0.67, 0.34 for 2nd order and 3rd order, 2.32 for 4th order, for SW-5 the ρ for 1st order is 0.39, 0.4 for 2nd order and 0.87 for 3rd order. The higher rho coefficient value ($\rho > 0.60$) indicates higher hydric storage during flood periods and it attenuates the erosion effects during elevated discharge (Mesa, 2009). Except SW-1, all the remaining four sub watersheds i.e., SW-2 varies between 0.26 to 0.74, SW-3 varies between 0.19 to 1.6, SW-4 varies between 0.34 to 2.32 and SW-5 varies between 0.39 to 0.87 have higher value ($\rho > 0.60$) which indicates higher hydric storage during flood periods and it attenuates the erosion effects during elevated discharge.

Table 5: Calculations of rho coefficient (ρ) for all five sub watersheds from the study area

Sr. No.	Sub Watershed Code	Rho Coefficient (ρ)			
		I	II	III	IV
1.	SW1	0.50	0.27		
2.	SW2	0.69	0.45	0.26	0.74
3.	SW3	0.73	0.19	1.6	
4.	SW4	0.67	0.34	0.34	2.32
5.	SW5	0.39	0.4	0.87	

Areal Aspect of River Basin Morphometry

It deals with 2D parameters like basin shape and area, drainage density, drainage texture, stream frequency, elongation ratio, circularity ratio, and form factor.

Drainage Density (D_d)

According to (Strahler, 1964) [51], D_d is defined as the total stream length in a given basin to the total area of the basin. D_d is the important indicator of landform element as it provides a numerical measurement of runoff potentiality and

landscape dissection (Mahala, A., 2019) [22].

D_d is known to vary with climate and vegetation (Ozdemir and Bird, 2009) [33], soil and rock properties (Moglen *et al.*, 1998) [30], relief and landscape evolution processes. The high drainage density in mountain environment is due to impermeable surface materials, sparse vegetation and high relief, whereas plateau environment bears low D_d due to high infiltration and low relief (Magesh and Chandrasekhar, 2014; Parveen *et al.*, 2012) [21, 35]. The D_d is calculated for all five sub watersheds (Table 6) and it varies between 1.42 km/km² to 1.57 km/km². For SW-1 the D_d is 1.44 km/km², for SW-2 the D_d is 1.57 km/km², for SW-3 the D_d is 1.52 km/km², for SW-4 the D_d is 1.49 km/km² and for SW-5 the D_d is 1.42 km/km². The low drainage density generally results in the areas of highly resistant or permeable subsoil material, dense vegetation and low relief. High drainage density is the resultant of weak or impermeable subsurface material, sparse vegetation and mountainous relief. Low drainage density leads to coarse drainage texture while high drainage density leads to fine (Nag & Chakraborty, 2003) [32]. Based on the D_d values (Table 6), the study area mostly falls under low drainage density zone (<2 km/km²) which indicates low relief, low slope, high infiltration capacity and low water regimes throughout the basin.

Stream Frequency (F_s)

Stream frequency is defined as the quantity of stream segments within basin per unit area of the basin as per (Horton, 1945) [15]. Stream frequency exhibits a positive correlation with drainage density in the watershed indicating an increment in stream population with respect to increase in drainage density. Climatic character, vegetation coverage, rock and soil types, rainfall intensity, infiltration capacity, relief, run-off intensity, permeability terrain, slope has played vital role in controlling the drainage frequency and density (Adhikari, S., 2020). The lower value of F_s indicates poor drainage network (Thomas *et al.*, 2010) [52]. Due to high slope and greater rainfall the stream frequency F_s increases in mountain areas, whereas low permeability and less available surface flow decrease the F_s value in plateau environment (Bali *et al.* 2011) [4]. The stream frequency is calculated for all five sub watersheds (Table 6) and it varies between 1.03 to 2.19 streams/km². For SW-1 the F_s is 1.03 streams/km², for SW-2 the F_s is 1.43 streams/km², for SW-3 F_s is 2.19 streams/km², for SW-4 the F_s is 1.15 streams/km² and for SW-5 the F_s is 2.13 streams/km². Based on the F_s value the SW-1 and SW-4 show low F_s indicates lower permeability of rock, less relief and low slope in plateau environment whereas remaining SW-2, SW-3 and SW-5 show moderate to low F_s , moderate relief, balanced infiltration capacity which might be attributable to less pervious sub-surface in the study area.

Drainage Texture (D_t)

Drainage texture is the total number of stream segments of all orders per perimeter of the basin as per (Horton, 1945) [15]. According to (Smith, 1950), drainage texture is an expression of the relative channel spacing in a fluvial dissected terrain and it depends upon a number of natural factors such as climate, rainfall, vegetation, rock and soil type, infiltration capacity, relief and stage of development of a watershed. The drainage texture is classified into five different classes as per (Smith, 1950) i.e., very coarse (<2), coarse (2-4), moderate (4-6), fine (6-8) and very fine

drainage texture (>8). Greater the drainage texture greater will be dissection and it leads to high erosion. The D_t is calculated for all five sub watersheds (Table 6) and it varies between 1.36 to 4.62 i.e., for SW-1 the D_t is 1.36, for SW-2 the D_t is 2.01, for SW-3 the D_t is 4.62, for SW-4 the D_t is 2.56 and for SW-5 the D_t is 2.81. Based on D_t value SW-1 falls under very coarse drainage texture (<2), SW-2, SW-4 and SW-5 falls under coarse drainage texture and remaining one i.e., SW-3 falls under moderate drainage texture.

Form Factor (R_f)

Form factor is the ratio of the area of the basin to the square of basin length (Horton, 1932) [32]. The value of R_f (>0.78) indicates perfectly circular basin whereas R_f (<0.78) indicates elongated basin (Strahler, 1964) [51]. The R_f indicates the flow characteristics of a basin (Castillo *et al.*, 1988) [7]. In elongated basin flood flows can be easily managed than that of circular basin (Mahala, A., 2019) [22]. The R_f value is calculated for all the five sub watersheds (Table 6) and the value ranges from 0.26 to 0.50. For SW-1 the R_f value is 0.50, for SW-2 the R_f value is 0.30, for SW-3 the R_f value is 0.42, for SW-4 the R_f value is 0.26 and for SW-5 the R_f value is 0.31. The R_f value of all five sub watersheds are less than 0.78 which indicates all the five sub watersheds are elongated in nature.

Circulatory Ratio (R_c)

According to (Miller, 1953) [29], the R_c is defined as the ratio of the area of the basin to the area of a circle having the same circumference as the perimeter of the basin. The R_c values depend upon stream frequency, drainage density, climate, geological structure, slope, relief, etc. of any basin. It is an indicative value determined the geomorphological stages of development of any basin (Mahala, A., 2019) [22]. The R_c value is calculated for all five sub watersheds (Table 6) and the value varies between 0.25 to 0.45. For SW-1 the R_c value is 0.45, for SW-2 R_c value is 0.26, for SW-3 the R_c value is 0.33, for SW-4 the R_c is 0.26 and for SW-5 the R_c value is 0.25. The R_c value of all five sub watersheds show elongated basin.

Elongation Ratio (R_e)

Elongation Ratio (R_e) is defined as the ratio between the diameter of the circle of the same area as the drainage basin to the maximum length of the basin (Schumm, 1956) [43]. The discharge of run-off is more efficient in circular basin than an elongated basin (Singh and Singh, 1997) [47]. Values close to 1.0 are typical of regions of very low relief, whereas values in the range 0.6 to 0.8 are usually associated with high relief and steep ground slope. The R_e value is calculated for all five sub watersheds (Table 6) which varies between 0.58 to 0.79 i.e., for SW-1 the R_e value is 0.79, for SW-2 the R_e value is 0.61, for SW-3 the R_e value is 0.73, for SW-4 the R_e value is 0.58 and for SW-5 the R_e value is 0.63. Based on R_e value of all five sub watersheds, the basin is usually associated with high relief and steep ground slope.

Constant of Channel Maintenance (CCM)

Constant of channel maintenance is calculated as the reciprocal of drainage density (Schumm, 1956) [43]. It can also be expressed as a required minimum area for the maintenance and development of a channel (Dutta and Roy, 2012) [11]. Low value of CCM indicates the area is under the influence of high structural disturbance, low permeability,

steep to very steep slopes and high surface runoff whereas high values of CCM indicates the area is under very less structural disturbances and less runoff conditions (G.P.O. Reddy *et al*, 2004) ^[40]. The CCM value is calculated for all five sub watersheds (Table 6) and it ranges from 0.63 to 0.70. For SW-1 the CCM value is 0.69, for SW-2 the value is 0.63, for SW-3 the value is 0.65, for SW-4 the value is 0.67 and for SW-5 the value is 0.70. CCM value of SW-1 and SW-5 has higher value while remaining SW-2, SW-3 and SW-4 have lower value.

Table 6: Calculations of areal aspects for all the five sub watersheds from the study area

Sr. no.	Sub Watershed Code	A (sq.km)	P (km)	L _b (km)	D _d	F _s	D _t	R _r	R _c	R _e	CCM
1.	SW1	47.35	36.01	9.72	1.44	1.03	1.36	0.50	0.45	0.79	0.69
2.	SW2	91.77	65.59	17.49	1.57	1.43	2.01	0.30	0.26	0.61	0.63
3.	SW3	165.15	78.19	19.79	1.52	2.19	4.62	0.42	0.33	0.73	0.65
4.	SW4	230.15	103.81	29.29	1.49	1.15	2.56	0.26	0.26	0.58	0.67
5.	SW5	85.28	64.59	16.54	1.42	2.13	2.81	0.31	0.25	0.63	0.70

Relief Aspect of River Basin Morphometry

It deals with 3D parameters like Maximum and Minimum Height of Basin, Basin Relief, Relief Ratio and Ruggedness Number.

Maximum (Z) and Minimum Height (z) of Basin

The maximum of basin (Z) for all the five sub watersheds ranges between 273 m to 562 m and minimum height of basin mouth (z) for all the five sub watersheds ranges between 148 m to 182 m (Table 7).

Basin Relief (H)

Basin relief (H) plays an important role in drainage development, surface and sub surface water flow, permeability, landforms development and erosion properties of the terrain (G.P.O. Reddy *et al*, 2004) ^[40]. It is the general morphometric parameters used to understand the morphological characteristics of basin (Raux *et al.*, 2011) ^[37]. It depends upon the underlain geology, geomorphology and drainage characteristics of the region and it is the best indicator of erosional stages of any river basin (Thomas *et al.* 2010) ^[52]. The basin relief is calculated for all the five sub watersheds (Table 7) and it varies between 125 to 399 m. For SW-1 the H is 374m, 378 m for SW-2, 385 m for SW-3, 399 m for SW-4 and 125 m for SW-5. Except SW-5, the remaining four sub watersheds i.e., SW-1, SW-2, SW-3 and SW-4 are having high relief greater than 150 m which indicates the gravity of water flow, low infiltration and high runoff conditions.

Relief Ratio (R_r)

Relief ratio is defined as ratio of basin relief to basin length (Schumm, 1956) ^[43]. Higher value of R_r indicates steep slope and high relief and low value of R_r indicates gentle slope and low relief (Adhikari, S., 2020). The relief ratio is calculated for all five sub watersheds (Table 7) and it ranges from 0.007 to 0.038. For SW-1 the R_r is 0.038, for SW-2 the R_r is 0.021, for SW-3 the R_r is 0.019, for SW-4 the R_r is 0.013 and for SW-5 the R_r is 0.007. Except SW-5, the remaining four sub watersheds i.e., SW-1, SW-2, SW-3 and SW-4 are having high relief ratio indicates steeper slope and high relief.

Ruggedness Number (R_n)

Ruggedness number is defined as the product of drainage density and relative relief. The R_n is high when both drainage density and relative relief are high (Ansari *et al.* 2012) ^[3]. It depends upon sharpness of native relief, amplitude of available drainage density and other environmental factors such as slope, rainfall, weathering, soil texture, natural vegetation etc. (Shankar & Dhaniranjn, 2014) ^[44]. The R_n is calculated for all five sub watersheds (Table 7) and it ranges from 0.17 to 0.59. For SW-1 the R_n value is 0.53, for SW-2 the R_n value is 0.59, for SW-3 the R_n value is 0.58, for SW-4 the R_n value is 0.59 and for SW-5 the R_n value is 0.17. Based on the R_n value SW-5 have low R_n value which indicates less susceptibility to erosion whereas SW-1, SW-2, SW-3 and SW-4 have high R_n value which indicates high susceptibility to erosion.

Table 7: Calculations of relief aspects for all the five sub watersheds from the study area

Sr. No.	Sub Watershed Code	Z (m)	z (m)	H (m)	R _r	R _n
1.	SW1	556	182	374	0.038	0.53
2.	SW2	554	176	378	0.021	0.59
3.	SW3	562	177	385	0.019	0.58
4.	SW4	553	154	399	0.013	0.59
5.	SW5	273	148	125	0.007	0.17

Conclusion

Traditional methods such as field observation, topographic maps and with the advanced methods of remote sensing and geographic information system (GIS) is one of the conventional and competent tools have been used for morphometric analysis. Morphometry plays an important role to study the land, floods control, eroded land characteristics. Morphometric parameters have been calculated in some part of Painganga River to study morphological and hydrological characteristics. The measurement of linear, areal and relief aspects are useful to study physical characteristics of basin. Painganga River is allocated as 5th order stream and the irregularities in stream length (L_n) in SW-3 and SW-4 indicates geological and morphological controls on river basin. The mean stream length (L_{sm}) of any given order is greater than that of lower order in all the sub watersheds except at order SW-2 is due to the fact that the streams fall within this order has stopped their channel lengthening much before than the lower order streams. The change in stream length ratio (R_L) from one order to another order indicates their late youthful stage of geomorphic development. The variation in the R_L between successive stream orders of the basin varies due to the differences in slope and topographic conditions. Bifurcation ratio (R_b) and Mean bifurcation ratio (R_{bm}) in SW-3 and SW-5 has high values which indicate strong geological and lithological controls of the basin and elongated shape of both the sub watersheds and the whole basin. In rho coefficient (ρ), the SW-1 have low values while remaining all the four sub watersheds i.e., SW-2, SW-3, SW-4 and SW-5 have high values which shows higher hydric storage during flood periods and it attenuates the erosion effects during elevated discharge. In areal aspect, all the five sub watersheds show low drainage density which indicates low slope and low relief. The stream frequency (F_s) in SW-1 and SW-4 have low values which indicates lower permeability of rock, less relief and low slope in plateau environment

whereas SW-2, SW-3 and SW-5 have moderate to low values which indicates moderate relief, balanced infiltration capacity which might be attributable to less pervious sub-surface in the study area. Drainage texture (D_t) of SW-1 having very coarse drainage texture which indicates very high erosion. SW-2, SW-4 and SW-5 shows coarse drainage texture and hard and compact underlying rock also and SW-3 shows moderate drainage texture. Circulatory ratio (R_c) of all the five sub watersheds value ranges from 0.25 to 0.45 which show that all the five sub watersheds are elongated in nature. Elongation ratio (R_e) of all the five sub watersheds ranges from 0.58 to 0.79 which indicates all the five sub watersheds are elongated and the basin is usually associated with high relief and steep ground slope. The constant of channel maintenance (CCM) in SW-1 and SW-5 has higher values which indicates the area is under less structural disturbances and less runoff condition whereas SW-2, SW-3 and SW-4 has higher values which indicates the area is under higher structural disturbances, low permeability, steep to very steep slopes and high surface runoff. In relief aspect, the Basin relief (H) of SW-1, SW-2, SW-3 and SW-4 shows higher basin relief which indicate the gravity of water flow, low infiltration and high runoff conditions. Relief ratio (R_r) of SW-1, SW-2, SW-3 and SW-4 are having high relief ratio indicates steeper slope and high relief while SW-5 having low relief ratio which indicates gentle slope and low relief. Ruggedness number (R_n) of SW-1, SW-2, SW-3 and SW-4 has high R_n value which indicates high susceptibility to erosion while SW-5 has low R_n value which indicates less susceptibility to erosion.

References

- Adikari S. Morphometric Analysis of a Drainage Basin: A Study of Ghatganga River, Bajhang District, Nepal. *The Geographic Base*,2020;7:127-144:2020. Doi: 10.3126/tgb.v7i0.34280Nepal Geography Student Society, CDG, TU
- Angillieri M. Morphometric characterization of the Carrizal Basin applied to the evaluation of flash flood hazards, San Juan, Argentina. *Quat. Int*,2012;253:74-79.
- Ansari ZR, Rao LA, Yusuf A. GIS based morphometric analysis of Yamuna drainage network in parts of Fatehabad area of Agra District, Uttar Pradesh. *J Geol Soc India*,2012;79:505-514
- Bali R, Agarwal KK, Ali SN, Rastogi SK, Krishna K. Drainage morphometry of Himalayan Glacio-fluvial basin, India: hydrologic and neotectonic implications. *Environ Earth Sci*,2011;66(4):1163-1174
- Bera A, Mukhopadhyay BP, Das D. Morphometric Analysis of Adula River Basin in Maharashtra, India using GIS and Remote Sensing techniques Geo-spatial Data in Natural Resources, 2018, 13-35
- Bull WB, McFadden LD. Tectonic geomorphology north and south of Garlock fault, California. *J. Geomorphol*,1977;1:15-32.
- Castillo V, Diazsegovia A, Alonso SG. Quantitative study of fluvial landscapes, case study in Madrid, Spain. *Landsc Urb Plan*,1988;16:201-217.
- Chandniha SK, Kansal ML. Prioritization of sub-watersheds based on morphometric analysis using geospatial technique in Piperiya watershed, India. *Applied Water Science*,2017;7(1):329-338. DOI: 10.1007/s13201-014-0248-9
- Chorley RJ, Schumm SA, Sugden DE. *Geomorphology*. Methuen and Co., Ltd., London, 1985.
- Clarke JJ. *Morphometry from map. Essays in geomorphology*. Elsevier, New York, 1966, 235-274
- Dutta S, Roy S. Determination of erosion surfaces and stages of evolution of Sangra drainage basin in Giridih district, Jharkhand, India. *Int J Geomat Geosci*,2012;3(1):63-73
- Engelhardt BM, Weisberg PJ, Chambers JC. Influences of watershed geomorphology on extent and composition of riparian vegetation. *J Veg Sci*,2012;23(1):127-139.
- Forzieri G, Gardenti M, Caparrini F, Hashim M. A methodology for the pre-selection of suitable sites for surface and underground small dams in arid areas: a case study in the region of Kidal, Mali. *Phys Chem Earth Parts A/B/C*,2008;33:74-85.
- Horton RE. *Drainage basin characteristics*, 2nd edn. transactions, American Geophysical Union, New York, 1932.
- Horton RE. Erosional development of streams and their drainage basins: hydro physical approach to quantitative morphology. *Bull Geol Soc Am*,1945;56:275-370.
- Joji VS, Nair AS, Baiju KV. Drainage basin delineation and quantitative analysis of Panamaram Watershed of Kabani River Basin, Kerala using remote sensing and GIS. *J Geol Soc Ind*,2013;82:368-378
- Kabite G, Gessesse B. Hydro-geomorphological characterization of Dhidessa river Basin, Ethiopia. *Int. Soil Water Conserv. Res*,2018;6(2):175-183
- Kim JC, Jung K. Fractal tree analysis of drainage patterns. *Water Resour Manag*,2015;29:1217-1230
- Kumar R, Kumar S, Lohani AK, Nema RK, Singh RD. Evaluation of geomorphological characteristics of a catchment using GIS. *GIS India*,2000;9(3)13-17.
- Lone A. Morphometric and Morphotectonic Analysis of Ferozpur Drainage Basin Left Bank Tributary of River Jhelum of Kashmir Valley, NW Himalayas, India. *J Geogr Nat Disast*,2017;7:208
- Magesh NS, Chandrasekhar N. GIS model-based morphometric evaluation of Tamiraparani sub basin, Tirunelveli district, Tamil Nadu, India. *Arab J Geosci*,2014;7:131-141
- Mahala A. The significance of morphometric analysis to understand the hydrological and morphological characteristics in two different morpho-climatic settings. *Applied Water Science*,2019;10:33. doi.org/10.1007/s13201-019-1118-2
- Manjare BS, Padhye MA, Girhe SS. (Morphometric Analysis of a Lower Wardha River sub basin of Maharashtra, India Using ASTER-DEM Data and GIS". *Proceedings of Geo-Enabling Digital India, 15th ESRI India User Conference New Delhi, 2014a*, 1-13.
- Manjare BS, Jakate V, Aparajit N. Morphometry Using Remote Sensing And GIS Techniques Of Kedar River Sub Basins of Purna River Basin, Buldhana District, Maharashtra, *IJPRET*, 2014; ISSN: 2319-507X, 2014b:2(1)1-8.
- Manjare BS. Prioritization of Wardha040 Sub-Watersheds for Sustainable Development and Management of Natural Resources: An Integrated Approach Using Remote Sensing, GIS Techniques *Journal of Geosciences Research*,2017;2:(2):187-192.

26. Manjare BS, Khan S, Jawadand SA, Padhye MA. "Watershed Prioritization In Some Part Of Wardha River Basin, Maharashtra India Using Morphometric Parameters: An integrated study of Remote Sensing And GIS" Proceedings of International Conference Select Proceedings of ICWEES-2016, Water Science and Technology Library, (ISBN 978-981-10-5800-4 ISBN 978-981-10-5801-1 eBook), Hydrologic Modeling Editors, Vijay P. Singh, Shalini Yadav, Ram Narayan Yadava, Springer Nature Singapore Pte Ltd, 2018, 353-366.
27. Manjare BS, Padhya Mithilesh, Kelawade Ankita. Morphometric analysis of Erai River Basin in Sedimentary landscape, Central India: A geospatial approach Indian Journal of Geosciences, Volume 74, No. 4 October - December, 2020, 417-432.
28. Mesa LM. Morphometric analysis of a subtropical Andean basin (Tucuman, Argentina), Environ Geol,2006:50:1235-1242
29. Miller V. A Quantitative Geomorphologic Study of Drainage Basin Characteristics in the Clich Mountain Area, Virginia and Tennessee. Department of Geology, Columbia University, New York, 1953, 389-402.
30. Moglen GE, Eltahir EAB, Bras RL. On the sensitivity of drainage density to climate change. Water Resour. Res,1998:34(4):855-862.
31. Nag S. Morphometric analysis using remote sensing techniques in the Chaka sub-basin, Purulia district, West Bengal. J. Indian Soc. Rem. Sens,1998:26(1):69-76.
32. Nag SK, Chakraborty S. Influences of rock types and structure in the development of drainage network in hard rock area. J. Indian Soc. Remote Sens,2003:31(1):25-35
33. Ozdemir H, Bird D. Evaluation of Morphometric parameters of drainage networks derived from topographic maps and DEM in point of floods. Environ. Geol,2009:56:1405-1415.
34. Pareta K, Pareta U. Quantitative geomorphological analysis of a watershed of Ravi River Basin, H.P. India. Int J Remote Sens GIS,2012:1(1):41-56.
35. Parveen R, Kumar U, Singh VK. Geomorphometric characterization of Upper South Koel Basin, Jharkhand: a remote sensing & GIS approach. J Wat Resour Prot,2012:4:1042-1050
36. Patton P, Baker V. Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls. Hydrol. Water Resour,1976:12:941-952.
37. Raux J, Copard Y, Laignel B, Fournier M, Massei N. Classification of worldwide drainage basins through the multivariate analysis of variables controlling their hydro sedimentary response. Glob Planet Change,2011:76:117-127
38. Reddy GPO, Maji AK, Gajbhiye KS. GIS for morphometric analysis of river basins. GIS India,2002:11(9): 9-14.
39. Reddy GPO, Maji AK. Delineation and characterization of geomorphological features in a part of lower Maharashtra metamorphic plateau, using IRS-ID LISS-III data. Jour Indian Soc Remote Sen,2003:31(4):241-250
40. Reddy GPO, Maji AK, Gajbhiye KS. Drainage morphometry and its influence on landform characteristics in Basaltic Terrain – A Remote Sensing and GIS Approach. Int J Appl Earth Obs Geoinf,2004:6:1-16.
41. Reddy GPO. Remote sensing and GIS in digital terrain modeling, In: Reddy G.P.O. and Singh S.K. (Eds.) Geospatial technologies in land resources mapping, monitoring and management. Geotechnologies and the environment, Springer, Cham,2018:21:201-222.
42. Reddy GPO, Kumar N, Sahu N, Singh SK. Evaluation of automatic drainage extraction thresholds using ASTER GDEM and Cartosat-1 DEM: A case study from basaltic terrain of Central India. Egypt J Remote Sen Space Sci,2000:21(1):95-104.
43. Schumm SA. The evolution of drainage system and slopes in Badlands at Perth Amboy, New Jersey. Bull Geol Soc Am,1956:67:214-236
44. Shankar S, Dhaniranjana. Drainage morphometry of flood prone Rangat watershed, Middle Andaman, India- A geospatial approach. Int. J. Innovative Technol. Explor. Eng, 2014, 3(11).
45. Shrivatra JR, Manjare BS, Paunikar SK. A GIS-based assessment in drainage morphometry of WRJ-1 watershed in hard rock terrain of Narkhed Taluka, Maharashtra, Central India., Remote Sensing Applications: Society and Environment,2021a:22:1-13.
46. Shrivatra JR, Manjare BS, Paunikar SK. Morphometric Analysis Based Prioritization of Sub-Watersheds of WRJ-1 Watershed of Narkhed Taluka, Nagpur District, Maharashtra Using Geospatial Techniques, Journal of Geosciences Research, July,2021b:6(2):242-250.
47. Singh S, Singh MC. Morphometric analysis of Kanhar River basin. National Geographical J. of India,1997:43(1):31-43.
48. Smith KG. Standards for grading texture of erosional topography. Am J Sci,1950:248:655-668
49. Strahler AN. Hypsometric analysis (area-altitude) of erosional topography. Geol Soc Am Bull,1952:63:117-142
50. Strahler AN. Quantitative analysis of watershed geomorphology. Trans Am Geophys Union,1957:38:913-920.
51. Strahler AN. Quantitative geomorphology of basins and channel networks. In: Chow VT (ed) Handbook of applied hydrology. McGraw Hill Book Company, New York, 1964.
52. Thomas J, Joseph S, Thrivikramaji KP. Morphometric aspects of a small tropical mountain river system, the southern Western Ghats, India. Int J Digit Earth,2010:3(2):135-156