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WATERSHED CHARACTERIZATION USING MORPHOMETRY AND RS-GIS TECHNIQUES FOR EFFECTIVE WATER RESOURCE MANAGEMENT

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ABSTRACT

Morphometric analysis with linear, areal, and relief aspects was carried out in the drought-prone watershed of Satara district, Maharashtra, to establish a correlation between terrain features and water dynamics. The advancement in RS-GIS techniques has enabled the spatio-temporal distribution of watershed parameters such as slope, elevation, land use, and various landforms that influence the water availability. The morphometric parameters have been evaluated for the Naygaon watershed in western Maharashtra. According to the study conducted, watershed's maximum elevation is 1224m and minimum is 499m. The slope ranges from 0 to 65.78^0 with higher slopes occupying the peripheral areas that facilitate surface runoff. The area depicts basaltic flows with colluvium/alluvium along the bank of the river. These lava flows are of massive, vesicular and unclassified basalt with low primary porosity, resulting in inadequate recharge. The study area exhibits volcanic landforms such as mesas, denudational hills, valley/valley fills and dissected plateaus. The upper part of the watershed shows parallel-subparallel and rectilinear drainage patterns that indicate structural control, whereas the lower area has dendritic drainage pattern that reveals textural homogeneity and a lack of structural control. The elongated shape of watershed is indicated by the form factor, circulatory ratio, and elongation ratio values. The average bifurcation ratio calculated for the watershed is 3.31, indicates that it is mountainous or has a high degree of dissection causing high surface runoff. The longitudinal profile of basin shows a steep gradient at origin, but gradually flattens out as the river erodes its base level. According to the various values of drainage density, stream frequency, infiltration number, and drainage texture, the study region is underlain by impermeable rocks that are responsible for recharge, runoff, and storage. The findings of this study would be useful in addressing water resource issues in the region and proposing remedial measures for long-term development.

***Keywords:** Groundwater, Morphometry, RS-GIS, Water resource,*

INTRODUCTION

In hard rock terrain, watershed development and management plans need to be designed with scientific and technical know- how that would help protecting the natural resources. The quantitative evaluation of drainage and its relative parameters contributes significantly to generate a plan for the sustainable development of the resources. Morphometric analysis is a technique commonly used to understand the watershed characteristics by various researchers (Rao and Babu 1995; Pakhmode et al. 2003; Sreedevi et al. 2005; John et al. 2006; Manu and Anirudhan 2008; Magesh et al. 2011). Morphometric analysis has also been found to be a reliable tool for identifying flood prone areas, evaluating the hydrological nature of the rocks exposed within the drainage basin, understanding the interrelationship between rock type, sites for water harvesting, decipher the recharge zones and watershed prioritization studies (Esper 2008; Pankaj and Kumar 2009; Bali et al. 2012).

Remote sensing and geographic information system (RS-GIS) techniques are frequently used to evaluate different morphometric parameters of the drainage basin/watershed because they offer a user-friendly environment as well as an effective tool for manipulating and analysing geospatial information (Gangalakunta 2004; Godchild and Haining 2004; Grohmann et al. 2007; Korkalainen et al. 2007; Yu and Wei 2008; Hlaing et al. 2008).

Groundwater is the major source of drinking water supply in Maharashtra. Every year, the state struggles with scarcity issues due to its physiographic characteristics and unpredictable rainfall. It is a noteworthy fact that the state, particularly in terms of drinking water, depends on groundwater for more than 80% of its needs. As a result, groundwater is becoming increasingly important in terms of both quality and quantity. With these facts in view, the authors have set out to compute morphometric parameters to better understand the water dynamics of the Naygaon watershed.

STUDY AREA

The Naygaon watershed having 126.56 km^2 spread in Khandala Taluka of Satara, Maharashtra state, is located between 18°01’20"N and 18°09’25"N latitudes and 73°52’00E" to 74°59’30"E longitudes (Fig. 1). On an average, the watershed receives 600 mm of rain per year, with more than 80% of that falling during the monsoon season (June– September). The watershed has a semi-arid climate, with temperature ranging from 36°C in the summer to around 18°C in winter. The elevation ranges from 499 to 1224 metres and higher elevation areas are towards the periphery of watershed. The climate in the area is subtropical. Geologically, it is a part of the vast

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Peninsular India. The geology of the area consists of deccan basalt and alluvium formations with brown and black soil. Agriculture is one of the most important occupations for the rural population, and groundwater is the prominent source of irrigation. Shirwal village is crossed by the National Highway (NH 48), which is part of the Golden Quadrilateral Highway. Shirwal is easily accessible from Mumbai, Pune, and Bengaluru.

Geology

The study area is in the Naygaon Watershed and is covered by Cretaceous-Eocene basaltic flows, with alluvium found along the river banks. The area has been mapped by the Geological Survey of India. The geological map of the research area is created at a scale of 1:25,000 using District Resource Map of Geological Survey of India and conducting the field traverses.

The Diveghat, Purandargarh, and Mahabaleshwar Formations are part of the Wai Subgroup which belongs to the Sahyadri Group of the Deccan Trap Supergroup, which are exposed in the region. The Wai Formation which is located over the Lonavala Subgroup comprises more than half of the entire Deccan basalt (Beane et al., 1986; Peng et al., 1994). With embedded flow tops, small plagioclase laths, pyroxene, and olivine, simple flows can be found (Beane et al., 1986). In general, the flow composition of the Wai Supergroup is more developed than that of equivalent flows, and GPBs with the most advanced compositions are scarce. Three types of basalt have been observed in the watershed: compact basalt, vesicular basalt, and unclassified basalt. The Nira River, which has the highest recharge rate, is rich in vesicular basalt (Fig. 2). Basalt has a lot of fractures and joints, both vertical and horizontal, which indicate secondary porosity. The area's total porosity is low because the compact basalt is impermeable.

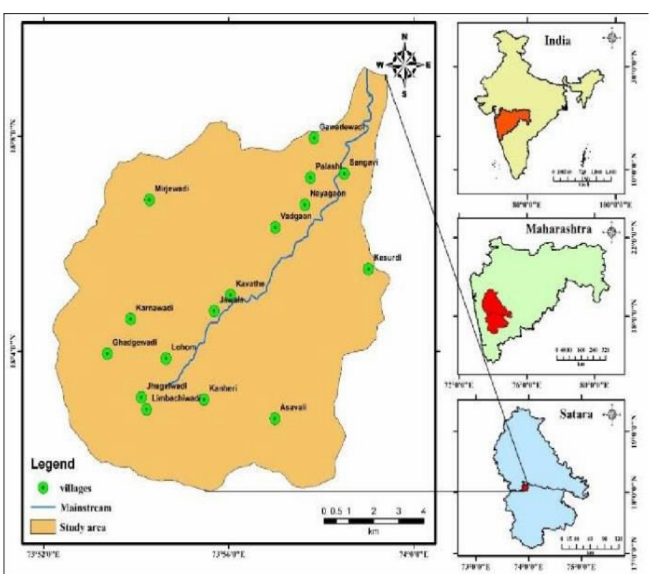

Fig 1: Location map of the study area

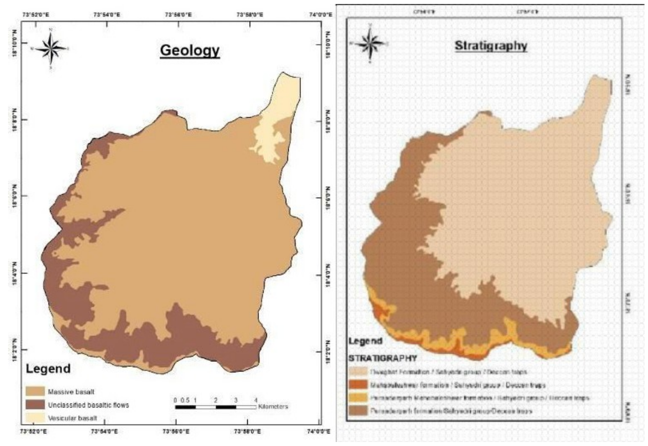

Fig 2: Geological map of the Naygaon watershed

Drainage Network

The drainage network map has been generated for the study area which shows that majority of first order streams occupy peripheral part of the watershed. The drainage pattern in the area resembles the branches of a tree's roots and can thus be classified as dendritic to sub-dendritic. Such a pattern appears on the lithographic surface of a rock with a homogeneous rock structure and similar resistance to weathering and other phenomena. The tributaries usually join the larger stream at an acute angle less than 90° in this pattern. The structure of the larger rivers and their tributaries resembles tree branches and forms a V-shaped pattern.

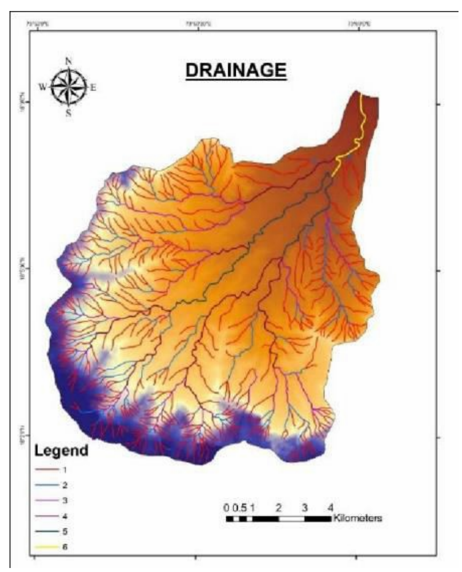

Fig 3: Drainage map of the Naygaon watershed

METHODOLOGY

The morphometric analysis of the Naygaon watershed was performed using ArcGIS and the Survey of India (SoI) toposheet at a scale of 1:50,000. The drainage network is digitized using the Arc-Editor tool by tracing it from the SoI toposheet. A few traverses along streams, road cuttings, and ghat sections were chosen to study the geology of the study area. The transverse and longitudinal profiles of the Naygaon stream were created using Global Mapper (version 14.0). The entire watershed has been chosen for this study of morphometric analysis covering linear, areal and relief aspects (Table 1).

Table 1: Formulae used for computing the various morphometric parameters

Sr. No.	Parameters	Formulae/Definition	Reference
Areal Aspects			
1.	Drainage Density (Dd)	$Dd = \Sigma Lt/A$ Where Dd = drainage density Lt-total stream length of all orders and A = area of the basin	Horton (1945)
2.	Stream Frequency (Fs)	$Fs = Nt/A$ Where Fs = drainage Frequency, Nt = total no. of streams of all orders, A = area of the basin	Horton (1945)
3.	Drainage Texture (T)	$T = Dd*Fs$ Where Dd = Drainage density and Fs = Stream Frequency	Smith (1950)
4.	Length of Overland Flow (Lg)	$Lg = 1/2*Dd$ Where Dd = Drainage density	Horton (1945)
5.	Constant of Channel maintenance (C)	$C = 1/Dd$ Where Dd = Drainage density	Schumm (1956)
6.	Form Factor (Ff)	$Ff = A/Lb^2$ Where A = area of the basin and Lb = basin length	Horton (1945)
7.	Circularity ratio (Rc)	$Rc = 4\pi A/P^2$ Where A = area of the basin and P = basin parameter	Miller (1953)
8.	Elongation ratio (Re)	$Re = 1.128(A/Lb)^{0.5}$ Where A = Area of the basin and Lb = basin length	Schumm (1956)
Linear Aspects			
9.	Stream Length (Lu)	Length of the stream	Horton (1945)
10.	Stream Order (Nu)	Hierarchical rank	Strahler (1957)
11.	Bifurcation ratio (Rb)	$Rb = Nu/N(u+1)$ Where Rb = bifurcation ratio Nu = no. of stream segments of given order and Nu + 1 = no of stream segments of next	Horton (1945)
12.	Stream Length ration (Rl)	$Rl = Lu/L(u-1)$ Where Lu = length of stream segments of given order and Lu - 1 = length of stream segments of next lower order	Horton (1945)
13.	Rho coefficient (R)	$R = Rl/Rb$ Where Rl = stream length ratio and Rb = Bifurcation ratio	Horton (1945)
Relief Aspects			
14.	Basin relief (R)	$R = H-h$ Where H = maximum elevation and h = minimum elevation	Schumm (1956)
15.	Relief ratio (Rr)	$Rr = R/Lb$	Schumm (1956)
16.	Ruggedness number	$Rn = R*Dd$	Strahler (1958)
17.	Slope (Sb)	$Sb = H-h/L$ Where H = maximum elevation, h = minimum elevation and L = longest axis	
18.	Melton ruggedness ratio (MRn)	$MRn = H-h/A^{0.5}$ Where H = maximum elevation, h = minimum elevation and A = area of basin	Melton (1965)

RESULT AND DISCUSSION

Morphometric parameters were computed to understand the surface and ground water dynamics within the Naygaon watershed. The linear, areal and relief parameters were computed to establish a correlation between the terrain characters and spatio-temporal distribution of water resource.

Linear Aspects

Perimeter: The outer boundary of the area of the watershed is called the Basin Perimeter. It can be used to determine the size and shape of a watershed because it is measured along the boundary between two watersheds. The Naygaon watershed has a 51.39 km perimeter.

Length of the basin: The basin length was defined by Schumn (1956) as the longest dimension of the basin parallel to the main drainage line. The Naygaon watershed has a basin length of 19 km.

Stream order: Stream ordering is the process of determining a hierarchical position of a stream within a drainage basin. The trunk stream is the highest order stream segment. The highest stream order observed in the study area is of sixth order. Stream order is important because it shows the rate of discharge in a basin.

Stream length: Stream length is a property that reveals the characteristic stretch of a drainage network component and its contributing basin surface. In the current study, the stream length of a sixth-order stream is 4.67 km (Table 2).

Table 2: Linear parameters of stream

Stream Order	Stream Number	Total length (km)	Mean Stream Length (km)	Cumulative Mean Stream Length
1st	342	253.80	0.74	0.74
2nd	83	63.13	0.76	1.50
3rd	21	41.00	1.95	3.45
4th	7	35.00	5.00	8.45
5th	2	14.33	7.17	15.62
6th	1	4.67	4.67	20.29

Stream frequency: It is the number of streams per unit area and is obtained by dividing total number of streams by total drainage area (Strahler 1968). The calculated stream frequency is 3.603 i.e. high grouped as those with low (< 2.5 streams/sq. km), moderate (2.6–3.5 streams/sq. km) and high stream frequency (> 3.5 streams/sq. km).

Bifurcation ratio (Rb): Strahler (1964) defines bifurcation ratio as the ratio of the number of streams of a given order to the number of streams of the next higher order. Rb is affected by physiography, slope and climatic conditions. The branching pattern of a drainage network is related to the bifurcation ratio. According to Hajam et al. (2013), a relatively high bifurcation ratio indicates an early hydrograph peak with the potential for flash flooding during storm events, whereas a relatively lower value of mean bifurcation ratio suggests geological heterogeneity, higher permeability, and less structural control in the basin. The higher values indicate the influence of geological structure on the drainage pattern and suffered more structural disturbances. As stated by Strahler (1964) and Schumm (1956), the bifurcation ratio values ranging between 3 and 5 indicate that the influence of geologic structures on the drainage pattern is less dominant. The bifurcation ratio of the study area ranges from 2.00 to 4.12 and mean bifurcation ratio is 3.31 (Table 3).

Table 3: Bifurcation ratio of Naygaon watershed

Watershed	Stream Order	Stream Number	Bifurcation Ratio
	1st	342	4.12
	2nd	83	3.95
	3rd	21	3.00
	4th	7	3.50
	5th	2	2.00
	6th	1	

Stream length ratio (Rl): The variation in Rl is a sign of differences in topography and slope, and as a result, it has a significant influence on discharge and various stages of watershed erosion (Sreedevi et al., 2004). A higher stream length ratio denotes a high rate of erosion. The achievement of geomorphic maturity is an example of the increase of Rl from lower to higher orders (Thomas et al., 2010). The mean length ratio is found to range from 0.41 (for Belur watershed) to 3.37 (Gangavalli watershed) for the watersheds studied by Prabhakaran and Jawahar (2018) under their study area. The stream length ratio varies from 0.24 to 0.85 for Naygaon watershed. The mean stream length ratio is 0.49 that falls under low (≤ 0.50) Rl category indicating a mature stage of erosion and low runoff.

Rho coefficient (R): This parameter is important in relating drainage density with the physiographic development of a watershed. It also aids in evaluation of storage capacity of entire drainage network system, and thus is a determinant of the critical degree of drainage development for a given watershed (Horton, 1945). The Rho coefficient for the watershed under consideration is 0.15.

Areal Aspects

Area: The area of the watershed, like the length of the stream drainage, is an important parameter. Schumm (1956) discovered an intriguing relationship between total watershed areas and total stream lengths supported by contributing areas. The basin area is calculated using Global Mapper software which is 256.56 sq. km.

Drainage density: Drainage density (Dd) is described as an expression of the proximity of channels and is quantitatively obtained by the ratio of total channel segment lengths within a basin over the basin area (Horton, 1945; Strahler, 1964). The average Dd of the Naygaon watersheds is 3.25 wherein the density of first order streams in high slope areas is very high followed by the higher order streams.

Drainage texture (T): Smith (1950) proposed that drainage texture is a measure of relative channel spacing in a fluvial dissected terrain that is heavily influenced by climate, vegetation, lithology, soil type, relief, and watershed stage of development. Smith [12] divides drainage texture into four categories: coarse (T 4), moderate (T = 4 - 10), fine (T value greater than 10), and ultra-fine or badlands topography (T value greater than 15). Because of the high value of drainage density, 11.72, the study area is classified as fine drainage texture. High drainage texture values indicate the presence of soft rock with poor erosion resistance.

Length of overland flow (Lg): The length of overland flow (Lg or AOLF) is the distance that water travels over land before being concentrated in specific stream channels. Horton (1945) defined this as the length of the non-channel flow path projected to the horizontal from a point on the drainage divide to a point on the adjacent stream channel. Other factors influencing overland flow length include rainfall intensity, infiltration rate, soils, vegetation cover, and so on. According to Prabhakaran, Jawahar (2018), the length of overland flow is shorter (≤0.70 km) in the Shobanapuram, Sengattupatti, Talugai, Kallar, Periyakarruppu Odai, and Kalungi watersheds, longer (> 0.90 km) in the Pulambadi, Valaiyur, Silaiyur, and Maruvattur watersheds, and moderate in the remaining watersheds (0.70–0.90 km). The value of overland flow length (> 0.90 km) for study area Lg is 1.62, indicating that the overland flow is longer here. This implies that the lag time in the watershed is likely to be longer, resulting in less flash food risk in the watershed. The early stage is distinguished by the maximum length of overland flow and old stages spotted as reduction in Lg.

Constant of channel maintenance (C): The constant-channel maintenance (C) gives an idea of infiltration and runoff of a drainage basin. This low derived value of constant-channel maintenance (0.30) indicates a low permeability of the drainage surface, resulting in low infiltration and high runoff (Dikpal et al., 2017).

Form factor (Ff): The form factor is used to predict the flow intensity of a defined watershed (Horton, 1945; Gregory and Walling, 1973). The Ff index also shows an inverse relationship with the square of the axial length as well as a direct relationship with peak discharge (Magesh et al., 2012). Form factor of watershed is 0.35, the value of Ff (0-0.6) (Horton, 1945) indicating a slightly elongated basin with flatted peak flow.

Circulatory ratio (Rc): Miller (1958) employed the dimensionless circulatory ratio Rc, which is defined as the ratio of basin area to the area of a circle with the same perimeter as the basin. The Rc of watershed is 0.60, indicating that the drainage basin has an elongated shape, mature topography, and a support dendritic pattern. (1956, Schumm).

Elongation ratio (Re): Schumm (1956) used an elongation ratio Re, defined as the ratio of the diameter of a circle with the same area as the basin to the maximum basin length. The ratio provides information about the hydrological behaviour or character of the basin, such as how a circular basin discharges runoff more efficiently than an elongated basin, while the time of concentration of runoff is shorter in the elongated basin, resulting in peak runoff [18]. More elongated

(Re 0.5), Elongated (Re=0.5-0.7), Less elongated (Re = 0.70.8), Oval (Re value 8 to 9), and Circular (Re value >0.9), according to Schumm (1956). The Basin's elongation ratio is 0.66, indicating an elongated basin shape.

Infiltration number: The infiltration number is calculated by multiplying Dd by the drainage frequency (Fs). The study area's infiltration number of 11.72 indicates that this drainage basin has low infiltration and high runoff (Das and Mukherjee, 2005; Joji et al., 2013; Elewa et al., 2016). In the drainage basin, a low infiltration number indicates a low rate of infiltration and high runoff, and vice versa.

Relief Aspects

Basin relief: The elevation difference between the highest and lowest points of the valley floor is referred to as basin relief. A The relief of the basin is 725 metres above mean sea level.

Relief ratio: The relief ratio, (ReRa) is the ratio of maximum relief of horizontal distance along the longest dimension of the basin parallel to the principal drainage line. Relief ratio measures the overall steepness of a drainage basin and is an indicator of the intensity of erosion process operation on slope of the basin. The relief ratio of the basin is 0.038 (Table 4) and according to Raut and Koirala (2017) if the relief ratio of a watershed varies from 0.036 to 0.21 then that basin is composed of resistant rocks, with intense relief and very steep slopes.

Ruggedness number: Strahler (1968) describes ruggedness number (HD) as the product of basin relief and drainage density and it usually combines slope steepness with its length. Extremely high values of ruggedness number occur when slopes of the basin are not only steeper but long as well. Prabhakaran and Jawahar (2018) classified watersheds based on Rn values into five categories: <0.1 subdued morphology;

0.1 - 0.4 slight morphology; 0.4 - 0.7 moderate morphology;

0.7 - 1.0 sharp morphology; >1.0 extreme morphological expression including badlands topography. The ruggedness number obtained for the current basin is 2.35, indicating a high value. Watersheds with high Rn values have dynamic geomorphic processes, long and steep slopes interrupted by sharp breaks in the slope due to rejuvenation processes, a high susceptibility to soil erosion and mass movement, and a high response to a change in peak discharge.

Melton Ruggedness ratio (MRn): The MRn is a slope index that provides spatialized representation of relief ruggedness within the watershed (Melton 1965). NW has an MRn of 0.06.

Gradient Ratio (Rg): Gradient ratio is a marker of channel undulation which assists the assessment of the runoff volume (Sreedevi et al., 2004). The Rg is 0.038 which reflects the mountainous nature of the terrain (Table 4).

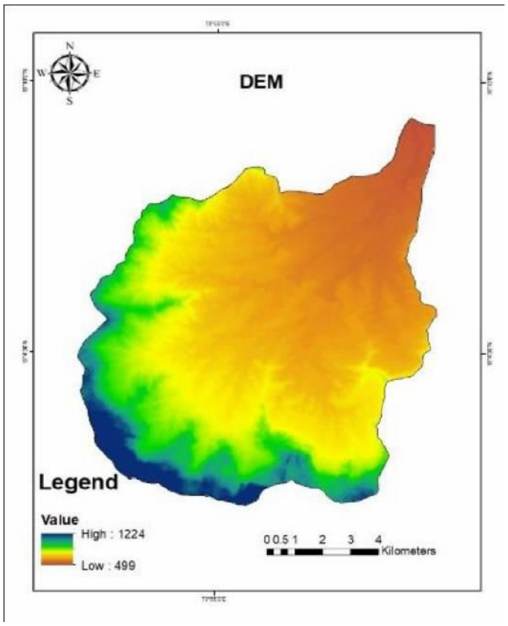

Fig. 4: Digital Elevation Model of the Naygaon watershed

Table 4: Obtained values of morphometric parameters.

Sr.No.	Parameters	Calculated Value
1.	Drainage Density (Dd)	3.26 km/km^2
2.	Stream Frequency (Fs)	3.60 km^{-2}
3.	Drainage Texture (T)	11.73 km/km^4
4.	Length of Overland Flow (Lg)	1.62 km
5.	Constant of Channel maintenance (C)	0.31 km
6.	Form Factor (Ff)	0.35
7.	Circularity ratio (Rc)	0.60
8.	Elongation ratio (Re)	0.67
9.	Bifurcation ratio (Rb)	16.57
10.	Stream Length ration (Rl)	2.49
11.	Rho coefficient (R)	0.15
12.	Basin relief (R)	0.72km
13.	Relief ratio (Rr)	0.038
14.	Ruggedness number (Rn)	2.36
15.	Gradient Index (Sb)	0.03
16.	Melton ruggedness ratio (MRn)	0.06

Longitudinal Stream Profile

Longitudinal profile is a lengthwise graph which is indicative of erosional history of river, bedrock lithology and climate. Presence of soft rock geology may be indicated by presence of local anomalies in longitudinal profile. Longitudinal and transverse profile helps in explaining topography of the basin and especially longitudinal profile indicates land slope (Fig. 5). In present curve, the river gradient is steep in the youthful stage. As the river moves towards mature and then old stage, it has eroded the base level and made the longitudinal slope gentler (Fig. 6).

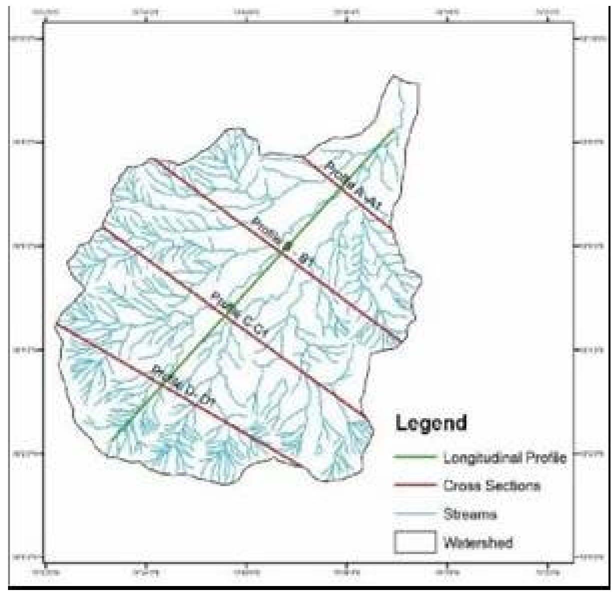

Fig. 5: Location of the longitudinal and transverse profiles of the study area

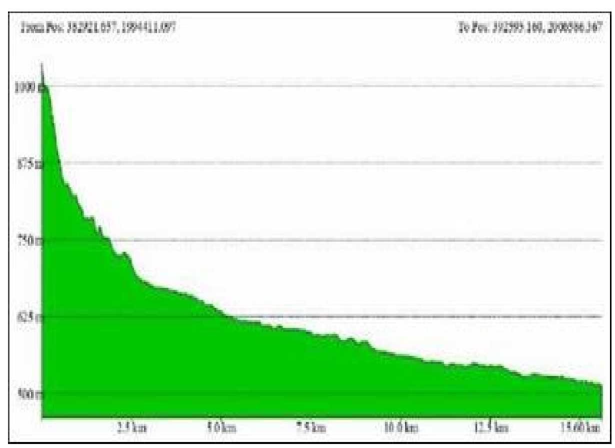

Fig. 6: Longitudinal Profile across the Naygaon watershed

Transverse Stream Profiles

Transverse profile indicates the energy of the river at a particular position and hence the topography of that area. In given watershed, four transverse profiles at different course of river have been generated (Fig. 7). At upper level, the higher energy of river is indicated by deep cutting by river channel. At this position, the valley sides are also steep. At a later profile, the vertical erosion by flowing river is reduced by a little but it is followed by increase in lateral erosion. This leads to formation of floodplain on both sides of river. At third profile, the river has exhausted most of its energy which is shown by its reduced capacity to do vertical erosion. The width of watershed has also shrunk which may be indicative of structural control like presence of high ridges. At last profile, the river is at its lowest energy level and hence most of load it might get deposited in floodplain.

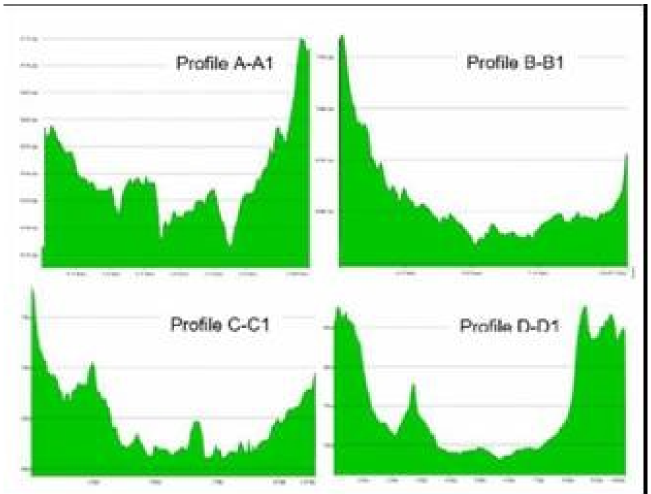

Fig. 7: Transverse Profile across the Naygaon watershed

CONCLUSION

Morphometric analysis of a drainage basin is a quantitative method of describing the characteristics of the surface form of a drainage pattern and provides significant information about the region's topography, geological structures, runoff, and hydrogeological properties of underlying rock. It is also useful in hydrological studies of a river basin/watershed. According to the current study, the Naygaon watershed is a sixth-order basin based on stream order. Here the drainage density value is 3.25 which suggests more surface runoff. Such drainage density values represent fine drainage and have a high potential for use in the construction of surface water harvesting structures. The values obtained for form factor, circulatory ratio, and elongation ratio indicate that the basin has an elongated shape. The mean bifurcation ratio is 3.31, indicating that the watershed is less affected by structural disturbances and that geological structures have little influence on the drainage pattern. The longitudinal profile shows a steep gradient at the start, but it gradually flattens out as the river erodes in the later part of its course. The high drainage density, stream frequency, infiltration number, and drainage texture values indicate that the study area is underlain by impermeable rocks. Morphometric analysis of the Naygaon Watershed in the Pune District of Maharashtra reveals a wealth of useful information for developing a watershed development plan for this area. This area is sparsely populated and prone to draughts. A proper ridge to valley watershed development plan is essential for mitigating the problem. In today's world, where water resources are becoming scarce, this process of assigning various attributes to drainage basins is essential for watershed development and locating sites for water harvesting.

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