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Study of Drainage Characteristics and its Implications for Watershed Management—A Case Study of the Dharma River Basin, Karnataka State, India

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ABSTRACT

The present study is carried out to understand the hydro-geological process over the Dharma watershed using drainage network characteristics and morphometric analysis. Marphometric analysis gives a quantitative description of drainage basin. Aster Digital Elevation model (DEM) and National Bureau of Soil Survey and Land Use planning (NBSS & LUP) soil data were used in the present study. Morphometric parameters were estimated using standard methods and the ArcHydro extension tool of ArcGIS. Fourth stream order basins from five sub-basins in the Dharma watershed were selected to understand the drainage characteristics. Results revealed that the watershed has an elongated shape, dendritic drainage pattern, gentle slope, low stream frequency, very low drainage density, and coarse drainage texture. Morphometric parameters of Dharma watershed indicate that produced surface runoff requires a longer duration to achieve the peak rate and runoff has a lower peak. Further, study results reveal that the Dharma watershed is less prone to soil erosion and flood hazards. The study results assist to understand the hydrological behavior of the ungauged Dharma watershed and which is a prerequisite for any sustainable management of the watershed resources.

Keywords: Dharma watershed, drainage characteristics, morphometric analysis, geomorphology

INTRODUCTION

Morphometry is one of the important aspects of watershed planning and management. Morphometry controls the dynamics of the drainage basin which includes both surface and subsurface hydrological processes of the drainage basin. It involves estimation of different parameters by analyzing the aerial, linear, relief and gradient parameters of the drainage network of the basin/watershed (Horton 1932, Majumdar 1982, Bhagwat et al. 2011). Morphometry is very useful in studies such as groundwater assessment, soil erosion, hydrological modeling, prioritization of watershed, natural hazard risk management, soil-water conservation and rehabilitation (Sreedevi et al. 2005, Sreedevi et al. 2009, Bhagwat et al. 2011, Choudhari et al. 2018, Jamwal et al. 2019).

Morphometry analysis in river basin management is initially used by Horton using topographical maps (Horton 1945). Many researchers have attempted to improve the methods and updated the morphometric parameters (Smith 1950, Miller 1953, Schumm 1956, Strahler 1957, Melton 1958). Due to its wide variety of applications, many researchers have used morphometry analysis in their studies. Initially, morphometric parameters are estimated manually. After the introduction of Geographical Information System (GIS) tools in extracting drainage characteristics using the application of satellite data, researchers have started using GIS tools to study the morphometry over the Indian subcontinent (Das and Mukherjee 2005, Bhagwat et al. 2011, Pandi et al. 2017, Choudhari et al. 2018, Jamwal et al. 2019). Dharma River watershed comes under the southern part of the Indian subcontinent. Despite the Dharma watershed is part of one of the major river basins, it exposed to water stress in recent decades. It's because of climate variability such as a decreasing trend in rainfall and an increasing trend in temperature (Madolli et al. 2014, 2015 and 2020). Though several watershed management schemes are executed in the dharma watershed, water resource problems have not mitigated up to the expected level. A possible reason may be not enough hydro-meteorological studies have been conducted at the micro-level of the Dharma watershed. Therefore, the present study was carried out to understand the watershed hydrological behavior using detailed morphometric analysis from the point of watershed management. This morphometric analysis can be used for water resource management, erosion studies, groundwater-related studies, etc.

MATERIALS AND METHODS

Study Area

The Dharma watershed is one of the sub-watersheds of the Varada river basin, followed by the Tungabhadra river basin which is tributary of the Krishna river basin in southern peninsular India (Fig. 1). Dharma watershed extended from 14.65 ^{0} N to 14.97 ° N latitude and 74.87 ° to 75.30 ° E longitude. The Dharma river ûows from west to east direction through the Sirsi, Mundgod, Hangal and Shiggaon talukas of Karnataka state, covering an area of 591.58 km^2. It is a non-perennial small river, joins the Varada River near the Kudal village, Haveri district (Fig. 1). The Monsoon season (June-September) is the principal season of receiving the most amount of rainfall over the Dharma watershed. The climate of the watershed is sub-tropical with average annual rainfall ranges from is 836 mm (Shiggaon area) to 2488 mm (Sirsi area). Dharma watershed has topography with an elevation range of 500 m to 742 m; the average land slope of 3.73 %. The major soil types of the present study area categorized under USDA textural classification are sandy clay loam followed by silty clay loam, clay and loamy soil. The major crops grown in the study area are paddy, maize, groundnut, jowar, soybean and cotton, etc.

Data and methods

In the present study, Shuttle Radar Topographic Mission (SRTM) 90 m Digital Elevation Model (DEM) was used to extract drainage characteristics of the Dharma watershed. The SRTM DEM data downloaded from the http://srtm.csi.cgiar.org/srtmdata/. In this study, the watershed, sub-watershed and drainage networks were delineated with the help of Arc-hydro tool interface using DEM data. Further, with the help of delineated drainage networks and watershed, morphometric parameters such as stream length ratio, bifurcation ratio, drainage density, stream frequency, length of overland ûow, mean stream length, elongation ratio, gradient ratio, circularity ratio, basin relief, etc. were estimated as per Horton (1945) and Strahler (1957) standard methods. The standard methods and equations were used to estimate morphometric parameters as shown

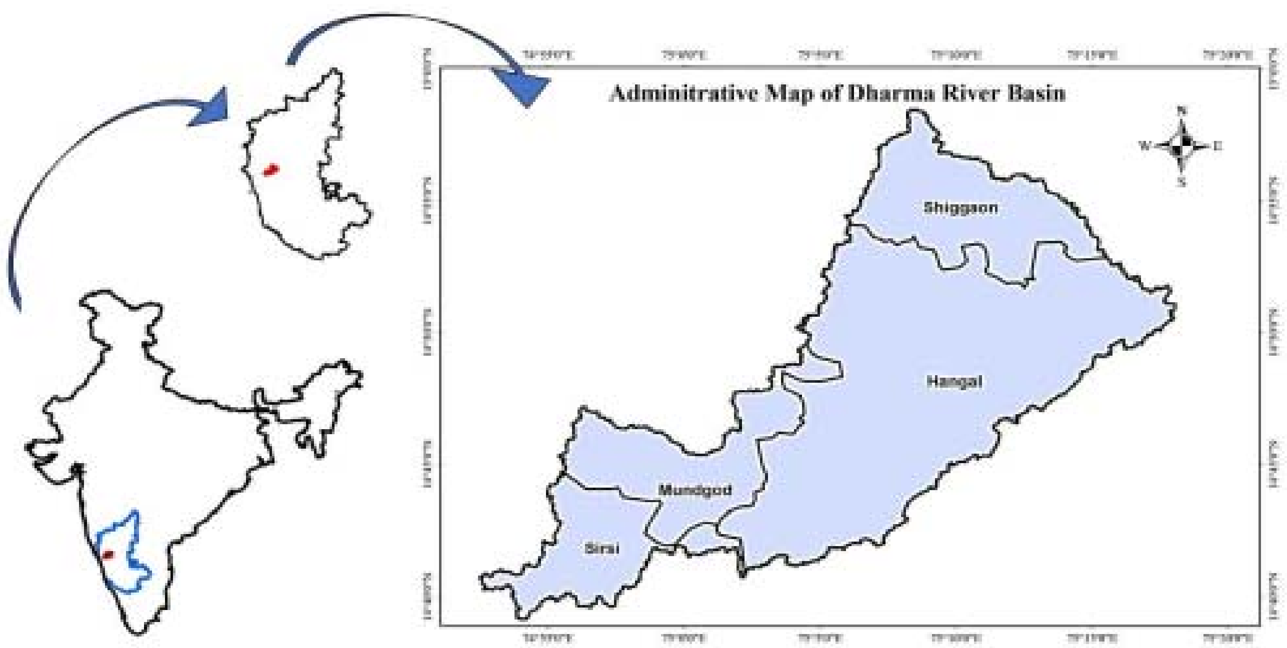

Figure 1. Geographical Map of Dharma Watershed

Table 1. Standard Methods of Morphometric parameters

Morphometric Parameter	Methods and Description	Reference
	Linear Aspects	
Stream Order (u)	Hierarchical ordering	Strahler (1957)
Stream Length (L_u)	Length of the stream	Horton (1945)
Mean Stream Length (L_m)	$L_m = L_u/N_u$	Horton (1945)
Stream Length ratio (R_l)	$R_l = L_u/L_{(u-1)}$; L_u is stream length of order u and $L_{(u-1)}$ is streamof the next lower order	Horton (1945)
Bifurcation ratio (R_b)	$R_b = N_u/N_{(u-1)}$); N_u is number of streams of any given order and $N_{(u-1)}$) is the next higher order	Horton (1945)
	Areal Aspects	
Elongation ratio (R_e)	R_e = {2 sqrt(A/ð)}/ L_b, L_b is basin length	Schumm (1956)
Circularity ratio (R_c)	$R_c = 4ðA/P^2$; P is perimeter of basin	Miller (1953)
Form factor ratio (F_f)	$F_f = A/L_b^2$; L_b is basin length	Horton (1945)
Stream frequency (F_s), no./km^2	$F_s = N/A$; N is total number of streams	Horton (1945)
Drainage density (D_d), km/km^2	$D_d = L_b/A$; L is total stream length; A is area of watershed	Horton (1945)
Drainage texture (D_t)	$D_t = D_d*F_s$	Smith (1950)
Texture Ratio (R_t)	$R_t = N_1/P$; Total number of first order streams	Horton (1932)
Constant of channel maintenances (C_{cm})	$C_{cm} = 1/D_d$	Schumm (1956)
Length of Overland flow (L_g)	$L_g = 1/(2*D_d)$	Horton (1945)
	Relief Aspects	
Basin relief (H), m	$H= H_{max}-H_{min}$; H_{max} is maximum elevation and H_{min} is minimum elevation within the basin	Schumm (1956)
Relief ratio (R_r)	$R_r= H/L_b$	Schumm (1956)
Relative relief ratio (R_{rr})	$R_{rr} = H*D_d/1000$	Melton (1958)
Basin Slope analysis (S_a)	$S_a = H_{max}/L_b$	Miller (1953)
Ruggedness number (R_n)	$Rn = H*D_d/1000$; H is in km	Schumm(1956)

in the Table 1. In the present study, a total of five sub-watershed has been delineated by specifying 5000 ha as the initial threshold drainage area. Typical characteristics of sub-watershed in the basin are shown in the Table 2 and Figure 2. Watershed and all sub-watersheds have long and narrow shape except sub-watershed 1, which has fan shape. The long and narrow shape indicates that basin has more overland flow and simultaneously basin has low peak runoff, longer duration hydrograph. While sub-watershed-1 has fan shape which indicates high peak and narrow hydrograph.

Dharma River watershed has two major agro-climatic zones i.e., Hilly zone (Sirsi and Mundagod Taluk) and Northern Transition zone (Hanagall and Shiggaon taluk) based on Food and Agriculture Organization (FAO) criteria (FAO 1983). Hilly zone receives rainfall in the range of 1401 – 2488 mm, while the Northern transition zone receives 836 – 1062 mm. The land use pattern of the Dharma watershed indicates a major portion of land covered by agricultural land of about 81.67% followed by forest area of 14.71%, range and pasture land of about 1.65%, and water bodies of about 2%.

Spatial distribution of different types of soil across the study area was obtained from the National Bureau of Soil Survey and Land-use Planning (NBSS & LUP), Government of India. The major soil types

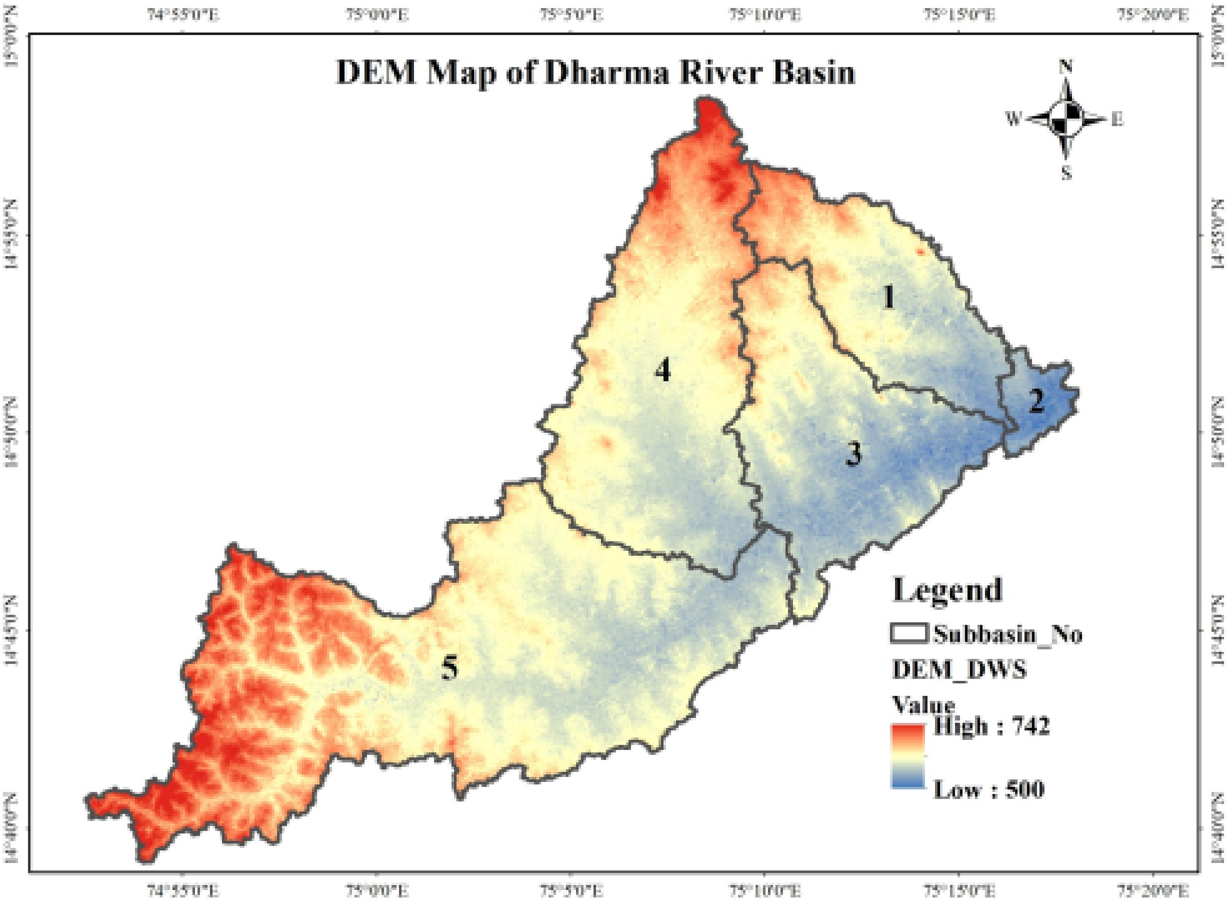

Figure 2. Location of Sub-basin and digital elevation map of Dharma watershed

found in the Dharma watershed are sandy clay loam (55.4%), silty clay (34.4%), clay (3.9 %) and loamy soil (6.3 %) (Fig. 3), percentage distribution of different soil classes were presented in Table 3. With morphometric parameters, distribution of different types of soil and land cover, how these parameters will influence dynamics of hydrological processes at basin and sub-watershed level is discussed in the present study.

RESULTS AND DISCUSSION

Linear aspects of the watershed

Number of Streams, Stream Length and Stream Length ratio

In the present study, order-wise stream numbers has been assessed as per the Strahler (1964). The stream order, order-wise stream numbers, order-wise stream length, stream length ratio and mean stream length of the Dharma watershed are given in Table 4. A total number of streams over the Dharma watershed were found about 164, the highest number of streams observed for 2nd order streams (76) followed by 1st order streams (63) (Table 4). However, total stream length is higher for 1st order streams (102.8 km) followed by 2nd order streams (53 km). While the 4th stream order has the highest mean stream length about 1.79 km. Stream length ratio is observed highest for the 1st order streams, while lowest in case of 2nd order streams. In general, there is a decrease in stream frequency as the stream order increases in the present study (Singh et al. 2019).

Stream order Dendritic stream pattern was found in the study area, which depicts the homogenous subsurface geological strata at the regional scale of the watershed (Fig. 4). The maximum of fourth stream order was observed, first-order has the highest number of streams. Here, the Dharma watershed

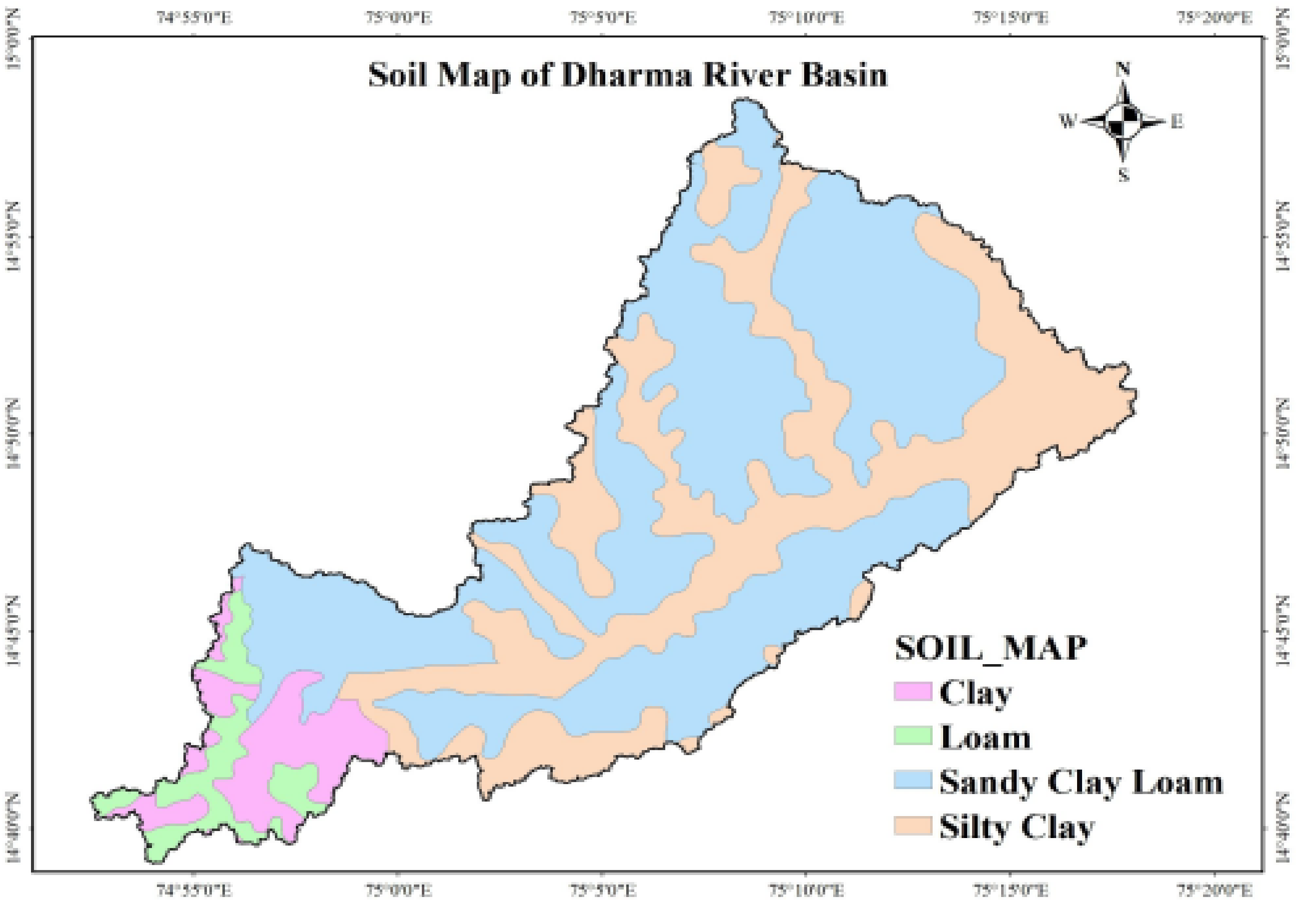

Figure 3. Soil map of Dharma watershed

Table 2. Typical characteristics of the Agro-climatic zones in the basin.

Subbasin	Area (km^2)	Normal Rainfall (mm)	Soil	Elevation (amsl)		
				Average	Minimum	Maximum
1	71.0	836	Silty Clay & Sandy Clay Loam	589.80	514	721
2	10.8	836	Silty Clay	538.26	507	571
3	100.1	836-1062	Silty Clay & Sandy Clay Loam	570.44	500	677
4	140.3	836-1062	Silty Clay & Sandy Clay Loam	600.39	540	742
5	269.4	1062-2488	Clay, Loamy, Silty Clay & Sandy Clay Loam	606.19	537	719

Table 3. Distribution of different types of soil in the Dharma Watershed.

Soil type	Area	Percentage of Area
Sandy Clay Loam	353	55.4
Loam	25	3.9
Clay	40	6.3
Silty Clay	219	34.4

drainage pattern indicating absolute conformity with Horton's law of stream number, where the total length of the streams gradually decreases with successive order (Mishra and Rai 2020).

Bifurcation ratio (R_b) Bifurcation ratio of the Dharma basin varies from 0.83 to 3.17 (Table. 4). Lower values of bifurcation ratio indicates flat regions and higher value associated with intensely fragmented areas (Mishra and Rai 2020). It was

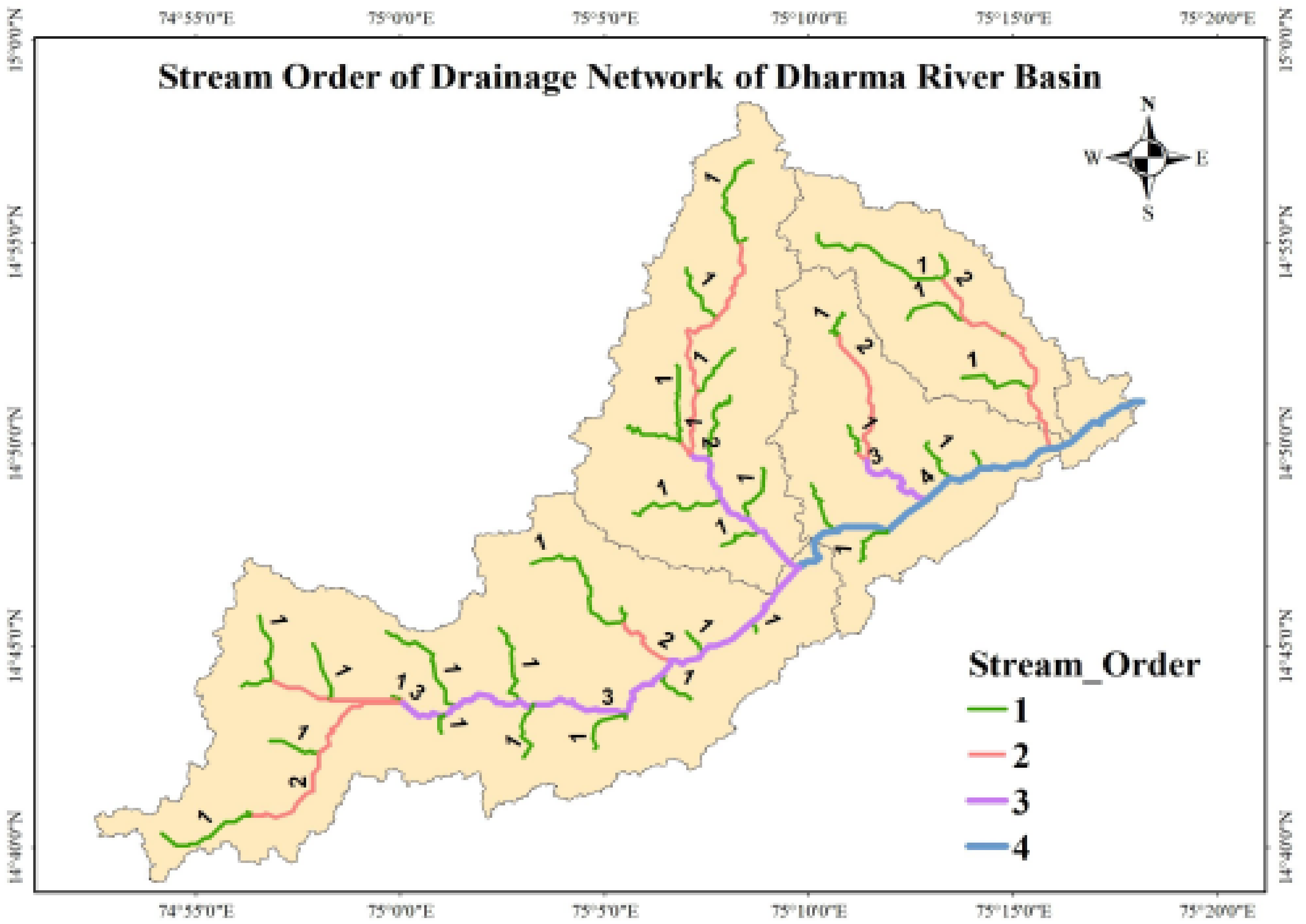

Figure 4. Stream order of drainage network of Dharma watershed.

Table 4: Linear morphometric parameters of the Dharma Basin.

Stream order	No. of streams	Stream length (km)	Mean length (km)	Bifurcation ratio (R_b)	Stream Length ratio (R_l)
1	63	102.18	1.62	0.83	1.926
2	76	53.06	0.70	3.17	1.494
3	24	35.51	1.48	2.18	1.807
4	11	19.65	1.79		

found that the bifurcation ratio is high for most of the third-order streams, while low in the case of the lower-order streams. The potential ability of runoff to cause the damage increases with increases in the bifurcation ratio. Therefore, the area near the third-order streams is more susceptible to flood compare to the lower stream order area. From the middle portion of a watershed to the east portion of the watershed exposed floods along the major streamline area. In these areas there is a chance of deposition of eroded soil will take place. The soil map (Fig. 3) indiacates that silty clay soil distribution is predominant along the stream paths, except for the hilly area, the watershed has a gentle slope. Therefore, apart from the area nearby the major stream, the remaining area of the watershed being rejuvenated, drainages, especially the first-order streams are in the process of development. Further, the 1st order streams have attained the theoretically minimum possible value of 0.83 (Table 4). The bifurcation ratio of the lower order indicates a lower value, which specifies that the basin is slightly dissected as well as has lesser chance of flash runoff discharge (Mishra and Rai 2020).

Areal Parameters

Elongation ratio According to Schumm's (1956) criteria for elongation ratio, the values between 0.5 – 0.7 indicate the basin is elongated and values less than 0.5 basin is more elongated. Dharma watershed has an elongation ratio of about 0.558, therefore the watershed is elongated (Table 5). For the elongated drainage basin, runoff has a longer duration hydrograph and squat with a slowly rising limb in the hydrograph (Strahler 1964).

Circularity ratio The circularity ratio is used to describe the nature of the basin, especially it is very helpful in the case of flood hazard studies (Miller 1953). The circularity ratio of the Dharma watershed found 0.119 which is a very low circularity ratio, which shows the watershed is not circular (Table 5). Generally, drainage basin has a lower sediment yield delivery ratio and high channel storage for the low circularity ratio values. In the case of the sub-watershed scale, a high circularity ratio was observed at sub-watershed -I, which reûects rapid discharge towards the outlet point.

Form factor ratio (R_f) It is the quantitative expression of a drainage basin. Basin is perfectly circular, if the form factor ratio value is more than 0.78, while the lower value indicates an elongated basin (Horton 1941, Strahler 1964). Higher value of Rf high peak flows of shorter duration, while lower values asscoited with indicates lower peak runoff with longer duration (Horton 1941, Mishra and Rai 2020). In the present analysis, the value of the form factor ratio was found about 0.244, which is a very low value (Table 5). This shows that watersheds will produce lower peak runoff for a longer duration for a given storm.

Stream frequency (F_s) Stream frequency factor is the measure of the closeness of the drainage. Higher values of stream frequency indicate rapid and more runoff, while predominant overland runoff and more infiltration in case of lower drainage frequency values (Thomas et al. 2010, Kanhaiya et al. 2018, Rai et al. 2018, Singh et al. 2019). Therefore, this parameter will be very helpful in the case of groundwater potential studies and soil-water conservation studies. For the present study area stream frequency factor was found 0.257 km/km^2 (Table 5). This value depicts, the watershed has more opportunity time to runoff water to get percolation to the substrata (Sreedevi et al. 2009). Therefore, if proper soil-water conservation measures are adopted at suitable locations, there is a possibility of increasing the groundwater potential in the watershed area (Sreedevi et al. 2009).

Table 5. Areal and Relief aspect morphometric properties of the Dharma Basin.

Morphometric Parameter	Representative value
Areal Aspects	
Elongation ratio (R_e)	0.558
Circularity ratio (R_c)	0.119
Form factor ratio (R_f)	0.244
Stream frequency (F_s), no./km^2	0.257
Drainage density (D_d), km/km^2	0.335
Drainage texture (D_t)	0.633
Texture Ratio	0.243
Constant of channel maintenances (C_{cm})	2.77
Length of Overland flow (L_g)	1.38
Relief Aspects	
Basin relief (H), m	242
Relief ratio (R_r)	0.047
Relative relief ratio (R_{rr})	0.934
Basin Slope analysis (S_a)	0.145
Ruggedness number (R_n)	0.081

Drainage density (D_d) The drainage density of a watershed is a very important parameter in assessing flood-related studies. Drainage density values suggest the speed of disposal of generated surface runoff over the catchment (Horton 1932). Further, Zãvoianu (1985) suggested that D_d has major influence on the runoff characteristics, infiltration, soil erosion and sediment load within the watershed. Higher the values runoff disposes of very quickly, while slow disposal of runoff takes place at lower drainage density values (Horton 1932). The drainage density of the Dharma watershed is found about 0.335, which is a very lower value (Table 5). Therefore, generated runoff disposes slowly and takes a long duration disposal time at the study area. Further, Singh et al. (2019) suggested that watershed will consists permeable subsurface/subsoil, coarse drainage texture, and good amount of vegetation for the low drainage density values.

Drainage texture (D_t) It is similar to the stream frequency of the drainage basin, which indicates the relative spacing of the streamlines in the basin (Horton 1945). If the drainage basin has higher drainage density values then the basin has fine drainage texture and vice versa. In detail, Smith (1950) suggests that, if $D_t < 2$ then very coarse drainage texture, D_t values between 2 – 4 indicates coarse drainage texture, moderate drainage texture for D_t values 4 -6, fine drainage texture for D_t values 6 -8 and very fine drainage texture for D_t values > 8. drainage texture (D_t) value of Dharma watershed found about 0.633 (Table 5). Therefore, the study area has a very coarse drainage texture.

Constant of channel maintenance (C_{cm}) Constant of channel maintenance inversely influence the erodibility of the basin (Schumm 1956). Higher values of C_{cm} indicate more drainage area is to produce a unit quantity of surface runoff and losses of surface runoff will take place in the form of percolation, evaporation, etc.; the opposite process will take place in the case of lower C_{cm} values (Schumm 1956). Soil is most erodible if C_{cm} is < 0.2 and least erodible if C_{cm} is > 0.5. Because of the topography and elongated shape of the basin, the watershed has a C_{cm} value of about 2.77 (Table 5). Therefore, erodibility of soil is very least, high permeability of subsoil, and gentle-to-moderate slope over the study area (Singh et al. 2019, Mishra and Rai 2020).

Length of Overland flow (L_g) It is the length of travel of generated runoff from generated point to a definite stream channel. It equals the half of constant of channel maintenance or half of the inverse of the drainage density (Horton 1945). It affects the watershed physiographic and hydrological characteristics. Further, its values suggest the intensity of occurrence of erosion either in the channel or over the land surface. More channel erosion if L_g value is < 0.4 and more sheet erosion if L_g value is > 0.7. The value of the length of overland flow (L_g) is found about 1.38 for the Dharma watershed, which indicates consists of relatively mature stage of the drainage development and sheet erosion is predominant compare to channel erosion over the study area (Table 5) (Singh et al. 2019).

Relief Parameters

Basin Relief, Relief Ratio, Relative Relief and Basin Slope analysis (Sa) The aerial and linear parameters give insights into the basin in terms of two-dimensional aspects of the basin. However, relief characteristics of watershed/basin will use the third dimension of the watershed aspects. The relief of the basin is the difference between maximum elevation (H_{max}) and lowest elevation (H_{min}) of the basin (Horton 1945, Strahler 1964). The study area has the highest and lowest elevation were found as 742m and 500m, respectively. Therefore, the total relief of the Dharma watershed was found at about 242m. Relief ratio is the indicator of erosion rate corresponding to basin slope (Schumm 1956, Strahler 1964). The value of the relief ratio of the Dharma watershed is about 0.047, which represents the moderate relief and gentle slope over the study area. The relative relief ratio of the Dharma watershed found about 0.934. The low relative relief ratio values are characteristic features of less resistant rocks.

Basin slope analysis (Sa) is the ratio of a difference between maximum elevation (H_{max}) of the basin to the length of the basin (Horton, 1945). The overall steepness of a drainage basin can be represented by the slope analysis (Sa) and it indicates the erosion rate on a slope of the basin. In the analysis, it was found that the basin has a slope of 0.047, which indicates the basin has a gentle slope. Overall, the values of basin relief, relief ratio, relative relief and basin slope analysis indicates that water has gentle slope. Therefore, basin has longer peak discharge and kinetic energy produced corresponding runoff water will be lesser, thus runoff has lesser erosive power in the Dharma watershed (Mishra and Rai 2020).

Ruggedness number (R_n) Structural complexity of the basin is indicated by the Ruggedness number. It is the function of drainage density and basin relief (Melton 1958, Strahler 1964). Higher the R_n values, drainage area is more prone to soil erosion and vice versa (Melton 1958, Strahler 1964). If R_n values are less than 0.18, the basin area is less prone to soil erosion. While basin area is more prone to soil erosion for R_n values are higher than the 0.79. The study area has an R_n value of about 0.081, which indicating the study area is less prone to soil erosion and watershed has lack of intrinsic structural complexity (Singh et al. 2019, Thomas et al. 2010).

CONCLUSION

The present study has been carried out to understand the hydrological behavior of a watershed by conducting morphometric analysis using GIS and remote sensing techniques. Areal, linear, and relief aspects of morphometric parameters were estimated using standard methods. A maximum of fourth stream order was found in the study area. The 1st order streams has the highest number of streams, while the overall length of streams is maximum for the 2nd order streams. The watershed has an elongated shape, dendritic pattern, gentle slope, low stream frequency, very low drainage density and coarse drainage texture. Besides, the constant channel maintenance of the basin indicates that the erodibility of soil is very least over the study area. Further, results of the morphometric analysis reveal that hydrological characteristics of the Dharma watershed can be inferred as the overland flow is predominant, a generated surface runoff will take a longer duration to achieve peak rate and the basin has low peak runoff. Therefore, study results indicated that the geometric forms are not ideal to increase the flood velocities, which contribute less available kinetic energy at streams, and erosion and transportation capacities. Thus watershed is less prone to soil erosion. Study results will provide insights into the soil-water resource planning and management over the Dharma watershed.

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Authors' Contributions: Umesh Madolli & J. T. Gudagur designed the study; Umesh Madolli Conceptualization; Methodology; analyzed the data, writing – original draft, review & editing; J. T. Gudagur supervised the entire work, review & editing; Mallappa Madolli contributed in analyzing the data, review, editing and final write up. All the authors read and approved the final manuscript.

Conflict of Interest: We declare that we have no conflict of interest.

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