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# A Sub-basin Level Assessment for Discharge Contribution to Floods in Upper Krishna River Basin, Maharashtra: A Geospatial Approach

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**Abstract:** *The evaluation of basin characteristics from the assessment of morphometric parameters helps in understanding the physical behaviour of the sub-basins which govern the flood discharges. Geographic Information System (GIS) and image processing techniques are implemented for the extraction of drainage networks and analysis of properties of basins for flood assessment and management using Phased Array L-Band Synthetic Aperture Radar (PALSAR) Digital Elevation Model (DEM) which provides 12.5 m spatial resolution data. All the sub-basins show a dendritic drainage network pattern and generally, it is considered as a group of resequent streams within a homogeneous lithology. To assess major influencing sub-basins contributing to flood in the main Krishna river, relevant basin morphometric parameters were applied. Statistical techniques like bivariate correlation analysis and Principal Component Analysis were applied for the identification of major contributing factors. The morphometric analysis of six major potential flood-prone river catchments of the upper Krishna basin discloses that the river like Krishna, Koyna and Doodhganga have a greater tendency to peak discharge within a short period in the main channel because of less Time of Concentration (Tc), high Relief Ratio (Rh) and high Ruggedness Number (Rn). The Warna and Koyna catchment has the highest drainage density (Dd), stream frequency (Sf), and Length of Overland Flow (Lg) causing greater surface runoff which influences the main Krishna river channel. The Elongation Ratio (Re) of all six sub-watersheds shows that the basins are having moderately elongated to elongated shapes. The Panchganga, Doodhganga and Yerla river catchments also have the highest Form Factor (Ff), Drainage Texture ratio (Rt), Length of Overland Flow (Lg), Infiltration Number (If) and Time of Concentration (Tc) which are the causes of moderate to high surface runoff contributing to the main Krishna channel. From the assessment of all influencing factors calculated for different sub-basins, it is observed that, though there are dams constructed across these channels, the Krishna, Doodhganga and Koyna are major flood-contributing rivers. Among these Krishna contributes maximum flood discharge because of its morphometric set-up. The main objective of the present study is to identify the major flood discharge contributing sub basins to the main Krishna river channel.*

**Keywords:** Upper Krishna river, morphometric analysis, floods, DEM, ArcMap.

## Introduction

After Bangladesh, India is known as one of the worst flood-affected countries in the world and accounts for 20% of the global death count due to floods (Agarwal *et al*., 1991). According to the National Commission on Floods (1980), in India, around 40 million ha of land are affected by floods, and on an average 18.6 million ha of land are affected annually. The annual average flood-affected cropped area is about 3.7 million ha (Roy *et al*., 2008). In India, floods are mainly caused by the vagaries of monsoons. Nearly, 75% of the rainfall in the entire country is concentrated over a short monsoon period of four months from June to September. During the monsoon seasons due to heavy rainfall floods occurs in many peninsular rivers like Krishna, Godavari, and Kaveri. In 2005, 2006, 2009, and 2019 due to unprecedented heavy rains, many districts of south Maharashtra and north Karnataka state were severely affected. The 2009 and 2019 floods caused enormous loss of life and property. The heavy rainfall along with huge amount of water discharge from the several major and minor reservoirs in the upper Krishna basin caused inundation and extensive damage to the agricultural lands in the floodplains. In addition, the main tributaries of the basin also contributed more water to the main river causing floods in low-lying areas. Due to the varying drainage morphometries, each sub-catchment has its distinct influence on the main river for flooding (Ozdemir and Bird, 2009). The analysis of the physical behaviour of the river catchment will help in understanding the geomorphic and hydrological problems like floods, soil erosion, and mass movement (Eze and Efiong, 2010). The morphometric analysis is helpful for a better understanding of the hydrological characteristics of the river basin (Nag and Chakraborty, 2003; Sreedevi *et al*., 2009). Morphometric studies of the rivers were first started by R.E. Horton and A.E. Strahler in the 1940s and 1950s respectively (Pidwirny, 2008). Morphometric parameters can be obtained through the measurement of linear, aerial and relief properties of the drainage basin. Pioneering works (Kumar *et al*., 2000; Verstappen, 1983; Strahler, 1957; Schumm, 1956; Miller, 1953; Smith, 1950; Horton, 1945) have studied and developed several morphometric parameters such as Stream Order (U), Stream Number (Nu), Stream Length (Lu), Mean Stream Length (Lsm), Stream Length Ratio (Rl), Bifurcation Ratio (Rb), Mean Bifurcation Ratio (Rbm), Drainage Density (Dd), Drainage Texture (T), Stream Frequency (Fs), Elongation Ratio (Re), Circularity Ratio (Rc), Form Factor (Ff), Length of Overland Flow (Lg), Basin Relief (H), Relief Ratio (Rh), Relative Relief Ratio (Rhp), Ruggedness Number (Rn), Time of Concentration (Tc) and Infiltration Number (If) for the behavioural analysis of surface drainage network and characteristics of the drainage basin. Through the utilisation of these parameters, the characteristics of the sub-basins are ranked for flood (Bhatt and Ahmed, 2014; Patel *et al*., 2012; Javed *et al*., 2009; Esper Angillieri, 2008; Roughani *et al*., 2007; Chopra *et al*., 2005; Alexander, 1972). Through the ranking of sub-basins, it can be determined which sub-basin can bring a higher amount of discharge due to excessive amount of rainfall (Patel *et al*., 2012). For the delineation of watersheds, drainage network extraction and morphometry of the catchment of the sub-basins have been studied by the conventional method. (Bhatt and Ahmed, 2014; Magesh *et al*., 2011; Amee and Dhiman, 2007; Srinivasa Vittala *et al*., 2004; Nag, 1998; Strahler, 1952; Horton, 1945; Smith, 1950). In recent times Remote sensing (RS) and Geographic information systems (GIS) facilitated scientific analysis in the field of hydrology and management of water resources. RS and GIS are effectively used for the extraction of spatial information, specifically for the delineation of watersheds and drainage network extraction (Bhatt and Ahmed, 2014; Ahmed *et al*., 2010; Bertolo, 2000).

The terrain can be represented in the digital format from Digital Elevation Model (DEM) which provides excellent input for the delineation of the watershed boundary and drainage network extraction through the automated procedure followed in any GIS software. The algorithm for automated extraction of drainage networks and delineation of watersheds was developed since the mid-eighties and have been applied in various GIS fields and conventional applications (Bhatt and Ahmed, 2014; Garbrecht and Martz, 2000). In the present study, an attempt has been made to delineate basin boundaries and drainage network extraction from ALOS PALSAR DEM provided by the Alaskan satellite facility (https://asf.alaska.edu) for the upper Krishna river basin through the use of GIS and RS techniques. The assessment of morphometric parameters regarding floods, which are derived from the ALOS PALSAR DEM is used to comprehend the hydrological behaviour of each sub-basin of the upper Krishna river which stimulates floods in the main Krishna river.

## Study area

The Krishna river is a part of the Indian peninsular river system. It is the second-largest river of the Indian Peninsula, which originates at Mahabaleshwar near Jor village in the extreme north of Wai taluka, Satara district, in western Maharashtra and merges into the Bay of Bengal at Hamasaladevi (near Koduru) in Andhra Pradesh, on the east coast. The length of the river is around 1400 km, and

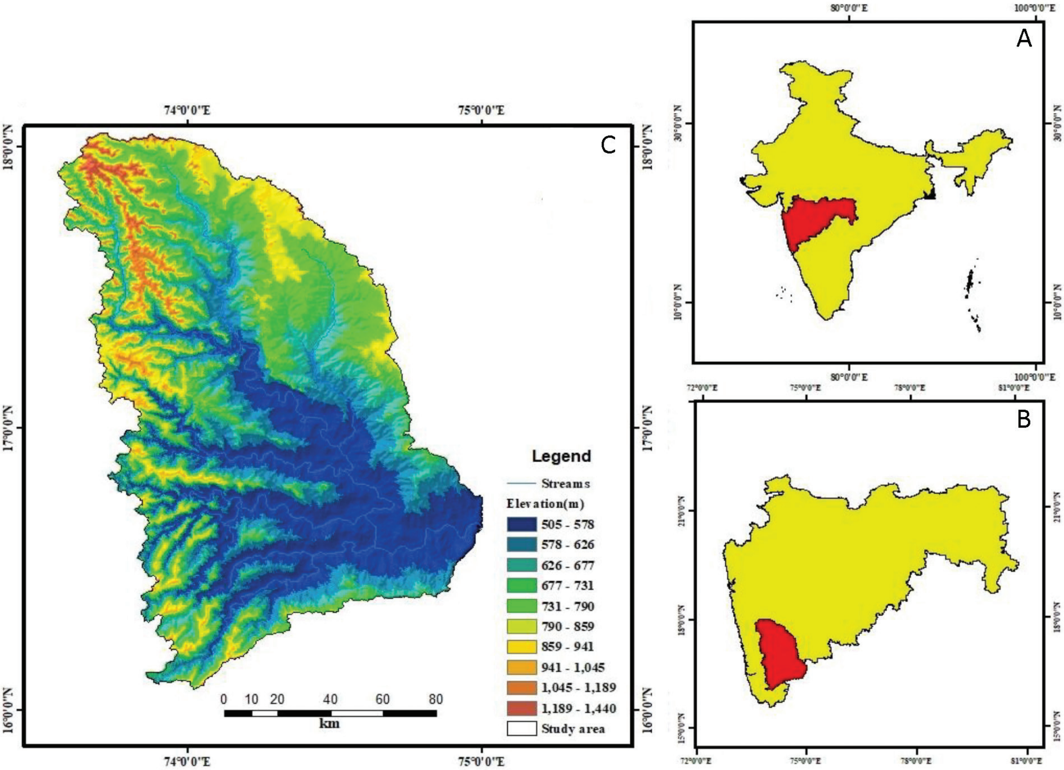


**Figure 1.** (A) Location of Maharashtra within India, (B) Location of the study area in Maharashtra and (C) DEM of upper Krishna basin based on ALOS PALSAR DEM by Alaska Satellite Facility.

it occupies an area of 2,58,948 km$^2$, which is nearly 8% of the total geographical area of the country. The Krishna river and its tributaries are interstate river systems flowing through the states of Maharashtra, Karnataka, and Andhra Pradesh (Superintendent Engineer Report, 2015).

*Location*

The Krishna river basin falls within the states of Maharashtra and a small part in Karnataka. The study area lies between 16º02′ N – 18º07′ N and 75º05′ E – 73º50′ E (Fig. 1) covering parts of Satara, Sangli, and Kolhapur districts in the state of Maharashtra.

The Krishna river is a 7th order stream having a catchment area of about 19331 km$^2$. The principal tributaries of the river basin consist of some major river systems and they are Koyna, Warana, Doodhganga, Panchganga and Yerla.

*Geomorphology*

The upper Krishna basin is roughly cylindrical shaped. The western end of the basin is flanked by Western Ghats i.e. the Sahyadri ranges. The Krishna river flows through the major physiographic zones of hills, ghats & plateaus, the foot hill zones and the plains (Superintendent Engineer Report, 2015).

*Geology*

Geologically, the study area comprises Deccan basaltic lava flows of upper Cretaceous to lower Eocene age and it is classified as ‘alluvium, laterite, and Deccan’ (Bhatt and Ahmed, 2014). A very large area is covered by the Deccan trap, and it is expected that the same type of soil will be found throughout the area. This is, however, not the case. There are differences in the soil type largely because of the presence of different climatic conditions, specifically rainfall. The soil types found in the basin are black soils, red soils, lateritic soils, alluvium soils, saline, and alkaline soils, together with mixed soils like red and black, red and yellow, etc. (Diddee *et al*., 2002).

*Climate and vegetation*

The presence of the high-altitude Western Ghats towards the western part of the study area with high amount of rainfall supports the growth of tropical evergreen forest. The eastern part of the study area experiences semi-arid to arid climatic condition with less forest cover, mainly consisting of tropical dry-deciduous type of vegetation. In addition to this natural vegetation, the area is one of the most intensely cultivated region, with major crops like sugarcane and cereals (Bhatt and Ahmed, 2014).

The climatic factors like precipitation and temperature, suggest that the upper Krishna river basin area lies in the tropical region where the rainfall varies between 500 mm to 6208 mm. The average annual rainfall in the upper Krishna basin is 1300 mm. The Mahabaleshwar taluka and Koregaon taluka of Satara district receive the maximum and the minimum rainfall respectively. The temperature of the area varies between 14°C in the winter to 36°C in the summer (Superintendent Engineer Report, 2015).

*Slope*

The degree of inclination of an object relative to the horizontal plane or the steepness of the terrain is termed as slope. The slope is controlled by the climatic and morphogenetic processes in areas which have varying resistance of rocks. The magnitude of slope exhibited by the upper Krishna river basin varies from 0º to 67.14°. The slope map of the upper Krishna basin is shown in Fig. 2. The higher slope in the study area is contributed by the Western Ghats. The presence of high slope results in rapid runoff with a high amount of soil loss, especially during the monsoons.

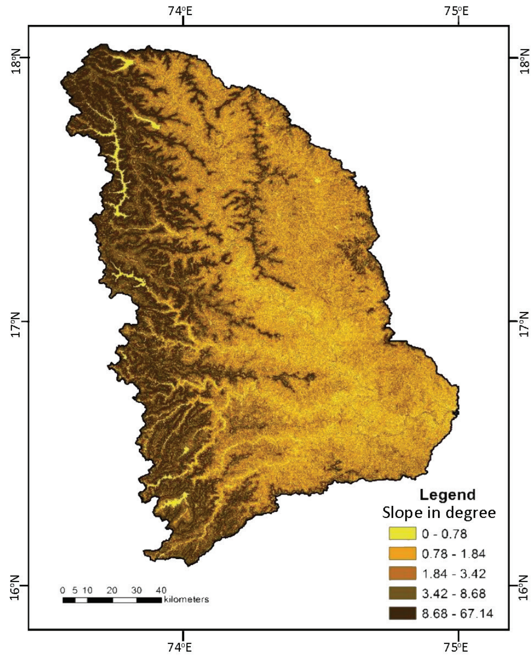


**Figure 2.** Slope map of the study area.

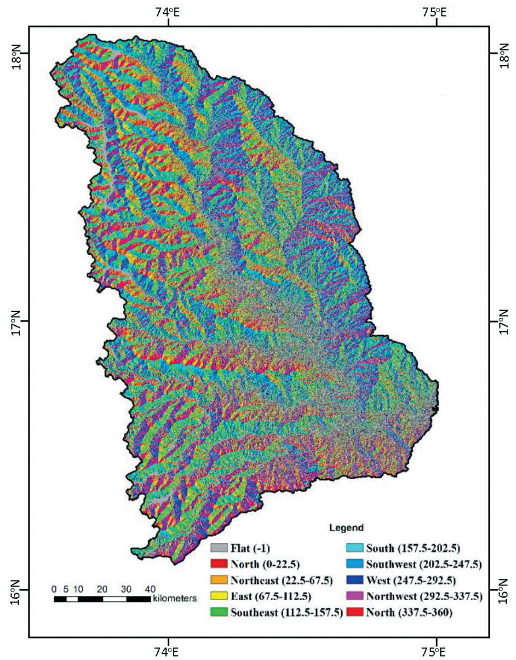


**Figure 3.** Aspect map of the study area.

*Aspect*

The aspect of a terrain indicates the direction in which it faces. The aspect influences the type of vegetation, precipitation patterns, snow melt and wind exposure. Using the output raster data, the direction of the aspect is derived in which 0º is true north; 90° aspects are towards the east, and so forth (Magesh *et al*., 2013). The aspect map of the upper Krishna basin is shown in Fig. 3. The dominant slope aspect observed in the study area is east facing where we can observe a high amount of vegetation cover.

**Data and methods**

The study is primarily based on the ALOS PALSAR DEM by Alaska Satellite Facility (https://asf.alaska.edu). This data set has been used to delineate the basins, generate streams, and create cross-sections of channels in ArcGIS, version 10.3. The detailed information of the dataset is discussed below:

*ALOS PALSAR*

The Phased Array L-Band Synthetic Aperture Radar (PALSAR) developed by Alaska Satellite Facility (ASF) is an active microwave sensor using L-Band frequency to achieve cloud-free and day and night land observation with the resolution of 12.5 m. The development of the PALSAR is a joint project between JAXA (Japan Aerospace Exploration Agency) and the Japan Resources Observation System Organization (JAROS). For this study, ASF data were downloaded from the official website (https://earthdata.nasa.gov/eosdis/daacs/asf).

The manual extraction of the drainage basin and stream network for a large area is a tedious task. To overcome this problem, two techniques have been used for analysing the morphometric parameters of the basin — one is the extraction of river basin boundary and the other is extraction of stream network from the river basin by using the ALOS PALSAR

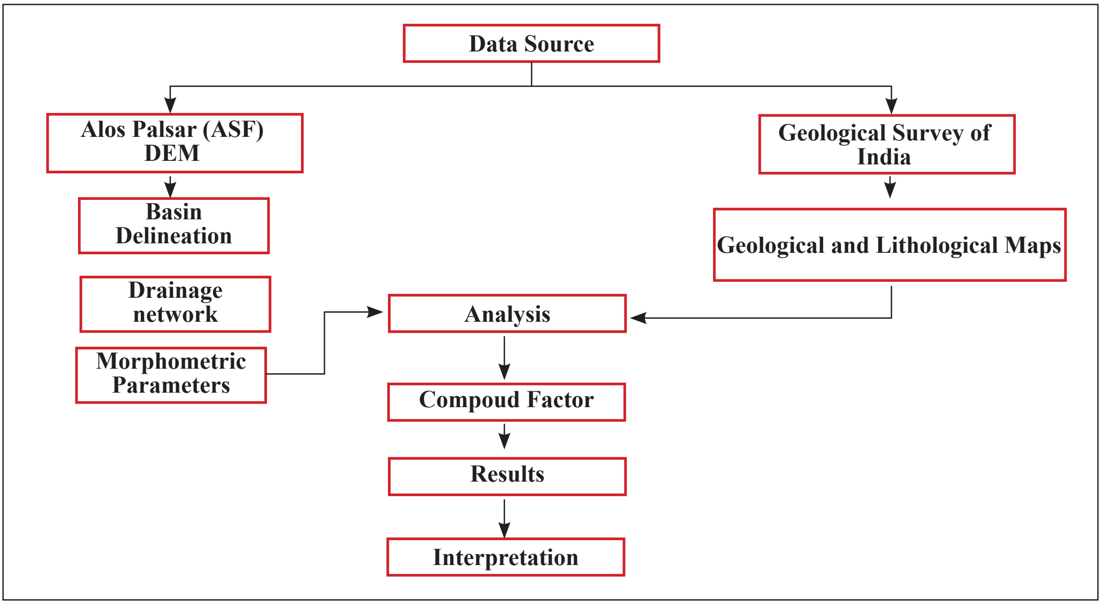


**Figure 4.** The flow diagram shows the methodology to generate basins, streams and other morphometric parameters.

Digital Elevation Model (DEM) in ArcGIS version 10.3 environment.

Creating a depression-less DEM is an important step to delineate any of the morphometric parameters. The flow chart (Fig. 4) shows the steps followed to generate the drainage basins and extract the stream network. The first step to delineate the river

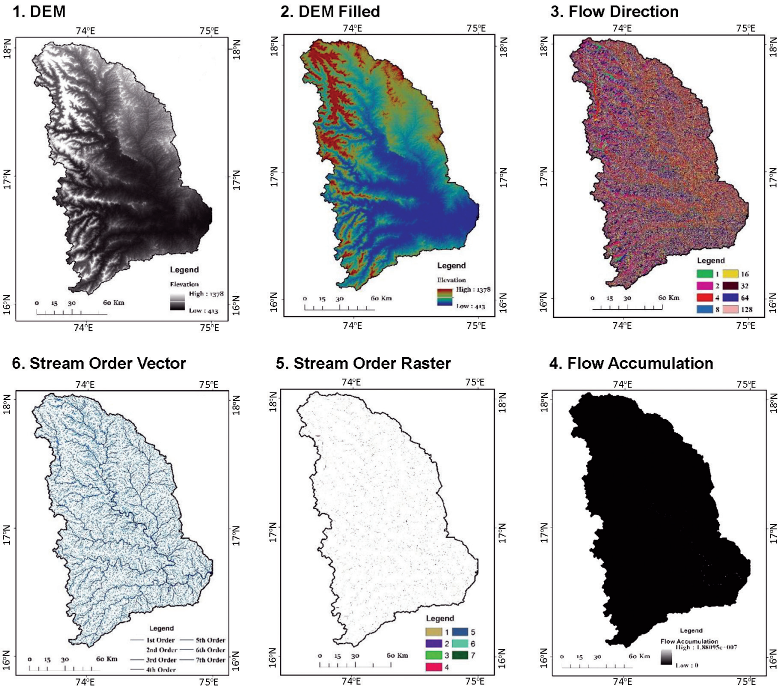


**Figure 5.** The six steps of extraction of drainage network from DEM.

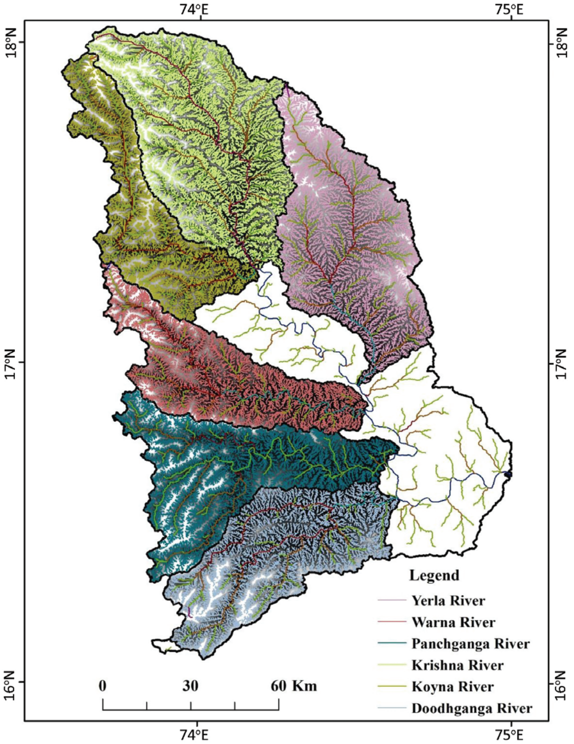


**Figure 6.** Sub-Basins of the upper Krishna basin.

basin is to fill the missing elevation points of the downloaded data by using the FILL command in the hydrology tool of ArcGIS which uses a linear interpolation method to derive values from neighbouring pixels. To determine where the basin drains, the Flow Direction tool is used which gives the direction of flow of each cell in the basin. Flow direction was determined by using the filled DEM. Flow Accumulation is the next step in hydrological modelling, which is generated from the flow direction raster. The threshold value 800 is assigned to generate a drainage network.

The watershed and basin tool in ArcGIS are used to delineate the basin boundary by giving input of flow direction raster and Pour Point. Then the Stream Order tool is used to extract the main stream, which has the maximum length. The extraction of the stream network has been done using a series of geoprocessing tools (Fig. 5). The sub-basins of the study area consisting of the major rivers like Krishna, Koyna, Warana, Panchaganga, Doodhganga, and Yerla, are accurately delineated by using the method explained above. In the next step the morphometric parameters (Table 1) of each basin are calculated and analysed using Microsoft Excel software.

## Result and discussion

### *Morphometric parameters*

The basic morphometric parameters such as basin area, basin perimeter, basin length, and the minimum and maximum elevation of the catchment are derived from the ALOS PALSAR DEM in ArcGIS version 10.3 environment (Table 2).

### *Linear aspect of river basin morphometry*

The linear aspects of the basin are related to the pattern of the channels in the drainage network. It includes a computation of stream

**Table 1.** Morphometric parameters and corresponding formulae

| Morphometric parameters | Formula and description | References |
|---|---|---|
| | Basic parameters | |
| Stream Order (U) | Hierarchical order | Strahler (1964) |
| Stream Number (Nu) | Number of stream segments of each order | Horton (1945) |
| Stream Length (Lu) | Length of the stream | Horton (1945) |
| Mean Stream Length (Lsm) | Lsm = Lu/Nu; where:<br>Lu = Stream length of order 'U', and<br>Nu = Total number of stream segments of order 'U' | Horton (1945) |
| | Derived Morphometric parameters | |
| Relief parameters | | |
| Basin Relief (H) | $H = h_{max} – h_{min}$; where:<br>H = Basin relief,<br>$h_{max}$ = The highest point elevation in the basin and<br>$h_{min}$ = The Lowest point/basin mouth elevation in the basin. | Strahler (1964) |
| Relief Ratio (Rh) | $R_h = h/L_b$, where:<br>$R_h$ = Relief ratio, h = Total relief of the basin and<br>$L_b$ = Maximum length of the basin. | Schumm (1964) |
| Ruggedness Number (Rn) | Rn = Dd *(H/1000); where:<br>H = Basin relief and $D_d$ = Drainage density. | Strahler (1964) |
| | Drainage parameters | |
| Bifurcation Ratio (Rb) | Rb = Nu/Nu+1; where:<br>Nu = Total number of stream segments of order 'u' and<br>Nu+1 = Number of stream segments of next higher order. | Schumm (1956) |
| Stream Length Ratio (Rl) | Rl = Lu/Lu-1, where:<br>Lu = Total stream length of order 'U' and<br>Lu-1 = Stream length of next lower order. | Horton (1945) |
| Drainage Density (Dd) | Dd = Σ Lu/A; where:<br>Lu = Total length of streams and A = Area of watershed. | Horton (1945) |
| Stream Frequency (Sf) | Fs = Nu/A; where:<br>Nu = Total number of streams<br>A = Area of watershed. | Horton (1945) |
| Infiltration Number (If) | If = Dd * Fs; where:<br>Dd = Drainage density ($km\ km^{-2}$) and<br>Fs = Drainage frequency / Stream frequency. | Zavoiance (1985) |
| Drainage Texture (Rt) | Rt = Nu/P; where:<br>Nu = total number of stream segments of all orders in a basin<br>P = Perimeter (km). | Horton (1945) |
| Length of Overland Flow (Lg) | Lg = 1/2 Dd; where: Dd = Drainage density. | Horton (1945) |
| Time of Concentration (Tc) | $Tc = 6.95(L^{1.15}/Bh^{0.385})$; where:<br>L = Main Stream Length (km) and Bh = Basin Relief (m). | Verstappen (1983), Kumar *et al.* (2000) |
| Constant of Channel Maintenance (Cc) | $C = 1/D_d$; where:<br>$D_d$ = Drainage density. | Schumm (1956) |
| | Basin slope and shape parameters | |
| Elongation Ratio (Re) | Re = Re=2√(A/π)/Lb; where:<br>A = Area of watershed<br>π = 3.14, Lb = Basin length. | Schumm (1956) |
| Circulatory Ratio (Rc) | $Rc = 4*\pi*A/P^2$; where:<br>A = Area of watershed, π = 3.14<br>P = Perimeter of the watershed. | Miller (1953) |
| Form Factor (Rf) | $Rf = A/(Lb)^2$; where:<br>A = Area of watershed, Lb = Basin length. | Horton (1932) |

**Table 2.** Basic parameters derived from sub-basins.

| Catchment | Basin Area (A) in km$^2$ | Perimeter (P) in km | Basin Length (L) in km. | Minimum Elevation (h) in m. | Maximum Elevation (H) in m. | Total Basin Relief in m |
|---|---|---|---|---|---|---|
| Krishna | 3497.86 | 351.27 | 98.41 | 466 | 1383 | 917 |
| Koyna | 1931.09 | 355.85 | 92.50 | 467 | 1382 | 915 |
| Panchganga | 138.79 | 394.92 | 93.31 | 433 | 952 | 519 |
| Dudhganga | 123.49 | 312.25 | 90.37 | 446 | 959 | 513 |
| Yerla | 3036.97 | 378.51 | 107.62 | 455 | 1011 | 556 |
| Warna | 2077.57 | 345.83 | 103.77 | 452 | 1032 | 580 |

order, stream number, stream length ratio, and bifurcation ratio which have been explained below:

### Reduction of the width of the rivers

The concept of stream order was introduced by Horton in 1932. Stream order is defined as a measure of the position of a stream in the hierarchy of tributaries (Leopold et al. 1964). The first-order streams are those that do not have any tributary and these normally flow during the wet season (Chow *et al*., 1988). All the rivers in the study area are ordered according to Strahler's method of stream ordering. The stream order and the total number of stream segments in each order for all the basins are shown in Table 3, where the Krishna river is the highest order stream (8th

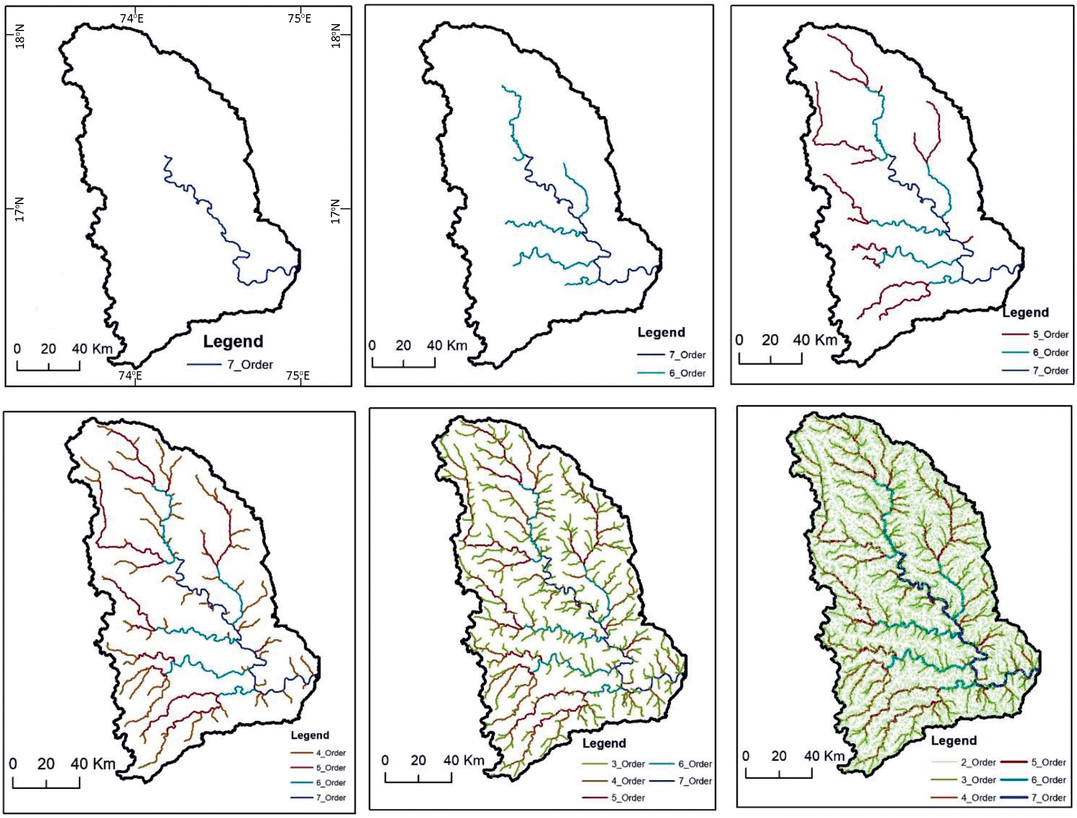


**Figure 7.** Order-wise stream network in upper Krishna sub-basin..

**Table 3.** Order-wise number of streams.

| Catchment | I Order | II Order | III Order | IV Order | V Order | VI Order | VII Order | Total No. of Streams |
|---|---|---|---|---|---|---|---|---|
| Krishna | 6645 | 1529 | 385 | 59 | 15 | 3 | 1 | 8637 |
| Koyna | 3508 | 804 | 182 | 32 | 7 | 2 | 1 | 4536 |
| Panchganga | 4610 | 862 | 232 | 47 | 9 | 3 | 1 | 5764 |
| Doodhganga | 4412 | 798 | 216 | 48 | 7 | 2 | 1 | 5484 |
| Yerla | 5607 | 1097 | 253 | 51 | 11 | 2 | 1 | 7022 |
| Warna | 3629 | 656 | 204 | 33 | 9 | 2 | 1 | 4534 |

order) and the remaining sub-basins are of 7th order (Fig 7).

The main channel through which most of the water is discharged is marked as the highest-order steam of a particular drainage basin. The stream order depends on the basin characteristics such as basin shape, size, and relief (Haghipour and Burg 2014).

The presence of a large number of streams indicates a topography which is dominated by the erosional process whereas smaller number of streams represents less erosion. The observation of the results indicates that all calculated values match Horton's (1945) scheme, which described that as the stream order increases the number of streams gradually decreases.

### Stream number (Nu)

The number of streams of different orders and the total number of streams of all the basins are counted independently using the ArcGIS environment. Generally, the number of streams gradually decreases with an increase in the order of streams. The number of streams of each order depends on the physiographic and structural conditions of the region (Magesh *et al*., 2013). The Krishna river basin shows a large number of streams, and the remaining sub-basins are smaller in size with lesser number of streams. The observation of the study area shows large number of 1st order streams which indicate that there is a high possibility of sudden flash floods after rainfall in the downstream areas (Chitra *et al*., 2011).

### Stream length (Lu)

The total stream length is calculated individually for each catchment using ArcGIS 10.3 environment using geometry command and the results are shown in Table 4. the stream length is the chronological development of the stream segments.

It is observed that the total length of the 1st order streams is maximum, and it is decreasing with an increase of the stream order. The total stream length of Krishna river is 7239.10 Km. The presence of longer lengths of streams represents areas with low gradient and the short-length streams indicate areas with steep slopes and fine texture (Strahler, 1964; Magesh *et al*., 2013).

**Table 4.** Order-wise Stream Length.

| Catchment | I Order | II Order | III Order | IV Order | V Order | VI Order | VII Order | Total Stream Length (Km) |
|---|---|---|---|---|---|---|---|---|
| Krishna | 3924.49 | 1837.95 | 805.17 | 316.23 | 195.17 | 85.10 | 75.00 | 7239.10 |
| Koyna | 2012.01 | 911.47 | 359.46 | 204.50 | 115.89 | 61.29 | 11.10 | 3675.72 |
| Panchganga | 2574.50 | 1289.25 | 507.33 | 197.58 | 173.58 | 83.53 | 56.76 | 4882.54 |
| Doodhganga | 2387.04 | 1227.06 | 527.48 | 208.84 | 124.32 | 100.84 | 34.93 | 4610.52 |
| Yerla | 2919.21 | 1428.61 | 712.54 | 348.79 | 133.50 | 76.34 | 48.97 | 5667.95 |
| Warna | 2136.66 | 1003.00 | 454.63 | 206.24 | 42.57 | 77.58 | 70.53 | 3991.17 |

**Table 5.** Mean Stream Length.

| Catchment | I Order | II Order | III Order | IV Order | V Order | VI Order | VII Order |
|---|---|---|---|---|---|---|---|
| Krishna | 0.59 | 1.20 | 2.10 | 5.36 | 13.01 | 28.37 | 75.00 |
| Koyna | 0.57 | 1.13 | 1.98 | 6.39 | 16.56 | 30.65 | 11.10 |
| Panchganga | 0.56 | 1.50 | 2.19 | 4.21 | 19.27 | 27.84 | 56.76 |
| Doodhganga | 0.54 | 1.54 | 2.44 | 4.35 | 17.76 | 50.42 | 34.93 |
| Yerla | 0.52 | 1.30 | 2.82 | 6.84 | 12.14 | 38.17 | 48.97 |
| Warna | 0.59 | 1.53 | 2.23 | 6.25 | 8.62 | 35.27 | 42.57 |

### Stream length ratio (Rl)

It is the ratio between the lengths of streams in a given order to the total length of streams in the next order (Horton, 1932). The observation during the study shows that the whole upper Krishna river watershed has a stream length ratio in the range of 0.36 to 2.85, which is shown in Table 5. Higher the stream length ratio more the chances of recharge (Table 5).

### Bifurcation Ratio (Rb)

The bifurcation ratio is related to the branching pattern of a drainage network (Schumm, 1956), which is defined as the ratio of the number of streams in a particular order to the number of streams in the next higher order in the drainage basin. The bifurcation ratio is a dimensionless property which shows the degree of integration between streams of various orders (Magesh *et al*., 2013). Generally, the mean bifurcation ratio varies between 3 and 5 which suggests that there is no structural influence on the drainage pattern; whereas a value greater than 5 suggests that the drainage pattern is dominated by some sort of geological control (Dikpal *et al*., 2017). In this study the mean bifurcation values (Table 6) of all the drainage basins range from 4.10 to 4.43. The Krishna river basin has a higher value i.e., 4.35 which implies that there is some amount of geological control over the drainage pattern.

### *Areal aspect of river basin morphometry*

The areal aspects are two-dimensional properties of a basin. The total area of the basin is shown in Table 2 which is 19331 km$^2$. The areal aspects of drainage basin include Drainage Density, Stream Frequency, Drainage Texture Ratio, Elongation Ratio, Circulatory Ratio and Form Factor ratio. These morphometric properties are explained below:

### Drainage density (Dd)

Drainage Density is the total length of streams of all orders per unit area of the basin (Table 1). The factors that affect drainage density are resistance to weathering, the permeability of underlying rock, climate, and vegetation. Low drainage density is favoured where the basin relief is low (Bhatt and Ahmed, 2014). The drainage density in the study area is ranging between 0.95 to 1.92 km km$^{-2}$. (Table 6). The value of the drainage density in the study area do not show significant variation. The high value of drainage density represents high relief and impermeable surface material.

### Stream Frequency (Sf)

The total number of stream segments of all orders per unit area is termed stream frequency (Horton, 1932). It is directly related to permeability, infiltration capacity and relief of the basin. Stream frequency also depends on the rainfall, relief, resistivity of rocks as well as drainage density of the basin

(Mahala, 2020). In the upper Krishna river basin, the stream frequency (Table 6) of all the catchments vary between 2.18 to 2.45. Low stream frequency, with little variation among the sub-basins indicates a poor drainage network developed over a uniform lithology.

### Drainage texture (Rt)

Drainage texture is defined as the total number of stream segments of all orders in a basin per perimeter length of the basin. It depends on several factors such as the amount of rainfall, type of soil, vegetation density, infiltration capacity and relief (Mahala, 2020). The drainage texture is classified into five different classes, and these are: coarse (<4 $km^{-1}$), intermediate (4 to10 $km^{-1}$), fine (10 to15 $km^{-1}$) and ultra-fine (>15 $km^{-1}$). Results of the drainage texture from the study area vary between 13.11 and 24.59 (Table 6), which indicates fine to ultra-fine texture (Smith, 1950; Bhatt and Ahmed, 2014).

### Elongation ration (Re)

The elongation ratio is defined as the ratio of the diameter of a circle of the same area as the basin to the maximum basin length (Schumm, 1956). The value of the elongation ratio varies from 0 to 1 i.e., highly elongated shape to circular shape. Circular basins are more efficient in the discharge of runoff than elongated ones because the concentration time is less in the circular basin (Magesh *et al*., 2013). The Krishna river basin has a moderate elongation ratio i.e., 0.68 which indicates that the basin is elongated. The other catchments of the study area are also representing a moderate elongation ratio (Table 6) and represents low peak flow for a long period.

### Circulatory ration (Re)

The circulatory ratio is defined as the ratio between the area of the basin to the area of a circle having the same perimeter (Strahler, 1964). The circulatory ratio depends on the stream frequency, drainage density, geological structure, climate, relief, and slope of the basin. The values between 0 to 1 represent the minimum and maximum circulatory of a basin. The result of the circulatory ratio in the study area varies from 0.19 to 0.36, where the Koyna river basin is showing the lowest value. The highest value 0.36 is of Krishna river basin (Table 6), which represents a less circular basin shape with low peak flow for a long period.

### Form factor ($R_f$)

The ratio of the area of the basin to the square of the basin length is known as the form factor (Horton, 1932). An elongated basin is represented by small value of the form factor. The value 0 indicates elongated characteristics of the basin whereas 1 indicates near-circular characteristics. The circular basin indicates high peak flow in a short period and lower values indicate low peak flow over a longer period (Mahala, 2020). The form factor values vary from 0.19 to 0.36 in the study region (Table 6) indicating elongated basins with low peak flow for longer periods.

### Infiltration number (If)

The infiltration number is a product of Dd and Fs (Table 1) and provides an idea about the infiltration characteristics of the catchment. The infiltration number is inversely proportional to the infiltration capacity of the basin (Romshoo *et al*., 2012). i.e., the higher the infiltration number, the lower will be the infiltration and the higher will be the runoff. In the upper Krishna river basin, Krishna has a lower infiltration number than all the other sub-basins (Table 6). It indicates that except Krishna, all other rivers in the upper Krishna river basin have lower infiltration and a high runoff rate.

**Table 6.** Derived morphometric parameters.

| Catchment \ Morphometric parameters | Drainage density (Dd) in km km$^{-2}$ | Stream frequency (Sf) | Drainage texture ratio (Rt) | Form factor (Ff) | Mean bifurcation ratio (Rbm) | Ruggedness number (Rn) | Relief ratio (Rh) | Elongation ratio (Re) | Circularity ratio (Rc) | Length of overland flow (Lg) | Constant of Channel Maintenance (Cc) | Infiltration Number (If) | Time of Concentration (Tc) | Basin Relief (H) in m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Krishna | 0.95 | 2.45 | 24.59 | 0.36 | 4.37 | 0.92 | 9.32 | 0.68 | 0.36 | 0.48 | 1.05 | 2.33 | 154.45 | 917 |
| Koyna | 1.90 | 2.35 | 12.75 | 0.23 | 4.10 | 1.74 | 9.89 | 0.54 | 0.19 | 0.95 | 0.53 | 4.47 | 166.97 | 915 |
| Panchganga | 1.89 | 2.24 | 14.60 | 0.30 | 4.21 | 1.00 | 5.56 | 0.61 | 0.21 | 0.94 | 0.53 | 4.23 | 182.12 | 519 |
| Doodhganga | 1.88 | 2.25 | 17.56 | 0.30 | 4.35 | 1.00 | 5.68 | 0.62 | 0.31 | 0.94 | 0.53 | 4.23 | 159.21 | 513 |
| Yerla | 1.86 | 2.31 | 18.55 | 0.26 | 4.43 | 1.02 | 5.17 | 0.58 | 0.27 | 0.93 | 0.54 | 4.23 | 182.92 | 556 |
| Warna | 1.92 | 2.18 | 13.11 | 0.19 | 4.18 | 1.11 | 5.59 | 0.50 | 0.22 | 0.96 | 0.52 | 4.19 | 194.74 | 580 |

Hence, waterflow during monsoon season accumulates to the main Krishna river within a short period.

### Length of overland flow (Lg)

The length of overland flow is nothing but the length of water flowing over the ground before getting accumulated into a definite stream channel (Horton, 1932). It is dependent on the lithology, climatic conditions, permeability, type of vegetation, relief as well as duration of erosion. It is about half of the reciprocal of drainage density. The length of overland flow in all the sub-watersheds is ranging from 0.48 to 0.96 which shows that the basins are experiencing very high structural control, high runoff conditions, and have higher overland flow. A higher value of the length of overland flow indicates a longer flow-path and a gentle slope.

### Constant of channel maintenance (Cc)

The constant of channel maintenance is defined as the inverse of drainage density (Schumm, 1956). Also, it can be stated as the area required to maintain one kilometre of linear stretch of the channel. In general, a higher constant of channel maintenance shows higher permeability of rock of a particular basin. It is observed that Krishna river has a higher constant of channel maintenance of 1.02 and in the other sub-watersheds the values vary from 0.52 to 0.54 (Table 6) which shows higher permeability of subsoil in Krishna Sub-watershed and moderate permeability in others.

### Time of Concentration (Tc)

The time of concentration is nothing but the time taken by basin water to travel from the source to its outlet (Table 1). A higher concentration time denotes a greater length that basin water has to travel from the most distant point to its outlet (Bhatt, S. and Ahmed, A., 2014; Ozdemir and Bird, 2009). In the upper Krishna river basin, it is observed that Krishna and Koyna (Table 6) have a lower value of time of concentration and it indicates that these river basins attain peak flow discharge in a short period. The Panchganga, Doodhganga, Yerla and Warna river basins show higher time concentration values which represent longer time for peak discharge.

*Relief aspects of river basin morphometry*

The relief aspects are considered as three-dimensional representation of the aspects which includes Basin relief, Relief ratio, Slope, Aspect, Relative relief, and Ruggedness number which are calculated and explained below:

Basin relief (H)

Basin relief is defined as the difference in elevation between the highest and the lowest point on the valley floor of the basin. The basin relief plays a significant role in landform development, having direct bearings on permeability, surface and sub-surface waterflow. It is also an important factor in understanding the denudational characteristics of the basin (Magesh *et al.*, 2011). Figure 1 represents the relief map of the study area, which is showing that the maximum elevation of the upper Krishna river basin is 1383 m and the value of basin relief is given in Table 2 for all the catchments. High basin relief indicates low infiltration rate as well as high runoff condition.

Relief ratio (Rh)

Relief ratio denotes the ratio between the total relief to the length of the principal drainage line. It depends on different factors of areal and relief characteristics of the basin. It is an indicator of erosional processes operating on the slopes of the basin and it also measures the overall steepness of the drainage basin (Kamala and Samynathan, 2018). In the study area, the value of the relief ratio ranges from 5.17 to 9.97 with an average relief ratio of 0.0056 (Table 6).

Ruggedness number (Rn)

The structural complexity of the basin with the association of relief and drainage density is shown by the ruggedness number. The Krishna river in the study area shows the highest ruggedness number as compared to the other catchments (Table 6). Basins with a high ruggedness number and fine drainage texture has high flood potential and lower value of ruggedness number indicates a lesser degree of low relief which causes less water flow (Bhatt and Ahmed, 2014).

**Results of bivariate correlation analysis**

Fourteen indices were used to identify which variables are their optimal descriptors in terms of both ease of measurement and interpretability. Bivariate correlation coefficient between each pair of variables was calculated for the measurement of intercorrelation amongst the variables (Table 7). The table is self-explanatory. Bivariate correlation analysis was carried out at 95%, 99% and 99.9% significance level for the all-morphometric parameters. Among all the parameters Stream frequency has significant correlation with Drainage density; Drainage texture and Form factor has significant relation with Drainage density. Mean bifurcation ratio, Ruggedness number and relief ratio does not show any significant correlation except Relief ratio to Stream frequency. Elongation and Circularity ratios show significant relation with Drainage density, Drainage texture and Form factor. Circularity ratio shows significant relation with Mean bifurcation ratio and Elongation ratio. Length of overland flow shows significant relation with Drainage density, Stream frequency, Drainage texture, Form factor, Elongation ratio and Circularity ratio. Constant of channel maintenance and Infiltration number are significantly correlated with Drainage density, Drainage texture, Circularity ratio and Length of overland flow. Time of concentration is significantly correlated only with Stream frequency and Form factor. Lastly, Basin relief has significant correlation with Stream frequency and relief ratio.

From the correlation analysis, it is clear that, in majority of the sub basins, the linear morphometric properties like Drainage density, Stream frequency, Length of overland flow, Infiltration number and

**Table 7.** Bivariate correlation matrix of morphometric properties of upper Krishna basin.

| Variables | Drainage density (Dd) (km km$^{-2}$) | Stream frequency (Sf) | Drainage texture ratio (Rt) | Form factor (Ff) | Mean bifurcation ratio (Rbm) | Ruggedness number (Rn) | Relief ratio (Rh) | Elongation ratio (Re) | Circularity ratio (Rc) | Length of overland flow (Lg) | Constant of Channel | Infiltration Number (If) | Time of Concentration (Tc) | Basin Relief (H) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Drainage density (Dd) (km km$^{-2}$) | 1 | | | | | | | | | | | | | |
| Stream frequency (Sf) | -.802* | 1 | | | | | | | | | | | | |
| Drainage texture ratio (Rt) | -0.874** | 0.716 | 1 | | | | | | | | | | | |
| Form factor (Ff) | -0.732* | 0.622 | 0.822 | 1 | | | | | | | | | | |
| Mean bifurcation ratio (Rbm) | -0.409 | 0.303 | 0.794 | 0.570 | 1 | | | | | | | | | |
| Ruggedness number (Rn) | 0.358 | 0.101 | -0.596 | -0.532 | -0.733 | 1 | | | | | | | | |
| Relief ratio (Rh) | -0.549 | 0.779* | 0.223 | 0.225 | -0.322 | 0.575 | 1 | | | | | | | |
| Elongation ratio (Re) | -0.734* | 0.627 | 0.849** | 0.998*** | 0.620 | -0.550 | 0.207 | 1 | | | | | | |
| Circularity ratio (Rc) | -0.766* | 0.539 | 0.940* | 0.757* | 0.808* | -0.640 | 0.105 | 0.792* | 1 | | | | | |
| Length of overland flow (Lg) | 1.000*** | -0.801* | -0.873*** | -0.736* | -0.407 | 0.361 | -0.546 | -0.737* | -0.764* | 1 | | | | |
| Constant of Channel | -1.000*** | 0.800* | 0.861*** | 0.720 | 0.387 | -0.344 | 0.561 | 0.720 | 0.752* | -1.000*** | 1 | | | |
| Infiltration Number (If) | 0.991*** | -0.719 | -0.873*** | -0.718 | -0.432 | 0.452 | -0.456 | -0.720 | -0.782* | 0.992*** | -0.991*** | 1 | | |
| Time of Concentration (Tc) | 0.607 | -0.729* | -0.613 | -0.729* | -0.284 | -0.030 | -0.622 | -0.736 | -0.651 | 0.605 | -0.600 | 0.538 | 1 | |
| Basin Relief (H) | -0.616 | 0.816** | 0.295 | 0.199 | -0.244 | 0.513 | 0.981*** | 0.186 | 0.152 | -0.614 | 0.628 | -0.531 | -0.548 | 1 |

Significant at: * 0.05 level; ** 0.01 level; ***0.001 level.

**Table 8.** Principal component analysis of morphometric properties of upper Krishna basin.

| Variables (Morphometric parameters) | Component | | | |
|---|---|---|---|---|
| | PC1 | PC2 | PC3 | PC4 |
| Drainage density (Dd) (km km–2) | -0.319 | 0.060 | 0.267 | -0.073 |
| Stream frequency (Sf) | 0.278 | -0.236 | 0.122 | -0.292 |
| Drainage texture ratio (Rt) | 0.315 | 0.148 | -0.024 | -0.248 |
| Form factor (Ff) | 0.286 | 0.131 | 0.322 | 0.430 |
| Mean bifurcation ratio (Rbm) | 0.187 | 0.377 | 0.132 | -0.609 |
| Ruggedness number (Rn) | -0.135 | -0.479 | 0.230 | -0.218 |
| Relief ratio (Rh) | 0.162 | -0.478 | 0.060 | 0.006 |
| Elongation ratio (Re) | 0.289 | 0.146 | 0.330 | 0.346 |
| Circularity ratio (Rc) | 0.288 | 0.206 | 0.069 | -0.272 |
| Length of overland flow (Lg) | -0.319 | 0.058 | 0.266 | -0.085 |
| Constant of Channel | 0.317 | -0.070 | -0.281 | 0.084 |
| Infiltration Number (If) | -0.313 | 0.009 | 0.344 | -0.121 |
| Time of Concentration (Tc) | -0.249 | 0.137 | -0.587 | -0.034 |
| Basin Relief (H) | 0.176 | -0.459 | -0.094 | -0.144 |
| Tentative Variables | Basin Shape and Stream Network | Relief Aspects | Basin Form | |
| Eigen Values | 9.0146 | 3.3244 | 0.9154 | 0.4968 |
| Explained Variance (%) | 64.40 | 23.70 | 06.50 | 03.50 |
| Cumulative Explained Variance (%) | 64.40 | 88.10 | 94.70 | 98.20 |

areal morphometric properties like Drainage texture, Form factor, Circularity ratio, Elongation ratio, and Constant of channel maintenance' have significant correlation.

## Results of principal component analysis

Principal component analysis (PCA) was carried out to extract four components. The results for this are given in Table 8. Which illustrates that about 98% of the total variation is explained by these four components. Component I explain 64% of the total variation. This component is loaded by Stream frequency, Drainage texture ratio, Form factor, Elongation ratio and Circularity ratio. All these variables are related to basin shape and stream network and therefore this component is labelled as basin shape and stream network component. The second important group of variables which explains about 23% of total variation are dominated by Basin relief, Mean bifurcation ratio. In component III the group has high loadings consisting of Form factor, Elongation ratio and Length of overland flow. All these parameters represent basin form. This component is responsible for 6% of the total variation. Component IV is responsible for 3% of variation and has loadings for Elongation ratio. Thus, this component is labelled as basin shape.

Overall, it can be stated from the analysis of PCA that the variables which has high loadings are Form factor, Drainage texture, Stream frequency, Elongation ratio and Circularity ratio. From both the analysis of bivariate correlation and PCA, it is clear the major flood contributing morphometric factors are related to basin shape, size and stream network.

## Compound factor and weightage

After the calculation of morphometric parameters, some of these were taken into consideration for the assessment of flood-influencing characteristics in each sub-basin catchment. The parameters like Mean bifurcation ratio (Rb), Drainage density (Dd), Stream frequency (Fs), Form factor (Rf), Length of overland flow (Lg), Infiltration number (If), Relief ratio (Rh), Ruggedness number (Rn) are directly proportional to flood runoff. It means that higher the value, greater will be the runoff. Therefore, the parameter was given the highest weightage 6 on a six-point scale, likewise, the second highest value was assigned as weightage 5 and so on. The lowest weightage assigned was 1 (Table 9).

Compound factors for all parameters were calculated by summing the weights of all parameters to the total number of parameters. From this, the basin which shows the highest compound factor value is more influenced by flood potential and a lower value shows less influence on flood potential of the main river channel. (Bhatt and Ahmed, 2014).

The morphometric analysis of six major potential flood-prone river catchments of the upper Krishna basin discloses that rivers like Krishna, Koyna and Doodhganga have a greater tendency to peak discharge within a short period because of less Time of concentration (Tc), high to moderate Relief ratio (Rh), and high Ruggedness number (Rn). The Panchganga and Yerla river catchments also have the highest Form factor (Ff), Drainage texture ratio (Rt), Infiltration number (If) and Time of concentration (Tc) which are the causes of moderate to high surface runoff contributing to the main Krishna channel. Warna river contributes medium to low surface runoff and has moderate influence on flooding of the main channel because of moderate Relief ratio (Rh), Ruggedness number (Rn), Infiltration number (If) and Time of concentration (Tc).

## Conclusion

After assessing all the sub-basins, it has been observed that the Krishna, Doodhganga, and Koyna rivers are the major contributors to floods. Among these, the Krishna river has the highest flood discharge due to its morphometric setup. The catchment areas of the Panchganga and Yerla rivers also contribute to moderate surface runoff into the main Krishna channel. The Warna river, on the other hand, contributes

**Table 9.** Compound Factor Analysis of morphometric properties of upper Krishna basin.

| Catchment \ Morphometric parameters | Drainage density (Dd) in km km$^{-2}$ | Stream frequency (Sf) | Drainage texture ratio (Rt) | Form factor (Ff) | Mean bifurcation ratio (Rbm) | Ruggedness number (Rn) | Relief ratio (Rh) | Circularity ratio (Rc) | Length of overland flow (Lg) | Constant of Channel Maintenance (Cc) | Infiltration Number (If) | Time of Concentration (Tc) | Compound Factor | Influence on main channel |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Krishna | 1 | 6 | 6 | 6 | 5 | 1 | 5 | 6 | 6 | 1 | 1 | 6 | 4.17 | High |
| Koyna | 5 | 5 | 1 | 2 | 1 | 6 | 6 | 1 | 2 | 6 | 6 | 4 | 3.75 | High |
| Panchganga | 4 | 2 | 3 | 4 | 3 | 3 | 2 | 2 | 4 | 5 | 5 | 3 | 3.25 | Moderate |
| Doodhganga | 3 | 3 | 4 | 5 | 4 | 2 | 4 | 5 | 3 | 4 | 4 | 5 | 3.83 | High |
| Yerla | 2 | 4 | 5 | 3 | 6 | 4 | 1 | 4 | 5 | 2 | 3 | 2 | 3.50 | Moderate |
| Warna | 6 | 1 | 2 | 1 | 2 | 5 | 3 | 3 | 1 | 3 | 2 | 1 | 2.50 | Low |

low surface runoff and has a moderate impact on the main channel.

From the bivariate correlation and principal component analysis it is observed that basin shape parameters like Form factor, Drainage texture, Elongation ratio and Circularity ratio and drainage network parameters like Drainage density, Stream frequency and Mean bifurcation ratio show more significant relation and act as dominant morphometric parameters for flood contribution to the main Krishna river channel. Apart from heavy rainfall, the discharge of huge amount of water from several major and minor reservoirs in the upper Krishna basin also causes inundation and extensive damage to agricultural land in the floodplain areas.

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