Statistical approach towards watershed prioritization of Narmada River Basin

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Abstract: The Narmada River basin, one of the most significant river systems in India, plays a vital role in the socio-economic and ecological development of the region. Understanding the basin's morphometric characteristics is essential for sustainable water resource management and environmental planning. This research work aims to conduct a comprehensive morphometric analysis of the Narmada River basin using GIS, by studying the parameters of geomorphologic significance. These parameters reflect the true nature of the response which the topography offers to the hydrological flow. In this study quantification of basins's characteristics is carried out, to provide valuable insights into its hydrological behavior, erosion susceptibility, potential for water resource utilization by prioritizing river basins using PCA (Principal Component Analysis). The PCA approach is applied keeping in mind the scale and volume of parameters and also to recognize their individual contribution towards the behavioral pattern and response.

Keywords: morphometric, GIS, Basin, PCA, hydrological

1. Introduction

Watersheds, the fundamental units of hydrological systems, exhibit complex topographical characteristics that significantly influence the flow of water, sediment transport, and overall basin health. The morphological analysis of watersheds has emerged as a crucial field of study, aiding our understanding of the dynamic interactions between geological, hydrological, and environmental processes. Montgomery and Buffington's seminal work in 1997 revolutionized this field by introducing the concept that channel morphology is a key determinant in shaping landscapes and controlling sediment transport within watersheds. Their research emphasized the importance of classifying watersheds based on their morphological characteristics and contributed to the development of models and tools for predicting erosion and sediment transport within river systems (Montgomery & Buffington, 1997). The significance of morphometric analysis in hydrological modeling and watershed management was demonstrated by Singh (1997), who reviewed various techniques for modeling in semi-arid areas, highlighting the importance of understanding basin characteristics.

Subsequent advancements in technology have furthered our ability to conduct detailed morphological analyses of watersheds. Pelletier et.al (2016) made significant contributions by introducing advanced techniques for extracting topographic attributes from high-resolution digital elevation models (DEMs). These techniques allow for precise characterization of watershed morphometry, enabling researchers to quantify parameters such as slope, aspect, curvature, and relief, which are critical for understanding watershed behavior (Pelletier et al. 2016). Mishra and Verma (2017) employed GIS technology to perform morphometric analysis of the Chakrar watershed in Madhya Pradesh,

India, illustrating the practical applications of morphometric parameters in assessing watershed characteristics. Kondolf et al. (2006) emphasized the use of morphometric analysis in process-based ecological river restoration, highlighting its role in visualizing three-dimensional connectivity for effective restoration efforts. Additionally, the study by Blöschl et al. (2017) demonstrated the relevance of morphometric analysis in assessing climate change impacts on European floods, illustrating its role in monitoring and adapting to changing environmental conditions. Watershed morphological analysis is not limited to natural processes but also encompasses the impacts of human activities on these fragile ecosystems. Smith and Mark (2010) investigated the effects of land use changes on watershed morphology, underscoring the importance of considering anthropogenic factors in watershed management strategies. Their research highlighted how urbanization, deforestation, and agricultural practices can alter the morphological characteristics of watersheds, leading to increased sedimentation in reservoirs and degraded water quality (Smith & Mark, 2010). Moreover, the morphological analysis of watersheds has become increasingly relevant in the face of climate change. Studies such as those by Vaze et al. (2010) have demonstrated how shifts in precipitation patterns and temperature can impact watershed morphology by affecting the timing and magnitude of stream flow. These changes can have cascading effects on ecosystems and human communities reliant on these watersheds for water supply, agriculture, and recreation (Vaze et al., 2010). In recent years, the integration of Geographic Information Systems (GIS) and remote sensing technologies has further enhanced our ability to analyze watershed morphology. Researchers are now able to combine high- resolution satellite imagery, LiDAR data, and field observations to create detailed models of watershed topography and land use. This interdisciplinary approach enables more accurate predictions of watershed behavior and aids in the development of targeted conservation and restoration strategies (Turner et al., 2015). The factors related to rill erosion of roads in forests within a mountainous watershed which bridged the gap by carrying out multivariate statistical analysis and field surveys and further investigated various factors influencing rill formation. Management of river basins has now become a priority to sustain them from erosions and mitigation from infrastructure damage, where they took hydro morphometric parameters into consideration of eighteen sub basins and used multivariate statistical approaches to comment in soil erosion, aquifer potential, permeability, infiltration.

These referenced studies collectively underline the significance of morphometric analysis in various aspects of hydrology. geomorphology and environmental management.

2. Study Area

The Narmada River basin, situated in central India, is one of the most significant and oldest river systems in the country (Figure 1). It holds immense ecological, social, and economic importance, supporting millions of people living in its vicinity. The basin covers a vast geographical area, traversing through the states of Madhya Pradesh, Gujarat, Maharashtra, and parts of Chhattisgarh.

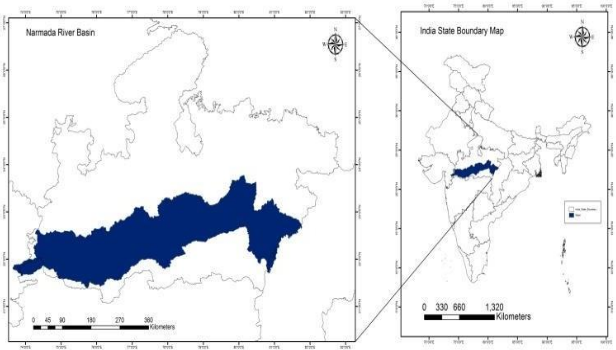

Figure 1. Narmada Basin

The Narmada River, also known as "Reva" in ancient texts, originates from the Amarkantak Plateau in the eastern part of Madhya Pradesh. Its source is marked by the confluence of the rivers Narmada Kund and Sonbhadra, located at an elevation of approximately 1,057 meters above sea level. From its origin, the river flows in a predominantly westward direction, meandering through the Satpura and Vindhya mountain ranges, creating a unique topography that has shaped the landscape of the region. Narmada River, with a total length of about 1,312 kilometers, is the fifth-largest river in India in terms of discharge. It drains into the Arabian Sea, forming an extensive and fertile delta in the Gulf of Khambhat. The river basin covers an area of around 98,796 square kilometers, encompassing diverse terrain, including dense

forests, plateaus, plains, and hills. The basin receives considerable rainfall during the monsoon season, contributing to the substantial flow of water throughout the year. The Narmada River basin has been a cradle of ancient civilizations, with historical evidence of human habitation dating back thousands of years. The basin is home to various indigenous communities, whose livelihoods are intricately tied to the river's resources. Agriculture is the primary occupation of the people living in the basin, and the fertile alluvial plains along the riverbanks support the cultivation of various crops, including wheat, rice, cotton, and soybeans.

The river has been harnessed for various water resource projects, contributing significantly to India's irrigation and power generation capacity. The Sardar Sarovar Dam, one of the largest dams in the world, is constructed across the river, providing irrigation water, drinking water, and electricity to millions of people. Additionally, several other dams, reservoirs, and canals have been developed to manage water resources effectively. River basin hosts a rich diversity of flora and fauna, serving as an essential ecological corridor. It supports numerous endemic and endangered species of plants and animals, making it a critical area for biodiversity conservation. The river and its tributaries provide habitats for various aquatic species and migratory birds. The river has been harnessed for various water resource projects, contributing significantly to India's irrigation and power generation capacity. The Sardar Sarovar Dam, one of the largest dams in the world, is constructed across the river, providing irrigation water, drinking water, and electricity to millions of people. Additionally, several other dams, reservoirs, and canals have been developed to manage water resources effectively. River basin hosts a rich diversity of flora and fauna, serving as an essential ecological corridor. It supports numerous endemic and endangered species of plants and animals, making it a critical area for biodiversity conservation. The river and its tributaries provide habitats for various aquatic species and migratory birds.

3. Morphometric Parameters

In geomorphology, morphometry is a quantification of morphology. Indices of watershed morphometry can interpret the shape and hydrological characteristics of a river basin. Morphometric analysis of watershed is the best method to identify the relationship of various aspects in the area. It is a comparative evaluation of different watersheds in various geomorphological and topographical conditions. Watershed is a natural hydrological entity from which surface runoff flows to a defined drain, channel, stream or river at a particular point. Drainage basin/watershed analysis based on morphometric parameters is very important for watershed planning since it gives an idea about the basin characteristics regarding slope, topography, soil condition, runoff characteristics, surface water potential, etc. The morphometric analysis of watershed aids to know the aspects of linear, areal, and relief parameters. Stream order, stream number, stream length, mean stream length, stream length ratio, bifurcation ratio, mean bifurcation ratio, drainage density, drainage texture, stream frequency, relief ratio, form factor, elongation ratio, circularity ratio, length of overland flow are the most common morphometric parameters. The definition and formula for each parameter are the same as stated in many papers. Unfortunately, there is no complete classification for all parameters.

4. Methodology

Delineation of drainage network is carried out using Cartosat digital elevation model (Figure 2) available at Bhuvan portal which is managed by Indian Space Research Organization.

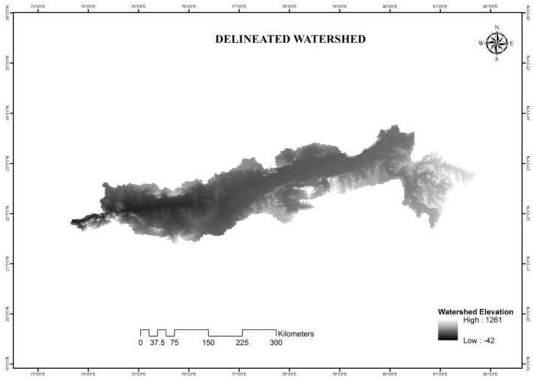

Figure 2. Basin DEM

In the due process, the digital elevation model is processed to fill the sinks present in the DEM data by averaging the nearby values.

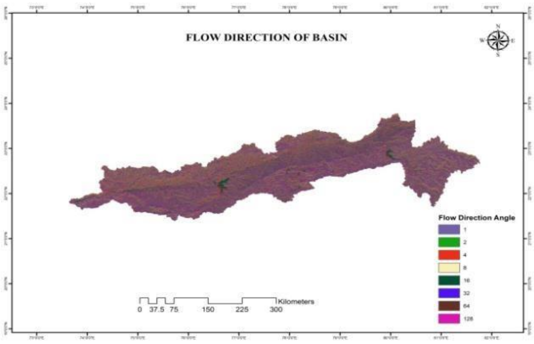

Figure 3. Flow direction

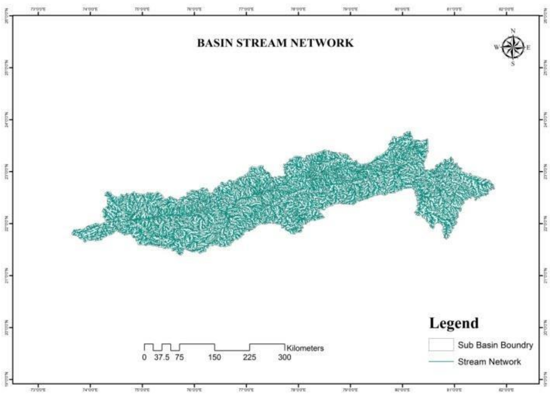

Figure 4. Derived Basin Streams from DEM.

Further, the flow direction (Figure 3) of the basin is calculated to estimate the direction of stream flow across the whole network. This direction is based on 8 components of direction on a vertical plane. Furthermore, streams (Figure 4) of the basin are delineated using the rastercalculator. The streams which have a contribution of more than five thousand small streams are taken into consideration.

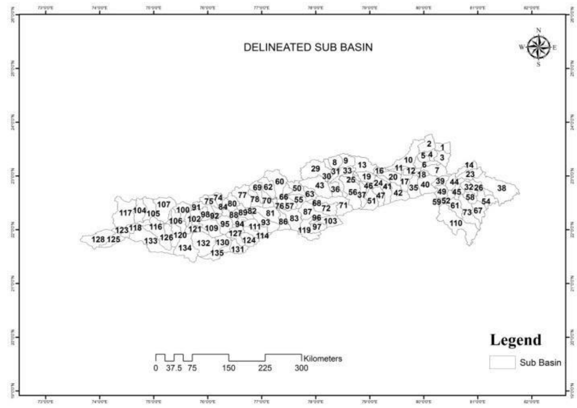

Figure 5 Derived Sub-basins

With the delineated network sub-basins are further delineated (Figure 3) using ArcSWAT. In all we got 135 sub-basins which make up the whole drainage network. They are further ordered by applying stream order function. The streams are then clipped out of their respective sub-basin.

For all one hundred and thirty five sub-basins, twenty four geomorphologic parameters under the heads of linear aspect, relief aspect, aerial aspect are calculated. These parameters included are listed in the table given below:-

1. Perimeter (km):

The perimeter represents the outer boundary of the watershed, outlining the area that contributes to the drainage network.

2. Shape Area (km):

Area of individual polygon within the watershed boundary is called the shape area.

3. Total stream Length (km):

Sum of length of all individual stream segments within the boundary of watershed.

4. Total stream No(Nu):

Total number of individual streams within the watershed.

5. Mean stream length (Lu):

It is a geomorphic parameter used to characterize the average length of stream segments within a watershed or drainage basin. It provides insights into the overall size and complexity of the stream network in a particular area. Calculating the mean stream length involves dividing the total stream length within the watershed by the number of individual streams or stream segments. The formula for mean stream length is as follows:

$$RL = \frac{\text{Total stream channel length (L)}}{\text{Number of streams or stream segment (N)}}$$

6. Bifurcation Ratio (Rb):

It is a geomorphic parameter used in the analysis of river or streamnetworks within a watershed. It quantifies the branching or splitting pattern of a river network by comparing the number of smaller- order streams to the number of larger-order streams. The bifurcation ratio is a valuable tool for characterizing the hierarchical structure and organization of river networks.

$$Rb = \frac{ber\ of\ streams\ of\ order\ n}{Number\ of\ streams\ of\ order\ n{+}1}$$

7. Form Factor:

Form factor is a geomorphic parameter used in the analysis of watersheds and river basins. It provides insights into the shape and elongation of the watershed or drainage basin. The form factor is often used to assess the relationship between the length and width of a watershed, which can have implications for various hydrological and geomorphic processes. The formula used to calculate the form factor:-

$$Ff = \frac{Area}{Length}$$

8. Mean stream length ratio (RL):

It used to assess the shape and complexity of a river network within a watershed or drainage basin. It is a dimensionless ratio that compares the mean stream length of a particular order (usually higher-order streams) to the mean stream length of the next lower order (usually lower-order streams) within a given river network. MSLR is commonly used in the field of geomorphology and hydrology to characterize the hierarchical structure of river networks and understand their spatial organization.

$$RL = \frac{\text{Mean stream length of higher order stream}}{\text{Mean stream length of next lower order stream}}$$

9. Elongation Ratio(Re)

It is calculated by dividing the dia of circle of same area as that of basin by maximum length of basin.

10. Drainage Density (Dd):

Drainage density is a fundamental geomorphic parameter used in the analysis of watersheds and river basins. It quantifies the extent of the stream or river network within a watershed, providing information about the density of streams and the spatial distribution of drainage channels. Drainage density is expressed as the total length of streams per unit area and is typically measured in units like kilometers per square kilometer (km/km²) or miles per square mile (mi/mi²).

$$Dd = \frac{\text{Total stream channel length (L)}}{\text{Watershed Area (A)}}$$

11. Stream Frequency (Fs):

Stream frequency is a geomorphic parameter used to quantify the density and spatial distribution of stream channels within a watershed or drainage basin. It provides information about how the stream network is distributed across the landscape. Stream frequency is often used in hydrological and geomorphological analyses to assess watershed characteristics and is a useful tool for understanding drainage patterns and potential areas of interest for various studies and management practices.

$$Sf = \frac{\text{Number of streams (N)}}{\text{Watershed Area (A)}}$$

12. Circulatory Ratio (Rc):

The Circulatory Ratio (Rc) is a geomorphic parameter used to quantify the degree of circularity or elongation of a drainage basin or ~~watershed. It provides~~ insights into the shape and flow characteristics of the watershed by comparing its actual perimeter (the length of the boundary that encloses the watershed) to the perimeter of a circle with the same area as the watershed. The Circulatory Ratio helps assess how closely the shape of the watershed resembles that of a circular basin. The formula used to calculate circulatory ratio is:-

$$Rc = \frac{4*3.14*\text{Watershed Area}}{\text{(WatershedPerimeter)\^{}2}}$$

13. Compactness coefficient (Cc):

The Compactness Coefficient, also known as the Pielou's Evenness Index or the Shape Index, is a geomorphic parameter used to assess the shape of a watershed or drainage basin. It quantifies the degree of compactness or elongation of the watershed by comparing the actual perimeter of the watershed to the perimeter of a circle with the same area. The Compactness Coefficient helps describe how closely the shape of the watershed resembles that of a perfect circle. The formula for calculating Cc is as follows:

$$Cc = \frac{\text{Watershed Perimeter}}{\text{Circumferance of equivalent circular area}}$$

14. Length of basin(Lb):

It typically refers to the main channel length or the longitudinal dimension of watershed.

15. Drainage Texture(Dt):

Drainage texture, also known as drainage pattern or stream pattern, is a geomorphic parameter used to describe the arrangement and organization of streams or rivers within a watershed or drainage basin. It characterizes how streams are distributed across the landscape and the overall spatial pattern of the drainage network. Drainage texture is an important aspect of watershed analysis and can provide insights into the geomorphologic and hydrological characteristics of a region.

16. Length of Overland Flow(Lo):

The length of overland flow, also known as the overland flow distance, refers to the distance water travels over the land surface before entering a stream, river, or other water body. It is an important parameter in hydrology and watershed analysis, as it helps determine the pathways and characteristics of surface runoff within a watershed.

The length of overland flow is influenced by various factors, including topography, soil properties, land use, and precipitation intensity. It plays a role in several hydrological and geomorphological processes, such as erosion, sediment transport, and the generation of surface runoff. Understanding the length of overland flow is essential for assessing flood risk, soil erosion, and water quality within a watershed.

17. Infilteration No (If), (Faniran 1968):
The infiltration number is the product of drainage density and stream frequency, and it reflects the infiltration potential of a watershed. Lower infiltration numbers indicate higher infiltration and lower run-off.

18. Lemniscate Ratio(K), (Strahler 1964):

It is used to assess the shape and elongation of a watershed or drainage basin. Specifically, it characterizes how closely the shape of a watershed resembles that of a lemniscate, which is a curve with a shape resembling the infinity symbol (∞). The Lemniscate Ratio is an indicator of the basin's shape complexity and can provide insights into its hydrological and geomorphologic characteristics. The formulae used to calculate Lemiscate Ratio:-

$$K = \frac{4\sqrt{A}}{P}$$

19. Elevation(H):

It refers to the vertical distance above or below a reference point, typically sea level. It is a fundamental parameter used to describe and understand the relief or topography of the Earth's surface. Here it is the maximum elevation point of the basin.

20. Elevation(h):
It is the minimum elevation point in the basin.

21. Relief(Bh):
It refers to the variation in elevation and terrain features on the Earth's surface within a specific geographic area. It describes the differences in height between the highest and lowest points in a given region or the ruggedness and complexity of the landscape. Relief provides insights into the topographic diversity and surface features of an area, and it is an essential parameter for understanding the Earth's physical geography.

22. Relief Ratio(Rh):
It is calculated by dividing relief with length of basin.

$$Rh = \frac{\text{Relief}}{\text{Length of Basin}}$$

23. Relative Relief (Rhp):
It is the ratio of highest elevation point to the basin perimeter.

24. Ruggedness No(Rn):
The Ruggedness Number (Rn) is a geomorphic parameter used to quantify the roughness or ruggedness of the terrain within a specific geographic area. It provides information about the variability in elevation or relief, helping to characterize the topographic complexity of a landscape. Ruggedness Number is commonly used in geomorphologic studies, terrain analysis, and landscape characterization. The formula used to find out Rn value is as follows:-

$$Rn = \text{Relief (Bh)} * \text{Drainage density (Dd)}$$

As it is observed that the number of parameters used in this paper is quite large in number and significant as well, hence dimensionality reduction comes into picture. It is a statistical concept in which multiple features of a dependency are projected to their components and those components then reflect the true nature of each variable. This method is called principal component analysis, as we find the principal component from all the features which is having maximum variance from the original data. In our study, the matrix (137 x 24) containing values of all the parameters is being standardized to scale all the features on a common level. The general value is represented by z as,

$$Z = \frac{\text{Value} - \text{mean}}{\text{Standard Deviation}}$$

Further using this standard matrix (zij), a covariance matrix is formed which denotes a comparison of each feature with that of another and finds a relationship which is either positive or negative in nature. This is a square matrix containing values of parameters varying about mean with respect to each other. For example, for a 3-dimensional data set with 3 variables *x*, *y*, and *z*, the covariance matrix is a 3×3 data matrix of this from:

$$\text{Cov (x1,x2)} = \sum_{i=1}^{n} (x1_l - \mu_1)(x2_i - \mu_1)/(n-1)$$

$$\text{Covariance Matrix} = \begin{Bmatrix} Cov(x,x) & Cov(x,y) & Cov(x,z) \\ Cov(x,x) & Cov(x,y) & Cov(x,z) \\ Cov(x,x) & Cov(x,y) & Cov(x,z) \end{Bmatrix}$$

Here below is the covariance matrix formed from the present set of parameters used in this study. From the graph above we can clearly distinguish the inter-relationship ship among all the parameters involved.

Further into it, eigen values and eigen vectors are computed in order to determine the principal components of the data. Principal components are basically the new variables which are constructed by a linear combination or a mixture of parameters.

These components are made in such a way that there exists no correlation between them and all the information of the parameters is being squeezed to first components representing the best case scenario.
Let A be a square nXn matrix and X be a non-zero vector for which

$$AX = \lambda X$$

for some scalar values λ, then λ is known as the eigenvalue of matrix A and X is known as the eigenvector of matrix A for the corresponding eigenvalue. It can also be written as :

$$AX - \lambda X = 0$$

$$(A - \lambda I)X = 0$$

where I is the identity matrix of the same shape as matrix A. The above conditions will be true only if (A − λI) will be non-invertible (i.e. singular matrix). These Eigen vectors are thus used further to transform the parameters into new space thus providing the principal components containing information off all the parameters. Using the first principal component having maximum information, we finally ranked the watersheds (Figure 6) and gave them the priority corresponding to the principal component value.

5. Results and Discussions

Here below (Table 1) are the derived values of standard deviation, mean and percentage deviation for all the parameters. By understanding the natural occurrence of these variables through the table 1, below we came to know that maximum deviation in percentage is of 472% in infiltration number and minimum is of 3.51% in relative relief.

This gives a significant insight regarding the runoff and infiltration characteristic of the basin as the deviation is far too high in case of infiltration number, the basin seems to have areas of high runoff and low infiltration and vice versa which makes it a compensatory watershed as well.

Likewise the relative relief has a minimum deviation in percentage which signifies the topography is overall uniform in most of the areas since the deviation is only 3.51 percent from its mean value. Other parameters where percent deviation from mean is significantly high include mean stream length (lu), drainage density (Dd), length of overland flow (lo). With 420% deviation in drainage density (Dd), higher values indicate a more closely spaced and interconnected network of streams within the watershed, while lower values suggest a less dense and more dispersed network. Drainage density can be influenced by various factors, including the geological characteristics ofthe area (such as rock type and faulting), climate (precipitation patterns), and human activities (such as urbanization and land use changes). Its hydrological response is also associated with the fact that watersheds with higher density tend to respond more rapidly to rainfall events, potentially leading to increased runoff, while lower drainage density watersheds may have slower responses. It can also be linked to erosion and sediment transport in a way that high drainage density is linked to increased erosion potential, as the greater number of channels can transport sediment more efficiently. This can have implications for sediment yield and water quality in the watershed.

Length of Overland flow (Lo) also showed a percentage deviation of 420% which exerts a keen focus to study the numbers obtained. It indicates that watersheds with steep slopes and rugged terrain are more likely to have shorter lengths of overland flow because water can quickly flow downhill and enter the stream network. In contrast, watersheds with gentle slopes may have longer overland flow paths.

Mean stream length (Lu) has a deviation of 269% from mean which portrays that, shorter streams may respond more quickly to rainfall events and contribute to rapid runoff, while longer streams may have more gradual responses and therefore the prioritization of the basin will get influenced based on its Lu value.

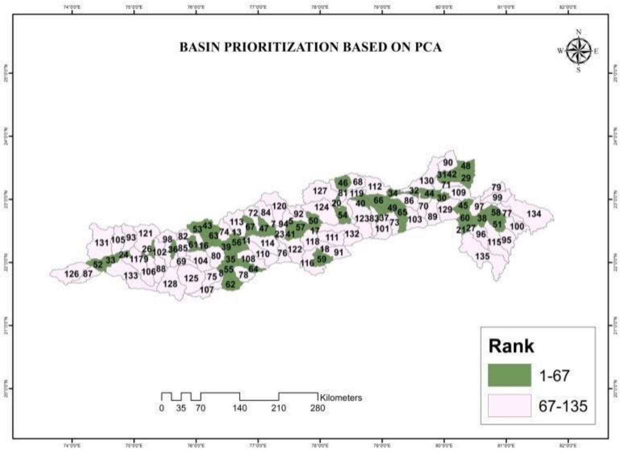

Figure 6. Priority wise sub-basin distribution

While understanding the overall geomorphology of the basin it came to be known that the average value of mean stream length length ratio (RL) came about to be 1.69, which is greater than 1 indicating that the basin has longer higher order streams as compared to next lower order streams which suggests that river network is relatively elongated and less branched. Bifurcation ratio (Rb) is observed to attain an average value of 3.97 which is greater than 3, portraying a relatively branched and dendritic pattern of streams with many smaller tributaries joining larger tributaries. The calculations also revealed an average value of form factor (Ff) to be 0.26 which is < 0.45, which typically indicates a more elongated and narrow watershed. It means that the watershed is relatively long and narrow as compared to its area.

Further we obtained the values of circulatory ratio (Cc) having an overall average of 0.16 which is less than 1 which confirms the results obtained from form factor, indicating that the basin is more elongated than a circular shape and that the water flow within the basin may be more oblong in nature. Another feature which throws more light towards the shape and geometry of the watershed is Lemniscate ratio (K), Our analysis revealed that the watershed has an average K value to be 0.98 which comes less than 1 portraying that the watershed is more elongated and complex than a lemniscates, specifically that shape is relatively complex.

Final results were based on the principal component analysis, which revealed that the top 50% priority basin as seen in the shade of green in the map above have a greater contribution from all the parameters towards all three aspects of measurement. The next 50% which are having lesser significant contribution are highlighted in lighter shades of white. The ranks are allotted from 1 to 135.

Table 1. Std. deviation and mean distribution

Parameter	StandardDev	MeanValue	% deviation
Perimeter(km)	99.705	210.676	52.674
Shape Area(km2)	491.460	647.497	24.099
Total Stream Length(km)	243.016	322.670	24.686
Total Stream No(Nu)	237.348	289.267	17.948
Mean streamlength (Lu)	8.034	2.176	269.228
Mean stream length ratio (RL)	2.548	1.693	50.520
Mean(Rb)	5.651	3.973	42.258
Form Factor	0.057	0.261	78.150
Elongation Ratio (Re)	0.057	0.574	90.144
Drainage Density (Dd)	0.159	0.031	420.062
Stream Frequency (Fs)	0.522	0.543	3.980
circul_ratio (Rc)	0.044	0.168	73.810
Compactnesscoeff (Cc)	0.364	2.512	85.493
length of basin (Lb)	22.776	47.826	52.377
Drainage Texture (Dt)	0.831	1.261	34.037
Length of Overland Flow (Lo)	0.079	0.015	420.062
Infilteration No(If)	0.125	0.022	472.678
Lemniscate Ratio(K)	0.151	0.988	84.689
high(ele)	256.481	621.948	58.762
low(ele)	119.636	217.481	44.990
Relief(Bh)	247.254	404.467	38.869
Relief Ratio(Rh)	5.015	9.074	44.726
Relative Relief(Rhp)	397.337	383.841	3.516
Ruggedness No(Rn)	6.686	2.442	173.845

From the map it can be inferred that the major contributions have occurred from basins which are running along beside the mainstream of river Narmada, whereas, the lesser contributory basins are located more apart from the mainstream. This suggests that topography beside the mainstream is comparatively uniform than as compared with rest of the parts of basin, which further indicates that these findings are crucial for effective water resource management, flood control, and land-use planning in the region.

6. Conclusions

The research work put forth in this paper is extensively done to obtain and observe a clear picture of the nature and characteristic of the basin and its behavior. This work is unique in its own way as we have put maximum parameters into consideration which affect basin's geomorphology and drive the flow of water based on their natural formation. The work opens up a new horizon of working with watershed management and sustainable land use management by observing the variations in morphometric parameters across the length and breadth of watershed and would also help in modeling the flow or forecasting natural calamities prior to their occurrence.

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