Morphometric Analysis of Pennar River Basin Using Remote Sensing & GIS

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Abstract — This study undertook a meticulous morphometric analysis of the Pennar River basin, employing ArcGIS 10.8 software. The research encompassed data procurement, involving digital elevation models (DEMs) and hydrological data from the basin, sourced primarily from SRTM data accessed via the USGS website. Leveraging the capabilities of ArcGIS, a comprehensive set of 32 morphometric parameters was computed. These parameters encompassed diverse facets of the basin's characteristics, including stream order, drainage density, stream frequency, bifurcation ratio, basin shape, and relief ratio, among others. The computations aimed to unravel the drainage pattern, basin shape, hydrological response mechanisms, and the overall geomorphological attributes of the basin. Employing ArcGIS for morphometric analysis furnished profound insights into the morphology and hydrological dynamics of the Pennar River basin. The Pennar River basin's morphometric analysis show-cases a diverse stream hierarchy with 2637 streams spanning 12710.93 km. Stream length ratios range from 0.288 to 1.487, with a mean of 0.652. Bifurcation ratios vary from 0.631 to 3.034. The basin covers 54905.1 km², with a circularity ratio of 0.315 and an elongation ratio of 0.409. Elevation features include a maximum of 1444 m, a minimum of -16 m, and a total relief of 1460 m, resulting in a relief ratio of 2.261.

Keywords: GIS, Remote Sensing, ArcGIS, Morphometry, River Basin

I. INTRODUCTION

Morphometric Analysis is the measurement and mathematical evaluation of earth's surface, shape and dimension of its landform (Clarke 1996; Agarwal 1998; Obi Reddy et al. 2002). River Drainage morphometry plays vital role in comprehension of soil physical properties, land processes and erosional features.

Utilizing Remote Sensing and GIS techniques is widely recognized as an efficient approach for delineating, updating, and conducting morphometric analyses of drainage basins. Such analyses play a pivotal role in hydrological investigations, particularly in assessing groundwater potential and management strategies. Various important hydrologic phenomena can be correlated with the physiographic characteristics of drainage basins such as size, shape, slope of drainage area, drainage density, size and length of the tributaries etc. (Rastogi et al., 1976). The physiographic attributes of drainage basins, such as size, shape, slope, drainage density, and tributary characteristics, are crucial for understanding various hydrologic processes. Remote sensing data, combined with conventional information, aids in ridge line delineation, priority assessment, erosion risk identification, water conservation planning, and site selection for infrastructure like check dams and reservoirs. The current study focuses on the drainage characteristics of the Pennar River Basin in Andhra Pradesh, India, using RS GIS-based morphometric analysis, offering insights into the basin's hydrological dynamics. This work contributes to a better comprehension of the basin's behavior, supporting informed hydrological management decisions.

II. STUDY AREA

The Pennar River is one of the major east flowing rivers in southern India. It rises in the Chennakesava hill of the Nandidurga range in Karnataka, flows in the North Westerly direction through Kolar and Tumkur districts of Karnataka and enters Andhra Pradesh in the Hindupur taluk of Anantapur district, runs Eastwards before draining into Bay of Bengal near Nellore. Located in peninsular India, the Pennar basin extends over states of Andhra Pradesh and Karnataka having an area of 55,213 Sq.km with maximum length and width of 433 km and 266 km respectively.

The basin lies between 77°1' to 80°10'E and 13°18' to 15°49'N and bounded by Erramala range on the North, by Nallamala and Velikonda ranges of Eastern Ghats on the East, by Nandidurga hills on the South and by narrow ridge separating it from Vedavathi valley of the Krishna Basin on the West. The other hill ranges in the basin to the South of the river are Seshachalam and Paliconda ranges.

1	Basin extent	77° 1' to 80° 10' E 13° 18' to 15° 49' N
2	Area (Sq.km)	55,213 (as reported by CWC) 54243.42 (GIS based)
3	States in the basin	Andhra Pradesh (87.48 %), and Karnataka (12.52%)
4	Mean Annual Rainfall (mm)	770.18 (0.5° Grid 1971-2005) 746.90 (1° Grid 1969-2004)
5	Mean Maximum Temperature (°C)	32.71
6	Mean Minimum Temperature (°C)	21.63
7	Highest Elevation (m)	1439
8	Live Storage Capacity (BCM)	4.82
9	Avg. Annual Water Potential (BCM)	6.32
10	Utilizable Surface Water (BCM)	6.90
11	Number of Sub Basins	2
12	Number of Watersheds	90

13	Number of water resources structures	Dams-58, Barrages-0, Weirs-1, Anicuts-2, Lifts-0, Power Houses-1
14	Highest Dam	Gorakallu Dam - 48.5 m
15	Longest Dam	Kanigiri Dam - 10 km
16	Longest Barrage/ Weir/ Anicut	Sangam Anicut- 1.24 km
17	Number of Irrigation projects	Major-7; Medium-14
18	Number of HE projects	1
19	Number of Groundwater observation wells	426
20	Number of Hydro-Observation Sites	8
21	Number of Flood Forecasting Sites	1

Table 1: Salient Features of Pennar Basin

Map 1: Location of Pennar Basin / Study area

Map 2: Pennar Basin Drainage

III. Methodology

The methodology employed in this study involves the digitization and analysis of the dendritic drainage pattern within the ArcGIS 10.8 software environment. To establish the stream order, the principles of Horton's law are applied. This involves labeling unbranched streams as first-order, while the convergence of two first-order streams designates a second-order stream. Similarly, third-order streams emerge from the union of two second-order streams, and so forth. The stream count for each order is meticulously recorded.

The drainage map, slope map, aspect map, elevation map, hill shade map, contour map incorporating basin boundaries, is digitized.

Standard methodologies and formulas, such as those proposed by Horton (1932, 1945), Smith (1954), Strahler (1964), Miller (1953), Schumn (1956), and Nookaratm (2005), are then employed to compute essential morphometric parameters. These parameters encompass both linear and shape aspects. Parameters like stream length, bifurcation ratio, drainage density, stream frequency, form factor, texture ratio, elongation ratio, circularity ratio, and compactness constant are derived from the drainage layer. The analysis provides insights into the drainage network's characteristics, its spatial distribution, and the overall shape of the basin, facilitating a comprehensive understanding of the Pennar River Basin's geomorphology.

IV. Morphometric Analysis

Morphometric analysis of a river basin is a quantitative approach that examines the morphological characteristics of a river system. It involves studying various parameters such as drainage network, basin geometry, drainage texture analysis, and relief characteristics to gain insights into the hydrological behaviour and landscape features of the basin.

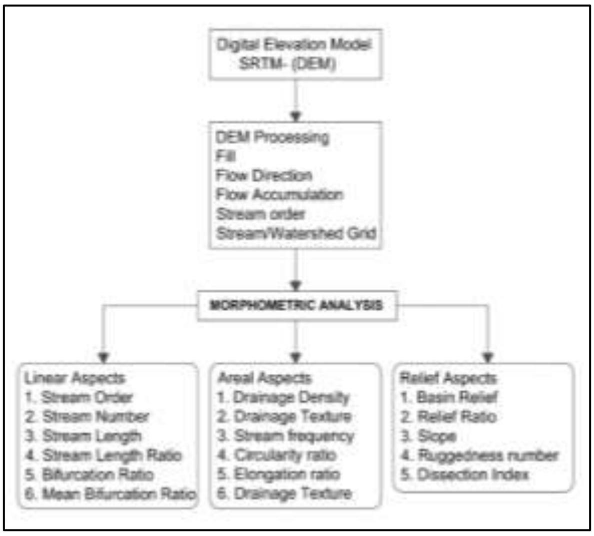


Fig. 1: Morphometric Analysis

Drainage network analysis focuses on the arrangement and connectivity of streams and rivers within the basin. By evaluating stream order, stream number, length, and bifurcation ratio, we can understand the hierarchical structure and flow patterns within the basin.

Basin geometry entails measuring the shape, size, and topographic features of the river basin. Parameters such as basin area, perimeter, circularity, and elongation ratios help in assessing the basin's hydrological response and flood potential.

Drainage texture analysis examines the spatial distribution of streams within the basin. Measurements of drainage density, intensity, and overland flow length provide information on flow concentration, erosion susceptibility, and sediment transport capacity.

Relief characteristics involve analyzing elevation variations, slope gradients, and relief ratios within the basin. Parameters like relief ratio and ruggedness number help understand topographic diversity, erosion potential, and geomorphic processes.

V. OVERVIEW OF ARCGIS

ArcGIS is a comprehensive geographic information system (GIS) software that offers various tools for managing, analyzing, and visualizing geospatial data. In the context of a metamorphic study of a river basin, ArcMap, one of the main components of ArcGIS Desktop, can be particularly useful.

ArcMap provides a user-friendly interface for creating, editing, and analyzing geospatial data in a map-centric environment. It offers a range of tools and functionalities that can aid in studying the metamorphic processes within a river basin.

For example, ArcMap allows us to import and integrate different types of data, such as geologic maps, satellite imagery, and digital elevation models (DEMs). By overlaying and analyzing these data layers, we can identify and map out various metamorphic features and processes occurring in the river basin.

Using ArcMap for river basin DEM analysis, maps such as elevation, slope, aspect, flow accumulation, drainage network, watershed delineation, and hillshade can be generated, aiding in visualizing, and analyzing terrain characteristics and hydrological features.

VI. DRAINAGE BASIN MORPHOMETRY

A. General

In general, 'Drainage basin' is an area of land drained by a river and its tributaries, bounded by a watershed (boundary). Morphometry is the science that deals with quantitative measurement of the shape or geometry of any natural forms.

This modern approach of quantitative analysis of drainage basin morphology was given inputs by Horton (1945) the first pioneer in this field. Horton's laws were subsequently modified and developed by several geomorphologists, mostly notably by Strahler (1952, 1957, 1958 and 1964), Schumm (1956), Morisawa (1957,1958), Scheidegger (1965), Shreve (1967), Gregory (1966,1968), Gregory and walling (1973).

Morphometric features are classified into three categories
- Linear aspects (one dimension)
- Aerial aspects (two dimension)
- Relief aspects (three dimension)

B. Linear Aspects

1) Stream Order (U)

The drainage network transport water and the sediments of a basin through a single outlet, which is marked as the maximum order of the basin and conventionally the highest order stream available in the basin considered as the order of the basin.

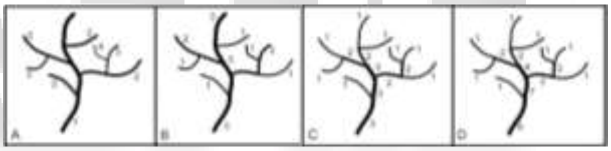


Fig. 2: A- Gravelius (1914); B- Horton (1945); C- Strahler (1957); D- Shreve (1966)

2) Stream Number (Nu)

The total number of stream segments present in each order is the stream number.

Nu is number of streams of order u. As the stream order increases in a drainage basin, number of streams decreases significantly.

3) Stream Length (Lu)

Total length of stream in a particular order. Stream of relatively smaller length are characteristics of areas with larger slopes and finer texture.

Generally, the total length of the stream segment is maximum in first order streams and decreases as the stream order increases.

4) Stream Length Ratio (Rl)

Ratio of the total stream length of the one order to the next lower order of the stream segment (Horton 1945).

An increasing trend in the stream length ratio from lower order to higher order indicates their mature geomorphic stage.

5) Bifurcation Ratio (Rb)

The bifurcation ratio is the ratio between the number of streams in one order to the number of streams in the next.

$$Rb = Nu / Nu+1$$

Where, Nu = Number of streams

u = stream order segment

6) RHO Coefficient (ρ)

It is the ratio of stream length ratio and bifurcation ratio. It indicates storage capacity of drainage network.

7) Stream Frequency (Fs)

The number of stream segments per unit area is termed Stream Frequency or Channel Frequency or Drainage Frequency.

8) Drainage Density (Dd)

Expresses the closeness of spacing of channels, thus providing a quantitative measure of the average length of stream channel for the whole basin.

Drainage Density = Total length of the streams / Area of the drainage basin.

9) Drainage Texture (Dt)

Drainage texture is the total number of stream segments of all orders per perimeter of that area. The areas having low drainage density have coarse texture while high drainage density leads to fine drainage texture.

10) Length Of Overland Flow (Lo)

Length of overland flow is a length of water over the ground before it gets concentrated into certain stream channels.

11) Drainage Intensity (Di)

Drainage intensity is the proportion of stream frequency to the drainage density. Lower values of drainage density, drainage texture and drainage intensity signify that the watershed is more prone to soil erosion.

12) Infiltration Number (If)

Infiltration number is an important parameter that indicates infiltration rate and surface runoff. It is obtained by multiplying stream frequency and drainage density.

13) Constant of Channel Maintenance (Ccm)

The constant of channel maintenance represents the drainage area required to maintain one unit of channel length; hence, it is a measure of watershed erodibility.

C. Areal Aspects

1) Drainage Area (A)

The entire area drained by a stream or system of streams such that all streams flow originating in the area is discharged through a single outlet.

2) Circularity Ratio (Rc)

The proportion of watershed area to the area of a circle which has the same circumference as that of basin perimeter.

3) Elongation Ratio (Re)

It measures the extent of elongation in a basin and is determined by dividing the longest basin length by the shortest basin width.

4) Form Factor Ratio (Ff)

It is defined as the ratio of basin area to the square of the basin length. The form factor provides a measure of relationship between catchment area and catchment length and effects on hydrology.

5) Lemniscate Ratio (K)

Lemniscate ratio is utilized to govern the gradient of the basin.

6) Shape Index (Sb)

It relates to the quantification of basin shape and provide a means for describing the hydrological characteristics of a river basin. It is the inverse of form factor.

7) Compactness Coefficient (Cc)

Compactness coefficient of a watershed is the ratio of perimeter of watershed to circumference of circular area, which equals the area of the watershed.

D. Relief Aspects

1) Basin Relief (H)

Basin relief is the elevation difference of the highest and lowest point of the valley floor.

2) Relief Ratio (Rh)

Relief ratio is defined as the ratio between the total relief of a basin i.e., elevation difference of lowest and highest points of a basin, and the longest dimension of the basin parallel to the principal drainage line.

Relative Relief = Maximum basin relief (H) / Maximum basin length (Lb)

3) Absolute Relief (Ra)

It is the highest elevation of a given location in a river basin.

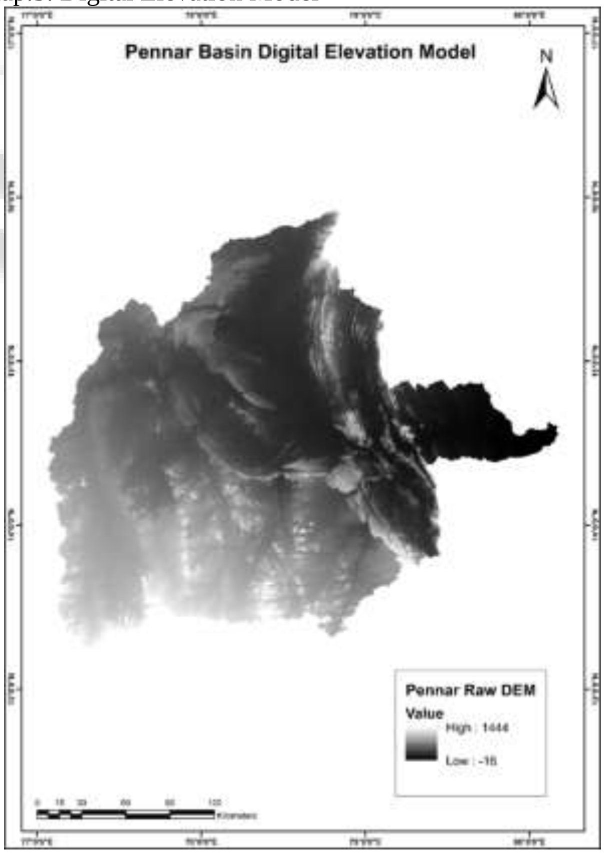
4) Dissection Index (DI)

It is the ratio of maximum relative relief to maximum absolute relief. It explains the nature and magnitude of the dissection in a terrain.

5) Ruggedness Number (Rn)

The ruggedness number combines the slope steepness and length indicating the extent of the instability of land surface.

Map.3. Digital Elevation Model



VII. STREAM CHARACTERISTICS

A. Strahler Stream Order

The Strahler system is based on the confluence (joining) of streams of the same order.

A 1st order stream has no other streams flowing into it. When two streams with different orders join, the resulting stream has the same order as the highest order of the two joining streams.

For example, when a first and second order stream join, the resulting stream is second order. When two streams with the same order join, the resulting stream has the next highest order than the joining streams. When two second order streams join, the resulting stream is third order.

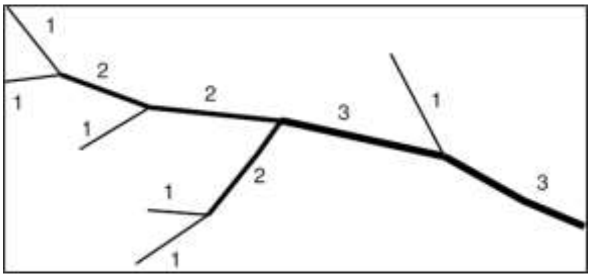
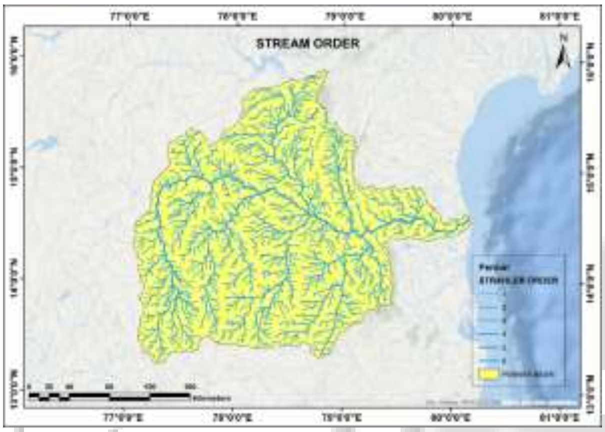


Fig. 3: Strahler Stream Order

Stream Order (U)	Stream Number (Nu)	Stream Length (Lu)	Mean Stream Length (Lsm)	Stream Length Ratio (Lur)	Bifurcation Ratio (Rb)
1	1327	6523.28	4.916	-	2.026
2	655	3317.87	5.066	0.508	2.134
3	307	1475.55	4.806	0.444	3.034
4	101	425.114	4.209	0.288	0.631
5	160	632.347	3.952	1.487	1.839
6	87	336.77	3.871	0.532	-
Total Streams	2637	12710.93	4.82	Mean Lur =0.652	Mean Rb =1.933

Table 2: Stream Characteristics



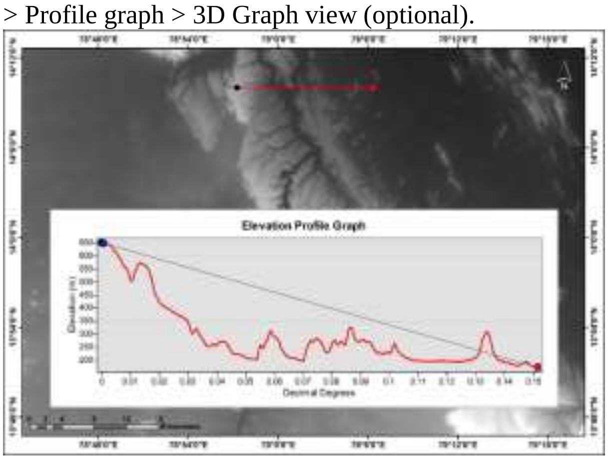
Map 4: Stream Order

B. *Elevation Profile Graph*

An Elevation profile graph is a visual representation of the terrain's elevation along a specific line or path. It provides valuable insights into the elevation changes along that line and helps you understand the topography of the landscape in a more detailed manner.

1) Command Pathflow

DEM > 3D Analyst Tools > Interpolate line > Select the line > Profile graph > 3D Graph view (optional).



Map 5: Elevation Profile

C. *Slope Map*

Slope represents the rate of change of elevation for each Digital Elevation Model (DEM) cell. It is the first derivative of a DEM.

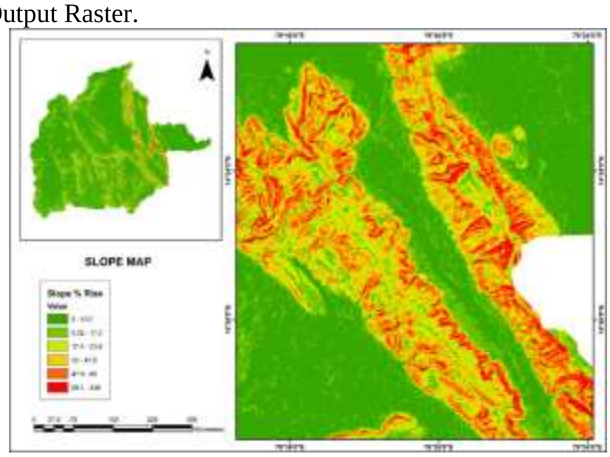
The inclination of slope can be output as either a value in degrees, or percent rise.

Degree: The inclination of slope is calculated in degrees. The values range from 0 to 90.

Percent Rise: The inclination of slope is calculated as percentage values. The values range from 0 to infinity. A flat surface is 0 percent rise, whereas a 45-degree surface is 100 percent rise. As the surface becomes more vertical, the percent rise becomes increasingly larger.

1) Command Pathflow

DEM > Spatial Analyst Tools > Surface > Slope > Input Raster > Output Measurement (Percent_rise) > Z- Factor > Output Raster.



Map 6: Slope Map

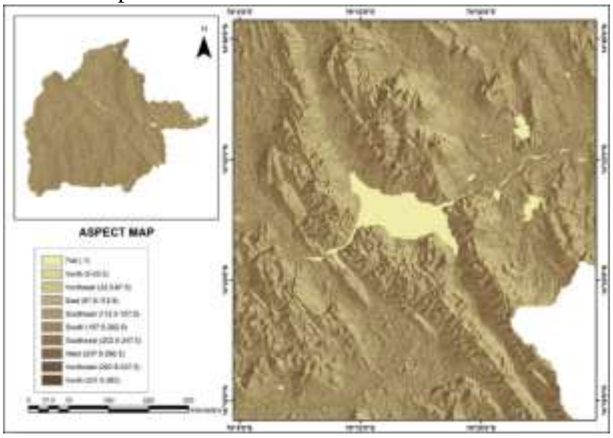
D. *Aspect Map*

Aspect identifies the downslope direction of the maximum rate of change in value from each cell to its neighbours. Aspect can be thought of as the slope direction. The values of the output raster are the compass direction of the aspect.

The Somasila dam reservoir's aspect characteristic is depicted on Map.7.

1) Command Pathflow

DEM > Spatial Analyst Tools > Surface > Aspect > Input Raster > Output Raster.



Map 7: Aspect Map

E. Hill Shade Map

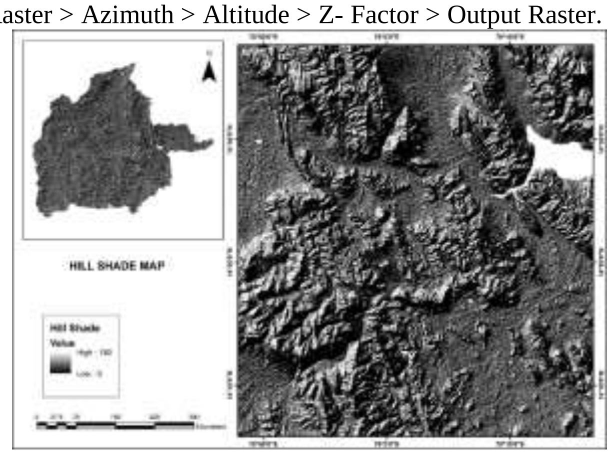
The hill shade function produces a grayscale 3D representation of the terrain surface, with the sun's relative position considered for shading the image. Hill shading is a technique for visualizing terrain determined by a light source and the slope and aspect of the elevation surface. It is a qualitative method for visualizing topography and does not give absolute elevation values.

Azimuth is the sun's relative position along the horizon (in degrees). This position is indicated by the angle of the sun measured clockwise from due north. An azimuth of 0 degrees indicates north, east is 90 degrees, south is 180 degrees, and west is 270 degrees. The default is 315 degrees, which is from the northwest.

Altitude is the sun's angle of elevation above the horizon and ranges from 0 to 90 degrees. A value of 0 degrees indicates that the sun is on the horizon, that is, on the same horizontal plane as the frame of reference. A value of 90 degrees indicates that the sun is directly overhead. The default is 45 degrees above the horizon.

1) Command Pathflow

DEM > Spatial Analyst Tools > Surface > Hill shade > Input Raster > Azimuth > Altitude > Z- Factor > Output Raster.



Map 8: Hill Shade Map

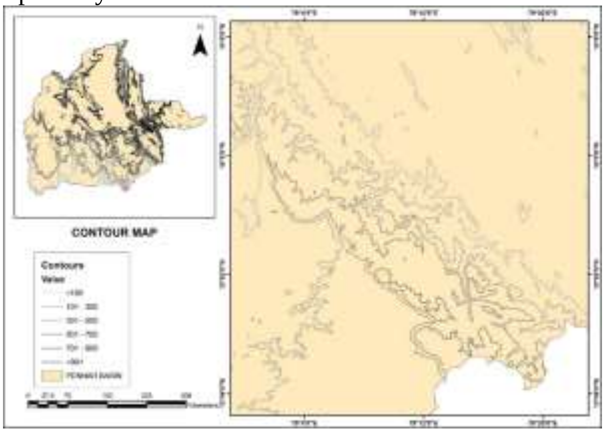
F. Contour Map

Contour map visually represent the three-dimensional surface of an area on a two-dimensional plane using contour lines. These lines connect locations of equal value in a raster dataset of elevation, allowing viewers to interpret terrain features and elevations.

Each contour line indicates a constant vertical distance from a reference level, and their spacing indicates the steepness of the terrain. Close contours indicate steep slopes, while widely spaced contours represent gentle slopes.

1) Command Pathflow

DEM > Spatial Analyst Tools > Surface > Contour > Input Raster > Contour Interval > Base Contour > Z- Factor > Output Polyline Features.



Map 9: Contour Map

G. Drainage density map

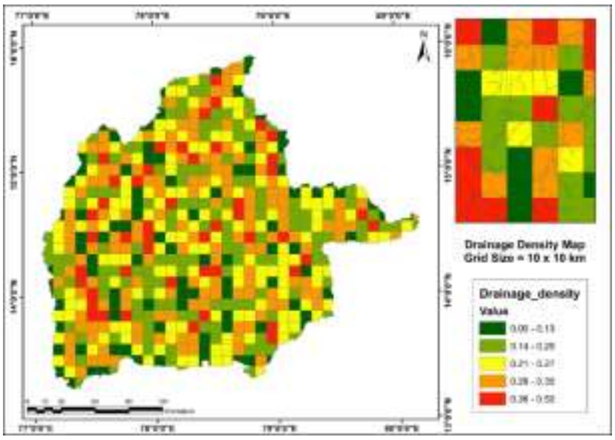
A drainage density grid map is a spatial representation of the drainage network within a study area. It provides valuable information about the density of stream channels, indicating areas with a higher concentration of streams and rivers compared to others.

This type of map is commonly used in hydrological and environmental studies to analyze the flow of water and identify potential flood-prone or erosion-prone regions.

1) Command Pathflow

Stream > Basin > Environment Settings > Workspace > Project to UTM > Cartography Tools > Grid Index Features > Polygon Width > Polygon Height > Clip Basin with Grid > Intersect Grid and Stream > Dissolve Page Numbers > Calculate Geometry Length > Join Data Page Number and Dissolve > Export Data > Calculate Geometry Area > Add Drainage Density Field > Length / Grid Area > Graduated Colours > Change Colour Ramp.

GRID SIZE USED = 10 x 10 km.



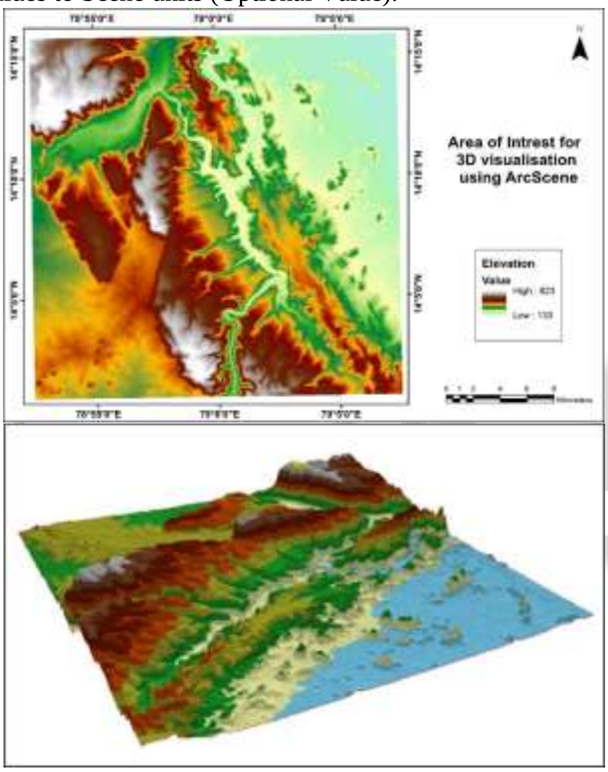
Map 10: Drainage Density Map

H. 3D Visualisation Using Arcscene

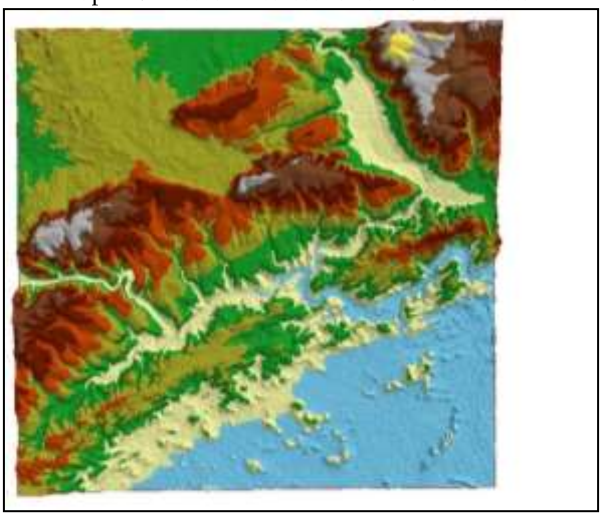
ArcScene is an ArcGIS software application used to visualize, analyze, and interpret geographic data in a 3D environment. It enables us to create and explore 3D scenes using elevation data, satellite imagery, and other geospatial datasets. With intuitive tools and realistic rendering, ArcScene helps us to gain valuable insights into the spatial relationships and characteristics of their data in a three-dimensional context.

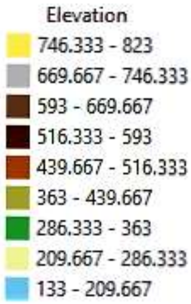
1) Command Pathflow

DEM > Rectangle > Create Area of Interest > Export Raster > 3d Analyst Tool > Raster to Tin > Launch ArcScene > Add data of Tin layer > Layer properties > Base heights > Elevation from surfaces > Floating on a custom surface > Elevation from features > Factor to convert layer elevation values to Scene units (Optional Value).



Map 11: Area of Interest for 3D Visualization





Map 12: 3D Visualization Using Arcscene

VIII. CONCLUSION

GIS and Remote sensing techniques have proved to be accurate and efficient tool in drainage delineation and their updation. The analyzed Morphometric results of the basin reveal a complex and well-developed drainage network with a stream order of 6 and a total of 2637 streams. The basin spans an area of 54905.1 km2 with a perimeter of 1479.71 km, and its shape is moderately elongated with some curvature in its boundary (Circularity Ratio of 0.315 and Lemniscate Ratio of 1.898). The total stream length is 12710.93 km, with an average stream length of 4.82 km. The drainage density is 0.231 km/km2, indicating a moderately dense network of streams.

The basin exhibits varying stream lengths (Stream Length Ratio: 0.288 – 1.487) and branching patterns (Bifurcation Ratio: 0.631 – 3.034), resulting in a mean stream length ratio of 0.652 and a mean bifurcation ratio of 1.933. The drainage texture is moderately branched (Drainage Texture: 1.782 km-1), with a low stream frequency of 0.048 km-2 and a drainage intensity of 0.208 km-1, indicating a moderately dispersed stream network.

Regarding relief aspects, the basin has a significant variation in elevation, with a maximum elevation of 1444 m and a minimum elevation of -16 m (below sea level). The total basin relief is 1460 m, resulting in a relief ratio of 2.261, suggesting a moderately high relief. The basin's shape index (7.576) and compactness coefficient (1.781) indicate a moderately complex and compact shape.

In conclusion, the morphometric analysis indicates that the basin possesses a well-developed and complex drainage system with moderate stream density and varied stream lengths. The basin's elongated shape, coupled with its rugged topography, may have implications for water flow, erosion patterns, and land management within the area.

The formulae used for evaluating morphometric parameters along with the calculated results of analysis are tabulated in Table 3.

No.	Parameters	Abbr.	Formula	Result
A) LINEAR ASPECTS				
1	Stream Order	U	Hierarchical rank	1 - 6
2	Stream Number	N_u	$Nu = N_1+N_2+...+N_n$	2637
3	Stream Length	L_u	$L_u = L_1+L_2+…+L_n$	12710.93 km
4	Mean Stream Length	L_{sm}	$L_{sm} = L_u/N_u$	4.82 km
5	Stream Length Ratio	R_l	$R_l = L_u/(L_{u-1})$	0.288 – 1.487
6	Mean Stream Length Ratio	R_{lm}	Average of the steam length ratio of all orders	0.652
7	Bifurcation Ratio	R_b	$R_b = N_u / N_{u+1}$	0.631 – 3.034
8	Mean bifurcation ratio	R_{bm}	Average of bifurcation ratio of all orders	1.933
9	Stream Frequency	F_s	$F_s = (\sum N_u)/A$	0.048 km^{-2}
10	Drainage Density	D_d	$D_d = (\sum L_u)/A$	0.231 km/km^2
11	Drainage texture	D_t	$D_t = (\sum N_u)/P$	1.782 km^{-1}
12	Infiltration Number	I_f	$I_f = F_s \times D_d$	0.011 km
13	Length of overland flow	L_o	$L_o = 1/(2D_d)$	2.164 km
14	RHO coefficient	ρ	$\rho = R_{lm}/R_{bm}$	0.337
15	Drainage Intensity	D_i	$D_{i\,=}\ F_s/D_d$	0.208 km^{-1}
16	Constant of channel maintenance	C_{cm}	$C_{cm\,=}\ 1/ D_d$	4.319 km^2/km
B) AREAL ASPECTS				
17	Area of Basin	A	GIS Analysis	54905.1 km^2
18	Perimeter of Basin	P	GIS Analysis	1479.71 km
19	Length of Basin	L_b	$L_b = 1.312 \times A^{0.568}$	645.705 km
20	Circularity Ratio	R_c	$R_c = 4\pi A/P^2$	0.315
21	Elongation Ratio	R_e	$R_e = (2/Lb) \times (A/\pi)^{0.5}$	0.409
22	Form Factor Ratio	F_f	$F_f = A/L_b^2$	0.132
23	Lemniscate ratio	K	$K = L_b^2/4A$	1.898
24	Shape Index	Sb	$Sb = 1/F_f$	7.576
25	Compactness Coefficient	C_c	$C_c = P/2(\pi A)^{0.5}$	1.781
C) RELIEF ASPECTS				
26	Maximum Elevation of basin	Z	GIS Analysis	1444 m
27	Minimum Elevation of basin	Z	GIS Analysis	-16 m
28	Total Basin relief	H	H = Z-z	1460 m
29	Relief Ratio	R_h	$R_h = H/L_b$	2.261
30	Absolute Relief	R_a	$R_a = Z$	1444 m
31	Dissection Index	DI	$DI = H/R_a$	1.011
32	Ruggedness Number	R_n	$R_n = D_d \times H/1000$	0.337

Tab.3. Results of Morphometric Analysis

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