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Quantitative Morphometric Analysis of the Markandahalla Basin, Kolar District, Karnataka Using Remote Sensing and GIS Techniques

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Abstract

The present study undertakes a quantitative morphometric analysis of the Markandahalla watershed using Survey of India topographic maps (1:50,000 scale), SRTM DEM (90 m), ASTER DEM (30 m), and Cartosat DEM (30 m) as primary data sources. A total of 95 morphometric parameters spanning drainage network, basin geometry, drainage texture, and relief characteristics were derived and evaluated. The drainage network was digitised from topographic sheets and extracted automatically from DEM data using ArcGIS 10.2. Basic, derived, and shape parameters were computed for basin analysis. SRTM, ASTER, and Cartosat DEM analyses indicate fine drainage texture. Shape parameters confirm that the Markandahalla basin is elongated. High-resolution DEM data (ASTER and Cartosat, 30 m) yielded lower percentage variation relative to SOI derived values and greater parameter accuracy compared to the coarser SRTM (90 m) input. These findings support watershed management planning, groundwater recharge assessment, and sustainable water resource development in the basin.

Keywords

Morphometric Analysis, DEM, SOI Toposheet, Markandahalla Watershed, Remote Sensing, GIS

1. Introduction

Geomorphology entails the systematic analysis of landscapes, their formative processes, and responses to changing energy and environmental conditions [1]. Over the past several decades, significant emphasis has been placed on quantitative physiographic methods for describing the evolution and behaviour of surface drainage networks [2]-[4]. The measurable attributes of the landscape termed morphometric properties are derived from terrain or elevation surfaces and the drainage network within a drainage basin. The study of drainage basins is fundamental to fluvial geomorphology, which examines the relationship between landforms and the processes that modify them.

Quantitative morphometric analysis of drainage basins was pioneered using topographic maps [2] [5] [6]. The present study aims to evaluate the morphometric characteristics of the Markandahalla basin comprehensively, employing remote sensing data and GIS-based analytical tools, which have become indispensable in contemporary morphometric investigations [7] [8].

2. Study Area

The Markandahalla basin, covering 823.89 km^2, lies between 12˚39' N to 13˚07' N

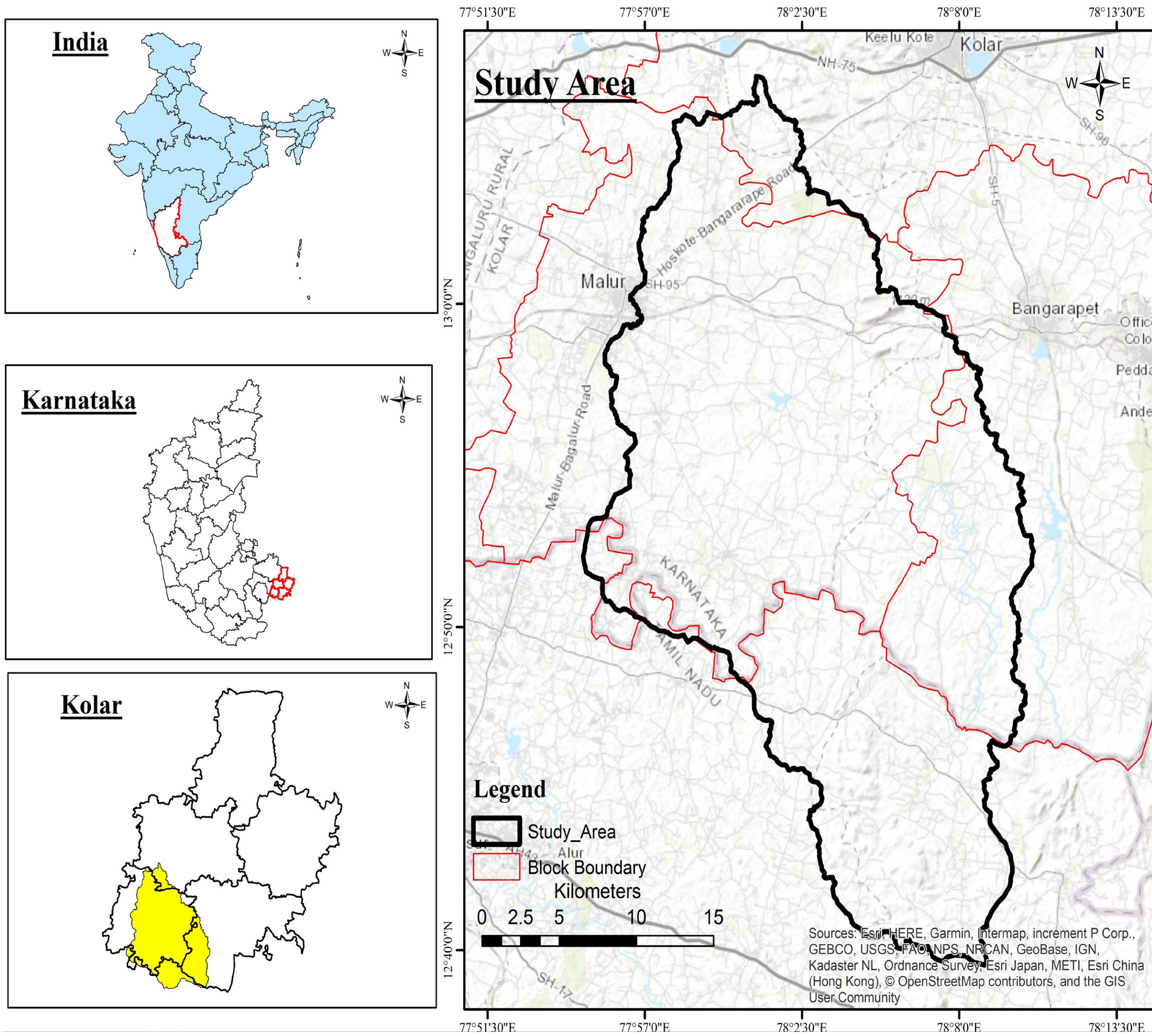


Figure 1. Location map of the Markandahalla basin.

latitude and 78˚01' E to 78˚14' E longitude. The basin originates northeast of Gollahalli, approximately 2.4 km from Narsapura, and joins into the Ponnaiyar River at Nedusalai, Tamil Nadu. Approximately 5% of the southern extent of the study area falls within Tamil Nadu State. The basin incorporates four principal tributaries: Markandahalla (46.78 km, north-south), Koppakerehalla (27.02 km, southwest), Basavanahalla (13.56 km, north), and Naiyallahalla (16.68 km, southwest). These fifth-order streams converge near Verupasandiram village, Krishnagiri district, Tamil Nadu, where Markandahalla joins the Ponnaiyar River.

The watershed is underlain predominantly by Peninsular Gneissic Complex (PGC) rocks including granitic gneisses and migmatites of Archean age, with localised exposures of schist and quartzite along the northern margins. Landuse within the basin is mixed, comprising agricultural land, scrub/grassland, and sparse deciduous forest cover, with limited built-up area confined to small settlements. The basin receives mean annual rainfall of approximately 800 mm, delivered primarily during the southwest monsoon (June-September), with less northeast monsoon contribution. The semi-arid seasonal rainfall regime, combined with the hard rock geology and moderate soil cover, controls drainage density, infiltration rates, and the hydrological behaviour inferred from the morphometric parameters discussed (**Figure 1**).

3. Methodology

Topographic maps numbered 55G/11, 55H/13, 55H/14, 55L/1, and 55L/2 were procured from the Survey of India (SOI) at 1:50,000 scale to manually delineate the drainage network in ArcGIS 10.2. Three DEM datasets were used: ASTER DEM (ASTGTMV003, 30 m, WGS 84/UTM Zone 44N), SRTM DEM (SRTM1S v3.0, 90 m, WGS 84/UTM Zone 44N), and Cartosat-1 DEM (CartoDEM Version 3R1, 30 m, WGS 84/UTM Zone 44N). All three were resampled to a common 30 m grid using bilinear interpolation prior to comparative analysis. All three exhibited less than 2% error in automated drainage extraction; this error estimate was derived by comparing automatically extracted stream network total lengths against the manually digitised SOI toposheet network, using total length deviation as the error metric [9]. The smaller the DEM cell size, the more precise the resulting parameters [9].

The automated drainage extraction workflow followed a standard sequence: i) DEM mosaicking and re-projection; ii) sink-filling using the ArcGIS Hydrology Fill tool to produce a hydrologically conditioned surface; iii) flow-direction computation using the D8 algorithm; iv) flow-accumulation raster generation; and v) stream initiation above a flow-accumulation threshold of 500 cells (equivalent to ~0.45 km^2 for ASTER/Cartosat and ~4.05 km^2 for SRTM), producing a vector channel network for order assignment and length measurement. Basin boundaries, fill, flow accumulation, flow direction, flow length, and stream order layers were generated using the Arc Hydro Tool; contour, slope, aspect, and hillshade layers were produced using the ArcGIS Surface Tool with ASTER DEM data (**Figure 2**).

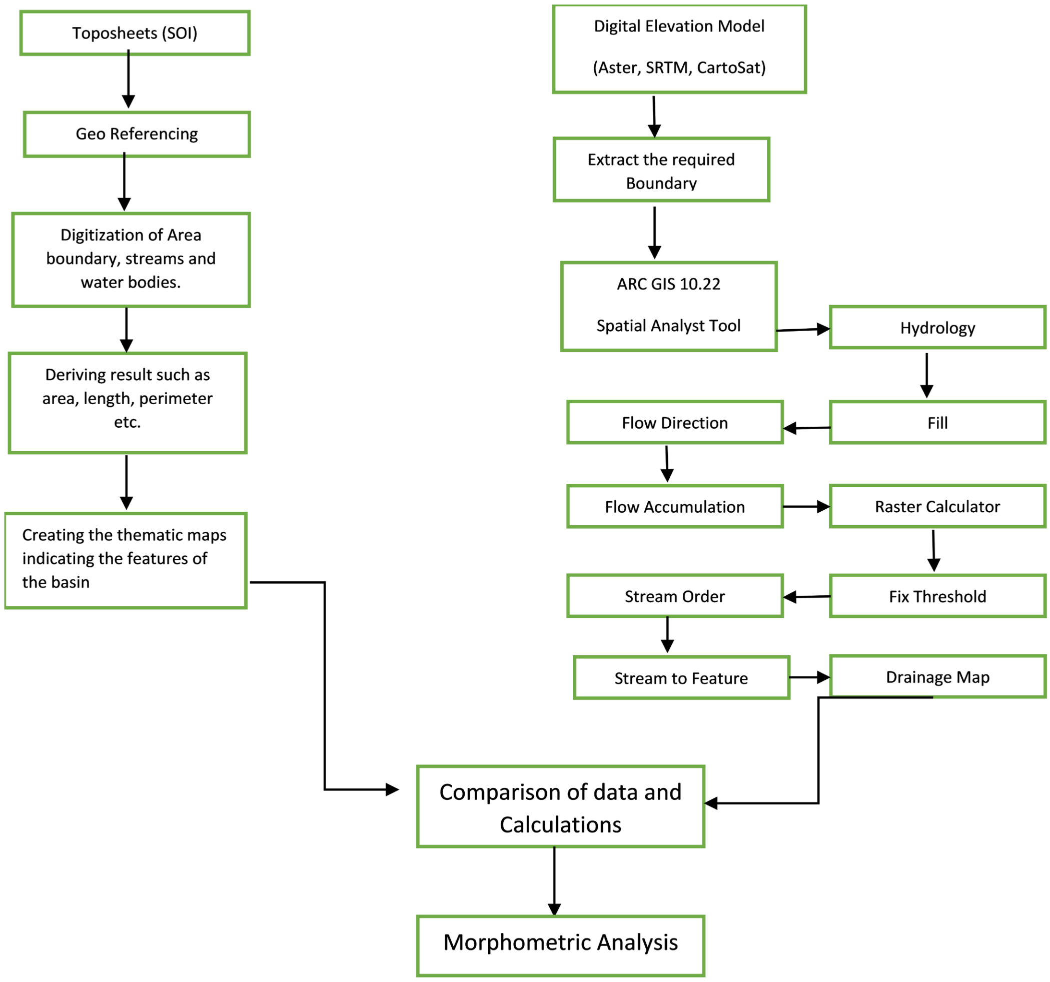


Figure 2. Methodology flowchart for morphometric analysis.

4. Results and Discussion

Horton [2] and Strahler [5] were the first to systematically quantify morphometric parameters of river basins. The morphometric characteristics of a basin contain essential information about its hydrological and geomorphic processes. The morphometric analysis of the Markandahalla basin was carried out using SOI toposheets (1:50,000) and ASTER/SRTM/Cartosat DEM data. A total of 97 parameters were computed: 21 using ArcGIS 10.2 hydrology tools and 74 using established mathematical formulae [5], giving a combined total of 95 parameters. Analysis is organised under four headings: drainage network, basin geometry, drainage texture analysis, and relief characteristics. Key results are summarised in **Table 1**.

Table 1. Morphometric parameters of the markandahalla basin.

No.	Parameter	Formula/Method	Reference	Result
		A. Drainage Network		
1	Stream Order (Su)	Hierarchical rank	Strahler (1952) [5]	1 - 6
2	1st Order Streams (Suf)	Suf = N1	Strahler (1952) [5]	1374

Continued

3	Stream Number (Nu)	$Nu = N1 + N2+,\cdots,+Nn$	Horton (1945) [2]	1771
4	Stream Length (Lu, km)	$Lu = L1 + L2+,\cdots,+Ln$	Strahler (1964) [6]	1396.30
5	Stream Length Ratio (Lur)	See Table 2	Strahler (1964) [6]	1.55 - 11.76
6	Mean Stream Length ratio (Lum)	See Table 2	Horton (1945) [2]	2.35
7	Weighted Mean Stream Length Ratio (Luwm)	See Table 2	Horton (1945) [2]	1.97
8	Mean Length, 1st Order (L1)	L1	Horton (1945) [2]	0.59
9	Mean Length, 2nd Order (L2)	L2	Horton (1945) [2]	0.92
10	Lu(1/2) = Lu1/Lu2	Lu(1/2) = Lu1/Lu2	Strahler (1952) [5]	0.54
11	Bifurcation Ratio (Rb)	See Table 2	Strahler (1964) [6]	3.00 - 5.07
12	Mean Bifurcation Ratio (Rbm)	See Table 2	Strahler (1964) [6]	4.30
13	Weighted Mean Bifurcation Ratio (Rbwm)	See Table 2	Strahler (1953) [10]	4.46
14	Main Channel Length (Cl, km)	GIS analysis	-	75.50
15	Valley Length (Vl, km)	GIS analysis	-	52.69
16	Minimum Aerial Distance (Adm, km)	GIS analysis	-	51.77
17	Channel Index (Ci)	Ci = Cl/Adm	Miller (1968) [11]	1.47
18	Valley Index (Vi)	Vi = Vl/Adm	Miller (1968) [11]	1.02
19	Rho Coefficient (ρ)	ρ = Lur/Rb	Horton (1945) [2]	0.13
		B. Basin Geometry		
20	Length from basin Centre to Mouth (Lcm, km)	GIS analysis	Black (1972) [12]	27.55
21	Width at Centre of Mass (Wcm, km)	GIS analysis	Black (1972) [12]	12.68
22	Basin Length (Lb, km)	GIS analysis	Schumm (1956) [13]	52.69
23	Mean Basin Width (Wb, km)	Wb = A/Lb	Horton (1932) [2]	15.60
24	Basin Area (A, km^2)	GIS analysis	Schumm (1956) [13]	823.89
25	Mean Area Ratio (Arm)	See Table 3	-	4.30
26	Weighted Mean Area Ratio (Arwm)	See Table 3	-	4.51
27	Basin Perimeter (P, km)	GIS analysis	Schumm (1956) [13]	162.00
28	Relative Perimeter (Pr)	Pr = A/P	Schumm (1956) [13]	5.09
29	Length-Area Relation (Lar)	$Lar = 1.4 \times A^{0.6}$	Hack (1957) [14]	78.64
30	Lemniscate Value (k)	$k = Lb^2/A$	Chorley (1957) [15]	0.81
31	Form Factor (Ff)	$Ff = A/Lb^2$	Horton (1932) [2]	0.30
32	Shape Factor (Sf)	$Sf = Lb^2/A$	Horton (1956) [2]	3.38
33	Elongation Ratio (Re)	$Re = 2(A/\pi)^{0.5}/Lb$	Schumm (1956) [13]	0.61
34	Ellipticity Index (Ie)	$Ie = \pi \times Vl^2/(4A)$	-	2.65
35	Texture Ratio (Rt)	Rt = N1/P	Schumm (1965) [16]	8.48
36	Circularity Ratio (Rc)	$Rc = 12.57 \times (A/P^2)$	Miller (1953) [11]	0.39

Continued

37	Circularity Ratio-Strahler (Rcn)	Rcn = A/P	Strahler (1964) [6]	5.09
38	Drainage Texture (Dt)	Dt = Nu/P	Horton (1945) [2]	10.92
39	Compactness Coefficient (Cc)	$Cc = 0.2841 \times P/A^{0.5}$	Gravelius (1914) [17]	1.60
40	Fitness Ratio (Rf)	Rf = Cl/P	Melton (1957) [18]	0.47
41	Wandering Ratio (Rw)	Rw = Cl/Lb	Smart & Surkan (1967) [19]	1.45
42	Basin Eccentricity (τ)	$\tau = [(\lvert Lcm^2 - Wcm^2\rvert)]^{0.5}/Wcm$	Black (1972) [12]	1.93
43	Centre of Gravity (Gc)	GIS analysis	Rao (1998) [20]	78.054°E, 12.888°N
44	Hydraulic Sinuosity Index (Hsi, %)	$Hsi = ((Ci - Vi)/(Ci - 1)) \times 100$	Mueller (1968) [21]	95.74
45	Topographic Sinuosity Index (Tsi, %)	$Tsi = ((Vi - 1)/(Ci - 1)) \times 100$	Mueller (1968) [21]	36.17
46	Standard Sinuosity Index (Ssi)	Ssi = Ci/Vi	Mueller (1968) [21]	1.45
47	Longest Dimension Parallel to Drainage (Clp, km)	GIS analysis	-	53.14
48	Valley Width (Vwid, m)	Valley width 0.5 km from basin mouth	-	849.13
49	Ratio N1 to Perimeter (PN1)	PN1 = N1/P	-	8.48
		C. Drainage Texture Analysis		
50	Stream Frequency (Fs)	Fs = Nu/A	Horton (1932) [2]	2.15
51	Drainage Density (Dd, km/km^2)	Dd = Lu/A	Horton (1932) [2]	1.69
52	Constant of Channel Maintenance (C, km^2/km)	C = 1/Dd	Schumm (1956) [13]	0.59
53	Drainage Intensity (Di Km/km^2)	Di = Fs/Dd	Faniran (1968) [22]	1.27
54	Infiltration Number (If)	$If = Fs \times Dd$	Faniran (1968) [22]	3.47
55	Drainage Pattern (Dp)	Visual interpretation	Horton (1932) [2]	Dendritic-sub-dendritic
56	1st Order Stream Frequency (Fst)	Fst = N1/A	Miller (1968) [11]	1.66
57	Flow Direction (Fdi)	Spatial Analyst Hydrology Tool	-	NW to SE
58	Length of Overland Flow (Lg, km)	$Lg = A/(2 \times Lu)$	Horton (1945) [2]	0.30
		D. Relief Characteristics		
59	Height of Basin Mouth (z, m)	GIS/DEM analysis	-	541
60	Maximum Basin Height (Z, m)	GIS/DEM analysis	-	1127
61	Total Basin Relief (H, m)	$H = Z - z$	Strahler (1952) [5]	586
62	Mean Height Value (Hmv, m)	Summary statistics	-	834
63	Relief Ratio (Rhl)	Rhl = H/Lb	Schumm (1956) [13]	0.011
64	Absolute Relief (Ra, m)	GIS analysis	-	1127
65	Relative Relief Ratio (Rhp)	$Rhp = H \times 100/P$	Melton (1957) [18]	0.04
66	Dissection Index (Dis)	Dis = H/Ra	Singh & Dubey (1994) [23]	0.52
67	Channel Gradient (Cg, m/km)	$Cg = H/(\pi/2 \times Clp)$	Broscoe (1959) [24]	7.02

Continued

68	Gradient Ratio (Rg)	Rg = (Z − z)/Lb	Sreedevi (2004) [25]	0.011
69	Basin Slope (Sw)	Sw = H/Lb	-	0.0112
70	Ruggedness Number (Rn)	Rn = Dd × (H/1000)	Patton & Baker (1976) [26]	0.99
71	Melton Ruggedness Number (MRn)	MRn = $H/A^{0.5}$	Melton (1965) [27]	20.42
72	Total Contour Length (Ctl, km)	GIS analysis	-	2312.24
73	Contour Interval (Cin, m)	GIS analysis	-	20
74	Length of Two Successive Contours (L1 + L2, km)	GIS analysis	Strahler (1952) [5]	379.25
75	Average Slope Width of Contour (Swc)	Swc = A/{(L1 + L2)/2}	Strahler (1952) [5]	4.34
76	Slope Analysis (Sa, degrees)	GIS Surface Tool	Rich (1916) [28]	1.56° - 36.24°
77	Average Slope (S, %)	S = (Z × (Ctl/H))/(10 × A)	Wentworth (1930) [29]	0.53
78	Mean Slope Ratio (Sm)	-	Wentworth (1930) [29]	5.73
79	Weighted Mean Slope Ratio (Swm)	-	Wentworth (1930) [29]	5.91
80	Mean Slope of Basin (θs)	θs = (Ctl × Cin)/A	Chorley (1979) [30]	0.56
81	Slope Gradient ($\tan\beta$)	GIS/DEM analysis	-	3.54
82	Maximum Slope (Smax, degrees)	GIS/DEM analysis	-	36.20
83	Minimum Slope (Smin, degrees)	GIS/DEM analysis	-	14.20
84	Slope Variability (Sva)	Sva = Smax − Smin	-	22.00
85	Slope Index (Sin)	Sin = H/Lb	Taylor & Schwarz (1952) [31]	11.12
86	Length-Slope Factor (LSf)	LSf = $1.4 \times [(A/22.13)^{0.4}] \times [(\tan\beta/0.0896)^{1.3}]$	Moore & Wilson (1992) [32]	113.26
87	Topographic Wetness Index (TWI)	TWI = $\ln(A/\tan\beta)$	Moore et al. (1991) [33]	4.74
88	Upslope Contributing Area (Aus)	Aus = Ctl/A	Moore et al. (1991) [33]	2.80
89	Relative Stream Power (SPr)	SPr = Aus × $\tan\beta$	Lindsay (2005) [34]	9.91
90	Relative Height (h/H)	See Table 4	Strahler (1952) [5]	0% - 100%
91	Relative Area (a/A)	See Table 4	Strahler (1952) [5]	0% - 100%
92	Hypsometric Integral (Hi, %)	Hypsometric curve	Strahler (1952) [5]	45.17
93	Erosion Integral (Ei, %)	Hypsometric curve	Strahler (1952) [5]	54.83
94	Stage of Basin (WSs)	Based on Hi	Strahler (1952) [5]	Mature
95	Clinographic Analysis (Cga)	$\tan\theta$ = Cin/Swc	Strahler (1952) [5]	2.33

4.1. Drainage Network

The drainage network facilitates the transport of water and sediments through a single basin outlet corresponding to the highest stream order. Stream order serves as the fundamental step in drainage basin analysis, and basin size varies considerably with stream order.

4.1.1. Stream Order (Su)

Stream ordering follows Horton's hierarchical scheme: an unbranched tributary constitutes a first-order stream; confluence of two or more first-order streams produces a second-order stream, and so on. The Markandahalla basin exhibits six hierarchical orders, consistent with dendritic drainage development on relatively uniform lithology [5].

4.1.2. Stream Number (Nu)

The total number of stream segments across all orders is 1,771. As required by Horton's (1945) law [2], segment counts decrease systematically with ascending order, exhibiting an inverse geometric progression. The equation used is:

$$\mathrm{Nu} = \mathrm{N1} + \mathrm{N2} + \cdots + \mathrm{Nn} \tag{1}$$

where N1 is the count of first-order streams and Nn is the count of nth-order segments.

4.1.3. Stream Length (Lu)

Stream length is the aggregate length of all individual channel segments within each order (Equation (2)). The total stream length of the Markandahalla basin is 1,396.30 km.

$$\mathrm{Lu} = \mathrm{L1} + \mathrm{L2} + \cdots + \mathrm{Ln} \tag{2}$$

4.1.4. Mean Stream Length (Lum)

Mean stream length is a dimensionless parameter reflecting the characteristic scale of drainage network components and their contributing sub-basin areas [6] (Equation (3)). With Lu = 1,396.30 km and Nu = 1771 stream segments, the mean stream length Lum = Lu/Nu = 1,396.30/1771 = 0.79 km. The value of 2.35 reported in Table 2 is the mean stream length ratio (Lurm), which is a distinct parameter representing the ratio of stream lengths across successive orders.

$$\mathrm{Lum} = \mathrm{Lu}/\mathrm{Nu} \tag{3}$$

4.1.5. Stream Length Ratio (Lur)

The stream length ratio is the ratio between the mean length of stream segments of a given order and those of the next lower order (Equation (4)). This ratio remains relatively constant across successive orders within a basin, and changes in this value indicate the stage of geomorphic development [35]. Values are presented in Table 2.

$$\mathrm{Lur} = \mathrm{Lu}/\mathrm{Lu} - 1 \tag{4}$$

Table 2. Stream order, length, and length ratio parameters of the Markandahalla basin.

Su	Nu	Lu (km)	Lu/Su	Lur	Lur-r	Lur × Lur-r	Luwm
1	1374	815.51	0.59	-	-	-	1.97
2	314	291.02	0.92	1.55	1105.13	1712.95	-
3	66	149.89	2.27	2.49	440.91	1084.63	-

Continued

4	13	56.13	4.31	1.89	206.02	389.37	-
5	3	63.38	21.12	4.90	119.51	585.59	-
6	1	20.37	20.37	0.96	83.75	80.40	-
Total	1771	1396.30	49.58	11.76	1955.32	3852.94	-
Mean	-	232.40	8.26	2.35	391.06	770.58	-

Su = stream order; Nu = number of streams; Lu = stream length; Lur = stream length ratio; Lur-r = stream length used in ratio; Luwm = weighted mean stream length ratio.

4.1.6. Bifurcation Ratio (Rb)

The bifurcation ratio links the hydrological regime to topological and climatic conditions and aids interpretation of basin shape and runoff behaviour. It is defined as the ratio of stream segments of order u to those of the next higher order (Equation (5)).

$$\mathrm{Rb} = \mathrm{Nu}/\mathrm{Nu} + 1 \tag{5}$$

In the present study, Rb ranges from 3.00 to 5.07, indicating the basin is largely free of significant structural disturbances. The mean bifurcation ratio is 4.30 and the weighted mean is 4.46 [10], both consistent with a natural, geologically undisturbed drainage system.

4.2. Basin Geometry

4.2.1. Basin Length (Lb)

Basin length, defined by Schumm (1956) [13] as the longest dimension parallel to the principal drainage line, is 52.69 km for the Markandahalla basin.

4.2.2. Basin Area (A) and Perimeter (P)

The basin area, calculated in ArcGIS 10.2, is 823.89 km^2. The basin perimeter, representing the horizontal projection of the water divide, is 162 km. The relative perimeter (Pr = A/P) is 5.09.

4.2.3. Shape Parameters

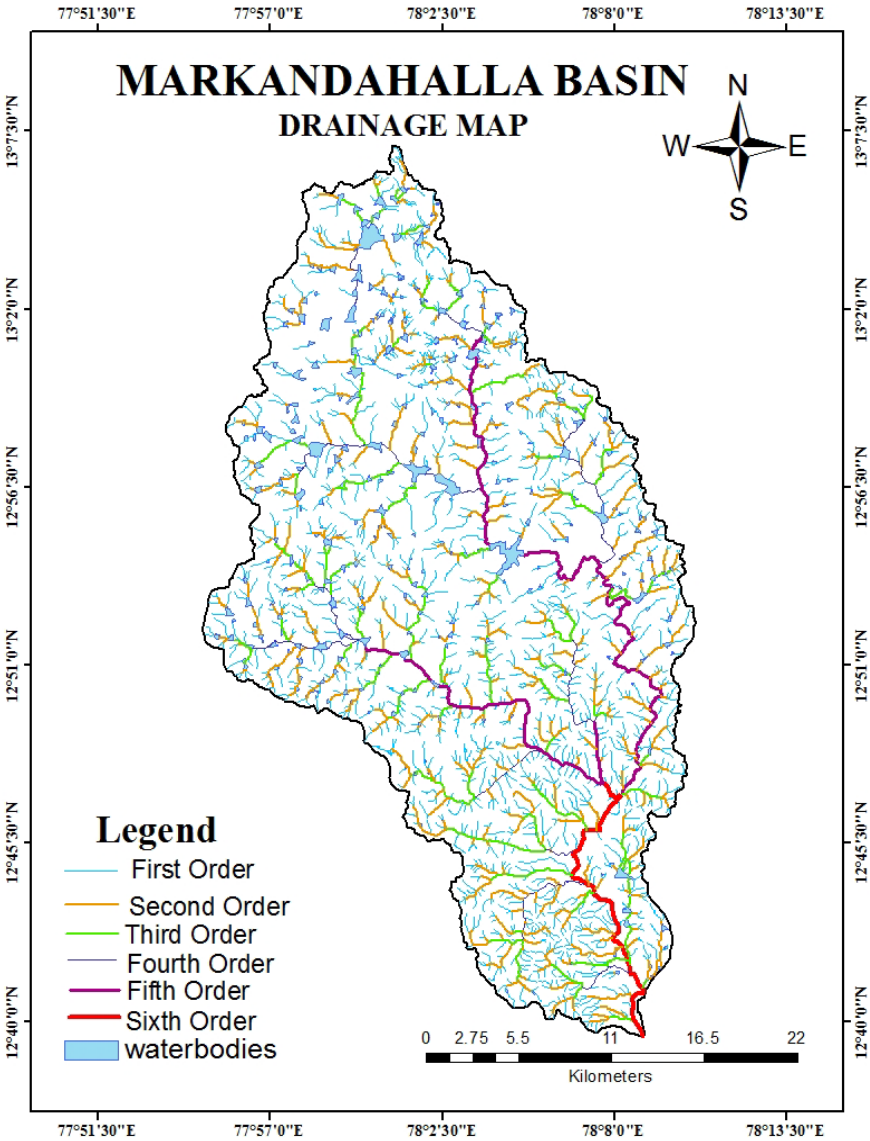
The form factor (Ff = 0.295), elongation ratio (Re = 0.613), and circularity ratio (Rc = 0.394) together confirm an elongated basin shape. The Lemniscate value (k = 0.814) falls within the ideal range for elongated basins (0.50 - 1.80), indicating proneness to erosion due to longer runoff paths. The compactness coefficient (Cc = 1.66) reflects surface undulations with gentle slopes. The fitness ratio (Rf = 0.472) indicates that the elongated basin favours relatively prolonged runoff concentration time and moderate infiltration opportunity, with good potential for groundwater recharge [36]. These basin geometry inferences regarding runoff behaviour and groundwater recharge represent morphometric approximations and would require independent hydrological or hydrogeological data for confirmation.

4.2.4. Sinuosity Index (Si)

The sinuosity index, defined as the ratio of channel length to down-valley distance, ranges from 1 to > 4. Rivers with Si ≥ 1.5 are classified as sinuous; those with Si > 1.5 are meandering [11]. The Markandahalla basin yields Si = 1.45, classifying it as sinuous.

4.2.5. Channel Index (Ci) and Valley Index (Vi)

The channel index (Ci = Cl/Adm = 1.47) and valley index (Vi = Vl/Adm = 1.02) were computed following Miller (1968) [11]. The hydraulic sinuosity index (95.74%) indicates that hydraulic factors predominantly control channel sinuosity (**Figure 3**).



Source: This was developed in ArcGIS 10.2.2 soft ware.

Figure 3. Drainage map of the Markandahalla basin from toposheets.

4.3. Drainage Texture Analysis

4.3.1. Stream Frequency (Fs)

Stream frequency, the number of stream segments per unit area [2], is 2.15 km^{-2}

for the Markandahalla basin. This value reflects a lithology-controlled stream network of moderate density.

4.3.2. Drainage Density (Dd)

Drainage density (Dd = Lu/A) is 1.69 km/km^2, indicating moderate drainage dissection [2] [5]. This value implies moderately permeable sub-soil with dense foliage, resulting in intermediate runoff and infiltration characteristics [37].

4.3.3. Drainage Texture (Dt)

The drainage texture (Dt = Nu/P) is 10.92, classifying the basin as very fine (Dt > 8) according to Smith (1950) [38]. This high Dt value reflects the influence of infiltration capacity and lithological characteristics on channel spacing.

4.3.4. Drainage Intensity (Di) and Infiltration Number (If)

The low drainage intensity (Di = 1.27) indicates that drainage density and stream frequency have limited influence on denudation of the land surface. The combined infiltration number (If = Fs × Dd = 3.47) confirms moderate infiltration characteristics. The length of overland flow (Lg = 0.30 km) signifies very low surface runoff.

4.3.5. Drainage Pattern (Dp)

The drainage pattern of the Markandahalla basin is dendritic to sub-dendritic, reflecting relatively uniform lithology unaffected by major structural disturbances. The dendritic pattern is especially well developed in basins with long geomorphic histories [36].

Table 3. Stream order and area ratio parameters of the Markandahalla basin.

Su	Nu	Am (km^2)	Ar	No. in ratio	Product of Am	Arm	Arwm
1	1374	0.13	-	-	-	-	-
2	314	0.56	4.30	1688	7258.40	-	-
3	66	2.68	4.78	380	1816.40	-	-
4	13	13.62	5.08	78	396.20	-	-
5	3	59.03	4.33	16	69.28	4.51	-
6	1	177.10	3.00	4	12.00	-	-
Total	1771	253.13	21.49	2166	9552.28	-	4.51
Mean	-	-	4.30	-	-	-	-

Su = stream order; Nu = number of streams; Am = mean area of stream order; Ar = area ratio; Arm = mean area ratio; Arwm = weighted mean area ratio.

4.4. Relief Characteristics

4.4.1. Relief Ratio (Rhl) and Gradient Ratio (Rg)

The relief ratio (Rhl = H/Lb = 0.011) is low, primarily attributed to resistant basement rocks and a low basin slope gradient [13] [39]. The gradient ratio (Rg = 0.011) reveals the sub-mountainous nature of the terrain. The total basin relief (H

= 586 m), derived from the difference between maximum elevation (Z = 1127 m) and basin mouth elevation (z = 541 m), represents moderate vertical variability.

4.4.2. Ruggedness Number (Rn) and Melton Ruggedness Number (MRn)

The ruggedness number (Rn = Dd × H/1000 = 0.99) combines slope steepness and length, integrating structural complexity and erosion potential [5] [26]. The low Rn value suggests the area is less prone to soil erosion. The Melton ruggedness number (MRn = $H/A^{0.5}$ = 20.42), a slope index providing a specialised depiction of relief ruggedness [27], indicates moderately rugged terrain with potential for higher erosional activity. These erosion susceptibility inferences are morphometric approximations and are not supported by independent sediment yield or erosion pin data in this study.

4.4.3. Dissection Index (Dis)

The dissection index (Dis = H/Ra = 0.52) indicates moderate vertical erosion and intermediate landform development, with a value between 0 (flat surface) and 1 (vertical cliff) [23].

4.4.4. Slope Analysis

Slope values range from **1.56˚ to 36.24˚** across the basin. The average slope (S = 0.534%) was computed following Wentworth (1930) [29]. The mean slope of the overall basin (θs = 0.56) was calculated using the contour-based method of Chorley (1979) [30]. These values confirm the gentle-to-moderate topographic character of the Markandahalla watershed, with steeper gradients confined to the upper catchment margins.

4.4.5. Hypsometric Analysis

Hypsometric analysis evaluates the distribution of basin area across elevation bands, providing insights into the erosional stage and geomorphic evolution. The hypsometric integral (Hi = 45.17%) and erosion integral (Ei = 54.83%) were computed following Strahler (1952) [5] using the percentage hypsometric method. A Hi value of 30% - 60% indicates a mature geomorphic stage [5]. The Markandahalla basin falls within this range, confirming it is in the mature stage of landscape development (**Table 4**).

Table 4. Hypsometric data for the Markandahalla basin.

Sl.	Elevation Range (m)	Elevation (m)	Height (h)	Area a (km²)	a/A	h/H
1	541 - 589	589	0	35.267	0.043	0.000
2	589 - 637	637	48	44.629	0.054	0.500
3	637 - 685	685	96	32.572	0.040	0.667
4	685 - 733	733	144	51.789	0.063	0.750
5	733 - 781	781	192	68.480	0.083	0.800
6	781 - 829	829	240	126.189	0.153	0.833
7	829 - 877	877	288	268.441	0.326	0.857

Continued

8	877 - 925	925	336	188.923	0.229	0.875
9	925 - 973	973	384	5.039	0.006	0.889
10	973 - 1021	1021	432	1.189	0.001	0.900
11	1021 - 1069	1069	480	0.668	0.001	0.909
12	1069 - 1117	1117	528	0.195	0.000	1.000

4.4.6. Clinographic Analysis (Cga)

Clinographic analysis captures the relationship between ground slope and elevation through Strahler's (1952) method [5] (Equation (6)). The clinographic angle of 2.33˚ reflects moderate terrain dissection consistent with a mature erosional landscape.

$$\tan\theta = \mathrm{Cin}/\mathrm{Swc}\text{, where } \mathrm{Swc} = \mathrm{Ac}\Big/\big[(\mathrm{L1}+\mathrm{L2})/2\big] \quad (6)$$

4.5. Comparative Analysis of DEM Sources

Table 5 presents the principal morphometric differences in drainage network parameters derived from the four data sources used in this study: SOI topographic maps (1:50,000 scale), ASTER DEM (30 m), SRTM DEM (90 m), and Cartosat DEM (30 m). The SOI-digitised network, serving as the reference dataset, yielded 1771 stream segments with a total length of 1396.30 km and drainage density of 1.69 km/km^2. The ASTER and Cartosat 30 m DEMs produced closely comparable results, with less than 1% variation in stream number and total stream length relative to the SOI reference, confirming the superior accuracy of 30 m resolution DEMs for morphometric parameter extraction. The SRTM 90 m DEM showed greater deviation (~8% lower stream number; ~7.7% shorter total stream length) owing to its coarser spatial resolution, which merges or omits lower-order channels. The drainage pattern remained consistently dendritic across all four sources. These results support the conclusion that higher-resolution DEMs (ASTER, Cartosat) yield lower percentage variation from ground-truth values and are preferred for quantitative morphometric studies in moderate-relief basins such as Markandahalla.

Table 5. Comparison of key morphometric parameters across data sources.

Parameter	SOI Toposheet (1:50,000)	ASTER DEM (30 m)	SRTM DEM (90 m)	Cartosat DEM (30 m)
Stream Order	6	6	5	6
Stream Number (Nu)	1771	1754	1632	1768
Stream Length (km)	1396.30	1378.42	1289.15	1391.06
Drainage Density (km/km^2)	1.69	1.67	1.56	1.69
Drainage Texture (Dt)	10.92	10.83	Fine	10.91
Drainage Pattern	Dendritic	Dendritic	Dendritic	Dendritic
% Variation vs SOI	-	<1%	~8%	<1%

Note: SRTM values represent the 90 m product; ASTER and Cartosat represent 30 m products. % Variation is computed relative to the SOI toposheet-derived reference values.

5. Conclusions

The morphometric analysis of the Markandahalla basin yields the following principal conclusions:

- The drainage network comprises six hierarchical stream orders with 1771 total segments and a cumulative length of 1396.30 km. Stream segment counts and lengths decrease systematically with ascending order, consistent with Horton's laws [2].
- The drainage pattern is dendritic to sub-dendritic, reflecting relatively uniform lithology free of major structural disturbances.
- The mean bifurcation ratio (4.30) and weighted mean (4.46) fall within the natural range, confirming absence of significant tectonic control on the drainage configuration.
- Shape parameters (Ff = 0.295; Re = 0.613; Rc = 0.394; k = 0.814) consistently indicate an elongated basin with lower peak flows, prolonged runoff, and moderate groundwater recharge potential.
- Drainage density (1.69 km/km^2) and stream frequency (2.15 km^{-2}) indicate moderate permeability and intermediate drainage development.
- Relief parameters including a low relief ratio (0.011), moderate ruggedness number (0.99), and dissection index (0.52) indicate gentle-to-moderate slopes with limited erosion susceptibility except in upper basin reaches.
- The hypsometric integral (Hi = 45.17%) places the Markandahalla basin in the mature geomorphic stage, with approximately 54.83% of the original landmass volume removed through erosion.
- SRTM, ASTER, and Cartosat DEM data indicate fine drainage texture and confirm that higher-resolution DEMs (ASTER, Cartosat at 30 m) yield lower percentage variation and greater accuracy in morphometric parameter extraction relative to the coarser SRTM (90 m) product (**Table 5**).
- Results support targeted basin management interventions including groundwater recharge enhancement, erosion control, and sustainable water resource planning for the Markandahalla basin.
- The conclusions regarding groundwater recharge, runoff behaviour, erosion susceptibility, and tectonic influence are based on morphometric inference from DEM and topographic data. Independent field-based hydrological, hydrogeological, or tectonic investigations are needed to substantiate these interpretations.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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