

Hydrogeomorphic Assessment for Sustainable Water Resource Management using a Geospatial Approach: A Case Study of the Nagod Watershed Area, Satna District, Central India

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Abstract

Sustainable water resource management is essential for maintaining the ecological balance and functional integrity of watersheds, particularly in regions experiencing increasing anthropogenic pressure. In this study, geospatial approach was employed to analyze the morphometric, hydrogeomorphological, and hypsometric characteristics of the Nagod watershed area, Central India, with the aim of supporting effective watershed and groundwater management. Drainage networks and watershed boundaries were derived from Survey of India toposheets and digital elevation model (DEM) data, and detailed morphometric analysis was carried out for five sub-watersheds by evaluating linear, areal, and relief parameters, including stream order, stream length, bifurcation ratio, drainage density, stream frequency, circularity ratio, and form factor. These parameters provide insights into hydrological processes such as runoff, infiltration, erosion, and sediment transport, and help in understanding watershed response to topographic and structural controls. Geomorphological analysis delineated major landforms such as plateau, pediplain, pediment, and escarpment, while geological analysis identified sedimentary formations of the Rewa and Bhander Groups as key controls on drainage development. Lineament analysis revealed dominant NE–SW and NW–SE trends, indicating structural influence on drainage orientation and groundwater movement. Hydrogeomorphic evaluation showed that pediplain and pediment units offer favourable groundwater recharge conditions, whereas plateau and escarpment regions are runoff-dominated. Hypsometric analysis indicates a mature to late-mature stage of geomorphic evolution, reflecting prolonged erosional processes. Overall, the study demonstrates that geospatial approach based morphometric and hydrogeomorphic analyses are effective tools for hydrological assessment, and the results provide valuable inputs for scientific planning, watershed prioritization, and sustainable natural resource management.

Keywords: Morphometric analysis, Hydrogeomorphic analysis, Watershed management, Geospatial Approach, Hypsometric analysis, Sustainable water resource.

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I. Introduction

Rapid industrialization, population growth, and intensive land-use changes have placed increasing stress on land and water resources in India, leading to declining water availability, accelerated soil erosion, and growing pressure on watershed systems. Effective watershed management, specifically through the application of morphometric analysis, is essential for addressing pressing environmental challenges such as soil loss, water shortages, and land degradation [18]. Accelerated population growth and anthropogenic developmental activities have significantly modified hydrogeomorphic frameworks, leading to the disruption of natural hydrological cycles [7]. The adoption of unsuitable farming techniques and deficient on-site management poses a direct threat to the ecological resilience and long-term sustainability of vital land-water systems [29]. Watershed-based morphometric analysis has emerged as an effective and widely adopted approach for quantitatively evaluating drainage basin characteristics and their control on hydrological processes such as runoff generation, infiltration, erosion, and sediment transport [8,26,28]. Studies demonstrate that morphometric parameters provide critical insights into basin geometry, drainage efficiency, and landscape evolution, thereby supporting groundwater assessment and watershed prioritization under changing environmental conditions [2,12,19,27]. Consequently, morphometric analysis has gained renewed importance as a scientific tool for integrated watershed management and climate-resilient water resource planning in diverse hydrogeomorphic settings [1,17].

Morphometric analysis has long been recognized as a fundamental component of hydrological and geomorphological studies. The conceptual foundation was established by Horton (1932, 1945) and further refined by Strahler (1952, 1964), who demonstrated that drainage network properties reflect underlying geological structure, lithology, and geomorphic evolution. Recent studies reaffirm that watershed configuration

and morphometric parameters serve as indicators of past and on-going tectonic, climatic, and denudational processes, thereby offering insights into basin development and hydrological behaviour [8,17,24,25,28]. Morphometric parameters are generally grouped into linear, areal, and relief aspects, each contributing to an improved understanding of drainage efficiency, basin shape, runoff characteristics, and groundwater potential.

Advancements in geospatial approaches have significantly enhanced the accuracy and efficiency of morphometric investigations. Digital elevation models (DEMs), satellite imagery, and GIS-based spatial analysis enable automated extraction of drainage networks and computation of morphometric indices, reducing subjectivity and improving reproducibility [1,4]. The integration of geospatial approach has therefore become a widely adopted and reliable approach for watershed delineation, prioritization, erosion risk assessment, groundwater potential evaluation, and sustainable planning of soil and water conservation measures [2,20].

Watersheds represent natural hydrological units in which surface and subsurface processes operate in an integrated manner, making them ideal for scientific investigation and management interventions. Morphometric characterization of watersheds under varying geomorphological and topographic settings allows for a comparative assessment of hydrological response and landscape evolution [12,14]. Furthermore, drainage patterns and stream network characteristics are strongly influenced by lithology, structural elements, geomorphology, vegetation, and soil properties, resulting in spatial and temporal variability in hydrological behaviour [23]. Consequently, systematic morphometric evaluation provides essential information for watershed planning, groundwater exploration, and sustainable water resource management, particularly in hard-rock and sedimentary terrains.

Overall, the application of geospatial approach based morphometric analysis offers a robust scientific framework for understanding watershed dynamics and supporting informed decision-making for integrated watershed management in the face of growing anthropogenic and climatic pressures [16,19,27].

The primary goal of this research is to evaluate the geomorphological and hydrological characteristics of the Nagod study area using geospatial approaches. The specific objectives are:

1. Morphometric Characterization: To quantify linear, areal, and relief parameters to assess drainage behaviour and watershed geometry.
2. Geomorphic Evolution: To determine the watershed stage of landscape development and erosion susceptibility through hypsometric analysis.

II. Study Area

The study area lies within Survey of India toposheet numbers 63D/10, 63D/11, 63D/14, and 63D/15, and is geographically located between 24°17'00" to 24°30'00" N latitude and 80°40'00" to 80°55'00" E longitude (Figure 1). It covers an areal extent of approximately 800 km². Nagod town, located near the central part of the study area, functions as an important administrative and socio-economic hub. The area includes several prominent villages such as Pallanpur, Paparenga, Regla, Kothi, Bandarha, PipriKalan, Akahi, Lagargawan, Dadri, Urdana, Ichol, Bihta, Khuzha, Koniya, Kalpura, Khoh, Itma, Bhatia Khurd, Bhatanwara, and Mainaha. The distribution of settlements shows a close association with river courses and road networks, emphasizing the influence of water availability and accessibility on habitation patterns. Unchehra, which lies within Satna tehsil, is situated in the south-western part of Satna district and approximately 29 km from Satna town, which serves as both the district headquarters and the administrative centre of the present study. The transportation network is well developed, with several metalled and un-metalled roads connecting major villages, and the National Highway (NH-39) passing through the south western part of the study area, ensuring regional connectivity. The study area is well connected by road and rail networks; the Satna–Maihar main road traverses the region, while Unchehra railway station provides the nearest rail access. Additionally, the Satna–Jabalpur broad-gauge line of the West Central Railway passes through the central part of the district, ensuring efficient regional connectivity. The drainage system is dominated by the Satna River and the Arman River, both of which traverse the area and play a crucial role in surface water availability, irrigation, and groundwater recharge. These rivers exhibit a dendritic to sub-dendritic pattern, reflecting lithological homogeneity with localized structural control.

The study area depicts a well-defined distribution of lithostratigraphic units belonging mainly to the Bhandar Group and Rewa Group, indicating a structurally controlled and sedimentary-dominated terrain. The northern part of the area is predominantly occupied by Upper Rewa Sandstone, representing resistant, coarse-grained sandstone formations that generally form elevated plateaus and ridges. Southward, this unit grades into Jhiri Shale, which occurs as a broad, continuous belt and reflects relatively low-energy depositional conditions, often associated with gentle slopes and moderate drainage density. The central part of the study area is characterized by Nagod Limestone, appearing as an elongated, east–west trending band, locally intercalated with limestone with shale, suggesting alternating carbonate and fine clastic sedimentation. These limestone-dominated units are significant from a hydrogeological perspective due to their comparatively higher secondary porosity and permeability. Further south, extensive exposures of Nagod Shale and Shirbu Shale dominate the

landscape, indicating fine-grained, low-permeability lithologies. Small, isolated patches of Upper Bhandar Sandstone are observed along the southern and southeastern margins, marking younger and more erosion-resistant sandstone units.

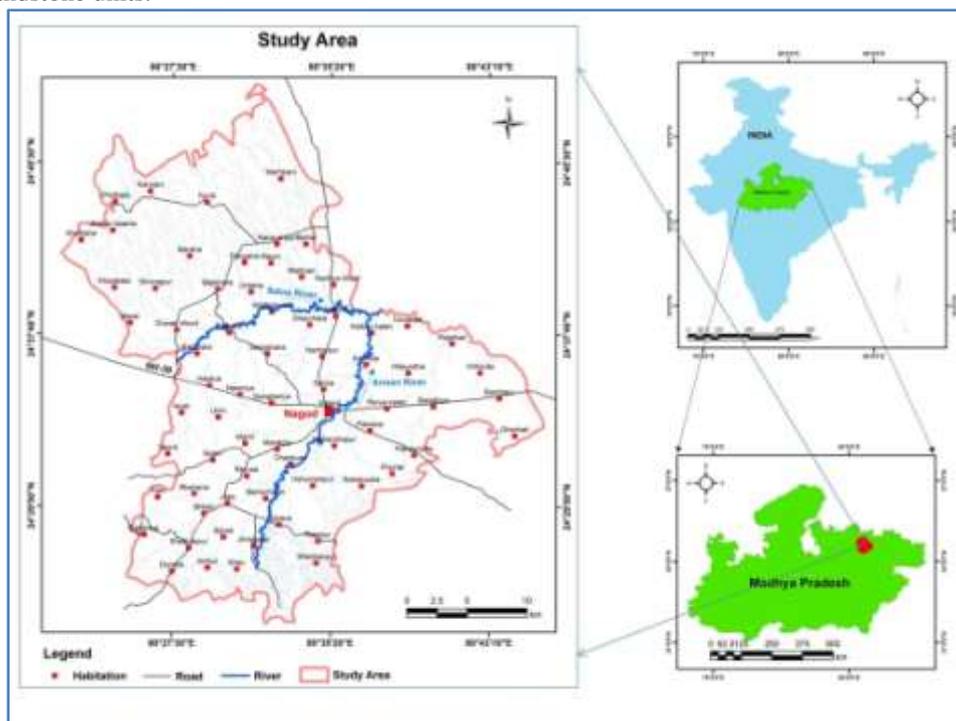


Figure 1: Location of the Study Area

III. Methodology

The methodology of the present study is based on geospatial approach to analyze the morphometric, geomorphological, hydrogeomorphological, lineament, and hypsometric characteristics of the Nagod watershed study area. Morphometric analysis was carried out using Survey of India (SOI) toposheets, which were georeferenced and digitized in a GIS environment to extract drainage networks and watershed boundaries. Quantitative morphometric evaluation involved the determination of key linear, areal, and relief parameters, including area, perimeter (circumference), stream order, stream number, stream length, bifurcation ratio, drainage density, stream frequency, drainage texture, basin length, form factor, elongation ratio, length of overland flow, density coefficient, and texture ratio. These parameters were computed following the standard methodologies proposed by Horton (1945), Strahler (1964), Schumm (1956), Miller (1953), and Nukratnam et al. (2005). The adopted procedures for calculating individual morphometric parameters are presented in Table 1. In addition, geomorphological analysis was performed using satellite imagery and digital elevation model (DEM) data to delineate major landform units and to understand terrain configuration and surface processes. Hydrogeomorphic analysis integrated geomorphology, drainage characteristics, and lithological information to evaluate groundwater occurrence and recharge potential. Hypsometric analysis was conducted using DEM-derived elevation data to generate hypsometric curves and to estimate the hypsometric integral, providing insights into the erosional status and geomorphic maturity of the basin. Prior to analysis, all datasets underwent systematic pre-processing, including georeferencing, projection standardization, mosaicking, clipping to the study boundary, DEM correction, sink filling, and drainage enforcement, ensuring consistency, accuracy, and reliability of the spatial analyses.

Table 1: Formula for computation of morphometric parameters

Linear Aspects (La)		
Stream order (U)	Hierarchical rank	Strahler (1964)
Number of Streams (Nu)	$Nu = N_1 + N_2 + \dots + N_n$	Horton (1945)
Stream length in km (Lu)	$Lu = L_1 + L_2 + \dots + L_n$	Horton (1945)
Mean stream Length (Lsm)	$Lsm = Lu / Nu$	Strahler (1964)
Bifurcation Ratio (Rb)	$Rb = Nu / Nu - 1$	Schumm (1956)
Stream length Ratio (RL)	$RL = Lu / Lu - 1$	Horton (1945)
Mean Bifurcation ratio (Rbm)	Avg. of Rb ratio of all orders	Strahler (1964)
Aerial Aspects (Aa)		

Basin Length (Lb)	$Lb=1.312 \cdot A^{0.568}$	Nookaratnam et al. (2005)
Circulatory Ratio (Rc)	$Rc= 4\pi A/P^2$	Miller (1953)
Compactness Constant (Cc)	$Cc= 0.2821 \cdot P/A^{0.5}$	Horton (1945)
Drainage density (Dd)	$Dd = Lu / A$	Horton (1932)
Drainage Intensity (Di)	$Di = Fs / Dd$	Faniran (1968)
Drainage Texture Ratio (T)	$T= Nu/P$	Horton (1945)
Elongation Ratio (Re)	$Re= (2/Lb) \cdot (A/\pi)^{0.5}$	Schumm (1956)
Form Factor (Rf)	$Rf= A/Lb^2$	Horton (1945)
Infiltration Number (If)	$If = Fs \cdot Dd$	Faniran (1968)
Length of overland flow (Lo)	$Lo = 1 / Dd \cdot 0.5$	Horton (1945)
Stream frequency (Fs)	$Fs = Nu/A$	Horton (1932)
Relief Aspects (Ra)		
Basin relief in m (H)	$H = Z - z$	Strahler (1957)
Relief ratio (Rh)	$Rh = H / Lb$	Schumm (1956)
Ruggedness Number (Rn)	$Rn=Dd \cdot (R/1000)$	Melton (1957), Strahler (1964)

HYPSONETRIC ANALYSIS

Hypsometric analysis is a widely used quantitative geomorphic tool in watershed studies that evaluates the distribution of elevation relative to area within a basin, typically by plotting a hypsometric curve and calculating the hypsometric integral (HI) to assess the stage of landscape evolution and erosion susceptibility [13,18].

The hypsometric analysis derived from SRTM DEM data reveals a moderately convex–concave hypsometric curve for the Nagod watershed, indicating a mature stage of geomorphic development. The computed hypsometric integral reflects moderate basin dissection and sustained fluvial erosion. The preservation of upland surfaces along with active incision in middle reaches suggests lithological control over landscape evolution. These characteristics imply moderate sediment yield and highlight the watershed’s suitability for soil and water conservation interventions.

IV. Results And Discussion

The results of the present study are derived from an integrated analysis of hydrogeomorphological and morphometric parameters, supported by statistical evaluation, graphical representation, and hypsometric analysis, providing a comprehensive understanding of the hydrological behaviour and geomorphic evolution of the Nagod study area.

Quantitative morphometric measurements provide valuable insights into the hydrological characteristics of the watershed. The study area comprises five sub-watersheds, and morphometric analysis was employed to evaluate and compare them by considering a range of parameters related to the linear, areal, and relief aspects of the drainage basin. The quantitative details of these parameters are presented in Tables 2, 3, and 4. Relationship between stream order and total stream length for the sub-watersheds within the study area and

Table 2: Sub-watershed wise input morphometric parameters

Sr. No.	Details of Sub Watershed	Basin Area (A) (km ²)	Perimeter (P) (km)	Elevation (m)			
				Std. Deviation	Max	Min	Mean
1.	SW-I	193.26	85.17	42.13	465	304	366.47
2.	SW-II	228.07	89.21	37.64	512	313	368.94
3.	SW-III	134.26	57.41	32.24	589	330	368.26
4.	SW-IV	98.94	54.36	29.04	566	315	353.14
5.	SW-V	176.44	74.91	12.47	423	297	329.43

Table 3: Linear Aspect of morphometric parameters

Sub Watershed (SW)	Stream Order						Mean Bifurcation ratio
	I	II	III	IV	V	VI	
SW I							
No. of stream (Nu)	208	41	10	3	1	-	3.87
Stream length (Lu)(km)	156.24	83.25	37.04	16.15	17.61	-	
Mean stream length (km) (Lsm)	0.75	2.03	3.70	5.38	17.61	-	
Stream length ratio(km)	0.53	0.44	0.44	1.09	0	-	

(Rl)							
Bifurcation Ratio (Rb)	5.07	4.10	3.33	3.00	0	-	
SW II							
No. of stream (Nu)	194	47	13	3	1	-	3.77
Stream length Lu (km)	164.27	86.2	76.88	9.94	11.86	-	
Mean stream length (km) (Lsm)	0.85	1.83	5.91	3.31	11.86	-	
Stream length ratio(km) (Rl)	0.52	0.89	0.13	1.19	0	-	
Bifurcation Ratio (Rb)	4.13	3.62	4.33	3.00	0	-	
SW III							
No. of stream (Nu)	233.00	60.00	15.00	4.00	1.00	-	3.91
Stream length Lu (km)	128.36	48.61	42.91	21.62	9.77	-	
Mean stream length (km) (Lsm)	0.55	0.81	2.86	5.41	9.77	-	
Stream length ratio(km) (Rl)	0.38	0.88	0.50	0.45	0	-	
Bifurcation Ratio (Rb)	3.88	4.00	3.75	4.00	0	-	
SW IV							
No. of stream (Nu)	171.00	43.00	9.00	1.00	1.00	-	4.69
Stream length Lu (km)	88.20	42.78	31.45	7.56	12.25	-	
Mean stream length (km) (Lsm)	0.52	0.99	3.49	7.56	12.25	-	
Stream length ratio(km) (Rl)	0.49	0.74	0.24	1.62	0	-	
Bifurcation Ratio (Rb)	3.98	4.78	9.00	1.00	0	-	
SW V							
No. of stream (Nu)	97.00	23.00	3.00	0.00	2.00	1.00	2.78
Stream length Lu (km)	68.01	47.99	21.38	0.00	15.23	1.15	
Mean stream length (km) (Lsm)	0.70	2.09	7.13	0.00	7.62	0.87	
Stream length ratio(km) (Rl)	0.71	0.45	0.00	0.00	0.08	0	
Bifurcation Ratio (Rb)	4.22	7.67	0.00	0.00	2.00	0	

Table 4: Aerial and Relief Aspect of morphometric parameters

Parameters	SW I	SW II	SW III	SW IV	SW V
Aerial Aspects (Aa)					
Drainage Density (Dd)	1.61	1.53	1.87	1.84	0.87
Basin Length (Lb)	26.08	28.65	21.20	17.83	24.77
Stream Frequency (Fs)	1.36	1.13	2.33	2.27	0.71
Drainage Texture ratio (T)	3.09	2.89	5.45	4.14	1.68
Form Factor (Rf)	0.28	0.28	0.30	0.31	0.29
Circulatory Ratio (Rc)	0.33	0.36	0.51	0.42	0.39
Elongation Ratio (Re)	0.60	0.59	0.62	0.63	0.60
Compactness Constant (Cc)	1.73	1.67	1.40	1.54	1.59
Drainage Intensity (Id)	0.85	0.74	1.25	1.23	0.82
Length of overland flow (Lo)	0.31	0.33	0.27	0.27	0.57
Infiltration Number (If)	2.18	1.73	4.36	4.19	0.62
Relief Aspects (Ra)					
Basin Relief (R)	161.00	199.00	259.00	251.00	126.00
Relief ratio (Rr)	6.17	6.94	12.22	14.08	5.09
Ruggedness Number (Rn)	0.26	0.30	0.48	0.46	0.11

Individual stream order versus total stream length plots reveals a consistent inverse relationship across all sub-watersheds, confirming Horton's law of stream lengths. Lower-order streams contribute the maximum total length, indicating intense dissection and active surface runoff processes. Sub-watersheds SW III and SW IV show steeper declines, reflecting high relief and structural influence, whereas SW V exhibits comparatively

shorter stream lengths and missing intermediate orders, suggesting stable terrain and favorable groundwater recharge conditions.

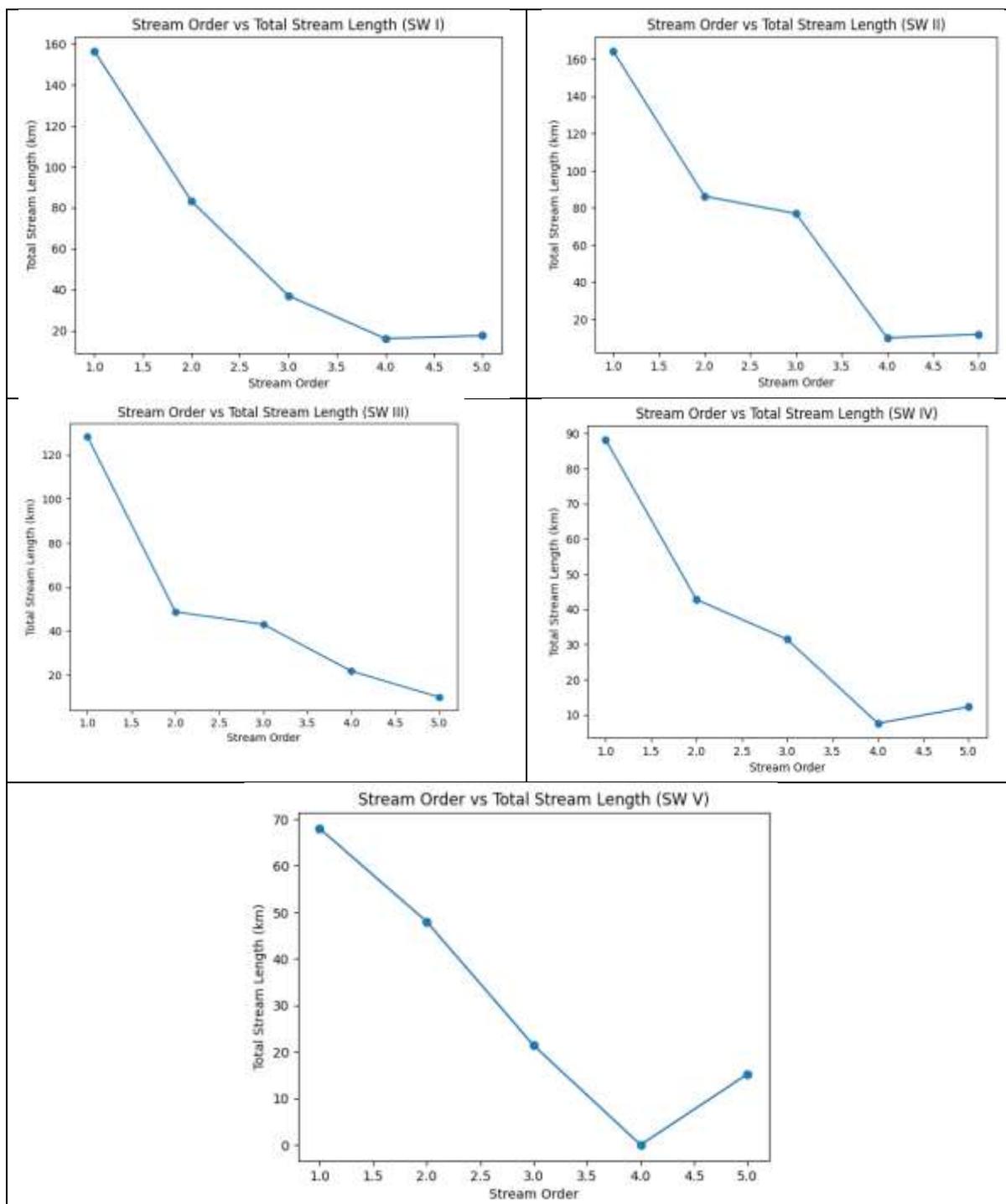


Figure 2: Relationship between stream order and total stream length for the sub-watersheds within the study area.

Hypsometric analysis based on elevation statistics reveals significant variation in geomorphic development among the sub-watersheds. The hypsometric integral values range from 0.15 to 0.39, indicating old to mature stages of landscape evolution. Sub-watershed SW-I exhibits a mature geomorphic stage with moderate erosion intensity, whereas SW-III and SW-IV show very low HI values, reflecting advanced denudation and prolonged erosional activity. The relatively low HI values of SW-II and SW-V further suggest subdued topography and stable geomorphic conditions. These results corroborate morphometric and relief characteristics

and provide critical insights for watershed prioritization and soil-water conservation planning (Table 5 and Figure 3).

Table 5. Integrated Morphometric–Hypsometric Assessment

Sr. No.	Sub-Watershed	Hmax (m)	Hmin (m)	Hmean (m)	HI	Geomorphic Stage	Morphometric Condition	Overall Erosion Risk
1	SW-I	465	304	366.47	0.39	Mature	Very high relief, high Dd, high Fs, high Rn	Very High
2	SW-II	512	313	368.94	0.28	Old–Mature	High relief, high Dd, high Rn	High
3	SW-III	589	330	368.26	0.15	Old	Moderate Dd, Fs, relief	Moderate
4	SW-IV	566	315	353.14	0.15	Old	Moderate Dd, lower Fs	Low–Moderate
5	SW-V	423	297	329.43	0.26	Old–Mature	Low Dd, low relief, high infiltration	Low

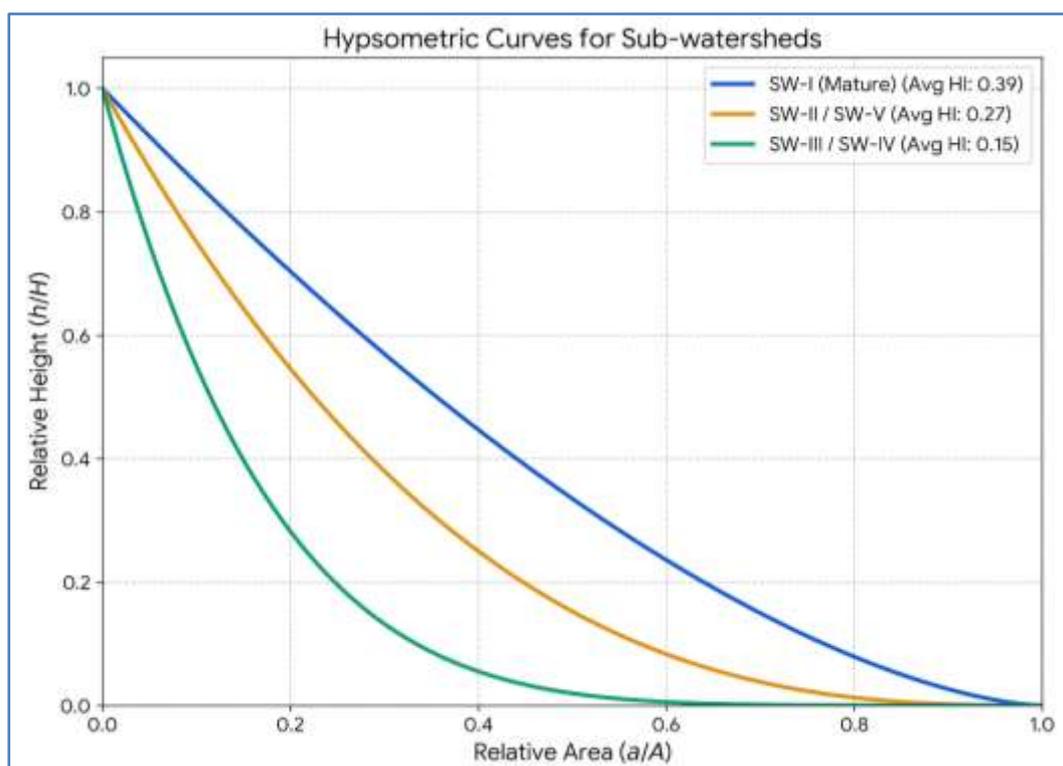


Figure 3: Hypsometric curve of the Nagod watershed derived from SRTM DEM

HYDROGEOMORPHIC ANALYSIS

The hydrogeomorphic analysis of the study area integrates geomorphology, lithology, drainage characteristics, and structural features to evaluate groundwater occurrence and movement (Figure 4). The area is characterized by distinct hydrogeomorphic units such as plateau, pediplain, pediment, escarpment, and valley-fill zones, each exhibiting different hydrological responses. Extensive pediplain and pediment units occupy the central part of the basin and are marked by gentle slopes, low relief, and thick weathered mantles, which promote higher infiltration and make these zones highly favorable for groundwater recharge. In contrast, plateau and escarpment regions, developed over resistant sandstone formations, display steep slopes, thin soil cover, and high surface runoff, resulting in comparatively poor groundwater potential.

The spatial distribution of drainage networks shows a close association with hydrogeomorphic units, reflecting the combined influence of terrain and lithology on surface and subsurface hydrological processes. Moderate drainage density in pediplain areas indicates balanced runoff–infiltration conditions, while higher drainage concentration along escarpments suggests rapid runoff and limited recharge. Lineament-controlled zones, particularly areas with high lineament density and intersections, enhance secondary porosity and permeability, thereby improving groundwater movement and storage. Valley-fill and low-lying zones associated with stream courses further contribute to localized recharge due to alluvial deposits and prolonged water retention.

Overall, the hydrogeomorphic configuration indicates a mature to late-mature stage of landscape evolution, where prolonged denudation and structural control have shaped landforms and groundwater conditions.

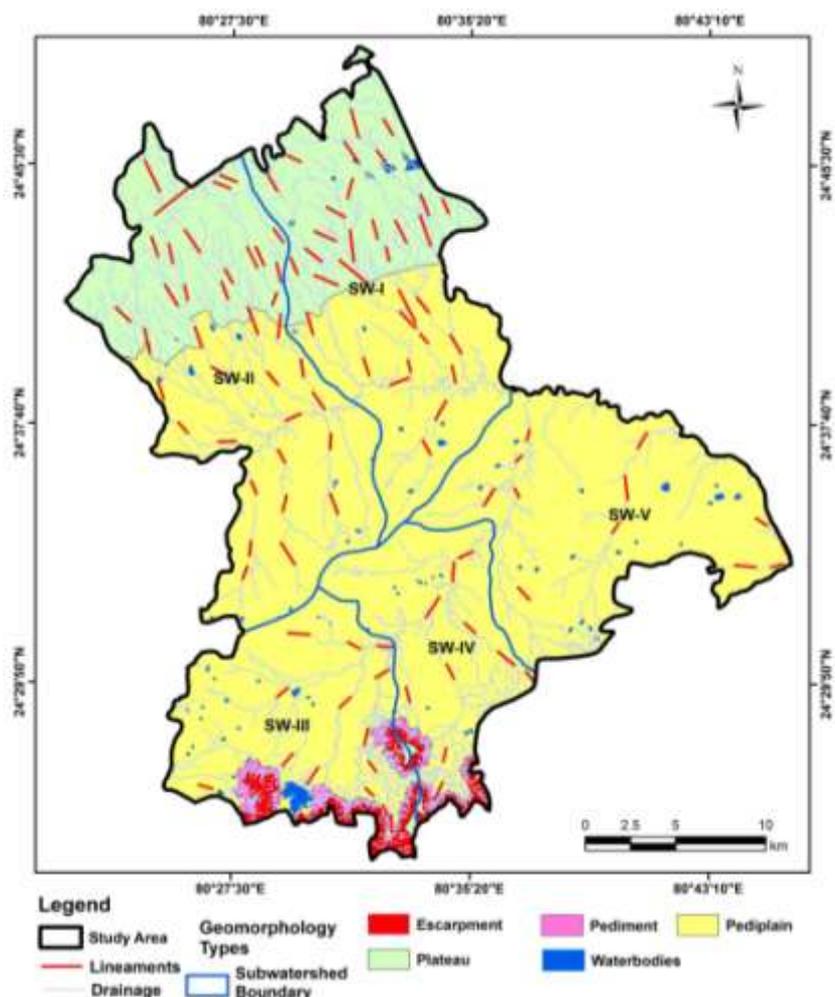


Figure 4: Hydrogeomorphic Map of the Study Area

V. Conclusion

The present study demonstrates the effectiveness of geospatial approach for analyzing the morphometric, hydrogeomorphological, structural, and geomorphic characteristics of the Nagod study area. Morphometric evaluation of the five sub-watersheds indicates systematic variation in linear, areal, and relief parameters, reflecting differences in drainage development, runoff behaviour, and infiltration potential. The dominance of lower-order streams, moderate drainage density, and elongated basin geometry suggest a balanced hydrological response with favourable groundwater recharge conditions in selected zones.

Geological and geomorphological analyses reveal a strong control of lithology and landforms on hydrological processes. Sedimentary formations of the Rewa and Bhandar Groups influence drainage and landform development, while extensive peditplain and pediment units indicate advanced denudational stages with enhanced infiltration capacity. In contrast, plateau and escarpment regions are characterized by higher relief, steeper slopes, and greater runoff, making them less suitable for groundwater storage. Lineament analysis identifies dominant NE–SW and NW–SE trends, highlighting structural control on drainage alignment and groundwater movement, with high lineament density zones representing favourable targets for groundwater development. Hypsometric analysis confirms that the basin is in a mature to late-mature stage of geomorphic evolution, as indicated by concave hypsometric curves and moderate hypsometric integral values, reflecting prolonged erosion and reduced relief. Overall, the integrated findings emphasize that groundwater occurrence, hydrological behavior, and landscape evolution are governed by the combined influence of basin geometry, lithology, geomorphology, structural features, and erosional stage. The study provides a scientific basis for sustainable watershed management and groundwater resource planning and can be effectively applied to similar geological settings.

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