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Integrating remote sensing and GIS for quantitative analysis of Nag River Basin, Maharashtra, India

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Abstract

Morphometric analysis of the extinguishing Nag River Basin, Maharashtra, India, will be a boon for the basin's conservation and sustainable development. Employing SRTM data and GIS tools, this analysis has proven to be a proficient method for extracting the river basin and determining its morphometric parameters, including drainage network, basin geometry analysis, texture and relief analysis etc. The Strahler method has been adapted for stream ordering in Arc GIS 10.3. The resulting extraction processes have unveiled that the river basin is dendritic to sub-dendritic type branching in east-west direction. The Nag River Basin stretch is about 810 square kilometres. Relief analysis has shown that the slopes within the Nag River Basin range from 1.2 to 23 degrees, and these changes in elevation are significantly impacted by the geological and geomorphological features present within the area. Moreover, the basin's mean stream length ratio is 0.55 km, indicating elongated shape with gentle slopes. From this study, it is understood that the development of the Nag River watershed and its streams is governed by the subsurface lithology present there.

Keywords: Morphometric analysis, Nag River Basin, SRTM, GIS, Total Stream Length Ratio.

Introduction

Water inadequacy has become the primary issue in many regions of Maharashtra state. Groundwater, being the most reliable source for irrigation, is being overused in many areas, including alluvial and hard rock terrain[1]. The groundwater supply in these places is under too much strain due to the irrigation of cash crops, and during the past few decades, the groundwater aquifer has been consistently overused. Additionally, the persistent issues in such places include the gradual loss in groundwater levels and the decrease in well yield[2]. The procurable water upgrades the yield of crops, which is directly an outcome of these water resources[3].

Geographical Information System (GIS) methods have made a substantial contribution towards groundwater management, providing a robust and reliable tool for conducting such studies[4,5]. The use of GIS in groundwater management provides a dependable means for collecting, organising, mapping, and monitoring data on natural resources, with a particular focus on water resources. To gain an understanding of the hydrological structure of the region, a range of interconnected factors must be considered, including lithology, structural features, slope, geomorphology, and land features[6]. The GIS enables the generation of thematic layers to analyse the baseline data related to these characteristics[7]. Morphometry encompasses the rigorous quantitative analysis of Earth's surface, including its shape, size, topographic features, and physical characteristics[8]. Topographical features are frequently used in structure and tectonic studies due to their well-documented manifestations in a region's landform features[9].

Various researchers have utilised remote sensing and GIS methodologies to conduct quantitative assessments of drainage and relief features for morphometric investigations in different drainage basins[10-14]. Analysing drainage basins, either individually or as a group, are relevant to geomorphology as they form distinct morphological regions. Therefore, a more comprehensive understanding of the overall landscape can be gained by examining the development of each drainage basin[15-17].

This study was conducted in the Nag River Basin of Nagpur district, Maharashtra, to compute various parameters such as drainage, shape, size, slope, and dimensions of landforms to assess the ground for improvement, conservation, and sustainable evolution.

Methodology

Geology of the study area: The Nag River Basin is located between top sheet numbers 55 O/4, 55 O/8, and 55 K/16 in the central region of India between Longitude 78°58'E to 79°12'E and Latitude 21°15'N to 21°05'N. The Nag River Basin encompasses an area of 810 sq. km. (Figure-1). The summer season in the Nag River Basin experiences intense heat with temperature up to 45°C, whereas the temperature during the winter season drops to 12°C. The city receives 1000–1200 mm of rainfall on average[18]. The Nag River appeared at a height of 398 metres above mean sea level in the hills of Lava village. It comes from a west-to-east direction. The stream flowing from Lava hills towards Ambazari Lake is known as the Nag River, while another stream flowing from Lava hills towards Gorewada Lake is known as the Pili River[19]. The stream coming from Sonegaon Lake is known as the Pohra River. The Nag River, which flows from Pardi village (near Pawangaon), forms the inferior stretch that meets the Kanhan River. Kanhan River further drains into Wainganga River. The stream flowing from Lava Hills to Ambazari has a length of 21 km, while the stream flowing towards Gorewada Lake is 18 km long.

Based on geological studies, the basin is underlain by three formations: the Deccan basalt, Lameta beds, and Tirodi gneissic complex[18]. The Archeans of this region are characterised by metamorphic and crystalline rocks, covered by a substantial layer of alluvium and soil that have been deposited by the tributaries of the Kanhan and Wainganga Rivers[20]. The Tirodi Gneissic Complex Group of Granitic Gneisses with Migmatite, which dates to the Archean and Palaeoproterozoic periods, makes up the majority of the study area's geology[18].

Morphometric elements and parameters: A comprehensive analysis of a drainage basin's geometry necessitates measurements of various aspects of the drainage network, such as its linear characteristics, areal features, relief facets, and slopes. The linear aspect focuses on certain laws linked with the stream characterization that include a hierarchical pattern of streams, stream order, and the relativity between stream length and the basin's area. The spatial basin features include analysis of the basin's perimeter, shape and size, frequency of stream, density and drainage texture etc. The relief component of the analysis focuses on relief (absolute and relative) ratios as well as the average slope of the basin.

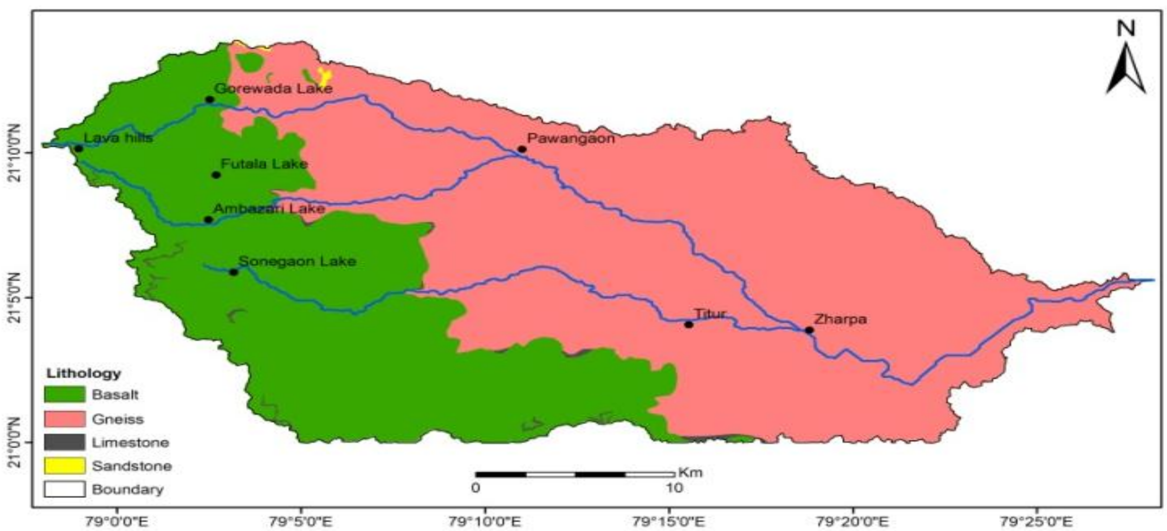

Figure-1: Geological Map of Nag River Basin (redrawn after bhukosh.gsi.gov.in).

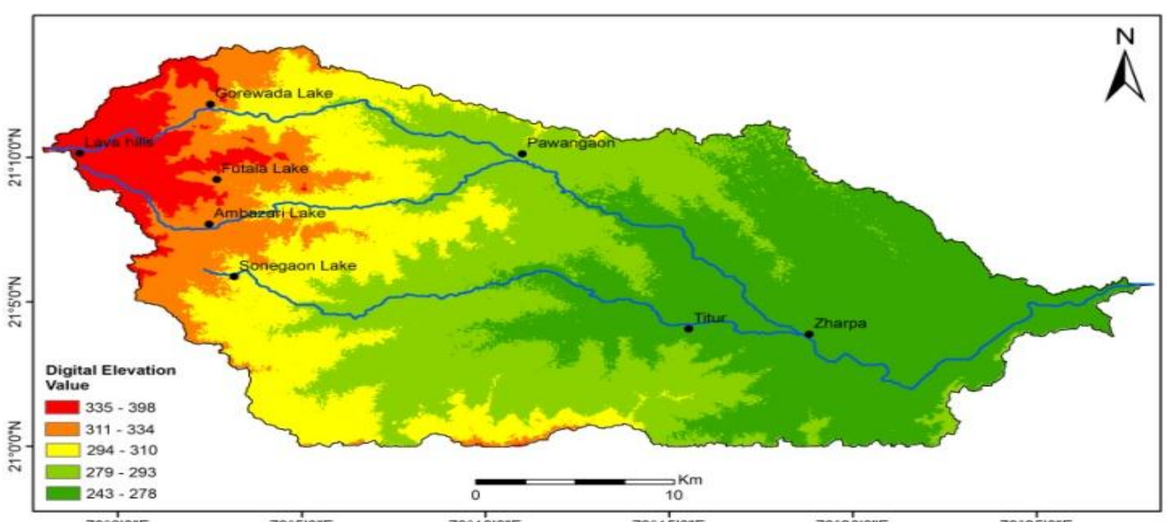

Figure-2: Digital Elevation Map (DEM) of Nag River Basin.

Using the formulas given by different researchers (Table-1), the morphometric parameters were computed. Arc GIS 10.3 is used for digitization, processing, and output production. As mentioned earlier, the Nag River Basin region was delineated using 1:50,000 scale Survey of India (SOI) top sheets (55 O/4, 55 O/8, and 55 K/16). The elevation map was created using a 1 arc-second SRTM-DEM, which provides a spatial resolution of 30 metres for global coverage (Figure-2). Flowchart depicts the methodologies used for demonstrating the morphometric analysis (Figure-3).

Results and Discussion

The GIS and remote sensing techniques have been extremely beneficial in researching various river parameter analyses. The mathematical analysis of morphometry reveals the river basin properties and related morphometric parameters are determined by examining the river basin's geometry, drainage network, texture, and relief (Table-1).

Drainage Network Analysis: Methodologies for the analysis of linear properties have been proposed by various workers[21-25]. These investigate the topological features of stream segments and their co-relation in the drainage network system. The linear features are connected to the stream pattern within a drainage network.

Stream Order (U): Horton[21] initially developed the system for classifying streams, and Strahler[23] modified it to some degree. The configuration of tributaries in relation to the major trunks in the system of channel ordering defines the stream order (U) that indicates the size of the segment of a stream channel. Order 1 denotes the smallest tributaries; order 2 develops when two initial order channels converge; order 3 is created when two 2nd order channels join; and so on. The mainstream is the one with the largest order number, through which sedimentation and discharge of water occur. A 7th order stream (U) was observed within the Nag River Basin (Figure-4, Table-2).

Stream Number (Nu): Following the drainage network's ordering, the total Nu segments within a basin are calculated by counting each segment of stream order U. It is observed that, the count of the stream decreases with the number of increasing orders, respectively[21]. There are 6231 computed streams within the entire river basin (Table-2).

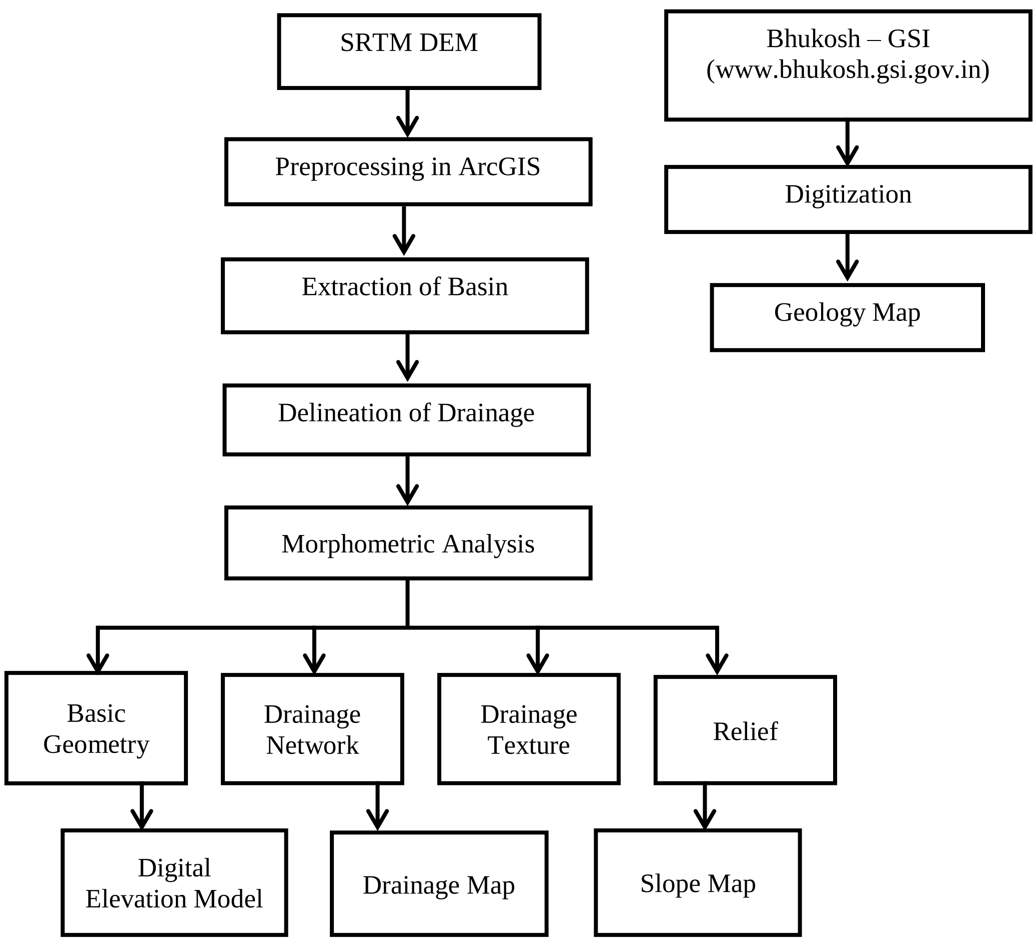

Figure-3: Flow Chart indicating delineation of River Basin and Morphometric Analysis.

Table-1: Formulae for the calculation of morphometric parameters.

Sr. no.	Morphometric parameters	Formulae	References
Basic Geometry Analysis			
1.	Basin Area (A)	GIS	
2.	Basin Perimeter (P)	GIS	
3.	Basin Length (Lb)	GIS	
4.	Basin Width (Wb)	GIS	
5.	Relative Perimeter (Pr)	A/P	33
6.	Length area relation (Lar)	1.4*A0.6	34
7.	Lemniscate's (k)	Lb2/A	35
8.	Form Factor (Ff)	A/Lb2	21
9.	Elongation ratio (Re)	(2/Lb)*(A/π)0.5	33
10.	Texture ratio (Rt)	N1/P	-
11.	Circularity ratio (Rc)	12.57*(A/P2)	37
12.	Drainage Texture (Dt)	Nu/P	21
13.	Compactness Constant (Cc)	0.2821*(P/A0.5)	39
14.	Fitness coefficient (Rf)	Cl/P	40
15.	Wandering ratio (Rw)	Cl/Lb	41
Drainage Network Analysis			
1.	Stream Order (U)	GIS	
2.	No of Stream (Nu)	GIS	
3.	Stream length (Lu)	L1+L2+L3+……+Ln	23
4.	Stream length ratio (Lur)	Lu/(Lu-1)	23
5.	Mean stream length ratio (Lsm)	-	21
6.	Bifurcation Ratio (Rb)	Nu/(Nu+1)	23
7.	Mean Bifurcation Ratio (Rbm)	-	23
8.	Main Channel Length (Cl)	GIS	
9.	Rho Coefficient (ρ)	Lur/Rb	21
Drainage Texture Analysis			
1.	Stream Frequency (Fs)	Nu/A	21
2.	Drainage density (Dd)	Lu/A	21
3.	Constant of Channel Maintenance (C)	1/Dd	33
4.	Drainage Intensity (Di)	Fs/Dd	43
5.	Infiltration Number (If)	Fs*Dd	43
6.	Drainage pattern (Dp)	GIS	
Relief Analysis			
1.	Height of basin mouth (z)	GIS/DEM	
2.	Maximum height of the basin (Z)	GIS/DEM	
3.	Relief ratio (Rhl)	Z/Lb	33
4.	Relative relief ratio (Rhp)	H*(100/P)	47
5.	Gradient ratio (Rg)	(Z-z)/Lb	45
6.	Ruggedness Number (Rn)	Dd*(H/1000)	46
7.	Melton ruggedness number (MRn)	H/A0.5	47

Table-2: Calculation of Drainage Network for Nag River Basin.

Stream Order (U)	Stream Number (Nu)	Stream length (Lu) in Km	Stream length ratio (Lur)	Bifurcation Ratio (Rb)
I	5453	1048.30	-	-
II	633	491.17	0.47	8.61
III	112	240.70	0.49	5.65
IV	24	128.12	0.53	4.67
V	6	60.91	0.48	4.00
VI	2	47.74	0.78	3.00
VII	1	24.92	0.52	2.00
Total / mean*	6231	2041.86	0.55*	4.66*

Stream Length (Lu): The stream length is a crucial parameter as it speaks about basin characteristics. Longer stream lengths indicate more uniform gradients, while streams with shorter lengths indicate that the region has steeper slopes and finer textures. It is observed that overall length of the stream segments often decreases with increase in stream order[26,27]. In the selected basin the drainage system is dendritic to sub-dendritic, with a seventh order. The total river basin measured stream length (Lu) is 2041.86 kilometres (Table-2).

Stream length ratio (Lur): It is defined as the ratio of the average length of stream length in a particular class to the average length of streams in the next subordinate level. Horton[21] stated that the surface flow discharge and the basin's erosional stage are enormously related to each other. The calculated value ranges from 0.47 to 0.78 (Table-2) for Nag River Basin, suggesting about the course of the river from youth to maturity.

Mean stream length ratio (Lsm): The Lsm is determined as the ratio of overall stream length in a basin with the total stream segments within the given order[21]. It aids in quantifying given basin stream network features. The calculated measure for the mean stream length is 0.55 km (Table-2).

Bifurcation ratio (Rb): The linear association between stream length and stream number established by Horton[21] shows that the count of streams in a basin of different orders resembles an inverse geometric series with an initial term of one and a common ratio equivalent to the bifurcation ratio.

The bifurcation ratio is the stream number in a single order (Nu) to the stream number in a higher order (Nu+1)[23,28]. Because basin geometry varies for different orders, the bifurcation ratio cannot always be equal for all orders but will generally remain constant. It normally ranges from 3.0 to 5.0 where the drainage pattern is settled by geology or structures[29]. This ratio ranged between 2 to 8.61 (Table-2), indicating that the basin has less structural influence and more variations in the stream frequencies[30]. Geomorphological control over the formation of a drainage basin's pattern is indicated by an Rb value of less than 5, whereas structural control is indicated by an Rb value greater than 5[31]. Given that the river basin's mean Bifurcation ratio (Rb) is 4.66 (Table 2), it is likely that geomorphological factors dominate river basin management.

Main Channel Length (Cl): From the upper border to the basin boundary, the Main Channel Length (Cl) is a path that follows the longest channel. The Nag River basin's Cl measures 71.43 km.

Rho coefficient (ρ): It is a crucial indicator that connects drainage density to the basin's physiographic evolution, making it less complex to evaluate the stream network's potential for storage and, eventually, assess the level of drainage growth within a river basin[21,32]. It can be defined as ratio of stream length ratio and bifurcation ratio[21]. Climate, geology, biology, geomorphology, and humans all are responsible for the variations in the ρ value. The river basin has a 0.12 Rho coefficient (ρ).

Basin Geometry Analysis: Basin Area (A): The basin area refers to the terrain that flows into a certain stream or river system. In such a region, the precipitation is gathered and drains into a single outlet, which is often a river, lake, or ocean. The basin has an area of 810 km^2 (Table-3).

Perimeter (P): The basin's perimeter corresponds to its enclosing area boundary. It is measured horizontally along the horizontal projection of the water divide. The basin perimeter is 174 km long (Table-3).

Length of Basin (Lb): It is the lengthiest path within a basin that runs along with the primary drainage path[33]. It is described as, the distance along a line drawn from the basin's mouth to a particular point on the perimeter surface that is equally spaced in the opposite direction from the basin's mouth around the perimeter. The basin perimeter is 48.02 km (Table-3).

Basin Width (Wb): It is the lengthiest dimension of the basin that is perpendicular to its major channel. The Nag River Basin is calculated to be 25.5 km wide (Table-3).

Relative perimeter (Pr): The enclosed area of the basin divides the relative perimeter which can be understood as the horizontal projection of the river network. This measure of the basin's shape could be used to compare the basin's relative compactness with other basins. A basin with a smaller Pr value is more compact, whereas a basin with a larger Pr value is more elongated. The relative perimeter of the basin is 4.66 (Table-3).

Length area relation (Lar): It can be defined for basins with huge areas where there is a link between the basin area and stream length[34]. The measured value for the basin is 77.84 (Table-3).

Lemniscate’s (k): The basin’s inclination is employed to define the Lemniscate value. It is obtained by calculating the fraction between basin area with the square root of its length[35]. The Lemniscate's basin was evaluated to be 2.85 (Table-3).

Form Factor ratio (Ff): The form factor is ratio of the area of the river basin to the square of its maximum length[21]. Results from the stream measurements can be used to predict flood occurrence, the amount of erosion, and the ability of the river to transport silt material. As tributaries merge into the main river at specific intervals, allowing improved groundwater percolation, this data could eventually result in a reduction of flood risks. The basin has a 0.35 form factor, which indicates an elongated shape (Table-3).

Elongation ratio (Re): The ratio of the square of the circle's radius to its longest achieved basin length has an area equal to that of the river basin. This shows that areas of the basin that have greater elongation values possess greater infiltration capacity and have less runoff, however, areas of the basin with circular shape have more runoff than infiltration rate[33]. The basin has a 0.67 Elongation ratio, indicating a slightly elongated shape[23] (Table-3).

Texture ratio (Rt): The result of the basin’s circumference is divided by the stream number present in the first order. The measured texture ratio (Rt) of the basin is 31.34 (Table-3), suggesting a coarse underlying lithology.

Circularity ratio (Rc): It is the comparison of the basin’s area to the area of a circle having a similar circumference to that of a river basin. Slope, relief of the basin, land use and land cover (LULC) is significant factors that strongly influence the circularity ratio of a river basin, as noted by Strahler A.N.[23]. The basin is considered a perfect circle if the circularity ratio value is equal to 1[36]; when the value is in the range of 0.4-0.5, it is considered elongated in shape with a permeable, homogeneous underlying layer present[37]. The Circularity ratio (Rc) is computed to be 0.34 (Table-3), demonstrating the basin's slightly circular shape, strong runoff flow, and less permeable subsurface layers.

Drainage Texture (Dt): Smith[38] has given the drainage texture as the outcome of the ratio between the stream number (Nu) and the circumference of the basin. Smith[38] further calculated the relative channel spacing of a river's dissected terrain, which is frequently impacted by factors like rainfall, lithology, vegetation, infiltration capacity, climate, and the river's evolutionary phase. It has been divided into five categories i.e. extremely coarse (2), course (2-4), moderate (4-6), fine (6-8), and very fine (>8). The drainage texture (Dt) of the basin is 35.81 (Table-3), indicating a remarkably fine texture depending upon the underlying strata.

Compactness Constant/Coefficient (Cc): It is described as the ratio of comparison between the basin perimeter and a circle having similar area to the river basin. The Compactness Constant (Cc) value is 1.74 (Table 3), and it does not depend on the basin size but is affected by the slope[39].

Fitness ratio/coefficient (Rf): It is used to assess the lithological characteristics[40]. It is obtained by dividing the primary channel length by the basin’s boundary length. The Fitness ratio (Rf) for the river basin has been calculated to be 0.41 (Table-3).

Wandering ratio (Rw): It is calculated by dividing the major channel length by the basin length[41]. The Wandering ratio (Rw) of Nag River Basin is computed to be 1.49 (Table-3).

Table-3: Calculation of Basin Geometry Parameters for Nag River Basin

Parameter	Result
Basin Area (A)	810 Km^2
Basin Perimeter (P)	174 Km
Basin Length (Lb)	48.02 Km
Basin Width (Wb)	25.5 Km
Relative Perimeter (Pr)	4.66
Length area relation (Lar)	77.84
Lemniscate’s (k)	2.85
Form Factor (Ff)	0.35
Elongation ratio (Re)	0.67
Texture ratio (Rt)	31.34
Circularity ratio (Rc)	0.34
Drainage Texture (Dt)	35.81
Compactness Constant (Cc)	1.74
Fitness coefficient (Rf)	0.41
Wandering ratio (Rw)	1.49

Analysis of drainage texture: Stream Frequency (Fs): A river basin's stream frequency can be measured as the sum of Nu present in the area. Maximum stream frequency is indicative of wider runoff, steeper terrain, an impermeable underlying surface, and less vegetation in high-relief conditions[21]. Minimum stream frequency signifies permeable strata with low relief. For the drainage basin, Stream Frequency (Fs) is 7.69 (Table-4).

Drainage density (Dd): It is acquired from the ratio of the total stream length to the basin's area[21]. The drainage density[25] is a quantitative indicator of the separation of the landscape and runoff potential. Considering its link with the surficial runoff and the permeability of the underlying layer, the Dd of a river basin represents the groundwater potential enclosed by the area[30]. The drainage density of 2.52 km/km^2 is obtained (Table-4) for the basin, indicating coarse texture and reflecting moderately permeable underlying strata with vegetation cover.

Constant of Channel Maintenance (C): A unit number of the basin's surface required for bearing the channel length represents 'C'. The greater value of C reveals that the area is dominantly controlled by the lithology that is highly permeable, having moderate runoff, a high infiltration, less dissection, and being less affected by the structural features[33]. The Channel Maintenance Constant (C) is 0.40 (Table-4).

Drainage Intensity (Di): It can be understood from the ratio of stream frequency to drainage density. Higher numbers indicate an elevated rate of soil erosion, however, the lower values imply the basin has a lower soil erosion rate[42]. The Drainage Intensity (Di) of the river basin is 3.05 (Table-4), which indicates a good drainage network with less compulsion towards flooding and erosion within the basin.

Infiltration Number (If): It is the result of the multiplication of Stream Frequency (Fs) with Drainage Density (Dd). It displays the percolation rate and surface runoff for the basin. Corresponding with the increase in percolation, surface runoff also increases. The decreasing value of the infiltration number corresponds to a lower rate of infiltration, and vice versa[43]. The river basin Infiltration Number (If) is 19.39 (Table-4), suggesting that the overall infiltration rate is low in the river basin and that it has maximum runoff.

Drainage pattern (Dp): The drainage pattern can be radial, centrifugal, trellis, dendritic, sinusoidal, etc. At the source, the drainage pattern (Dp) of the river is radial; however, it develops a dendritic and sinusoidal nature away from the source (Figure-4 and Table-4).

Relief Analysis: Relief ratio (Rr): It compares basin length to relief and is a dimensionless ratio. It indicates both the rate of erosion on the inclination and the degree of steepness across the river basin[44]. In this basin, the Relief ratio (Rr) is 3.23 (Figure-5, Table-5), indicating a moderate to high slope in the NW part and a gentle slope in the remaining basin.

Table-4: Calculation of Drainage Texture for Nag River Basin

Parameters	Result
Stream Frequency (Fs)	7.69
Drainage density (Dd)	2.52Km/Km^2
Constant of Channel Maintenance (C)	0.40
Drainage Intensity (Di)	3.05
Infiltration Number (If)	19.39
Drainage pattern (Dp)	Radial, Dendritic, Sinusoidal

Relative relief (Rhp): Relative relief (Rhp) is the maximum height of the basin by its length. The Nag River Basin has a Relative relief ratio (Rhp) of 89.08 (Table-5).

Gradient ratio (Rg): It is defined as the ratio of the difference between the maximum height of the basin and height of basin mouth to the length of basin[45]. The slope is considered the crucial parameter. The basin Gradient ratio (Rg) is 3.23 (Table-5).

Ruggedness Number (Rn): The topography of the river will be less harsh and will thus have a lower value, and vice versa[46]. The Ruggedness Number (Rn) is calculated to be 0.39 (Table-5). The lower Rn value implies less rugged topography.

Melton ruggedness Number (MRn): Melton[47] referred to it as the relief ratio (Rhl) to the basin area (A) raised by a factor of 0.5. It signifies the uneven terrain present within the river basin. The Melton ruggedness number (MRn) obtained for basin is 5.45 (Table-5). This implies that the bed load of the river is moderate under transportation.

Table-5: Calculation of Relief Parameters for Nag River Basin

Parameters	Result
Height of basin mouth (z)	243 m
Maximum height of the basin (Z)	398 m
Relief ratio (Rhl)	3.23 m
Relative relief ratio (Rhp)	89.08 m
Gradient ratio (Rg)	3.23
Ruggedness Number (Rn)	0.39
Melton ruggedness number (MRn)	5.45

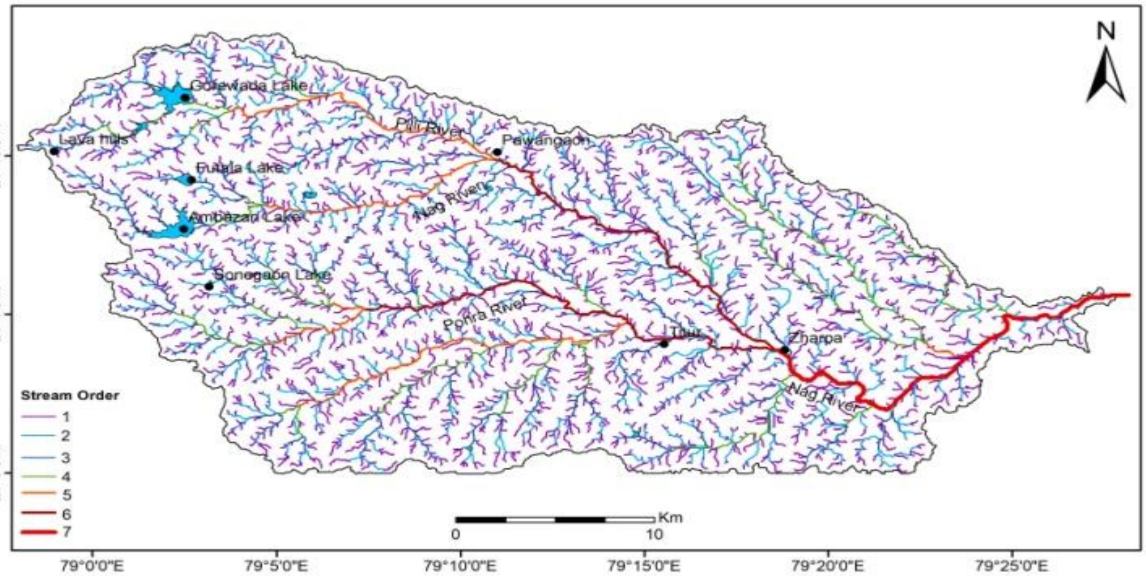

Figure-4: Drainage Map of Nag River Basin.

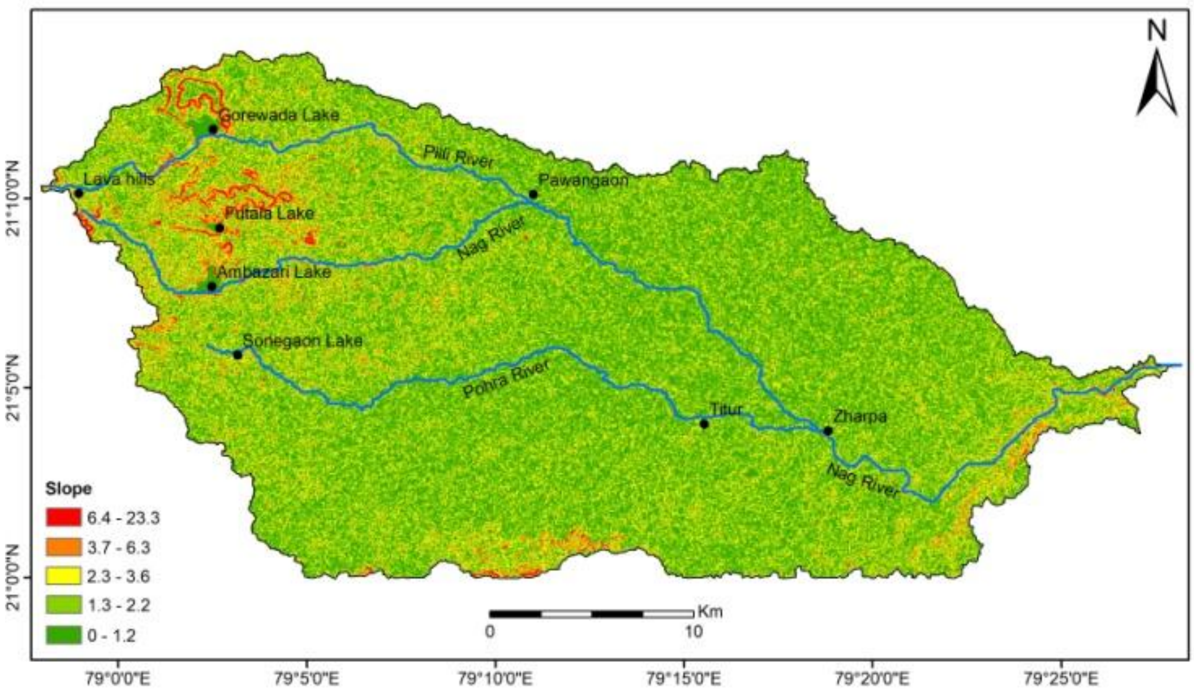

Figure-5: Slope Map of Nag River Basin.

Conclusion

The study provides a quantitative analysis of the fundamental geometry, drainage network, and drainage texture of the Nag River Basin. The findings reveal important characteristics of the basin, including a gentle slope, hard and highly resistant underlying strata, and a naturally elongated shape. It is observed that the drainage basin does not exhibit any structural control. There is a substantial amount of geomorphic diversity within the basin, based on the variations in different morphometric parameters. There is an increasing density of streams within the basin based on the drainage density. Additionally, certain regions exhibit higher slope values, indicating steep gradients along the river course. Rivers flow in sinusoidal pattern, maintaining their elongated shape as they flow from high to low elevation. These observations highlight the influence of subsurface lithology on the development of the Nag River watershed and its associated streams.

The following findings of this study have several notable implications that contribute to the scientific understanding of the Nag River Basin and have practical implications for water resource management and environmental conservation in the region. i. Understanding the fundamental characteristics of the Nag River Basin, including its gentle slope and resistant underlying strata, can aid in predicting and managing water flow patterns, erosion rates, and flood risks in the region. ii. The knowledge of the basin's elongated shape and drainage density is essential for assessing the hydrological processes, sediment transport, and ecological dynamics within the Nag River watershed. iii. The findings can contribute towards decision-making and sustainable land use planning, ensuring the preservation and proper management of water resources in the Nag River Basin. iv. This study underscores the significance of subsurface lithology in shaping the hydrological features of a river basin, emphasizing the need for comprehensive geological assessments in similar contexts. v. The scientific understanding of the Nag River basin's geomorphology can serve as a foundation for further research, modeling, and predictive studies related to water resource management and environmental conservation in the region.

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