Integrated Geospatial Analysis of Watershed Morphometry, Terrain Characteristics, and Hydro-Geomorphological Processes in the Brahmani Watershed, Western India

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Abstract

Remote sensing and GIS have become necessary to understand the watershed activities and for the sustainable management of land and water resources. This becomes all the more essential in areas where the rocks are hard, porosity is low and rock formation affects groundwater and erosion. Geospatial technologies have advanced in the recent years, still watershed studies involving terrain-hydrological assessments are limited in Rajasthan because of its diverse physiography. The present study aims to assess the Brahmani River watershed of Rajasthan and Madhya Pradesh. This study presents an integrated hydro-geomorphological framework by combining DEM-derived morphometric parameters with multiple spectral indices (NDWI, NDMI, and EWI) to evaluate watershed behaviour and groundwater recharge potential in a semi-arid watershed of western India. For watershed analysis and delimitation NASA SRTM Landsat 8 - OLI/TRIS imagery was used for 30m resolution.

Keywords: Watershed, remote sensing, GIS, morphometric analysis, geospatial analysis

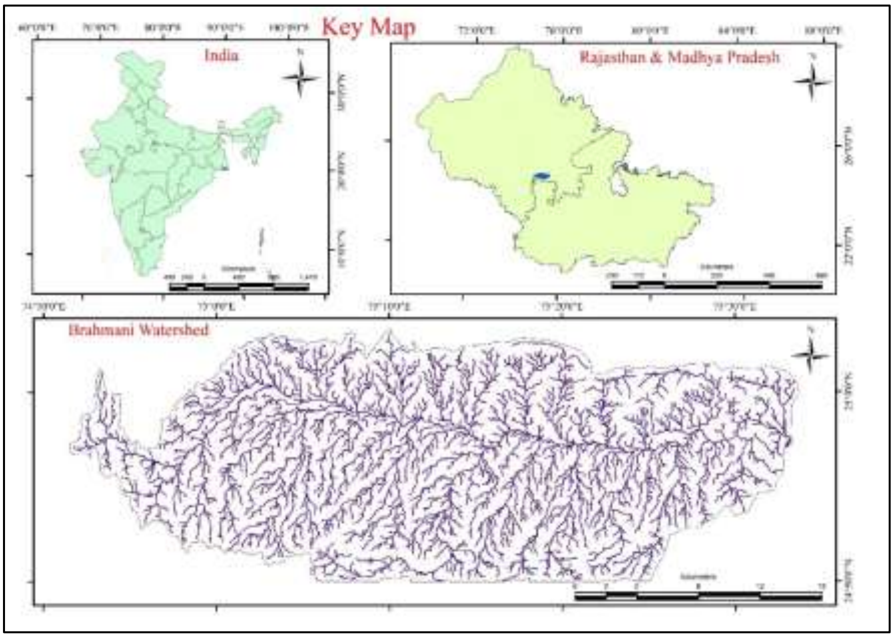
Introduction

In a watershed surface runoff, sediment movement and groundwater recharge are important geomorphic units. Morphometry is the mathematical measurement and quantitative analysis of the Earth's surface and landforms comprising of three aspects: Linear, aerial and relief. While terrain analysis is also important for geospatial studies as relief, slope and drainage patterns help us to understand the geomorphological process going on in the region (1), (2). Conventional morphometric methods have made it easier to objectively and consistently assess linear, areal, and relief properties across a range of physiographic contexts. These methods have now been improved by advancements in remote sensing (RS) and geographic information systems (3). Furthermore, hydrological indices derived from multispectral satellite imagery, such as the Normalized Difference Water Index (NDWI), Normalized Difference Moisture Index (NDMI), and Evapotranspiration Water Index (EWI), offer dynamic environmental information on watersheds, including vegetation strength and health, evaporation patterns, moisture conditions, and surface water availability. (4), (5), (6).

The drainage basin, which is divided from neighbouring basins by a drainage boundary, consists of the rivers and streams that convey the water as well as the land surfaces from which water flows into those channels. Like a siphon, the drainage basin gathers all of the water in the area it covers and directs it into a river. A water divide is a physical barrier, such as a ridge, hill, or mountain, that separates each drainage basin from neighbouring basins. The easiest way to determine how different properties in the area relate to one another is through morphometric assessment of the watershed. It is a comparative assessment of multiple watersheds under varying topographical and geomorphological conditions. The watershed has emerged as the fundamental planning unit for all hydrologic assessments and initiatives. Finding comprehensive stream properties through the measurement of several stream characteristics was the primary goal of this endeavour. The ability of geographic information systems (GIS) to compile spatial data from various sources into a single environment made them an important tool for watershed demarcation.

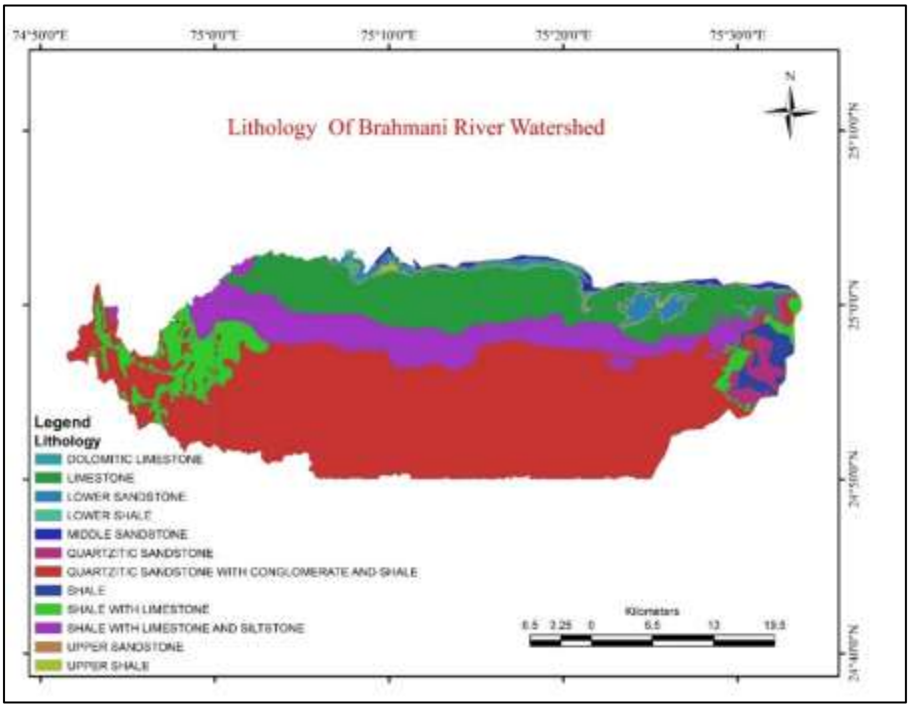
Reliable information about the area's geology, hydrology, geomorphology, and land use can be gleaned from the drainage pattern and texture because the development of landforms and drainage systems depends on the bed rock lithology and structures connected to them (7). The morphometric analysis gives insight into the watershed's geological and geomorphological history, river morphology, basin geometry, and recent diastrophism (8). Different morphometric parameters such as stream length (Lu), bifurcation ratio (Rb), drainage density (D), stream frequency (Fs), texture ratio (T), elongation ratio (Re), circularity ratio (Rc), form factor ratio (Rf), relief ratio (Rh) and river profile were used by Yadav et al.,2022 to analyse the pattern of drainage in Eru River watershed.

An extensive evaluation of the geospatial methods for precisely describing the topography of the Brahmani Watershed, a significant tributary of the Chambal River, is presented in this research. The Upparmal plateau inside the Deccan plateau is one of the dissected plateaus that the Brahmani River



Map 1 Study Area

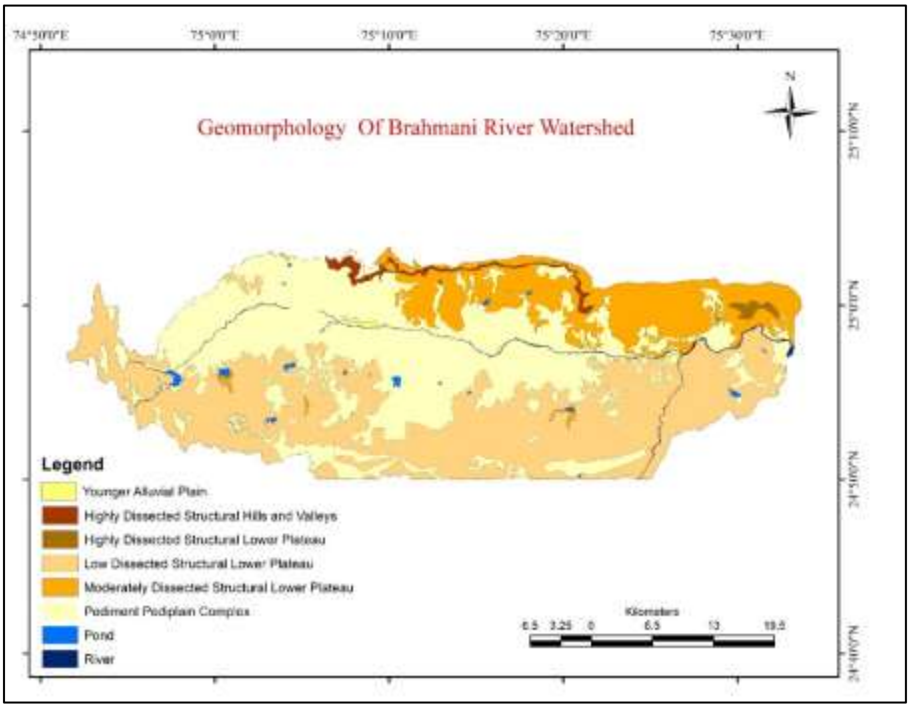
passes through. The region has a wide variety of geological formations, from shale and alluvial deposits to hard rock (limestone and quartzitic sandstone) lithology (Map 2). Even though the area receives enough rainfall, lithological limitations and overuse of groundwater resources present serious problems. These intricate issues have been addressed, and a number of studies have shown that watershed assessment requires the spatiotemporal evaluation of terrain features (9), (10), (11).



Map 2 Lithology

Knowledge of geomorphology is crucial for terrain analysis because it sheds light on a number of factors, including the mechanisms underlying the current landscape, how geological processes have historically functioned, how land use has evolved over time, and how to manage natural hazards and resources like soil and water. The Brahmani River Watershed's geomorphological map shows a diverse landscape formed by both depositional and erosional processes.

Pediplains, younger alluvial plains, dispersed hills and valleys, plateaus, and waterbodies that show signs of human modification are examples of geomorphological characteristics. With pediplains making nearly 40% of the study area, the region has good groundwater potential. Runoff and soil erosion are



Map 3 Geomorphology

encouraged by the existence of dispersed hills and valleys. Arcgis software was used to create the geomorphic map (Map3).

Study Area

Brahmani River watershed lies in Bhilwara and Chittaurgarh districts of Rajasthan and Neemuch district of Madhya Pradesh. It lies in the between $74^{0}51^{l}50^{11}$E to $75^{0}33^{l}48^{11}$E longitudes and $25^{0}3^{1}$ 40^{11}N to $24^{0}50^{l}$ N latitudes (Map 1). The total geographical area covered is about 1261.16 sq. km. The annual average rainfall is around 865.7 mm (12). The region is characterized by undulating topography.

Methodology

To gain a thorough understanding of the basin's hydrological behaviour and landscape history, this study combines classic quantitative morphometric analysis with satellite-derived spectral indices. The structural and geometric properties of the watershed are determined by evaluating linear, aerial, and relief morphometric parameters obtained from a Digital Elevation Model (DEM). While these factors define the terrain's physical layout and structural control over drainage, they are static indicators. To capture the basin's dynamic, surface-level response in terms of moisture retention and open water distribution, multi-spectral remote sensing indices (NDWI, NDMI, and EWI) were extracted from satellite imagery.

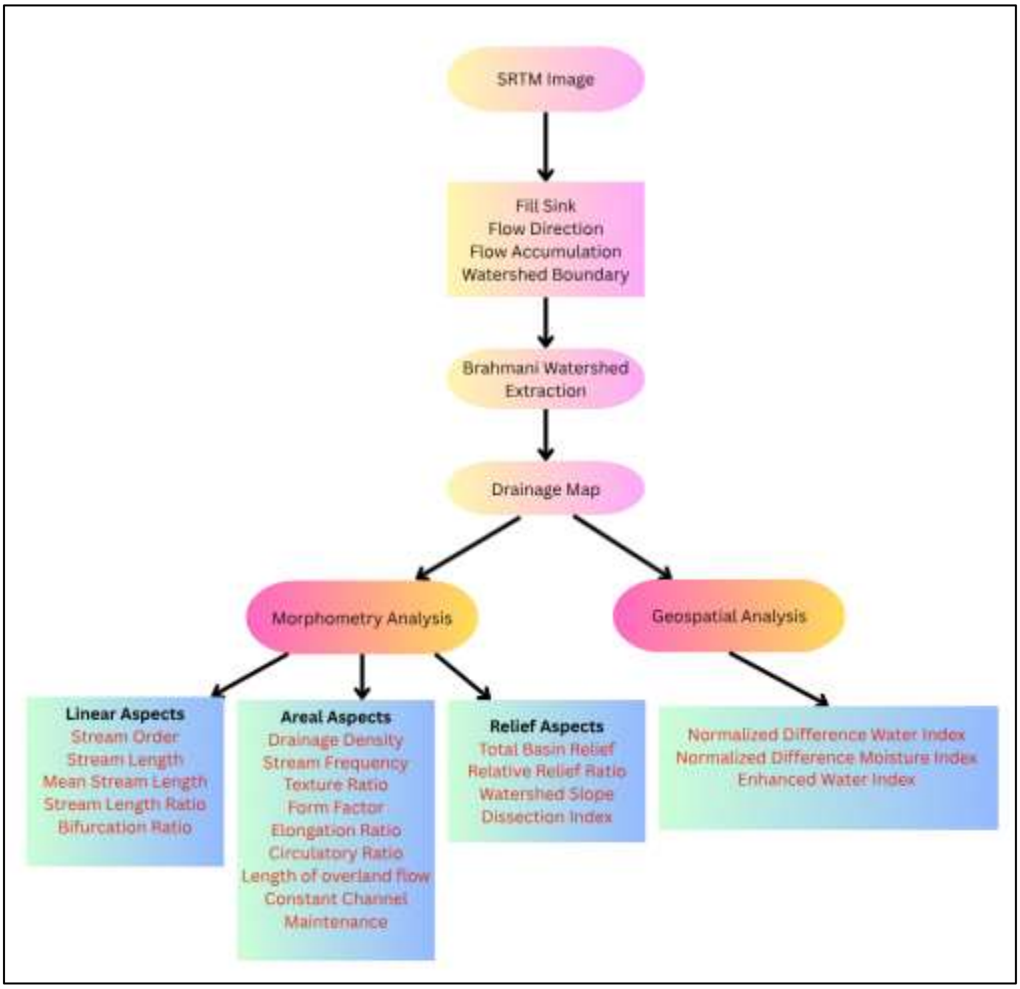


Figure 1 Flow chart of the study

In this study, the watershed border, drainage network, and morphometric parameter analysis were extracted using SRTM Landsat-OLI/TRIS DEM data (30m). The research area's drainage network was extracted using raster-format, 30-meter-resolution SRTM Landsat-OLI/TRIS satellite imagery that was downloaded from Open Topography and USGS Earth explorer. Drainage channels and other metrics were extracted using the hydrology tool within the ArcGIS 10.8 software's spatial analysis tools. The Brahmani River watershed was defined using DEM fill, slope, flow accumulation, stream order, and basin. Combining these physical relief measures with surface spectral data enables a thorough, multidimensional evaluation of how terrain morphology effects the spatial distribution of water and soil moisture across the watershed.

Results and Discussion

The total geographical area of the Brahmani River watershed is 1261.16 sq. km. The geology, topography and rainfall conditions of the region affect the drainage which is of dendritic pattern. The research area's drainage network was extracted using raster-format, 30-meter-resolution SRTM Landsat-OLI/TRIS satellite imagery that was downloaded from Open Topography. Using ArcGIS 10.8 software, the linear, areal, and relief characteristics of the study region are calculated in order to obtain the morphometric analysis.

A. Linear Aspects

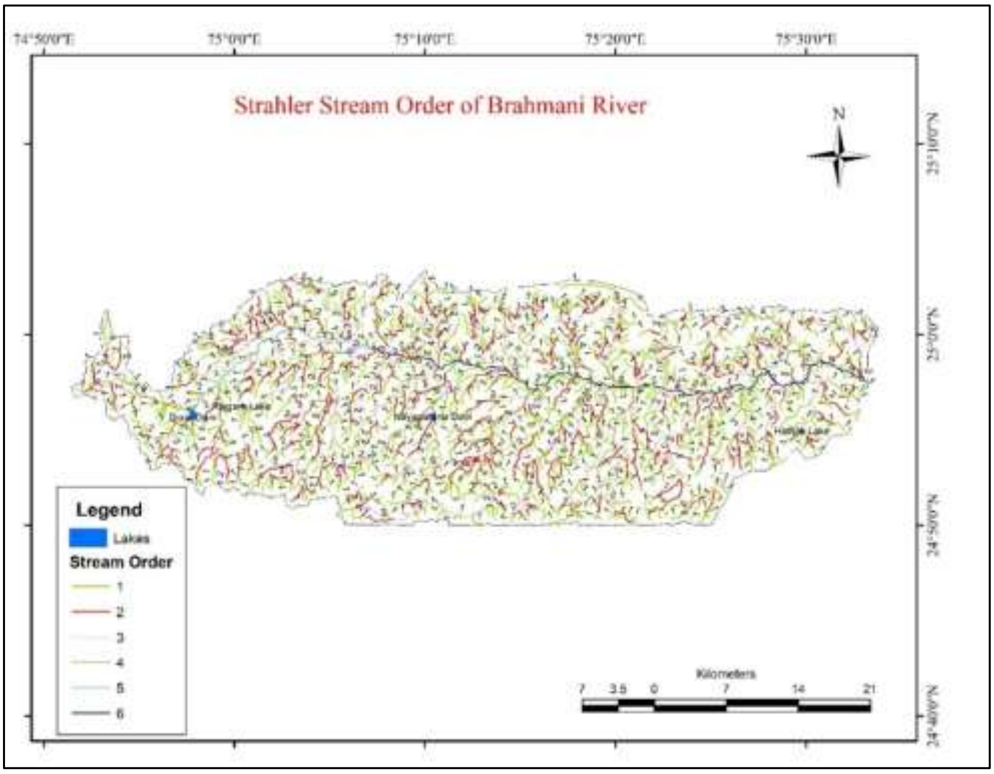
One-dimensional characteristics such as Stream Order, Stream Number, Bifurcation Ratio, and Stream Length ratio are examples of linear aspects. This demonstrates how the channel patterns of the drainage network match the topological characteristics of stream segments, and the study depends on the open linkages of the stream network. Table 1 shows the methods of calculating linear aspects.

Table 1. Methods of calculating Linear aspects of morphometric parameters

Morphometric Parameters	Formula	References	Results
Stream order (U)	Hierarchical order	Strahler,1952	6
Stream Length (Lu)	Length of the stream	Horton, 1945	2243.34 km
Mean stream length (Lsm)	Lsm=Lu/Nu; Where, Lu=Mean stream length of a given order (km), Nu=Number of stream segment.	Horton, 1945	0.64 km
Stream length ratio (RL)	RL= Lu / Lu-1 Where, Lu= Total stream length of order (u), Lu-1=The total stream length of its next lower order	Horton, 1945	0.92
Bifurcation Ratio (Rb)	Rb = Nu / Nu+1 Where, Nu=Number of stream segments, present in the given order, Nu+1= Number of segments of the next higher order	Schumm, 1956	2.06

Stream Order (U)

In hydrology and geomorphology, the hierarchical size and location of rivers and streams within a watershed are ranked using a system called stream order. Small, unbranched headwater streams are



Map 4 Strahler Stream Order

classified as first-order, while large rivers like the Amazon are classified as 12th-order. The Strahler method is the approach that hydrologists and geographers utilize most often. Geoscientists can deduce certain physical and biological features of a river without having to visit it by knowing the stream order. Table 2 illustrates that the first order stream has the highest frequency, followed by the second, third, and fourth order streams, in that sequence.

Table 2- Order wise Stream Numbers

Stream order (U)	Stream Number (Nu)	Total Length(km)	Mean Stream Length (Km)	Cumulative Mean Stream Length (Km)
1st	1621	1183.85	0.73	0.73
2nd	773	551.6	0.71	1.44
3rd	457	293.98	0.64	2.08
4th	201	123.96	0.62	2.7
5th	53	35.23	0.66	3.36
6th	117	54.71	0.47	3.83

Stream Numbers (Nu)

The number of stream segments in each order is referred to as stream number. Typically, the number of stream segments reduces with increasing order. However, in this case, stream numbers grow. The number of streams is directly proportional to the area of the contributing watershed and channel extent. A total of 3222 streams were identified, with 1621 being of first order, 773 of second order, 457 of third order, 201 of fourth order, 53 of fifth order, and 117 of sixth order. Stream network analysis revealed predominantly dendritic drainage patterns, indicating textural uniformity and absence of structural control.

Stream length ratio (RL)

The stream length ratio, defined as the ratio of a given order's mean stream length to the next lower order, has a significant impact on the basin's surface flow, discharge, and erosion stage (13). The calculation is presented below:
RL 21= 0.71/0.73 = 0.97
RL 32= 0.64/0.71 = 0.9
RL 43=0.62/0.64 = 0.97
RL 54=0.66/0.62 = 1.06
RL 65=0.47/0.66 = 0.71
The RL of successive stream orders in the basin varies slightly because to differences in slope. Variable stream length ratios among orders typically imply differences in slope, rock composition, and terrain.

Mean Stream Length (Lsm)

Strahler defined mean stream length (Lsm) as the characteristic size of stream network components and contributing surfaces. The mean stream length was computed by dividing the mean stream length of each order by the number of stream segments (see Table 2). The average stream length in the research area is 0.73 km for the first order, 0.71 km for the second order, 0.64 km for the third, 0.62 km for the fourth, 0.66 km for the fifth, and 0.47 km for the sixth order. The mean stream length is 0.7 kilometers. The size and topography of a watershed directly affect the length of the mean stream. Longer mean stream lengths in lower orders mean that water travels further in narrow channels, which has a direct impact on watershed lag and peak discharge. Steep slopes typically inhibit the development of long stream segments, resulting in shorter average stream lengths than flat plains.

Bifurcation Ratio (Rb)

This is the ratio of the number of streams in one order to those in the next higher order. It assesses the level of branching within a drainage network. It is calculated by the formula: Rb = Nu / Nu+1
Where, Nu = stream number
Nu +1 = stream number of higher order
Rb 12 = 2.1
Rb 23 = 1.69
Rb 34 = 2.27
Rb 45 = 3.79
Rb 56 = 0.45, Mean bifurcation ratio is 2.06

The bifurcation ratio is a dimensionless characteristic whose value typically ranges from 3 to 5. However, in certain research, this amount might range from 15 to 1. A low bifurcation ratio suggests minimal structural disturbance and stable drainage patterns (14). A lower bifurcation ratio indicates that fewer tiny streams feed into bigger ones, resulting in a longer elongated basin form and a delayed, lower climax flood surge.

B. Areal Aspects

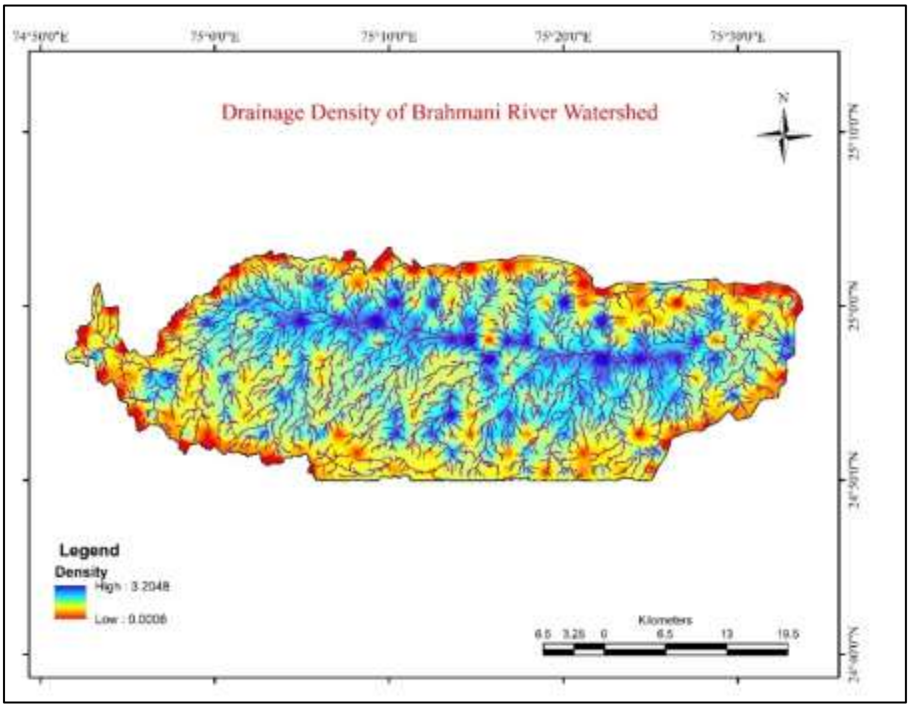
Areal features refer to two-dimensional parameters such as basin shape, area, stream frequency, drainage density, drainage texture, elongation ratio, circularity ratio, and form factor. The watershed covers 1261.16 square kilometers and has a circumference of 228.19 kilometers.

Drainage Density (Dd)

Drainage density is defined as the total length of streams per unit area. Drainage density is a key morphometric parameter that impacts the time it takes for surface runoff to reach the master stream outflow, as well as the shape and discharge peak of the basin. Surface runoff travels faster to the master stream and outlet in basins with high drainage density, while it takes longer to reach the mainstream in basins with low drainage density. It is linked to stream head source location, relief, climate, vegetation, soil, and rock properties in the area. Low drainage density is favourable in areas with resistant or highly permeable subsoils, dense vegetation cover, and low relief. Drainage density (Map 5) in the Brahmani watershed is 1.78km/km2, indicating that the watershed landscape is composed of moderately permeable subsurface materials, dense vegetative cover, or low structural relief, allowing for greater infiltration than higher surface discharge.

Table 3. Methods of calculating Areal aspects of morphometric parameters

Drainage density (Dd)	Dd=L/A Where, L=Total length of stream, A= Area of basin.	Horton, 1945	1.78 km/km^2
Stream frequency (Fs)	Fs=N/A Where, L=Total number of streams, A=Area of basin	Horton, 1945	2.55 km^{-2}
Texture ratio (T)	T=N1/P Where, N1=Total number of first order stream, P=Perimeter of basin.	Horton, 1945	7.1/km
Form factor (Rf)	Rf=A/(Lb)² Where, A=Area of basin, Lb=Basin length	Horton, 1945	0.142
Elongation ratio (Re)	R_e = 2/Lb x (A/ π)$^{-1/2}$ Where, A=Area of basin, π=3.14, Lb=Basin length	Schumm, 1956	0.4245
Circulatory ratio (Rc)	Rc=4πA/P²Where A= Area of basin, π=3.14, P=Perimeter of basin.	Miller,1953	0.304
Length of overland flow (Lg)	Lg=1/2Dd Where, Drainage density	Horton, 1945	0.28km
Constant channel maintenance(C)	C=1/Dd Where, Dd= Drainage density	Horton, 1945	0.562km



Map 5 Drainage Density

Stream Frequency (Fs)

It is the total number of stream segments from all stream orders per unit area (13). Stream frequency in the studied area is 2.55 per sq. km. The results indicate normal well-spaced channel framework. Fs = Nu/A.
Where, A = Area of the basin (1261.16 square kilometers).
Nu = Stream Number (3222)

The study found a positive association between stream number and drainage density in the watershed, showing that increased drainage density leads to more streams. Drainage frequency and density are influenced by various factors such as climatic conditions, vegetation cover, rock and soil types, rainfall concentration, infiltration capacity, relief, run-off intensity, permeability, and slope.

Texture ratio (T)

Drainage morphometric study relies on texture ratio, which is influenced by terrain relief, infiltration capacity, and underlying lithology (15). The calculation involves dividing the number of first-order streams by the watershed's perimeter. The studied area has a texture ratio of 7.1 per km, indicating dense, fine drainage networks, steeper slopes, and less permeable bedrock. This leads to faster surface runoff and increased soil erosion vulnerability.

Form factor (Rf)

The area of the watershed divided by the square of its length is known as the form factor. The numerical index that is frequently used to depict various basin shapes is called the form factor (13). It is expressed as $Rf = A/L^2$
Where, A = Area of the basin (1261.16 sq. km) L2 = Basin length (94.4 km)
A low form factor value 0.142 (less than 0.5) reinforces that the basin is highly elongated. It will experience flatter peak flows spread out over a longer duration rather than flash-floods.

Elongation Ratio (Re)

The diameter of a circle with the same area as the drainage basin divided by the basin's greatest length is known as the elongation ratio. It is calculated by the formula

$$R_e = 2/Lb \times (A/\pi)^{-1/2}$$

Where, A=Area of basin, π=3.14, Lb=Basin length
It is an indicator of the river watershed's morphology and is primarily influenced by geology and climatic factors. Its value ranges from unity, or 1, in the circular shape, to zero in the severely elongated shape. According to Strahler's categorization, values below 0.6 denote a highly elongated shape with steep topography and strong structural trends. The Brahmani watershed's elongation ratio is 0.4245.

Circulatory Ratio (Rc)

The circularity ratio, a dimensionless feature, is the ratio of a watershed's areas to the area of a circle with the same diameter as the watershed's perimeter. Its value falls between 0 and 1, and values near 1.0 indicate the basin's circular form, which is structurally determined by the watershed's slope, climate, relief, geological features, land use and cover, and stream length and frequency. The watershed's circulatory ratio value of 0.304 indicates an elongated shape, modest runoff flow, and excellent subsurface permeability. The watershed's morphometric form metrics, namely the Circulatory Ratio (0.304) and the Form Factor (0.142), converge to show a relatively elongated, non-circular basin geometry that significantly controls its hydrological response. A value of 0.304, according to Miller's categorization, indicates that the basin only covers 30.4% of the area of a complete circle with the same perimeter, indicating significant structural stretching and a mature geomorphic evolutionary stage. The low Form Factor of 0.142, which denotes a tiny catchment width in relation to its axial length, reflects this severe elongation. This combined geometric profile ensures a substantially flattened, attenuated storm hydrograph from a hydrological perspective. Runoff from the remote upper reaches follows an extended axis, arriving at the outlet long after lower flows have cleared. This structural delay efficiently spreads out the entire discharge volume over time, minimizing deadly, synchronized peak flows and making the watershed extremely resilient to abrupt flash flooding dangers.

Length of overland flow (Lg)

The length of overland flow refers to the amount of water that travels over land before entering stream systems. According to Horton (13), the length of overland flow (Lg) is a crucial factor in determining the hydrology and physiography of a drainage basin. It is inversely related to half the reciprocal of drainage density. In this study, the overland flow length was 0.28 km, indicating reduced runoff in the area. A drainage density of 1.78 is quite low, indicating that the landscape contains widely dispersed streams. The resulting length of overland flow of 0.28 indicates that rainwater travels a greater distance across the land surface before entering a channel, giving it more time to soak into the soil. This generally suggests flat to undulating landscape, permeable soils, or extensive vegetation cover.

Constant channel maintenance (C)

The Constant of Channel Maintenance (C) is the minimal land area required to support and maintain a single unit length of a stream channel. It was developed by hydrologist Schumm to show the quantitative link between drainage basin area and channel network length. It is determined using the reciprocal of drainage density (or twice the length of the overland flow). The result of 0.5622 km^2/km. implies very permeable soils, flat terrain, or dense vegetation where a vast land area is required to provide adequate surface runoff to sustain a stream.

C. Relief Aspects

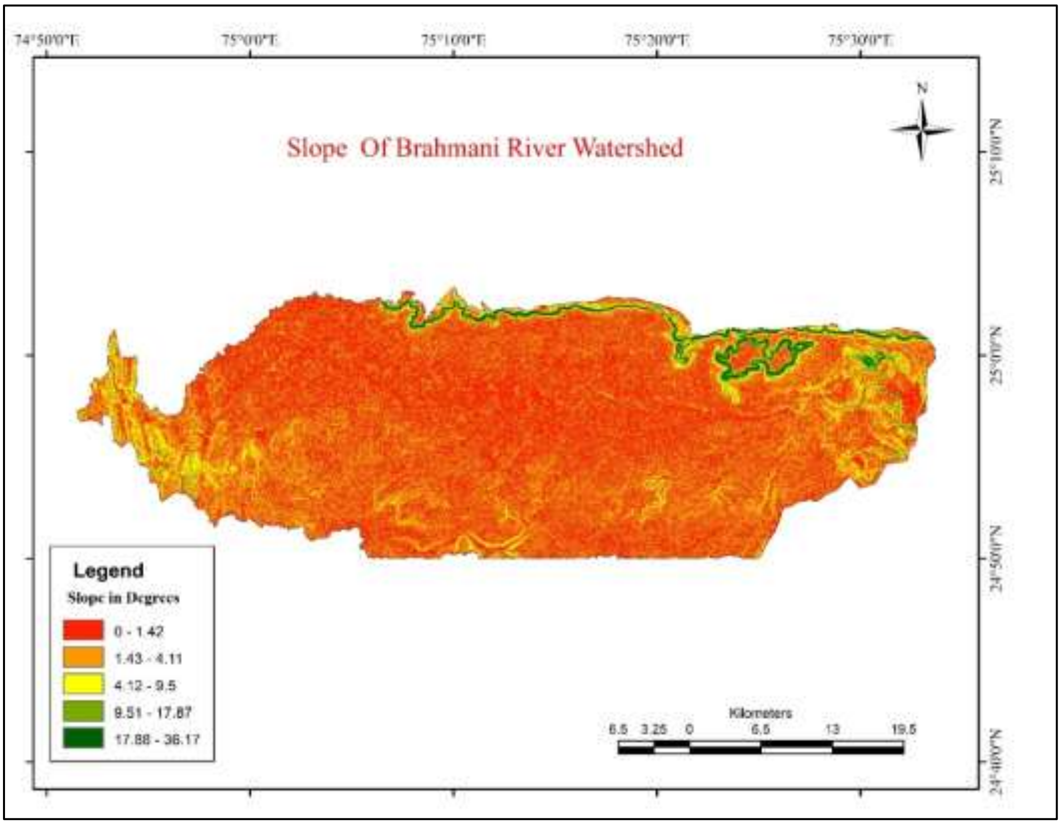
The relief of a drainage basin refers to its three-dimensional properties, including area, volume, and vertical dimensions of landforms.

Table 4. Methods of calculating Relief aspects of morphometric parameters

Total basin relief (H)	H = Highest – Lowest Height	Strahler (1952)	312 meters
Relative relief ratio (Rhp)	H*100/P	Melton (1957)	0.137
Watershed Slope (Sw)	Sw=H/Lb	Sreedevi et al., 2005	0.003

Slope

The nature and volume of infiltration and runoff are determined by the watershed's slope. Slope analysis is crucial in morphometric and geomorphological studies of the Brahmani watershed. Drainage basins with steep channel gradients and high average slope create more runoff than those with gentle slopes due to discouraged surface detention and infiltration of rainwater. The degree of slope in the Brahmani watershed ranges from 0 to 36.17 (Map 6). The slope of the Brahmani watershed is significant, ranging from 0 to 36.17 degrees, indicating a transition from low-relief floodplains to rugged upper catchments. The lower limit of 0 degrees indicates widespread flat terrains with channel migration and deposition dominating. In contrast, the greatest slope of 36.17 degrees suggests steep outer hills, which accelerate



Map 6 Slope Map

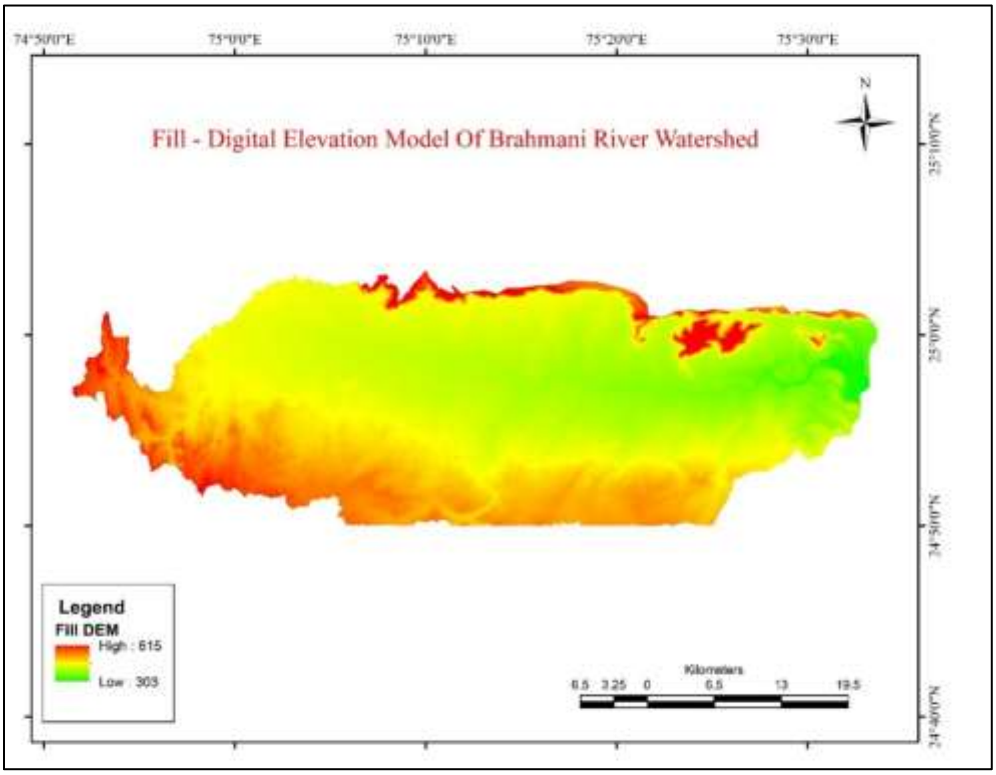
surface runoff and increase soil erosion risk. This topographic mismatch emphasizes the importance of dual-action management, which includes implementing strong soil conservation technologies (e.g., terracing, check dams) in the high-gradient headwaters and drainage maintenance systems to minimize waterlogging in the lower plains.

Ruggedness Number (Rn)

The ruggedness number measures the terrain's structural complexity, including relief and drainage density. Geologists use this number to study the morphology of terrain and gain a better grasp of how complicated geomorphic processes shape the surface. The product of maximum basin relief and drainage density occurs when both parameters are within the same unit. The watershed has a Rn value of 0.555 and a low roughness rating, indicating reduced soil erosion. A number of 0.555 implies a combination of low drainage density and moderate to level slopes. Runoff accumulates slowly, reducing erosion danger.

Relative Relief

Relative relief is an important morphometric measure for evaluating the morphological properties of any terrain. It represents the difference between the study area's lowest and highest points. The watershed's elevation is 615m above mean sea level, with the lowest relief at 303m above sea level. The



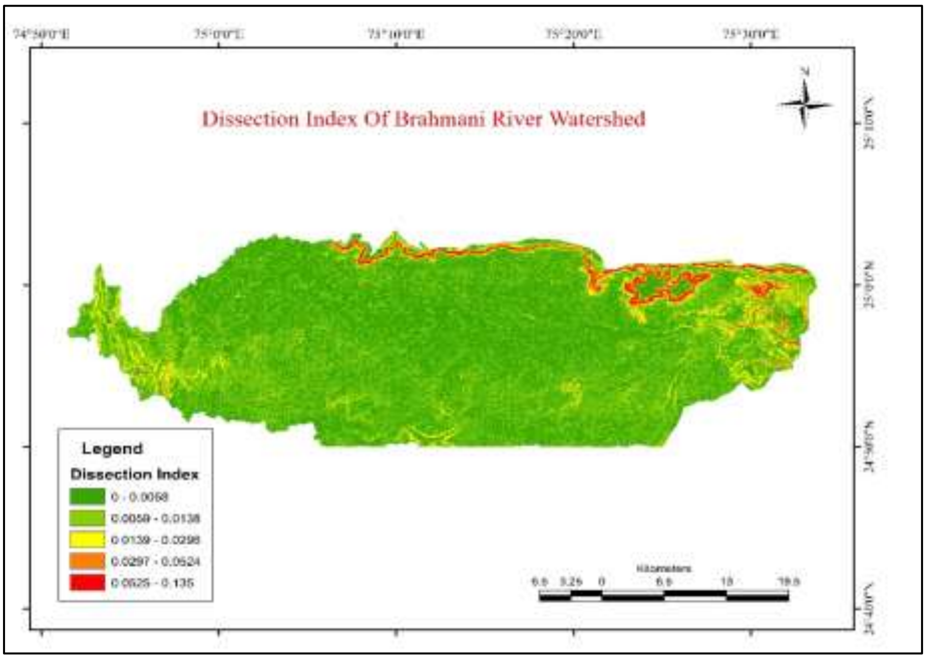
Map 7 Relief Map

watershed had an overall relief (H) of 312 meters (Map 7). A high relief number implies an area with high water flow, low permeability, and high runoff. Relative relief (16) was also calculated using the formula given as: Rhp = H*100/P Where, P is perimeter in meters.

It is 0.137 for the Brahmani watershed. The low relief indicates a gentle slope, and the area could be basically used for agricultural activities.

Dissection Index (DI)

In geomorphometry, the dissection index (DI) is a ratio-based scale that assesses a landscape's degree of dissection (valleys and ravines), vertical erosion, and surface roughness. It was first described by Dove Nir in 1957 and is computed as the ratio of absolute relief to relative relief (DI = Relative Relief / Absolute Relief). The DI ranges from 0 to 1. Zero represents a completely flat surface with no



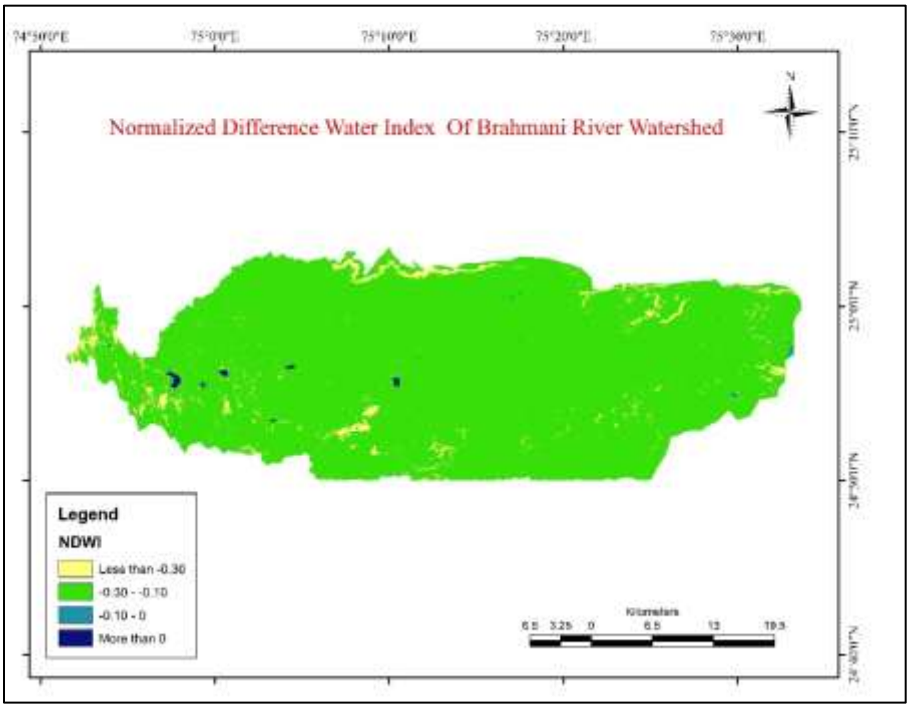
Map 8 Dissection Index Map

vertical erosion while a value of 1 shows a vertical cliff. The Brahmani watershed has values very low that is maximum 0.135 showing a flat or penultimate stage (Map 8).

Geospatial Analysis

Normalized Difference Water Index (NDWI)

By taking advantage of the different reflectance properties of water in the green and near-infrared (NIR) wavelengths, McFeeters (17) developed the Normalised Difference Water Index (NDWI), which was used to identify surface water bodies. While vegetation, bare soil, and populated regions typically generate negative NDWI values, water bodies show relatively high reflection in the green band and considerable absorption in the NIR band. In order to evaluate the geographical distribution of surface water resources in the Brahmani watershed, NDWI was computed using Landsat 8 Band 3 (Green) and Band 5 (NIR). The NDWI values in the study area (Map 9) range from - 0.4344 to 0.0598. Water bodies, such as streams, ponds, and sections of the Brahmani River channel, are indicated by positive NDWI



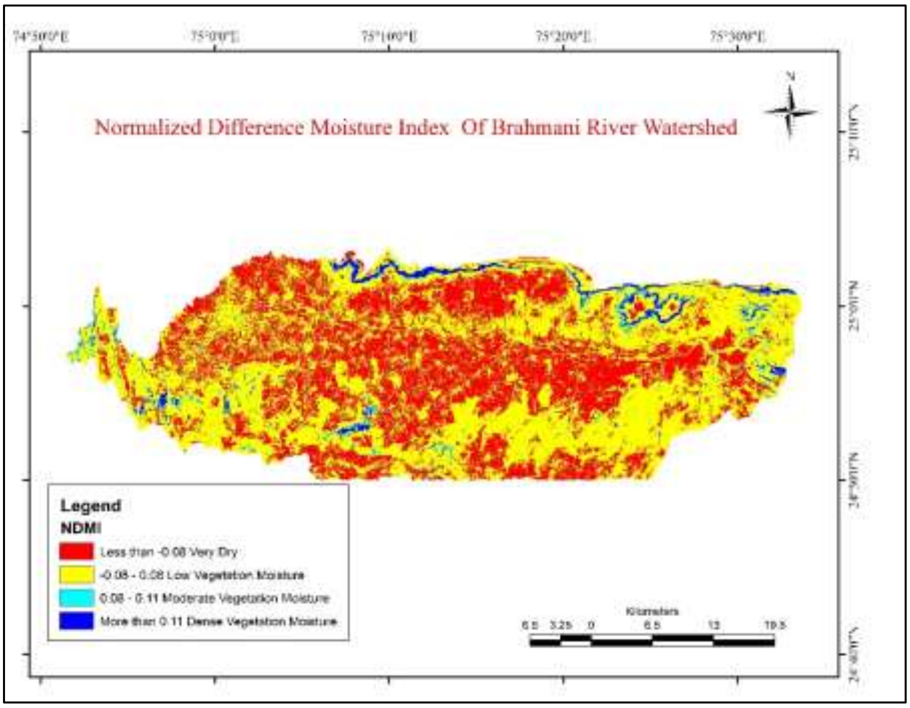
Map 9 NDWI Map

values (0.0598). In addition to highlighting open water features in satellite images, NDWI is helpful for evaluating water quality problems, particularly when estimating turbidity.

Normalized Difference Moisture Index (NDMI)

The Normalized Difference Moisture Index (NDMI) is a spectral index used to estimate vegetation and soil moisture. It uses a ratio of near-infrared (NIR) and short-wave infrared (SWIR) bands: NDMI = (NIR - SWIR) / (NIR + SWIR). Its readings in the watershed range from −0.2818 to 0.2538, suggesting considerable geographical variance in vegetation and soil moisture levels. Positive NDMI values show steadily rising vegetation and soil moisture, while negative values are associated with dry surfaces such barren ground, exposed rock, populated regions, and agricultural fields lacking moisture.

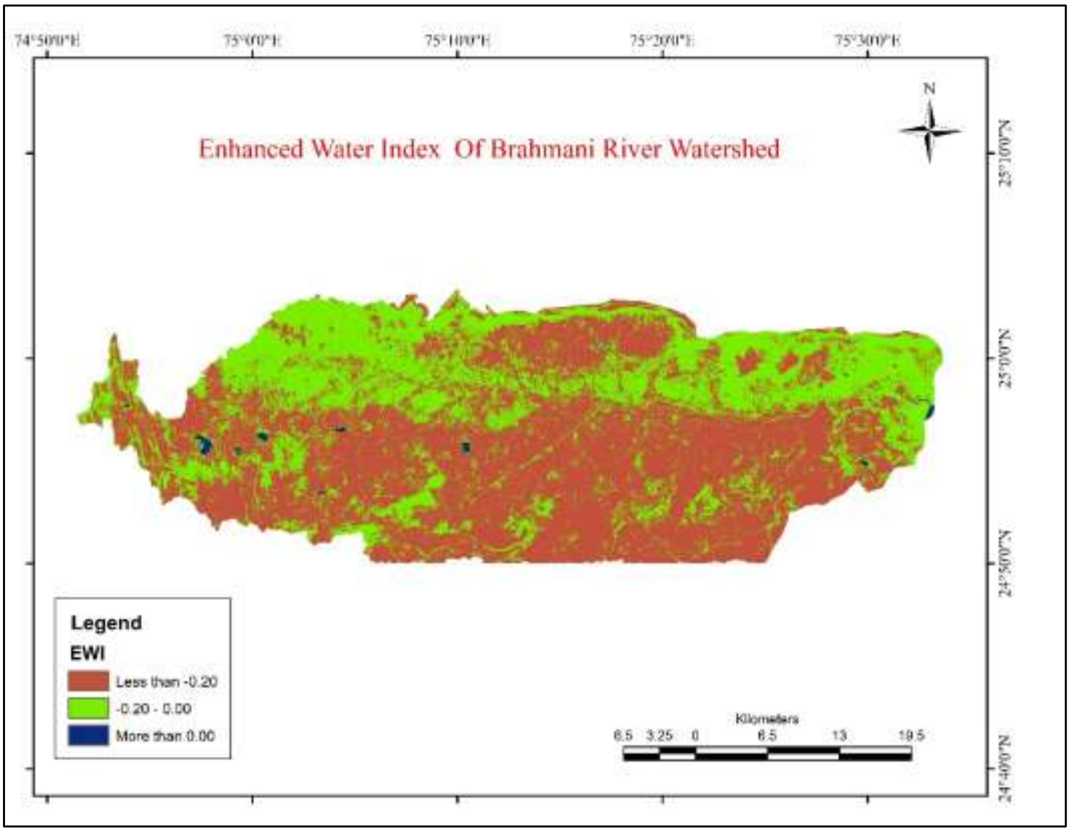
The highest NDMI values are associated with irrigated croplands, dense forest vegetation, wetlands, and areas adjacent to rivers and reservoirs. The watershed's semi-arid climate is reflected in the majority of the study area's low to moderate NDMI values (Map 10), but irrigated agricultural tracts and natural drainage corridors are associated with localised high-moisture zones. The study area has been categorised into four classes as: Very Dry (-0.08), Low Vegetation Moisture (0.08), Moderate Vegetation Moisture (0.11) and Dense Vegetation Moisture (0.2538). The study reveals that the entire watershed has moderate to low moisture, emphasising the need for prioritisation.



Map 10 NDMI Map

Enhanced Water Index (EWI)

The Enhanced Water Index (EWI) is a spectral index used in remote sensing and satellite images processing to detect and map surface water. It derives water characteristics from digital photos by analysing how various wavelengths of light bounce off the Earth's surface. Standard indexes, such as the Normalised Difference Water Index (NDWI), frequently mistakenly identify mountain or building shadows as water. EWI tackles this problem by using certain Short-Wave Infrared (SWIR) bands to distinguish between water's reflected signals and dark surfaces that appear to be the same. The values of EWI range from -1 to +1. Positive numbers strongly indicate the existence of open surface water. Higher positive values correspond to highly translucent, pure water bodies (such as rivers, lakes, or reservoirs). Values near zero indicate very saturated areas such as wetlands, marshes, mudflats, and active floodplains. Negative values refer to dry land, which includes dense vegetation, bare soil, rocks, and urban built-up regions.



Map 11 Enhanced Water Index Map

Map 11 shows EWI ranges from -0.3957 to 0.0673 implying that the study region consists entirely of non-water surfaces ranging from dry land to highly humid soil/built-up structures, with a total absence of open water bodies. The closer the values are to -0.3957, the drier or more densely vegetated the land is in that specific part of watershed. The areas hitting your maximum of 0.0673 are likely urban structures, hill shadows, or localized zones with high soil moisture (moist agricultural fields/wetlands), but they have not accumulated enough surface water to be classified as open pools or streams.

Conclusion

This work effectively combined satellite-derived spectral indices with detailed morphometric analysis to characterise the hydro-geomorphological behaviour of the studied watershed. The basin's structural geometry identifies it as a highly sophisticated sixth-order stream system with an extended, structurally regulated layout. Low areal values confirm this, with a form factor of 0.142, elongation ratio of 0.4245, and circulatory ratio of 0.304. These geometric parameters suggest a delayed peak-flow response and minimal vulnerability to flash floods. Furthermore, the mean bifurcation ratio of 2.06 indicates robust structural control over the drainage network and few geological disruptions.

Remote sensing and morphometric studies confirm the basin's lack of permanent open surface water. Satellite indices reveal a primarily terrestrial, well-drained terrain, with the Normalised Difference Water Index (NDWI) ranging from -0.4344 to 0.0598 and the Enhanced Water Index (EWI) from -0.3957 to 0.0673. The maximum values do not meet the positive thresholds required for open water pools. Instead, they reflect excessive soil moisture and urban/topographic shadows. This spectral profile corresponds to the region's coarse drainage density of 1.78 km/km^2 and a low stream frequency of 2.55 km^{-2}. Because of very permeable soils and a dense vegetation canopy, the landscape favours significant groundwater penetration over lateral surface erosion. This dynamic is structurally emphasised by a 0.28 km long overland flow and a channel maintenance constant of 0.562 km. These figures show that a significant contributing area is required to support a single linear km of stream channel.

Relief dynamics support this peaceful hydrological regime. The basin has a total relief of 312 meters but works on a minimal watershed slope of 0.003, a low relative relief ratio of 0.137, and a low roughness number of 0.555. This flat-to-gentle topography lacks the kinetic energy required for strong channel incision or high overland velocity. Instead, it works in unison with the highly permeable soil and canopy structure to keep rainwater in. This moisture retention explains the wide range of the Normalised Difference Moisture Index (NDMI), which varies from -0.2818 to a highly positive 0.2538.

In conclusion, the watershed serves as an infiltration-dominated basin. Despite its complex 6th-order hierarchy, the combination of extensive plant cover and porous lithology effectively suppresses surface runoff and inhibits channel formation. The basin's low surface water indices (EWI, NDWI) and moderate moisture index (NDMI) indicate that it serves as a critical regional groundwater recharge zone rather than an active surface collector. These findings establish a robust empirical basis for localised water resource management. To maintain the basin's natural hydrologic equilibrium, they prioritise underground water harvesting, waterlogged soil management in areas where positive moisture thresholds are exceeded, and focused ecological conservation efforts.

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