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Remote Sensing and GIS-Based Evaluation of Morphometric Parameters of Madhupur Tract Basin

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Abstract: Evaluating the complexity of the water system is essential to balance its utilization, maintenance, and management. A quantitative description of the drainage system, an essential aspect of the characteristics of a basin, can be assessed by the morphometric characteristics at a defined scale. Morphometric analysis quantitatively studies landforms' physical dimensions and characteristics within a drainage basin. The Madhupur Tract, a large upland area in central Bangladesh, is surrounded by the Jamuna-Brahmaputra River floodplain. Geologically, the Madhupur Tract predominantly consists of older Pleistocene deposits, with a mix of clay, silt, and sand. The drainage pattern in the Madhupur Tract is primarily dendritic, resembling a tree-like structure. Madhupur Tract Drainage Basin is a basin with 9,025 streams of different order, covering an area of almost 3,677 km^2. It is very elongated in shape with rapid discharge in a short period. Lower-order streams are high in number, probably due to the elevated nature of the area. A gradual decrease in the number of streams can be seen inversely decreasing with increasing stream order. The consistent decrease in the number of streams in relation to stream order throughout the basin indicates the dominance of erosional landforms. The changes in stream length ratio throughout the basin show that the area is in the early stages of irregular hydrological behavior. The overall drainage density of the Madhupur Tract Basin is high in lower reaches, indicating less porous rock in the bed surface, high slope, and high-water flow regimes. The low form factor value indicated the elongated nature of basins with low peak flow for longer. Flood flows of elongated basins can be more easily managed than circular basins. The relief ratio of Madhupur Tract Basin was measured to be around 0.156, apparently very low, indicating minimal elevation differences with a relatively flat or gently undulating terrain. The ruggedness number of the Madhupur Tract Basin is 33.54. A low ruggedness indicates a relatively smooth and uniform landscape with gradual elevation changes. Both surface water and groundwater interactions influence the Madhupur Tract's drainage system. The lateritic formations in the region contribute to the formation of aquifers, affecting the groundwater flow and the overall drainage dynamics.

I. Introduction

Assessment of the complexity of the water system is needed to equate the utilization, maintenance, and management of the system, as well as the occurrence, distribution, movement, and properties of water on earth (Khan & ElKashouty, 2023). The development of water resources necessitates the assessment of the complexity of the water system for equate utilization, maintenance, and management of the system, encompassing the occurrence, distribution, movement, and properties of water on earth and their relationship with the environment within each phase of the hydrological cycle. A quantitative description of the drainage system, an essential aspect of the characteristics of a basin, can be assessed by the morphometric characteristics at a defined scale and synthesize the hydrological responses (Mahala, 2020; Bogale, 2020).

Morphometric analysis quantitatively studies landforms' physical dimensions and characteristics within a basin or drainage basin (Kumar et al., 2015). It analyzes the shape of the Earth's surface and landforms. Measuring and calculating various parameters, including stream length, drainage density, & relief ratio, characterizes the terrain's shape, size, and relief. The analysis gives valuable insights into the processes occurring in a Basin, aiding in assessing its behavior, erosion potential, and overall landscape characteristics. Water management studies are needed to protect the limited water resources because surface water resources are rare in most places. (Mahala, 2020; Bogale, 2020)

Morphometric studies are essential for effective basin management and sustainable utilization of water resources. The outcome of the analysis of linear and areal parameters is dependent on determining the effect of catchment characteristics and the distribution of stream networks of different orders within the area. (Khan & ElKashouty, 2023; Arulbalaji & Gurugnanam, 2017)

The objective of the present study was to analyze the Madhupur Tract Basin's linear, areal, and relief morphometric attributes. Remote Sensing (RS) and Geographical Information System (GIS) techniques were used to update drainage and surface water bodies and evaluate the basin's linear, relief, and aerial morphometric attributes. Analyses of drainage efficiency, sediment transport, and topography variations helped assess runoff, erosion, and land stability. The findings will support sustainable watershed management, flood mitigation, and effective land use planning in the region. (Arefin & Alam, 2020)

Madhupur Tract

The Madhupur Tract, a large upland area in central Bangladesh, is surrounded by the Jamuna-Brahmaputra River floodplain (Hossain et al., 2014). (Figure 1). The southern part of this tract is known in Bangla as Bhawal Garh, and the northern part as Madhupur Garh. Geologically, it is a terrace one to ten meters above the adjacent floodplains (Rahman et al., 2005). The total

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extent of this Tract is 4,244 sq km. The main section stretches from just south of Jamalpur in the north to Fatullah of Narayanganj in the south. Most of Dhaka City is on this Tract. Madhupur Tract has seven small outliers; four are in the east and three in the north (Rahman et al., 2005).

The Madhupur Tract is an exposed Quaternary interfluve between two pathways for the Brahmaputra River (Pickering et al., 2013). The Madhupur Tract is an uplifted Pleistocene Interfluve tilted to the east. The western margin of the Madhupur Tract is a fault, termed the Madhupur Fault, which has several echelon linear segments with underlying faults being correct lateral strike-slip faults. There are different interpretations of the faults underlying the Madhupur Tract. (Morgan and McIntire, 1959; Alam, 2007). The Lalmai hills and the Madhupur locality represent tectonically uplifted blocks. Still, the whole Barind tract and the significant portion of the Madhuput tracts are not tectonically uplifted; instead, these originated by erosional-depositional processes (Towhida et al., 2006). The western margin of the Madhupur tract is an erosional feature due to river truncation (Hossain et al., 2014; Figure 2).

Geologically, the Madhupur Tract predominantly consists of older Pleistocene deposits, with a mix of clay, silt, and sand. The landscape is marked by dissected plateaus and numerous small hills, creating a varied topography (Figure 3). It consists of uplands with closely or broadly divided terraces connected to shallow or large, deep valleys. Erosional processes, including the weathering of rocks, have contributed to the forming of characteristic landforms in the area. The soils here are generally classified into three main categories: Madhupur clay, Madhupur gravelly clay, and Madhupur sandy loam. These soil types influence the region's agricultural practices, impacting crop selection and yield.

The drainage pattern in the Madhupur Tract is primarily dendritic, resembling a tree-like structure (Figure 3). The rivers and streams in the region flow in a pattern where smaller tributaries join larger rivers, forming a network that drains the water from the plateau. The area is drained by several rivers, including the Old Brahmaputra, Arial Khan, and Karatoya, which play a significant role in shaping the hydrological characteristics of the area.

Both surface water and groundwater interactions influence the Madhupur Tract's drainage system. The lateritic formations in the region contribute to the formation of aquifers, affecting the groundwater flow and the overall drainage dynamics (Figure 4).

II. Methodology

The morphological features were retrieved using Arc Hydrology methods with the input of digital elevation model earth observation datasets, which are significant in comprehending the spatial arrangement of stream network features. These are widely applied in deriving detailed linear, relief, and areal morphometric parameters. Geomorphological Assessments of terrains were done automatically based on Shuttle Radar Topography Mission - Digital Elevation Model (SRTM-DEM) high-resolution images of terrain and landscape. Data set characteristics are explained in Table 1. Arc toolbox in GIS 10.3 was used to analyze the morphologic characteristics of the basin, including ArcHydro Tools for watershed delineation, Spatial Analyst for slope, aspect, and drainage density, and Hydrology Tools for stream order and flow direction. Zonal Statistics and Raster Calculator tools were used to analyze terrain attributes. GIS techniques offer a powerful tool for analyzing, managing, and extracting spatial information for better understanding. (Ehsani et al. 2010; Figure 4)

The study area was delineated in a GIS environment with the help of Arc-GIS 10.3 assigning Universal Transverse Mercator (UTM), World Geodetic System (WGS dating from 1984 and last revised in 2004), and 43N Zone Projection System.

Spatial analyst tools of hydrology options within the Arc toolbox were used to assess the flow direction and accumulation direction to prepare a basin map. Raster calculation was conducted to generate stream networks and correct the location of the basin outlet. The basin was categorized into three morphometric aspects: linear, relief, and shape. The methodology adopted for computations of morphometric parameters with formulae is listed in Table 2.

The topographic wetness index (TWI) is calculated to assess the hydro-geomorphic features of a drainage basin, describing topography's influence on soil moisture distribution and surface runoff. (Beven & Kirkby, 1979). The Topographic Position Index (TPI), first introduced by Weiss (2001), classifies landforms based on elevation differences between a focal point and the surrounding area. The TWI was calculated using gridded DEM. The negative TPI value indicates that the central point is lower than its surrounding average height, whereas positive TPI indicates a position higher than its average height. (Günther et al., 2014; De Reu et al., 2013; Sørensen et al., 2006).

III. Result and Discussion

Quantitative evaluation of the morphometric parameters describes the basin characteristics; each parameter was classified into different dimensional aspects, namely, linear aspects, areal aspects, and relief. The arrangement of streams in a drainage system constitutes the drainage pattern, which reflects mainly structural or lithologic controls of the underlying rocks. The following description explains the characteristics of the Madhupur basin.

Madhupur Tract Drainage Basin has been divided into 49 basins. They have an area coverage of almost 8,200 km^2, with an average area of 168 km^2. These basins are generally elongated in shape, with a total perimeter of almost 380 km (Figure 5).

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Linear Morphometric Parameters

Linear aspects explain the one-dimensional parameters to indicate channel patterns of the drainage network and the topological characteristics.

Stream Order

Stream Ordering was proposed by Strahler (1957). It is a hierarchical relationship between stream segments and their connectivity. First-order streams are the smallest, unbranched ones; second-order segments are formed when two first-order streams confluence; segments of third-order are formed when two second-order streams combine, and so on. It is the first step of drainage analysis based on the hierarchical ranking of streams. Higher-order streams generally exhibit increased discharge and drainage area, playing a crucial role in shaping the overall hydrological patterns of a region. This stream order depends on the basin shape, size, and relief characteristics of such basin (Haghipour and Burg 2014).

The total number of streams of the Madhupur Tract area or basin is 9,025, covering an area of almost 8,200 km^2. Lower-order streams are high in number, probably due to the elevated nature of the area. A gradual decrease in the number of streams can be seen inversely decreasing with increasing stream order. (Figure 6; Table 3)

The consistent decrease in the number of streams to stream order (average 57.67 %) throughout the basin indicates the dominance of erosional landforms. Higher order streams (4th, 5^{th} order) are fewer due to their alluvial deposits. Basins with high stream numbers have higher runoff and rapid peak flow than those with low stream numbers (Bhat et al., 2019).

Geological factors influence the high density of low-order streams in the Madhupur Tract basin, which promotes surface runoff and stream formation. Anthropogenic activities, including deforestation and agricultural expansion, increase runoff and erosion (Brammer, 2016).

Stream Numbers

Stream number refers to the count of individual streams within a specified area. It is a quantitative measure of the density of the stream network. High stream numbers suggest a denser network, indicating intricate drainage patterns and potential susceptibility to various hydrological processes.

The interplay between stream order and stream number yields valuable information about basin characteristics. Madhupur Basin, with a high stream order and low stream number, indicates a more hierarchical and organized drainage pattern, with a few major rivers dominating the landscape. (Table 4)

Bifurcation Ratio (Rb)

The Bifurcation Ratio (Rb) quantifies the branching pattern of a drainage basin's stream network. It is calculated by dividing the number of streams of a given order by the number of streams in the next higher order (Mayhew, 2015). Bifurcation ratios typically range between 3.0 and 5.0 in basins where geological structures exert minimal influence on drainage patterns. The drainage network is shaped by homogeneous lithology and uniform erosion processes from minimal structural control (Chowdhury, 2016). The mean bifurcation ratio of 2.54 in the Madhupur Tract basin suggests that geological structures moderately influence the drainage pattern, reflecting a balance between lithological uniformity and structural control, denoting water-carrying capacity and related flood potentiality. (Horton, 1945; Strahler, 1957; Joji et al., 2013; Table 3; Table 4)

The bifurcation ratio of streams in the basin ranges from 1.56 to 3.16 (Table 5). The low Rb indicates a dendritic or tree-like drainage pattern, with stream segments tending to converge into more significant streams at a lower rate.

Stream Length

Stream length was calculated using the Horton law that indicates the successive stage of stream segment development. (Horton,1945; Table 2) A direct geomorphic and hydrological sequence can approximate from different order stream lengths (Castillo et al., 1988). Generally, most numbers of the streams are of the 1st order and decrease as the stream order increases. Such a trend indicates discrepancies and inconsistencies in the lithology of the area. Studies suggest higher stream lengths in a mountain–plain front than in a plateau–plain front river basin. (Sreedevi et al. 2005). The stream length ranges from 1610 km (1st Order) to 77 km (5th Order). (Table 5)

A higher stream order with a lower stream length (Figure 7) can indicate specific geomorphological and hydrological characteristics with anthropogenic influence on the basin, thus requiring a holistic understanding of the local geomorphology, hydrology, and anthropogenic impact. It indicates diverse topographic features, steep gradients, or rugged terrain, causing streams to cover relatively shorter distances. And also influenced by growing urbanization altering the natural stream patterns,

Mean Stream Length

The mean stream length indicates the basin's early stage of geomorphic development. This causes discrepancies in surface flow discharge and sedimentation (Mahala, 2020). The mean stream length for 1st-order streams is 0.17 km, 2nd-order streams are 0.15 km, 3rd-order streams are 0.18 km, 4th-order streams are 0.22 km, and 5^{th}-order streams are 0.30 (Table 5). The total length

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of streams decreases with the increase of stream order, giving a negative linear change, showing dendritic type type drainage pattern (Figure 7). The low mean value of high-order streams indicates that development stopped. Relatively higher values indicate low erosion potentiality, which denotes old erosional landform development. (Table 4)

Stream Length Ratio

The stream length ratio is vital to the discharge the basin's surface flow and erosional stages (Horton, 1945). The ratio between stream orders 1 & 2, 3 & 4, and 4 & 5 are almost similar, ranging between 0.44 and 0.55. The changes in stream length ratio denote that the area is in an early stage of geomorphic development, and the area has a high potentiality of frequent changes shortly, indicative of irregular hydrological behavior. (Table 5)

Areal Morphometric Parameters

Stream Frequency (Fs)

Stream frequency is the total number of stream segments irrespective of the order per unit area (Horton, 1945). It may also be defined as the ratio between the total number of stream segments cumulative of all orders and the basin area (Table 2). Different stream frequencies through the basin with the same drainage density may be possible. Permeability, infiltration capability, and basin relief correlate with stream frequency. In reaction to runoff processes, it offers a drainage basin response. The drainage density of the basin, initial resistivity of the rocks, relief, and precipitation all affect stream frequency. Stream frequency at the Madhupur Tract basin is 5.101 number/km^2, indicative of an immediate surface runoff. High slope and greater precipitation increase stream frequency (Sf), whereas low permeability and less available surface flow decrease stream frequency (Bali et al., 2011; Thomas et al., 2010; Table 6).

Drainage Density

Drainage density is calculated as the expression of the closeness of channel spacing within a basin, as it provides a numerical measurement of runoff potentiality and landscape dissection (Horton, 1945). It measures the ratio of the total length of streams irrespective of stream order to the per unit area of the basin (Joji et al., 2013; Magesh & Chandrasekhar, 2014; Table 2). It depends upon that basin's underlain geology, relief, geomorphology, climate, vegetation, etc. (Parveen et al., 2012; Obeidat et al., 2021). Slope gradient and relative relief are the main controlling factors on drainage density (Magesh et al., 2011). Low drainage density values prevail in basins with low relief and vice versa (Strahler, 1957). Low drainage density indicates highly permeable subsoil material under dense vegetation, low relief, and low runoff, whereas high drainage density implies high runoff and low infiltration rate. Madhupur Tract basin has a drainage density of 0.86 and is fast-drained. (Harllin & Wijeyawickrema, 1985; Kelson & Wells, 1989; Horton, 1945; Table 6)

The drainage density throughout the Madhupur Tract Basin ranges from 0.01 to 69.48 km/km^2, indicating significant lithology, topography, and land use heterogeneity (Rahaman et al., 2017). The overall drainage density is 0.86 km/km^2.

High drainage density in lower reaches indicates less porous rock in the bed surface, high slope, and high water flow regimes. Low drainage density is observed in the basin's northern plain areas due to low relief and high permeability. Drainage Density of the Madhupur Tract basin can be considered low to moderate. (Table 6; Figure 8)

Texture Ratio (Rt)

Texture ratio (Rt) is calculated from stream frequency and drainage density (Horton, 1945; Table 2). It is also the ratio between the total stream segments and the basin's perimeter. Infiltration capacity is the single critical factor influencing texture ratio, as recognized by Horton. It is also an essential fluvial parameter that denotes the relative spacing of the drainage network of any basin. Infiltration capacity is an essential factor influencing texture ratio. (Horton, 1945; Table 3)

Form Factor (Rf)

The Form Factor in the context of river morphology refers to a dimensionless parameter used to quantify the shape or elongation of a drainage basin. It is calculated by dividing the basin's area (A) by the square of its length (L), providing insights into the basin's overall form (Horton 1932; Table 2). The value of Ff is always less than 0.7854, which indicates a perfectly circular basin, often in regions with uniform topography and drainage patterns (Bali et al., 2011). Flood flows of the elongated basin can be more easily managed than those of the circular basin (Castillo et al. 1988). The average form factor of the study area is 0.058, indicative of a very elongated basin. (Table 3)

Elongation Ratio (Re)

Elongation Ratio is a dimensionless parameter used in geomorphology to quantify the degree of elongation or stretching of a landform, such as a drainage basin or a basin (Schumm 1956). It is calculated by dividing the longest dimension of the landform by its perpendicular width. It is also a significant index of basin shape (Gayen et al. 2013). It can be crucial for understanding the landform characteristics and their implications for hydrological processes. Changes in the Elongation Ratio may also be relevant for assessing vulnerability to specific environmental changes (Gayen et al. 2013; Table 6). ER assesses the planimetric

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characteristics of drainage basins or basins, with a lesser value suggesting a comparatively wider landform. The ER value of the Madhupur tract basin is 4.68. (Table 4)

Circularity Ratio (Rc)

The circularity Ratio quantifies the circularity or roundness of a basin. It is calculated by dividing the landform's area by the square of its perimeter. (Strahler, 1957; Table 2). It is crucial to understand the landform characteristics and their implications for hydrological processes and to assist in quantitatively characterizing the shape and organization of basins (Strahler, 1957). Peak discharge from high precipitation will impact basins with a high circular ratio. Rc's high, medium, and low values show the Basin's development stages. (Table 6)

The average circularity ratio value of the Madhupur Tract basin is 0.32, which indicates its near-circular characteristics. (Table 3)

Relief Morphometric Parameters

Basin Relief (H)

Basin relief indicates the variation in elevation within a basin. It assists in understanding landform characteristics and the overall terrain complexity. Basin relief measures the difference in elevation between the highest and lowest points within a drainage basin. Higher basin relief indicates more varied and rugged topography, while lower relief suggests a relatively flat or gently sloping landscape (Sreedevi et al., 2009). A steeper relief often leads to faster runoff, increased erosion potential, and dynamic river systems. The measured basin relief value of the Madhupur Tract Basin is 39, inferring a gently sloping and undulating landscape with fast runoff. (Table 3; Table 6)

Relief Ratio (Rr)

The Relief Ratio is a dimensionless parameter that characterizes the relative difference in elevation between the highest and lowest points within a specified area, often expressed as a ratio (Schumm, 1956; Soni, 2017). The relief ratio of Madhupur Tract Basin was measured to be around 0.156, apparently very low, indicating minimal elevation differences with a relatively flat or gently undulating terrain.

Basin Slope (Sb)

Basin slope, also known as drainage basin slope or basin slope, refers to the average gradient or incline of the land within a specific drainage basin or basin. It measures how steep or gentle the terrain is within the entire basin, providing insights into the overall topographical characteristics of the drainage area. (Schumm, 1956; Soni, 2017)

Ruggedness Number (Rn)

The ruggedness number, also known as the terrain ruggedness index (TRI), measures a landscape's topographic complexity or roughness (Schumm, 1956). It quantifies the variability in elevation within a specified area, providing information about the physical characteristics of the terrain. (Strahler, 1956; Selvan et al., 2011; Adhikari, 2020) The ruggedness number of the Madhupur Tract Basin is 33.54. A low ruggedness indicates a relatively smooth and uniform landscape with gradual elevation changes. This may correspond to plains, lowland areas, or regions with minimal topographic variation. (Table 3; Table 6)

IV. Conclusion

Madhupur Tract Drainage Basin has an area coverage of almost 3,677 km^2 and a perimeter of almost 380 km. The form factor value of the basin is 0.05, which signifies that it is very elongated in shape. Such a low form factor implies that this drainage basin experiences rapid discharge in a short period.

The total number of streams of the Madhupur Tract area or basin is 9,025, covering an area of almost 8,200 km^2. Lower-order streams are high in number, probably due to the elevated nature of the area. A gradual decrease in the number of streams can be seen inversely decreasing with increasing stream order. The consistent decrease in the number of streams in relation to stream order throughout the basin indicates the dominance of erosional landforms. Higher-order streams are less in number due to the alluvial deposits. The changes in stream length ratio denote that the area is within the early stage of geomorphic development of irregular hydrological behavior.

The overall drainage density of the Madhupur Tract Basin is high in lower reaches, indicating less porous rock in the bed surface, high slope, and high water flow regimes. Low drainage density is observed in the basin's northern plain areas due to low relief and high permeability. The low form factor value indicated the elongated nature of basins with low peak flow for longer. Flood flows of elongated basins can be more easily managed than circular basins. The average circularity ratio value of the Madhupur Tract basin indicates its near-circular characteristics. It also suggests substantial peak flood runoff during the monsoon season and neo-tectonic upliftment. It also alludes to decreased peak flow characteristics and mature geomorphological adjustment. The relief ratio indicated that Madhupur Tract has high relief with a high slope. An extremely high value of ruggedness number occurs when both variables are significant and the slope is steep.

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Declaration

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Conflict of interest

To the best of their knowledge, the authors declare that there shouldn't be any conflict of interest as this work was done as part of a nationally approved project.

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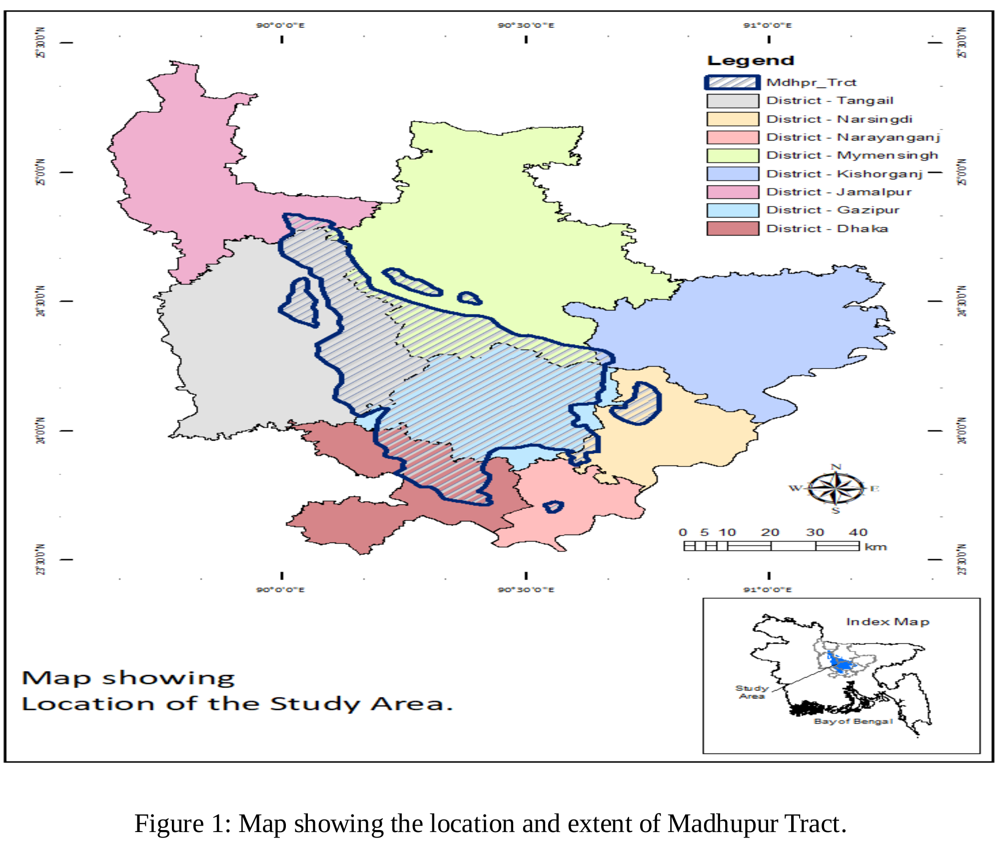

Figure 1: Map showing the location and extent of Madhupur Tract.

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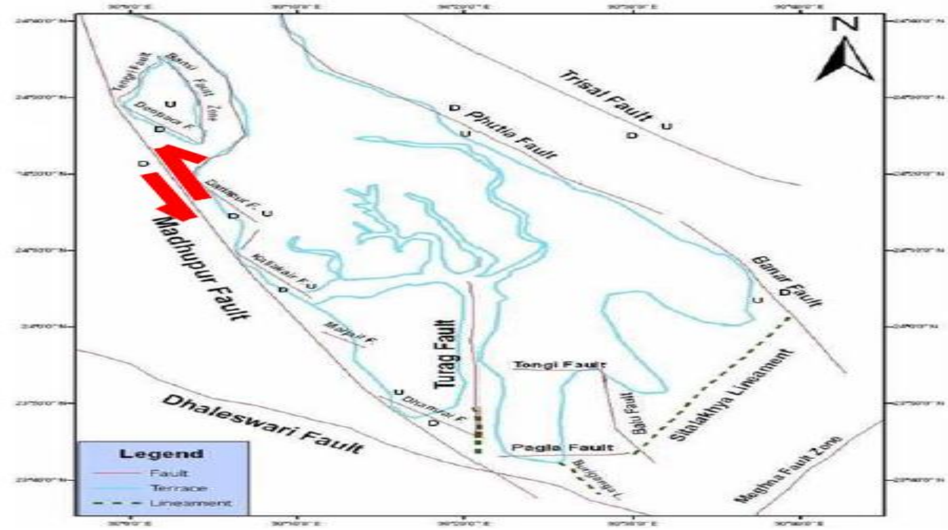

Figure 2: Structural elements in and around Madhupur Tract. This figure also shows the direction of the strike-slip movement along the Madhupur Fault (Source: Maitro & Akhter, 2010).

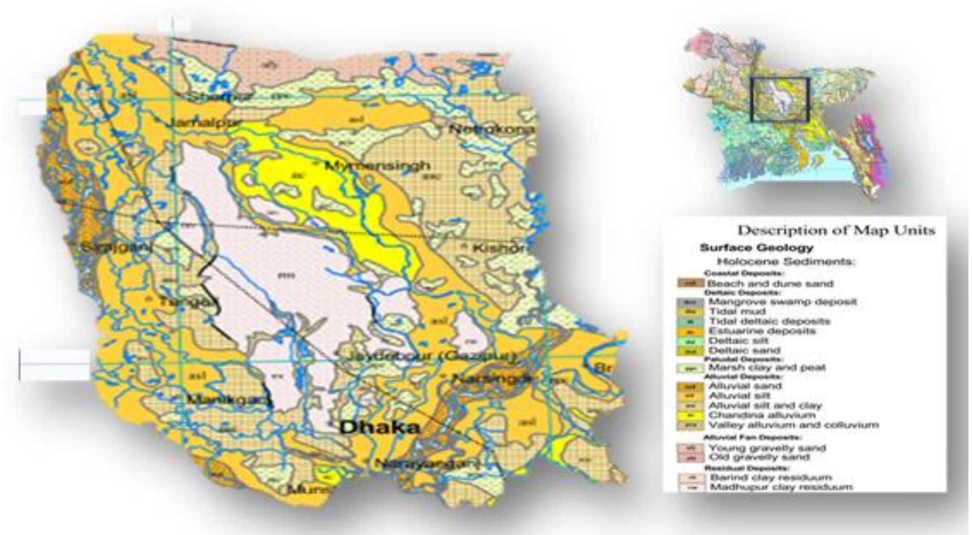

Figure 3: Surface geology Map of the study area and surroundings**.**

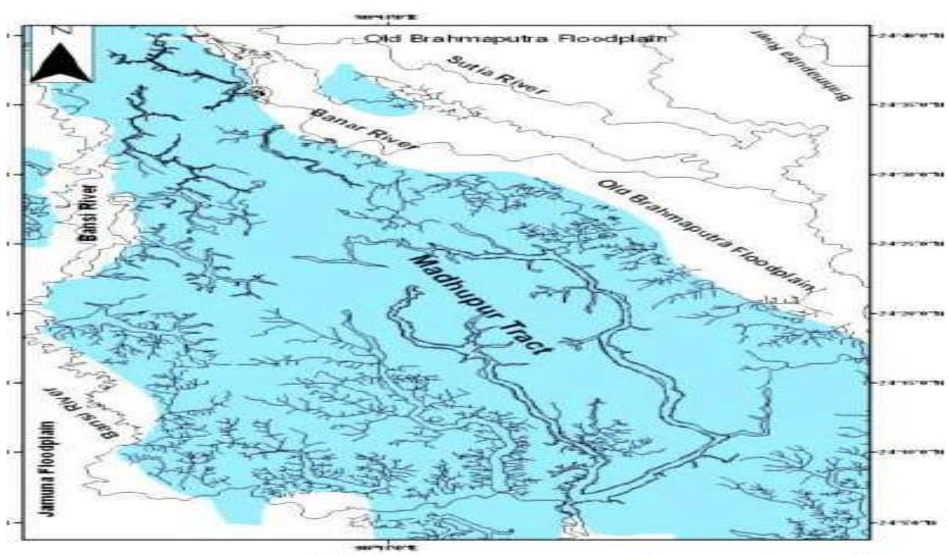

Figure 4: A drainage map of the Madhupur Tract Area (modified from Begum et al., 2009).

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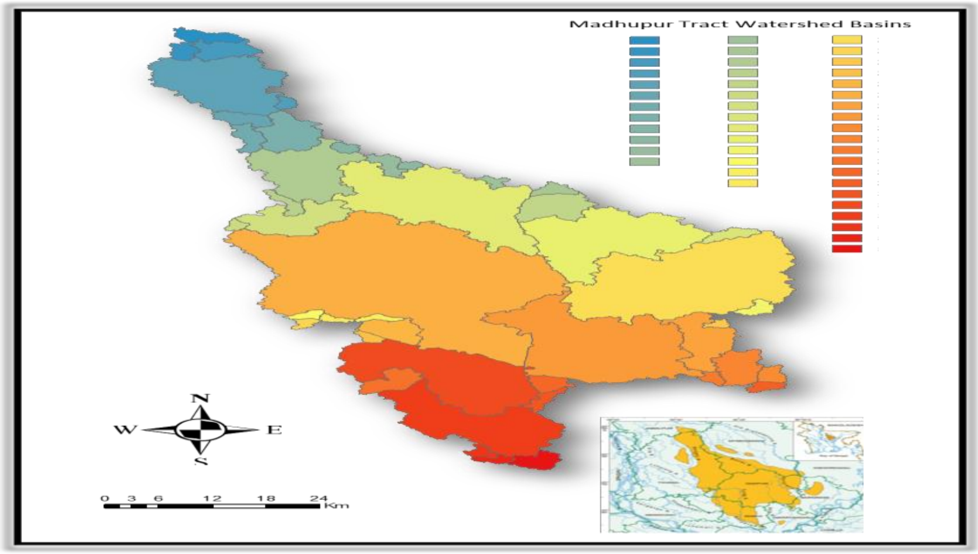

Figure 5: Map showing basin basins of Madhupur Tract study area. Each basin is identified by individual color shade.

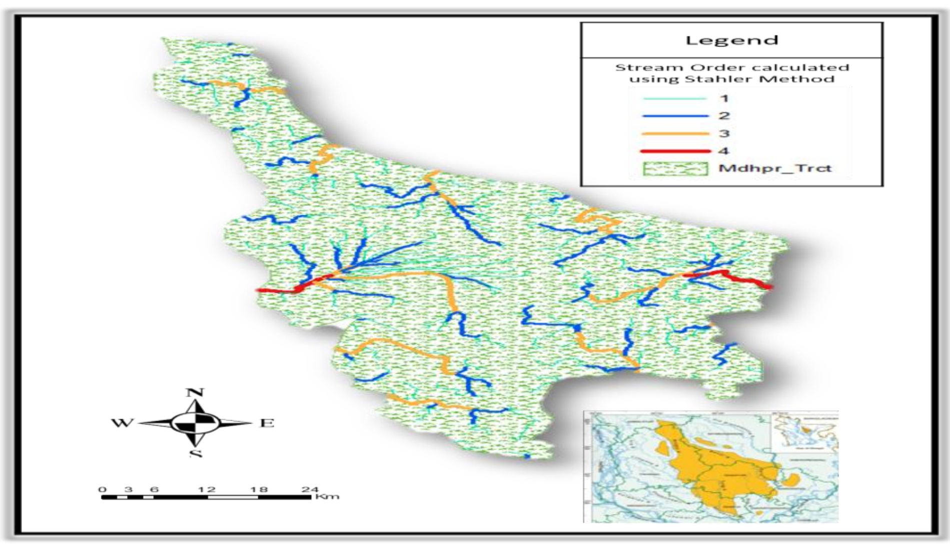

Figure 6: Stream order map of Madhupur Tract basin, calculated using Strahler method.

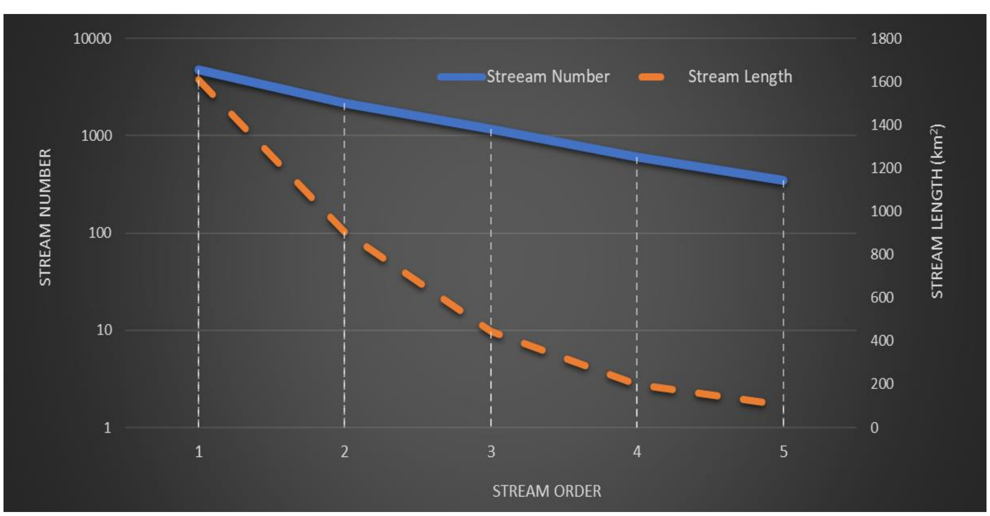

Figure 7: Stream Order vs Stream Number vs Stream Length.

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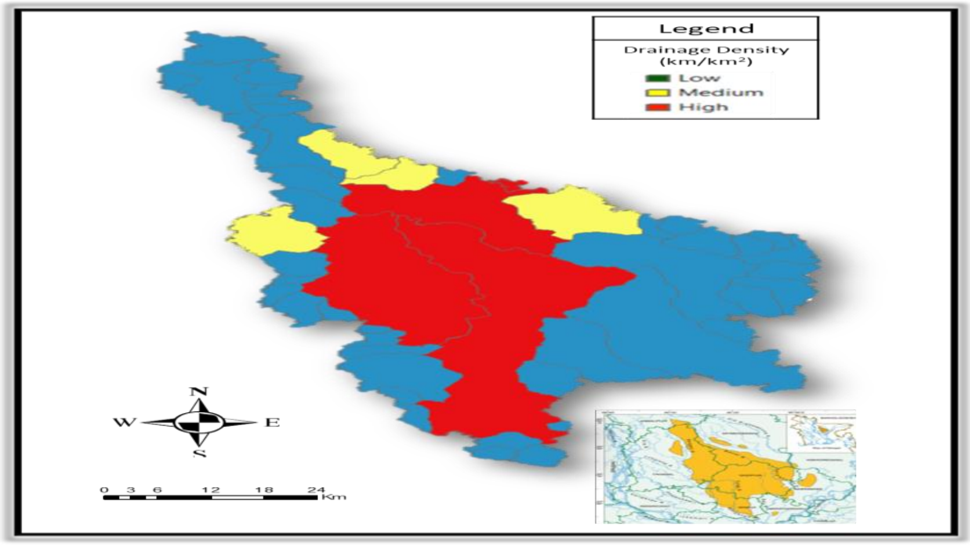

Figure 8: Drainage Density characteristics of the Madhupur Tract Basin area.

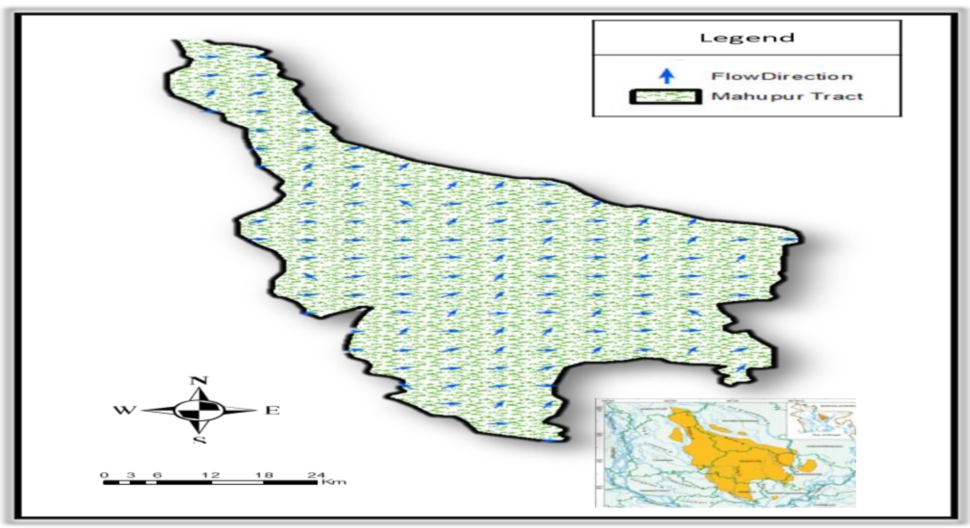

Figure 9: Map showing Stream Flow direction over the Madhupur Tract Basin.

Table 1: Characteristics of data sources used for the morphometric study.

Data Type	Data Source
Landsat image (land use map)	GloVis, Landsat 8 OLI (Panchromatic band of 15 m × 15 m, visible, NIR, SWIR bands of 30 m × 30 m and thermal band of 100 m × 100 m resolution), 2014, row/path- 43/138
Digital elevation model (DEM)	USGS 1 arc second, UTM-45, WGS 1984
Drainage Density Map	DEM (USGS 1 arc second), 30 m × 30 m resolution, UTM-45, WGS 1984

Table 2: Morphometric Parameters (Methodology adopted for Computations of Linear and Areal Morphometric Parameters with formulae.

Linear Aspect	Basin Perimeter	**P**	km	Outer boundary of drainage basin / basin	Schumm (1956)
	Basin Length	$\mathbf{L_b=1.312 \times A^{0.568}}$	km	Length of basin	
	Stream Order	**Sμ**	no.	Hierarchical rank	Strahler (1964)
	Stream Number	**Nμ**	no.	number of streams of a given order 'μ'	
	Stream Length	**Lμ**	km	the total length of streams (km) of all order 'μ'	Horton

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	Mean Stream Length	$L_{sm} = \frac{L_u}{N_u}$	km	L_u = total length of streams (km) of a particular order ‘u’ N_u = Total number of streams of a particular order ‘u’	(1945)
	Stream Length Ratio	$R_L = \frac{L_{um}}{L_{um} + 1}$	ratio	L_{um} = mean stream length of a particular order ‘u’ L_{um} + 1 = mean stream length of next higher order ‘u + 1’	
	Bifurcation Ratio	$R_b = \left\lfloor \frac{N_u}{N_{u+1}} \right\rfloor$	ratio	N_u = number of streams of a particular order ‘u’ N_u + 1 = Number of streams of next higher order ‘u + 1’	Schumm (1956)
	Mean Bifurcation Ratio	R_{bm}	ratio	mean of bifurcation ratios of all orders	
Areal Aspect	Basin Area	**A**	km^2	Area from which water drains	Strahler (1964)
	Form Factor	$F_f = \frac{A}{L_b^2}$	ratio	A = area of the basin (km^2) L_b = basin length (km)	Horton (1945)
	Drainage Density	$D_d = \frac{L_\mu}{A}$	km / km^2	L_μ = length of all stream (km) A = Basin area (km^2)	
	Stream Frequency	$F_s = \frac{N_u}{A}$	/ km^2	N_u = total number of streams of a given basin A = total area of basin (km^2)	
	Circularity Ratio	$R_c = \frac{4\pi A}{P^2}$	km	A = area of the basin (km^2) P = perimeter of the basin (km)	Strahler (1964)
	Elongation Ratio	$R_e = \frac{P}{\pi L}$	km	P = outer boundary of a drainage basin (km) L = basin length (km)	
	Texture Ratio (Drainage Texture)	$D_t = \frac{N_u}{P}$	/ km	N_u = total number of streams of a given basin P = perimeter of the basin (km)	Smith (1950)
	Constant Channel Maintenance	$CCM = \frac{1}{D_d}$	km	D_d = drainage density	Strahler (1964)
Relief Aspects	Basin Relief	$H = R - r$	m	R = highest relief r = lowest relief	Schumm (1956)
	Relief Ratio	$R_r = \frac{H}{L_b}$	ratio	H = relative relief (m) L_b = length of the basin (m)	
	Dissection Index	$D_i = \frac{H}{R}$	ratio	H = relative relief (m) R = absolute relief (m)	
	Basin Slope	$S_b = \frac{H}{L_b}$	ratio	H = relative relief (m) L_b = length of the basin (m)	Miller (1953)
	Ruggedness Number	$R_n = R - D_d$	ratio	R = Basin Relief D_d = drainage density	Schumm (1956)
Index	Topographic Wetness Index (TWI)	$TWI = ln\left(\frac{a}{tan\,\beta}\right)$	ratio	a = Upslope contributing area per unit contour width (m²/m) β = Slope angle in radians	Beven and Kirkby (1979)
	Topographic Position Index (TPI)	$TPI = Z_i - \bar{Z}$	ratio	Z_i = Elevation of the target cell $\bar{Z}$ = Mean elevation of neighboring cells within a specified radius	Weiss (2001)

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Table 3: Morphometric results for the Madhupur Tract basin.

Linear Aspect	Basin Perimeter	km	380
	Basin Length	km	139
	Stream Order	no.	5^{th} Order
	Stream Number	no.	18,757
	Stream Length	km	3,163
	Mean Stream Length	km	1.56
	Stream Length Ratio	ratio	0.47
	Mean Bifurcation Ratio	ratio	2.54
Areal Aspect	Basin Area	km^2	8,200
	Form Factor	ratio	0.06
	Drainage Density	km / km^2	0.55 - 2.06
	Stream Frequency	/ km^2	14.57 - 205.51
	Circularity Ratio	km	0.32
	Elongation Ratio	km	4.68
	Texture Ratio (Drainage Texture)	/ km	9.8
Relief Aspects	Basin Relief	m	39
	Relief Ratio	ratio	0.16
	Ruggedness Number	ratio	35.54

Table 4: Ranges and classification of morphometric parameters.

Stream Numbers

Numbers	Level
High Stream Numbers:	dense and intricate stream network
	regions with numerous small tributaries, resulting in a complex
	high degree of connectivity between different parts of the watershed
Low Stream Numbers	less dense and more straightforward stream network
	areas with fewer tributaries and a more straightforward drainage
	regions characterized by more uniform topography.
Spatial Distribution	the heterogeneity of the landscape - with different geological or topographical characteristics.

Stream Length

Type		Interpretation
Stream Order	Consistent	Higher order streams have longer lengths - integrate the flow from multiple tributaries.
	Inconsistent	Anthropogenic actoivities - urbanization or channelization modifying landscape and influencing spatial distribution of
Long Streams		large drainage area with high discharge, shapes the hydrological characteristics of the watershed
Varying Lengths		heterogeneity of the landscape - associated with different geological or topographical features

Bifurcation Ratio (Rb)

Rb	<	3	5	>
Level	Low Bifurcation Ratio	Intermediate Bifurcation Ratio	High Bifurcation Ratio	

Circulatory Ratio (Strahler, 1957)

Value	< 1	1	> 1
Class	Indicates a well-rounded shape.	Suggests an irregular or more elongated shape compared to a perfect circle.	Indicates a more convoluted or complex shape with multiple inlets or

Form Factor (Pérez, 1979)

Factor	<	0.22	0.3	0.37	0.45	0.6	0.8	1.2	>
Shape of Basin		Very	Elongated	Slightly Elongated	Neither elongated not widened	Slightly widened	Widened	Very Widened	Surrounding the Drain

Drainage Density (Pérez, 1979)

Density	0.1	1.8	3.6	5.6
Class	Low	Moderate	High	

Mean Slope - mainstream (IBAL, 2009)

slope (%)	1	5	11	17
Class	Slight	Moderate	Steep	

Mean Slope - watershed (Pérez, 1979)

slope (%)	0	2	5	10	15	25	50	>
Class - Land	Flat	Slight	Fairly Rough	Rough	Extremely Rough	Steep	Very Streep	

Elongation Ratio (Strahler 1964)

Value	<1	1	> 1
Class	Indicates a landform that is wider than it is long.	Represents a perfectly square or equidimensional landform.	Indicates a landform that is longer than it is wide.
	Suggests a relatively rounded or circular shape.		Suggests an elongated or linear shape.

Table 5: Linear morphometric results against stream orders across the Madhupur Tract basin.

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		Stream Order				
		1	2	3	4	5
Linear Aspects	Stream Number	9396	6018	2273	813	258
	Bifurcation Ratio	1.56	2.65	2.80	3.16	
	Mean Bifurcation Ratio	2.54				
	Stream Length (km)	1610	887	412	176.58	77
	Mean Stream Length (km)	0.17	0.15	0.18	0.22	0.30
	Stream Length Ratio	0.55	0.46	0.43	0.44	

Table 6: Ranges and classification of areal and relief aspects of morphometric parameters.

FORM FACTOR *(Pérez, 1979)*

Form factor (approximate values)	Shape of the basin
<0.22	Very long
0.22 to 0.30	Elongated
0.30 to 0.37	Slightly elongated
0.37 to 0.45	Neither elongated nor widened
0.45 to 0.60	Slightly widened
0.60 to 0.80	Widened
0.80 to 1.20	Very widened
>1.20	Surrounding the drain

DRAINAGE DENSITY *(Pérez, 1979)*

Drainage density (approximate values)	Class
0.1 to 1.8	Low
1.9 to 3.6	Moderate
3.7 to 5.6	High

MEAN SLOPE - the mainstream *(IBAL, 2009)*

Mean slope of the main stream (%)	Class
1 to 5	Slight
6 to 11	Moderate
12 to 17	Steep

MEAN SLOPE - basin/basin *(Pérez, 1979)*

Mean slope (%)	Land
0 to 2	Flat
2 to 5	Slight
5 to 10	Fairly rough
10 to 15	Rough
15 to 25	Extremely rough
25 to 50	Steep
>50	Very steep