GIS base morphometric analysis of Teesta river basin in Eastern Himalayas

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ABSTRACT

The study proposes that using a geographic information system (GIS) can effectively characterize the morphometric condition of the Teesta River catchment. Remote sensing (RS) satellites, specifically ALOS PALSAR and Landsat 8 OLI/TIRS, provide high-resolution imagery data to identify river basins and their stream networks. The Teesta River is a tributary of the Brahmaputra River, originating from two glacial lakes. The study focuses on conducting a detailed morphometric examination of the basin, which includes dividing it into nine sub-watersheds for calculating various morphometric parameters. Mathematical analysis is applied to factors such as flow direction, accumulations, stream length, order, drain density, bifurcation ratio, frequency, and circulatory ratio [2,3]. The drainage pattern within the 7,733.80 km2 basin is predominantly sub-dendritic to dendritic. The topography and geological composition of the area influence the flow order of streams within the catchment. The density of the studied area is 0.67 km2/km2, indicating it is a sixth-order basin. The research area has undergone a geomorphic stage, as evident from the increasing length ratio of streams from lower to higher orders.

Keywords: Teesta Watershed, Morphometric Analysis, Landsat, DEM, RS& GIS

INTRODUCTION

The drainage basin is a crucial unit in hydrology and geomorphology (Ministry of Water Resources, River Development, and Ganga Rejuvenation, 2013). Precipitation serves as the primary water source in watersheds, and integrated modelling techniques are valuable for identifying watershed problems such as resource overburdening, water stress among populations, and governance crises [18,19,20,33]. Challenges in watershed management include securing water supply, managing water variability, protecting ecosystems, addressing climate change risks, increasing public knowledge, and considering political perspectives [17,3]. Therefore, an integrated approach is essential for developing comprehensive watershed management plans [4,20].

Morphometric studies employ remote sensing (RS) and geographic information systems (GIS) techniques to quantify the geometry and networks of drainage basins [10,11,14] RS, particularly using satellite images, offers a comprehensive perspective for studying drainage basins, while GIS and GPS technology contribute significantly to addressing land and water resource sustainability issues (ESRI, 2021). GIS-based evaluation, using accurate and low-cost data sources like the Shuttle Radar Topographic Mission (SRTM), enables the analysis of hydrological systems (USGS, n.d.). Digital Elevation Models (DEMs) derived from SRTM data are utilized to determine morphometric parameters such as catchment area, drainage density, network order, relief, and network diameter [9,10,12,13]. RS data and spatial analysis within a GIS environment facilitate the delineation and categorization of drainage areas [15,16,11]. In the context of the Teesta River catchment, the research project aims to employ GIS and RS technology to calculate morphometric parameters and characteristics, with the Kanhar River serving as a reference point [26,27,28]. This approach aligns with recent discoveries and studies discussed earlier in the article [29,30,34,35].

STUDY AREA

The River Teesta flows through gorges and waterfalls in the Sikkim Himalayas before reaching Rangpo, where it merges with the Rangpo River and Teesta Bazaar. The Rangeet River, the main tributary, joins the Teesta River near the Teesta Bridge, where highways from Kalimpong and Darjeeling converge. It then flows southward into West Bengal. After splitting in Jalpaiguri, the river briefly touches the Cooch Behar district before entering Bangladesh at Fulchori, where it merges with the Brahmaputra River. The Teesta River ultimately empties into the Brahmaputra at TeestamukhGhat in Kamarjani-Bahadurabad, in the Rangpur district of Bangladesh. The Teesta and its tributaries are fast-flowing mountain rivers that carry a significant amount of debris and pebbles, resulting in high velocity and turbulent flow.

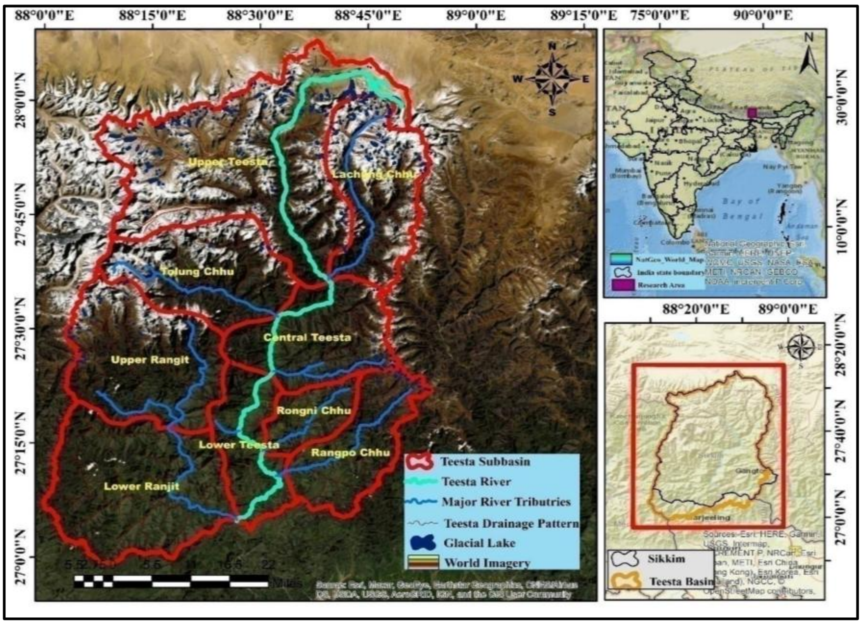

Fig. 1 Study area MAP of the Teesta River Catchment

In order to identify the kind of Land Use Land Cover (LULC) and forest classes present in the research area, the LULC classes of the area were classified by applying classification techniques on remotely sensed satellite imagery [35, 12, 36,37]., as can be shown in **Fig.1**. The figure shows that the majority of the area is covered by forests, that glaciers make up approximately one-fourth of the area, and that the remaining area covers the lower part of the watershed and is comprised of cropland, settlement areas, and water bodies including rivers and ponds, and barren terrain [40].

Physiography of the area

The Sikkim Eastern Himalayas can be classified into five different zones based on elevation: subtropical (below 1000 meters), warm temperate (1000-2000 meters), cold temperate (2000-2500 meters), cold (2500-4000 meters), and frigid (above 4000 meters). The Teesta River receives most of its water from glacier melt and rainfall, with the northern part of the Teesta basin being mostly covered by glaciers. The region is home to over 315 glacial lakes and a diverse range of plant and animal species. It is influenced by the monsoons from the Bay of Bengal, with significant variations in rainfall across different locations.

The terrain and landscape of Sikkim are challenging and formidable. Three sides of the state are bordered by the towering peaks and spurs of the Greater Himalayas. The Greater Himalayas extend in a convex shape to the north, while the Singalila range marks the western border between Nepal and India. The Donkya range forms the eastern boundary and is relatively isolated, with two passes, Nathu la and Jalepa la, providing access to trade routes between Sikkim and Tibet. Mt. Khangchendzonga, the third-highest mountain in the world with an elevation of about 8,596 meters, is the state's prominent peak. It is surrounded by other notable peaks such as Jano, Kabru, Pandim, Narsin, and Siniolchu. The valleys of Lachen and Lachung are the only populated areas in the rugged northern part, while the southern part of Sikkim is lower, more open, and cultivated, with significant erosion caused by the Teesta River and its tributaries.

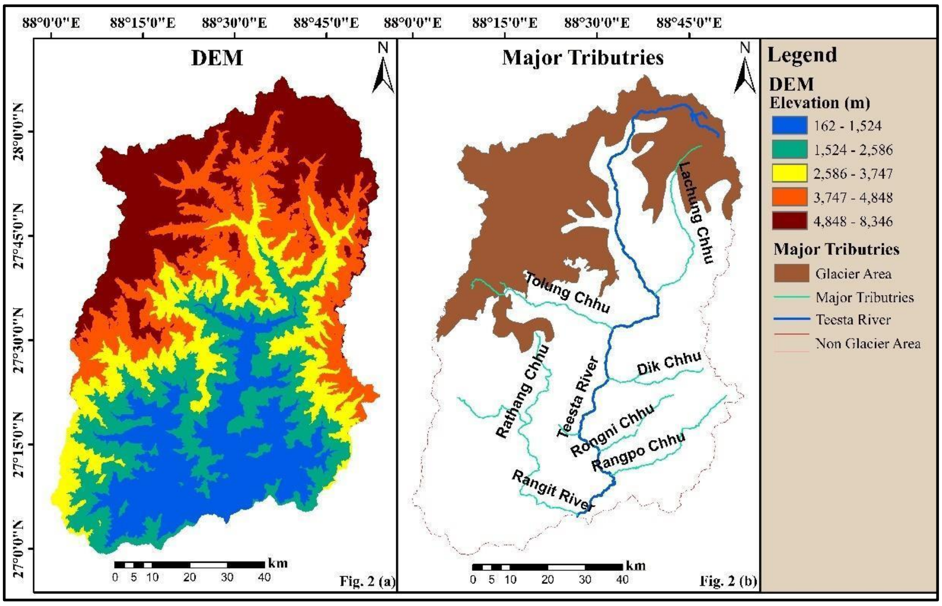

Fig. 2 DEM and Major Tributaries

Land use land cover (LULC) and Forest Type

Land Use and Land Cover (LULC) is an important aspect for morphometric analysis as it affects infiltration and stream flow in the area. In the study area, the major land use types identified from Landsat ETM+ images are Forest, Glaciers, and Water bodies including streams and glacial lakes [24]. The population in the basin is minimal, mainly concentrated in the southern portion, resulting in negligible urbanization impact on the watershed. The scenic forests and landscapes in cities like Peijing, Shilling, and Darjling attract tourists.

Sikkim's diverse physiography and climate allow for the cultivation of various crops such as fruits, potatoes, ginger, large cardamom, and vegetables [25]. Horticulture is prominent in the subtropical region, occupying a significant portion of the land. Forests are a valuable natural resource in Sikkim, covering a substantial portion of the state's geographical area. The State Forest Department manages 82.31% of the state's area, and the overall forest cover is 47.08% with a tree cover of 39 square kilometers. The composition of forests varies from deciduous to tropically dry types in Rangit and Teesta Valley, while high altitudes feature alpine scrub and grassland [40].

Table 1 LULC classes of the Teesta River catchment

S No.	Classes	Code	Area (km^2)
1	Barren land	BARR	775.21
2	Snow and Ice	SNOW	1975.25
3	Grassland	GRAS	653.23
4	Water bodies	WATR	58.8
5	Evergreen Broad leaf Forest	FOEB	2777.36
6	Crop land	AGRR	739.36
7	Mixed Forests	FRST	103.04
8	Built-up Land	URLD	35.51
9	Plantations	CRIR	100.81
10	Deciduous Broadleaf Forest	FODB	465.89

Table 2 Forest classes of the Teesta River catchment

S No.	Class	Code	Area (km^2)
1	East Himalayan Mixed Coniferous Forest	MCF	174.98
2	Oak Rhododendron Forest	ORF	419.21
3	Cultivable and other land	CLT	1771.62
4	Snow Covered Area/Glaciers/Alpine Barren	SNW	2129.2
5	East Himalayan Sub Alpine Birch Fir Forest	SPF	411.32
6	East Himalayan Moist Mixed Deciduous Forest	MDF	62.09
7	East Himalayan Wet Temperate Forest	WTF	1649.17
8	Alpine Scrub Pasture	ASP	1116.43

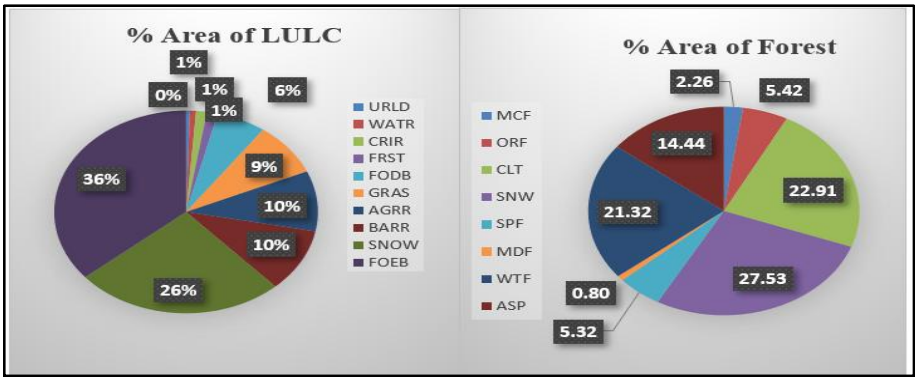

Fig. 3 Distribution Area of LULC and Forest

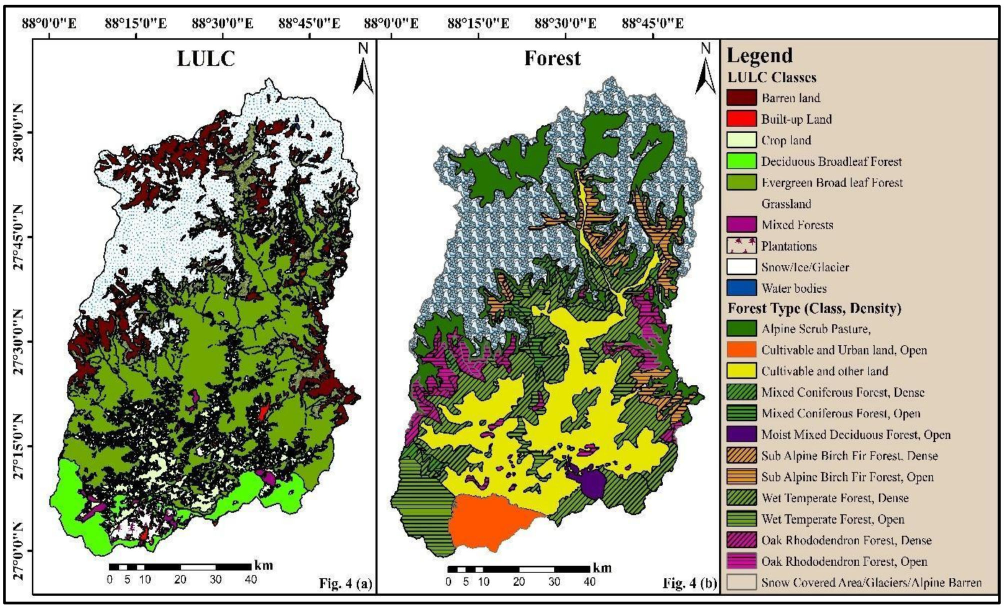

Fig. 4 LULC & Forest Type in Catchment

Soil

Soil is one of the important parameters for the study of the morphometric characteristics of any watershed. The soil map of the Teesta basin is depicted in **Fig. 5.** The major soil classes can be divided into three types, the major area is covered with loam which is composed of sand, silt, and a small portion of clay in it, Sandy loamy consisting of sand and silt is another type and Glacier soil present in the higher elevations which are composed of with rocky terrain and ice blocks shown in **Fig. 5** & **Table 3**. Due to snow they are covered in snow cover for the majority of the year and are thus, substantially less exposed to the atmosphere [21].

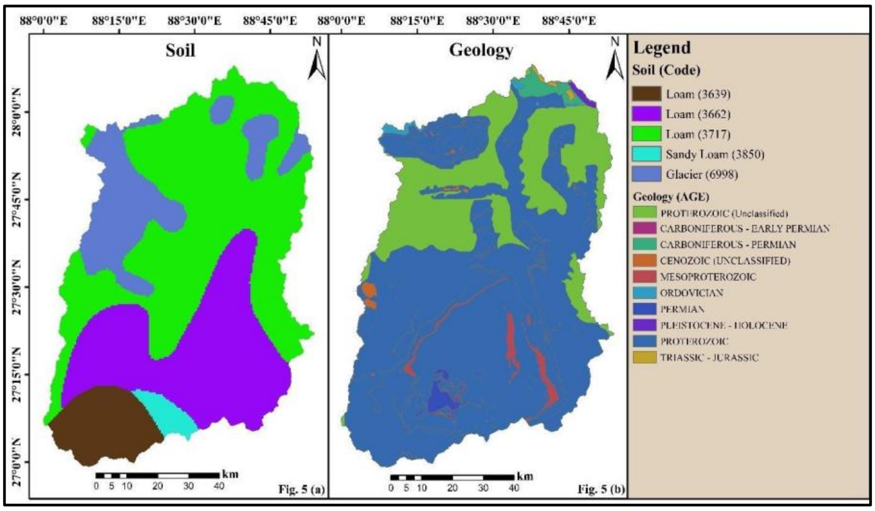

Fig. 5 Soil and Geology Type

Since most of Sikkim is made up of Darjeeling gneiss, the soil is mostly shallow, brown clay that is low in lime, magnesium, phosphorous, and nitrogen. But it has a lot of potassium in it. The soil ranges from sandy loam to silty clay loam. Soil depth can be anywhere from 30 cm to 150 cm or even more than 150 cm.

Table 3: Soil Type of the catchment

S NO.	Soil Type	Code	Area (km^2)
1	Loam1	3639	644.7744
2	Loam2	3662	2173.509
3	Loam3	3717	3590.466
4	Sandy_Loam	3850	155.772
5	Glacier	6998	1169.274

METHODOLOGY ADOPTED

The downloading of geographical data is the first step in doing the morphometric analysis of the basin, which includes the DEM, which is a type of topographical data that shows how altitude is distributed on the surface of the Earth [12, 17]. Thereafter, to outline the watershed area of interest SRTM with a spatial resolution of 30m is used. Hydrology tools were used for further delineation of the watershed which involves a number of steps, such as figuring out the flow direction based on changes in elevation and slope and figuring out the flow accumulation, which is the number of cells on the slope that flow towards each cell. This made it possible to outline the streams. After the watershed was drawn, the GIS platform was used to figure out the slope, aspect, drainage pattern, stream order, and drainage density [22,23,38]. The Horton classification system was then used to figure out the order of the streams. Horton, Schumm, Strahler, and Mueller's methods and formulas were used to figure out the morphometric parameters [7,8,41,44].

Aspect

The aspects map, derived from SRTM-DEM with a 30m resolution, provides information on the direction of mountain slope faces and its implications for the local climate and vegetation distribution in the research area [33]. West-facing slopes generally tend to be warmer than east-facing slopes due to the afternoon sun being the hottest time of the day [33]. The aspect values range from -1 to 360, with -1 representing a flat surface and values increasing in a clockwise direction [33]. In the Teesta watershed, the slopes predominantly face east and southwest, indicating lower vegetation cover and moisture content compared to west-facing slopes [32,33].

Slope

According to Burrough in (1986), the slope grid is characterized by the highest rate of change in value that occurs from one cell to the values of its neighbours. The Teesta River basin currently has a slope that ranges from 0 to 86.33. which is shown in **Fig.6** presents a slope map of the catchment defining the variation in the degree of slope (Pande & Moharir 2017). Basin has been categorized into the zone on the basis of their elevation which has been discussed in **Table.4.**

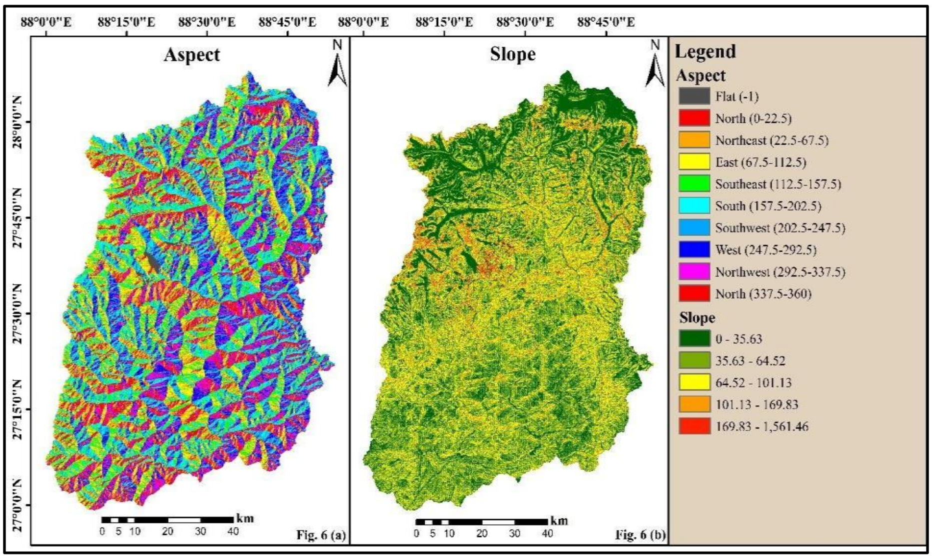

Fig. 6 Aspect and slope map

Table 4. The slope is divided into Zones

S No.	Zones	Slope description
1	Lower Hills	It has a hilly topography with sections of flat, farmed ground and is located between an altitude of 300-1,800 mtrs& the slope varies from 150-300 mtrs.
2	Upper hills	This region's elevation ranges from 1,800-3,000 mtrs. In this zone, there are significant forested areas and slopes varies from 150-300 mtrs.
3	Alpine Zones	The Alpine zone refers to the region between 3,000-4,500 mtrs. It is covered in grassland and shrub and slope area about 300-600 mtrs.
4	Snow Land	At elevations above 4,500 metres, there is always snow and no vegetation because of mostly area covered by snow and debris and slope area about 600 mtrs.

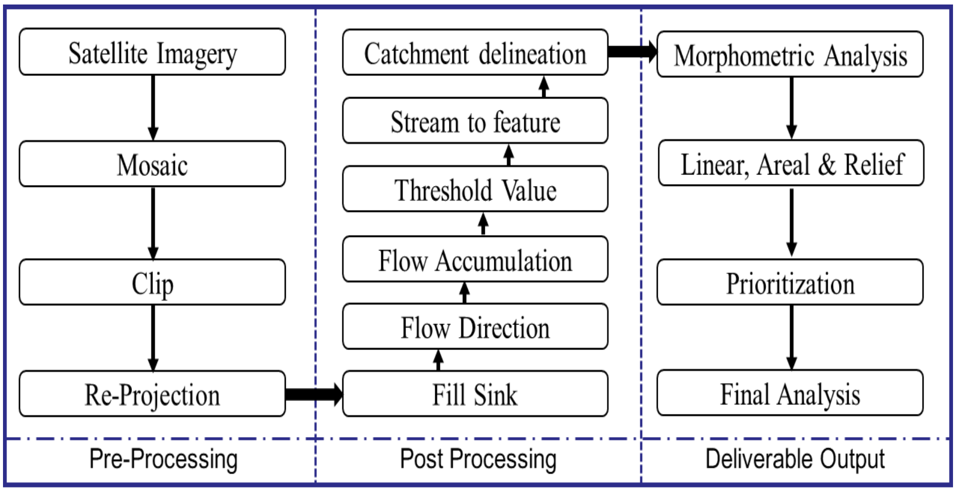

Fig. 7 Methodology Flowchart

Start with mosaicking all scenes using the help of the mosaic pro-2D model in ERDAS IMAGINE software. After undergoing mosaicking, the ALOS PALSAR-DEM picture was re-projected using the Universal Traverse Mercator (UTM) 45 Zone coordinate system. Using the spatial analyst tool in ArcGIS, we constructed the contour map with intervals of 200 meters from these points. With the help of the surface analysis tool created a slope map, and it revealed that 46.84% of class 1 from 0-50 slope, 42.91 class 2 from 50-100 slope, 8.1% of class 3 from 100-50, 1.55% of class 4 from 150-200 and 0.57% class 5 >200. The topography map was prepared using SRTM_DEM data. The steep slope of more than 600 m in the Upper Teesta &Lachung Chhu Basin elevation around the slope is greater than 6000 m, in the middle part slope is vary from 300-600 m, and around the elevation is 6000-1800m and the last lower Teesta Basin slope is 150-300 m and elevation around the basin is 1800-600 meter (Source: Repoirt NATMO, Kolkata 2007).

In order to carry out a morphometric analysis of the Sikkim, Teesta catchment, it was necessary to gather the linear, areal, and relief parameters of the catchment. The entire methodology adopted for analysis has been discussed in **Fig.7**.

Linear Aspect

The phrase "linear aspect of channel system" can also apply to the linear elements of a drainage system. When doing a morphometric study of a basin, parameters like stream length & order, mean length of the stream ratio, and bifurcation ratio were considered.

Stream Length (L_u)

The methodology outlined by Strahler has been used to rank the streams that are located within the Sikkim district and drain into the Teesta River basin (1964). The average stream length has been calculated for each order which is given in **Table 5.**

According to Horton's law for stream length, the total length of stream segments is largest in first-order streams and decreases as the stream order increases. This applies to all stream orders (1945).

Table 5. Shows the average and total stream lengths for each stream order

Stream Order	Number (N)	Length (L)	Segment (%)	Mean Stream length (L_{sm})	Bifurcation Ratio (R_b)
1	2238	2568182.08	50.13	1147.53	2.15
2	1040	1311813.74	23.3	1261.36	1.96
3	530	615867.87	11.87	1162.01	1.64
4	324	355636.32	7.26	1097.64	1.85
5	175	178340.22	3.92	1019.09	1.11
6	157	140185.72	3.52	892.9	1

Stream Order (S_o)

The stream order' concept was first established by Horton in 1945, who was the American civil engineer and soil scientist widely regarded as the father of modern hydrology. Following the assignment of stream orders, the individual segments that comprise each order are counted to ascertain the total number of segments for the given order (o). The lengths of the various portions of the stream are measured using GIS-specific tools (Aziz et al. 2020). There are a total of 4,464 stream segments in the study region, with a total of 6 stream orders. The first order stream contains 2238 stream segments, accounting for 50.13% of the total. There are overall segments 1040 in the second order stream, which accounts for 23.30%; there are 530 segments in the third order stream, which accounts for 11.87%; there are 324 segments in the fourth order stream, which accounts for 7.26%; there are 175 segments in the fifth order stream, which accounts for 3.92% and there are 157 segments in the sixth order stream, which accounts for 3.52%.

Mean Stream Length (L_{sm})

The average stream length, which serves as a defining parameter, can be used to characterize the drainage network as well as the surfaces that are connected to it Strahler's method [43]. The average stream length, also referred to as L_{sm}, was determined by first calculating the overall stream length, and then dividing that figure by the total number of streams [43]. The following is an example of a typical stream's length in the area under investigation: For the first order, there are 1147.53 mtr.; for the second order, there are 1261.36 mtr.; for the third order, there are 1162.01 meters; for the fourth order, there are 1097.64 meters; for the fifth order, there are 1019.09 mtr.; and for the sixth order, there are 892.90 mtr.. The length of the stream generally increases as the order continues, which contributes general increase.

$$L\_sm \ = L\_u/n \tag{1}$$

Where L_u is the average stream length of the specific order, N_u is the number of segments in the stream and L_{sm} is the mean length of the stream.

Ratio of Stream Length (L_{ur})

The stream length ratio is the ratio of the mean stream length of a given order to the mean stream length of the next lower order. This ratio, which has a significant correlation with streamflow and discharge, is known as the stream length ratio. This proportion may also be referred to as the stream length ratio [7,8,43]. The R_L values that are discovered across streams that are ranked in a different order within the basin demonstrate that there are variations in the topography and slope of the area.

$$L\_ur = L\_u/(L\_u + 1) \tag{2}$$

Where L_u defines length of the stream of specific order and is the ratio of stream length

Bifurcation Ratio (R_b)

The bifurcation ratio (Rb) in watersheds without geological distortions ranges from 3.0 to 5.0. In areas with steeply sloping rock layers and narrow valleys separated by ridges and ridge crests, a high value of Rb can be expected. The geometry of the basin plays a significant role in determining Rb, with elongated basins typically having higher Rb values.

The bifurcation ratio is calculated by dividing the total number of streams in one order by the total number of streams in the next order. It is an important parameter for estimating the topological features and runoff characteristics of a watershed. The bifurcation ratios can vary depending on the sequence due to the changing geometry of the watershed. However, in the presented stream network, the bifurcation ratios appear to be stable across all orders. The bifurcation ratio can be calculated using the following equation:

$$R\_b = N\_u/(N\_u + 1) \tag{3}$$

Where, N_u is the number of segments of stream of that order 'u' and R_b = bifurcation ratio.

Basin Length (L_b)

The longest measurement of a watershed that is parallel to its primary drainage channel is referred to as the basin length, abbreviated as L_b. The basin's length can be calculated in one direction, and the breadth can be calculated in a direction roughly parallel to the measuring length.

Basin Perimeter (B_p)

Table 6 shows the specifics of the Sikkim watershed, which has a circumference of 624.42 km and is divided into overall nine sub-watersheds which were categorized by major tributaries. The nine sub-watershed has the largest perimeter 412.74 km, while the nine sub-watershed has the smallest 99.06. The perimeter of the watershed has been calculated using the Arcmap perimeter geometry function [31].

Areal Aspect

The qualities of a watershed that exist in only two dimensions are referred to as the areal aspect of the basin. It is concerned with the entire region that, when arranged on a flat plane, contributes to the channel segment in the provided sequence across the land flow. It also takes into account all lower-order streams. This feature is made up of the following components: drainage density and texture, form factor, stream frequency, circularity ratio, elongation ratio, and length of overland flow.

Basin Area (A_u)

According to Padmaja Rao (1978), the accumulation of drainage in a basin leads to an increase in its total area over time. Initially, the basin may have a pear-shaped form, but as the cycle progresses, it tends to become longer. The shape of the basin is significant as it influences the characteristics of stream discharge. A longer, elongated basin generally exhibits a longer lag time, while a circular basin is more likely to experience a larger peak flow [43]. To quantify basin shapes, three dimensionless ratios are commonly used: the form factor, circularity ratio, and elongation ratio. In the case of the Teesta River catchment, which covers an area of 7733.80 km2, it stretches for a total length of 195 kilometers [6]. Larger catchments, like the Teesta River catchment, tend to have longer lag times as rainwater takes more time to reach the main channel due to the greater distance it has to travel compared to smaller basins [6].

Drainage density (D_d)

According to Horton [7,8], drainage density is an important indicator of the linear scale of landform features in stream-degraded terrain. It is defined as the total length of all orders of channels divided by the drainage area. The density of drainage lines is influenced by factors such as runoff, surface roughness, and climate in the study area. Increased rainfall leads to more runoff and the need for more drainage lines. However, areas with permeable subsurface and vegetation cover can reduce runoff by enhancing infiltration capacity. The drainage density in the study area was found to be 0.67 km/km2, indicating moderately permeable subsurface, significant plant cover, and relatively gentle relief [1].

To visualize the drainage density and other features, a GIS platform was used to create a drainage density map and a hillshade map, as shown in Figure 8(a) and (b)

$$D\_d = (\sum L\_u)/A\_u) \tag{4}$$

Where, L_u to length of the total stream for all orders in kms., A_u is the area of the basin and Dd is the Drain density.

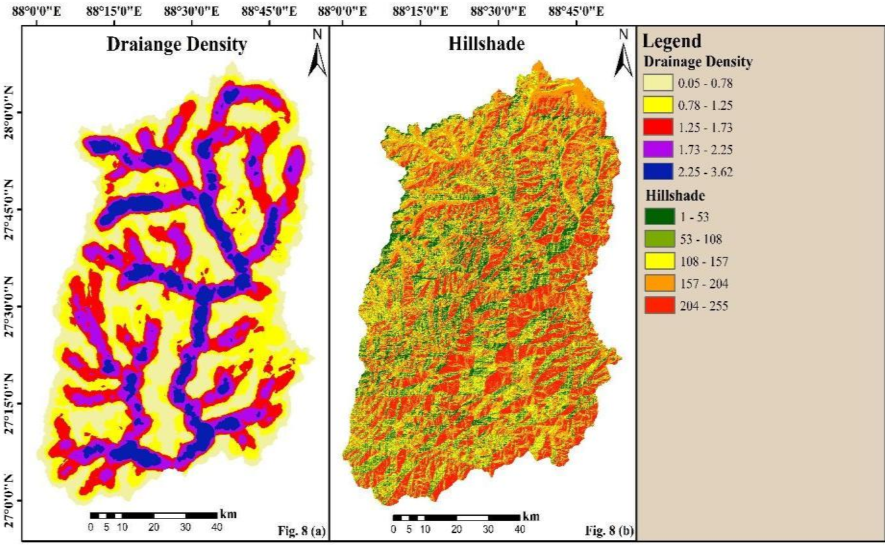

Figure 8. (a) Drainage Density Map (b)Hillchade Map

Drainage Intensity (D_i)

It can be defined as the ratio of stream frequency of the area to the drainage density of that area. It is considered that if any catchment has low drainage intensity then it would have a higher possibility of soil erosion [3]. Value of Di for the Teesta watershed is 0.83, due to high drainage intensity, stream flow increases which may give rise to conditions like floods, landslides etc. [42].

$$D\_i = F\_s * D\_d \qquad (5)$$

Where, Fs is stream frequency & Dd is drain density

Drainage texture (D_t)

The drainage texture changes according to a variety of different elements including various factors like infiltration capacity, lulc, climatic, geological and topographical conditions, etc. [39]. The formula for calculating drainage texture is as follows: drainage density (D_d) multiplied by stream frequency (F_s).

All of the factors play a significant role in determining drainage texture [1], which was defined by Smith (1950), as a measure of relative channel spacing in a fluvial-dissected environment. According to Smith, there are five distinct types of drainage texture. These include extremely coarse (2), coarse (2 to 4), moderate (4 to 6), fine (6 to 8) and very fine (> 8). [31,32]. Teesta River Basin comes under the fine drainage texture type with a texture value of 7.15.

$$D\_t = N\_u/P \qquad (6)$$

Where, N_u is the no. of segments of stream of that order, P s Perimeter of the basin in km. and 'D_t' is Drainage Texture.

Stream Frequency (F_s)

There is a strong association between drainage density and drainage frequency for all sub-catchments, and drainage frequency is a good indicator of the rise in stream flow in response to an increase in drain density [5,6]. The number of streams that flow through an area of a watershed has a one-to-one correlation with its drainage frequency or channel frequency [7,8]. This suggests that there is a strong association between the drain density of the sub-watershed. The higher the drainage frequency value, the greater the amount of runoff giving rise to excess soil erosion [5,6].

The number of stream segments of any order per unit of area is what we call stream frequency [7,8]. Here in the present work stream frequency for the watershed is 0.58 km^2.

$$F\_s = (\sum N\_u)/A\_u \tag{7}$$

Where, N_u number of streams for all orders, A_u is the area of the basin and F_s is stream frequency.

Circulatory Ratio (R_c)

It is calculated by comparing the area of the catchment (Au) to the area of the circle (Ac) that has the same perimeter (Pr) as the basin (Miller 1953). It is more impacted by the stream length, frequency, and gradient of streams of various orders as opposed to the slope characteristics and drainage pattern of the basins, which have less of an impact [5]. The ratio is 0.08 for the basin of the Teesta River.

$$R\_c \ = \ 12.57 * (AuA\_u/B\_p\ ^2) \tag{8}$$

Where, A_u and B_p are the area and perimeter of the watershed and R_c is the circulatory ratio.

Elongation Ratio (R_e)

According to Schumm's theory from 1956, the elongation ratio is the ratio of the diameter of a circle that is the same area as the drainage basin to the maximum length of the basin. This ratio is expressed as a ratio of diameter to length. The value of re has a tendency to shift between 0.13 and 0.13 in a diverse range of situations, the nature of which can be either climatic or geologic in origin. Values of Re that are close to one suggest locations that have little topographic relief, but values that fall within the range are typically associated with regions that have a significant amount of topographic relief and a steep ground slope [41]. When taken into account with Strahler's range, it would appear that the region in question possesses a substantial elevation disparity.

$$R\_e \ = \ 2/\ L\_b \ \ * \sqrt{(A\_u \ /\pi\ )} \tag{9}$$

Where L_b is basin length, A_u is area and R_e is the Elongation ratio

Form Factor (F_f)

As per Horton, 1945; Gregory & Walling 1973 theory, a watershed's flow intensity can be predicted with the help of form factor if the area being studied is well-defined. In addition to this, the index of F_f displays the inverse relationship with the square of the axial length as well as the direct association with peak discharge (Magesh et al, 2012, Julius & Jay 2018). The F_f of the Teesta watershed is equal to 0.42. The F_f values for the various parameters are given in Table 2.

$$F\_f = \ A\_u/L\_b\hat{}2 \tag{10}$$

Where A_u and L_b is area & length of watershed respectively and Ff is the form factor

Compactness coefficient (C_c)

It is the ratio between the circumference of the watershed and the perimeter of a circle that has the same area as the watershed (Potter, 1957, Withanage et al. 2014). It is depending on the slope of the basin but is unaffected by the size of the basin. Within the scope of this study, the value for the compactness coefficient was 0.011.

$$C\_c = 0.282 * B\_p \ / A\_u \tag{11}$$

Where, B_p, is basin perimeter, A_u is basin area and C_c is compactness coefficient

Infiltration Number (I_f)

To determine the infiltration number of a catchment or drainage basin, just multiply the drain density of a basin by the number of streams that run through it. This will give you the infiltration number. It is a parameter that offers some insight into the characteristics of the infiltration system that the basin possesses. If the result is higher, then it indicates that there is less absorption and that there is more runoff. The basin in question has lithology that is characterized by being hard and impermeable. According to this investigation, the number of infiltrations is 4. The formula for number 12 is provided below (Ansari et al. 2012).

$$I\_f = D\_t * F\_s \tag{12}$$

Where $\mathbf{D_t}$ is the Drainage Texture, $\mathbf{F_s}$ is the Stream frequency

Length of overland flow (L_o)

The length of the overland flow, shown by the symbol Lg, refers to the distance that water travels across land prior to being divided up into its separate stream courses. Lg is a measure of channel spacing and degree of dissection, and it is approximately half the reciprocal of the drainage density. It is the mean horizontal length of the flow channel in a first-order basin from the split to the stream (Thomos et al. 2010). The value of the Lg parameter for the Teesta basin, as determined by the morphometric study, is 2.99. It can be deduced from the high Lg value that the precipitation in question travelled a considerable distance before becoming condensed in stream channels. On the other hand, low Lg levels suggest that precipitation will swiftly make its way into the stream. This is particularly relevant with regard to the upper watershed. (Chitra et al. 2011, Ket-ord et al. 2013, Magesh et al. 2013).

$$L\_o = 1 \, / \, D\_d * 0.5 \tag{13}$$

Where D_d is drain density and L_o is Length of overland flow

Relief Aspect

In addition to linear and aerial characteristics, the altitude of the basin is also a significant aspect for consideration. Relief describes this extra dimension. It is crucial in establishing the drainage systems of a basin, including the efficacy of erosion, transport, and deposition as well as the overall energy of a river, among other things (Karim 2021). Some parameters like relief ratio, channel gradient and ruggedness number that can be used to express relief are as follows -

Relief Ratio (R_h)

The relief ratio, denoted as Rh, represents the relationship between the maximum elevation and the horizontal distance along the longest dimension of a basin perpendicular to the major drainage line (Schumm 1956). As the area and size of a sub-basin increase within a drainage basin, the Rh value generally decreases due to its proportional relationship with the sub-basin area (Gottschalk 1964, Ansari et al. 2012). The relief of a drainage basin reflects the overall steepness of the watershed and serves as an indicator of the erosion intensity on the basin slope. The R-values for each sub-basin are provided in the table, indicating a gradual slope and moderate relief (Table, Schumm 1956). The relief ratio (Rh) quantifies the relationship between maximum elevation and horizontal distance in a basin. Larger sub-basins within a drainage basin tend to have lower Rh values. The relief ratio is an important indicator of the steepness and erosion intensity within a watershed.

$$R\_h \;=\; H \,/\, L\_b \tag{14}$$

Where L_b and H are the basin relief and length

Channel Gradient (R_g)

Refers to an overall decline in elevation that occurs from the source of each drainage basin's trunk channels all the way to the mouth of those channels. It is a measurement that has no dimensions. In most cases, the upper course of the juvenile stage of a river is characterized by a channel gradient that is relatively steep, whereas the southern course of the tributaries/river typically has a drainage gradient that is relatively shallow. The steeper V-curved ravine is joined with higher channel slopes, which are represented by Rg values that are higher. The gradient of a channel is actually the result of a dynamic interplay between the power of the stream and the lithological features of the basin. It can also be stated as:

$$R\_g \;=\; E\_s / \, E\_m \, L\_b \tag{15}$$

Where R_g is the ratio of channel gradient, E_s defines the elevation value at the source, and E_m is the elevation value at the inlet.

Ruggedness Number (R)

The roughness number, according to Strahler in 1968 can be defined as the outcome of the catchment relief and D_d [43]. This figure combines the slope's length and steepness. It serves as a gauge for surface roughness. The Son basin's Rn value was determined to be 3.10. Because of the relief and drainage density, a watershed with a low ruggedness value has a complicated structure and is less prone to lose soil (43). The variation in Rn values demonstrates how the watersheds' slope and relief vary.

$$R\_n \;=\; H \,*\, D\_d \tag{16}$$

Where, H is basin relief, D_d is the density of drains and R_n is Ruggedness No.

Table 6. Values of morphometric parameters considered for the study

Linear Aspect		
Total number of Stream(N_u)	Calculated Using GIS Tool	4464.00
Stream Order (S_o)	Calculated Using GIS Tool	6

Stream Length(L_u)	Calculated Using GIS Tool	861670.99 km
Mean Stream length(L_{sm})	Calculated Using GIS Tool	1096.76
Basin Perimeter(B_p)	Calculated Using GIS Tool	624.42 km
Basin Length(L_b)	Longest dimension of basin in direction of main stream	135.66km
Ratio of Stream length(L_{ur})	$L_{ur} = L_u/(L_u + 1)$	2
Bifurcation Ratio(R_b)	$R_b = N_u/(N_u + 1)$	1.0 - 2.15
Areal Aspect		
Basin Area(A_u)	Total area Covered by catchment	7733.80 km^2
Stream length(L_u)	Total length	5170.02
Drain Density(D_d)	$D_d = (\sum L_u)/A_u)$	0.67km/km^2
Stream Frequency(F_s)	$F_s = (\sum N_u)/A_u)$	0.58 km^2
Form Factor (F_f)	$F_f = A_u/L_b^2$	0.42
Circulatory Ratio (R_c)	$R_c = 12.57 * (AuA_u/{B_p}^2)$	0.08
Elongation Ration (R_e)	$R_e = 2/ L_b * \surd(A_u /\pi)$	0.134
Infiltration Number (I_f)	$I_f = D_t * F_s$	4.13
Compactness coefficient (C_c)	$C_c = 0.282 * B_p / A_u$	0.01
Drainage Texture (D_t)	$D_t = N_u/P$	7.15 unit/km
Relief Aspect		
Drainage intensity (D_i)	$D_i = F_s * D_d$	0.86
Relief Ratio (R_h)	$R_h = H / L_b$	60.33
Ruggedness Number(R_n)	$R_n = H * D_d$	0.40
Length of Overload Flow(L_o)	$L_o = 1 / D_d * 0.5$	2.99 km
Channel Gradient (R_g)	$R_g = E_s/ E_m L_b$	0.0016

CONCLUSION

Quantitative morphometric analysis using DEMs enables the study of linear, areal, and relief aspects, providing insights into the physical and meteorological characteristics of a basin. In the case of the Teesta watershed, the values of Rb, Re, Dd, Fs, Lo, Rg, and Hc (as shown in Table 6) indicate a basin located in a region with steep slopes and rugged topography. The catchment area is ecologically significant, with diverse plant species, forests, glaciers, glacial lakes, and various mountainous rock structures and soil types. The drainage system is influenced by the geography and geology of the area, featuring multiple stages, including a stable mature phase at middle and lower elevations and an unstable youthful stage. The quantitative morphometric analysis utilizes GIS data to examine river basin characteristics. The Teesta watershed has a dense dendritic drainage network up to the sixth order. The high Rb values suggest that the basin will experience a less intense peak flow over an extended period, reducing the likelihood of floods. The low Dd value indicates substantial vegetation cover and permeable subsoil in the catchment. Similarly, the low Rc value suggests porous sub-soil conditions and low runoff discharge rate. The elongated shape of the catchment, reflected in the low Re and Rf values, contributes to a lower and longer-lasting peak. The lower Fs and Id values indicate slower runoff clearance from the catchment.

However, the catchment's relatively high Re, If, and Fs values, indicating a steeper and shorter flow peak, suggest limited water absorption into the soil, reduced groundwater recharge, and increased flood risk due to the steep slope and moderately permeable subsoil. While elongated catchments with high Rb values may offer some advantages in managing future floods, it is crucial to implement long-term management strategies and protective land use/cover measures to mitigate flood risks, especially with increasing population and potential changes in precipitation patterns. In summary, quantitative morphometric analysis provides valuable insights into basin characteristics and flood risk potential. While the Teesta watershed exhibits certain favourable attributes, proper precautions and long-term management strategies are essential to address potential floods caused by severe rainfall and changing land use patterns.

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