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Research article

Morphometric analysis of Halda River basin, Bangladesh, using GIS and remote sensing techniques

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ABSTRACT

GIS and remote sensing techniques were effectively used to analyse the morphometric parameters including linear, geometric, basin texture (aerial) and relief aspects of the Halda River Basin, Bangladesh. Along with measuring the morphometric parameters using predetermined formulas, advanced geo-computing tools of spatial analysis, cartography, math, geoprocessing and geometric analysis were employed to carry out the spatial distribution of selected parameters, especially aerial parameters. The linear aspect indicates the basin is six-order and oval-shaped. The bifurcation ratio (4.03) and relevant parameters indicate the moderate effect of geology and structural control is evident. The mean stream length (1.27) and Rho value (ranges between 0.11 and 0.20) indicate high runoff in steep areas and hydrologic storage capacity in flat areas. The stream frequency (0.83), drainage density (1.22), drainage intensity (0.68), infiltration ratio (1.02), length of the overland flow (0.41), and constant of channel maintenance (0.82) indicate the presence of moderate hard rock, less structural disturbances and moderate to high surface runoff in the basin. Basin relief (489 m), relative relief (2.02), ruggedness number (400), Melton's ruggedness number (12.43), and mean slope (9.33%) indicate the potential of high erosion and material transfer. The spatial distribution of selected aerial aspects significantly correlated to elevation and slope. The hierarchical pattern and spatial distribution of the morphometric parameters indicate areas with high slopes and lower-order streams have a high potential to be affected by soil erosion, landslides and flash floods, elsewhere, the areas with low slopes are prone to short-duration riverine floods. The research findings will help policymakers for integrated river basin management, agricultural development, and water management. In addition, researchers of morphohydrological, geological and climatological research will be beneficiary.

1. Introduction

Morphometric analysis of drainage basin indicates the mathematical and geometrical analysis of land surface characteristics such as configuration, shape and dimension [1,2]. Morphometric analysis is successfully carried out by measuring the linear, relief, aerial, and geometric properties of the drainage basin [3–10].

Morphometry of drainage basin provides insightful information and characteristics of geological, morphological [11–17], geomorphological [14,18–20], hydrological process [20] and the complex interrelationship of the process [20]. Physical characteristics of soil, underlying geological and structural control, landform evolution and related erosional processes can be well understood

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through morphometric analysis [3,13,14,18,19,21,22]. It provides information about the slope and relief characteristics, rock hardness or softness of the drainage basin [14,18,22]. The morphometric parameters and their complex interrelationship provide information about flooding potentiality, sediment movement, erosion capability, surface runoff, and infiltration of drainage basin [23–25]. As a result, morphometric analysis of drainage basin has significant application in water resource management [26], agricultural management [27], river basin management and planning [28,29], land use planning [30,31], natural resource conservation [32], river ecology and ecosystem study [33,34], flood and flash flood risk assessment [35–38], climate change studies etc. [39]. According to topography and climate, morphometric parameters and their interrelationship vary from basin to basin. Thus, the dominating variables of a specific river basin or watershed can be understood by comprehending the interrelationship of the morphometric parameters [4,40].

Recent development of GIS and remote sensing technology facilitates cost-effective, fast and precise analysis of drainage basins by providing freely accessible DEM (Digital Elevation Model) data which is very efficient in morphometric analysis [4]. Two widely used DEMs in morphometric analysis are Shuttle Radar Topographic Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) [41–43] whereas, SRTM-DEM has been widely using due to its higher spatial accuracy over ASTER-GDEM [44,45] at basin scale [46]. The hydrological analysis tool of GIS software can process DEMs to extract basin area and

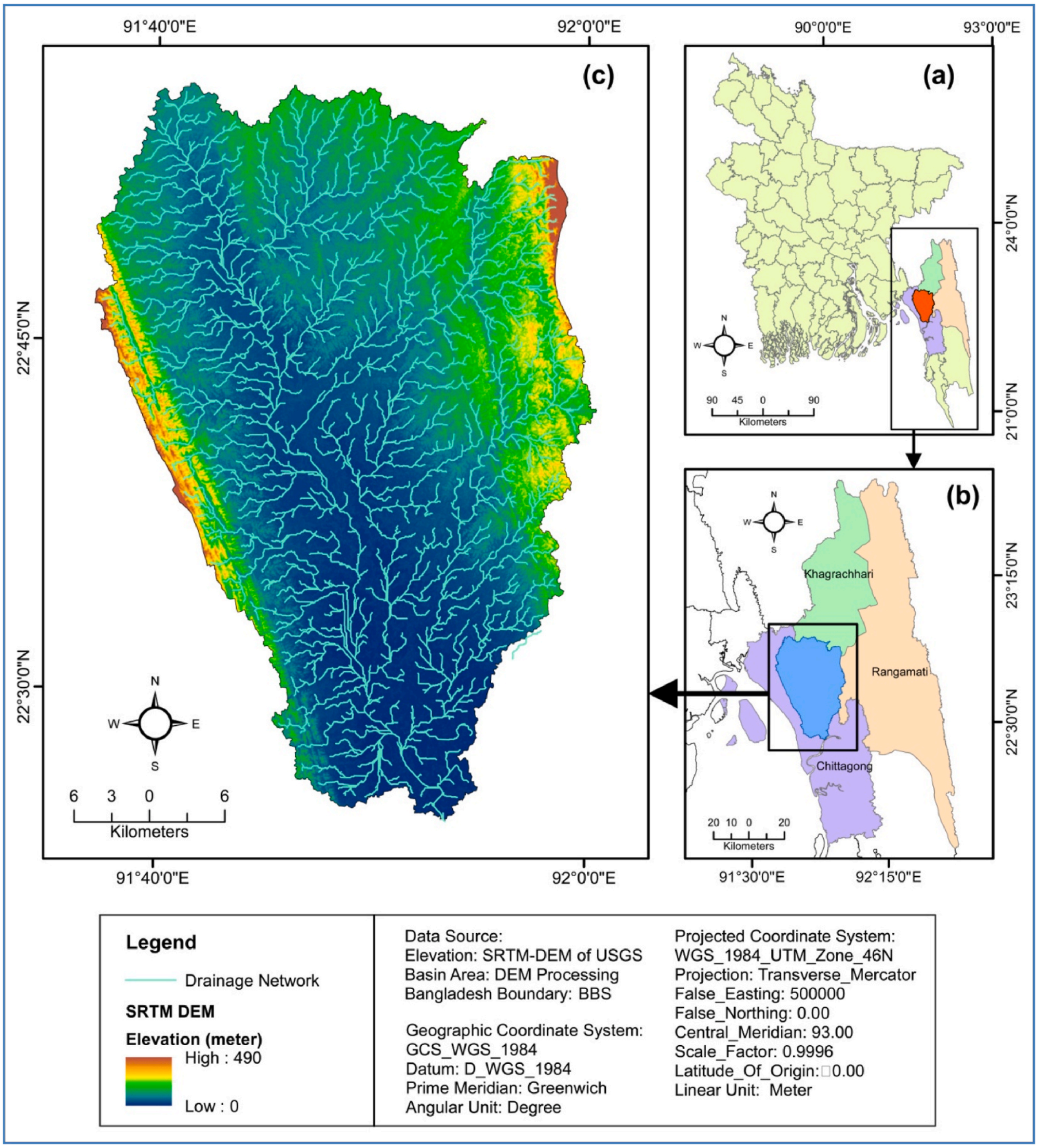

Fig. 1. Location of Halda basin and stream order of Halda River. a) Location of Halda basin in Bangladesh and b) in Chattogram District and c) basin and stream network of Halda basin.

stream network and its pattern [7,47]. Besides, through the geospatial analysis the mathematical and geometrical values of the extracted parameters can be measured [4,5,8,48–50]. Basin area, basin length, stream network and order, length of streams and elevation of different locations in the drainage basin are the basic parameters measured through geospatial and hydrological analysis in the GIS environment [5,51–53]. Morphometric analysis of drainage basins has been conducted extensively by extracting morphometric parameters from SRTM-DEM using GIS software for different environmental, geologic, climatic and hydrologic settings across the world [4–10,19,54–59]. However, the specific application of morphometric parameters measures the relationship with other factors or events such as neotectonic or geologic evolution, hydrological flow assessment, hazard investigation etc. [4,60–63], which largely limits the in-depth understanding of geomorphometric, hydrologic and environmental characteristics of the drainage basin [58,64]. Although understanding the morphometric characteristics of drainage basins cut significant importance, there is a limited study that has been conducted in Bangladesh [10,65,66].

For Halda Basin, considering its significance, some research was conducted on fish diversity [67], water flow dynamics and environmental flow requirements [68], land cover change [69,70], economic value of river [71], climate change impact [72], engineering activities etc. [70,73]. However, no research was conducted on the morphometric analysis of this important river basin. In such circumstances, studying the morphometric properties of the Halda basin using GIS and remote sensing technology cuts significant importance to understand its geomorphometric characteristics of this important river basin. The current research aims to measure the morphometric parameters of the Halda River Basin using remote sensing and GIS technology.

The findings of the research will also be helpful for policymakers for integrated river basin management, natural resource management and planning, sustainable agricultural planning, groundwater and surface water management and planning etc. and for future research on detailed morphohydrological, geological and climatological investigation etc. in the study area.

2. Materials and methods

2.1. Study area

The Halda River flows across Halda Valley, located in the southeastern hilly regions of Bangladesh (Fig. 1a-c). The SRTM-DEM elevation is shown in Fig. 1 a and river basin was extracted by DEM analysis. The total length of the river is 81 km and around 34 small tributaries are connected with the main channel. 29 km of the river is navigable by large boats across the year and another 16–24 km is navigable by small boats [68,74]. The Halda River has both ecological and commercial importance to Bangladesh. This tidal river is the only natural breeding ground for carp fish where eggs are naturally fertilized [71]. In addition, it is the only freshwater source of Chattogram city dwellers providing drinking water [69]. The topsoil of the Halda basin ranges from loam to clay and the distribution is deep and flat. There is rapid soil permeability and reduced moisture capacity of soil in the Halda basin. Naturally, the basin is

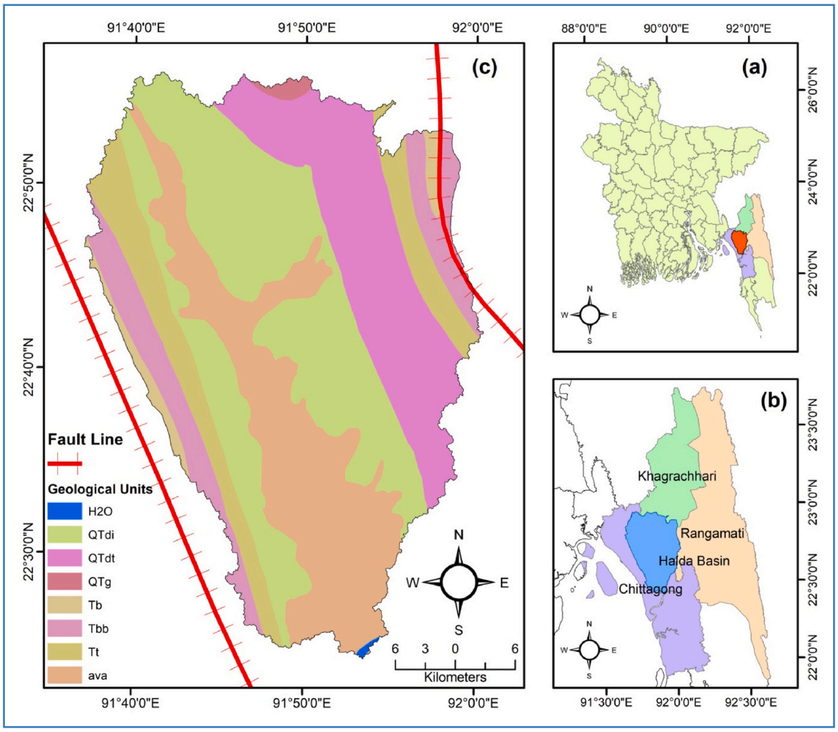

Fig. 2. Geology of the study area. a) Location of Halda basin in Bangladesh and b) in Chattogram District and c) Geological units of Halda basin.

dominated by tropical evergreen forests and deciduous forests. Moreover, shrubs are a common natural cover [72]. The topmost land use of the Halda basin is agriculture [69,72,75]. Though the river is very important for Bangladesh, the river is facing several anthropogenic pressures such as industrial contamination, cutting and filling of existing oxbow lakes, expansion of urbanization, sand collection from the river, and extensive agricultural activities [68,69,75]. Moreover, the impact of climate change also affects the hydrological properties of the Halda Basin leading to depletion of all types of natural resources [70].

The Halda is one of the few rivers, from source to end, located in the boundary of Bangladesh. The river originates from the up-stream of the Halda basin in the west and diminished in the Karnafuli River in the east [75]. The river originated from the Halda Chara fountain located in the Ramgarh Upazila of Khagrachhari District. The river flows through Fatikchari, Hathhazari and Raozan Upazilas of Chattogram district and is connected with many tributaries originating in the high hills located on both sides of the basin [70,72,75,76]. Halda is one of the major tributaries of Karnafuli and is considered the third important river of Chattogram followed by Karnafuli and Sangu [77]. The river basin is bounded by two anticlines of Sitakunda Hill ranges on the west and south-west side and Rangamati Hill Ranges on the north and north east side [78]. In the north it is bounded by parts of Lusai Hills and in the south it meets with the Karnafuli River near Kalurghat Bridge before meeting the Bay of Bengal [79]. The Halda valley can be considered as the low elevated plateau of Sitakunda and Rangamati hill ranges [78]. The Halda basin is located on the leeward side of the Sitakunda hill ranges which dissects this basin from the direct influence of the Bay of Bengal [78,80]. On the other hand, the basin is located on the windward side of the Rangamati hill range altitude of which is higher than the Sitakunda hill ranges [78]. These have provided the Halda River with a unique physiographic, topographic, and climatic condition [79].

The geological evolution of the hills dates back to the Miocene period when the collision between the Indian and Eurasian plates occurred and the Chattogram hill tracts uplifted. Fig. 2 c shows the geological setting of the study area and Fig. 2a and 2b shows the location of the Halda basin area in Bangladesh and Chattogram District, respectively. Tertiary and Quaternary sediments are the most dominant geological soil composition of the study area where a number of synclines and anticlines developed over these hill slopes. Easily-weatherable feldspar and unconsolidated sedimentary rocks are the dominant surface strata of this region [81]. The large portion of the surface soils is covered by moderately developed soils (Cambisols) and groundwater-affected soils (Gelysols) [82]. Climatologically the study area belongs to the tropical monsoon climate [83].

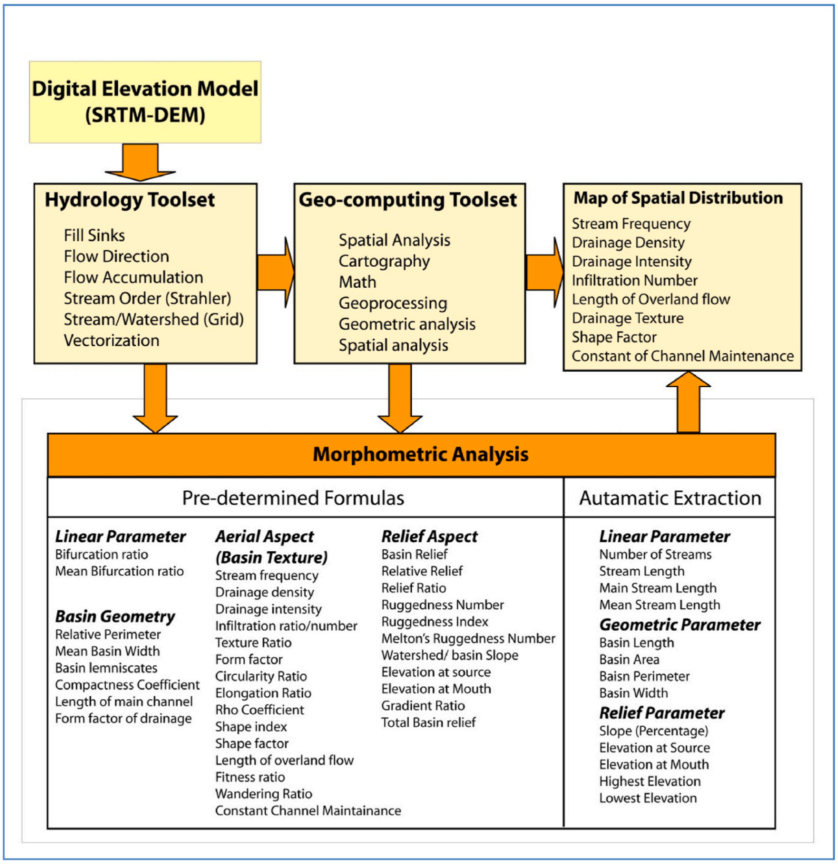

Fig. 3. Methodological flow of the research.

2.2. Data acquisition and morphometric analysis

30-m SRTM (Shuttle Radar Topographic Mission) DEM (Digital Elevation Model) was acquired directly from the USGS Earth Explorer website (link: https://earthexplorer.usgs.gov/). The vertical accuracy of SRTM-DEM is relatively higher than ASTER GDEM [44,45] and this systematic error restricts ASTER GDEM for immediate use [44]. Moreover, SRTM DEM provides more advantages in topographic data delineation and is more accurate compared to ASTER GDEM [46]. Although AOLS PALSAR DEM open source and has finer resolution (12.5) than SRTM DEM, however, some research showed lower of horizontal and vertical accuracy of ALOS PALSAR compared to SRTM DEM [84]. Moreover, SRTM DEM is robust in terrain characteristics displaying in basin scale [85,86].

The methodological flow of the research is shown in Fig. 3. The watershed boundary of Halda Basin and the stream network were

Table 1
Morphometric parameters calculated for Halda River basin.

S/N	Parameter	Formula	References
Drainage Network (linear)			
1	Stream order (U)	Hierarchial rank	Strahler (1964)
2	Stream length (Lu) (km)	Length of the stream	Horton (1945)
3	Mean stream length (Lsm)	$Lsm = \frac{Lu}{Nu}$	Strahler (1964)
3	Stream Length Ratio (Ri)	$Ri = Lu/Lu - 1$	Horton (1945)
5	Bifurcation ratio (Rb)	$Rb = \frac{Nu}{Nu - 1}$	Schumm (1956)
6	Mean Bifurcation ratio (Rbm)	Rbm = Mean of all Bifurcation ratios	Schumm (1956)
Basin Geometry			
7	Basin Area (A) km^2	GIS analysis	
8	Basin Perimeter (P) km	$= 2(length + width)\ km$	Schumm (1956)
9	Relative Perimeter(Pr)	Pr = A/P	Schumm (1956)
10	Basin Length (Lb) km	GIS analysis	
11	Length Area Relation (Lar)	$Lar = 1.4 \times A^{0.6}$	Hack (1957)
12	Mean Basin Width (Wb) km	$Wb = A/Lb$	Horton (1932)
13	Basin lemniscates (K)	$K = LbA^2/A$	Chorley (1957)
14	Compactness Coefficient(Cc)	$Cc = 0.2821 * P/A^{0.5}$	Chorley et al. (1957)
15	Length of main channel (Lc)	GIS analysis	
16	Form factor of drainage (Ff)	$Ff = A/Lb^2$	Horton (1932)
Basin texture analysis (Aerial Aspect)			
17	Stream frequency (Fs)	$Fs = \frac{Nu}{A}$	Horton (1932)
18	Drainage density (Dd)	$Dd = \frac{Lu}{A}$	Horton (1932)
19	Drainage intensity (Di)	$Di = \frac{Fs}{Dd}$	Faniran (1968)
20	Infiltration ratio/number(If)	$If = Fs * Dd$	Faniran (1968)
21	Texture Ratio (Tr)	Tr = N/P (N = all streams)	Horton (1945)
22	Form factor (Rfb)	$Rfb = A/Lb^2$	Horton (1932)
23	Circularity Ratio (Rc)	$Rc = 4\pi A/P^2$	Miller (1953)
24	Elongation Ratio (Re)	$Re = 2\sqrt{\left(\frac{A}{\pi}\right)}/Lb$	Schumm (1956)
25	Rho Coefficient (Rho)	$Rho = Ri/Rb$	Horton (1945)
26	Shape index (Sw)	$Sw = 1/Fs$	Horton (1932)
27	Shape factor (Sf)	$Sf = Lb^2/A$	Horton (1932)
28	Length of overland flow (Lof) km	$Lof = 1/2Dd$	Horton (1945)
29	Fitness ratio (Rf)	$Rf = Lc/P$	Melton (1957)
30	Wandering Ratio (Rw)	$Rw = Lc/Lb$	Smart & Surkan (1967)
31	Constant Channel Maintenance (CCM)	$C = 1/Dd$	Horton (1945)
Relief Characteristics			
32	Maximum Elevation (Ma) m	GIS analysis	
33	Minimum Elevation (Mi) m	GIS analysis	
34	Basin Relief (Bh)	Bh = Ma - Mi	Schumm (1956)
35	Relative Relief (Rr)	$Rr = B_h/P$	Horton (1945)
36	Relief Ratio (Rh)	$R_h = B_h/Lb$	Schumm (1956 and 1963)
37	Ruggedness Number (Rn)	$Rn = B_h * Dd$	Strahler (1958)
38	Ruggedness Index (Ri)	$Ri = Dd * \left(\frac{Rr}{1000}\right)$	Schumm (1956)
39	Melton's Ruggedness Number (Mrn)	$Mm = (Ma - Mi)/A^{0.5}$	Melton (1965)
40	Watershed/basin Slope (Sb)	$Sb = H/Lb$	Miller (1953)
41	Elevation at source (Es)	GIS analysis/DEM	
42	Elevation at Mouth (Em)	GIS analysis/DEM	
43	Gradient Ratio(Rg)	Rg = (Es-Em)/Lb	Sreedevi et al. (2005)
44	Total Basin relief (H) m	H = Ma-Em	Strahler (1952)
45	Mean slope (%)	GIS analysis	
46	Maximum slope (%)	GIS analysis	

automatically extracted from SRTM DEM using Hydrology tools of ArcMap 10.5 software. The morphometric parameters of linear, geometric, basin texture (aerial), relief characteristics are processed using spatial analysis tools and calculated by predetermined mathematical formulas (Table 1).

Linear morphometric parameters describe the linear dimensions and characteristics of features related to linear landforms especially river networks in the natural landscape [1–3,11–18]. In the current research Linear parameters included measure for the Halda basin are Stream order (U), Stream length (Lu) (km), Mean stream length (Lsm), Stream Length Ratio (Ri), Bifurcation ratio (Rb), and Mean Bifurcation ratio (Rbm).

Geometric parameters measure the shape and form of landforms and drainage features by measuring and encompassing the length,

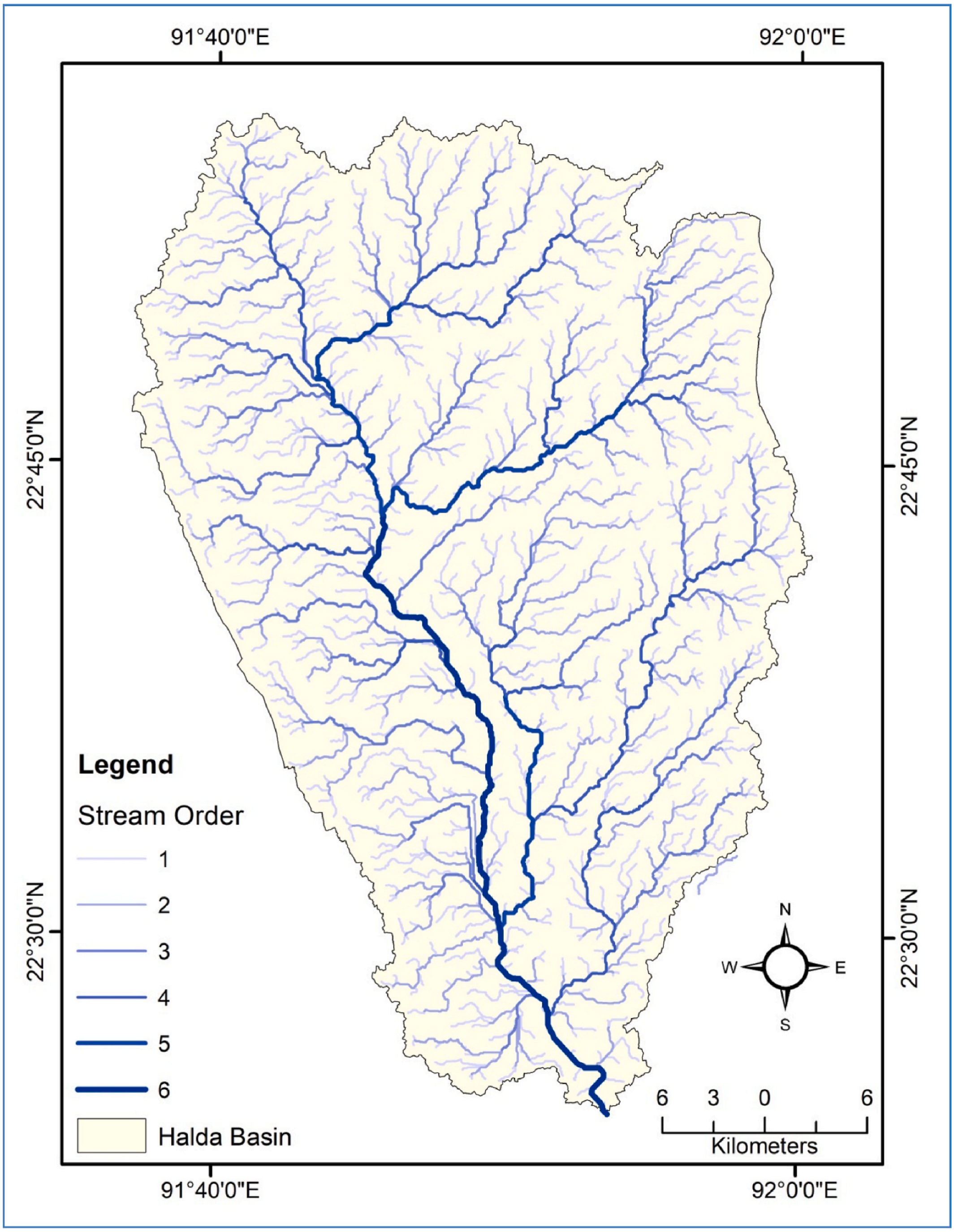

Fig. 4. Stream order of Halda Basin.

width, area and perimeter of the basin outline [1–3,11–18]. Basin Geometry parameters measured in the current research are Basin Area (A), Basin Perimeter (P), Relative Perimeter(Pr), Basin Length (Lb), Length Area Relation (Lar), Mean Basin Width (Wb), Basin lemniscates (K), Compactness Coefficient(Cc), Length of the main channel (Lc), and Form factor of drainage (Ff).

The Basin Texture (Aerial) aspect focuses on the spatial arrangement of different features specifically relevant to streams into the basin boundary [1–3,11–18]. Basin Texture (Aerial) parameters include Stream frequency (Fs), Drainage density (Dd), Drainage intensity (Di), Infiltration ratio/number(If), Texture Ratio (Tr), Form factor (Rfb), Circularity Ratio (Rc), Elongation Ratio (Re), Rho Coefficient (Rho), Shape index (Sw), Shape factor (Sf), Length of overland flow (Lof), Fitness ratio (Rf), Wandering Ratio (Rw), and Constant Channel Maintenance (CCM).

Basin relief characteristics describe the vertical dimension and variation of elevation, terrain, topographic features and landforms in the basin area [1–3,11–18]. Basin relief characteristics measured are Maximum Elevation (Ma), Minimum Elevation (Mi), Basin Relief (Bh), Relative Relief (Rr), Relief Ratio (Rh), Ruggedness Number (Rn), Ruggedness Index (Ri), Melton's Ruggedness Number (Mrn), Watershed/basin Slope (Sb), Elevation at source (Es), Elevation at Mouth (Em), Gradient Ratio(Rg), Total Basin relief (H), Mean slope (%), and Maximum slope (%).

The spatial distribution of eight important aerial aspects namely a) Stream Frequency, b) Drainage Density, c) Drainage Intensity, d) Infiltration Number, e) Length of Overland flow, f) Drainage Texture, g) Shape Factor, and h) Constant of Channel Maintenance are also measured using geoprocessing tool of ArcMap 10.5 software. A 1 km^2 grid was prepared using the grid square method covering the study area using GIS software [87,88]. The grid was then used to automatically extract the corresponding information of the stream network using geo-processing tools. The correlation between the spatial distribution of the aerial aspects and Elevation and Slope was measured using Pearson's correlation in CRAN-R programming software [89].

The geo-computing tools (i.e. raster calculator of spatial analyst tool) were used to further analysis of the parameters in the GIS environment following the predetermined equations of Table 1. Basin length and Basin width were measured using the geometric analysis tool of ArcMap 10.5 software.

3. Result and discussion

3.1. Drainage pattern

According to the form and texture of the streams, the drainage pattern of the study area is dendritic where the tributaries are joined to the main stream at an acute angle (Fig. 4). This is the most common drainage pattern which resembles the twigs of the tree [59, 90–92]. Subsurface geology, surface structure, slope, local topography, and terrain condition affects the formation and shape of drainage pattern in the watershed [90,91].

3.2. Linear aspect

One dimensional characteristics of the drainage basin are represented by linear parameter which includes the linear features of the drainage basin. The result of the linear features of the drainage basin analysed in this research is shown in Table 2.

3.2.1. Stream order (U)

The first and significant step in basin morphometric analysis is stream ordering. The Stream Order of the current research is identified using Strahler's (1952) [13] ordering scheme and the Halda basin is classified as the six-order basin. The presence of a large amount of stream segments indicates the basin is largely dominated by erosional processes [54].

The total number of streams in the Halda basin is 1287. The basin is classified as sixth order. Streams belonging to the first, second, third, fourth, fifth and sixth orders are 991, 222, 55, 15, 3 and 1, respectively. The presence of higher amounts of lower-order streams in a river basin generates more water flow [19]. The large amount of lower-order streams in the Halda basin indicates its potential to be affected by flash floods during excessive rainfall [61,93]. The lower-order streams are more dominated in the hilly areas in the basin (Fig. 4) which indicates the potential of landslides due to the erosional process triggered by the lower-order streams.

The number is inversely correlated with stream order in a drainage basin [12]. It is an indication that with the increment stream order, stream frequency tends to decrease. Fig. 5 a illustrates the correlation between stream number and stream order in the Halda basin.

Table 2
Linear parameters of Halda basin.

Stream Order	Stream number	Bifurcation Ratio	Stream Length (Km)	Mean stream length (km)	Cumulative stream length (km)	Stream Length Ratio	Rho
1	991	4.46	934.05	0.94	0.94	–	–
2	222	4.04	483.55	2.18	3.12	0.52	0.13
3	55	3.67	244.52	4.45	6.62	0.51	0.13
4	15	5	128.77	8.58	13.03	0.53	0.13
5	3	3	57.07	19.02	27.61	0.44	0.11
6	1	–	45.32	45.32	64.34	0.79	0.20

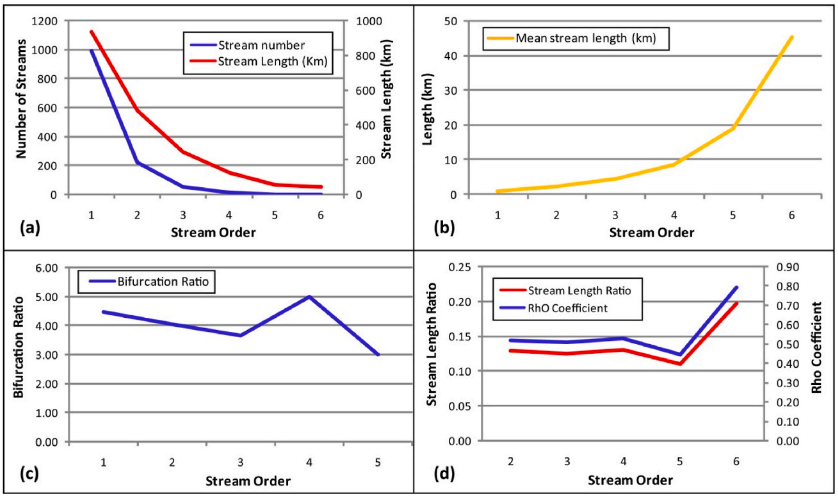

Fig. 5. Interrelationship between stream order and a) stream number and stream length, b) mean stream length, c) bifurcation ratio and d) stream length ratio and Rho coefficient.

3.2.2. Stream length (Lu)

The total stream length of the Halda basin is 1893.28 km. The sum of the length of streams in a given order is the total stream length of that order [12] and the sum of the lengths of all the streams is the total stream length of the basin. Less pervious bedrock produces huge numbers of streams with short lengths and porous bedrock produces a low amount of streams with relatively longer lengths. Few streams with longer lengths are common in well-drained basins. Short channels are common in areas with steep slopes [58,94,95]. The steep slope in the high elevated areas in the Halda basin produces numerous streams of lower order with short length. Stream length decreases with increasing stream order (Fig. 5a) and the lower order streams typically have high stream length.

3.2.3. Mean stream length (Lsm)

Mean stream length is measured by dividing the entire length of all streams by the total number of streams in a basin [14]. Mean stream length has a significant correlation with size and other inherent characteristics of stream networks. The surface of the watershed also has an influence on mean stream length [14]. The low Lsm indicates higher runoff and high erosion in the basin area [94,96]. The Lsm of the basin ranges from 0.94 km to 45.32 (Table 2). The low Lsm occurs in areas of first-order streams. Mean stream length positively correlated with stream order and the higher order streams have higher mean stream length (Fig. 5b).

3.2.4. Stream length ratio (Ri)

Ri is calculated by dividing the mean stream length (Lsm) of an order by its lower order. The lower value of Ri was found for the 4th order stream (0.44) and the higher value was found for the 6th order stream (0.79) (Fig. 5 d and Table 2). According to Sreedevi et al. (2005) [97], erosional phase, surface runoff, characteristics of terrain features, and steepness of slope affect Ri. The Ri value of all orders in the Halda basin is very low indicating the domination of the erosional process. Ri value is positively related to stream order (Fig. 5d).

3.2.5. Bifurcation ratio (Rb) and mean bifurcation ratio (Rbm)

The bifurcation ratio is calculated by dividing the total number of streams in an order by the total number of streams in its succeeding order [14]. This dimensionless property reflects the branching patterns of the stream network in the drainage basin. The bifurcation ratio varies between 3.0 and 5.0 when geological structures have negligible impact on drainage basin [14,98]. In the Halda River basin mean bifurcation ratio is 4.03 indicating a minor impact of geological structures on the branching pattern of the streams [55,99]. The bifurcation ratio of individual orders varies between 3 and 5 (Fig. 5 c and Table 1). However, generally Rb values tend to be higher in the first and second-order streams indicating accelerated erosion in the corresponding areas [100]. Rb values of the Halda basin followed this principle, except for fourth-order streams. The fourth stream order has the highest bifurcation ratio followed by the first and second order. This indicates the location of the fourth-order streams is mostly affected by underlying geology followed by the areas of first and second-order [31,101]. Besides, areas of first-order streams are also affected by soil erosion due to the accelerated erosion power of the first-order streams [58,95]. Low Rb values are also responsible for producing higher peak flow during flooding whereas; extended but low peak flow produces high Rb values [102]. Areas of fourth-order streams also have a high chance of being affected by rapid flood events.

Rbm value also indicates the drainage basin pattern. A higher Rbm value is obtained for an elongated river basin which emerged under long-term structural control and relatively soft erodible rock formation [103]. A lower Rbm value was obtained for the circular basin whereas the Rbm value of current research infers Halda basin is an oval-shaped basin.

3.2.6. Rho Coefficient (Rho)

The Rho coefficient indicates the relationship between the physiography of the basin and the drainage density. Climatic, geologic and morphological conditions, land use patterns and other anthropogenic interventions affect Rho Coefficient. Rho coefficient has a relationship of the parameter with geomorphic development and drainage density which provides an indication of the storage potential of streams in the drainage basin [56,58,104]. The Rho value of the Halda River varies between 0.11 and 0.20 (Table 2 and Fig. 5d) indicating a high potential for hydrologic storage during excess rainfall and flood period. Areas with lower-order streams have a high potential for more hydrologic storage.

3.3. Basin geometry

Parameters representing the areal aspect of the Halda basin measured are tabulated in Table 3. The Halda basin covers an area of 1548.74 square kilometres and its perimeter is 241.71 km. The ratio between the perimeter and area of a basin is known as Relative Perimeter (Pr) [105], the value of which is 6.41 in the studied basin. The Basin Length and Mean Basin Width (Wb) measured for the Halda basin are 62.42 km and 24.41 km, respectively. Basin length is the linear distance from the source to the mouth of the basin [59]. The mean basin width is calculated by dividing the Basin area by the basin length [11]. The basin width measured by the spatial analysis tool is 38.39 which is the largest distance of the basin width [49,106]. The length-area relation value of the basin is 114.85 which is derived from a function measuring the relationship between the length of the stream and the area of the basin [107–109]. The length of the main channel calculated from the extracted stream is 78.85 km; whereas the previous study confirms it is 81 km [68,74]. The main stream indicates the largest flow path in the river basin extending from the source to the mouth [59,88,108]. Lemniscate's of the basin is measured following the equation of Chorley et al. (1957) [110] and the value of the basin is 2.52. The value of Lemnisctae's indicates higher inception occurs in the areas of lower stream order [10]. The ratio between basin length and width is 1.63. Lemnisctae's ratio, basin length and width indicate that the lower order streams with shorter distances carry the sign of circularity whereas the longer order streams produce the elongated nature of the drainage basin [10,53,111,112].

3.4. Aerial aspect

The whole area projected upon a plane, containing the stream network from lower to higher order generating overland flow is referred to Aerial aspect of the basin. The Aerial parameters of the Halda basin measured are tabulated in Table 4.

3.4.1. Stream frequency (Fs)

The number of streams per square kilometre is Stream Frequency. According to Horton (1945) [12], high stream frequency produces higher surface runoff and low water infiltration in the basin. In addition, high stream frequency is common in the areas with steep slopes, high relief and scattered vegetation. Moreover, stream frequency provides information about basin evolution as stream development is largely affected by surface rock structure, vegetation cover and rainfall amount [49,59,106,113]. The stream Frequency of the Halda basin is 0.83, indicating moderately hard rock covered by large vegetation. The spatial distribution of stream frequency shows the highest value in the study area ranging between 8.1 and 16.0 per square kilometre (Fig. 6a). Areas of high stream density consist of soft rocks and along these areas, groundwater availability will be high [114,115].

3.4.2. Drainage density (Dd)

Drainage density indicates the mean length of streams per unit of area in square kilometres. It illustrates the degree of stream development in the studied basin. It numerically appraises the capacity of surface runoff generation and landscape dissection in the basin [62,116,117]. According to Horton (1945) [12], it also reveals the water travel time because close proximity of the steam network produces high drainage density. Generally low vegetated areas produce high drainage density and have a high probability of flooding. In addition, high relief and hard rock (less pervious) produce high stream density [118]. In a humid climatic region, Langbein (1947) [119] stated that drainage density ranges from 0.5 to 2.09 square kilometres. In the Halda basin, drainage density is 1.22, indicating well-drained basin conditions in the subtropical humid climate region [120–124]. The spatial distribution of drainage density shows the highest drainage density in the study area ranging between 2.5 and 4.2 km per square kilometre (Fig. 6b). The discharge will be higher in these regions of the Halda Basin. Water travel time in these areas will be low, but high rainfall can cause flash floods [63,117,125,126]. The spatial distribution indicates the presence of the Halda basin in subtropical humid climate zones [122], which was difficult to infer from the overall basin value.

Table 3
Geometric parameters of Halda basin.

Parameter	value	Parameter	value
Area	1548.740	Mean Basin Width (km)	24.81
Perimeter	241.712	Lemniscate's	2.516
Relative parameter	6.407	Compactness coefficient	1.745
Basin Length	62.423	Length of main channel (km)	78.85
Length area relation	114.846	Basin Width	38.39

Table 4
Areal parameters of Halda basin.

Parameters	Value	Parameters	Value
Stream Frequency	0.831	Elongation ratio	5.619
Drainage Density	1.222	Shape Index	1.20
Drainage Intensity	0.68	Shape factor	2.52
Infiltration ratio/ number	1.02	Length of overland flow	0.41
Texture ratio	5.32	Fitness ratio	0.33
Form factor ratio	0.40	Constant of channel maintenance	0.818
Circulatory ratio	0.333	Wandering ratio	1.26
Elongation ratio	0.711		

3.4.3. *Drainage intensity (Di)*

According to Faniran (1968) [128], it is the ratio of Stream Frequency and drainage density. The drainage intensity of the Halda basin is 0.68 indicating comparatively high surface runoff, highly vulnerable to flash floods and soil erosion, but slightly vulnerable to riverine floods [128,129]. Moderate denudation process is active in the study area and the terrain affects the streams and erosional process [57,106,108,129,130]. The spatial distribution of drainage intensity shows the highest values in the study area above 3 per square kilometre (Fig. 6c). Drainage intensity varies spatially over the study area occurring either following the drainage line or along the areas with high elevation and steep slope.

3.4.4. *Infiltration ratio/number (If)*

The product of Stream Frequency and drainage density is the infiltration ratio (If) [127]. It is inversely correlated to infiltration capacity and positively correlated to surface runoff. The infiltration ratio of the Halda river is 1.02, indicating moderate runoff and moderate infiltration capacity, indicating the potential for moderate flooding [37,38]. The spatial distribution of the Infiltration ratio shows the highest values in the study area above 8 per square kilometre (Fig. 6d). The spatial distribution shows high values occur following the high density and longer lengths of streams. Moreover, relatively lower land with steep slope gradients contains low values of infiltration number. The areas that have values between 1 and 4 have a high chance of being affected by flash floods, soil erosion and landslides [62]. On the other hand, areas with high values have a higher chance of being affected by riverine floods. Moreover, there is a high chance of groundwater availability in areas with low infiltration ratio values.

3.4.5. *Length of overland flow (Lof)*

Like drainage density and stream frequency, the Length of overland flow is affected by underlying geological, structural control, rock hardness, relief, water permeability and infiltration, erosional capacity, climatic condition, and vegetation pattern [12,105]. The Length of the overland flow of the Halda basin is 0.41 indicating low to moderate surface runoff [51,95,131]. The spatial distribution of the Length of overland flow shows the highest value in the study area is above 0.8 in some areas (Fig. 6e). The areas having values above 0.6 which are located along steep slopes and highly elevated areas, will face very high overland flow during intensive rainfall; whereas, the values of Length of overland flow in relatively plain land are below 0.4 which will produce less overland flow [104,129]. According to Schumm (1956) [105] and Horton (1945) [12], areas of low values are not affected by structural control and geology; rather these areas have soft rock formation and low relief. Water permeability and infiltration are higher in these areas because, theoretically, water discharge will be lower in these areas.

3.4.6. *Texture ratio/Drainage Texture (Tr)*

It is the ratio of total stream segments and the basin perimeter [12]. It illustrates the relative spacing of streams per unit basin perimeter accounts for significant importance in geomorphology [12]. According to Smith (1950) [132], the Texture Ratio depends on the geomorphic development of the basin, underlying lithology, soil type, vegetation pattern, rainfall amount and basin relief. The texture ratio of the Halda basin is 5.32. Smith (1950) [132] stated that a texture ratio value between 4 and 6 indicates moderate texture of the basin. The spatial distribution of the Texture ratio shows the highest value in the study area ranging between 2.1 and 4 per square kilometre (Fig. 6f). The value indicates the low to moderate texture of the basin whereas the overall value indicates moderate texture [59,64].

3.4.7. *Form factor ratio (Rfb)*

Form factor ratio indicates the circularity of the basin and it is calculated by dividing the basin area by the square of the basin length. Higher form factor value indicates high surface runoff with a short duration [11,12,118]. According to Gopinath Girish et al. (2016) [118], a perfectly circular basin has a form factor value of 0.78. The form factor of the Halda basin is 0.4 indicating the basin is oval shaped (not perfectly elongated or circular) and its medium peak flows in medium time duration [133]. It can be affected by short-time flooding such as flash flooding during prolonged rainfall [59,130].

3.4.8. *Circularity ration (Rc)*

The circularity ratio of the basin is measured using the formula of Miller (1953) [134]. The circularity ratio of the Halda basin is 0.33. According to Miller (1953) [134], this value indicates there is a partial control of geologic material on stream development, the

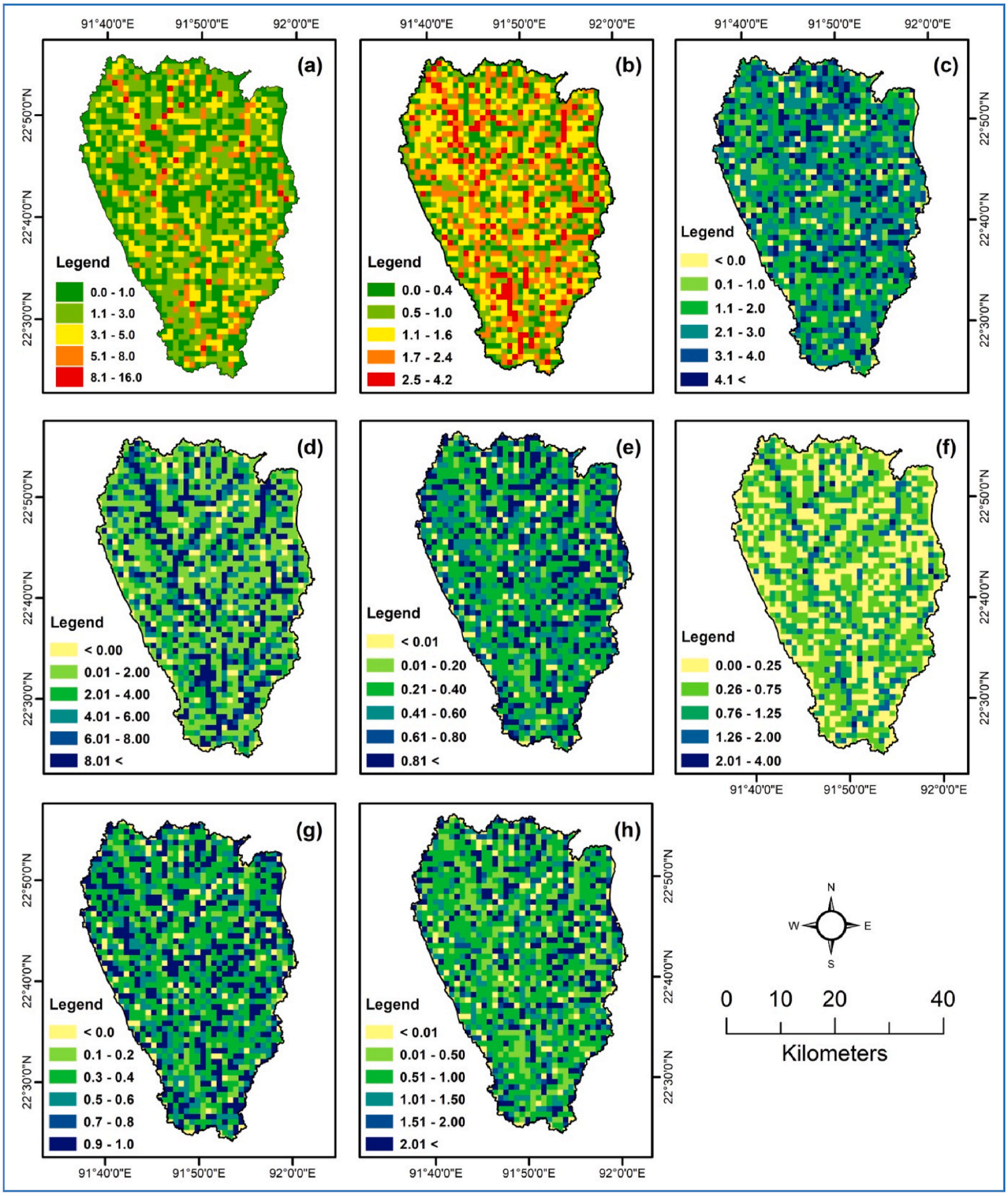

Fig. 6. Spatial distribution of a) Stream Frequency, b) Drainage Density, c) Drainage Intensity, d) Infiltration Number, e) Length of Overland flow, f) Drainage Texture, g) Shape Factor and h) Constant of Channel Maintenance.

basin is elongated to oval-shaped, and the basin is moderately permeable. In addition, Miller (1953) [134] stated that the high, medium and low value of the Circularity ratio represents the youth, middle and old stages of stream development, respectively.

3.4.9. Elongation ratio (Re)

Generally, the Elongation ratio varies between 0.6 and 1 in diverse geologic and climatic settings. According to Strahler (1964) [14], in areas with steep slopes and high relief Elongation ratio varies between 0.6 and 0.8. For a circular, oval and elongated basin value of the Elongation ratio will be > 0.9, 0.9–0.8 and < 0.7, respectively. Normally, a circular basin produces high surface runoff (discharge) and low infiltration [118,135]. The elongation ratio of the Halda basin is 0.71 indicating less elongation of the basin, high gradient and elevation, and moderate structural effect [58,106].

3.4.10. Shape index (Sw)

The Shape index of the basin is 1.20 (Table 4), calculated by following the equation in Table 1. The Shape index is reciprocal of the Form Factor and illustrates basin elongation. High shape index value obtained for elongated basins and long-duration flood discharge [136]. The Shape index value of the Halda basin indicates relatively low elongation (oval-shaped basin) and moderate flood discharge [64,137].

3.4.11. Shape factor (Sf)

The Shape Factor is the reciprocal of stream frequency indicates the spacing of streams in the river basin. A high value indicates high spacing in stream distribution [60,88]. The Shape Factor of the Halda basin is 2.5 indicating relatively high spacing of streams over the basin. The spatial distribution of the Shape factor (Fig. 6g) indicates low spacing is a common pattern in the areas with a high amount of lower-order streams. These areas also have steep slopes and high elevations. However, areas with longer lengths and higher-order streams showed relatively high spacing.

3.4.12. Fitness ratio (Rf) and Wandering ratio (Rw)

The fitness ratio indicates the topographic fitness of the basin and is measured by dividing the main channel length by the basin perimeter [15]. The Wandering ratio is calculated by dividing the main stream length by the basin length [138]. The fitness ratio (Rf) and Wandering ratio (Rw) of the Halda basin are 0.33 and 1.26, respectively.

3.4.13. Constant of channel maintenance (C)

Schumm (1956) [105] postulated the concept of Constant of Channel maintenance and it is the inverse value of drainage density. It indicates the required surface (square kilometre) to sustain and develop a stream of 1 km. The C is largely affected by geologic and climatic conditions; soil permeability, terrain conditions, discharge time and vegetation cover [139]. A higher C value indicates rocks are more permeable in the basin [140]. The C value of the Halda basin is 0.82 indicating less structural disturbances and moderate surface runoff. A low C value defines negatively affects the length of overland flow [5,10]. The spatial distribution of the Constant of channel maintenance shows the highest value in the study area above 2.1 per square kilometre (Fig. 6h). The lower values are distributed in the steep slopes and high elevated areas. These areas are less permeable and discharge time is low.

3.5. Relief aspect

The relief aspect depicts the three-dimensional features of the drainage basin such as volume, altitude etc. The relief aspect of the basin is significantly affected by underlying geology, structural control, drainage characteristics and the geomorphological condition of the basin. Plateau-plain front of the basin has relatively lower relief compared to the mountain-plain front. As a result mountain plain front is more prone to erosion which can be inferred from relief [141].

From the relief aspect, diverse characteristics of the geo-hydrological condition of the basin can be measured and inferred. The relief is the basin is largely related to elevation and its distributional pattern over the basin. The maximum and minimum elevations of the study area measured are 490 m and 1 m, respectively (Table 5).

3.5.1. Basin relief (Bh) and total basin relief (H) m

The highest upward distance between the highest point and the lowest point in the basin is known as Basin Relief (Bh). Flood characteristics and the potential of sediment or material volume transfer are significantly affected by Bh. Moreover, it is one of the important conditioning factors of stream gradient [105]. Bh can be used to understand the denudation features of the basin [142]. The lower the Bh the minimum the runoff generation and debris movement in the basin. The Bh of the study area is 489 m (Fig. 7a). According to Thomas et al. (2010) [141], rivers within the plateau-plain front generally have lower relief whereas; mountain-plain front rivers have high basin relief. The Halda basin is located on the plateau of Sitakunda hill range and Ragamati hill range, though the plateau is small, the river basin fulfils the postulation of Thomas et al. (2010) [141]. The difference between the highest elevation and the elevation at the mouth of the basin is known as Total basin relief [13]. The Total Basin relief (H) of the Halda basin is 489 m.

3.5.2. Relief ratio (Rh) and relative relief (Rr)

The Relief Ratio (Rh) is calculated by dividing the total relief of the basin by basin length. It assesses the steepness of the basin and

Table 5
Relief parameter of Halda basin.

Relief Parameters	Value	Relief Parameters	Value
Maximum Elevation (m)	490	Melton's Ruggedness Number	12.43
Minimum Elevation (m)	1	Elevation at Source (m)	54
Basin Relief (m)	489	Elevation at Mouth (m)	1
Relative relief	2.02	Gradient Ratio	0.85
Relief Ratio	7.83	Total Basin relief (m)	489
Ruggedness Number	400.01	Maximum Slope (%)	141.45
Ruggedness Index	0.0025	Mean Slope (%)	9.33

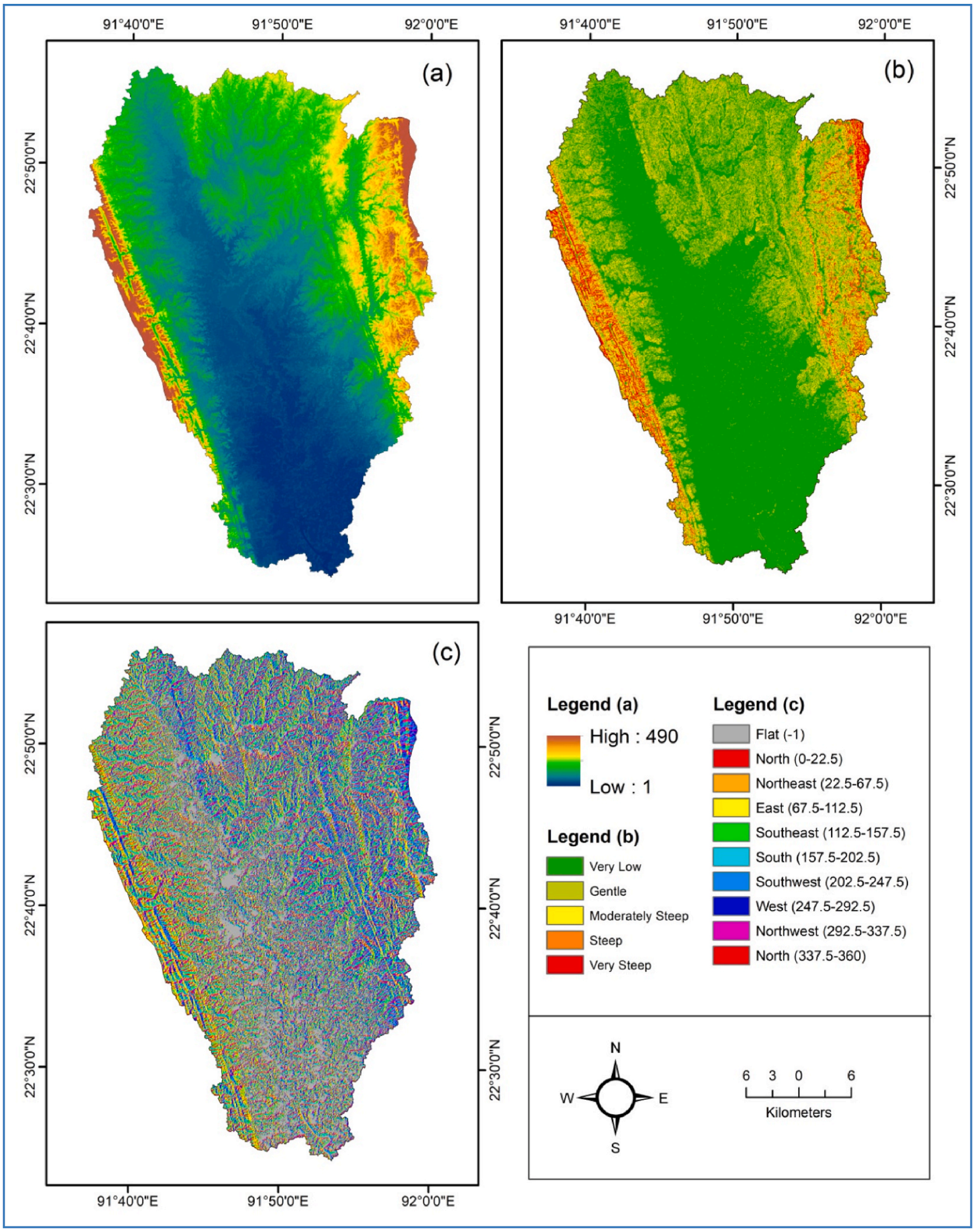

Fig. 7. a) Elevation, b) Slope and c) Aspect of the study area.

inferences the runoff generation and the strength of the erosional process within the basin [143]. The size and area of the drainage basin are inversely related to Relief Ratio (Rh). The relief ratio of the Halda basin is 7.83. Relative relief (Rr) is calculated by dividing the total relief of the basin by basin length [105]. The relative relief of the Halda basin is 2.02.

3.5.3. Ruggedness Number (Rn), Ruggedness Index (Ri), Melton's Ruggedness Number (Mrn)

According to Strahler (1958) [98], Ruggedness Number is the ratio of total basin relief and drainage density. Selvan et al. (2011) [144] stated that the Ruggedness Number depicts the unevenness of the surface. The Ruggedness Number of the Halda basin is 400. Ruggedness Index (Ri) takes into account the local topography, the degree of drainage density, and some geographic factors such as soil type, rainfall amount, slope condition, and denudation process to depict their combined effect [145]. The Ruggedness Index of the

Halda basin is 0.0025. Melton (1965) [146] postulated Melton's Ruggedness Number (Mrn) as an index of slope. It illustrates the ruggedness of relief within the river basin. The Mrm of Halda Basin is 12.43.

3.5.4. Gradient Ratio (Rg)

To measure the runoff volume of the watershed Sreedevi et al. (2009) [142] postulate the concept and measurement process Gradient Ratio (Rg). Rg depicts the channel undulation within the basin supports understanding and measuring the runoff volume. The Rg of the Halda basin is 0.85 indicating a gentle slope and moderate runoff generation with high infiltration.

3.5.5. Slope analysis

Slope steepness has a positive relation with soil erodibility [147] and a negative relation with infiltration capacity [19]. The higher slope percentage causes more erosion in a basin condition when other variables are constant [147]. The lower slope causes more infiltration compared to the higher slope [147]. The percentage of slope can be measured and demarcated from DEM data by a plane tangent to the topographic surface [4]. In this research, the percentage of the slope is calculated from SRTM-DEM using the tangent function [148]. The lowest slope is 0%, the mean slope is 9.33% and the maximum slope is 141.45% was obtained for the Halda basin (Fig. 7b and 7c). Maximum slope is observed in the two anticlines on both sides of the study area ranging between 40% and 141%. Whereas, the middle part from north to south has the lowest slope ranges between 0 and 10%. This low-slope area is the collection and transportation zone of the Halda basin (Fig. 7b and 7c). This low region is also nutrient-rich and suitable for agriculture and human settlement [69,70]. The infiltration rate is also higher in this zone, which has a higher potential for groundwater recharge. Proper sediment management in the area could prosper agricultural production [68,70,72,73].

3.6. Correlation among selected morphometric parameters

The correlation among the Elevation, Slope, Drainage Density, Stream Frequency, Infiltration Number, Length of Overland Flow, Drainage Intensity, Drainage Texture, Shape Factor, and Constant of Channel Maintenance and their significance in the study area is shown in Fig. 8. Correlation was measured using the Pearson method. The Elevation and Slope showed a significant positive correlation. Drainage Density, Stream Frequency, Infiltration Number, and Drainage Texture showed a significant negative correlation to both Elevation and Slope at 99% confidence level in Halda Basin. Besides, the Shape Factor has a negative correlation with Elevation at 90% confidence level and an insignificant negative correlation with Slope. The previous study also demonstrated an inverse relationship between first-order drainages in the basin source and drainage density. It occurs, because, the valley slope is not affected by changes in altitude and slope of the drainage basin. Rather, local slope and elevation variations largely affect the channel initiation [149–151]. In a high-relief humid climatic landscape drainage density positively correlates with relief [152], however, in the current research drainage density showed a negative relation to elevation and slope.

On the other hand, the Length of Overland Flow and Constant of Channel Maintenance showed a positive correlation with Elevation at 90% confidence level and Drainage Intensity showed an insignificant positive correlation. Length of Overland Flow, Drainage Intensity and Constant of Channel Maintenance showed a positive correlation at 90% significance level with Elevation. The Length of Overland Flow, Drainage Intensity and Constant of Channel Maintenance were inversely related to drainage density, as a result, they showed a positive relationship to elevation slope. However, the relationship can be changed due to the physiographic setting of the

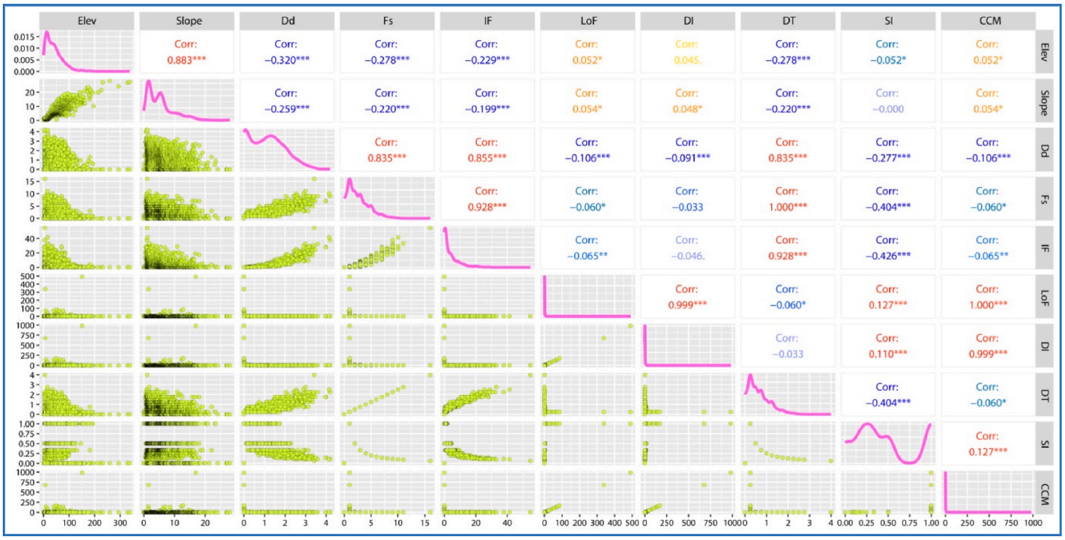

Fig. 8. Correlation among Elev = Elevation, Slope, Dd = Drainage Density, Fs = Stream Frequency, If = Infiltration Number, Lof = Length of Overland Flow, Di = Drainage Intensity, Dt = Drainage Texture, Sf = Shape Factor, and CCM=Constant of channel maintenance.

study area as Oguchi (1997) [151] reported a negative correlation between drainage density and relief. The imitation of drainage in the upslope area is largely affected by soil erosion and landslides which limits the casual positive relationship to relief or other factors, although, theoretically higher number of streams should be produced in the high elevated and steep slope areas.

The measured morphometric parameters showed diversity in correlation patterns among them. The value indicates drainage density has a significant positive correlation to Stream Frequency, Infiltration Number and Drainage Texture, and a significant negative correlation to Length of Overland Flow, Drainage Intensity, Shape Factor, and Constant of channel maintenance. The significant positive correlation value for the three variables is 0.835. The highest negative correlation was found for the Shape Factor (−0.27) followed by the Length of Overland Flow (−0.106), Constant of Channel Maintenance (−0.106) and Drainage Intensity (−0.091). The correlation values indicate that areas with high drainage density also have high Stream Frequency, Infiltration Number and Drainage Texture and low Length of Overland Flow, Drainage Intensity, Shape Factor, and Constant of channel maintenance.

The Frequency Ratio has a significant positive correlation to Drainage Texture and Infiltration Number at 99% confidence level. It showed a significant negative correlation with the Length of Overland Flow (95% confidence), Shape Factor (99% confidence) and Constant Channel Maintenance (95% confidence); whereas an insignificant negative correlation with Drainage Intensity. Areas with a high-frequency Ratio also have high Infiltration Number and Drainage Texture but low Shape Factor, Length of Overland Flow and Constant of Channel Maintenance.

The infiltration ratio has a significant positive correlation with Drainage Texture (99% confidence) and a significant negative correlation with Shape Factor (99% confidence), Length of Overland Flow (95% confidence) and Constant of Channel Maintenance (95% confidence) and an insignificant negative correlation with Drainage Intensity. Areas with high Infiltration Ratios also have high Drainage Texture but low Shape Factor, Length of Overland Flow, Constant of Channel Maintenance and Drainage Intensity.

Length of Overland Flow has a significant positive correlation with Constant of Channel Maintenance, Drainage Intensity and Shape Factor at 99% confidence interval whereas significant negative correlation with Drainage Texture at 90% confidence interval. Areas with a high Length of Overland Flow will have a high Constant of Channel Maintenance, Drainage Intensity and Shape Factor but low Drainage Texture. Drainage Intensity has a significant positive correlation with Shape Factor and Constant of Channel Maintenance (99% confidence) and an insignificant negative correlation with Drainage Texture. Drainage Texture has a significant negative correlation with Shape Factor (99% confidence) and Constant of Channel Maintenance (90% confidence). Shape Factor significant positive correlation with Constant of Channel Maintenance (90% confidence).

From some sub-basin scale studies, although no statistical correlation was measured, it is understood that there are diverse positive and negative correlations among the parameters in the basin, except for minor variation [153–155], a negative relation was found between drainage density and drainage intensity whereas a positive correlation was found in the current study. Inferences of Sreedevi et al. (2012) [154] for the correlation between Drainage density, Drainage Texture, Stream frequency, and Constant of channel maintenance resemble the current research. A negative correlation between drainage density and other parameters except for a positive correlation to shape index was inferred from Soni (2017) [136]. It is inferred from Sakthivel (2019) [156] that there is a positive correlation between the length of overland flow and the constant of channel maintenance and drainage density and stream frequency, additionally, a negative relationship was found among drainage density, stream frequency and length of overland flow and constant of channel maintenance which resembles to the current research. The correlation of the current research and the previous studies indicates the inherent relationship among morphometric parameters within the basin boundary which varies according to physical setting, climatic condition, local topography and especially the spatial unit of measurement such as sub-basin or grid. This relationship is crucial for understanding the inherent characteristics of the drainage basin. The parameters that have a positive correlation will accelerate the similar morphological, tectonic, geological, and climatological processes as a result these parameters can be used as vice versa using these correlation values. Areas also have similar or alternating environmental conditions such as slope steepness, flooding, erosion, vegetation cover, groundwater potential etc.

3.7. Environmental vulnerability inferred from morphometric parameters

In Halda Basin, drainage density, stream frequency, drainage intensity, infiltration ratio, and texture ratio indicate less permeability, moderate erosional process and moderate surface runoff generation. Moreover, the length of overland flow, along with these parameters, indicates a medium flow path with low to gentle slopes. Analysis of these parameters supports the identification of hazard potential zones [62,117,125,126], groundwater availability and recharge potential zones [10,56,58,104,114,115] and agricultural suitability zones. The areas containing lower-order streams and moderate to very steep slopes are highly vulnerable to landslides and flash floods [61,93,117,126]. Areas with higher-order streams and low slopes have a high potential to be affected by riverine floods with short to medium duration [31,37,128,129].

The funnel-shaped lower areas of the Halda basin receive the accumulated water from the uphill and nutrients and sediments are produced due to the soil erosional process active in the uphill containing lower-order streams [57,58,95,100,106,108,129,130]. This area is suitable for agricultural activities, especially rice, oil seeds and vegetables [69,70,72,75]. The high hill areas are suitable for tea cultivation, as the relative elevation and slope of the areas are comparatively high and the area receives huge rainfall [68,69,75] due to its location in a sub-tropical humid climate [83,120]. The lower areas are suitable for infiltration and are suitable for groundwater sources. The low elevated funnel-shaped basin area is also suitable for human settlement and most of the people Halda basin live here. Flood occurrence can affect the settlement and the agricultural products in the areas.

4. Conclusion

Halda River is one of the major tributaries of the Karnafuli River located on the plateau of the Sitakunda Hill ranges and Rangamati Hill ranges. The Halda basin has generally low slopes except for two high hill areas on the north and south sides. The basin with an area of 1548.74 square kilometres, a perimeter of 241.712 km and a length of 62.42 is oval-shaped. The drainage pattern is dendritic composed of 1287 streams where most of the streams are lower orders. The Halda basin is categorized as sixth sixth-order basin. The length of the lower-order streams is higher than higher-order streams. The bifurcation ratio indicates that streams are moderately affected by underlying geology and the higher order streams are developed over homogenous surfaces whereas most of the lower order streams, especially first-order streams are affected by steep slopes and higher elevation of Sitakunda and Rangamati hill ranges. The high elevation and steep slopes are present on these two sides covering a relatively small area; whereas the rest of the areas, mainly the middle part containing main streams and the higher order streams, have very low elevation (0–5 m) and low slope (0–9%). This lower area of the Halda basin is funnel-shaped and receives the total runoff generated from the high hills surrounding the north, south and west sides and transfers it to the Karnafuli River in the south-west. The texture Ratio, Form factor, Circularity ratio and Elongation ratio of the Halda basin are oval-shaped, less permeable, medium peak flood generated in the basin. In addition, the geological and structural control, and vegetation pattern moderately affects the stream development in the study area. The geomorphologic process (erosional process) driven by rainfall largely affects stream development in the Halda basin. The correlation among Drainage Density, Stream Frequency, Infiltration Number, Length of Overland Flow, Drainage Intensity, Drainage Texture, Shape Factor, and Constant of channel maintenance indicates they can be used as alternatives to each other to infer relevant information about drainage basins. Also by measuring this type of correlation from diverse environmental settings significant information about drainage basin morphology can be found.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Md. Sharafat Chowdhury: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The author declare that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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