Morphometric analysis and watershed prioritization in relation to soil erosion in Dudhnai Watershed

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Abstract

Morphologic parameters of a watershed could help in segregating critical sub-watersheds for taking up conservation practices and mitigation interventions. Determination of critical watersheds or prioritization of sub-watersheds is inevitable for efficient and sustainable watershed management programs and allocation of its natural resources. The traditional methods of determination of morphologic parameters are time consuming, expensive and requires huge labor. However, the process becomes easier, cheaper and faster with the advent of Geographical Information System (GIS) and remote sensing technologies. In the present study, a combined approach of using toposheet, remotely sensed digital elevation model and morphometric ArcGIS toolbox has been adopted to determine morphometric parameters in Dudhnai river basin, a sub-basin of river Brahmaputra which is prone to both erosion and sedimentation. Seven sub-watersheds of Dudhnai have been prioritized by using the morphometric parameters and ranked them according to its vulnerability to soil erosion. The results of bifurcation ratio, drainage density, drainage intensity and constant of channel maintenance showed that Dudhnai watershed is a well-dissected watershed with less risk to flooding and soil erosion. However, significantly high values of infiltration number and ruggedness number obtained are indicative of very low infiltration which may result in high surface runoff and soil erosion. The study also revealed that channel erosion is stronger than sheet erosion in the basin. The prioritization of the sub-watersheds implied that Chil sub-watershed is the most susceptible sub-watershed that needs greater attention for soil and water conservation measures. The results of the present study could aid various stakeholders who are involved in the watershed development and management programs.

Keywords Morphologic parameters · Watershed management · Digital elevation model · Soil erosion · Prioritization of sub-watersheds

Introduction

Drainage networks are one of the most sensitive elements of landscape, and topography plays an important role in shaping its form and fluvial dynamics. Drainage networks and flowing pattern of a river are dynamic in nature which vary over both time and space, and are influenced by several factors such as geology, structural components, geomorphology, vegetation and soils of the area (Rekha et al. 2011). Due to the increase in demand of natural resources such as land and water, management of these resources at a watershed scale has become one of the important strategies

for attaining a sustainable environment (Hema et al. 2021). Watershed management aims at the sustainable use of available natural resources to maximize production with little or no hazard to the environment (Nigam et al. 2017; Bajirao et al. 2019). Water, a vital natural resource, can be scarce in many regions as well as surplus in others which call for optimum utilization and management especially in reservoirs (Radwan et al. 2017). A well-planned watershed management practice can overcome poor watershed conditions such as excessive runoff, low productive yield, accelerated soil erosion and poor infiltration as well as natural hazards such as drought and floods (Choudhari et al. 2018). Therefore, decision makers need to be aware about the watershed characteristics and the hydrological processes occurred within the watershed. Hydrological processes within a watershed are influenced by the watershed characteristics which can be appropriately studied through morphometric analysis.

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Morphometry may be defined as the mathematical analysis of the earth's surface that describes its topographic reliefs (Clarke 1966; Pakhmode et al. 2003). Rastogi and Sharma (1976) mentioned that several phenomena related to hydrology can be correlated with the physiographic characteristics of watersheds. Morphometric analysis gives a comprehensive interpretation about the hydrologic response such as surface runoff generation, infiltration capacity and even groundwater potential. Other basin characteristics such as travel time, time to peak and intensity of erosional processes can be predicted with better insight and accuracy through morphometric analysis (Altaf et al. 2013), and it could be a good alternative in ungauged watersheds where information on hydrology, geology, geomorphology and soil are scarce (Romshoo et al. 2012; Puno and Puno 2019). Further, morphometric analysis could be of great help in evaluation of drainage basin, analysis of flood frequency, management of natural resources and its conservation and nonetheless erosion controls (Tukura et al. 2021). The information as a result of morphometric analysis of watersheds could be used as decisive tool in water resource management, conservation of soil erosion, landslide susceptibility mapping, evaluation of groundwater potential, and prioritization of watersheds (Sreedevi et al. 2009; Sujatha et al. 2013; Salvi et al. 2017; Jena and Dandabati 2019). Morphometric studies were first initiated in the middle of the twentieth century using conventional approach based on manual analyses of topographic maps (Horton 1945; Strahler 1952, 1964; Schumm 1956). The conventional approach of analyzing river morphometrics is a very tedious job which consumes lots of time and labor. However, with the advancement in geospatial and computational technologies, more precise and accurate assessment can be performed with much ease. In cases, where topographic maps are not available, satellite terrain data such as digital elevation model (DEM) may be used to determine morphometric parameters of a watershed. Digital elevation models are easily integrated in Geographical Information System (GIS) (Moore et al. 1991) and also provide continuous data unlike contours in topographic maps. Scientific literatures which used DEMs for morphometric analysis in recent years are Nag (1998); Korup et al. (2005); Lindsay and Evans (2008); Wang et al. (2010) and Jacques et al. (2014). In context to India, Chopra et al. (2005), Kale and Shejwalkar (2007), Rudraiah et al. (2008), Sreedevi et al. (2009), Patel and Sarkar (2010), Pareta and Pareta (2011), Altaf et al. (2013) and Magesh et al. (2013). Also, studies which used satellite data and GIS tools in morphometrics for developing watershed management studies include Nag (1998); Das and Mukherjee (2005); Das et al., (2016) and Senthamizhan et al. (2016).

Several mountainous watersheds are being degraded and many are in critical condition due to deforestation, expansion of built-up area, jhum cultivation, etc. needing

comprehensive management plans to pursue sustainable development of these degraded watersheds (Francisco and Rola 2004). Prioritization of watersheds is one of the important steps in the process of managing watersheds with regards to cost, type of projects and to prioritize development programs. In recent years, morphometric analysis has become a burning research topic to many policy planners and researchers particularly in the field of watershed management. Prioritization of sub-watersheds can be based on the objectives of the process such as runoff generation, flooding, development of groundwater potential and extent of soil erosion. Pandey et al. (2007) explained that sub-watershed prioritization is a method of ranking sub-watersheds based on the extent of soil erosion and criticality condition of drainage areas. Various factors such as soil loss, land use land cover, morphometric variables, socio-economic condition of the inhabitants, etc. may be considered for prioritization of sub-watersheds. Various scientific literatures have discussed the involvement of morphometry in watershed prioritization such as, Noorkaratnam et al. (2005) in positioning check dam by prioritization of micro-watersheds using sediment yield index (SYI) model; Khan et al. (2001) in Guhiya basin based on the sediment yield index; Said et al. (2018) in Nagmati river watershed for taking up soil and water conservation activities. Rahmati et al. (2019) developed automated GIS-based tool for prioritization of sub-watershed to reduce any possible uncertainty. Chandniha and Kansal (2014) used morphometric analysis to determine the priority for watershed management of nine sub-watersheds in Piperiya watershed. Application of morphometric analysis and watershed prioritization for flood risk assessment are found in the studies by Syed et al. (2017) and Obeidat et al. (2021). Abdeta et al. (2020) used morphometry and watershed prioritization as a decision tool for proper watershed management planning in Gidabo basin, Ethiopia. Borah and Deka (2020) prioritized 14 sub-watersheds of Jamuna river in Assam based on the morphometric parameters and categorized the watersheds into low, medium and high priority zones with regards to management of land and water resources. In view of the importance of morphometric analysis in the watershed management programs, this study had been taken up to study the watershed characteristics and river morphology in Dudhnai river basin. This study also attempted to prioritize sub-watersheds of Dudhnai river basins formed in its seven major tributaries.

Study area

Dudhnai River is one of the north flowing tributaries of the mighty river Brahmaputra. The river originates in the hilly regions of Meghalaya plateau, flows through the hilly state of Meghalaya for majority of its path, and meets with

the Krishnai River before joining the river Brahmaputra. The Dudhnai river basin partly lies in the East Garo Hills (approximately 83 %) district of Meghalaya and partly in the Goalpara district of Assam (approximately 17 %). Dudhnai river form a flood plain in the Assam region which are frequently inundated due to flash floods and siltation of erosive materials brought during the flash flood. The study area (shown in Fig. 1) has an area of 483.76 km², out of which approximately 20% lies in flood plain region and the rest lies in the hilly terrain. The watershed is characterized by undulated topography in the upland regions with elevation ranges from 47 m to 688 m as given by the Shuttle Radar Topographic Mission (SRTM) DEM. The study area falls under humid sub-tropical climate with intense pre-monsoon and monsoon rainfall from May to

October. The average annual rainfall of the basin is 2638 mm (Singh, 2020). This high rainfall causes lot of erosion problems in the southern hilly region and siltation problems in the northern plain areas. The average annual temperature ranges between 19 °C and 30 °C. Agriculture (jhum or shifting cultivation at the hill slopes and traditional rice cultivation at the lower plain region) and forest are the main livelihood of the people inhabited in the basin. The people in the basin cultivate rice as their principal crop. However, tea plantations are also carried out in higher land areas. Other crops grown in the basin are sugarcane, mustard, pulses, cashewnut and jute. Jhum cultivation practice are still extensive and is one of the major reasons of degrading fertility in this region. The soil in the hilly region of this basin is laterites and

Fig. 1 Study area: Dudhnai watershed and its seven major sub-watersheds

loamy in nature. In the northern plain areas, the soils are mostly new alluvium formed by the deposition of silt due to floods. Because of this reason and also due to heavy rainfall in the basin, the soils are slightly acidic in nature, and the texture of the soil is mostly sandy loam to silt loam. The Dudhnai watershed has been considered in the present study by taking into account the effect of soil erosion and siltation especially in the lower part of the basin near Goalpara.

Data

The Shuttle Radar Topographic Mission (SRTM) DEM Version 3 with a spatial resolution of 30 m was downloaded from earth explorer (<https://earthexplorer.usgs.gov/>). Four topographic maps having toposheet number 78K/9, 78K/10, 78K/13 and 78K/14 were also downloaded from Manichitra, Nakshe Portal website under the Survey of India (SOI) (<http://soinakshe.uk.gov.in/>) authenticated by Aadhar number. The toposheets are of the scale of 1:50,000; however, contours were absent in

them. Moreover, in many places, stream networks are discontinued and missing.

Methodology

The four downloaded toposheets were converted into TIFF files and then georeferenced individually in ArcGIS software. The toposheets so obtained also contained the legends which may create matching errors after digitization. To overcome this issue, four separate polygon shapefiles were digitized which exactly matched the boundary of the toposheets. The georeferenced toposheets were then clipped and merged into one composite toposheet using mosaic tool in ArcGIS to cover the entire study area. Finally, the merged toposheet has been digitized to obtain stream network of the watershed. As explained earlier, the toposheet contains many missing stream links, which were filled subsequently from network analysis of DEM. The overall flowchart of the methodology to carry out morphometric analysis is shown in Fig. 2.

Ahmed et al. (2010) explained that watershed prioritization and its management practices rely on the accurate delineation of watershed which will result in accurate determination of stream flow paths and its contributing areas. Stream

Fig. 2 Method for carrying out morphometric analysis

network generation from DEM in this study area showed significant spatial difference from ground truth especially near the outlet of the watershed. This may be attributed to very little variation in relief within the flood plain region. Carrying out morphometric analysis on the digitized drainage network consumes lots of effort and time. Processes such as stream ordering for each segment, its nomenclature, merging and splitting stream segments at appropriate locations eat-up a lot of time even with the help of advance computational tools such as GIS. The stream networks resulted from 30 m digital elevation model of SRTM do not fall along the true natural river network, particularly in the northern low-lying areas of the study area. The digitized stream networks from the toposheets are used to **burn-in** the DEM and the original DEM is reconditioned. Then, the reconditioned DEM was used to delineate watershed boundary, drainage network and stream order network using “Hydrology” tool of ArcGIS. The D8 (eight directions) flow direction algorithm was applied to determine the flow directions in the study area. According to this algorithm, water can flow from each raster cell to its eight neighboring adjacent cells. The algorithm calculates the steepest downslope neighbor cell and assign an integer code ranging from 1 to 255 depending upon the directions of flow. Seven sub-watersheds namely, Rongma, Rongitt, Manda, Chil, Sarangma, Chitukona and Chilapara which cover the major tributaries of Dudhnai River were delineated. One of the most important steps in delineating drainage network is the “cell threshold” value which defines the number of raster cells to start a stream grid. The threshold value is inversely proportional to drainage density i.e., greater threshold value will result in lesser number of streams. With careful visual comparisons between the

drainage network from toposheet and streams generated with various thresholds, a value of 75 (number of cells) was found appropriate for the study area. It is to be noted that, the optimum threshold value of 75 cells is for the toposheet at the scale of 1:50,000, and will vary for toposheets of different scales. The stream order map of the study area is shown in Fig. 3. The Dudhnai watershed and its seven sub-watersheds basin area, basin perimeter, basin length, main channel length and length of stream order were calculated using the capability of ArcGIS.

With all the capabilities of advanced GIS tools to manipulate data and enhance computational speeds, researchers still face hindrances in morphometric analyses. An automated morphometric toolbox for ArcGIS written in python language developed by Beg (2015) has been used to determine the linear, areal and relief aspects of Dudhnai and its seven sub-watersheds (Fig. 1). Singh et al. (2021) also adopted this toolbox for determining the morphometric parameters in Pare watershed in Arunachal Pradesh. More details about the toolbox can be obtained from the scientific literature of Beg (2015). This toolbox requires minimum data including digital elevation model (DEM), stream order shapefile and a watershed boundary, all in projected coordinate system. The morphometric parameters determined by this toolbox along with their formulae and authors are illustrated in Table 1.

One of the objectives in this study is to prioritize watersheds with respect to erosion and flood risks. Linear morphometric parameters such as mean bifurcation ratio and average length of overland flow; areal morphometric parameters such as drainage density, drainage texture, stream frequency, form factor, elongation ratio, circularity ratio and compactness coefficient; and relief morphometric parameters such

Fig. 3 Stream order map of the study area

Table 1 Morphometric parameters and their formulae

Morphometric Parameter	Formula	Author
Number of stream orders (N_u)	$N_u = N1 + N2 + \dots + Nn$	Horton (1945)
Length of stream orders (L_u)	$L_u = L1 + L2 + \dots + Ln$	Horton (1945); Strahler (1964)
Bifurcation Ratio (R_b)	$R_{b_m} = \frac{\frac{N1}{N2} + \frac{N2}{N3} + \dots + \frac{Nn-1}{Nn}}{n-1}$	Schumm (1956); Strahler (1964)
Average bifurcation ratio (Rb_m)	$R_{b_m} = \frac{\frac{N1}{N2} + \frac{N2}{N3} + \dots + \frac{Nn-1}{Nn}}{n-1}$	Strahler (1957)
Total Basin Area (A) (Km ²)	Projected area enclosed by watershed boundary	Schumm (1956)
Total Basin Surface Area (As) (km ²)	Integrated surface area enclosed by watershed boundary	
Total Basin perimeter (P) (Km)	Length of horizontal projection of watershed divide	Schumm (1956)
Basin Length (L_b) (Km)	Distance from outlet to farthest point on watershed boundary	Schumm (1956)
Main Channel Length (L_c) (Km)	Length of longest water course	
Fitness ratio (R_f)	$R_f = L_c/P$	Melton (1957)
Form factor (F_f)	$F_f = A/L_b^2$	Horton (1932)
Shape Factor (S_f)	$S_f = 1/E_f$	Strahler (1964)
Relative perimeter (R_p)	$R_p = A/P$	Schumm (1956)
Length Area Relation (Lar)	$Lar = 1.4 \times A^{0.6}$	Hack (1957)
Rotundity coefficient (R_c)	$R_c = L_b^2 \times \pi / 4A$	Strahler (1964); Zavoianu (1985)
Mean Basin Width (W_b)	$W_b = A/L_b$	Horton (1932)
Drainage Texture (D_t)	$D_t = N_u/P$	Horton (1945)
Compactness Coefficient (C_c)	$C_c = 0.282 \times P/\sqrt{A}$	Horton (1945)
Circularity ratio (R_c)	$R_c = 4 \pi A / P^2$	Miller (1953)
Elongation ratio (R_e)	$R_e = \frac{D_c}{L_b} = 1.129 \times \frac{\sqrt{A}}{L_b}$	Schumm (1956)
Drainage density (D_d) (Km/km ²)	$D_d = \sum_{i=1}^k \sum_{j=0}^N L_{uj} / A$	Horton (1932); Strahler (1964)
Stream frequency (F) (number/Km)	$F = \sum_{i=1}^k N_u / A$	Horton (1932)
Constant of channel maintenance (Ccm) (km ² /km)	$Ccm = 1/D_d$	Schumm (1956); Strahler (1964)
Infiltration Number (Ifn)	$Ifn = F \times D_d$	Faniran (1968); Pareta and Pareta (2011)
Drainage Intensity (D_i)	$D_i = F/D_d$	Faniran (1968); Pareta and Pareta (2011)
Average Length of Overland Flow (L_g) (Km)	$L_g = 0.5 \times D_d$	Horton (1945)
Height of basin outlet (m)	DEM	
Maximum Height of basin (m)	DEM	
Total Basin Relief (H)	$H = Z - z$	Strahler (1952)
Relief Ratio	$Rhl = H/L_b$	Schumm (1956); Melton (1957)
Relative Relief Ratio	$Rhp = H \times 100/P$	Melton (1957)
Gradient Ratio	$Rg = (Z - z)/L_b$	Pareta and Pareta (2011)
Ruggedness Number	$R_n = D_d \times (H/1000)$	Strahler (1964)
Melton Ruggedness Number	$MRn = H/0.5A$	Melton (1965)
Terrain Undulation Index	$TUi = As/A$	Beg (2015)

as relief ratio and ruggedness number were selected for consideration in the prioritization of watersheds. Weightages were assigned to each of the parameters depending on their importance with respect to soil erosion risk. Higher weightage signifies greater importance of the parameters in relevance to occurrence of soil erosion. The weightages assigned in this study are 30%, 40% and 30% to the linear, areal and relief morphological aspects of the watershed, respectively. These weightages are then equally distributed among the 2

linear, 7 areal and 2 relief morphometric parameters, respectively. The rationale behind assigning different weightages to these three aspects is to prevent the results from inclining toward the areal morphological aspect because it has seven factors as compared to two factors each for the other two aspects. Morphometric parameters such as bifurcation ratio, drainage texture, drainage density, stream frequency, length of overland flow, relief ratio and ruggedness number have direct relationship with soil erodibility while other

parameters such as form factor, compactness coefficient, circulatory ratio and elongation ratio have inverse relationship with soil erodibility. Higher priorities (numerically small) are given to the sub-watersheds having higher soil erodibility and vice versa. All seven sub-watersheds of Dudhnai basin are assigned a priority rank ranged from 1 to 7 depending upon the magnitude of each morphometric parameters. Each priority rank is then multiplied by their respective weightages, and the sum of all the morphometric parameters for each sub-watershed is the compound rank for that watershed. Finally, based on the magnitude of compound ranks, the sub-watersheds have been ranked and assigned a priority value. The lowest numerical value of compound rank has been given the highest priority of rank 1 indicating the most vulnerable sub-watershed needing soil conservation measures. While the largest numerical value of compound rank has been given the lowest priority of rank 7 indicating the least vulnerable to soil erosion.

Results and discussion

Morphometric analysis helps in understanding the linear, areal and relief aspects of watersheds (Pareta and Pareta 2012; Magesh et al. 2013; Rai et al. 2014; Ali et al. 2016) which can be useful in decision-making process of watershed development projects. The results of the execution of morphometric tool in Dudhnai watershed and its seven sub-watersheds as illustrated in Table 2, show that Dudhnai river is a 6th order river formed by 2122, 505, 107, 26 and 7 numbers of 1st, 2nd, 3rd, 4th and 5th order streams, respectively. The total length of the streams in the watershed is 1327.6 km with average bifurcation ratio of 4.75. The bifurcation ratio varies with the irregularities in the geological development of the drainage basin (Gabale and Pawar 2015). Kale and Gupta (2001) mentioned that bifurcation ratio ranging between 3 and 5 indicate natural drainage system within a homogenous rock. Higher bifurcation ratio indicates well-dissected drainage basins (Horton 1945) leading to less chances of flood and erosion risk (Eze and Efiog 2010). The form factor of the watershed was found as 0.28 indicating elongated watershed. Higher values signify circular watershed with a value of 0.754 for perfectly circular watershed (Pareta and Pareta 2011). Similarly, elongation ratio of 0.59 also proves the elongated nature of the watershed. According to Pareta and Pareta (2011), based on elongation ratio, a watershed can be classified as circular (0.9–0.1), oval (0.8–0.9), less elongated (0.7–0.8), elongated (0.5–0.7), and more elongated (< 0.5). The stages of a watershed can be indicated by circularity ratio with low, medium and high values representing youth, mature and old stages of the watershed. The circularity ratio for Dudhnai watershed is 0.21 indicating elongated and youth

stage. The compactness coefficient of the Dudhnai watershed is 2.19 which is a parameter, dependent only on the slope and independent of the size of watershed. Drainage texture can be classified into five different textures i.e., very coarse (<2), coarse (2–4), moderate (4–6), fine (6–8) and very fine (>8) as given in Pareta and Pareta (2011). For the Dudhnai watershed, this value is 16.4 which can be categorized as very fine drainage texture. Stream frequency are categorized into five different classes viz., low (<5), moderate (5–10), moderately high (10–15), high (15–20) and very high (>20). The stream frequency in Dudhnai watershed is 5.76 no. of streams/km² indicating moderate nature. In general, high drainage density reflects rapid hydrological response to the rainfall events while low drainage density means slow hydrological response. The drainage density of the Dudhnai watershed is 2.76 km/km². According to Schumm (1956), landforms are classified based on constant of channel maintenance as more erodible (<0.2), moderate erodible (0.2–0.3), moderately low erodible (0.3–0.4), low erodible (0.4–0.5) and least erodible (>0.5). Channel maintenance constant of Dudhnai watershed is 0.36 km²/km indicating moderately low erodibility nature of the watershed. Drainage intensity of a watershed is indicative of the effectivity of both drainage density and stream frequency together on the surface denudation. The drainage intensity in the Dudhnai watershed is moderate having a value of 2.08. High infiltration number of 15.92 found for Dudhnai watershed is an indicative of low infiltration and high runoff. According to Horton (1945), lower values of the length of overland flow (<0.4) are indicative of strong channel erosion while higher values indicate stronger sheet erosion. Dudhnai has 0.18 km average length of overland flow signifying pronounced channel erosion in the whole watershed. Relief ratio measures the overall steepness of a watershed and can be used to represent intensity of erosion process (Schumm 1956). In the Dudhnai watershed, the value of relief ratio is 0.0154. The watershed has a high ruggedness number of 1.77 indicating high risk of soil erosion.

All the sub-watersheds taken up in this study for prioritization are having 5th order streams. In terms of area, Manda sub-watershed is the largest while Chilapara sub-watershed is the smallest. Puno and Puno (2019) explained that morphometric parameters such as bifurcation ratio, length of overland flow, drainage density, drainage texture, and stream frequency have direct effects on soil erosion while other parameters such as form factor, elongation ratio, circularity ratio, and compactness coefficient have inverse effects on soil erosion. This can be understood as, in those parameters which have direct relationship with soil erosion, higher rank (lower values) should be assigned for higher values of the morphometric parameters. The derivative parameters of relief ratio and ruggedness number also have a direct relationship with soil erosion. As mentioned earlier, higher

Table 2 Analysis results of the morphometric parameters of Dudhnai watershed and its seven sub-watersheds

Morphometric parameters		Dudhnai	Rongma	Rongitt	Manda	Chil	Sarangma	Chitukona	Chilapara
Number of streams	1st order	2122	302	162	450	376	158	193	96
	2nd order	505	66	39	109	93	32	41	29
	3rd order	107	11	7	22	24	9	9	5
	4th order	26	3	2	6	7	2	2	2
	5th order	7	1	1	1	1	1	1	1
	6th order	1	–	–	–	–	–	–	–
	Total	2768	383	211	588	501	202	246	133
Length of streams	1st order	670.7	90.9	54.3	142.1	121.0	48.9	58.7	31.2
	2nd order	309.6	39.6	29.1	64.2	55.0	21.9	31.4	11.4
	3rd order	161.5	21.5	11.6	43.6	23.4	8.0	20.1	7.5
	4th order	89.0	12.0	5.9	13.2	21.4	16.3	13.8	4.1
	5th order	61.5	8.8	6.5	21.9	13.7	3.8	1.4	4.7
	6th order	35.3	–	–	–	–	–	–	–
	Total	1327.6	172.7	107.5	285	234.6	98.9	125.4	58.9
Bifurcation ratio	1:2	4.20	4.58	4.15	4.13	4.04	4.94	4.71	3.31
	2:3	4.72	6.00	5.57	4.95	3.88	3.56	4.56	5.80
	3:4	4.12	3.67	3.50	3.67	3.43	4.50	4.50	2.50
	4:5	3.71	3.00	2.00	6.00	7.00	2.00	2.00	2.00
	5:6	7.00	–	–	–	–	–	–	–
	Average	4.75	4.31	3.81	4.69	4.57	3.75	3.94	3.40
Basin area (km ²)		480.4	60.56	38.9	101.89	84.77	38.35	46.57	20.14
Basin surface area (km ²)		500.18	104.98	58.39	161.02	144.18	63.63	63.77	32.41
Basin perimeter (km)		168.79	42.29	38.36	79.5	52.91	43.17	48.02	29.89
Basin Length (km)		41.71	8.77	11.01	22.25	11.24	11.61	12.75	9.82
Main channel length (km)		54.66	18.9	16.54	29.8	16.00	16.98	14.25	11.09
Fitness ratio		0.32	0.45	0.43	0.37	0.30	0.39	0.30	0.37
Form factor		0.28	0.79	0.32	0.21	0.67	0.28	0.29	0.21
0.21 Shape factor ratio		3.62	1.27	3.11	4.86	1.49	3.52	3.50	4.79
Relative perimeter		2.85	1.43	1.01	1.28	1.60	0.89	0.97	0.67
Length area relation		56.9	16.42	12.59	22.44	20.09	12.48	14.03	8.48
Rotundity coefficient		2.85	0.99	2.45	3.82	1.17	2.76	2.74	3.76
Mean basin width		11.52	6.91	3.53	4.58	7.54	3.30	3.65	2.05
Drainage texture		16.4	9.06		5.5	7.39	4.68	5.12	4.45
Compactness coefficient		2.19	1.54	1.75	2.24	1.63	1.98	2.00	1.89
Circulatory ratio		0.21	0.43	0.33	0.20	0.38	0.26	0.25	0.28
Elongation ratio		0.59	1.001	0.64	0.51	0.92	0.60	0.60	0.51
Drainage density (km/km ²)		2.76	2.85	2.76	2.8	2.77	2.58	2.69	2.92
Stream frequency (number/km ²)		5.76	6.32	5.42	5.77	5.91	5.27	5.28	6.60
Constant of channel maintenance (km ² /km)		0.36	0.35	0.36	0.36	0.36	0.39	0.37	0.34
Infiltration number		15.92	18.04	14.99	16.14	16.36	13.59	14.23	19.29
Drainage intensity		2.08	2.22	1.96	2.06	2.14	2.04	1.96	2.26
Average length of overland flow (km)		0.18	0.18	0.18	0.18	0.18	0.19	0.19	0.17
Height of basin outlet (m)		47	286	286	86	75	61	51	48
Maximum height of basin (m)		688	688	659	604	720	643	592	605
Total basin relief (m)		641	502	373	518	645	582	541	557
Relief ratio		0.0154	0.0573	0.0339	0.0233	0.0574	0.0501	0.0424	0.0567
Relative relief ratio		0.38	1.19	0.97	0.65	1.22	1.35	1.13	1.86
Gradient ratio		0.0154	0.0573	0.0339	0.0233	0.0574	0.0501	0.0424	0.0567
Ruggedness number		1.77	1.43	1.03	1.45	1.79	1.50	1.46	1.63
Melton Ruggedness number		29.25	64.5	59.8	51.32	70.06	93.99	79.27	124.11

Table 2 (continued)

Morphometric parameters	Dudhnai	Rongma	Rongitt	Manda	Chil	Sarangma	Chitukona	Chilapara
Modified Melton Ruggedness number	28.66	48.99	48.81	40.82	53.72	72.96	67.75	97.84
Terrain undulation index	1.04	1.73	1.50	1.58	1.7	1.66	1.37	1.61

priorities are given to the sub-watershed having higher soil erodibility and vice versa. For example, the average bifurcation ratio of Rongma and Rongitt sub-watersheds are 4.31 and 3.81, respectively (Table 2). Thus, because of higher bifurcation ratio value, the soil erodibility in Rongma is higher than in Rongitt. Therefore, the Rongma sub-watershed is assigned a higher priority rank of 3 as compared to the priority rank of 5 for Rongitt (Table 3). Similarly, all sub-watersheds are ranked for other morphometric parameters depending on its magnitude and the nature of erodibility. As a result of such interpretation, the seven tributaries sub-watersheds of Dudhnai watershed are prioritized as shown in Table 3.

The sub-watershed Manda has been assigned the rank 1, meaning this sub-watershed has the highest probability of soil erosion with respect to bifurcation ratio. Similar interpretation can be made from Table 3. Based on the compound rank, the priority rank of the sub-watersheds has been assigned in the order as Chil, Manda, Sarangma, Chilapara, Chitukona, Rongma and Rongitt. This result of the study indicates that the sub-watershed Chil, the second largest sub-watershed, is the most vulnerable watershed to soil erosion, and therefore, it should be taken as the first priority for carrying out conservation and mitigation intervention while Rongitt could be given the least priority. Looking at the amount of erosion occurring in the basin, we suggest to construct check dams along the Dudhnai River as well as plantation of tree species and vegetations along the degraded hill slopes.

The traditional method of watershed prioritization involves works such as digitization of contours in the toposheet or comprehensive field survey, digitization of stream networks, stream segmentation to separate stream orders and manual measurements of stream length, counting

of streams and calculation of watershed area, watershed perimeter as well as other related variables to calculate morphometric parameters. Therefore, this traditional method cost a lot of time, expenditure and labor. The GIS technique adopted in this study to calculate morphometric parameters and to determine watershed priorities saves time, money and labor. The structure of stream network generated by any kind of GIS operation on digital elevation model depends upon the threshold provided during the process. The hybrid toposheet-DEM stream network delineation helps in deciding an appropriate threshold. Moreover, the remote sensing-based digital elevation model often failed to delineate the stream network to the actual ground truth particularly in flat regions where slope changes within short distances. The use of hybrid-DEM stream network delineation eliminates this issue by using the actual flow networks from the toposheet. Watersheds are used for different purposes such as cultivation, infrastructural development, recreational activities, forestry etc. Therefore, it is important to know the purpose of the watershed in its prioritization. Also, the knowledge of soil characteristics such as texture, soil depth etc. are important parameters that could aid in watershed prioritization. In the present study, only morphometric parameters resulted from combined dataset of DEM and toposheets were considered for watershed prioritization. However, it can be further improved through incorporation of information regarding land use land cover and soil characteristics.

Conclusions

Different watersheds have different hydrological behaviors based on their morphometric and topological characteristics, and therefore, identification of critical watershed is a

Table 3 Sub-watershed ranks based on the morphometric parameters w.r.t. soil erosion

Sub-watershed Weightage	R_{bm} 0.30	L_g	D_d 0.40	D_t	F	F_f	R_e	R_c	C_c	Rhl 0.30	R_n	Compound rank	Priority
Rongma	3	6	2	2	2	7	7	7	1	2	6	4.15	6
Rongitt	5	3	5	4	5	5	5	5	3	6	7	4.98	7
Manda	1	5	3	3	4	1	1	1	7	7	5	3.84	2
Chil	2	4	4	1	3	6	6	6	2	1	1	2.80	1
Sarangma	6	1	7	6	7	3	3	3	5	4	3	4.04	3
Chitukona	4	2	6	5	6	4	4	2	6	5	4	4.14	5
Chilapara	7	7	1	7	1	2	2	4	4	3	2	4.05	4

necessary step in watershed management programs. Further, the morphometric parameters helped in understanding various terrain parameters such as nature of bedrock, infiltration capacity, surface runoff, etc. The present study illustrated the procedure of delineating and quantifying morphometric parameters in the Dudhnai and its seven tributaries sub-watersheds with the help of high-resolution digital elevation model within the ArcGIS environment. This study also illustrated the application of automated morphometric tool and showed its capability in determining geomorphometric parameters at the cost of lesser time and labor. The study found that a threshold value of 75 cells is appropriate for the toposheets at the scale of 1:50,000. Setting this threshold, Dudhnai is classified as 6th order watershed. The bifurcation ratio of the watershed is found as 4.75 meaning a well-dissected natural drainage system within a homogenous rock with less chance of flood and erosion risk. The drainage density, drainage texture and the stream frequency of Dudhnai were found as 2.76 km/km², 16.4 and 5.76 no. of streams/km², respectively, indicating well-drained watershed. The constant of channel maintenance of Dudhnai watershed is found as 0.36 km²/km indicating moderately low erodible soil. However, the study also observed high value of infiltration number (15.92) and ruggedness number (1.77) which indicate very low infiltration, high surface runoff and higher risk of soil erosion. The average length of overland flow for Dudhnai watershed was observed as 0.18 km indicating stronger channel erosion than sheet erosion. Another objective of this study is to prioritize sub-watersheds of the Dudhnai watershed relative to soil erosion. In the process, out of 7 sub-watersheds, Chil sub-watershed was observed as the most susceptible to land degradation due to their inherent morphometric characteristics being prone to soil erosion, followed by Manda, Sarangma, Chilapara, Chitukona, Rongma and Rongitt, respectively. Overall, morphometric analysis attempted in this study is found satisfactory in understanding the watershed characteristics. It is also helpful in relation to watershed prioritization with respect to the susceptibility to soil erosion. Further, the results provide useful information for watershed managers to assist in decision making with more informed characteristics of the watershed. We also suggest decision makers to allocate funds for controlling soil erosion based on the priority obtained in this study.

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Data availability The data used in the research are from the public domain.

Declarations

Conflict of interest The research work is done within the capabilities of the authors and not associated with any private organization, so the conflict of interest is absent.

Ethical approval The data used in the research are from the public domain, therefore, there is no need for ethical approval. The manuscript is not submitted to any other journal before submission to this journal and further not submitted simultaneously to another journal.

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