Integrating Digital Elevation Model (DEM) and Geographic Information System (GIS) for Hydro-geomorphic Characterization of sub-watersheds in Geba River Basin, Tigray, Ethiopia

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Integrating Digital Elevation Model (DEM) and Geographic Information System (GIS) for Hydro-geomorphic Characterization of sub-watersheds in Geba River Basin, Tigray, Ethiopia.

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Abstract

Geba River Basin, which is the site of high socio-economic importance, is affected by high water stress, frequent drought, flooding, and soil erosion. Yet, its hydro-geomorphology is not well investigated. This study focuses on characterizing the hydro-geomorphology of sub-watersheds found in the Geba River basin in terms of their topographic ruggedness, groundwater recharge potentiality, and soil erosion susceptibility. During the study, many step-wise procedures have been followed: First, the entire drainage basin was segmented into 12- sub-watersheds using the DEM as a database and GIS as a data processing environment. Second, the drainage network of each of the watersheds was generated by assigning a common threshold value. Third, geomorphic parameters that characterize the sub-watersheds were quantified using the GIS processing function and standardized mathematical equations. Forth, the compound factor value of each of the parameters was calculated using the weighted sum approach. Finally, using the calculated compound factor as an input, the sub-watersheds were ranked in terms of their topographic ruggedness, groundwater recharge potentiality, and soil erosion susceptibility. Results show that sub-watershed-5, sub-watershed-8, and sub-watershed -9 are characterized by a steep slope and high rugged topography compared to the other sub-watersheds. Further, sub-watershed-4 and sub-watershed-6 are the most promising sites for groundwater recharge potential. Moreover, sub-watershed-1, sub-watershed-5, and sub-watershed-9 are the most susceptible to soil erosion. It is strongly believed that the output of this work helps planners and decision-makers in resource conservation measures and selection of groundwater recharge potential sites.

Keywords: Remote Sensing, River basin, GIS, Tigray

Introduction

At present, the world is suffering from different natural and man-made crises, such as flooding, land degradation, depletion of resources, pollution, and climate change. Rapid industrialization, urbanization, and overpopulation growth are the likely causes for these sufferings. These sufferings are potential threats to human lives. The worst is loaded in developing countries like Ethiopia where the dependency on rain-fed agriculture and low adaptive capabilities are experienced (World Bank Group,2020). Recently, these challenges are becoming pressing issues for researchers to investigate the extent of the problem and forward possible solutions. Taking time to study the characterization of drainage basins is an integral part of the solution since drainage basins are considered as the basic units for the management of land and water (Moore et al., 1991).

The drainage basin, alternatively named the watershed, is a finite part of landmass whose runoff is drained through a single outlet (Wondimu,2014). The nature of geology, geomorphology, and soil are the contributing factors for its development (Clarke,1966). The attributes that characterize the configuration, shape, and dimension of the drainage

basins are called parameters (Kabite and Gessesse,2018). Measuring and mathematical analysis of these parameters is useful for the evaluation of the hydrogeological property, landform process, runoff, and erosion (Strahler,1964).

The study of drainage morphometry has a long time history. Strahler (1954), Horton (1945), and Miller (1953) are considered as amongst the giants. The method they used was the conventional approach in which information was extracted from topographic maps and field surveys on a manual basis. However, this method is time-consuming, labor-intensive, and difficult to implement in large drainage basin systems (Fenta et al.,2017). From the last three decades, the advancement of geospatial technologies, including remote sensing and geographic information system remarked improvements both in data source and methodology for information extraction (Wondimu, 2014). The digital elevation model (DEM), one of the products of remote sensing technology, used as a database is fast, precise, updated, and cheap for extracting information (Grayson and Ladson,1991), while the geographic information system (GIS) provides a flexible environment for the manipulation of spatial information (Mohammed et al., 2018).

Following the advent of remote sensing and GIS technologies, several pieces of research related to drainage morphometry have been undertaken in different corners of the world (Chandrashekar et al., 2015; Dubey et al., 2015; Juan, 2008; Magesh et al., 2011; Malik et al., 2011; Pareta et al., 2011; Patel et al., 2013; Perucca and Angilieri, 2011; Singh et al., 2013; Thomas et al., 2012; Turcotte et al., 2001). The information obtained from the analysis of the drainage morphometry has been served as an input for different practical purposes, including groundwater prospect mapping (Thomas et al. 2012), sustainable water conservation (Suma and Srinivasa,2017), water resource management (Farhan and Anaba 2016), quantitative drainage characterization (Reedevi et al.,2009; Chandrashekar et al.,2015), and understanding drainage structures (Turcotte et al.,2001).

The northern part of Ethiopia, where the Geba river basin is situated, is characterized by a semi-arid climate and is fragile. Its fragile nature coupled with steep slopes, intense seasonal rainfall, and high population and livestock densities is the potential cause for huge soil erosion and land degradation (Zenebe et al.,2008). The Geba drainage basin is an area of high socio-economic importance but highly affected by water stress, recurrent drought, flooding, and erosion. Understanding the hydro-geomorphology of the drainage basin plays an important role in mitigating these problems. Yet, researches related to this issue are less documented. Fenta et al (2017) analyzed the quantitative morphometry of the Agulae watershed (North-eastern part of the Geba River Basin) using remote sensing and GIS techniques. The analysis revealed that the watershed is characterized mainly by the dendritic type of drainage pattern, elongated shape, fine drainage density, and high relief. Applying the same technique, Gebre et al (2015) undertook an analysis on Chelekot micro-shed attributes (South-eastern part of the Geba drainage basin). Dendritic type of drainage pattern, texture homogeneity, less elongated shape, medium drainage density, and moderate relief were found as the watershed characteristics.

This study addresses the hydro-geomorphic characteristics of sub-watersheds of the Geba River Basin with the aid of remote sensing and GIS techniques. It encompasses the following main objectives: (i) drainage network extraction, (ii) quantification of geomorphic parameters, and (iii) characterization of sub-watersheds concerning the topographic ruggedness, groundwater recharge potentiality, and soil erosion susceptibility.

2. Materials and Methods

2.1 Overview of the study area

The study is carried out in the Geba river basin located in the Tigray region of the Northern part of Ethiopia, covering a total drainage area of 5137 Km². It is the major tributary of the Tekeze River basin, the upper drainage part of the Blue

Nile River basin. Geographically, it is bounded by latitudes 12°55'00" to 14°10'00" north and longitudes 38°45'00" to 39°35'00" east (Fig.1). Above mean sea level, its elevation expands from 926 meters (at the outlet point) to 3300 meters (at the source). Like most parts of Ethiopia, it exhibits a semi-arid climate in which the rainfall is concentrated in the summer season. The precipitation and temperature show high spatial variation within the region of the drainage basin, i.e., the mean annual precipitation ranges from 400mm (Eastern part) to 950 mm (western part), while its temperature varies from 6.5°C (Northern high land) to 32°C (western lowland). The majority of the portion of the drainage basin is covered by Mesozoic sediments, whereas Precambrian rocks, Tertiary volcanic, and Dolerites cover a small portion of it. Most low land parts of the basin are covered by shrubs and bare lands, and the high land parts are mostly cultivated, and with some forests.

Fig. 1 Geographical Location of Geba River Basin

2.2 Data sources

In contrast to the conventional approach in which information is extracted on a manual basis, the use of DEM as data makes the process simple, manageable, and with better accuracy. It should be noted, however, that DEMs are not free of errors (Forkuor and Maathuis, 2012). Commonly, DEM is the product of satellite sensors, like Advanced Space born Thermal Emission and Reflection Radiometer (ASTER) and Shuttle Radar Topography Mission (STRM). In this study, we adopted SRTM-DEM as a database since it is less affected by weather conditions compared to ASTER-DEM (Kabite

and Gessesse,2018). It was downloaded from <http://earthexplorer.usgs.gov>, a commonly open data source owned by the United States Geological Survey. The DEM data is available with 30m and 90 m spatial resolutions. In the present case, we used the DEM database with 30m spatial resolution considering that more accurate terrain factors are observed from 30m DEM compared to the 90m DEM (Chen et al.,2018). It is worthy to note that using only the automated DEM data has potential limitations in generating actual information about drainage systems (Turcotte et al.,2001). Reconditioning it with high-resolution topographic maps increases its credibility (Callow et al.,2007). For this purpose, the topographic map that bounds the study area was collected from <https://mapstor.com>.

2.3 Drainage network extraction

Before the extraction of the drainage networks, the tiles of the STRM-DEM and topographic sheets that cover the study area were mosaicked and then projected to a common system of WGS–1984, zone 37°N. From the projected topographic map, natural stream networks used to recondition the raw DEM were prepared through digitizing.

After preparing the projected raw DEM and natural stream networks to update the raw DEM data, the process of drainage extraction was followed. For this purpose, the Arc Hydro tool, one of the extensions of the ArcGIS was utilized. The rationality for using this tool is that it is automated and more consistent compared to the manual approach (Wondimu 2014; Fenta et al.,2017). This tool consists of different step-wise procedures and processing functions.

In the first step, the raw DEM data was reconditioned with the natural stream network extracted from the topographic map via ‘DEM reconditioning’ algorithm. To attain the flow continuity, the local depressions of the reconditioned DEM were removed using the ‘sink filling algorithm’. Then, the flow direction of the depression-free DEM was determined based on the "D8" flow model in which eight flow directions are possible. Using the flow direction as input, the flow accumulation network was created using the “flow accumulation function. Next, the threshold value was determined using the “Stream Definition” function. The threshold value is the initiation value that determines the nature of the drainage network. Assigning different threshold values results in different values of drainage density. For DEM data with the same spatial resolution, the higher the threshold value, the sparse the channel networks will be generated (Chen et al.,2018). Hence, determining the appropriate threshold value is an important precondition in drainage network extraction. However, the appropriate threshold value needed to extract the drainage networks is still unsolved (Liu et al,2014). Professional knowledge, field knowledge and google earth observations are some of the experiences in determining the threshold values (Moges and Bhole,2015). In this study, a threshold area of 0.32Km² was allocated to extract the drainage network of all the sub-watersheds following the suggestion forwarded by Tarboton et al.(1992).

2.4 Quantification of Geomorphic parameters

After delineating the sub-watersheds and extracting the drainage network, the geomorphic parameters that characterize the watersheds were quantified. In this respect, the basic parameters like the Area, Perimeter, Basin Length, maximum Elevation, and minimum Elevation, Length of streams, Stream order, and the number of streams was generated directly from the ArcGIS processing functions (Table.1). The other parameters were calculated based on different standardized mathematical equations using the basic parameters as inputs (Table.2). For simplicity of analysis, the geomorphic parameters were clustered into four domains, notably linear, shape, areal, and relief geomorphic parameters.

Table 1 Basic geomorphic parameters directly calculated in GIS processing function

Parameters	Sub-watersheds											
	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
Area (A)(Km ²)	960	730	696	46	216	262	332	326	907	172	182	295
Perimeter(P)(Km)	314	272	228	54	130	118	151	139	231	122	92	138
Basin Length(L_b)(Km)	65	56	54	12	28	31	35	35	63	24	25	33
Minimum elevation (h)(m)	1778	1770	1760	1740	1280	1600	1740	926	1280	1790	1620	1800
Maximum elevation (H)(m)	3300	3100	2860	2460	2830	2770	2680	2160	2830	2550	2640	2760

Table 2 Geomorphic parameters and their standardized mathematical methods

S.no	Geomorphic parameters	Symbolic representation	Methods of calculation	Measuring unit	Reference
Linear geomorphic parameters					
1	Stream order	U	Hierarchical ranking		(Strahler,1964)
2	stream number	N_u	$N_u = N_1 + N_2 + \dots + N_n$		(Horton,1945)
3	stream length	L_u	$L_u = L_1 + L_2 + \dots + L_n$	Km	(Horton,1945)
4	Mean stream length	L_m	$L_m = L_u / N_u$	Km	(Strahler,1964)
5	Stream length ratio	R_l	$R_l = L_u / L_{(u-1)}$		(Horton,1945)
6	Bifurcation ratio	R_b	$R_b = N_u / N_{(u+1)}$		(Horton,1945)
Shape geomorphic parameters					
7	Form factor	F_f	$F_f = A / L_b^2$		(Horton,1932)
8	Elongation ratio	R_e	$R_e = (2 / L_b) \times (A / \pi)^2$		(Schumm,1956)
9	Circulatory ratio	R_c	$R_c = 4\pi A / P^2$		(Miller,1953)
10	Compactness coefficient	C_c	$C_c = P / (2 \times (\pi A)^{1/2})$		(Gravelius,1941)
Areal geomorphic parameters					
11	Stream frequency	F_s	$F_s = N_u / A$	1/Km ²	(Horton,1945)
12	Drainage texture	D_t	$D_t = N_u / P$	1/Km	(Horton,1945)
13	Drainage density	D_d	$D_d = L_u / A$	Km/Km ²	(Horton,1932)
14	Infiltration number	I_f	$I_f = D_d \times F_s$	1/Km ³	(Faniran,1968)
15	Length of overland flow	L_o	$L_o = 1 / (2 \times D_d)$	Km	(Horton,1945))
16	Constant of channel maintenance	C	$C = 1 / D_d$	Km	(Schumm,1956)
Relief Geomorphic parameters					
17	Basin relief	R	$R = H - h$		(Schumm,1956)
18	Relief ratio	R_r	$R_r = (H - h) / L_b$		(Schumm,1956)
19	Ruggedness number	R_n	$R_n = D_d \times (H - h)$		(Schumm ,1956))
20	Molten Ruggedness number	M_{rn}	$M_{rn} = R / A^{1/2}$		(Melton,1965)
21	Channel gradient	C_g	$C_g = (H - h) / (\pi / 2 \times L_b)$		(Singh et al.,2014)
22	Dissection index	D_{in}	$D_{in} = (H - h) / H$		(Gravelius,1941)
23	Hypsometric Integral	HI	$HI = \sum_{k=0}^{k=n} \frac{a_k}{k+1}$		(Harlin ,1978)

3. Results and discussion

3.1 Linear geomorphic parameters

These parameters mainly describe the one-dimensional property of drainage basins. The drainage pattern, Stream order, stream number, stream length, mean stream length, stream length ratio and bifurcation ratio are included in this category. Table 3 displays the quantified values of these parameters.

The drainage pattern is the arrangement of drainage channels in the drainage basin. In the present study, dendritic drainage pattern was found dominant in the majority of the sub-watersheds except in SW-3, SW-6, and SW-9, where parallel drainage pattern is observed in their fourth-order streams (Fig.2). Drainage basins with a dendritic pattern are characterized mainly by homogeneous texture with a lack of structural control (Banerjee et al.,2017) and impermeable geology (Soni,2017).

The stream order shows the position of streams in the hierarchy of streams. In this work, we adopted the system of stream ordering introduced by Strahler (1964) due to its simplicity (Tribhuvan, PR, and Sonar,2016). It was found that SW-4 and SW-10 are fourth-order streams, SW- 3 is a sixth-order stream, and the remained majority of the sub-watersheds are fifth-order streams (Fig.2). The extended order stream of SW-3 up to 6 remarks that SW-3 produces a large quantity of stream flow compared to the other sub-watersheds (Kabite and Gessesse,2018).

Stream number indicates the number of streams in each stream order. It can be observed from Table3 that the total number of streams ranges from 44 to 990, belonging to SW-4 and SW-1 respectively. One likely reason for this variation might be the lithological difference among the sub-watersheds. Further, it is observed that more than 65 % of the streams are concentrated in the first-order stream in all the sub-watersheds and decrease with increasing stream order. The result is in line with the existed literature reported by Horton(1945), stating that “the number of streams of each order forms an inverse geometric sequence against the stream. The graph of stream number as a function of stream order for SW-12 as a representative sample (Fig.3a) confirms that increasing the stream order results in the exponential decay of the stream number. Such type of trend is more pronounced in drainage basins with homogeneous subsurface material (Nag and Lahiri,2011).

The stream length is the measured length of streams. The highest total stream length recorded, in this study, is 1169, corresponding to SW-9. It is also observed that more than 50% of the measured length is concentrated in the first-order stream and decreases with increasing stream order in all the sub-watersheds, which favors the idea forwarded by Horton (1945), stating that an increase in stream order results in the decrease in stream length. This is confirmed in the graph of stream length versus the stream number for SW-12 as a representative sample (Fig 2b), where the stream length decreases exponentially with an increase in the stream order. The possible reason for this could be the slope variation among the steam orders (Wondimu, 2014).

The mean stream length relates to the size of the contributing area with the drainage network. It is shown that low mean stream length values are concentrated in the lower stream orders and increase with increasing stream order. “Law of stream lengths” proposed by Horton (1945) states that mean stream length increases with the order of streams. This is evident in the regression equation connecting the mean stream length and stream order for WS-12 as a representative sample (Fig.2c)

The stream length ratio is the ratio of the length of a given stream order to the length of the next lower order. Among the sub-watersheds, SW-8 exhibits the highest stream length ratio (0.74), while SW-11 is with the lowest value (0.4). The morphological differences in the sub-water watersheds might be the likely reason for this variation (Horton,1945).

Bifurcation ratio is the ratio of the stream number of the lowest order to the stream number of the next higher order. In this study, the calculated bifurcation ratio varies from 3.35 to 6.01 belonging to SW-4 and SW-9 respectively. According to Horton (1945), drainage basins with less distorted geological structures have bifurcation ratios ranging between 3.0 and 5.0. However, it can decrease and increase from the specified range for flat and mountain areas respectively (Farhan 2017). Hence, SW-4, with a low bifurcation ratio, is nearly flat and less structurally disturbed (Nag 1998), while SW-9 is highly dissected and structurally disturbed leading to extensive erosion and sediment transportation.

Fig. 2 Drainage Pattern and stream orders of sub-watersheds in Geba River Basin

Table 3 Quantified values of linear Geomorphic Parameters

Parameters	Sub -Watersheds											
	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
Stream -Order (U)	5	5	6	4	5	5	5	5	5	4	5	5
Number of streams												
N _{u1}	772	614	593	32	200	202	288	311	756	138	155	480
N _{u2}	170	122	115	9	44	49	70	70	160	37	38	56
N _{u3}	37	30	39	2	7	11	19	16	45	8	7	16
N _{u4}	10	5	8	1	2	3	2	3	12	1	2	3
N _{u5}	1	1	2		1	1	1	1	1		1	1
N _{u6}			1									
$\sum N_u$	990	772	756	44	254	266	380	401	974	184	203	556
Stream length												
L _{u1}	655	478	443	30	138	188	231	223	614	120	134	196
L _{u2}	383	262	227	20	65	85	125	97	287	60	50	107
L _{u3}	140	93	88	10	17	28	58	69	121	19	32	49
L _{u4}	64	47	68	2	19	21	33	18	97	21	17	16
L _{u5}	59	56	31		23	23	6	28	50		1	14
L _{u6}			9									
$\sum L_u$	1301	936	798	62	262	345	453	435	1169	220	234	382
Mean stream length												
L _{m1}	0.91	0.78	0.75	0.94	0.69	0.93	0.8	0.72	0.81	0.87	0.86	0.41
L _{m2}	2.25	2.15	1.97	2.22	1.48	1.73	1.79	1.38	5.79	1.62	1.32	1.91
L _{m3}	3.78	3.10	2.26	5	2.43	2.55	3.05	4.31	2.69	2.36	4.57	3.06
L _{m4}	6.4	9.4	8.5	2	9.5	7	16.6	6	8.03	21	8.5	5.33
L _{m5}	59	56	16.5		23	23	6	28	50		1	14
L _{m6}			9									
$\sum L_m$	1.31	1.21	1.35	1.42	1.03	1.30	1.19	1.08	1.2	1.20	1.15	0.69
Stream length ratio												
R _{l (2/1)}	0.58	0.55	0.51	0.67	0.47	0.45	0.54	0.43	0.47	0.5	0.37	0.55
R _{l (3/2)}	0.37	0.35	0.39	0.5	0.26	0.33	0.46	0.71	0.42	0.32	0.64	0.46
R _{l (4/3)}	0.46	0.51	0.77	0.2	1.12	0.75	0.57	0.26	0.80	1.10	0.53	0.32
R _{l (5/4)}	0.92	1.19	0.46		1.21	1.10	0.18	1.56	0.52		0.06	0.88
R _{l (6/5)}			0.29									
Mean R _l	0.58	0.65	0.48	0.46	0.72	0.66	0.44	0.74	0.55	0.64	0.4	0.55
Bifurcation ratio												
R _{b (1/2)}	4.54	5.03	5.16	3.56	4.55	4.12	4.11	4.44	4.73	3.73	4.08	8.57
R _{b (2/3)}	4.59	4.07	2.95	4.5	6.29	4.45	3.68	4.38	3.56	4.63	5.43	3.5
R _{b (3/4)}	3.7	6	4.88	2	3.5	3.67	9.5	5.33	3.75	8	3.5	5.33
R _{b (4/5)}	10	5	4		2	3	2	3	12		2	3
R _{b (5/6)}			2									
Mean R _b	5.71	5.03	3.88	3.35	4.09	3.81	4.82	4.29	6.01	5.45	3.75	5.1

Fig. 3 Relationship between Linear geomorphic parameters and Stream order (SW-12): (a) Stream order versus Stream number, (b) Stream order versus Stream length, (c) Stream order versus mean Stream length.

3.2 Shape geomorphic parameters

The Geomorphic parameters, such as Form factor, Elongation ratio, Circulatory ratio, and Compactness coefficient describe the shape of the drainage basin which is important in determining the rate at which water flows into the streams (Fenta et al.,2017). The quantified distribution of these parameters is depicted in Table 4.

Table 4 Quantified values of Shape Geomorphic Parameters

Parameters	Sub-Watersheds											
	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
F_f	0.23	0.23	0.24	0.32	0.28	0.27	0.27	0.27	0.23	0.30	0.29	0.27
R_e	0.17	0.17	0.17	0.20	0.19	0.19	0.19	0.19	0.17	0.20	0.19	0.19
R_c	0.12	0.12	0.17	0.20	0.20	0.23	0.20	0.21	0.21	0.15	0.30	0.20
C_c	2.90	2.83	2.44	2.25	2.50	2.10	2.34	2.20	2.20	2.62	1.92	2.27

From the distribution, it is shown that the Form factor ranges from 0.23 (SW-1, SW-2, SW-9) to 0.32 (SW-4), the Elongation ratio is similar for all the sub-watersheds (i.e., 0.2), the Circulatory ratio extends from 0.1 (SW-2) to 0.3 (SW-11), and the Compactness coefficient rises from 1.92 (SW-11) to 2.9 (SW-1). Drainage basins with Form factor, Elongation ratio, and Circulatory ratios close to 0 are more elongated, and these close to 1 are more circular (Miller,1953; Schumm,1956; Strahler,1964). On the other extreme, drainage basins with low Compactness coefficients are more circular and with high Compactness, coefficients are more elongated. The more circular, the low the infiltration capacity, high runoff, and exposure to soil erosion (Patel et al.,2013).

3.3 Areal geomorphic parameters

These parameters describe the degree of dissection of the terrain from which the infiltration capacity of drainage basins can be determined (Farhan,2017; Meshram and Sharma,2017). The Stream frequency, Drainage density, Drainage texture, Infiltration number, Length of overland flow, and Constant channel maintenance are the examples included under this category. Table 5 presents the estimated values of these parameters.

Table 5 Quantified values of Areal Geomorphic Parameters

Parameters	Sub-Watersheds											
	SW-1	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7	SW-8	SW-9	SW-10	SW-11	SW12
F_s	1.03	1.06	1.09	0.96	1.18	1.02	1.14	1.23	1.74	1.07	1.12	1.89
D_t	3.15	2.84	3.32	0.81	1.95	2.25	2.52	2.88	4.22	1.51	2.21	4.03
D_d	1.36	1.28	1.15	1.35	1.21	1.32	1.36	1.34	1.29	1.28	1.29	1.29
I_f	1.40	1.36	1.25	1.29	1.43	1.34	1.56	1.65	1.38	1.37	1.43	2.44
L_o	0.37	0.39	0.33	0.37	0.41	0.38	0.37	0.37	0.39	0.39	0.39	0.39
C	0.73	0.78	0.87	0.74	0.82	0.76	0.73	0.75	0.78	0.78	0.78	0.77

As indicated in the table, the lowest Stream frequency (0.96Km^{-2}) is recorded in SW-4 and the highest value (1.89Km^{-2}) belongs to SW-12, indicating that SW-4 comprises permeable surface material compared to the other sub-watersheds (Dubey et al.,2015). The calculated minimum Drainage density is 1.15 Km/Km^2 (SW-3) while the maximum is 1.36 Km/Km^2 (SW-1, SW-7). Further, all the sub-watersheds have a drainage density of $< 2\text{Km/Km}^2$. According to Smith's (1950) classification system, all the sub-watersheds belong to a very coarse drainage density. Drainage basins in this category are characterized by permeable material, low runoff, and high infiltration rate (Nautiyal,1994).

Except SW-9 and SW-12, having drainage textures of 4Km/Km^2 , all the sub-watersheds possess drainage textures of $< 4\text{Km/Km}^2$. Based on Smith's (1950) classification, SW-9 and SW-12 are nearly moderate, while the remained are coarse-textured. This leads to the conclusion that SW-9 and SW-12, with a sparse relative spacing of the streams, are characterized by high infiltration capacity and base flow (Horton,1945).

Moreover, the tabulated minimum and maximum values of the infiltration number are 1.25 Km^{-2} and 2.44 Km^{-2} , belonging to SW-3 and SW-11 respectively. According to Strahler (1964), the infiltration number and the infiltration capability are inversely related. In light of this, SW-11 with high infiltration number experiences low infiltration capability, whereas SW-4 with a low infiltration number exhibits high infiltration capability. The distribution also shows that a similar value of the length of overland flow (0.4Km) is recorded in all the sub-watersheds, which is relatively high. Drainage basins exhibiting a high length of overland flow have high infiltration capacity compared to drainage basins with a low length of overland flow (Chandrashekar et al.,2015). Similarly, all the sub-watersheds are found to have a similar constant of channel maintenance (0.8Km), which is relatively large, indicating that the watersheds have relatively high infiltration capacity with less surface runoff (Sreedevi et al.,2013).

3.4 Relief Geomorphic parameters

In this study, the parameters characterizing the Relief of the terrain, namely the basin Relief, Relief ratio, Ruggedness number, molten ruggedness number, Channel gradient, Dissection index, and Hypsometric Integral are incorporated. These parameters have the potential to describe the direction of the water flow (Gudu Tufa,2018), erosional potential (Fenta et al.,2017), instability (Rekha et al.,2011), and the structural complexity (Dubey et al. 2015) of a terrain. The numerical distribution of these parameters is indicated in Table 6.

Table 6 Quantified values of Relief Geomorphic Parameters

parameters	Sub-Watersheds											
	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
R	1.522	1.330	1.100	0.720	1.550	1.170	0.940	1.234	1.550	0.760	1.020	0.960
R _r	0.02	0.02	0.02	0.06	0.06	0.04	0.03	0.04	0.02	0.03	0.04	0.03
R _n	2.07	1.70	1.27	0.97	1.88	1.54	1.28	1.65	1.99	0.97	1.31	1.24
M _{rn}	0.05	0.05	0.04	0.11	0.11	0.07	0.05	0.07	0.05	0.06	0.08	0.06
C _g	0.01	0.02	0.01	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.03	0.02
D _{in}	0.46	0.43	0.38	0.29	0.55	0.42	0.35	0.57	0.55	0.29	0.39	0.35
HI	0.4	0.5	0.5	0.2	0.5	0.4	0.5	0.5	0.4	0.6	0.4	0.5

The distribution shows that maximum basin Relief (1.522Km=1522m) is observed in SW-1 and minimum (0.720Km=720m) is recorded in SW-4). The Relief ratio rises from 0.02 to 0.06 - the smallest value corresponds to SW-1, SW-2, SW-3, SW-9, and the highest value relates to SW-4 and SW-5. This confirms that SW-4, experiencing a relatively high Relief ratio, is at high risk of soil erosion (Magesh et al. 2011). Among the sub-watersheds, maximum (2.07) and minimum (0.97) Ruggedness numbers are recorded for SW-1 and WS-4 respectively. Hence, WS-4 is more unstable and complex leading it to continuous soil erosion (Wondimu,2014). The Molten Ruggedness number of the sub-watersheds is bounded within a range of 0.05 and 0.11. The Distribution further reveals that the channel gradient ranges between 0.01 and 0.04. The minimum value relates to SW-1 and SW-3, and the maximum corresponds to SW-4 and SW-5. On the other hand, the maximum value of the dissection index is 0.6 (SW-5, SW-8, and SW-10) and the minimum value is 0.2 (SW-4). A lower value of dissection index is indicative of flat terrain and the higher values are indicative of steep slopes (Pal et al.,2012).

3.5 Hypsometric curve and Hypsometric Integral

Hypsometry is related to the analysis of the distribution of elevation within a given area of landmass (Willgoose and Hancock,1998). Working with hypsometry involves generating the hypsometric curve (HC) and tabulating hypsometric integrals (HI). The hypsometric curve connects the distribution of the relative elevation against the relative area. The curve exhibits a cumulative probability distribution and is represented by a continuous polynomial function in the following way (Harlin,1978):

$$f(x) = a_0 + a_1x + a_2x^2 + \dots + a_nx^n \quad (1)$$

In this regard, the function, $f(x)$ represents relative elevation fitted to the hypsometric curve by regression, x denotes the relative area, and $a_1, a_2, a_3 \dots a_n$ are constants generated from regression.

Commonly, the curve exhibits three shape types: convex- shape, S-shape, and concave- shape. These shapes provide a clue to the geomorphic development of landscapes. According to Strahler (1952), the convex-shaped, S-shaped, and concave-shaped curves are indicative of youthful, mature, and old stages of development respectively. To better understand the geomorphic development of the sub-watersheds, the hypsometric curve (relative elevation versus relative area) of each of the sub-watersheds was plotted (Fig.4). From the graphs, it is observed that the hypsometric curve of SW-4 reflects a relatively concave shape, SW-10 shows a relatively convex shape around its outlet, and the other 10 sub-watersheds are S-shaped, suggesting that SW-4 is relatively at a youthful stage, SW-10 is relatively at the old stage and the remainders are at the maturity stage of development.

Fig. 4 Generated Hypsometric Curves of Sub-watersheds in Geba River Basin

The Hypsometric Integral (HI) is the representation of the total area below the hypsometric curve (Schumm,1956). Practically, it determines the mass of the rock and soil material that remained after erosion ((Luo,2002). Its value is obtained by integrating the relative elevation function $f(x)$ within the limits of a unit square as follows (Harlin,1978):

$$HI = \iint_R dx dy = \int_0^1 f(x) dx \quad (2)$$

Substituting equation (1) of $f(x)$ in to equation (2) becomes,

$$HI = \int_0^1 (a_0 + a_1x + a_2x^2 + \dots + a_nx^n) dx = \sum_{k=0}^{k=n} \frac{a_k}{k+1} \quad (3)$$

Where, R , x , and y represent the area below the hypsometric curve, relative area, and relative elevation respectively.

In the present study, before computing the hypsometric integrals, the hypsometric curve [equation (1)] was made fitted to different polynomial orders by regression using the least square fit ($R^2=99$) from which the coefficients, $a_0, a_1, a_2, \dots a_k$ are obtained (Fenta et al.,2017). Table 7 shows the polynomial orders and their corresponding coefficients for all the sub-watersheds. The values of the coefficients of the polynomial orders were then substituted into equation (3) to compute the Hypsometric Integrals. As such, WS-2, WS-3, WS-5, WS-7, WS-8, and WS-12 shared the same value ($HI=0.5$), WS-10, WS-6, WS-9, and WS-11 have a common value ($HI=0.4$), WS-4 with $HI=0.2$, and WS-10 with $HI=0.6$. The hypsometric integral values, 0.5, 0.4, 0.2, and 0.6 respectively signifies that about 50%, 40%, 20%, and 60% of rock masses of the sub-watersheds are still existed (Fenta et al.,2017).

Strahler (1952), classified the values of the hypsometric integrals concerning the stage of geomorphic development. Accordingly, drainage basins with $HI \geq 0.6$ fall under the youthful stage, drainage basins with $0.3 \leq HI \leq 0.6$ are indicative of the maturity stage, and those with $HI \leq 0.3$ are related to the old stage of development. With this regard, WS-4 is a typical representative of the old stage, WS-10 is at a youthful stage of development, and the remainders are at the maturity stage of development

Table 7 Order of Polynomials and corresponding coefficients of sub-watersheds in Geba River Basin

Sub- water Shades	Order of polynomial at (R ² =0.99)	Coefficients of polynomial distribution						
		a ₀	a ₁	a ₂	a ₃	a ₄	a ₅	a ₆
SW-1	5	0.9015	-5.443	25.415	-56.565	56.946	-21.236	
SW-2	2	0.9531	-0.751	-0.1632				
SW-3	3	0.95	-2.6144	4.8345	-3.1297			
SW-4	5	0.9555	-6.6375	30.159	-65.232	63.412	-22.658	
SW-5	2	0.9585	-0.7874	-0.1151				
SW-6	5	0.9161	-6.2905	32.234	-74.184	75.562	-28.228	
SW-7	5	1	-4.6179	26.551	-68.236	74.171	-28.805	
SW-8	6	0.9211	-3.848	16.762	-30.904	12.662	18.911	-14.451
SW-9	4	0.9158	-3.0833	7.6365	-9.2887	3.8472		
SW-10	4	0.9576	-1.6982	0.4602	4.9123	-4.6083		
SW-11	5	0.9356	-5.4774	27.811	-66.984	70.977	-27.237	
SW-12	5	0.9787	-7.7914	45.377	-108.13	110.64	-41.069	

3.6 Hydro-geomorphic characterization of the sub-watersheds

The ultimate intention of this study is to characterize the sub-watersheds in terms of their topographic ruggedness, groundwater recharge potentiality, and soil erosion susceptibility. Based on their strong association, 6 quantified geomorphic parameters were incorporated in the topographic ruggedness analysis (Table 8), 11 parameters in the groundwater recharge potentiality (Table 9), and 8 parameters in the soil erosion susceptibility characterization (Table 10). In the process of characterizing the sub-watersheds, the weighted sum approach, mostly applied for watershed prioritization (Malik et al.,2019) was adopted. This approach involves preliminary priority ranking, generating correlation matrix, weightage calculation, compound factor estimation, and categorization, (Jothimani et al.,2020).

Preliminary priority ranking of sub-watersheds

This procedure involves the ranking of the sub-watersheds based on the calculated geomorphic parameters. For geomorphic parameters that are directly related to the focus in need (In this case, topographic ruggedness, groundwater recharge potentiality, and erosion susceptibility), a rank of “1” is given for the largest value, rank of “2” is given for the second largest value, and so on for all the sub-watersheds . On the other extreme, for parameters that are inversely related to the focus in need, rank of “1” is given for the smallest value, a rank of “2” is given for the second smallest value, and so on, for all the sub-watersheds (Aher et al.,2014). Further, for sub-watersheds with equal values of parameters, equal priority rank was allocated (Malik et al.,2019). Table 8, Table 9, and Table 10 show the preliminary priority ranking of the sub-watersheds concerning topographic ruggedness, groundwater recharge potentiality, and soil erosion susceptibility respectively.

Table 8 Preliminary Priority ranking of sub-watersheds concerning Topographic ruggedness

Parameters	Ranking of sub-watersheds											
	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
R	2	3	6	11	1	5	9	4	1	10	7	8
R _r	4	4	4	1	1	2	3	2	4	3	2	3
R _n	1	4	9	11	3	6	8	5	2	11	7	10
M _m	5	5	6	1	1	3	5	3	5	4	2	4
C _g	4	3	4	1	1	3	3	3	3	3	2	3
D _{in}	3	4	7	9	2	5	8	1	2	9	6	8

Table 9 Preliminary Priority ranking of sub-watersheds concerning groundwater recharge potentiality

Parameters	Ranking of sub-watersheds											
	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
F _s	3	4	6	1	9	2	8	10	11	5	7	12
I _f	7	4	1	2	8	3	9	10	6	5	8	11
D _d	8	3	1	7	2	5	8	6	4	3	4	4
D _t	9	2	10	1	3	5	6	8	12	2	4	11
L _o	4	2	5	4	1	3	4	4	2	2	2	2
F _f	1	1	2	7	4	3	3	3	1	6	5	3
R _c	1	2	3	4	4	7	4	5	6	2	8	4
R _e	1	1	1	3	2	2	2	2	1	3	2	2
C	8	3	1	7	2	5	8	6	3	3	3	4
C _c	1	2	5	8	4	10	6	9	9	3	11	7
R _b	11	8	4	1	5	3	7	6	12	10	2	9

Table 10 Preliminary Priority ranking of sub-watersheds concerning the soil erosion susceptibility.

Parameters	Ranking of sub-watersheds											
	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
R	2	3	6	11	1	5	9	4	1	10	7	8
R _r	4	4	4	1	1	2	3	2	4	3	2	3
C _g	4	3	4	1	1	3	3	3	3	3	2	3
R _n	1	4	9	11	3	6	8	5	2	11	7	10
M _m	5	5	6	1	1	3	5	3	5	4	2	4
R _b	2	2	9	12	8	10	6	7	1	3	11	4
D _d	1	6	8	2	7	4	1	3	5	6	5	5
HI	3	2	2	4	2	3	2	2	3	1	3	2

Generating Correlation Matrix

The correlation matrix shows the cross-correlation among the geomorphic parameters. Before the correlation matrix, a matrix of standardized parameters (A) was formed (Tignath, 2015). This matrix satisfies the following equation:

$$A = (a_{ij} - a_j) / S_j \quad (4)$$

In this equation, a_{ij} represents i th observation on the j th parameter, a_j shows the mean of the j th parameter, and S_j is the standard deviation of the j th Parameters.

Hence, the correlation matrix (R) with 'N' number of geomorphic parameters in terms of the matrix of standardized parameters (A) and its transpose (A') is given as follows:

$$R = (A \times A') / N \quad (5)$$

Following this, the correlation matrix for topographic ruggedness (Table 11), groundwater recharge potentiality (Table 12), and soil erosion susceptibility (Table 13) were generated at a 5% level of significance.

Table 11 Correlation matrix and weightage of geomorphic parameters related to topographic ruggedness

	R	R _r	R _n	M _m	C _g	D _{in}
R	1.00	-0.23	0.98	-0.13	-0.17	0.88
R _r	-0.23	1.00	-0.24	0.97	0.90	-0.01
R _n	0.98	-0.24	1.00	-0.15	-0.20	0.87
M _m	-0.13	0.97	-0.15	1.00	0.94	0.03
C _g	-0.17	0.90	-0.20	0.94	1.00	-0.03
D _{in}	0.88	-0.01	0.87	0.03	-0.03	1.00
Sum of correlation coefficients	2.33	2.39	2.26	2.65	2.44	2.73
Grand total	14.81	14.81	14.81	14.81	14.81	14.81
Weightage	0.16	0.16	0.15	0.18	0.16	0.18

Table 12 Correlation matrix and weightage of Geomorphic Parameters related to groundwater recharge potentiality

	F _s	I _f	D _d	D _t	L _o	F _f	R _c	R _e	C	C _c	R _b
F _s	1.00	0.73	-0.08	0.74	0.29	-0.24	0.18	-0.14	0.05	-0.27	0.48
I _f	0.73	1.00	0.14	0.45	0.23	0.05	0.12	0.20	-0.19	-0.17	0.22
D _d	-0.08	0.14	1.00	-0.17	0.14	0.19	0.05	0.29	-0.99	-0.08	0.18
D _t	0.74	0.45	-0.17	1.00	-0.12	-0.79	-0.11	-0.70	0.17	0.04	0.57
L _o	0.29	0.23	0.14	-0.12	1.00	0.21	0.18	0.30	-0.20	-0.03	0.25
F _f	-0.24	0.05	0.19	-0.79	0.21	1.00	0.45	0.96	-0.20	-0.43	-0.56
R _c	0.18	0.12	0.05	-0.11	0.18	0.45	1.00	0.42	-0.01	-0.95	-0.52
R _e	-0.14	0.20	0.29	-0.70	0.30	0.96	0.42	1.00	-0.30	-0.42	-0.43
C	0.05	-0.19	-0.99	0.17	-0.20	-0.20	-0.01	-0.30	1.00	0.03	-0.22
C _c	-0.27	-0.17	-0.08	0.04	-0.03	-0.43	-0.95	-0.42	0.03	1.00	0.50
R _b	0.48	0.22	0.18	0.57	0.25	-0.56	-0.52	-0.43	-0.22	0.50	1.00
Sum of correlation coefficients	2.73	2.79	0.67	1.07	2.24	0.63	0.82	1.15	-0.86	-0.79	1.47
Grand total	11.93	11.93	11.93	11.93	11.93	11.93	11.93	11.93	11.93	11.93	11.93
Weightage	0.23	0.23	0.06	0.09	0.19	0.05	0.07	0.10	-0.07	-0.07	0.12

Table 13 Correlation matrix and weightage of geomorphic parameters related to soil erosion susceptibility

	R	R _r	C _g	R _n	M _{rn}	R _b	D _d	HI
R	1.00	-0.23	-0.17	0.98	-0.13	0.37	-0.16	0.08
R _r	-0.23	1.00	0.90	-0.24	0.97	-0.69	0.08	-0.41
C _g	-0.17	0.90	1.00	-0.20	0.94	-0.52	0.03	-0.42
R _n	0.98	-0.24	-0.20	1.00	-0.15	0.42	0.03	0.02
M _{rn}	-0.13	0.97	0.94	-0.15	1.00	-0.61	0.07	-0.47
R _b	0.37	-0.69	-0.52	0.42	-0.61	1.00	0.18	0.40
D _d	-0.16	0.08	0.03	0.03	0.07	0.18	1.00	-0.39
HI	0.08	-0.41	-0.42	0.02	-0.47	0.40	-0.39	1.00
Sum of correlation coefficients	1.74	1.39	1.55	1.86	1.61	0.54	0.83	-0.20
Grand total	9.32	9.32	9.32	9.32	9.32	9.32	9.32	9.32
Weightage	0.19	0.15	0.17	0.20	0.17	0.06	0.09	-0.02

Weightage Calculation

The weightage, indicating the degree of influence of each of the geomorphic parameters was calculated from the correlation matrix. This was done by dividing the sum of the correlation coefficients of each variable by the grand total. The sum of the correlation coefficients is obtained by adding all the row elements of the correlation coefficients, while the grand total is obtained by adding all the column elements of the sum of correlation coefficients.

Compound factor estimation

The compound factor (CF) is the priority quantitative value based on which the sub-watersheds can be characterized (prioritized). Mathematically, it can be represented by the following mathematical formula (Aher et al. 2014):

$$CF = \sum_{j=1}^N \sum_{i=1}^M (W_j \times R_i) \quad (6)$$

Where W_j denotes the j th weightage of the parameter obtained from the correlation matrix, R_i signifies the i th rank of the parameter assigned in the preliminary priority ranking, N represents the total number of parameters, and M shows the total number of ranks.

Based on this equation, the compound factor value of each of the parameters was estimated and presented in Table 14.

Table 14 Compound factor value and corresponding ranks of sub-watersheds

Sub-watersheds	Topographic ruggedness		Groundwater recharge potentiality		Soil erosion susceptibility	
	Compound factor	Rank	Compound factor	Rank	Compound factor	Rank
SW-1	3.19	4	5.26	7	2.86	2
SW-2	3.82	5	3.48	3	3.95	5
SW-3	5.93	10	3.99	4	6.46	12
SW-4	5.53	8	1.96	1	5.60	9
SW-5	1.47	1	5.35	8	2.35	1
SW-6	3.94	6	2.62	2	4.37	6
SW-7	5.94	11	6.18	9	5.53	8
SW-8	2.91	3	6.81	11	3.73	4
SW-9	2.91	2	6.78	10	3.00	3
SW-10	6.55	12	4.56	5	6.44	11
SW-11	4.25	7	4.7	6	4.76	7
SW-12	5.9	9	7.84	12	5.81	10

It is shown that the calculated compound factor value ranges from 1.47 (SW-5) to 6.55 (SW-10) for the topographic ruggedness, 1.96 (SW-4) to 7.84 (SW-12) for the groundwater recharge potentiality, and 2.35 (SW-5) to 6.46 (SW-3) for soil erosion susceptibility. The sub-watersheds with the lowest compound factor are assigned as a priority rank of '1', these with the next lowest value are given the priority rank of '2', and so on until the last priority rank is attained (Kandpal et al.,2017). Practically, it means that SW-5 is the most topographically rugged and hence the most sensitive to soil erosion, and SW-4 is the most preferable in groundwater recharge potentiality.

Commonly, sub-watersheds with a similar range of compound factor values are grouped for prioritization in the soil and water conservation measures. Adopting the work of Aher et al. (2014), the sub-watersheds in this study are characterized (categorized) as very high, high, moderate, low, and very low for the topographic ruggedness, groundwater potentiality, and soil erosion susceptibility (Table 15).

From the table, it is evident that SW-5, SW-8, and SW-9 are in the very high category concerning the topographic ruggedness, SW-4 and SW-6 are in the very high category with the groundwater recharge potentiality, and SW-1, SW-5, and SW-9 are in a very high category with the soil erosion susceptibility. This suggests that SW-5, SW-8, and SW-9 are more topographically rugged and mountainous, SW-4 and SW-6 are the most promising sites for groundwater recharge potentiality, and SW-1, SW-5, and SW-9 are the most sensitive to soil erosion.

The analysis further confirms that the majority of the sub-watersheds in the very high category in the topographic ruggedness are also in the very high category in the soil erosion susceptibility but in the very low category in the groundwater recharge potentiality. This indicates that highly rugged terrains are more susceptible to soil erosion, but are characterized by low groundwater recharge potentiality.

Table 15 Final characterization of the sub-watersheds based on the compound factor values

Hydro-geomorphic characterization	Compound factor range	Category	Sub- watersheds
Topographic ruggedness	1.47- 2.91	Very high	SW-5, SW-8, SW-9
	>2.91- 3.94	High	SW-1, SW-2, SW-6
	>3.94- 4.25	moderate	SW-11
	>4.25- 5.94	Low	SW-3, SW-4, SW-7, SW-12
	>5.94- 6.55	Very low	SW-10
Groundwater recharge potentiality	1.96- 2.62	Very high	SW-4, SW-6
	>2.62- 3.99	High	SW-2, SW-3
	>3.99- 4.7	Moderate	SW-10, SW-11
	>4.7- 5.35	Low	SW-1, SW-5
	>5.35-7.84	Very low	SW-7, SW-8, SW-9, SW-12
Soil erosion susceptibility	2.35-3.00	Very high	SW-1, SW-5, SW-9
	>3- 3.95	High	SW-2, SW-8
	>3.95- 4.76	Moderate	SW-6, SW-11
	>4.76- 5.81	Low	SW-12, SW-7, SW-4
	>5.81- 6.46	Very low	SW-3, SW-10

Conclusion

This study is an attempt to characterize the hydro-geomorphology of sub-watersheds found in the Geba River basin, which is an area of high socio-economic importance, but vulnerable to water stress, frequent drought, flooding, and soil erosion. For this purpose, the integrated approach of the Digital Elevation Model (DEM) and the Geographic Information System (GIS) was utilized. The Digital Elevation model was served as a data source from which all the necessary information was extracted, while the Geographic Information System was served as a platform for the data processing.

The methodology applied in the study involves the following approaches: Before all, the DEM representing the whole Geba river basin was decomposed into twelve sub-watersheds using GIS processing units. Next, extraction of the drainage networks of each of the decomposed sub-watersheds was performed. Following this, the geomorphic parameters that define the linear, areal, shape, and relief of the sub-watersheds were calculated using mathematical methods suggested by different experts. Then, the calculated geomorphic parameters were grouped according to their strong association with the topographic ruggedness, groundwater potentiality, and soil erosion susceptibility. Further, the compound factor of each of the parameters determining the topographic ruggedness, groundwater recharge potentiality, and soil erosion susceptibility was estimated using the weighted sum approach. Finally, the calculated value of the compound factor was used as an input to categorize the sub-watersheds into very low, low, moderate, high, and very high in terms of their topographic ruggedness, groundwater recharge potentiality, and soil erosion susceptibility.

The main findings of the whole process are the following: (i) sub-watersheds -5, sub-watershed-8, and sub-watershed- 9 are highly topographically rugged, (ii) sub-watershed - 4 and sub-watershed - 6 are the most promising sites for groundwater recharge potential, (iii) sub-watershed -1, sub-watershed- 5, and sub-watershed-9 are found to be the most susceptible for soil erosion, (iv) sub-watersheds at the very high category about the topographic ruggedness are also at the very high category about the soil erosion susceptibility, but in the very low category about the groundwater potentiality. From the findings, it can be concluded that topographic ruggedness has a strong association with soil erosion susceptibility and groundwater recharge potentiality, in which highly topographically rugged terrains are more susceptible to soil erosion and less favorable for groundwater recharge potentiality.

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Statement on the conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Availability of data and materials

Authors of this article can confirm that the necessary data supporting the conclusions of this article are included with in the article.

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