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GEOSPATIAL APPROACH FOR QUANTITATIVE ANALYSIS AND IMPLICATIONS OF DRAINAGE MORPHOMETRY OF THE ANTSOKIA, ETHIOPIA

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ABSTRACT

This study employed remote sensing data, geographic information systems, and statistical methods to analyze the morphometric features of the Antsokia watershed and its sub-watersheds. It assessed drainage network, watershed geometry, drainage texture, and relief characteristics. The Antsokia watershed is drained mainly by a sixth-order river with a dendritic pattern. The mean bifurcation ratio (Rb) was 3.9, indicating a typical branching pattern, while sub-watersheds showed higher Rb values (>5), suggesting steep terrain. The longest flow path is 42.5 km, marked by knickpoints due to lithological changes and major faults. The watershed's elongated shape indicates longer peak flows, aiding flood management. Drainage texture analysis revealed fine drainage, implying soft rock prone to erosion prevails. Most of the watershed comprises high relief and steep slopes (78 %), including hills, breaks, and low mountains. The S-shaped hypsometric curve with a hypsometric integral of 0.4 suggests the watershed is in a mature stage of geomorphic evolution and equilibrium. Sub-watershed morphometric parameters varied spatially, categorized into low, moderate, and high clusters. Overall, this study enhances understanding of Antsokia watershed's characteristics, aiding in sustainable resource management and decision-making.

Keywords: Morphometric analysis, Watershed characteristics, Remote sensing, and Geographic information system

INTRODUCTION

Sustainable livelihood and increased food production in agriculturally based developing countries require the availability of sufficient water and fertile land. In sub-Saharan Africa, unsustainable livelihoods often contribute to the degradation of important watershed resources; among the degrading watershed resources, fresh water and soil fertility take the lead in posing significant socioeconomic, ecological, and environmental roles, especially for developing countries, including Ethiopia, where a traditional agricultural-based economy is dominant. As a result of the dependency of increasing populations on traditional subsistence agriculture, most of the Ethiopian highlands are experiencing degradation of watershed resources (Wassie, 2020). Ever since people began manipulating land, various approaches and techniques were practiced to reduce degradation of watershed resources. However, system thinking or modern watershed (generally a drainage area) management started in the mid-20th century and adapted in most countries with the aim of controlling water pollution, sedimentation, soil erosion, floods, and discharge extremes.

A watershed can be defined as an area biophysically delineated by water flow, drained by a current or system of currents towards one exit point or gathering area (Bruijnzeel & Leendert, 2004). A watershed represents a logical natural unit for the management or study of water resources and, as water is intricately linked to land use and management, to land (Cheng *et al*., 2015). According to the US Environmental Protection Agency (EPA), rapid progress has been made in reducing water pollution from point discharges such as those from industrial plants and sewage treatment plants. However, problems of pollution from non-point sources such as agricultural land persist and have gained increased prominence as point sources have diminished. The EPA is promoting the watershed approach with the expectation that it will lead to further improvements in water quality.

Watershed management projects begin with the proposition that some natural resources are best managed on a watershed basis. During the last few decades, watershed management has gained recognition and importance in both environmental protection and the well-being of people living in watershed areas. For example, in its 'Bhutan 2020' policy document, the Bhutan government named watershed management as the "single most important strategy to maintain the resource base to support the national economy. A drainage basin/watershed is a land area drained by a stream and its tributaries having a common outlet for surface runoff. Studying drainage basins is vital for a better understanding of the hydrological processes.

Hydrological processes like runoff, soil erosion, and sediment transport are highly influenced by the morphometric characteristics of the drainage basin. Thus, morphometric analysis of a drainage basin is considered to be the most appropriate method for the proper planning and management of the watershed (Tufa *et al*., 2015). Morphometric analysis represents a relatively simple approach to describe the hydro-geological behavior, landform processes, soil physical properties, and erosion characteristics and, hence, provides a holistic insight into the hydrologic behavior of watersheds (Strahler, 1954).

The watershed's morphometric parameters are reflective of its hydrological response to a considerable extent and can be helpful in synthesizing its hydrological behavior and water balance. A quantitative morphometric characterization and analysis of a watershed is considered to be the most satisfactory for proper watershed management planning and implementation of soil and water conservation measures. The characterization of geomorphic attributes enables us to understand the relationship among different aspects of the basin's drainage pattern and also enables a comparative evaluation of different drainage basins developed in various geologic and climatic regimes (Gebre *et al*., 2015). In Ethiopia, watershed development planning started in the 1980s with large watersheds (Zeleke, 2004). However, large efforts remained mostly unsatisfactory due to a lack of effective community participation, a limited sense of responsibility for assets created, and unmanageable planning units (MoARD, 2005).

Ethiopia is one of the main constraints for agricultural productivity, resulting from the interaction of natural and anthropogenic factors, including erratic rainfall, rugged topography, and unsustainable land management practices, both in areas of food crops and in grazing lands, where soil erosion by water constitutes the most widespread and damaging process of soil degradation (Yaebiyo *et al*., 2015).In general, watershed degradation resulted in a long-term reduction in the quantity and quality of water and land resources, which negatively impacted the livelihoods of the rural poor, who rely on these resources for their subsistence and livelihoods. This spurred the Ethiopian government to launch an extensive soil and water conservation (SWC) program, which began in the early 1970s (Nyamekye *et al., 2015*).

In response to the famine in the northern part of the country during the period 1973-1974, for example, the World Food Programme (WFP) supported the Food for Work (FFW) project, which was launched in 1974 initially as an emergency relief initiative (Giordano & Langan, 2016). Integrated watershed management (IWM) is becoming an increasingly important concept all over the world, and attention is shifting to overall socio-economic welfare along with better water and soil conservation. The global population is continuing to grow rapidly (Basuki *et al., 2022*). The ever-increasing pressure on the natural resources is further increased in intensity by the even faster economic growth the country has witnessed in the past decades (UNEP, 2011). Unprecedented economic activity in areas such as agriculture, industry, power, and communication are affecting land-use patterns in many ways (Karpuzcu & Delipinar, 2014).

Remote sensing data, along with increased resolution from satellite imagery, makes these technologies appear poised to make a large impact on land resource management initiatives involved in monitoring of land use and land cove (LULC) mapping and change detection (Younus *et al*., 2015). These tools enable researchers to determine varying spatial ranges in semiarid regions that are undergoing severe moisture stresses due to the combined effects of rainfall variability, climate change, and growing population (Gebre *et al*., 2015). Significant advances in remote sensing technology have led to the availability of higher-quality digital elevation models (DEMs) (Gebremedhin *et al*., 2018). For instance, the availability of Shuttle Radar Topography Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEMs free of charge via http://earthexplorer.usgs.gov/ has provided new potentials in watershed-scale quantitative morphometric analysis (Fenta *et al*., 2017).

According to a recent comparative study by Thomas *et al*. (2016), topographic attributes extracted from the spaceborne (SRTM and ASTER) DEMs are in agreement with those derived from topographic maps. Their study also revealed that despite the coarser resolution (i.e., 90 m), SRTM DEM shows relatively higher vertical accuracy and better spatial relationship of topographic attributes than the finer resolution (i.e., 30 m) ASTER DEM when compared with topographic maps (Preety *et al., 2022*). Surface hydrological indications are promising scientific tools for assessment and management of water resources (Krysanova & White, 2015). Drainage morphometric analyses are a prerequisite for selection of water recharge sites, watershed modeling, runoff modeling, watershed delineation, groundwater prospect mapping, and geotechnical investigation (Rahaman *et al*., 2017).

The drainage network analysis is generally performed using the prevailing geological variation, topographic information, and structural set of a basin and their interrelationships (Saady *et al*., 2016). Digital elevation models (DEMs), such as the DEM and other types of models, were used to extract diverse geomorphological parameters of drainage basins, including drainage networks, catchment divides, slope gradients, and aspects (Ariza *et al., 2015*). Catchments are delineated automatically by using a digital elevation model (DEM) and manually by using a topographic map to delineate watersheds (Akram *et al., 2012*).

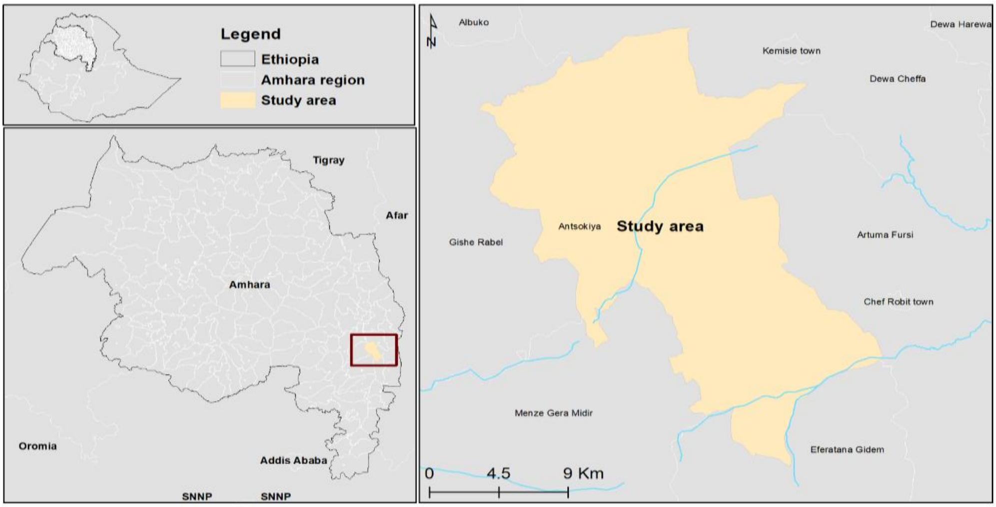
This study aims to assess the morphometric characteristics of the Antsokia watershed using GIS and remote sensing, focusing on hydrological behavior and management potential. It evaluates stream ordering, length, and bifurcation ratios to identify flood-prone areas and regions vulnerable to erosion. Additionally, spatial variability in drainage density and watershed area is analyzed to inform conservation efforts. The hypotheses suggest that higher bifurcation ratios increase flood susceptibility, higher drainage density correlates with impermeable subsoils, and the integration of GIS and remote sensing accurately delineates watershed boundaries. Addressing a gap in Ethiopian highlands research, this study demonstrates how GIS-based morphometric analysis can enhance flood risk assessment and resource management in understudied regions.

METHODS AND MATERIALS

Discerption of Study Area

Antsokia Gemza is a woreda in the Amhara Region of Ethiopia. This district is partly named for one of the districts of Shewa, Antsokia. Part of the North Shewa Zone, Antsokia Gemza is bordered on the south by Efratana Gidim, on the southwest by Menz Gera Midir, on the west by Gishe, and on the north and east by the Oromia Zone. The administrative center is Mekoy; other towns in Antsokia Gemza include Majete. Local landmarks in this district include the Tomb of Saint Gelawdewos, where the head of the Holy Emperor of that name was buried in 1562. This study was particularly conducted in the southeast part of this district, named “Mesno Locality,” and the study watershed has 11 sub-watershed areas. The Geographic Location: the area extends between 10° 30ʾ 30’’ N latitude to 39° 58ʾ 30’’ Longitude. The study area covered 148.08 km2 with an elevation range between 3057 m and 1404 m (Fig. 1).

Fig. 1: Geographic Location of Study Area.



Research Methodology

This study utilized a computer running ArcGIS 10.8 along with data that includes a 30-meter resolution Digital Elevation Model (DEM) of the study watershed extracted from the Ethiopian Elevation Model (ET_DEM). Additionally, administrative boundaries and a topographic map document were used for manual analysis and physical identification of stream features within the watershed. The study follows a sequence of hydrologic terrain analysis steps: (1) filling sinks, (2) calculating flow direction, and (3) calculating flow accumulation. An outlet point is then used to delineate the watershed, encompassing all points upstream of the defined outlet.

Stream networks are identified based on a flow accumulation threshold within the watershed, and hydrologic tools are employed to delineate stream segments and their respective catchments. The stream network is subsequently converted into vector format. This process yields a comprehensive set of hydrological information for the watershed, all derived from the DEM using the ArcGIS Toolbox, as illustrated in Figure 2, and also the formula for the morphometric parameter represented in Table 1.

Fig. 2: Schematic framework of the methodology

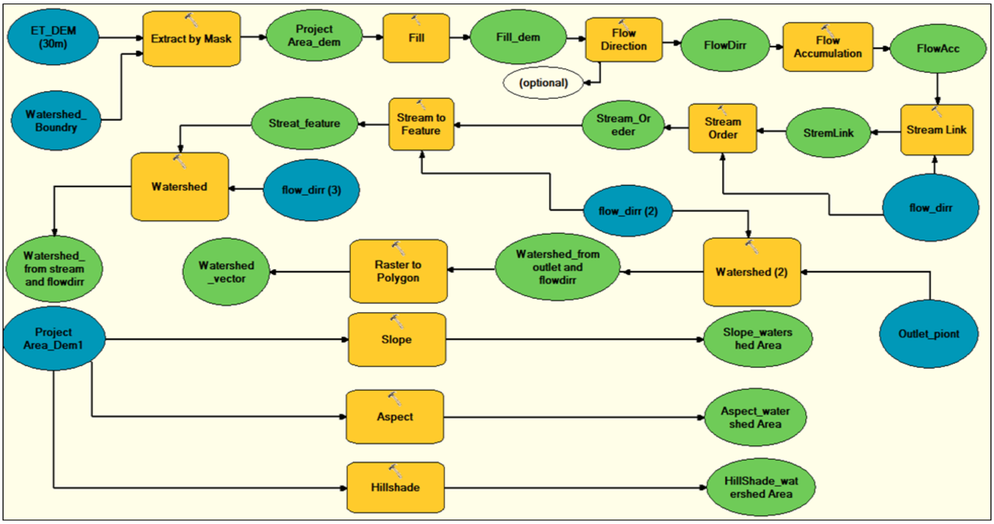


Table 1: Method (formula) to drive Statistical value of hydrological parameter

No	Character/parameter	Method/Definition	Source
1	Drainage basin area (A), Km^2	the surface area of the watershed from ArcGIS	Horton (1932)
2	Drainage basin parameter (P), Km	Length of the boundary of the watershed	Horton (1932)
3	Stream Order (U)	Hierarchical Order (rank)	Strahler (1964)
4	Basin Length (Lb), Km	1.312*Asq0.568, where A = Area of the drainage basin	Horton (1932)
5	Stream Length (Lu), Km	Length of the Stream (Km)	Horton (1945)
6	Mean Stream Length (Lsm), Km	Lsm = Lu/Nu where, Lu = total stream length of order 'U', Nu = stream length of the next higher stream order	Strahler (1964)
7	Stream length ratio (RI)	RI = Lu/(Lu-1) where, Lu = Total number of stream segment of order 'U', Lu-1 = Stream length of the next lower order	Horton (1945)
8	Bifurcation Ratio (Rb)	Rb = Nu/(Nu+1), Where, Nu = Total number of stream segments of order 'U', Nu+1 = Number of segments of the next higher order	Horton (1945)
9	Drainage density (Dd),	Km/Km2 = Lu/A, where Lu = Total length of stream and A = Area of watershed	Horton (1932)
10	Drainage texture (Dt), per Km	Dt = Nu/P, Where, Nu = Total number of streams of all orders and P = Basin perimeter measured in km	Horton (1945)

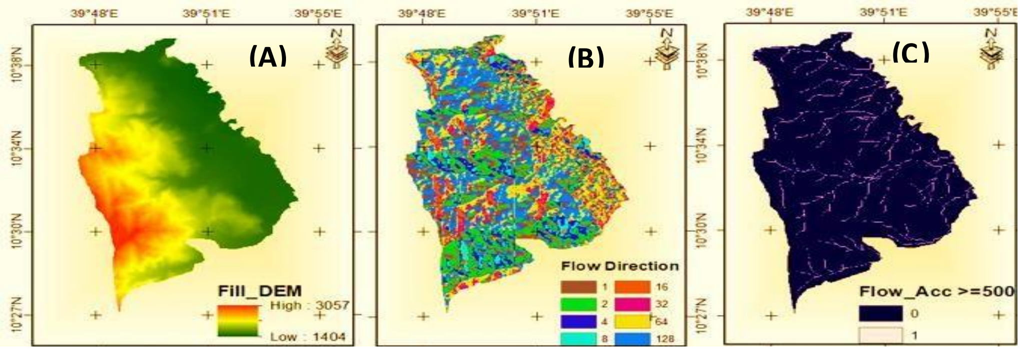
11	Texture ratio (T), per Km	T = N1/P, Where N1= Total number of first order stream and p = basin perimeter	Horton (1945)
12	Stream frequency (Fs), per Km^2	Fs = N/A, Where, N = Total number of stream and A = Area of watershed	Horton (1945)
13	Form Factor (Rf)	Rf = A/ Lbsq2, Where, A = Area of the watershed and Lb = Maximum basin length	Horton (1932)
14	Length of Over Land Flow (Lo),	Lo = 1/(2Dd), Where, Dd = Drainage density(km)	Horton (1945)
15	Circularity Ratio (Rc)	Rc = (4π A)/P2, Where, A = Area of the Watershed and P = basin Perimeter	,,
16	Elongation Ratio (Re)	Re = (2/Lb) x (A/π)0.5, Where, A = Area of the Watershed, Lb = Maximum Basin length	”
17	Infiltration number (If)	If = Fs x Dd Where Dd= Drainage density (km/km2) and Fs = Stream frequency	Faniran (1968)
18	Constant channel maintenance (C)	km2/km, C = 1/Dd, Where, Dd = Drainage Density	Schumm (1956)
19	Compactness coefficient (Cc)	Cc = (0.2821P)/A0.5, Where A = Area of the basin (km2) and P = Basin perimeter	Gravelius (1941)
20	Basin Relief (Bh)	Bh = H – h, where H and h are the elevations of highest and lowest point of the watershed	Strahler (1952)
21	Relief Ratio (Rh)	Relief Ratio (Rh) Rh = Bh/Lb, Where, Bh = Basin Relief, Lb = Basin length	Schumm (1956)
22	Relative relief (Rr)	Rhp = H x 100/P, Where H = Maximum basin relief and P = basin perimeter	Melton (1957)
23	Ruggedness number (Rn)	Rn = Bh x Dd, Where, Bh = Basin Relief and Dd = Drainage Density	Strahler (1954)
24	Dissection index (Dis)	Dis = Bh/Hmax, Where Bh= Basin Relief and Hmax = Maximum relief	Gravelius (1941)

RESULTS

Result of hydrological parameter

This section presents maps of hydrological elements such as fill, flow direction, flow accumulation, stream links, stream order, and watershed boundaries, along with surface features like slope, aspect, hill-shade, and contour lines. The analysis evaluates 24 morphometric parameters for 11 sub-watersheds using methods and equations from Table 1. Fig. 3 shows the extracted hydrological parameters, including filled DEM, flow direction, flow accumulation, and stream order. Comparisons and discussions of these parameters are provided for each sub-watershed.

Fig. 3: Fill, Flow Accumulation, Direction of study area (DEM)

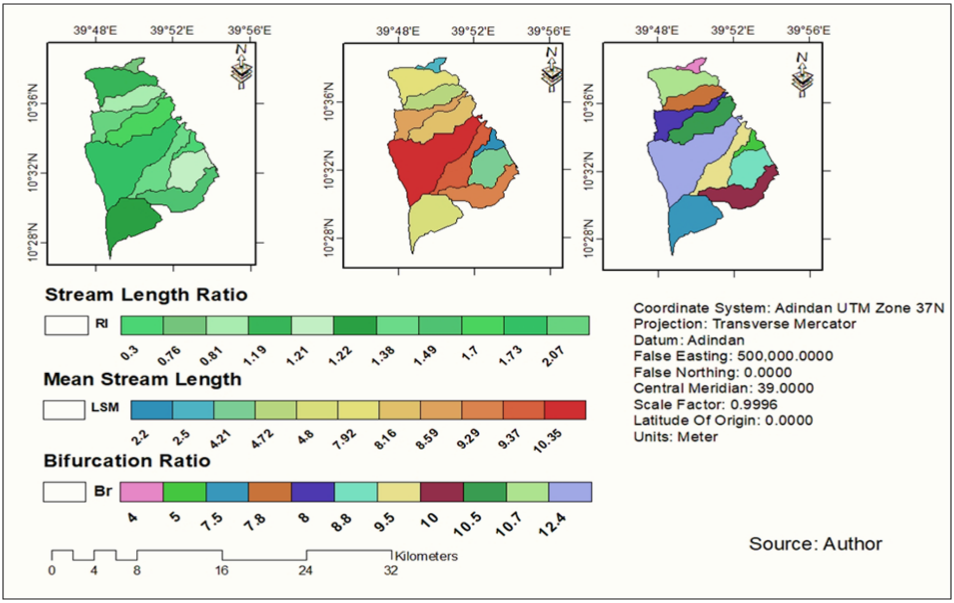


The Flow Direction tool generates a raster showing the direction water flows from each cell to its steepest downslope neighbor, using eight specific values (1, 2, 4, 8, 16, 32, 64, 128) to indicate flow direction, such as west (16) or east (1). The flow accumulation raster depicts the total accumulated flow into each cell, identifying areas of high concentration (white) as stream channels and low concentration (black) as regions with minimal flow. Cells with zero accumulation highlight ridges or topographic highs, providing a comprehensive view of the landscape's hydrological patterns (Fig. 3).

Quantitative result of linear parameter

Linear aspects are measurements of the linear feature of the watershed and used to evaluate the morphometric characteristics of project area watersheds or sub-watersheds; stream network, stream length, stream order (U), basin length (Lb), stream length (Lu), mean stream lengths (Lsm), stream length ratio, and bifurcation ratio (Rb) are discussed below (Fig. 4).

Fig. 4: Stream length Ratio (RI), Mean (LSM) and Bifurcation Ratio (Br)



This study applied Strahler's stream ordering system, classifying the watershed up to the 4th order. The number of streams (Nu) was 228, 61, 17, and 4 for the 1st to 4th orders, respectively. Total stream lengths (Lu) were 4.37 km to 76 km across the sub-watersheds SW1-SW11. Results show that stream length decreases with increasing order, reflecting typical drainage network patterns.

Table 2: Stream Length and Mean Stream Length

	Stream Length (LU).km					Mean Stream Length (Lsm)				
SW	**1st**	**2nd**	**3rd**	**4th**	**Total**	**1st**	**2nd**	**3rd**	**4th**	**Total**
SW1	2.490	1.88	0.00	0.00	4.370	0.62	1.88	0.00	0.00	2.50
SW2	18.66	7.70	5.97	0.00	32.33	0.67	1.28	5.97	0.00	7.92
SW3	9.160	8.41	3.39	0.00	20.96	0.65	0.68	3.39	0.00	4.72
SW4	10.11	4.30	7.06	0.00	21.47	0.67	0.86	7.06	0.00	8.59
SW5	15.23	8.94	3.43	2.51	30.11	0.73	1.49	3.43	2.51	8.16
SW6	4.380	1.32	0.00	0.00	5.70	0.88	1.32	0.00	0.00	2.20
SW7	13.75	10.35	3.40	0.43	27.90	0.60	1.48	1.70	0.43	4.21
SW8	18.44	6.730	6.85	0.00	32.10	0.84	1.68	6.85	0.00	9.37
SW9	45.21	16.21	7.71	6.87	76.0	1.03	1.35	1.10	6.87	10.35
SW10	14.11	7.950	7.38	0.00	29.40	0.59	1.33	7.38	0.00	9.29
SW11	20.25	7.41	6.30	0.01	33.90	0.72	0.93	3.15	0.00	4.80
Total	171.8	81.2	51.5	9.80	314.3	8.00	14.3	40.0	9.8	72.1

LU = stream Length, Lsm = Mean stream Length, SW sub watershed, Tot=Total for Lsm and Lu, km= kilometer, 1st, 2nd, 3rd, 4th, 5th =Show stream order of basin from first-fifth order respectively.

Mean Stream Length

The mean stream length (Lsm) was calculated by dividing the total stream length of order 'u' by the number of streams of that order. Lsm varied from 2.02 km to 10.45 km, with lower-order streams exhibiting greater values than higher orders, likely due to slope and topography variations. The mean stream lengths for the sub-basins (SW1-SW11) were 2.50 km, 7.92 km, 4.72 km, 8.59 km, 8.16 km, 2.20 km, 4.21 km, 9.37 km, 10.35 km, 9.29 km, and 4.80 km. Generally, mean stream length increases from first to higher orders, while total stream length decreases. Table 3: Stream length Ratio and Bifurcation Ratio of each sub watershed.

Stream Length Ratio

Stream length ratio (RL) represents the mean stream length of one order compared to the next lower order. In this study, all sub-watersheds, except SW5, exhibit a geometric progression in stream lengths, with RL increasing with stream order, as shown in Table 3.

Table 3: Stream Length Ratio and Bifurcation Ratio

	Stream Length Ratio, RI =Lu/(Lu-1)				Bifurcation Ratio (Rb), RB=Nu/(Nu+1)			
SB	**2nd/1st**	**3rd/2nd**	**4th/3rd**	**Total**	**1st/2nd**	**2nd/3rd**	**3rd/4th**	**Total**
SW1	0.76	0.00	0.00	0.76	4.0	0.0	0.0	4.0
SW2	0.41	0.78	0.00	1.19	4.7	6.0	0.0	10.7
SW3	0.40	0.40	0.00	0.81	2.8	5.0	0.0	7.8
SW4	0.43	1.64	0.00	2.07	3.0	5.0	0.0	8.0
SW5	0.59	0.38	0.73	1.70	3.5	6.0	1.0	10.5
SW6	0.30	0.00	0.00	0.30	5.0	0.0	0.0	5.0
SW7	0.75	0.33	0.13	1.21	3.3	3.5	2.0	8.8
SW8	0.36	1.02	0.00	1.38	5.5	4.0	0.0	9.5
SW9	0.36	0.48	0.89	1.73	3.7	1.7	7.0	12.4
SW10	0.56	0.93	0.00	1.49	4.0	6.0	0.0	10.0
SW11	0.37	0.85	0.00	1.22	3.5	4.0	0.0	7.5
Total	5.3	6.8	1.8	13.8	42.9	41.2	10.0	94.1

LR = stream Length ratio, Lsm = Mean stream Length, SB sub-basin, RB, Bifurcation Ratio, Tot=Total, 1st, 2nd, 3rd, 4th, 5th =Show stream order of basin first-fifth order respectively.

Table 4: Area, perimeter, basin length and stream number of each sub-basin/watershed

	Number of stream (NU)					Area (km2)	Basin Length	Perimeter	
SW	1st	2nd	3rd	4th	Total		(Lb).km	(p).km	100/P
SW1	4	1	-	-	5	2.070	1.98	8.34	11.99
SW2	28	6	1	-	35	14.38	5.96	19.62	5.10
SW3	14	5	1	-	20	9.320	4.66	15.59	6.41
SW4	15	5	1	-	21	10.44	4.97	23.13	4.32
SW5	21	6	1	1	29	13.91	5.85	20.79	4.81
SW6	5	1	-	-	6	2.960	2.43	10.82	9.24
SW7	23	7	2	1	33	12.48	5.50	16.22	6.17
SW8	22	4	1	-	27	13.36	5.72	24.59	4.07
SW9	44	12	7	1	64	37.75	10.3	33.41	2.99
SW10	24	6	1	-	31	13.56	5.77	23.32	4.29
SW11	28	8	2	1	39	17.86	6.75	20.00	5.00
Total	228	61	17	4.0	310	148.1	59.9	215.8	64.4

U = stream order, Nu = stream number, SB sub-basin, A= Area of basin, Lb= Basin length, p= perimeter of each basin

The perimeters of the sub-watersheds SW1-SW11 range from 8.34 km to 33.41 km, indicating varying shapes from circular to elongated (Table 5). The majority exhibit high drainage density, while SW6 and SW11 show lower values, suggesting different topographic conditions (Fig. 5a). Basin length (Lb) aligns with these variations, highlighting differences in watershed morphology.

Table 5: Quantitative value of Aerial parameters for each sub watershed of study area

.	Statistical Result OF Areal Aspect In each Sub Watershed/Basin									
S-W	**Dd**	**Dt**	**Fs**	**ff**	**Rc**	**Re**	**Lo**	**If**	**C**	**Cc**
SW1	2.11	0.60	2.42	0.53	0.37	1.15	0.24	5.10	0.47	2.27
SW2	2.25	1.78	2.43	0.40	0.47	1.75	0.22	5.47	0.44	0.77
SW3	2.25	1.28	2.15	0.43	0.48	1.60	0.22	4.83	0.44	0.94
SW4	2.06	0.91	2.01	0.42	0.25	1.64	0.24	4.14	0.49	1.25
SW5	2.16	1.39	2.08	0.41	0.40	1.74	0.23	4.51	0.46	0.84
SW6	1.93	0.55	2.03	0.50	0.32	1.25	0.26	3.90	0.52	2.06
SW7	2.24	2.03	2.64	0.41	0.60	1.70	0.22	5.92	0.45	0.73
SW8	2.40	1.10	2.02	0.41	0.28	1.72	0.21	4.84	0.42	1.04
SW9	2.01	1.92	1.70	0.35	0.42	2.16	0.25	3.41	0.50	0.50
SW10	2.17	1.33	2.29	0.41	0.31	1.73	0.23	4.96	0.46	0.97
SW11	1.90	1.95	2.18	0.39	0.56	1.84	0.26	4.15	0.53	0.63
Total	23.5	14.9	23.9	4.7	4.5	18.3	2.6	51.2	5.2	12.0

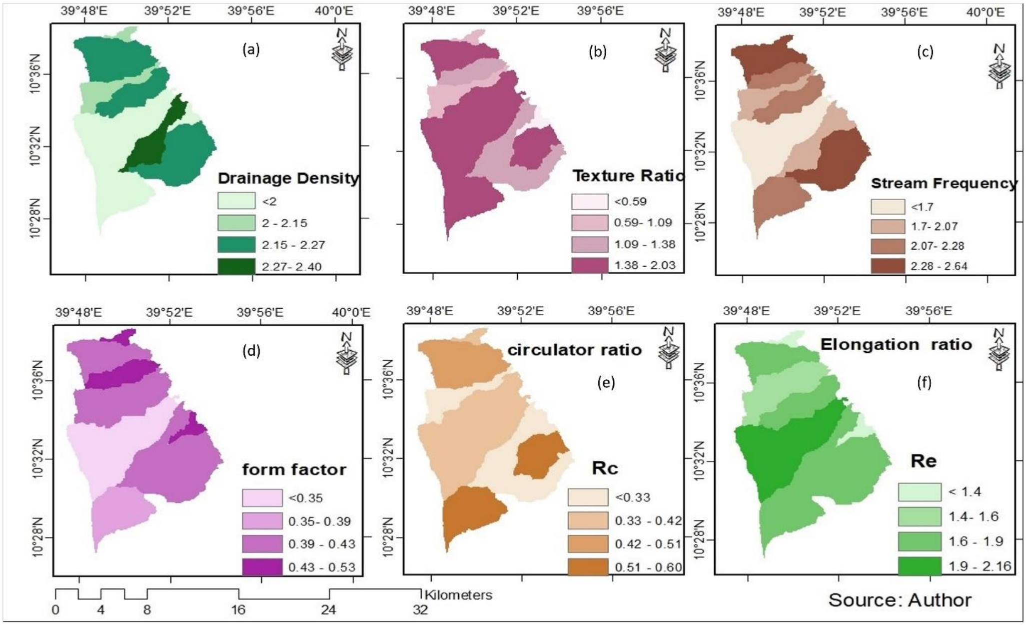
Dd= Drainage Density, Dt =Drainage texture, Fs = stream frequency, ff= form factor, Rc= circular ratio, Re= elongation ratio, Lo=length over lad, If= infiltration number, C=constant channel, CC= compactness coefficient

Drainage Texture (Dt)

Drainage density, defined as the total number of stream segments of all orders per perimeter, varies among the sub-watersheds SW1-SW11. According to the classification, all sub-watersheds except SW7 exhibit a very coarse texture with drainage densities of less than 2, while SW7 falls between 2 and 4, indicating a coarse texture (Table 5, Fig. 5b).

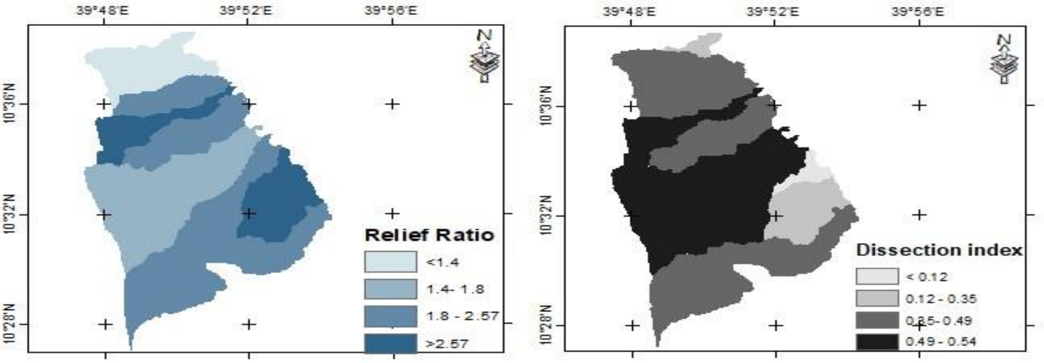
The form factor (ff) indicates that SW9 and SW11 have elongated shapes with values less than others, suggesting flatter peak flows (Table 6, Figure 5d). Stream frequency (Fs) ranges from 1.70 to 2.64 per km², reflecting increased runoff potential (Table 6, Fig. 5c). The circulatory ratio (Rc) and elongation ratio (Re) suggest that lower elongation correlates with higher relief. The length of overland flow (Lo) varies from 0.21 km to 0.26 km, indicating differences in surface slope (Table 5). The constant of channel maintenance (C) ranges from 0.42 to 0.53 sq km/km, highlighting the basin's relief characteristics, while compactness coefficient (Cc) values range from 0.50 to 2.27, indicating deviations from circularity (Table 6). Basin relief (Bh) shows a maximum elevation of 3045 m in SW11 and a minimum of 1400 m in SW5, both classified under the Woina Dega agro-ecological zone (Table 6).

Fig. 5: Reclass Map Showing Aerial Aspects of study watershed



Source: Author

Fig. 6: Reclass Map showing selected Relief Aspects of study watershed



Relief Ratio (Rh)

The respective variation and comparison value for relief ratio of subbasins/watersheds are present (Table 6 & Fig. 6).

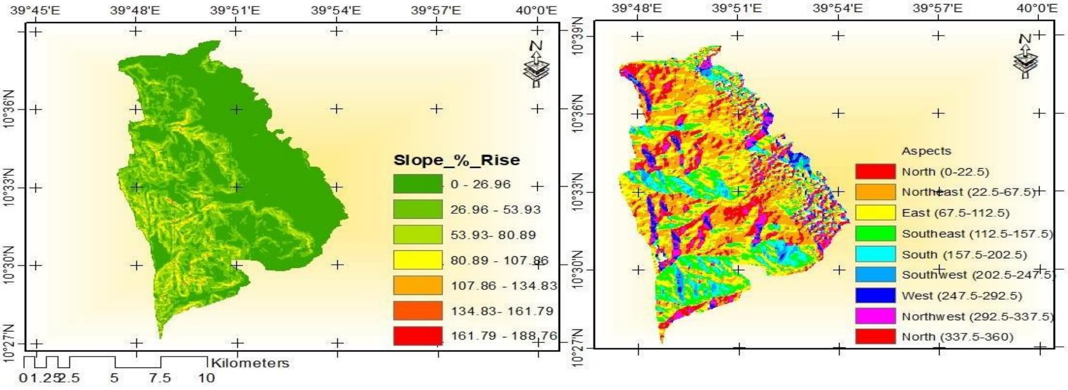
Relative relief (Rr) is reported as a ratio of maximum relief to the basin perimeter, with values shown in Table 6. The dissection index (Dis), indicating the degree of vertical erosion, ranges from 0 to 1, where lower values signify flatter landscapes and higher values indicate steep slopes (Table 6). In this analysis, the dissection index for all sub-watersheds (SW1-SW11) is less than 1, suggesting predominantly gentle terrain with limited vertical relief.

Table 6: Values of Relief morphometric parameters for each sub watershed/basin of project area

Quantitative value OF relief Aspect							
SW	**H-max**	**h-min**	**Bh**	**Rh**	**Rr**	**Rn**	**Dis**
SW1	1637	1427	210	105.9	19628	443.3	0.13
SW2	2217	1411	806	135.1	11300	1812.1	0.36
SW3	2430	1405	1025	219.9	15587	2305.2	0.42
SW4	2765	1405	1360	273.5	11954	2796.9	0.49
SW5	2703	1400	1303	222.6	13001	2820.5	0.48
SW6	1613	1441	172	70.8	14908	331.2	0.11
SW7	1978	1440	538	97.8	12195	1204.0	0.27
SW8	2837	1425	1412	246.9	11537	3384.1	0.50
SW9	3064	1421	1643	159.2	9171	3307.8	0.54
SW10	2667	1447	1220	211.5	11437	2648.7	0.46
SW11	3045	1673	1372	203.4	15225	2609.6	0.45
Total	26956	15895	11061	1946.6	145942	23663	4.20

SW= Sub watershed Basin Relief (Bh), Relief Ratio (Rr), Relative relief (R) Rhp, Ruggedness number (Rn), Dissection index (Dis) Dis = H/Hmax, Where H = Basin Relief and Hmax = Maximum relief Basin.

Fig. 7: Slope and Aspect Map



Watershed average slope provides insights into the topography, calculated as the maximum rate of elevation change between locations. The slope classifications include Flat (0-26°), Gentle (26-53°), Moderately Gentle (53-80°), Very Gentle (80-107°), Steep (107-134°), Moderate Steep (134-161°), and Very Steep (>161°), as depicted in Fig. 7. The basin slope (Sb) and aspect map generated from the study area's elevation illustrate the varying inclines and orientations across the watershed (Table 7).

Table 7: Aspect of (combined sub basin) watershed of project area

Degree of bearing	Quadrant/direction of bearing
0-22.5^0	North
22.5 -67.5^0	North east
67.5-112.5^0	East
112.5-157.5^0	South east
157.5-202.5^0	South
202,5-247.5^0	South west
247.5-292.5^0	west
292.5-337.5^0	North east
337.5-360^0	North

The aspect of the study watershed showed as in the above figure14 and table7 represent the respective bearing of slope from o to 360^o

Relationship between different Morphometric Variable

Table 8 presents the correlation results, where the correlation coefficient (r) values range from -1 to +1, indicating the strength and direction of the association between variables. A positive sign (+) signifies a direct relationship, meaning that an increase in one variable corresponds to an increase in the other, and vice versa. Conversely, a negative sign (-) indicates an inverse relationship, where an increase in one variable is associated with a decrease in the other (Fig.8).

Fig. 8: Graphs show relationship among selected morphometric parameters for the 11 sub-watersheds

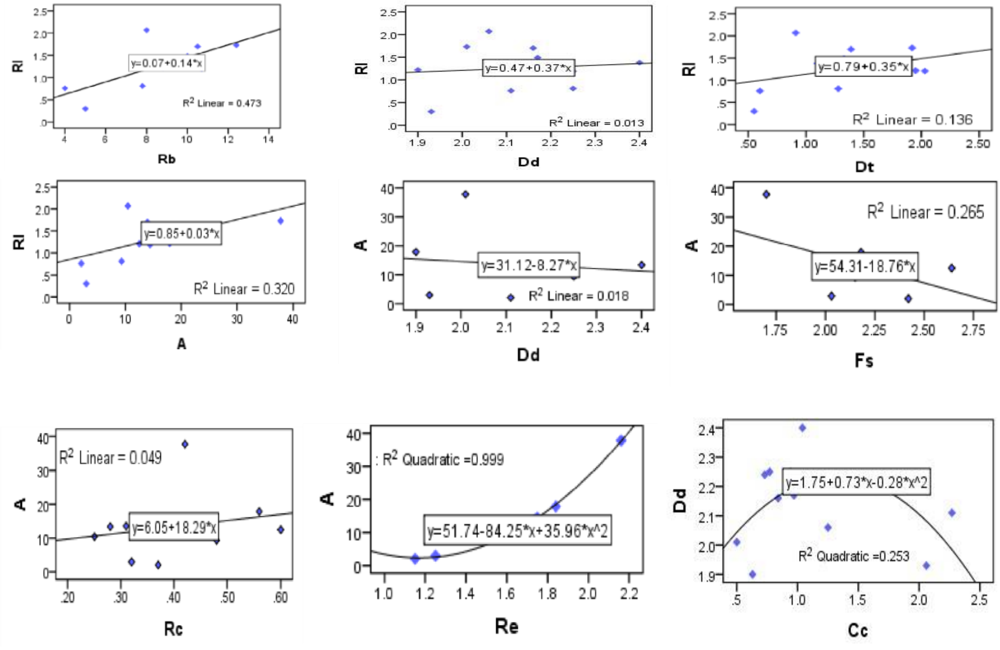


Table 8: Correlation matrix among selected morphometric parameters for the 11 sub-watersheds

	RI	Rb	A	Lb	Dd	Dt	Fs	ff	Rc	Re	Lo	If	C	Cc	Rh	Rn	Dis
RI	1.00																
Rb	0.688*	1.00															
A	0.566	0.798**	1.00														
Lb	0.644*	0.871**	0.977**	1.00													
Dd	0.112	0.316	-0.134	-0.031	1.00												
Dt	0.369	0.687*	0.703*	0.78**	0.063	1.00											
Fs	-0.313	-0.286	-0.515	-0.444	0.334	0.145	1.00										
ff	-0.692	-0.901	-0.84	-0.94	-0.116	-0.82	0.308	1.00									
Rc	-0.197	0.109	0.22	0.259	-0.049	0.75**	0.469	-0.292	1.00								
Re	0.687*	0.902**	0.92**	0.98**	0.052	0.81**	-0.378	-0.97	0.278	1.00							
Lo	-0.167	-0.352	0.128	0.008	-0.98	-0.132	-0.387	0.167	-0.019	-0.091	1.00						
If	-0.178	-0.058	-0.431	-0.332	0.69*	0.162	0.91**	0.165	0.354	-0.246	-.729*	1.00					
C	-0.092	-0.304	0.159	0.065	-0.99	-0.042	-0.368	0.072	0.039	-0.014	.985**	-.713*	1.00				
Cc	-0.589	-0.852	-0.74	-0.86	-0.202	-0.89	0.118	0.96**	-0.481	-0.93	0.271	-0.02	0.17	1.00			
Rh	0.686*	0.37	0.191	0.313	0.247	0.029	-0.402	-0.457	-0.353	0.41	-0.28	-0.21	-0.216	-0.411	1.00		
Rn	0.783**	0.752**	0.66*	0.758**	0.22	0.406	-0.558	-0.81	-0.162	.808**	-0.23	-0.33	-0.173	-0.727	.837**	1.00	
Dis	0.816**	0.783**	0.68*	0.781**	0.198	0.474	-0.5	-0.85	-0.088	.840**	-0.23	-0.29	-0.163	-0.78	.832**	.988**	1.00

*The full names of parameters are given in (Table 1), * Statistically significant correlations at $p < 0.05$*

DISCUSSION

This study classified stream orders from 1 to 4 in the Antsokia watershed using Strahler's system and ArcGIS tools. First-order streams exhibited the longest cumulative lengths, decreasing with higher orders. The mean stream length varied between 2.02 km and 10.45 km, correlating with flatter areas. A bifurcation ratio (Rb) ranging from 2 to 6 indicated increased surface runoff potential in higher value regions. Areal parameters revealed that smaller sub-watersheds like SW1 and SW6 had lower water volumes, while SW9 had higher streamflow. Most sub-watersheds featured impermeable subsoils, except SW6 and SW11, which showed greater permeability.

Stream ordering is a fundamental step in the morphometric analysis of drainage basins, providing insight into the extent of stream branching within a watershed. The Strahler method, a modification of Horton's system, is widely used due to its simplicity and effectiveness in classifying stream networks (Strahler, 1954). In this hierarchical ranking method, first-order streams have no tributaries, second-order streams have only first-order tributaries, and so on. This structure helps to characterize the hydrological and geomorphological dynamics of watersheds.

Stream length is a critical hydrological parameter reflecting the runoff potential and flood behavior of a drainage basin. Higher stream lengths are typically associated with gentler slopes and smoother terrain, while shorter stream lengths indicate steeper slopes and more rugged landscapes (Dubey *et al*., 2015). The total stream length generally decreases as stream order increases, which is consistent with Horton's laws of stream length (Horton *et al*., 1954). This relationship provides insights into the geological and geomorphological evolution of the watershed and helps predict flood risks and surface runoff patterns.

The mean stream length is an important hydrological characteristic that reflects the drainage network's structure and its associated surfaces (Strahler, 1954). The observed variation in Lsm suggests that lower-order streams, typically found in steeper areas, may contribute to greater lengths due to their more intricate branching. This trend emphasizes the relationship between stream order, slope, and topography. As the stream order increases, the cumulative stream length decreases, illustrating the typical hierarchical organization of drainage networks. Understanding these patterns can provide insights into the hydrological behavior of the watershed, influencing water flow, sediment transport, and flood dynamics.

The increasing stream length ratios among sub-watersheds reflect a hierarchical structure critical for understanding drainage networks (Farhan *et al*., 2016). The consistent geometric progression, except in SW5, underscores the influence of geological variations on stream morphology and hydrological dynamics. These changes highlight the ongoing evolution of the landscape, emphasizing the interplay between geological materials and hydrological processes. Basin area is a fundamental factor in morphometric analysis, as it directly influences the volume of water generated from a drainage sub-basin and its capacity for stream flow (Smith, 1950).

The findings indicate that smaller areas like SW1 and SW6 are associated with lower stream flow, suggesting limited water generation potential. Conversely, SW9's larger area correlates with increased stream water volume, highlighting the importance of basin area in determining hydrological behavior across sub-watersheds. The relatively equal area and topographic values of the other sub-watersheds indicate similar hydrological responses, underscoring the role of area in watershed management and hydrological modeling. Basin perimeter plays a crucial role in determining the shape of drainage basins, with shorter perimeters resulting in more circular shapes, while longer perimeters create narrower and more elongated basins. Additionally, basin length, measured from the outlet to the water divide, is integral to understanding watershed morphology (Horton, 1945). The observed high drainage density in most sub-watersheds suggests significant topographic variation and potentially impermeable subsurface materials, indicating a need for rehabilitation and conservation efforts. In contrast, the lower drainage densities of SW6 and SW11 may suggest more stable geological conditions, emphasizing the importance of considering basin shape and drainage characteristics in watershed management.

Horton (1945) suggests that drainage texture reflects the characteristics of the underlying surface, with impermeable areas exhibiting a higher density of drainage lines. The observed drainage density patterns align with Smith's (1950) classification, indicating variations in hydrological behavior across the sub-watersheds.

The form factor provides insight into the flow characteristics of the basins, with elongated basins exhibiting longer duration flood flows, facilitating easier management than circular basins. The observed stream frequency supports the notion that increased frequency corresponds to higher runoff, highlighting the importance of drainage density in hydrological behavior. The circulatory and elongation ratios reinforce the relationship between relief and basin shape, suggesting that lower elongation ratios are linked to steeper slopes. Additionally, the length of overland flow serves as an indicator of surface slope steepness, with implications for runoff dynamics.

The constant of channel maintenance emphasizes the landform size needed to support channel development, while the compactness coefficient reflects the basin's deviation from circularity, affecting discharge concentration. Overall, these morphometric parameters illustrate the hydrological and geomorphic characteristics of the study area, which align with established frameworks in watershed analysis.

The relative relief provides insights into the basin's morphological characteristics, where a lower value may indicate less pronounced topographic features. The dissection index, as defined by Sukristiyanti *et al.* (2017), helps to understand the degree of landscape dissection, supporting effective land use planning and erosion management in the studied area. Higher dissection indices typically signify significant vertical erosion, potentially impacting drainage patterns and watershed management strategies (Pareta *et al.*, 2011). Thus, the findings underscore the need for ongoing assessment of the physical landscape to inform sustainable practices. Understanding watershed slope is essential for assessing hydrological processes and land use planning. The classification of slopes indicates the potential for erosion and runoff, influencing sediment transport and water management strategies. As noted by Panda (2016), the aspect map further complements slope analysis by revealing the directional orientation of the watershed, which can affect microclimates and vegetation patterns. Such detailed topographical insights are crucial for developing sustainable practices and mitigating land degradation.

The correlation coefficients provide essential insights into the relationships between variables in the study. Positive correlations suggest complementary dynamics, while negative correlations may highlight competing influences. Understanding these relationships is crucial for guiding further research and practical applications in the relevant fields. Therefore, the analysis of correlation strengthens the foundation for informed decision-making and effective resource management in watershed studies (Smith, 1950; Johnson & Lee, 2018; Farhan, 2017).

CONCLUSION

A comprehensive understanding of hydrology and associated environmental risks is crucial for the effective and sustainable management of natural resources. This study utilized integrated remote sensing and GIS-based hydrological analysis to assess the watershed characteristics of the Mesno watershed and its sub-watersheds. The analysis revealed that the watershed is drained by four-order rivers across 11 sub-watersheds. The distribution of stream orders indicates that these sub-basins are predominantly situated in mountainous and highly dissected regions with steep slopes and largely homogeneous geological materials. Notably, all sub-watersheds except SW1 exhibited bifurcation ratios greater than 5, suggesting a geologically mountainous terrain characterized by low infiltration rates and a propensity for flash floods. Most sub-watersheds displayed drainage density values below 2, indicating a very coarse texture, while SW7 recorded a drainage density between 2 and 4, reflecting coarse texture. Overall, the study encompassed 11 sub-watersheds and derived 23 morphometric parameters from three perspectives—areal, linear, and relief—demonstrating considerable spatial variability. This analysis contributes valuable insights for improved management and planning activities within the study area, supporting sustainable watershed management strategies.

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CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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