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MORPHO-TECTONIC ANALYSIS OF TEKEZE WATERSHED IN ETHIOPIA USING GEOINFORMATICS

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Abstract

This study examines the morpho-tectonic settings of the drainage system in the northwestern Ethiopian plateau by focusing on the Tekeze River. The plateau is underlain by Precambrian crystalline rocks, overlain by EOCENE and Late Oligocene basalts. An attempt is made to study the underlying geology of Tekeze river basin and its significance in morphometry e.g., linear, relief and areal parameters. Further to analyze the influence of topography and geology on morphometry integrating Remote Sensing data and GIS techniques. The study used ArcGIS software for the computation, delineation of the boundary and morphometric analysis of the watershed using topographical maps and SRTM DEM data. Total area of watershed is 84738.55 Sq. Km. Total numbers of 18 rock types were mapped out in watershed and most of the area is covered by the Basalts (36.01%). The steep relief explained by complex geological history represented in major geological terrains starting from Archaen (about 40 billion years ago) till Quarternary period (about 11 thousand years ago) and marine sediments occurring in the western part. The Quantitative analysis of drainage network shows that the river is having the dendritic pattern. The drainage density is low which indicates the coarse drainage pattern. Drainage texture, stream frequency and the form factor of the watershed are 0.04, 0.12 and 0.69 respectively. The bifurcation ratio of the watershed ranges from 1.68 to 12 and the elongation ratio is 0.78 which refers to high relief of the study area. The mean bifurcation ratio of the whole watershed is 13.71 indicating that the drainage pattern is greatly influenced by geological structures.

Key Words: *Morphometric Analysis, Watershed, Geology, GIS, Drainage Density, Tekeze River, Ethiopia.*

Introduction

The development of a drainage system over space and time is influenced by several variables such as geology, structural components, geomorphology, soil and vegetation of an area through which it flows (Magesh *et al*., 2013). The development of stream networks can be better understood by studying the nature and type of drainage patterns and by a quantitative morphometric analysis (Horton, 1945; Strahler, 1964). It provides a quantitative description of the drainage system, which is an important aspect of the characterization of basins Strahler, 1964). The measurements are performed through measurement of linear, aerial, relief, gradient of channel network and contributing ground slope of the basin (Nautiyal, 1994; Nag and Chakraborty, 2003; Magesh *et al*., 2013). Morphological characteristics such as stream order, drainage density, channel slope, relief, length of overland flow, stream frequency and other morphological aspects of watershed are important in understanding the hydrology (Romshoo *et al*., 2012). The basin morphometric characteristics of various basins have been studied by many researchers using conventional methods (Romshoo *et al*., 2012 and Smith, 1950) and remote sensing and GIS methods (Shah and Babar, 2009; Lattman and Perizek, 1964; Bedi and Bhan, 1978; Raju *et al*., 1985; Satyanarayana, 1991). In various researches, morphometric analyses were used for basin characterization (Srinivasa *et al*., 1997; Sinha *et al*., 1990; Goswami *et al*., 1996).

Application of remote sensing provides a reliable source for the preparation of various thematic layers for morphometric analysis. The advent of geographic information systems (GIS) allowed the digital extraction of morphometric parameters from digital elevation models (DEMs), for the quantitative characterization of landforms (Patil *et al*., 1999; Burrough *et al*., 1998). The processed DEM can be used for generating the stream network and other supporting layers. Geographical information systems (GIS) have been used for assessing various basin parameters, providing flexible environment and powerful tool for determination, interpretation and analysis of spatial information related to river basins. In many cases such technology has enabled researcher to determine varying spatial ranges in semi-arid regions which are undergoing severe moisture stresses due to the combined effects of rainfall variability, climate change and growing population (Wilson and Gallant, 2000; Singh *et al*., 2011; Grohmann *et al*., 2007). In the present study Digital elevation models (DEMs), such as from the ASTER and other types of models were used to extract diverse geomorphological parameters of drainage basins, including drainage networks, catchment divides, slope gradient and aspect, and upstream flow contributing areas (Panhalkar, 2014; Mark, 1984). I present geomorphological quantification of Tekeze River in the mountainous terrain of the North Western Ethiopian highland. I examined 20 DEM-derived morphometric parameters, and analysed these parameters have a direct bearing upon the underlying geomorphol ogical characteristics.

Study Area

The study was conducted in Tekeze watershed lying in north western Ethiopian plateau only. Tekeze is also known as the Takkaze and is a major river of Ethiopia. It rises in the central Ethiopian Highlands near Mount Qachen within Lasta, from where it flows west, north, then west again, forming the westernmost border of Ethiopia and Eritrea from the confluence of the Tomsa with the Tekezé at 14°11′N 37°31.7′E to the tri point between the two countries and Sudan at 14°15′27″N 36°33′37″E (Figure 1). It carves its channel through the Adigrat formation and then the Precambrian crystalline rocks by navigating its way around Mount Ras

Dashen. After entering northeastern Sudan at the tri point it joins the Atbarah River, which is a tributary of the world's largest river i.e., Nile. The length of Tekeze River in Ethiopia is 608 km and its average elevation is 1850 m amsl (Figure 2).

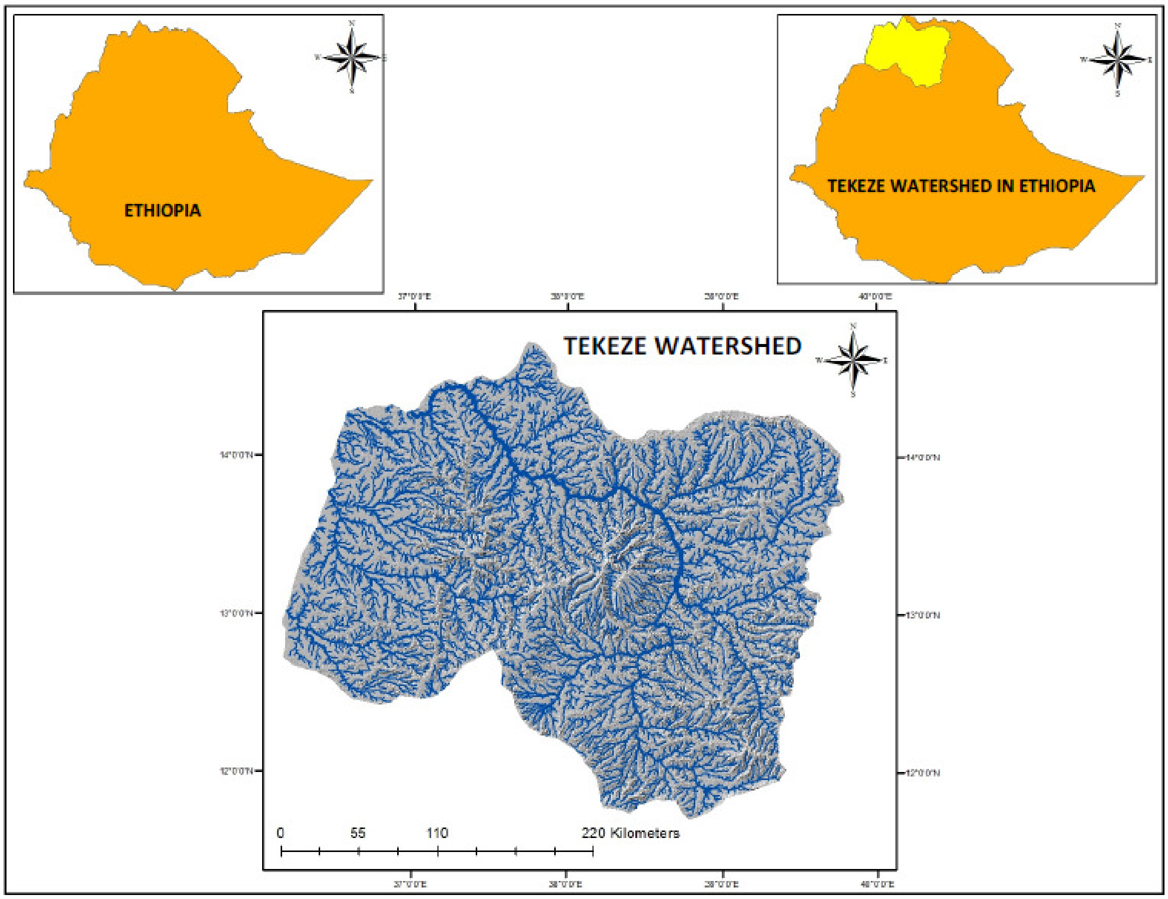


Figure 1: Map of Ethiopia showing Study Area

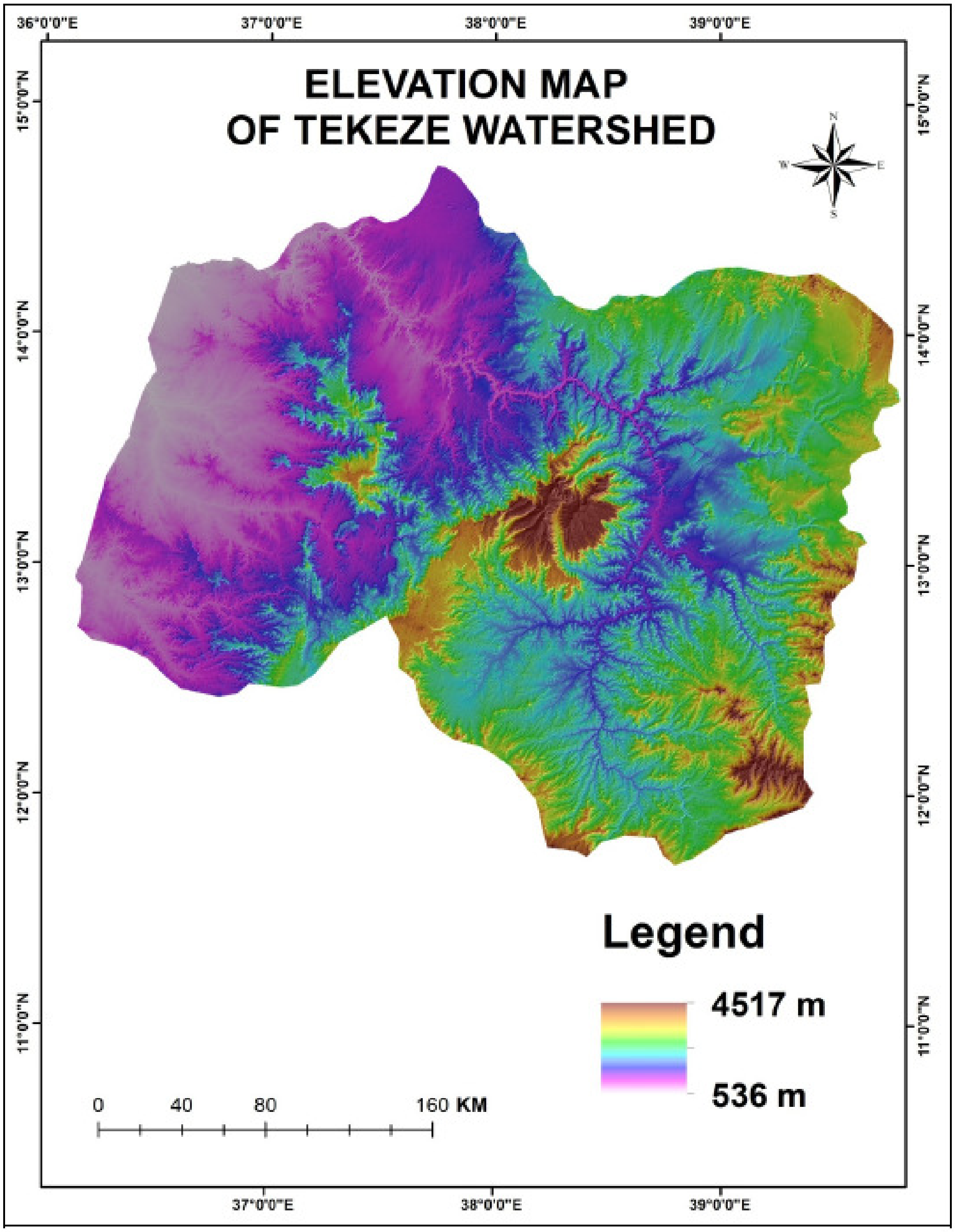


Figure 2: Elevation map of Tekeze watershed

Methodology

Extraction of River Basin and Stream Network

The Tekeze river basin was extracted from the Shuttle Radar Topographic Mission (SRTM) Digital ElevationModel (DEM) with a spatial resolution of 90 data downloaded from USGS website. The Watershed was delineated by using various geoprocessing techniques and morphometric analysis was carried out using ArcHydro and Hydrology tool in ArcGIS 10 as shown in the methodology chart (Figure 3). Based on the drainage order, the drainage channels were classified into different orders (Strahler, 1964). The highest stream order in the study area was computed as seventh. The perimeter, cumulative length of streams and basin length were measured in GIS and are expressed as A, P, L and Lb respectively. Parameters such as stream number (Nu), stream order (U) , stream length (Lu), stream length ratio (RL), bifurcation ratio (Rb), relief ratio (R/L), elongation ratio (Re), drainage density (Dd), drainage texture (T), form factor (Ff)circulatory ratio (Rc) and elongation ratio (Re) have been analysed using the standard mathematical formulae given in Table 1 (Strahler, 1964). Moreover, the aspect and slope map of the study area were derived from the STRM DEM using the aspect and slope tool in ArcGIS 10 Spatial analyst module.

Preparation of Geological Map

The geological map was procured from the Geological Survey of Ethiopia. This map was digitized in the form of different polygons representing different rock groups and their respective rock types in ArcGIS 10. Accuracy assessment of the vector geological map for entire study area was done. All the geological classes were numbered map-wise and sample was chosen for field verification using Jensen 1986 equation.

Intersection of Geology and the Drainage Network

The drainage network of the study area was intersected with geology map using feature intersect tool in ArcGIS. This showed the total stream length drained by the respective stream order through individual rock type.

Evaluation of Morphometric Parameters

In the present analysis all the three important aspects of morphometric analysis i.e., Areal, Linear and Relief have been analyzed. Various morphometric parameters have been examined and the detailed calculations with the parameter definitions are given in Table 2. Tekeze River has a dendritic pattern of drainage (Figure 4) and has the total basin area of 84738.55 m^2 in Ethiopia.

Relief Aspects

Relief of watershed measures its overall steepness and is an indicator of the intensity of the soil erosion processes taking place on the slopes. High relief is an indicator of high slope gradient of slopes and the watershed in general (Schumm, 1956). The highest relief of the Tekeze watershed is 4517 m whereas the lowest point is 536 m amsl. The relief ratio *Rr* is 11.37 which is a high value.

Similarly, Aspect plays an important role in the distribution of vegetation cover. Aspect refers to the direction of a slope. The aspect of the study area was calculated as a relief aspect (Figure 5). The compass direction of the aspect was derived from the output raster data value 0 is true north and a 90 aspect is to the east, and so forth. The slopes have moderate vegetation cover with some soil moisture also. Another important relief parameter i.e., slope was calculated. The slopes were categorized into six classes (i) 0-6 %, (ii) 6-12 %, (iii) 12-18 % (iv) 18-27 %, (v) 27-39 % and (vi) >39 %. Most of the terrain of Tekeze basin is not much sloppy ranging from 12-18 %. (Figure 6)

Linear Aspects

The analysis shows that the total area, perimeter and the basin length of the Tekeze watershed in Ethiopia is 84738.55 Sq. Km, 1364.4 Sq. Km and 350 Km respectively. The primary step in any drainage basin analysis is stream orders designation and is based on ranking of streams. Ranking of streams has been carried out based on the method proposed by Strahler. It is observed that the maximum frequency is in first order streams. Large number of streams was found in the first and second orders. The order wise stream numbers and their linear characteristics are shown in table 2. As the stream order increases the total number of streams decrease. Figure 7 shows different stream orders of drainage network in Tekeze River basin. Total number of 7 stream orders has been derived from the analysis which is attributed to the steep gradient of the basin from the source to outlet. Similarly, Stream length is one of the most important hydrological features of the basin because it reveals the surface run-off behaviors. The total stream length (Lu) 28788.54 Km, has been computed based on the law put by Horton, 1932. As per Strahler 1957 the total length of stream segments is maximum in first order streams and decreases as the stream order increases. The mean stream length is a dimensionless property, characterizing the size aspects of drainage network and its linked surface. The mean stream length (Lsm) ranging from 2.66 to 330 and their ratio ranging from 1.06 to 6.08 have been also computed in GIS environment. The values of total length, mean length and length ratio of the diverse stream orders are given in table 2. Mean stream length of any given order is greater than that of the lower order and less than of its next higher order. The bifurcation shows a small range of variation for different regions or for different environment except where the powerful geological control dominates. The results showed that the bifurcation ratio (Rb) values ranging between 2.03 and 12.0. Therefore the steep irregularities in the bifurcation ratio of Tezeke River are attributed to the diverse basin geological and lithological development (Table 5).

Areal Aspects

While carrying out the analysis of areal aspects different morphometric parameters like drainage density, stream frequency, drainage texture, form factor, circularity ratio, elongation ratio and length of overland flow have been discuss in details.

Drainage density (Dd) is one of the important indicators of the landform element and provides a numerical measurement of landscape dissection and runoff potential (Chorley, 1969). It was found to be 0.34 in the present study. Similarly as per Smith drainage texture, the texture value below 4 is designated as coarse; 4–10 as intermediate; above 10 as fine and above 15 as ultra-fine texture. The results indicated that the drainage texture is 0.04 which indicates that the study area has a weak or permeable subsurface material with intermediate drainage. The quality of drainage texture is determined by the amount and type of precipitation and character of surface run-off of an area with high precipitation as thunder showers loses greater percentage of rainfall, absorption capacity of soil, which influences the rate of surface run-off. Furthermore Low stream frequency indicates sparse drainage network which favours permeability and groundwater recharge. It is an index of the various stages of landscape evolution and in the present study it was found to be 0.12.

Form factor is another important parameter which indicates the flow intensity of a basin for a defined area. The calculated form factor is 0.69. Circulatory ratio is another important parameter of morphometric study. The low, medium and high values of the circulatory ratio are indications of the youth mature and old stages of the life cycle of the river basins. The range 0.4 to 0.5 specifies strongly elongated and extremely permeable homogenous geologic materials. The calculated circulatory ratio in this study is 0.57 which indicates more or less elongated shape of watershed. Similarly the elongation ratio values vary from 0.6 to 1.0 for most of the basins. It ranges from 0.6 to 0.8 for regions of high relief and the values close to 1.0 have very low relief with circular shape. In the present study it was found to be 0.78 which refers to high relief of the study area. In addition to it, the overland flow which is the length of water over the ground before it gets concentrated into definite stream channels. Larger the value of overland flow means longer flow path and less slope gradient. This calculated value of length of overland flow in this study is 5.89. It is related inversely to the average slope of streams and it is directly equal to the reciprocal of drainage density (Horton, 1945; Kaliraj *et al*., 2014). The high Lg value indicates that the rainwater had to travel relatively longer distance before getting concentrated into stream channels (Chitra *et al*., 2011).

Tectonic Analysis

The drainage pattern of any region replicates mainly structural or lithological controls of the underlying rocks. The drainage pattern of Tekeze River indicates that the area has structural or tectonic controls explained by complex geological history represented in major geological terrains starting from Archaen (about 40 billion years ago) till Quarternary period (about 11 thousand years ago) and marine sediments occurring in the western part. There are various morphometric parameters which have a direct bearing on the underlying rocks e.g., the connection between the bifurcation ratio and the stream length ratio is determined by geological characteristics. Similarly permeability of the rock formations and the rock characteristics in a basin defines the Stream length and their ratio Also rock structure defines frequency and extent of jointing, fracturing and the flow contacts and weathering along them.

Total numbers of 18 rock types belonging to 16 rock groups formed during 12 geological periods were mapped in the present study. Out of them Alkaline and Transitional Basalt belonging to Ashangi formation of Eocene period and Flood Basalt belonging to Aiba basalt formation of Middle and Late Oligocene period comprise 30514.64 Sq. Km. (31.06 % of the study area) (Table 4 figure 8) and 14782.19 Sq. Km. (17.44 % of the study area) respectively. Alkaline and Transitional Basalt has taken most of the western and south eastern part of the study area whereas Flood basalt was found dominated in the central part and a few locations in the east and north. Alkaline and Transitional Basalt rocks were found to be drained by 8584.76 Km (29.82% of total stream length) of stream length (Figure 9) which includes Stream order 1 (3035.6 Km), Stream order 2 (2844.22 Km), Stream order 3 (1646.42 Km), Stream order 4 (702.57 Km) and Stream order 5 (355.95 Km) whereas Flood basalt is drained by 3071.97 Km (10.67% of total stream length) comprising of Stream order 1 (2404.5 Km), Stream order 2 (240.75 Km), Stream order 3 (240.75 Km), Stream order 4 (113.45 Km) and Stream order 6 (17.02 Km) (Table 5). Similarly Tsalite formation characterized with Metaandesite, Metadacite, Chlorite, Limestone, Quartzite rocks covers total area of7.95 %,is distributed in the northern part of the Tekeze river basin and is drained by 2757.97 Km (9.58% of total stream length) of stream length which includes Stream order 1 (1305.3 Km), Stream order 2 (747.86 Km), Stream order 3 (302.33 Km), Stream order 4 (251.21 Km) and Stream order 7 (151.27 Km).

Tarmaber Gussa formation which includes Alkaline and Transitional Basalt with Trachyte and Phonolite rocks comprises 6.92% of total study area was found in central and southern part. These rocks are drained by1675.77 Km (5.82% of total stream length) stream length which includes Stream order 1 (1139.57 Km), Stream order 2 (355.44 Km) and Stream order 3 (180.76 Km). Also the Adigrat formation characterized with Sandstone covers 6.71% of the total study area, distributed mostly in the east and central part. It is drained by 2861.98 Km (9.94% of total stream length) stream length which includes Stream order 1 (1303.7 Km), Stream order 2 (713.56 Km), Stream order 3 (392.56 Km), Stream order 4 (118.85 Km), Stream order 5 (169.31 Km), Stream order 6 (133.21 Km) and Stream order 7 (30.79 Km).

Besides it some Alluvial and lacustrine depositions belonging to Pliocene and Quartenary period covering 4.48 % of the total area were found in west, northwest and north eastern part. These deposits are drained by 1540.71 Km (5.35% of total stream length) of stream length which includes Stream order 1 (886.66 Km), Stream order 2 (272.29 Km), Stream order 3 (109.22 Km), Stream order 4 (89.24 Km), Stream order 5 (157.93 Km) and Stream order 7 (25.37 Km). Similarly the Limestone of Antalo formation covers 4.48% of the study area is found only in east of the study area. It is drained by 1313.41 Km (4.56% of total stream length) of stream length which including Stream order 1 (796.83 Km), Stream order 2 (147.45 Km), Stream order 3 (196.09 Km), Stream order 4 (101.78 Km) and Stream order 5 (71.26 Km). The important Sandstone and Conglomerate of Shiraro formations comprises total of 4.45% is found in patches in the north and east. These rocks are drained by total of 1652.88 Km (5.74% of total stream length) of stream length comprising of Stream order 1 (932.8 Km), Stream order 2 (384.43 Km), Stream order 3 (239.76 Km) and Stream order 5 (95.89 Km).

The rest is shared by Sandstone, Shale, Conglomerate and Tillite rocks of Gura and Gilo Formations covering 3.34% and is found in the patches in northeast. These rocks are drained by total of 809.97 Km (2.81% of total stream length) of stream length comprising of Stream order 1 (528.41 Km), Stream order 2 (119.67 Km), Stream order 3

(105.22 Km) and Stream order 4 (56.67 Km). Tembien formation (Chlorite, Graphite, Limestone and Dolomite) contribute total 1.81% and is found in north and northeast. It is drained by 726.89 Km (5.74% of total stream length) of stream length including Stream order 1 (418.4 Km), Stream order 2 (152.55 Km), Stream order 3 (117.53 Km), Stream order 5 (38.41 Km). Alage formation (Transitional and Sub alkaline Basalt rocks) contribute 1.19%of the total study area isfound in south east. It is drained by 364.52 Km (1.27% of total stream length) of stream length comprising of Stream order 1 (284.2 Km) and Stream order 2 (80.32 Km). Baro formation (Hornblend, Amphibole, Similarite, and Silicate rocks and minerals) add total of 1.16% and is found in scattered patches in the east. It is drained by 467.07 Km (1.62% of total stream length) of stream length comprising of Stream order 1 (232.5 Km), Stream order 2 (134.24 Km) and Stream order 3 (100.33 Km). Didikama and Adwa formations (Slate, Dolomite, Trachyte and Phonolite, Granite and Syenite rocks) contribute total of 0.66% and are found in north and northeast of the study area. These rocks are drained by total of 335.48 Km (1.17% of total stream length) stream length comprising of Stream order 1 (139.84 Km), Stream order 4 (132.97 Km) and Stream order 7 (62.67 Km).

Conclusions

The present study has proved that the geoprocessing technique used in GIS is an effective tool for computation and analysis of various morphometric parameters of the basin and helped to understand various terrain parameters such as nature of the bedrock, the area traversed by individual stream order. It was analysed that the Tekeze River is well drained in nature with the stream order varying from 1 to 7. The basin is dominated by lower order streams and the total length of stream segment is maximum in first order streams. The basin is more or less elongated in shape with rugged relief and steep slope due to the lower elongation ratio (0.57). Stream frequency and drainage density are the prime criterion for the morphometric classification of drainage basins, which certainly control the runoff pattern, sediment yield, and other hydrological parameters of the drainage basin. The Dd was found to be lower in Tekeze basin, which is an indicative of existence of impermeable rocks.

Table 1: Linear, relief and areal morphometric parameters of Tekeze Watershed in Ethiopia

S/No	Parameter	Formulae	Reference
1	Basin area	A	
2	Basin perimeter	P	
3	Total number of streams	Nu	
4	Total stream length	Lu	
5	Basin length	Lb	
6	Stream Order (U)	Hierarchical rank	Strahler (1964)
7	Stream Length (Lu)	Length of the stream	Horton (1945)
8	Mean Stream Length (Lsm)	Lsm: Lu/Nu	Strahler (1964)
9	Stream Length Ratio (RL)	RL: Lu=Lu/ (Lu-1)	Horton (1945)
10	Bifurcation Ratio (Rb)	Rb: Nu/Nu+1	Schumm (1956)
11	Mean Bifurcation Ratio (Rbm)	Rbm: Average of bifurcation ratios of all order	Strahler (1957)
12	Drainage Density (Dd)	Dd: Lu/A	Horton (1945)
13	Drainage Texture (T)	T: Dd x Fs	Smith (1950)
14	Stream Frequency (Fs)	Fs: Nu/A	Horton (1945)
15	Elongation Ratio (Re)	Re: 2√(Basin Area/3.14)/basin Length	Schumm (1956)
16	Circulatory Ratio (Rc)	Rc: 4..A/P2	Strahler (1964)
17	Form Factor (Ff)	Ff: A/L2	Horton (1945)
18	Length of Overland Flow (Lg)	Lg: 1/D x 2	Horton (1945)
19	Relief	R = *H-h*	Hadley and Schumm (1961)
20	Relief Ratio	Rr = *R/L*	Schumm (1963)

Table 2: Results of morphometric analysis of Tekeze Watershed in Ethiopia

S. No	PARAMETER	FORMULAE	RESULTS							
1	Basin area	A	84738.55 Km^2							
2	Basin perimeter	P	1364.4 Km^2							
3	Total number of streams	Nu	10109							
4	Total stream length	Lu	28788.54 Km							
5	Basin length	Lb	350 Km							
				I	II	III	IV	V	VI	VII
6	Stream Order (U)	Hierarchical rank		5441	2680	1599	434	48	4	1
7	Stream Length (Lu)	Length of the stream	28788.54 Km	14458.25	7535.49	3598.82	1526.57	888.38	450.22	330.81
8	Mean Stream Length (Lsm)	Lsm: Lu/Nu	2.85 Km	2.66	2.81	2.25	3.52	18.51	112.56	330.81
9	Stream Length Ratio (RL)	RL: Lu=Lu/ (Lu-1)			1.06	0.80	1.56	5.26	6.08	2.94
10	Bifurcation Ratio (Rb)	Rb: Nu/Nu+1			2.03	1.68	3.68	9.04	12.00	4.00
11	Mean Bifurcation Ratio (Rbm)	Rbm: Average of bifurcation ratios of all order	13.71							
12	Drainage Density (Dd)	Dd: Lu/A	0.340							
13	Drainage Texture (T)	T: Dd x Fs	0.04							
14	Stream Frequency (Fs)	Fs: Nu/A	0.12							
15	Elongation Ratio (Re)	Re: 2√(Basin Area/3.14)/basin Length	0.78							
16	Circulatory Ratio (Rc)	Rc: 4..A/P2	0.57							
17	Form Factor (Ff)	Ff: A/L2	0.69							
18	Length of Overland Flow (Lg)	Lg: 1/D x 2	5.89							
19	Relief	R = *H-h*	3981							
20	Relief Ratio	Rr = *R/L*	11.37							

Table 3: Lithology of Tekeze Watershed in Ethiopia

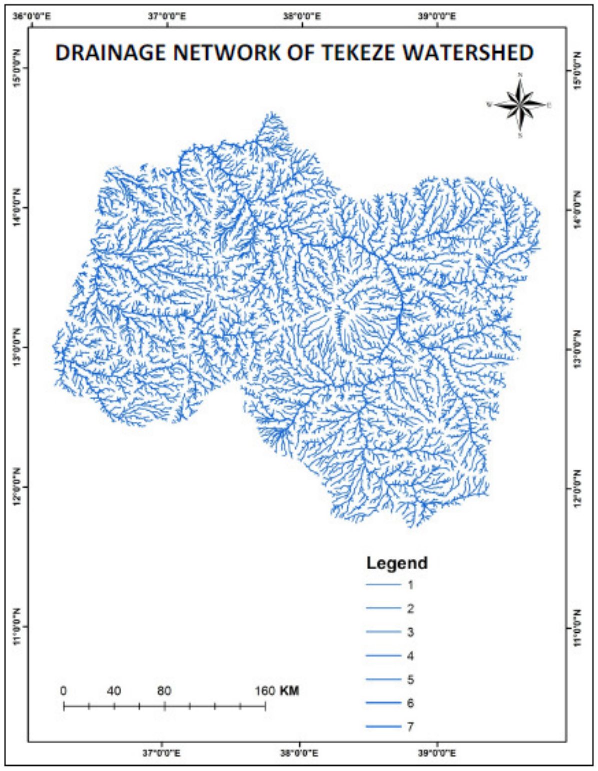
S.NO	ROCK	DISCRIPTION
1	**BASALT**	Is a dark-colored, fine-grained, igneous rock composed mainly of plagioclase and pyroxene minerals. It most commonly forms as an extrusive rock.
2	**CALCIUM SILICATE**	A metamorphic rock consisting mainly of calcium-bearing silicates, such as diopside and wollastonite, and formed by metamorphism of impure limestone or dolomite; associated with skarn-type mineral deposits.
3	**CONGLOMERATE**	Is a coarse-grained clastic sedimentary rock that is composed of a substantial fraction of rounded to subangular gravel-size clasts, e.g., granules, pebbles, cobbles, and boulders, larger than 2 mm (0.079 in) in diameter.
4	**DACITE**	Is an igneous, volcanic rock. It has an aphanitic to porphyritic texture and is intermediate in composition between andesite and rhyolite.
5	**DOLOMITE**	Is a sedimentary rock composed primarily of the mineral dolomite, CaMg(CO3)2. Dolomite is found in sedimentary basins.
6	**AMPHIBOLE**	Amphibolite is a metamorphic rock that contains amphibole, especially the species hornblende and actinolite, as well as plagioclase.
7	**GRANITE**	Is a light-colored igneous rock with grains large enough to be visible with the unaided eye. It forms from the slow crystallization of magma below Earth's surface.
8	**LIMESTONE**	Is a sedimentary rock, composed mainly of skeletal fragments of marine organisms such as coral, forams and molluscs.
9	**ANDESITE**	Is an extrusive igneous, volcanic rock, of intermediate composition, with aphanitic to porphyritic texture.
10	**PHONOLITE**	Is an uncommon extrusive igneous rock, volcanic rock, of intermediate chemical composition between felsic and mafic, with texture ranging from aphanitic (fine-grain) to porphyritic (mixed fine- and coarse-grain).
11	**QUARTZITE**	Is a nonfoliated metamorphic rock composed almost entirely of quartz. It forms when a quartz-rich sandstone is altered by the heat, pressure, and chemical activity of metamorphism.
12	**SANDSTONE**	Is a clastic sedimentary rock composed mainly of sand-sized minerals or rock grains.
13	**SHALE**	Is a fine-grained sedimentary rock that forms from the compaction of silt and clay-size mineral particles that we commonly call "mud."
14	**SLATE**	Is a fine-grained, foliated metamorphic rock that is created by the alteration of shale or mudstone by low-grade regional metamorphism.
15	**SYENITE**	Is an intrusive rock, belonging to the alkali series of intermediate plutonic rocks.
16	**TILLITE**	Is a clastic sedimentary rock, formed by the burial and subsequent hardening of a glacial till.
17	**TRACHYTE**	Is an extrusive rock, belonging to the alkali series of intermediate volcanic rocks.

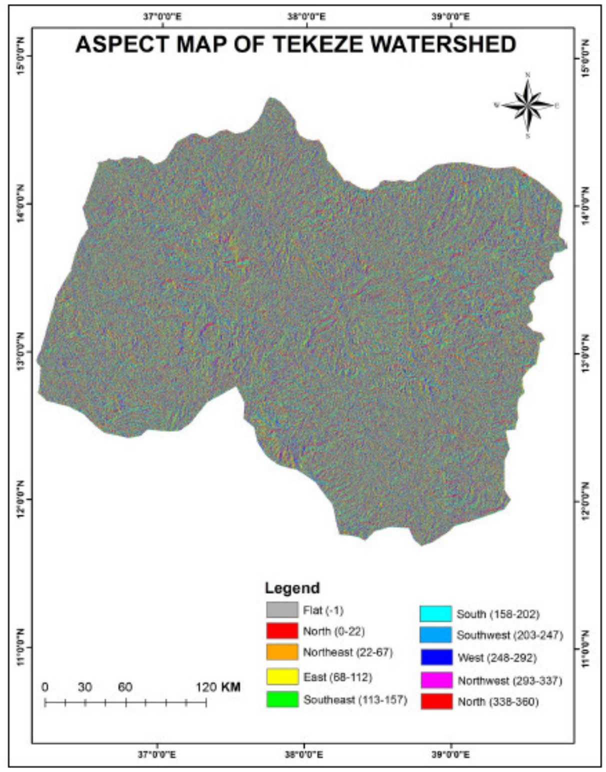
Table 4: Lithology of Tekeze Watershed in Ethiopia.

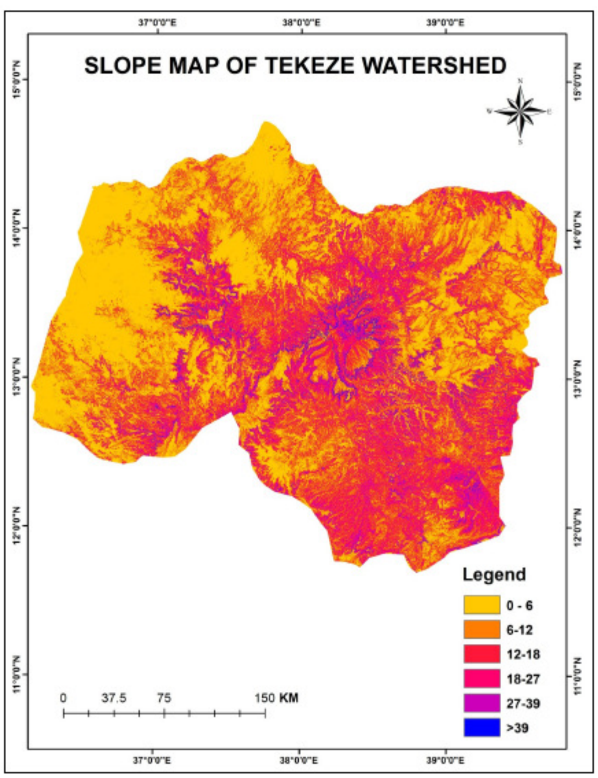
ROCK PERIOD	ROCK GROUP	ROCK TYPE	AREA In Km	Percentage
ARCHAEN	Baro Group	Hornblende - Biotite, Garnet - amphibole, Garnet - Sillimanite, Calc - Silicate	979.80	1.16
EOCENE	Ashangi Formation	Alkaline and Transitional Basalt	30514.64	36.01
EARLY - LATE JURASSIC	Adigrat Formation	Sandstone	5683.41	6.71
LATE JURASSIC	Antalo Formation	Limestone	3798.51	4.48
LATE PALEOZOIC_TRIASSIC	Gura and Gilo Formations	Sandstone, Shale, Conglomerate and Tillite	2828.84	3.34
LATE PROTEROZOIC	Didikama Formation	Slate and Dolomite	337.20	0.40
	Tembien Group	Metarhyolite-chlorite, Graphite, Limestone and Dolomite	1537.51	1.81
	Tsaliet Group	Meta andesite, Dacite, Metarhyolite-chlorite, Limestone and Quartzite	6732.69	7.95
	Upper Proterozoic	Undifferentiated	887.00	1.05
	Shiraro Formation	Sandstone and Conglomerate	3772.32	4.45
MIDDLE MIOCENE	Adwa Formation	Trachyte and Phonolite Plug	161.24	0.19
MIDDLE AND LATE OLIGOCENE	Aiba Basalts	Flood Basalt	14782.19	17.44
OLIGOCENE - MIOCENE	TarmaberGussa Formation	Alkaline and Transitional Basalt with Trachyte and Phonolite Plug	5865.39	6.92
	Alage Formation	Transitional and Subalkaline Basalt	1012.38	1.19
PLIOCENE - PLIESTOCENE	Undivided Lacustrine and Fluvial Sediments	Sandstone, Silt, Gravel and Conglomerate	1804.46	2.13
PRECAMBRIAN AND PHANEROZOIC INTRUSIVE		Granite and Syenite	62.65	0.07
		Tectonic Granite	1987.71	2.35
QUARTENARY UNDIFFERENTIATED	Alluvial and lacustrine deposits	Sand, Silt, Clay, and Limestone	1990.63	2.35

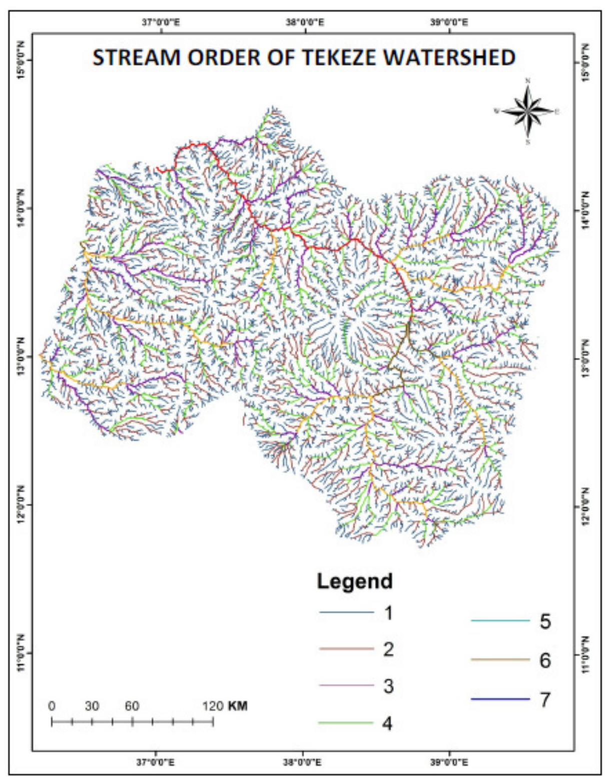
Table **5**: Morpho-tectonic Analysis of Tekeze Watershed in Ethiopia

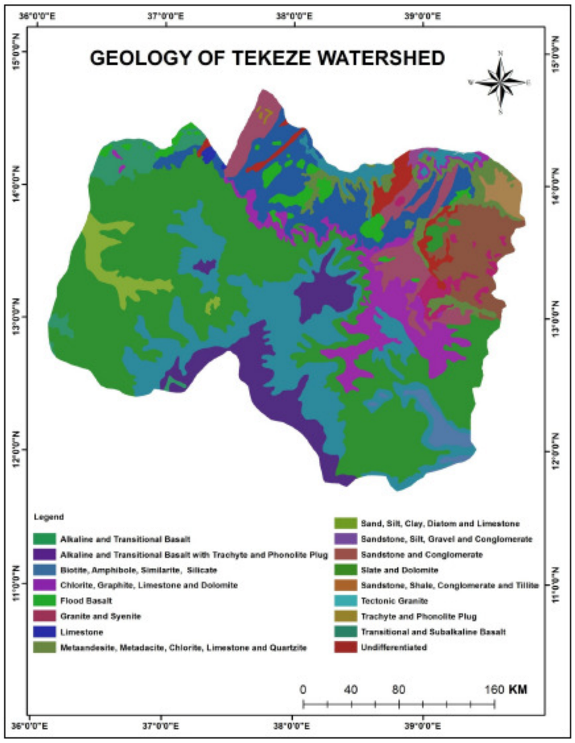
ROCK SYSTEM	ROCK TYPE	STREAM ORDER 1	STREAM ORDER 2	STREAM ORDER 3	STREAM ORDER 4	STREAM ORDER 5	STREAM ORDER 6	STREAM ORDER 7
ARCHAEN	Hornblende - Biotite, Garnet - amphibole, Garnet - sillimarite, Calc - Silicate	232.5	134.24	100.33				
EOCENE	Alkaline and Transitional Basalt	3035.6	2844.22	1646.42	702.57	355.95		
LATE JURASSIC	Limestone	796.83	147.45	196.09	101.78	71.26		
LATE PALEOZOIC_TRIASSIC	Sandstone, Shale, Conglomerate and Tillite	528.41	119.67	105.22	56.67			
LATE PROTEROZOIC	Slate and Dolomite	60.6			132.97			62.67
	Chlorite, Graphite, Limestone and Dolomite	418.4	152.55	117.53		38.41		
	Meta andesite, Dacite, Metarhyolite-chlorite, Limestone and Quartzite	1305.3	747.86	302.33	251.21			151.27
	Undifferentiated	176.1						
	Sandstone and Conglomerate	932.8	384.43	239.76		95.89		
MIDDLE MIOCENE	Trachyte and Phonolite	28.2						
MIDEDLE AND LATE OLIGOCENE	Flood Basalt	2817.6	1390.16	296.25	113.45		17.02	
OLIGOCENE - MIOCENE	Alkaline and Transitional Basalt with Trachyte and Phonolite	1139.57	355.44	180.76				
	Transitional and Subalkaline Basalt	284.2	80.32					
PLIOCENE - PLIESTOCENE	Sandstone, Silt, Gravel and Conglomerate	448.57	171.43		89.24	157.93		
PRECAMB AND PHANEROZOIC INTRUSIVE	Granite and Syenite	51.04						
	Tectonic Granite	460.69	193.44	112.32	59.54			60.66
QUARTENARY UNDIFFERENTIATED	Sand, Silt, Clay, and Limestone	438.09	100.86	109.22				25.37
TRIASSIC - MIDDLE JURASSIC	Sandstone	1303.7	713.56	392.56	118.85	169.31	133.21	30.79
		14458.2	7535.63	3798.79	1626.28	888.75	150.23	330.76

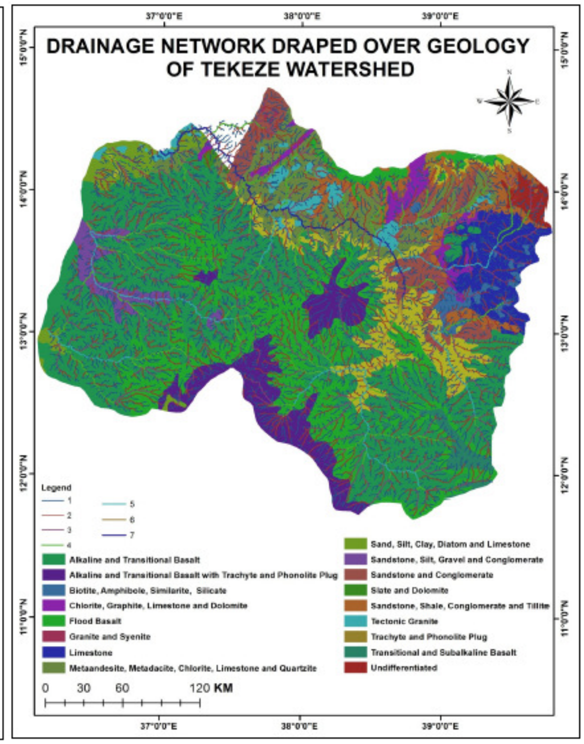

DRAINAGE NETWORK OF TEKEZE WATERSHED
Legend
1
2
3
4
5
6
7
0 40 80 160 KM


ASPECT MAP OF TEKEZE WATERSHED
Legend
Flat (-1)
North (0-22)
Northeast (22-67)
East (68-112)
Southeast (113-157)
South (158-202)
Southwest (203-247)
West (248-292)
Northwest (293-337)
North (338-360)
0 30 60 120 KM


SLOPE MAP OF TEKEZE WATERSHED
Legend
0 - 6
6-12
12-18
18-27
27-39
>39
0 37.5 75 150 KM


STREAM ORDER OF TEKEZE WATERSHED
Legend
1
2
3
4
5
6
7
0 30 60 120 KM





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