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RESEARCH

Hydrological and Morphometric Characterization of Anambra-Imo River Basin Using Remote Sensing

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Abstract
Environmental problems related to flooding, water management, and landslide often emanate from disruption of river basin within a geographical locality. In this study, the Anambra-Imo river basin which drains the five southeastern states of Nigeria and a part of Kogi State in the northcentral was studied by combining the remote sensing technique and geographic information system (GIS). With the aid of digital elevation model (DEM) of the geographical region, the linear and spatial morphometric attributes of the basins such as drainage density (Dd), drainage texture (Dt), circularity ratio (Rc), elongation ratio (Re), constant of channel maintenance (Cm), form factor (Rf), infiltration number (If), stream frequency (Sf), length of overland flow (Lo), and compactness index (Ci) were obtained. The results of the analysis showed that the basins have a well-developed dendritic and parallel-type drainage pattern with a NE-SW orientation suggesting a relationship between fracture orientation and physiographic features. Anambra Basin is a sixth-order basin having a total of 1462 streams with a length of 13,682.9 km, while the Imo river basin is a fifth-order basin having a total of 208 streams with a total length of 1320.57 km. Morphometric analyses yielded infiltration numbers of 0.3 and 0.11, elongation ratios of 0.35 and 0.29, and form factors of 0.26 and 0.54; compactness indexes of 1.4 and 1.06; lengths of overland flow of 0.46 and 2.18; circularity ratios of 0.49 and 0.84; constants of channel maintenance given of 0.93 and 4.34; relief ratios of 0.61 and 0.35; and ruggedness numbers of 0.19 and 1.5 for Anambra and Imo river basins respectively. These results have thrown light on the underlying factors responsible for flooding and gullying in the study area as a combination of climatic and geological characteristics of the study area.

Keywords Anambra-Imo river basin · Hydrological process · Watershed delineation · Flooding · Remote sensing

Introduction

Detailed characterization of drainage basins is very critical to the understanding and resolution of varieties of environmental issues, such as water management, landslide and flood prevention, and aquatic dead zones [34]. A drainage basin is a part of the earth's surface that is drained by mainstream and its tributaries [37]. It is an ideal unit for the interpretation and analysis of fluvial originated landforms, where they exhibit an example of an open system of operation [67]. It is a fundamental geomorphic unit of land, and its properties govern all flow of surface; thus, it is an open system in which and from which energy flows [5]. One of the early accomplishments of fluvial morphometry was the classification of branching drainage network, an ingenious numbering system derived by Horton [15] and modified by Strahler [71]. Horton [15] developed a scientific approach to the hierarchical classification of streams and basins. It is crucial in any hydrological investigation such as assessment of groundwater potential, groundwater management, basin management, and environmental assessment [37].

A drainage basin morphology reflects various geological and geomorphological processes over time [72]. The

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morphometric analysis of the drainage basin and channel network plays vital roles in understanding the geo-hydrological behavior of drainage basins and the geologic structure that controls the river system in the watershed [24]. River basin characterization is a powerful tool for understanding the hydrology and sustainable management of water resources as well as effective flood and erosion control. Studies on drainage basin morphometry have been conducted over the years by many researchers using different techniques as well as either studying one or more of the basin elements (linear, aerial, and relief) depending on the characteristics of the drainage basin. Withanage et al. [69] analyzed 17 morphometric parameters for the Gal Oya river basin, Sri Lanka, which they classified as a sixth-order river network (as per the Strahler classification) with a dendritic drainage pattern and moderate drainage texture and reduced risk of flooding. Cunha and Bacani [9] characterized the morphometry of Indiana river basin, Brazil, using shuttle radar topographic mission (SRTM) and geographic information system (GIS) techniques and found that the basin had low susceptibility to flooding but a higher risk of erosion due to the morphology of the relief and lithological structure of the basin. Takal et al. [61] studied the morphometry of the Upper Helmand river basin, Afghanistan, using Arc-GIS for the analysis. They observed that it was a fifth-order basin with a dendritic pattern and high levels of infiltration evaporation and transpiration. Tesfaye et al. [63] studied Tigra Basin and reported that the micro-watershed drainage network is of dendritic type, indicating homogeneity in texture, and required less structural controls. Several other studies of river basin morphometry have also been done on Wadi Qena river basin in Egypt [39], the Gostani river basin in India [27], Khair-Kuli basin in India [28], Shakkar basin in India [48], and Mohr basin in India [64]. In Nigeria, river basins that have received attention include Yedzaram catchment [21], Calabar river basin [13], Ogbere and Ogunpa basins [4], and Upper Mamu river basin [33]. Nyaba river basin [67], Obe river basin [30], Lamurde river basin [36], Upper Yedzaram river basin [1], Owu basin [46], Osun river basin [10], Lower Niger river basin [45], and Oguta basin [66].

One of the best things that have happened in river basin characterization is the adaptation and accurate application of GIS and remote sensing to a very complex and dynamic system. A combination of remote sensing and GIS affords accurate morphometric characterization of river basins [49]. Sreedevi et al. [56] revealed that the GIS and remote sensing techniques are the most convenient method for morphometric analysis as the satellite images provide a synoptic view of a large area and are very useful in the analysis of drainage. The application of GIS-based to shuttle radar topographic mission (SRTM) and advanced spaceborne thermal emission and reflection radiometer (ASTER) data have been found very useful in the study of hydrological systems such as river basins [47, 73].

Anambra-Imo river basin is a composite river basin comprising Anambra and Imo river basins draining the five southeastern states of Nigeria and a part of Kogi State in the northcentral. This hydrological entity is under the administration of the Anambra-Imo River Basin Development Authority. The Anambra-Imo River Basin Development Authority is one of the 12 river basin development authorities in Nigeria established for sustainable and holistic management of water resources in Nigeria. Sadly, these hydrological administrative units have woefully failed in their core mandate to the extent that even basic hydrological data on these basins are not available, and gauging stations have been allowed to decay without any effort to rehabilitate them. Also, hydrological studies on Anambra and Imo states are few and segmented. A lot remain unknown regarding the characteristics of the basin parameters and their effects on the hydrologic processes within the basin. This research will hopefully fill this important gap in knowledge. Therefore, this study was aimed at undertaking a morphometric and hydrological characterization of the Anambra-Imo river basin using remote sensing. Hence, the specific objectives of this research were to determine the linear, areal, and relief morphometric characteristics as well as to determine the hydrological characteristics of the catchment area under review.

Methodology

Study Area

Anambra-Imo river basin (AIRB) is located in Southeastern, Nigeria. AIRB is largely located within the southeastern states of Enugu and Anambra and the north-central state of Kogi (Fig. 1). Water resources in the basin are managed and controlled by the Anambra-Imo River Basin Development Authority which is one of the 12 river basin authorities in Nigeria contained in the eight hydrological entityies. The AIRB covers an area of 18,441 km^2, comprising two distinct rivers, namely Anambra River (Anambra river basin 12,670 km^2) and Imo River (Imo river basin 5770 km^2). The basin experiences a tropical wet-and-dry climate with an average of 8 months of rainfall between March and October and 4 months of dry season between November and February. On average, the annual rainfall amount varies between 1800 and 2000 mm [107]. The Anambra River originates from Ankpa in Kogi state. The river meanders through other states southward to empty into the River Niger at Onitsha. The drainage basin extends from 6° 00′N to 7° 30′N and 7° 00′E and 6° 30′E and has many tributaries some of which include Ezechie-Oda River, Okpo-Ishe River, Mamu River, Adada River, and Oji River. The eastern flank of the study area has

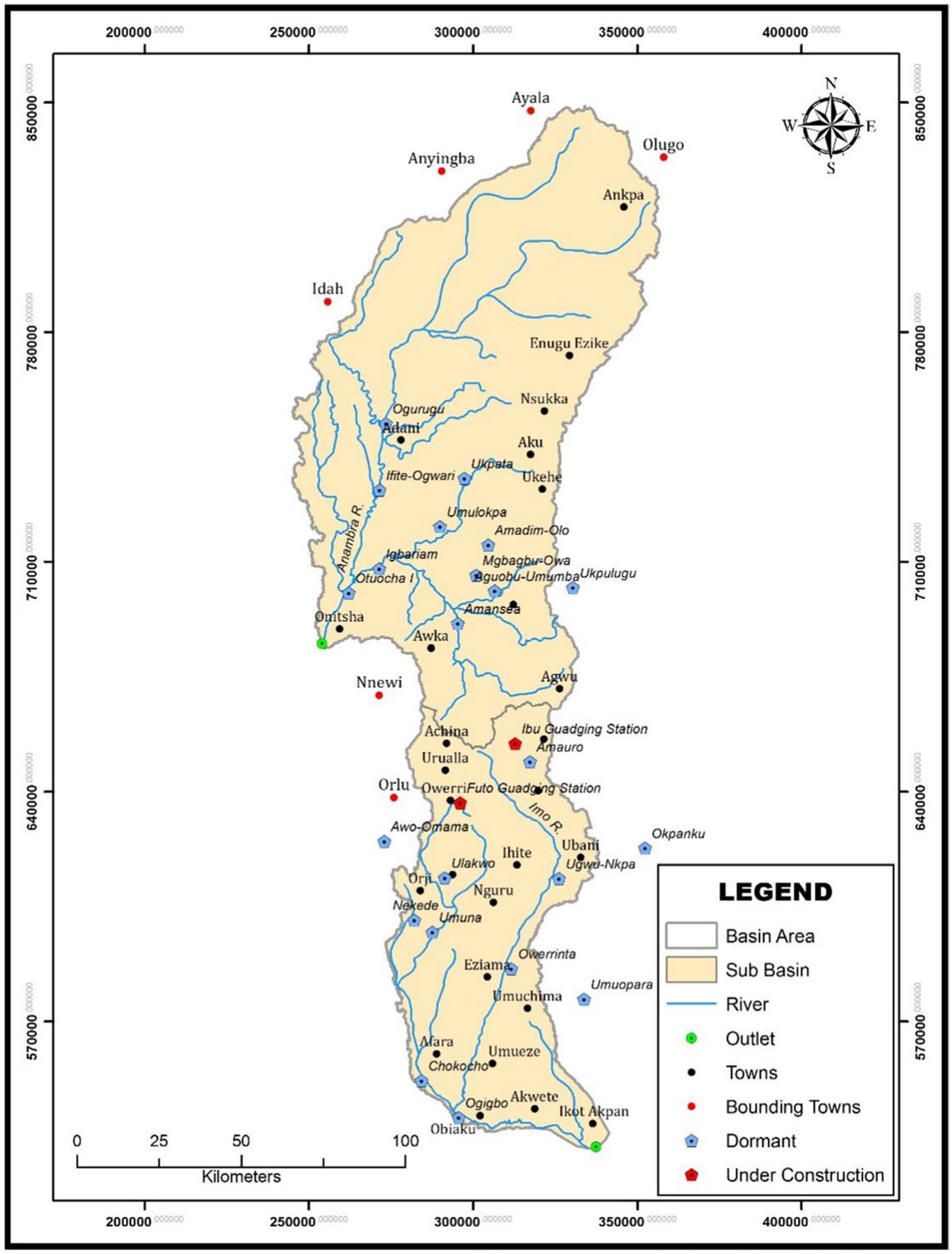

Fig. 1 Anambra-Imo river basin showing major rivers and gauging stations

a general elevation of 100 m, mostly covered by alluvium from the waters of the rivers [32].

The Anambra River is underlain by different geologic formations affected by many earth processes which in many ways have given rise to a distinct landform. The eastern flank of the study area has a general elevation of 100 mm, which is described as a lowland because of denudation activities. The lowland region is covered mostly by alluvium from the waters of the rivers [32].

The Imo river basin lies on latitude 4° 45′N and 5° 50′N, longitude 6° 35′E and 7° 30′E, and takes its course from the Okigwe/Akwa upland. The basin experiences heavy rainfall with an average of 152 rainy days per year, particularly during the rainy seasons (April–October). The superficial rainfall distribution is bimodal with peaks in July and September and a break in August. The rainy season begins in March and lasts until October or early November. However, variation occurs in rainfall amount from year to year. In terms of relief, the Imo river basin is characterized by three main landform regions: a highland region of elevation of 340 mm in the northern section covering Orlu, Ideato, Okigwe, and Ihitte-Uboma local government areas; a moderate elevation of about 175 mm which covers midway between the north and southern sections of the state as well as the river valleys of the stream that rises in the highland regions of the

Table 1 Morphometric parameters and formula

Parameters	Formula	Reference
Linear morphometric parameters		
Stream order (Sμ)	Hierarchical rank	[59]
Bifurcation ratio (Rb)	Rb = Nμ / Nμ + 1	Schumm (1956)
Mean bifurcation ratio (Rbm)	Rbm = Average of bifurcation ratios of all orders	[59]
Stream number (Sn)	Sn = Total number of stream segments	Schumm (1956)
Stream length (Lμ)	Length of the stream	[15]
Mean stream length (Lsm)	Lsm = Lμ/Nμ	[59]
Stream length ratio (RL)	RL = Lsm / Lsm-1	[15]
Length of overland flow (Lg)	Lg = 1/2D km	[15]
Basin perimeter (P)	*P* = Outer boundary of drainage basin	[51]
Areal morphometric parameters		
Basin area (A)	-	[60]
Drainage density (Dd)	D_d = Lμ/A	[14]
Stream frequency (Fs)	Fs = Nμ/A	[14]
Drainage texture (Dt)	Dt = Nμ /P	[54] and [15]
Form factor ratio (Rf)	$Rf = A/Lb^2$	[31]
Elongation ratio (Re)	Re= $\sqrt{A}$ /π / Lb	[51]
Circularity ratio (Rc)	$Rc = 4\pi A/ P^2$	[23]
Compactness index (Ci)	Ci = 0.282 P/ $\sqrt{A}$	[14]
Constant of channel maintenance (C)	Cm = 1/ D_d	[51]
Relief ratio (Rh)	$R_h = H/Lh$	[51]
Ruggedness number	$Rn = R_b D_d$	Strahler [58]
Relative relief	Rr = H/P * 100	Melton [98]

state; and the lowland regions in the southern areas of the state.

Data Source and Analysis

Data on topography, land use, soil, climate, and stream discharge required for this study were obtained from different sources. The DEM is required for watershed delineation into sub-basins. Hence, the DEM (30 × 30 m resolution) of the Anambra-Imo river basin was obtained from the United States Geological Services (USGS) database via https://earthexplorer.usgs.gov/. The ArcGIS (version 10.5.1) was used for the watershed delineation processes using the projected DEM data. The watershed delineation entails the segmentation of watersheds into several "hydrologically" connected sub-watersheds for use in watershed modelling. The "Flow Direction" tool was used to calculate the flow direction for each cell in the DEM. The "Flow Accumulation" tool was used to calculate the number of upstream cells that contribute flow to each cell as determined by the flow direction raster. The "Watershed" tool was used to delineate the sub-basins based on the flow direction and accumulated flow volume. In the "Watershed too," the "Pour Point" tool was used to extract the watershed outlets while the "Stream Network" tool was used to create a stream network from the pour points. The utilization of ArcGIS software, along with other associated extensions, has resulted in delineating watershed in the Anambra-Imo river basin. In this study, the morphometric and hydrological characterization has been carried out to obtain parameters like the stream order, stream length, bifurcation ratio, stream length ratio, basin length, drainage density, stream frequency, elongation ratio, circularity ratio, form factor, and basin relief using the mathematical formula as given below in Table 1.

A total of 1670 streams and 63 hydrological response units were delineated from the DEM using GIS. Table 2 shows that the delineated sub-basins ranged from very small (0.1 to 1.0 km^2) to very large sub-basins (> 500 km^2). About 73% of the sub-basins have areas greater than 100 km^2 and account for about 97% of the entire river basin. The largest sub-basin was 2222 km^2 located on the NE flank of the Imo river basin, followed by another basin (772 km^2) situated on the SE flank of the Imo river basin. All the sub-basins, as clearly presented in Fig. 2, have a characteristic elongated geometry with a NE–SW orientation. This NE–SW orientation suggests a relationship between fracture orientation and physiographic features [35].

Linear Characteristics of Anambra-Imo River Basin

Stream order is a measure of the relative size of streams or location of a stream within reach. The designation of stream orders is the first step in drainage basin analysis. It expresses

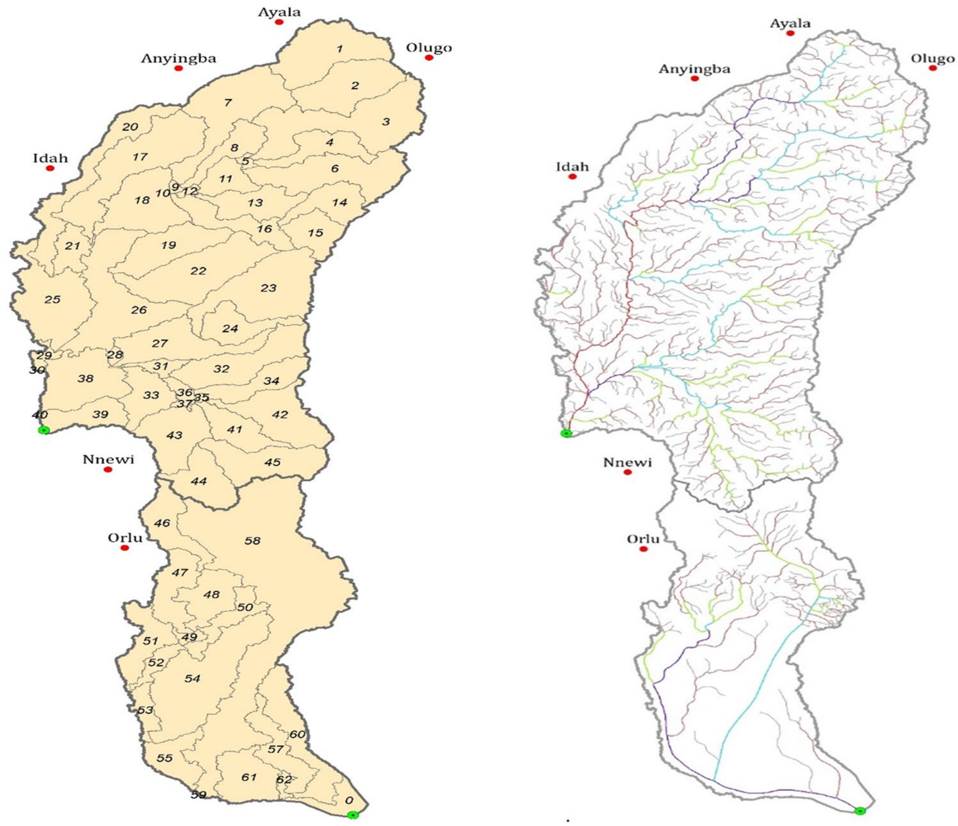

Fig. 2 Map of the Anambra-Imo river basin showing **a** delineated sub-basins and **b** stream network and orders

the hierarchical relationship between stream segments, their connectivity, and the discharge coming from contributing watersheds or sub-watersheds [68, 40]. In the present study, the channel segments of the basin order were ranked according to Horton-Strahler's stream ordering method. The Anambra-Imo river basin was found to be fifth (Imo) and sixth (Anambra) orders respectively with a total of 1670 streams revealing a well-developed dendritic and parallel-type drainage pattern with a NE–SW orientation. As shown in Table 3, most basins discussed in the literature belong to the fifth- and sixth-order categories. The Anambra Basin has 1462 streams with a total length of 13,682.91 km, while the Imo Basin has 208 streams with a total length of 1320.57 km. This dendritic drainage pattern is indicative of homogenous soil texture and lack of structural control [57]. Ritter and Michael [44] observed a uniform lithology for the development of a dendritic drainage pattern. In the Anambra basin, first-order streams accounted for 76.90%; second-order accounted for 18.12%; third-order accounted for 3.35%; fourth-order accounted for 0.95%; fifth-order accounted for 0.54%; and the sixth-order accounted for 0.06% of streams. The corresponding percentage distributions of stream orders in the Imo Basin are 65.38%, 25.96%, 5.28%, 2.88%, and 0.48%, respectively. This inverse relationship between a number of stream segments and stream order, as shown in Fig. 2, has long been confirmed by researchers who have studied other river basins around the world (Table 3). However, a few exceptions have been identified in the literature. These include the Gongola river basin in Nigeria where the relationship between stream order and length of stream has a parabolic shape with maxima at the second order. This deviation from the normal relationship between stream order and stream length is indicative of variable lithology and tectonic control. The Imo Basin has no sixth-order stream (Fig. 3). The variation in stream order and size of tributary basins largely depends on the physiographical, geomorphological, and geological conditions of the region. Higher stream order is associated with greater discharge as well as lower permeability and infiltration rate [57]. In both river basins, over 90% of the streams are of first and second orders, which suggests a very permeable surface with good vegetation cover to enhance infiltration. On the other hand, Jenita and Zahid [18] argued that the dominance of first-order streams is an indication of susceptibility to erosion.

The total length of first-order streams in the Anambra-Imo river basin is 3272.07 km, while the total length of sixth-order streams is 1962.41 km. However, the average length of first-order streams is 2.58 km, while that of sixth-order streams is 1736.10 km. Stream length is a very critical hydrological feature of the basin which is used to identify the surface runoff characteristics of the streams. The mean stream length reveals the characteristic size of the drainage

Table 2 Categorization of watersheds in the Anambra-Imo river basin

Class and definition by size	Mini-watershed 0.1 to 1.0 km^2	Micro-watershed 1.0 to 10 km^2	Milli-watershed 10 to 100 km^2	Subwatershed 100 to 500 km^2	Watershed > 500 km^2
Number	3	4	10	35	11
Percentage by number (%)	4.8	6.3	15.9	55.6	17.5
Percentage by size (%)	0.002	0.08	2.21	52.25	45.45
Total area (km^2)	0.31	15.32	408.31	9635.89	8381.26
Perimeter (km)	6.30	57.30	639.90	5840.60	3390.40

network components and its contributing basin surfaces [59]. Longer lengths of the stream are generally indicative of flatter gradients; relatively smaller lengths are features of areas with steep slopes [41]. The data from this study, as well as obtained by other researchers as shown in Table 3, indicate a linear relationship between the total length of streams and basin area regardless of geographical location (Fig. 4). This is because larger basins will require longer drainage path. This is not true for several streams and basin area. Figure 4 shows that the number of streams in a basin is not dependent on the size of the basin but on climatic and geologic characteristics of the basin.

Spatial Aspects of Anambra-Imo River Basin

The areal parameters considered in this study are drainage density (Dd), drainage texture (Dt), circularity ratio (Rc), elongation ratio (Re), constant of channel maintenance (C), form factor (Rf), infiltration number (If), stream frequency (Sf), length of overland flow (Lo), and compactness index (Ci). Table 4 presents a summary of the results of these parameters considered in this work.

Drainage Density (Dd)

The drainage densities of the Anambra-Imo river basin are 1.08 (Anambra Basin) and 0.23 (Imo Basin). Drainage density is classified as low if the value is less than 5 km/km^2. Drainage density is an important morphometric parameter which indicates the response of the basin to runoff processes [70]. A low drainage density value suggests a poorly drained basin with a slow hydrologic response [16], and it is often recorded in regions with highly permeable subsoil material, dense vegetative cover, and low relief. Therefore, the drainage density values of Anambra and Imo Basins generally indicate porous subsurface material, good vegetation cover, and medium relief [3], causing more infiltration of water and recharging groundwater aquifers. By implication, porous soils are easily detached and transported by overland flow, leading to erosion. Soil erosion has been particularly linked with river sedimentation, groundwater pollution, and other surface water quality challenges in the Imo basin area [29].

Given that low relief is associated with reduced velocity of runoff, the plurality of gully erosions and landslides within the Anambra-Imo basin are attributed to the weak and poorly consolidated sandy lithologic units, the coastal plain sands, and their weathered products. The low drainage density of Anambra and Imo Basins may well explain the prevalence of gully sites of the basins [79]. There are more than 450 active gullies and landslides ranging from a depth of 5 m to over 120 m on both sides of Awka-Nanka-Umuchu-Orlu cuesta of the Anambra river basin which have defied numerous remediation efforts [80].

Soil erosion is a critical environmental and ecological hazard in the basins, causing land degradation with severe socioeconomic consequences. Communities in both river basins have been threatened to the extent of being displaced due to the rapid expansion of gully sites, and link roads have been washed off [81]. This has further resulted in large areas of arable land as well as low productivity as a result of top soil denudation. Land use changes have also contributed significantly to the alteration of drainage characteristics of basins. Increased flood discharges in the Awka, Anambra state, have been partly attributed to recent changes of drainage density occasioned by the increase in paved surfaces (comprising mostly of rooftops, roads, and yards) due to urbanization and modification to drainage network [82]. Such low drainage density values recorded for the Anambra-Imo river basin are associated with flood, high groundwater potential, and high erosional and landslide potential. It thoroughly explains the prevalence of gully erosion in Anambra and Imo Basins. Anambra and Imo are among the most erosion-prone regions in the country. The situation is further aggravated by rapidly changing and unsustainable land uses. Aggressive land development without corresponding efforts to attenuate the enormous amounts of runoff generated represents a grave environmental risk which manifests in the form of urban flooding and gully erosion [83].

Drainage Texture (Dt)

The drainage texture values for the basins are 2.56 (Anambra river basin) and 2.81 (Imo river basin). Drainage texture less than 2 indicates a very coarse texture, between 2 and 4 as coarse texture, 4 and 6 as moderate texture, between 6 and 8 as fine texture, and greater than 8 as excellent drainage

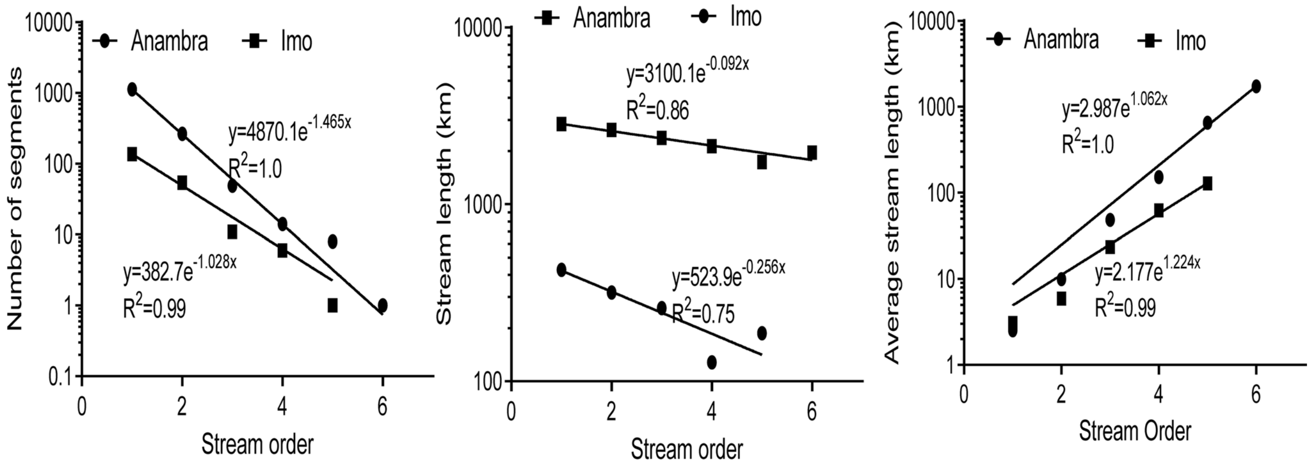

Fig. 3 Characteristics of streams in the Anambra-Imo river basin

texture [55]. It is a measure of the relative spacing of drainage lines [55]. Fine drainage texture results when weak rocks are unprotected by vegetation, whereas coarse texture results from resistant or impermeable rocks. Drainage texture has a positive relationship with drainage density, and the factors that control drainage texture such as climate, vegetation type and density, rock and soil type, infiltration capacity, relief, and the evolutionary stage of basin development are the same factors that control drainage density. Low drainage density leads to coarse drainage texture, while high drainage density leads to fine drainage texture [84], both depending on the infiltration capacity of the underlying strata [54]. Drainage texture is also known to be to be inversely related to the rate of runoff and directly related to the infiltration capacity. From the result, it can be deduced that the Anambra-Imo river basin falls into the very coarse texture category and this indicates good permeability of subsurface material and infiltration capacity, lower runoff rate, and significant recharge of groundwater. Groundwater forms a major source of water supply in the Anambra-Imo river basin with an estimated annual recharge ranging from 17 to 21.4% for the annual precipitation [79].

Stream Frequency (Sf)

Stream frequency is the total number of stream segments of all orders per unit area [14]. It is positively correlated with drainage density and drainage texture, depending mainly on the lithology of the basin, and reflects the texture of the drainage network [51]. The stream frequencies of Anambra-Imo Basin are 0.12 (Anambra Basin) and 0.036 (Imo Basin), which are considered low. Generally, low stream frequency is related to permeable surface lithology, dense vegetation cover, low relief, and high infiltration capacity [26, 36, 43], which are the same factors that control drainage density and drainage texture. It is one of the main contributing factors to the genesis and development of soils and surface lithology [85]. Low stream frequency values indicate low dissection intensity, while high values indicate high dissection intensity. The low values of drainage density, stream frequency, and drainage intensity mean that surface runoff is not quickly removed from the basin, encouraging higher overland flow, making it highly susceptible to flooding, gully erosion, and landslides [75]. Most cases of a flash flood, gully, and landslide sites in Anambra and Imo have been associated with low linear morphometric parameters. Low stream frequency in planar basins encourages higher overland flow, which enhances the chances of flooding [75]. The ever-expanding gullies and landslides of the Nanka and Agulu communities of Anambra have been associated with the low values of these linear morphometric parameters. Morisawa [25] disclosed that most basins underlain by clay, shale, and sandstone together with a generally low relief would have a low stream frequency.

Infiltration Number (If)

Infiltration number is a product of the drainage density and stream frequency of a basin. It indicates the infiltration capacity, vegetation cover, permeability of soil cover, and runoff (Rao and Yusuf, 2013). The infiltration number plays a significant role in observing the infiltration characteristics of the basin. According to Pranjit et al. [40], higher values are indicative of low infiltration, and lower values are indicative of high infiltration. The infiltration numbers of the Anambra-Imo river basin are 0.3 (Anambra Basin) and 0.11 (Imo Basin), and this is a pointer to a low runoff and high infiltration in the basin area. These are far lower than the values (1.46 to 3.40) obtained for Kilange River catchment in Adamawa, Northern Nigeria [50].

Table 3 Comparison of Anambra-Imo river basin characteristics with other basins

Name of river basin	Country	Area (km^2)	Number of streams	Drainage pattern	Total length of stream (km)	Length of stream order (km)								Reference
						1st	2nd	3rd	4th	5th	6th	7th	8th	
Anambra	Nigeria	12,670	1462	Dendritic	13,682.9	2845.16	2632.52	2372.63	2134.09	1736.10	1962.41	-		This study
Imo	Nigeria	5770	208	Dendritic	1320.57	426.91	318.64	259.57	128.05	187.20	-	-		This study
Trans Yamuma	India	289.41	8842	Dendritic	430.39	266.38	88.15	39.17	17.17	10.62	4.0	4.7	0.2	[57]
River Gongola	Nigeria	27,390.25		Dendritic		79	128	78	35	26	-	-	-	[2]
Vaitama	India	3795	3133	Dendritic	4184	2208	994	461	200	256	65	-	-	[74]
Ulhas	India	4733	3793	Dendritic	5014	2627	1197	529	337	167	103	54	-	[74]
Lules	Argentina	787	7016	Dendritic	2486.27	1342.12	590	273	150.97	59	32.17	39	-	[22]
Gal Oya	Sri Lanka India	1873	1396	Dendritic	1881.91	780.76	451.19	283.82	181.45	107.15	77.54	-	-	[69]
Gilgit	Pakistan	13,538	2390	Dendritic	6572.75	3253.84	1601.93	846.71	429.33	227.14	93.79	120	-	[75]
Dhid'hessa	Ethiopia	28,637	34,586	Dendritic	33,468	16,742.9	8251.3	4438.8	2212.8	905.9	291.9	344.4	280.1	[76]
Muthirapuza	India	271.75	135		204.96	105.08	44.08	26	29.80	-	-	-	-	[78]
Pambar	India	288.53	132		228.16	118.15	69.11	15.08	25.82	-	-	-	-	[78]
Bharathapuzha	India	5988.56	4426	Dendritic	6380.08	3323.7	1468.4	352.35	153	201.25	95.01	-	-	[20]
Arqa	Lebanon	143	736	Dendritic	405	191	111	46	34	23	-	-	-	

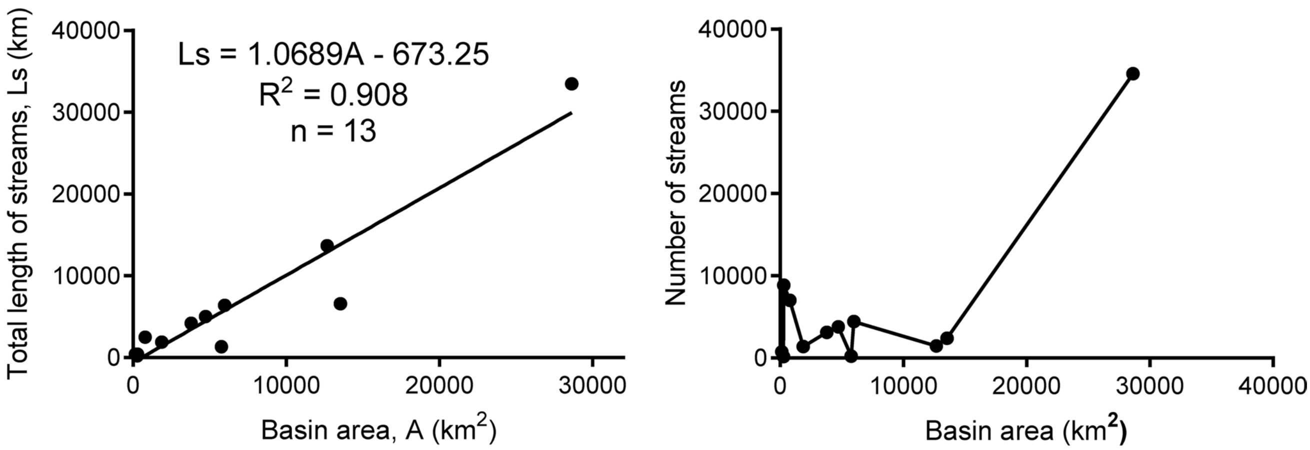

Fig. 4 General relationship between basin area and stream parameters

Table 4 Areal morphometric parameters of the basin

Parameters	Anambra Basin	Imo Basin	Remark
Drainage density	1.08 km^{-1}	0.23 km^{-1}	Imo—low density Anambra—moderate density
Drainage texture	2.56	2.81	Coarse-textured
Stream frequency	0.12	0.036	Low frequency
Infiltration number	0.3	0.11	High rate of infiltration
Circularity ratio	0.49	0.87	Anambra (elongated) Imo (somewhat circular)
Elongation ratio	0.35	0.29	Highly elongated
Constant of channel maintenance	0.93	4.35	Anambra Basin is more susceptible to erosion than Imo Basin
Form factor	0.26	0.54	Imo will experience high peak discharge Anambra will experience low peak discharge
Compactness index	1.4	1.06	
Length of overland flow	0.46	2.18	Longer overland flow in Imo than in Anambra

Elongation Ratio (Re)

The elongation ratio is a parameter used to describe the shape of a basin. It is evaluated as the ratio of the diameter of a circle whose area is equal to the area of the basin and the maximum length of the basin. The value of the elongation ratio ranges from 0.6 to 1.0 when a wide range of climatic and geological conditions are considered [59]. It is classified as circular (0.9–1), oval (0.8–0.9), less elongated (0.7–0.8), elongated (0.5–0.7), and more elongated (<0.5). A circular basin is more efficient in the discharge of runoff than an elongated basin [53]. Regions with low elongation ratios are susceptible to more erosion due to steep ground slopes and increased runoff, whereas regions with high values are known for high infiltration capacity, low relief, and low runoff [43, 59]. The elongation ratios of the Anambra-Imo basin are 0.35 (Anambra Basin) and 0.29 (Imo Basin), respectively, indicating elongated basins with relatively moderate relief. Elongated basins experience longer overland and streamflows with reduced peak flow. Low values of elongation ratio indicate that the basin is susceptible to erosion and high sediment load [50].

Circularity Ratio (Rc)

Circularity ratio is the ratio of basin area to the area of a circle of the equal perimeter [23]. The circularity ratio is used as a quantitative measure of a basin's shape [59], and it indicates the dendritic stage of a basin. It is controlled by the stream length, stream frequency, climate, land use, land cover, relief, geological structures, and slope steepness of the watershed. High values of circularity ratio indicate circular basins, whereas low values of circularity ratio indicate elongated basins with permeable lithology [8, 52]. Miller's [23] description of basins, whose circularity ratios are between 0.4 and 0.5, indicated strongly elongated and highly permeable basins with homogeneous geological materials. Circularity ratios are uniform between 0.6 and 0.7 for homogenous lithology and 0.4 and 0.5 for quartzitic terrain [42]. The circularity ratios for Anambra and Imo Basin are 0.49 and 0.84, respectively. The circularity ratio of the Anambra Basin indicates the presence of elongation character, which corroborates Miller's [23]) range of values that suggest permeable subsurface lithology. According to Miller and Summerson's [86] description of circularity ratio between 0.4 and 0.7, it could be surmised that Anambra Basin is strongly elongated and is underlain by a highly permeable homogenous lithology. The circularity ratio for Imo Basin is high and falls outside the Miller's range (0.4–0.5), suggesting that the basin is somewhat circular with less pervious subsurface material. Such a high circularity ratio is also associated with low catchment area, steep slope, and short concentration-time [87]. Gully sites are common features in the basin with a short concentration-time and a quick discharge.

Form Factor (Ff)

Form factor can be defined as the ratio of basin area to the square of basin length [14]. Lower values of the form factor are associated with elongated basins, while higher values are associated with circular basins. The value of the form factor will always be less than 0.79 for a perfectly square catchment [7]. Basins with high form factors experience larger peak flows of shorter duration, whereas elongated watersheds with a low form factor experience low peak flows of longer duration [15]. Horton [15] extended the form factor to predict the intensity of flow in a drainage basin of a defined area. The form factor values for the Anambra and Imo Basin are 0.26 and 0.54, respectively. The values of form factor indicate that the basins are slightly elongated and will, therefore, experience reduced peak flow and longer flow durations. However, on a comparative scale, Imo will experience shorter flows than Anambra. Small values of form factor have an implication on both the hydrologic and geomorphic processes of a basin. The flow of water in elongated basins is distributed over a more extended period and is easier to manage than in circular ones [88]. Again, flows of shorter duration and high hydrograph peaks are associated with flash floods [20, 65]. Therefore, the elongated nature of the basins may well explain the high incidence of flash floods in the basin.

Compactness Index (Ci)

Compactness index is defined as the ratio of the perimeter of the catchment to the circumference of a circle whose area is equal to that of the given basin. It provides a numerical measure of the resemblance of a basin shape to a regular circle [89]. The compactness index of a catchment basin manifests the climate regime, lithology, and vegetation, and gives an insight into the infiltration characteristics of the catchment. According to Tauer and Hamborg [62], the index of a circular drainage basin equals 1, and increases to 1.15 when the basin is square. The value of compactness index can exceed 3 for very elongated basins. The compactness index also has implications on the concentration-time distribution in a catchment basin. The more homogeneous the concentration-time, the more the overland runoff will concentrate rapidly and accumulate to increase the overland flow. Elongated forms with non-homogeneous concentration-time will offer the direct opposite. The compactness indexes for the Anambra-Imo river basin are 1.4 (Anambra Basin) and 1.06 (Imo Basin), respectively. The higher compactness index for the Anambra Basin shows that it is more elongated and therefore will experience a longer concentration-time than the Imo river basin with a shorter time of concentration and a higher risk of flooding and swamp. Higher values of compactness index have also been associated with more risk of erosion hazard [90]. However, the use of compactness index as an indicator of hydrological response has been questioned. This is because compactness index only describes the shape of the basin, and not its alignment towards the outlet [14]. There are also concerns about the inaccuracies in measuring the basin perimeter due to scale dependence [91, 92].

Length of Overland Flow (Lo)

Length of overland flow (Lo) is the length of water over the ground before it concentrates into a distinct stream channel. Its value is approximately equal to half of the drainage density [15]. It is referred to as the mean horizontal length of the flow path from the water divide to the stream in a first-order basin, and it is a measure of stream spacing and degree of dissection. The length of overland flow is considered a dominant hydrologic and morphometric factor [93]. It has a significant effect on the hydrological and topographic development of the basin. It also reflects infiltration characteristics and its variation in time and space [38]. The length of overland flow is significantly influenced by geologic and pedologic characteristics of the basin as well as rainfall intensity and vegetation [15]. Under near-homogeneous geological conditions, Thomas [77] reported rainfall, vegetation, and pedologic characteristics of a basin as the dominant factors controlling the length of overland flow. The lengths of overland flow for the basin are 0.46 (Anambra Basin) and 2.18 (Imo Basin). The high overflow value for the Imo Basin indicates that rainwater had to travel a relatively long distance overland before getting concentrated into stream channels [6]. However, the low overland flow value of the Anambra Basin indicates that rainwater will enter the stream quickly [19]. The low value of the length of overland flow is also a pointer to steeply sloping terrain and lower length of sheet flow of the Anambra Basin. This is because high drainage, high relief energy, and steep slopes diminish the length of overland flow and expedite the formation and conveyance of floods with the associated problems of erosion [94].

Constant of Channel Maintenance (Cm)

The constant of channel maintenance is the inverse of drainage density [51]. It is an important property of landform and represents the drainage area required to develop and maintain a unit length of the channel [95]. The constant of channel maintenance is a measure of basin erodibility and depends on the slope of the basin, the degree of resistance of the underlying material, and the duration of an erosional activity. Basins with low values of the constant of channel maintenance are associated with the weakest or very low resistance soils, sparse vegetation, and mountainous terrain. In contrast, high values are associated with resistance soils, vegetation, and comparably plain terrain. The Cm for the Anambra and Imo drainage basins are 0.93 (Anambra Basin) and 4.34 (Imo Basin), respectively. Therefore, the Anambra Basin, which would require about a 0.93-km^2 basin area to sustain the 1-km length of the drainage channel, is under the influence of high structural disturbance, low permeability, steep to a very steep slope, and high surface runoff, whereas the Imo basin would require about a 4.34-km^2 basin area to sustain the 1-km length of the drainage channel. Such high values are indicative of low-to-moderate slope, high infiltration, resistant soils, reduced surface runoff, and high baseflow. Higher values of Cm indicate a higher resistance to erosion as well as higher permeability.

Relief Aspects of Anambra-Imo Drainage Basin

Ebisemiju [11] defined relief as the difference between the highest and lowest elevations in a basin area. According to Eze [12], the relief of a place exerts a strong control on the runoff characteristics of the basin by influencing the rate of infiltration, erodibility, and other hydrological properties of the basin. Relief aspects of a basin relate to the three-dimensional features of the basin involving area, volume, and altitude of vertical dimensions of landforms wherein different morphometric methods are used to analyze the terrain characteristics. The relief characteristics computed in the Anambra-Imo drainage basin include relief ratio, relative relief, ruggedness number, and basin topography.

Relief Ratio (Rh)

The relief ratio is the ratio between the total relief of a basin and the longest dimension of the basin parallel to the main drainage line [51] and is strongly correlated to the hydrologic characteristics of a basin. According to Schumm [51], the relative ratio is a dimensionless height-length ratio equal to the tangent of the angle formed by two planes intersecting at the mouth of the basin, one representing the horizontal, the other passing through the highest point of the basin. A high relief ratio indicates high erosive power of discharge and the overall steepness of a drainage basin, which controls the rate of conversion of potential energy to the kinetic energy of the water streaming through the catchment. Relief ratio is vital in understanding the denudational characteristics of a watershed because a low relief ratio is a distinctive trait of less resistant rocks [96, 97]. Relief ratio also makes a comparison of the relative relief of any watershed possible without reference to the differences in the scale of topography. A high value of relief ratio is the characteristic of the hilly region, whereas low values suggest flat terrain. A high relief ratio with steep slope makes basins vulnerable to landslide, while areas with low relief ratio have a higher chance of flood during intense rainfall. High basin relief has also been implicated in the spread of wildfire and the high incidence of debris flow in Northern Utah, USA (2000–2004) (Santi et al. 2013). The relief ratios of the Anambra-Imo river basin are 0.61 (Anambra Basin) and 0.35 (Imo Basin); this indicates that the basin is composed of resistant rocks, intense relief, and steep slope. Therefore, the higher relief ratio in Anambra basin explains the incidences of a landslide, especially in the Agulu-Nanka region of the Anambra State.

Relative Relief (Rr)

Relative relief (Rr) is the ratio of relief (*H*) to the perimeter of the basin [98]. It could also be evaluated by normalizing the distribution of maximum height of terrain by its length [99]. The relative reliefs of the basins are 0.003 for Anambra Basin and 2.32 for Imo Basin. Relative relief contributes an important morphometric parameter that could be used for the general estimation of morphological characteristics of a basin reflecting the relative distribution of terrain gradient at the local level. Watersheds having higher relative relief have higher runoff potential. Relative relief indicates the potential energy available for erosion and mass wasting [100], and it is recommended as a proxy indicator for landslide susceptibility and gully development. Therefore, the more significant the difference in the relative relief, the higher the probability of erosion, gully development, and landslide. In general, relative relief has been concluded to be a useful parameter for the prediction of landslide susceptibility. Incidences of landslide are concentrated in areas of significantly high relative relief [101–103]. Coexistence of high relative relief with the cropping out of large rocks encourages rock slides and avalanches [104], which is a particularly dangerous form of landslide because of high velocity.

Ruggedness Number (Rn)

Ruggedness number is the product of drainage density (Dd) and basin relief. It indicates the structural complexity and denudational attributes of a catchment. The values of ruggedness number for the basin area were found to be 0.19 (Anambra Basin) and 1.5 (Imo Basin). Values of ruggedness number less than 1 are considered low and associated with terrains of flat and low morphology. Terrains of uneven and sharp morphology normally have moderate values (> 1 and < 2) of ruggedness number. Very high and extreme values (> 2) characterize very rough and uneven terrain [105]. Low relief ratios and ruggedness numbers are emblematic of groundwater zones. In contrast, watersheds having high values of ruggedness number can be described by high susceptibility to soil erosion, landsliding, quick hydrological response, and increase in peak discharge. The ruggedness number is exceptionally high when both the basin relief and drainage density are high. Ruggedness number for Anambra Basin suggests a watershed of subdued relief, that is less prone to erosion, with a high groundwater potential [106]. This does not, however, agree with the proliferation of gullies in some sections of the Anambra Basin. This indicates that the preponderance of gully erosion in Anambra Basin can be attributed to causes other than basin relief. The relative relief for Anambra Basin does not explain the proliferation of gully sites in Anambra. Active gully sites account for nearly 2% of the landmass in Anambra and Imo states, with Anambra hosting over 500 gullies [31]. Nanka in Anambra is one of the biggest landslide sites in Nigeria and is characterized by unconsolidated, friable, and collapsible sandstones capped in some places by lateritic overburden [17]. This is further complicated by massive deforestation, intense rainfall, and increased runoff resulting from aggressive urbanization.

Conclusion

Based on the present investigation conducted in the Anambra and Imo river basins using the remote sensing approach, the first-, second-, third-, fourth-, fifth-, and sixth-order streams of the Anambra basin accounted for 76.90%, 18.12%, 3.35%, 0.95%, 0.54%, and 0.06%, respectively, and that of the Imo Basin corresponds to 65.38%, 25.96%, 5.28%, 2.88%, 0.48%, and 0% for the first-, second-, third-, fourth-, fifth-, and sixth-order streams, respectively. This is indicative that over 90% of the streams are of first and second orders in both river basins, suggesting a very permeable surface with good vegetation cover that can influence infiltration. It was also observed that the drainage densities of both river basins were below 1.1 km/km^2 revealing a porous subsurface material, fine vegetation covers, and medium relief. The low drainage density recorded within the river basins suggests a high vulnerability to flooding, landslide, and high groundwater potential. Anambra Basin is strongly elongated and is underlain by a highly permeable homogenous lithology while Imo Basin is somewhat circular with less pervious subsurface material. Anambra river basin will experience a longer concentration-time which may lead to a higher risk of flooding within the Imo river basin. Thus, this study is poised to warn against extensive deforestation, excess flooding, and increased overflow caused by widespread of urbanization.

Abbreviations A: Basin area (km^2); Ci: Compactness ratio; Cm: Constant of channel maintenance; Dd: Drainage density (km/km^2); Dt: Drainage texture; Fs: Stream frequency; H : Maximum basin relief ; h: Elevation difference ; Lμ: Total length of streams of order "μ" (km); Lb : Maximum basin length (km); Lg: Length of overland flow; Lh: Longest dimension of the basin; Lsm: Mean stream length; Lsm-1: Mean stream length of next lower order; Nμ: Number of stream segments of a given order; Nμ +1: Number of stream segments of next higher order; P: Outer boundary of drainage basin measured in kilometers; Rb: Bifurcation ratio; Rc: Circularity ratio; Re: Elongation ratio; Rf: A/Lb^2; Rh: Relief ratio; RL: Stream length ratio; Rn: Ruggedness number; Rr: Relative relief; Rbm: Average of bifurcation ratios of all orders; Sn: Total number of stream segments

Author Contribution Chidozie Charles Nnaji conceptualized and designed the research and also took part in data analysis and manuscript drafting. Onyekachi Mark executed the fieldwork. PraiseGod Emenike, Ekene Nwankwo, Chekwubechukwu Chibueze, and Nkpa Ogarekpe took part in data analyses and manuscript drafting.

Data Availability No datasets were generated or analyzed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

Ethical Approval Ethical approval was not required for this study.

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