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Delineation of Morphometric Attributes of Ajaokuta River Basin in Nigeria Using Earth Observation System Based Data and GIS

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Abstract

In contemporary times, the pace of climatic changes is increasing at an alarming rate, therefore there is a need to adopt the most reliable technologies to monitor and sustain our environments. Therefore, the aim of this study is to define the morphometric attributes of Ajeokuta River Basin using earth observation system based data in geographic information system environment. Morphometric characterization of the basin has been carried out to understand the spatial variations in morphometric parameters and evaluate hydrological, geological and topographical attributes by analyzing SRTM DEM data using ArcGIS10.5. Surface analysis, linear and areal morphometric attributes of the catchment has been derived and Strahler (1964) stream order method was used for stream ordering. Drainage attributes such as stream order, stream number, stream length, mean stream length, Bifurcation ratio, drainage density, stream frequency circulatory ratio form factor, elongation ratio, etc, have been calculated in order to understand the environmental processes in the watershed. Investigation revealed that the river basin is a 4th order basin, with 1st order streams mostly dominating. Results revealed that there are one (1) fourth order streams, three (3) third order streams, twelve (12) second order streams and forty-one (41) first order streams. Further morphometric assessments revealed that the basin has a drainage density of 0.1125 km^{-1}, stream frequency of 0.0105, circulatory ratio of 0.765, elongation ratio of 0.960, form factor of 0.729, basin length of 84 km, 57 streams with a total stream length of 607 kilometers draining and area of 5393 square kilometers. These geometric attributes attest that the basin is drainage course textured, oval in shape and of low discharge potential. These results are invaluable for watershed management, agricultural land-use planning, flood and erosion analysis and control and for sustainable environmental planning and development within the catchment.

Subject Areas

Hydrology

Keywords

Morphometric, Hydrology, Drainage, Watershed, SRTM

1. Introduction

1.1. Background

Despite that Ajeokuta River Basin is one of the most hydrological important sub-catchment of the lower Niger basin, its morphometry and hydrology are not well known. This study aimed to characterize the hydro-geomorphology of the basin through basin morphometry analysis. Studies on river and stream ordering systems abound all over the world as a result of the relevance of water to the sustenance of life (Abiodun *et al.* 2018) [1]. In this study, the topographical, hydrological and geological processes of the basin have been investigated and understood by drawing inferences from morphometric analysis. Hydrology deals with surface and ground water flow, geomorphology is the science of landform whereas geology is the study of the earth, the material of which it is made, the structure of those materials and the processes acting upon them (Kuldeep 2012) [2]. Studies have shown that there is a relationship between hydrological processes, land form and geological condition of a given area. Hydro-geomorphometric attributes of a watershed are indispensable for its proper management. Watershed management is a method to protect and improve the quality of water and also control erosion in the watershed (Sangeetha 2019) [3]. It has to do with procedures taken for proper management and optimal use of all land and water resources in a basin with minimum hazard to natural environment. Flow route analysis is invaluable for various purposes. Apart from flood and erosion mitigation, urban planning and designing of drainage networks, it is fundamental for morphometric assessment of a drainage basin and knowledge of quantitative attributes of a drainage basin is inestimable for watershed management. Drainage analysis is fundamental before any construction in a given basin as it helps for a good understanding of flow regime so as to control flood and erosion. Recently with the advent of earth observation system (remote sensing) based data and GIS techniques, more precise data generation for the morphometric analysis can be done (Sreedevi *et al.* 2005) [4]. E.O.S provides the opportunities to get a synoptic view over a large area. Digital elevation model (DEM) data are fundamental in deriving primary topographic attributes which serve as input variables to a variety of hydrologic and geomorphologic studies (Jonathan *et al.* 2017 [5]; Ahuchaogu *et al.* 2021 [6]). Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Shuttle Radar Topographic Mission (SRTM) provide the data of DEM and are very useful for hydrological analysis and extraction of the stream network of a drainage basin (Sumantra 2016) [7]. Therefore, the purpose of this study is to define the morphometric attributes of Ajeokuta River Basin using SRTM data in a geographic information system environment.

1.2. Study Area

The basin is oval in shape and measured approximately 5395 km^2. It is a sub-catchment of the lower Niger basin in Nigeria and is geographically located between latitude 6˚50'N and latitude 7˚30'N and between longitude 6˚00'E and 6˚30'E. Annual precipitation is within the range of 1000 mm to 1500 mm and relative humidity of 70% in the wet season. The average daily wind speed is 89.9 km/hr. Wind speed is usually at its peak in March and April. The drainage network is characterized by streams and rivers of various sizes and having perennial, intermittent and ephemeral flow regimes. The basin is characterized by undulating topography. The highest and lowest points in the basin are approximately 32 and 463 m above mean sea level, respectively (**Figure 1**).

2. Methods and Materials

This study was carried out as per the methodology shown in **Figure 2**. The primary data used for this study is Shuttle Radar Topographic Mission (SRTM) covering the study area, Catchment map of Nigeria, and political map of the catchment area. The Shuttle Radar Topography Mission (SRTM) imagery covering the study area was acquired through the U.S. Geological Survey Earth Resources Observation and Science Center (EROS) using the web address: http://earthexplorer.usgs.gov. The environmental dataset in this study has been projected to Nigeria UTM zone 32 coordinate system WGS84 datum. The study area was extracted from the drainage basin/catchment map of Nigeria in ArcMAP environment. The map was first georeferenced by means of image to image registration using the geo-referenced administrative map of Nigeria states to georeference image of the drainage basin map of Nigeria. ArcGIS 10.5 (ArcMap 10.5) was utilized to extract the basins boundary clipping of the study area from the (SRTM) data to actual shape, hydrological analysis and features extraction. Sufer15 has been utilized for surface analysis and map stacking. The extraction is in form of digitizing and shape-files creation for the catchment area and the river systems in the study area. ArcGIS10.5 has been utilized for all stream related calculations. The analysis covered in this study includes surface analysis, linear and areal morphometry, and these assisted in the interpretation of geological hydrological and topographical condition of the basin.

2.1. Data Preparation and Processing

Data preparation and processing have been conducted as per the methodology shown in **Figure 2**. The clipped DEM data has been subjected to the following processes:

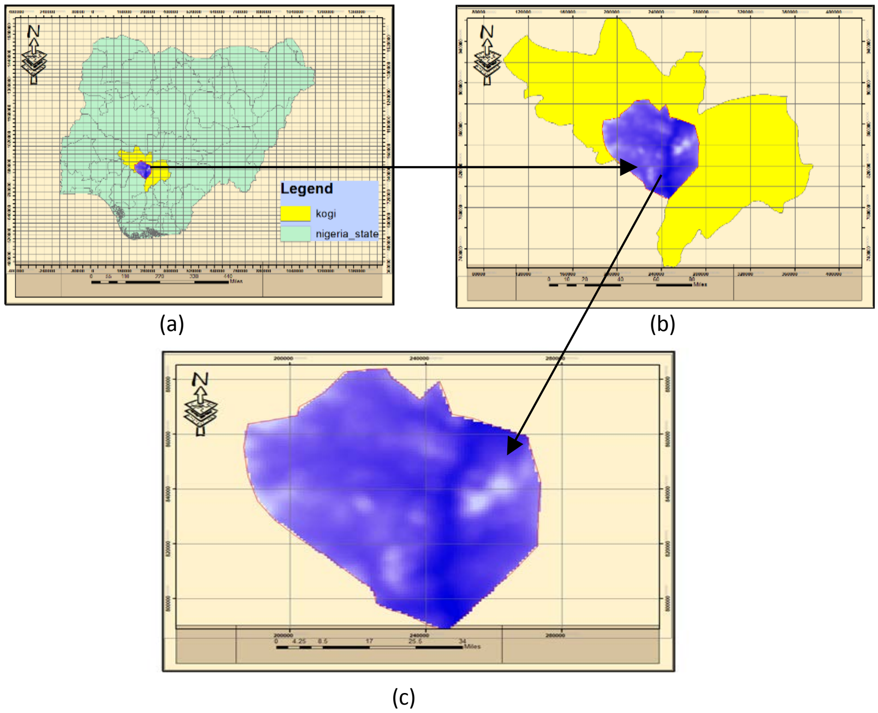

Figure 1. Study Area. (a) map of Nigeria showin Kogi State; (b) map of Kogi State showing Ajeokuta River Basin; (c) Ajeokuta River Basin.

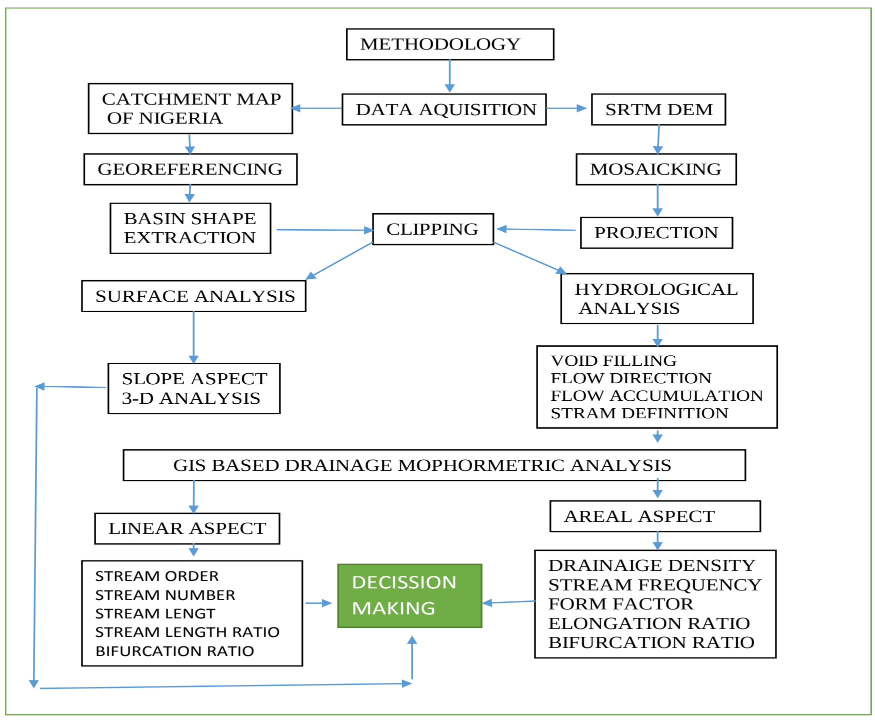

Figure 2. Methodological flow chart.

1) **Terrain analysis:** this includes slope, aspect, digital elevation mudel, 3-D surface analysis.

2) **Hydrological analysis:** this includes fill, flow directions, flow accumula-

tion, channel network definition

3) Linear and Areal Morphometry; this include stream order, stream number, total stream length, bifurcation ratio, drainage density, stream frequency, elongation ratio, circulatory ratio et

2.1.1. Slope, Aspect, 3-D and Flow Surface Analysis

Terrain analysis has been carried out using the surface module of spatial analysis tool of ArcGIS and Sufer15.Slope is the gradient or rate of maximum change in value from each cell to its neighbor (Burrough, 1986 [8]; Abiodun *et al.* 2016 [9]). The slope tool in ArcMap calculates the maximum rate of change in value from each cell to its neighbors and Aspect shows the direction of slope. The slope direction grid can be used effectively for advance topographical modeling such as identifying and characterizing areas of high-water runoff and landslide, estimating the portion of land that will receive high and low solar illumination for agricultural research purposes. The aspect of a terrain is measured clockwise (in degrees) from 0 to 360. 3-D analysis of the basin has been carried out using the 3D function of surfer11. This GIS method has the ability to produce shade-free 3-D image of a landscape that gives same visual impression to all audience located in any viewing direction (Nkeki *et al.* 2014) [10]. The technique uses the DEM information to simulate the real world. 3-D model provides quick understanding, for stakeholders in landscape and physical environment profession, even for non-professional on the real world nature of the topography and its relationship with flow direction.

2.1.2. Hydrological Analysis

The Arc-Hydrology tool of ArcGIS10.5 has been used for all hydrological analysis. The first step in processing drainages from DEM is to fill all depressions in the DEM data. A sink cell does not have associated drainage value. This depression filled DEM is fundamental in computation of the flow direction. The flow direction grid reveals the destination of the water flowing across the surface of the land based on landscape morphology. Progressively, the flow direction grid has been utilized as the primary impute for computation of flow accumulation grid. Each flow accumulation grid contains a value which is a function of the number of upstream cells flowing into it. Progressively, the flow accumulation grid has been subjected to stream definition (visualization) and segmentation algorithms. The stream definition is based on a specified threshold that is usually applied to reveal the stream length. It tries to determine the number of accumulating cells that define a stream cell.

2.1.3. Linear Morphometry

Stream order (U)

This is basically the first step in morphometric analysis of a drainage basin. It is defined as a measure of the position of a stream within a drainage network in a river basin. This study employed stream ordering system as per Strahler (1964) [11] in which a finger stream without a tributary is regarded as 1st order stream.

2nd order stream begins where two first order stream joined and so on.

Stream lengths (Lu)

This is the length of all streams having order **Su**. The stream length has been generated based on the law proposed by Horton R.E (1945) [12] using calculate geometry module of ArcGIS. The average lengths of streams of each of the different orders in a river basin tend closely to approximate a linear geometric series in which the first term is the total length of streams of the first order. Wherever the bedrock and formation is permeable, only a small number of relatively longer streams are formed but, a large number of streams of smaller length are developed where the bedrocks and formations are less permeable (Sethupathi *et al.* 2011) [13]. It is generally accepted that mean stream length related to the size of the drainage network

Stream number (Nu)

The stream number (Nu) is defined as a number of streams in each order (Horton 1945) [12]. It is inversely proportional to stream order in the sense that the higher the order the lower the stream number. As per Horton (1945) [12] the number of stream segments of each order form an inverse geometric sequence with the order number. In this study the number of streams in the various orders were calculated using calculate geometry module.

Bifurcation ratio (Rb)

The Bifurcation ratio is described as the ratio between the numbers of stream segments of any given order to the number of streams of the next higher order. If Rb of a river basin is low, there is a higher chance of flooding, as the water will be concentrated in one channel rather than spread out (Sayeed *et al.* 2017) [14]. Bifurcation ratio may assist the hydro analyst to assess the geological and lithological character of the catcment In line with the above definition, bifurcation ratio has been calculated using the formula; Rb = Nu/Nu + 1.

2.1.4. Areal Morphometry

Drainage density (Dd)

Drainage density is a function of the total length of the stream in a given drainage basin and the area of that drainage basin. It is influenced by Geology of basin. Permeable rocks with a high infiltration rate have low drainage density and vice-versa. Horton (1945) [12] argued that the value of the drainage density ranges from 0.93 km/km^2 to 1.24 km/km^2 in the steep impervious area of the high precipitation region and zero for the permeable basin with high infiltration rate. The total stream length and the area of the basin has been measured with calculate geometry module and these were fundamental to the calculation of the drainage density.

Stream frequency (Fs)

It is the ratio of a total number of channels cumulated for all orders within a given drainage basin and the area of that drainage basin. Reddy *et al.* (2004) [15] reported that low values of stream frequency Sf indicate presence of a permeable subsurface material and low relief vice versa. In the present study, the total number of streams and rivers in the basin has been measured using Calculate geometry tool in GIS environment. These datasets have been combined with the area of the basin to derive the drainage frequency of the basin using the formula; Fs = Nu/A

Form factor (Ff)

This is defined as the ratio of the basin area to the square of the basin length. Form factor is a dimensionless quantity and a factor for description of the different shape of basin. Basins with high form factors portrays high peak flows of shorter duration, whereas, elongated drainage basin with low form factors depicts lower peak flow of longer duration (R. E. Horton, 1945 [12]; Sayeed *et al.* 2017 [14]). The value of the form factor varies from 0 (highly elongated shape) to the unity, *i.e.*, 1 (perfect circular shape). In this study Form factor has been computed using the formula; $Ff = A/L^2$.

Elongation ratio (Re)

This is defined as the ratio of diameter of a circle having the same area as of the basin and maximum basin length (Schumm 1956 [16]; Praveen *et al.* 2014 [17]). It is a measure of the shape of the river basin and it depends on the climatic and geologic types. A circular basin is more efficient in runoff discharge than an elongated basin (Singh and Singh 1997 [18]; Praveen *et al.* 2014 [17]).

Circulatory ratio (Rc)

Miller (1953) [19] appraised that circularity ratio is the ratio of the area of the basins to the area of circle having the same circumference as the perimeter of the basin. It is a dimensionless parameter which provides a quantitative index of the shape of the basin (Jha VC (1996) [20]. Circular basin has a maximum efficiency of discharge, whereas an elongated basin has the least efficiency. It is a factor for discharge prediction in an ungauged basin, particularly in a time of flood. In this study Circulatory ratio was computer using the formula; Rc = 4πA/P2

3. Result and Discussion

Following the purpose of this study, earth observation system (E.0.S) based data has been used in GIS window to investigate hydrological, topographical and geological processes in Ajeokuta River Niger basin. The topographical models derived includes DEM (**Figure 3**), slope map (**Figure 4**), Aspect (**Figure 5**) and 3-D surface model of the basin (**Figures 6-9**). Hydrological model developed include; flow direction model (**Figure 10**), Drainage map (**Figure 11**), drainage order map (**Figure 12**). Geological, topographical and hydrological processes on the basin have been interpreted based on metric attributes of the basin extracted which include; basin area, basin length, circulatory ratio (Rc), perimeter of the basin, form factor (Ff), stream frequency, drainage density, stream number, stream length, and bifurcation ratio of the basin and these are summarized in **Table 1**

Figures 3-5 are the digital elevation model, slope and aspect map of the study area. These models show elevation range of 32 to 463 m above mean sea level. It also show sharp slopes range of 87˚ to 90˚ within the basin with north east, East, south east and southern facing sloping grids mostly dominating the basin.

Table 1. Morphometric attributes of Ajeokuta River Niger basin.

PARAMETER	FORMULA	REFERENCE	RESULT
Basin Area	GIS Software analysis		5395 sq km
Basin Length	GIS Software analysis		86 km
Circulatory Ratio (Rc)	Rc = 4 pA/P2	Strahler (1964)	0.765
Elongation ratio (Re)	Re = D/L = 1.128 HA/L	Schumm (1956)	0.960
Perimeter of Basin	GIS Software analysis		296 km
Form Factor (Ff)	$Ff = A/L^2$	Horton (1945)	0.729
Stream Frequency	Fs = Nu/A	Horton (1945)	0.0105
Drainage Density	Dd = Lu/A	Horton (1945)	0.089612 km^{-1}
Total number of streams	Nu = N1 + N2 + … Nn	Horton (1945)	57
Total Length of streams and river	Lu = L1 + L2 + … Ln	Horton (1945)	607 km

Stream Order	Stream Number (Nu)	Stream Length	Mean Stream Length (Lsm)	Bifurcation Ratio (Rb)	Stream Length Ratio
1	41	287	7	3.42	
2	12	156	13	4	0.543554007
3	3	92	30.67	3	0.58974359
4	1	72	72		0.782608696

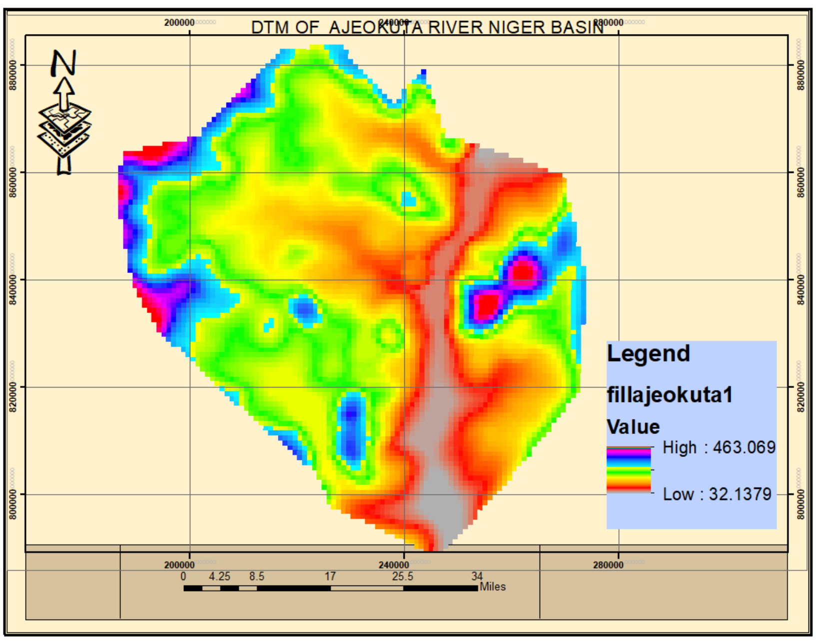

Figure 3. Digital elevation model of the study area.

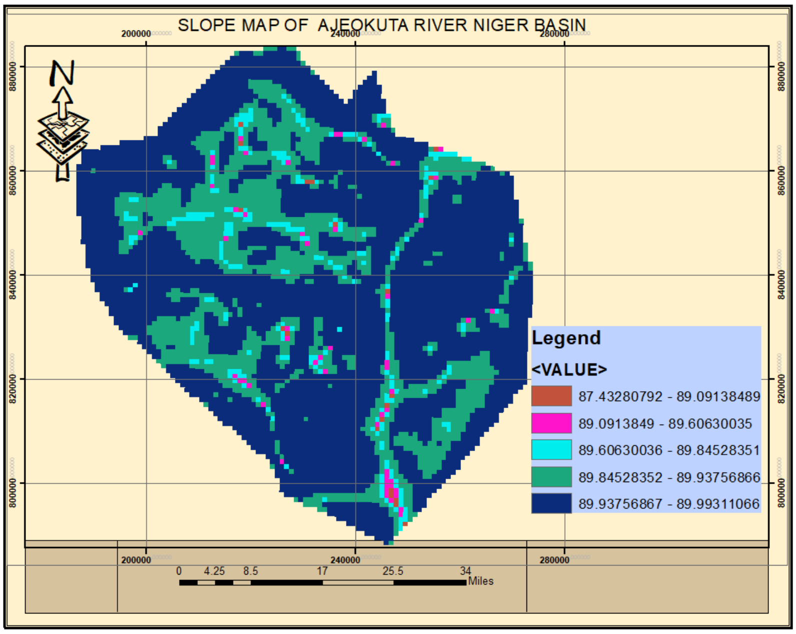

Figure 4. Slope map of the study area.

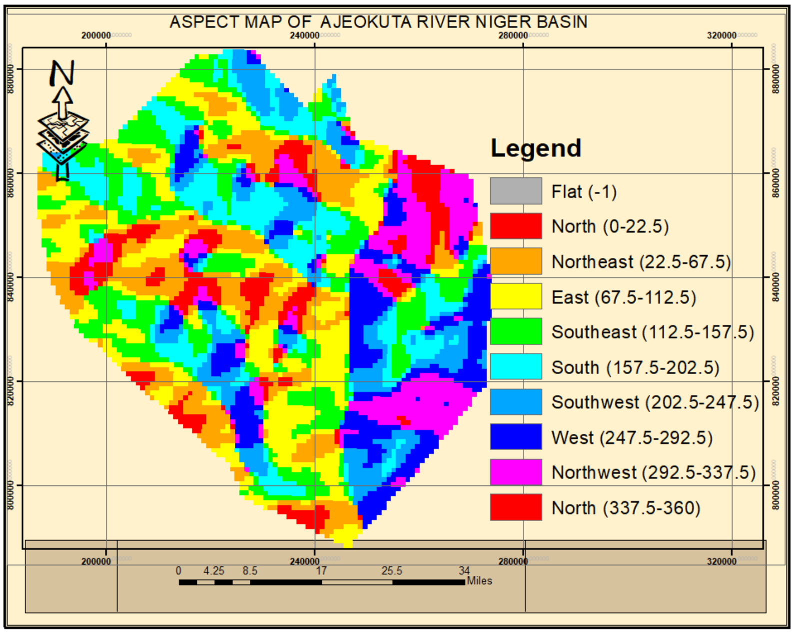

Figure 5. Slope aspect of the study area.

Figure 6 and Figure 7 are stack of hydro-terrain on the 3-D surface model of the catchment revealing undulating surface. This analysis shows that flow routes are naturally located between the valleys and are structurally controlled. These flow routes are the result of the natural morphology of the landscape. Hydrological character of a given area is a function of the surface in which it flows. In other wards landform of a particular area partly depends on interaction between the geology and natural drainages. This is because water tries to find it routes through easily erodible path.

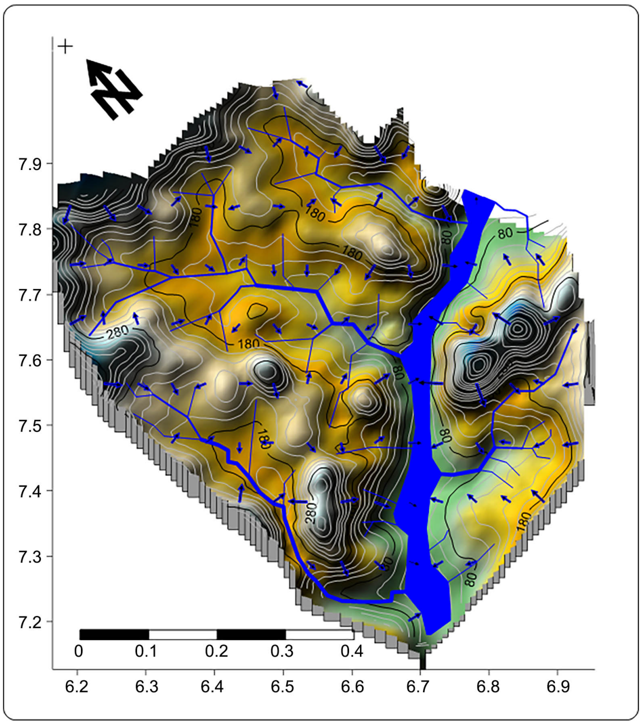

Figure 6. A stack of the drainage map on the 3-D model of the study area.

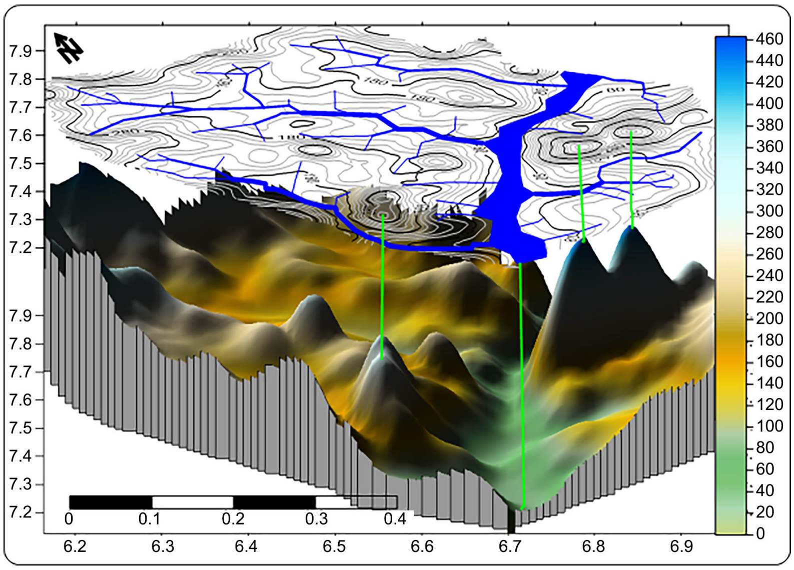

Figure 7. A stack of the drainage and Contour map on the 3-D model of the study area.

Figure 8 and **Figure 9** show direction of surface flow vectors. These directions are towards the valleys where natural flow routes are located. This analysis is indispensable in urban drainage construction as the natural flow routes form the primary drainage system that drains water away from the urban areas. Most of the flooding experience in the urban areas is because these natural flow routes have been blocked by urban construction. To ensure flow efficiency, drainage networks will have to be designed considering the natural flow routes and their sub-catchments. In every city, there are already existing natural flow routes. These routes are the result of the natural morphology of the landscape and have efficiently drained the runoff of their sub-catchments over the years. For design efficiency, these natural flow routes should form the primary drainage routes of the sub-catchment which drain water captured from the secondary and tertiary drainage networks off the catchment.

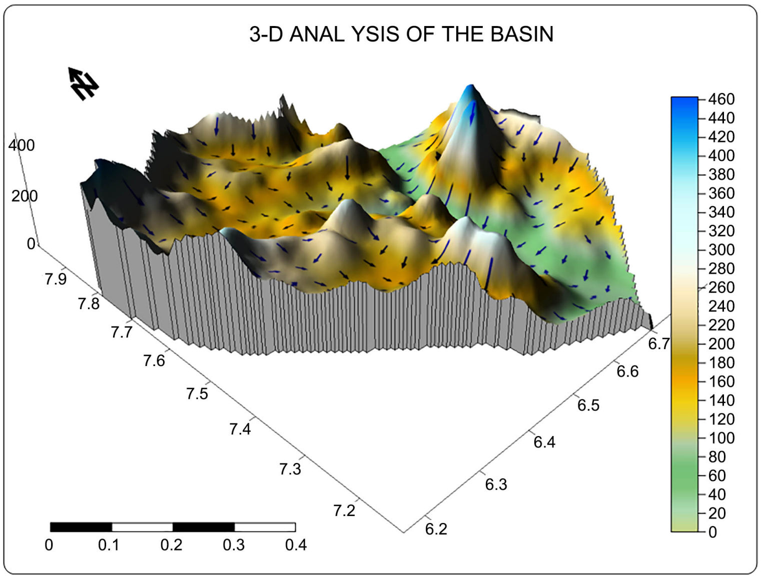

Figure 8. 3-D model showing direction of surface flow.

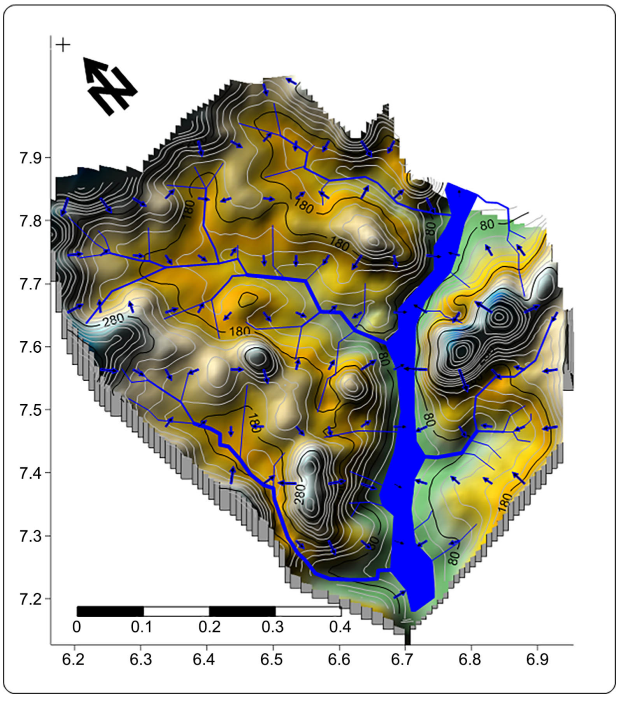

Figure 9. A rotated view of the elevation model showing directions of flow vectors.

Figures 10-12 portray the flow direction grid drainage and stream order map respectively. The flow grid assigns numbers to each cell within the grid network. The value assign to a particular grid depend on the direction of flow based on the underlying topography. This grid is fundamental to generation of flow accumulation on which the drainage definition (Figure 11) depends. Figure 12 shows that the basin is a 4th order basin with river Niger positioned highest in the hierarchy and with first order mostly dominating in number. A summary of the other attributes of the basin is shown in Table 1.

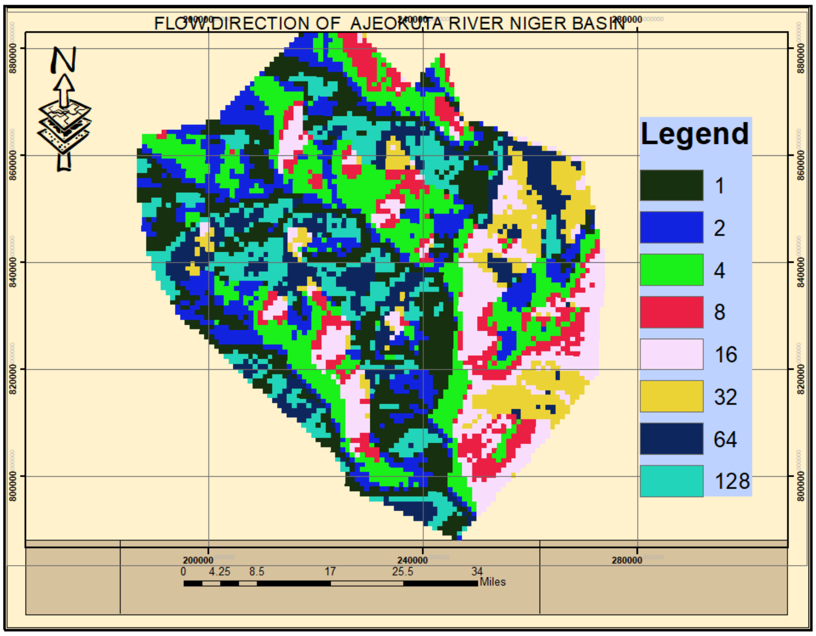

Figure 10. Flow direction grid of the study area.

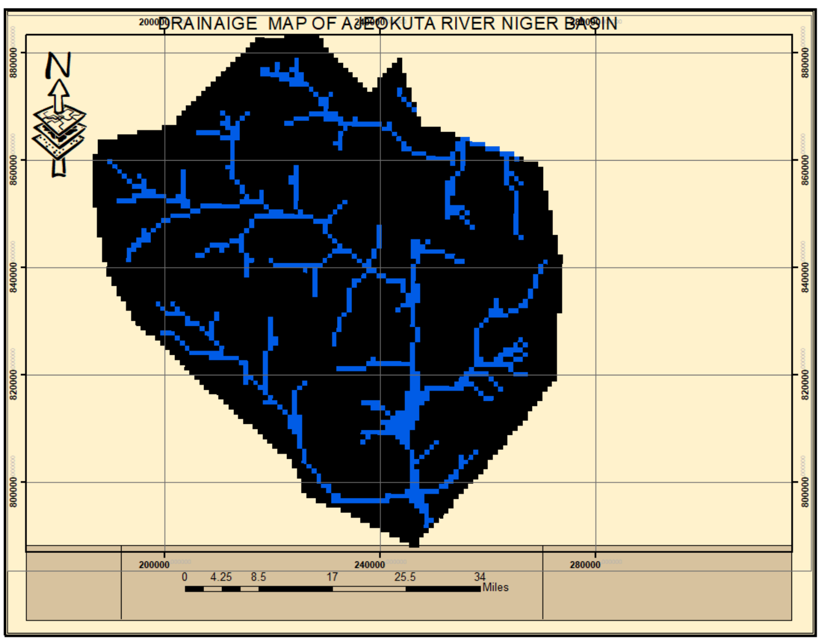

Figure 11. Drainage Map of the study area.

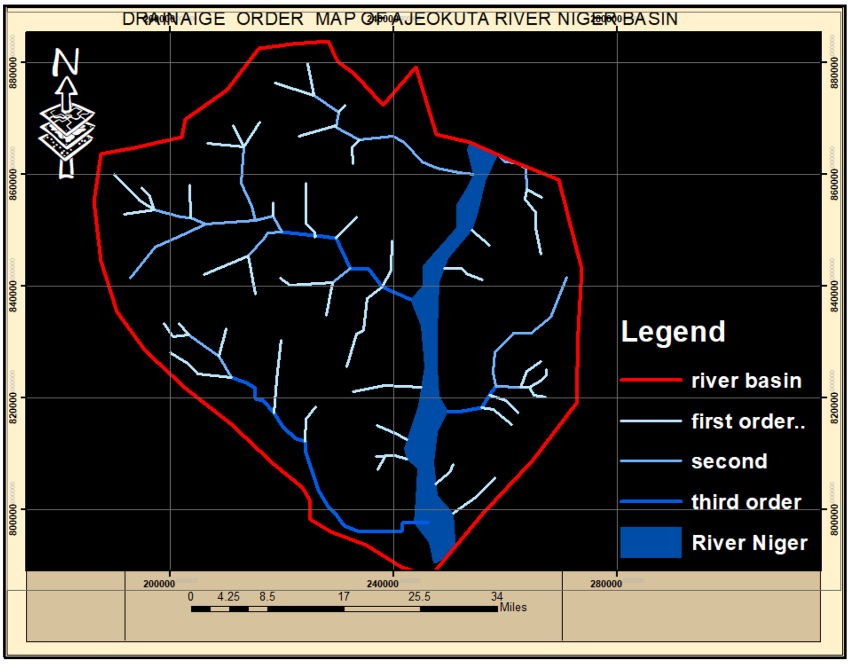

Figure 12. Drainage order Map of the study area.

4. Conclusion

The determination of stream network behavior and their interrelation with each other is of great importance in many water resources studies. Drainage morphology analysis is essential for a good understanding of hydrological, geological and topographical antecedents of a river basin, which is fundamental in watershed management. The use of ground based data capture for such analysis is cumbersome. However, in contemporary times, the use of E.O.S based data in the GIS platform is gaining popularity for such analysis. In this study, remote sensing satellite data (SRTM) and GIS tools for drainage analysis have been employed to evaluate several drainage parameters. Therefore, the morphometric analysis of the Ajeokuta River Niger basin was delineated. The river basin is designated as a 4th order basin, and 1st order streams are mostly dominating. Results revealed that there are one (1) fourth order streams, three (3) third order streams, twelve (12) second order streams and forty-one (41) first order streams. Further morphometric assessments revealed that the basin has a drainage density of 0.1125 km^{-1}, stream frequency of 0.0105, circulatory ratio of 0.765, bifurcation ratio range of 3 to 4, elongation ratio of 0.960, form factor of 0.729, basin length of 84 km, and 57 streams with total stream length of 607 kilometers draining and area of 5393 square kilometers. These geometric attributes attest that the basin is drainage course textured, oval in shape structurally controlled and of average infiltration and discharge potential.

Conflicts of Interest

The authors declare no conflicts of interest.

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