GIS-based approach for morphometric characteristics and development of hydrographs for the upper watershed of Jebba Reservoir, Nigeria

A.G. Adeogun[1], A.A. Mohammed[2], H.O. Ganiyu[1,*], A.W. Salami[2,3]

[1]Department of Civil Engineering, Kwara State University, Malete, 241104, Nigeria
[2]National Centre for Hydropower Research and Development, University of Ilorin, Ilorin, 240003, Nigeria
[3]Department of Water Resources and Environmental Engineering, University of Ilorin, Ilorin, 240003, Nigeria

ABSTRACT

Nigeria's Jebba sub-basins are synonymous to frequent flooding, high rate of erosion, depletion of soil nutrients and unsustainable water use. The uncontrolled flooding may be a result of numerous factors related to topography, geology, climate and human activity. The present work was an attempt to describe the application of Geographical Information System (GIS) and Digital Elevation Model (DEM) for the estimation of morphometric characteristics of eight sub-basins in the upstream watershed of Jebba reservoir, Nigeria. Morphometric characteristics such as topographic, areal, relief and network were determined. Soil Conservation Service (SCS) technique was applied to estimate hydrographs. The study revealed that sub-basin number 3 had the lowest time of concentration and maximum depth of runoff while sub-basin number 2 had maximum ratio of circulation of 1.8 and it is tagged as the area that is highly prone to flood. The peak runoff in the sub-basins ranged between 330.10 and 924.86 m^3/s (25-year return period) and for 100-year intervals ranged between 502.69 to 1408.40 m^3/s. The estimated peak runoffs can be adopted for designing and constructing erosion control structures in the catchment area.

Keywords: Catchment area; Digital elevation model; Drainage network; Hydro-meteorology; Soil conservation service.
DOI: https://dx.doi.org/10.4314/ejst.v14i3.5

INTRODUCTION

Morphometry is a **mathematical** analysis and measurement of shape and dimension of earth surface (Bajirao *et al*., 2019). Hydro-morphology is used in river basin planning to present hydro-morphological processes with characteristics of water

* Corresponding Author: habeeb.ganiyu@kwasu.edu.ng

bodies. Proper formulation of plans and its attendance consequence requires dependable information on morphologic factors, soil characteristics and land use, which affect the nature of a catchment. In addition, it is very essential to determine the relationship between watershed and ecosystem dynamics. Flooding is responsible for over 30% of actual amount used during disasters and for 70% of the households displaced through naturally occurring disasters (Ramshoo *et al*., 2012). But many countries put necessary programs of study and monitoring of the hydro-geological factors that contribute to flood vulnerability.

In the past, morphometric characteristics of a basin were determined using mathematical models. The recent application of Geographical Information System (GIS) tools allows simple and reliable interface for effective management of morphometric parameters. Hydro-morphological assessment of rivers is very vital in studying the flow pattern of rivers. Some of the previous studies on the hydro-morphometric characteristics of catchments revealed that Spatial Information Technologies (SIT), particularly GIS and Remote Sensing (RS) were commonly used tools in determining the hydro-morphometric characteristics of water resources in a catchment (Koshak and Dawood, 2011). These results provide necessary information needed to predict and determine the quantity of water associated with a flood disaster and predict the direction of flow and total discharge, which is useful for the design of hydraulic structures (Ajibade *et al*., 2010). Other similar studies reviewed in this study are summarized in Table 1. The study area is a sub-basin in the lower Niger River basin of Nigeria with an estimated population of 178,840. The analysis of the various parameters that constitute a river watershed is of utmost importance in river basin planning, evaluation, and management.

In the Jebba sub-basins, frequent flood, severe erosion, soil nutrient depletion and unsustainable water use were common events. Topography, geology, climate and human activity may have caused the flooding. Before the construction of the Jebba dam, flooding occurred once in seven to 10-year intervals (Atakpu, 1999). However, after the construction of the dam, floods occurred perennially with very high discharge of the River Niger and its tributaries in September and December causing a lot of havoc to the people living at the downstream of the dam (Pearce, 2001; FGN, 2006; Olukanni and Salami, 2010). The current study was necessary because from the literature reviewed, the Jebba sub-basin has not been a part. Studies like this one help identify areas that are prone to flooding and erosion and help mitigate the future occurrence of flooding in the study area.

Table 1. Morphometric studies reported in the past.

No.	Country	Studied area	Method used	Result	Reference (s)
1	Nigeria	Lower Niger river basin	DEM, GIS, Soil Conservation Service (SCS)	Morphometric parameter contributed to flooding	Salami *et al*. (2016)
2	Egypt	Wadi Dahab	GIS	30% of sub-basin prone to flooding	Omran *et al*. (2012)
3	India	Lower Gostani River B asin	GIS	Very low drainage density	Nageswara *et al.* (2010)
4	India	Parbhani district	GIS	Basin was in 4th order	Waikar *et al.* (2014)
5	India	Pargi river basin	GIS	Dendritic drainage pattern	Kuntamalla *et al*. (2018)
6	India	Pambar river basin	SRTM	Basins were of sixth order	Thomas *et al.* (2012)
7	India	Uttar Pradesh	GIS, DEM	Constant bifurcation ratio	Srivastava *et al.* (2014)
8	India	Bettahalasuru river basin in Bangalore	SRTM DEM	Low stream frequency	Amulya *et al.* (2018)
9	India	Kukar, Suha and Ratewal sub-watersheds	GIS	Dendritic drainage pattern	Kaur *et al.* (2014)
10	India	Sub-river basin of Krishna river	GIS, RS	High circulation ratio	Zende *et al.* (2013)
11	Morocco	Middle Atlas basin	GIS, DEM	Insignificant basin slope	Chadli and Boufala (2018)
12	Iran	North Fars catchment	SRTM, DEM	Reliable drainage control	Mokarram and Sathyamoorth (2015)
13	Nigeria	Ofu river	RS, GIS	Flatter peak direct runoff	Alfa *et al*. (2019)

Spatial Information Technologies, particularly Geographical Information Systems (GIS) and Digital Elevation Model (DEM) are efficient tools to determine the morphometrical properties of drainage basins for water resources management and environmental planning (Koshak and Dawood, 2011).

In contrast to the current study, streamflow and return periods were not considered in previous studies during the morphometric characterization of river basins. The aim of the current study was assessing the morphometric characteristics of the upstream catchment of Jebba River, Niger State, Nigeria, with specific objectives of estimating basin parameters, computing morphometric parameters and developing hydrographs.

METHODOLOGY

The study location is on Latitude 8.99° to 10.31° N and Longitude 4.79° to 5.01° E. It has a perimeter of 567 km and an area 12,992 km^2. The study area is a sub-basin in the lower Niger River basin of Nigeria (Figure 1).

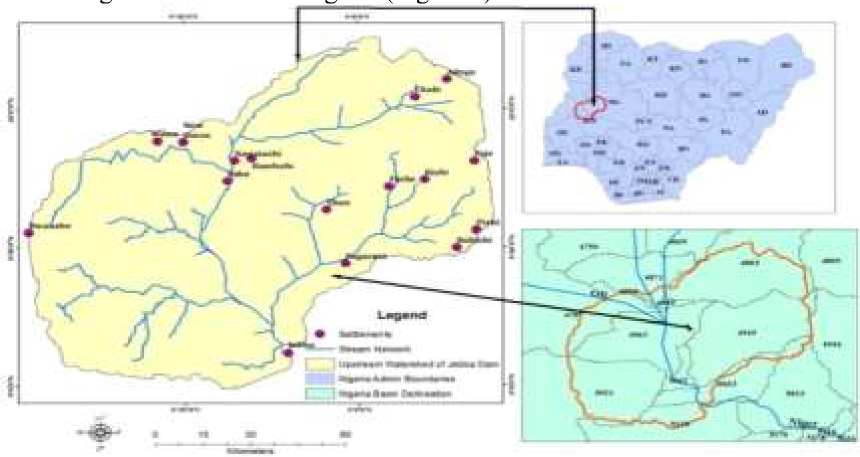

Figure 1. Map of Nigeria showing upstream watershed of Jebba Dam (Adeogun *et al*., 2016)

The morphological parameters applied in this work were estimated using the DEM, stream network and the catchment which was delineated with Arc GIS tools and used to determine the morphological characteristics of the sub-catchments. The procedure **described** in Abel (2005) was adopted to characterize the catchment. The DEM of resolution 90 m × 90 m used in this study was obtained from Shuttle Radar Topographical Mission (SRTM) of United States Department of Agriculture

(USDA) (CGIAR, 2020). The DEM was applied to obtain information about the river watershed.

Morphometric parameters of the study area

Generally, the morphometrical characteristic of a watershed is normally explained by association between the number of streams and order in a watershed, mean stream length in each order, stream slope in each order and the watershed area of the streams (Strahler, 1964). The morphometrical features of the sub-basins such as land slope, stream order, stream number, length of stream, stream length of sub-basins, area of sub-basins, catchment area, sub-basin numbers, maximum and minimum height were determined from the DEM and ArcGIS. The morphometrical parameters of the sub-basins were estimated using the morphometrical features of the sub-basins and the Eq. (1) to Eq. (5) the details of which can be found in Romshoo *et al.* (2012) and Salami *et al.* (2016).

$$\text{Compactness factor } (K_c) = 0.28\left[\frac{P}{A^{\frac{1}{2}}}\right] \quad (1)$$

$$\text{Concentration time} (T_c) = \left[\frac{0.886L^3}{H}\right]^{0.385} \quad (2)$$

$$\text{Elogation ratio} (R_e) = \frac{2\left[\sqrt{\left(A/\Pi\right)}\right]}{L_u} \quad (3)$$

$$\text{Circulatory ratio} (R_c) = \frac{4\Pi A}{P^2} \quad (4)$$

$$\text{Form factor ratio} (R_f) = \frac{A}{Lb^2} \quad (5)$$

Where:

P = Basin perimeter (m)	L_u = Total stream length of all orders (km)
A = Watershed area (km^2)	L = Main stream length (km)
H = Altitudinal difference (m)	π = 3.14

Estimation of runoff for the sub-basins

Sub-basin runoff was estimated using Soil Conservation Service (SCS) method that was developed by the United States Department of Agriculture (USDA) in 1917 and the morphometric parameters to generate hydrographs for the sub-basins (Raghunath, 2006). Unit hydrograph ordinates were generated from the estimated morphometric parameters of the sub-basins and the SCS method presented in Eq. (6)

to Eq. (11) in accordance with Salami *et al.* (2009). The runoff hydrograph was generated using hydrographic convolution as presented in Eq. (12). The generated unit hydrographs were used to produce storm hydrographs of 25, 50, 75 and 100% return periods for the sub-basins within the basin area. Flow chart of the methodology adopted in this study is presented in Figure 2.

$$Q_p = \frac{0.208A\ Q_d}{t_p} \quad (6)$$

$$t_p = \frac{t_r}{2} + t_l \quad (7)$$

$$t_l = 0.6t_c \quad (8)$$

$$t_c = 0.0195\left(\frac{L^{0.77}}{S^{0.385}}\right) \quad (9)$$

$$Q_d = \frac{\left(P^* - I_a\right)^2}{P^* + 0.8S} \quad \text{for} \quad P^* > 0.2S \quad (10)$$

otherwise

$$Q_d = 0 \quad \text{for} \quad P^* \le 0.2S$$

$$S = \frac{25400}{CN} - 254 \quad (11)$$

where:

L = Length of channel (km)
S = Slope of channel
Q_p = Peak discharge (m^3/s)
A = Watershed area (km^2)
Q_d = Quantity of runoff (mm)
t_p = Time to peak (hr)
t_c = Time of concentration (min)
t_l = Lag time (min)
P^* = Precipitation accumulated (mm)
$I_a = 0.2S$
I_a = Initial abstraction
CN = 75 for small grain and good conditions soil in group B
R = Excess rainfall increase (cm)
U = Ordinates of unit hydrograph ($m^3/s/cm$)
Q_n = Peak runoff (m^3/s)

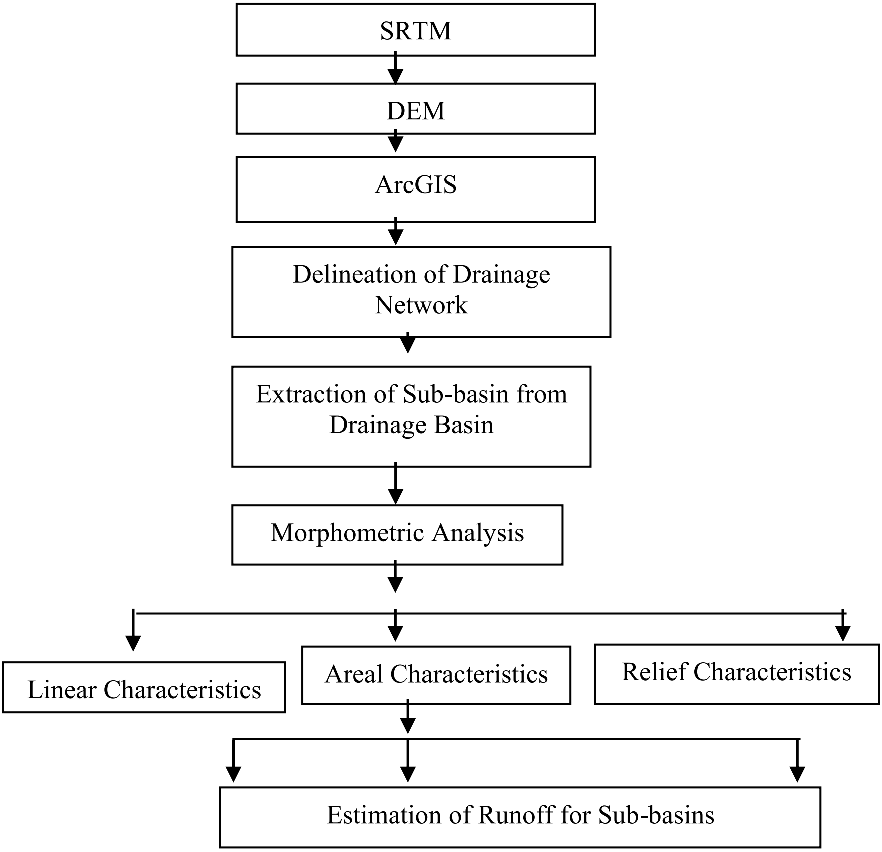

Figure 2. Flow chart of methodology adopted in the study

RESULTS AND DISCUSSION

Estimation of basin morphometric characteristics

Figure 3 shows the DEM for the basin and Figure 4 the sub-basins generated for the basin area. The results of topographic and linear characteristics of the area are presented in Table 2, indicating four stream orders in the watershed. The 1st stream order had total number of 20 with total length of 102.4 km; the 2nd stream order had eight streams with length of 70.3 km; the 3rd stream order was seven with length of 56.39 km and the 4th stream order had four with total length of 24.29 km. It was demonstrated that the ratio of bifurcation had a small variation range for varied regions within different environments.

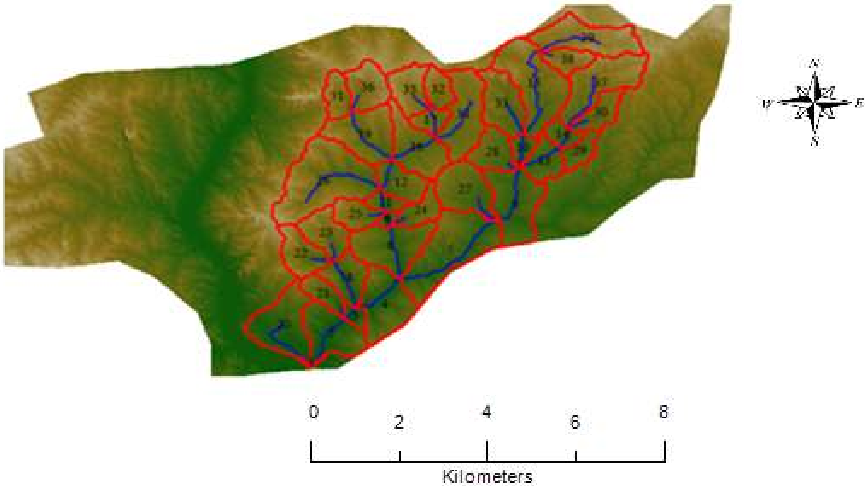

Figure 3. Digital elevation model (DEM) of the watershed attributed with stream networks.

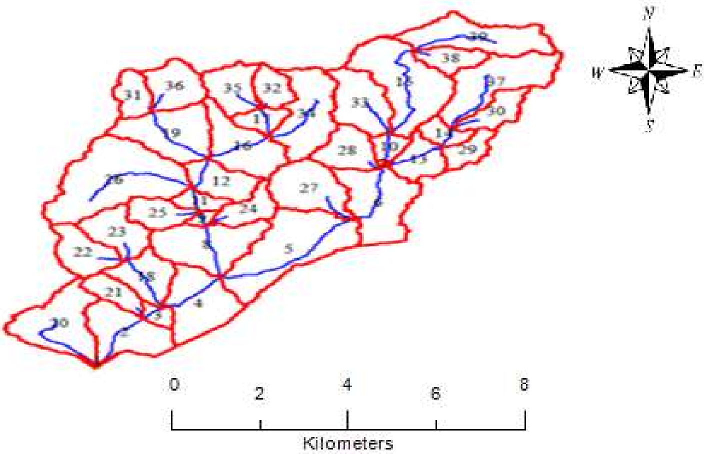

Figure 4. Delineation of the upper catchment of Jebba Reservoir into Sub-basins.

The average ratio of bifurcation of 1.8 indicates that the hydro-geological structures had significant impact on the drainage characteristics of the watershed. Similar result was reported before (Khosak and Dawod, 2011).

Table 2. Topographic characteristics of the channel.

River basin	Stream order	Number of streams (N_u)	Total length of streams(km) (L_u)	Log N_u	Log L_u
Upstream Jebba Watershed	1	20	102.4	1.3	2.01
	2	8	70.627	0.9	1.85
	3	7	56.29	0.85	1.75
	4	4	24.29	0.6	1.39
Ratio of bifurcation					
1st/2nd order	2nd/3rd order	3rd/4th order	Mean bifurcation ratio		
2.5	1.143	1.75	1.8		

The overall stream segments revealed that they were thirty-nine (Table 3); this translates to twenty segments of streams in the first order which accounts for 51.3%; eight stream segments were found in the second order which represents 20.5%; seven and four stream segments are available in the third and fourth orders which are 17.9 and 10.3%, respectively.

The entire catchment area was partitioned into eight sub-catchments (Table 4); the sub-basin areas range from 14.64 to 161.32 km^2, while the perimeters of the sub-basins range from 19.05 to 139.85 km. The main stream length which is an important hydro-morphometrical parameter ranges from 3.18 to 23.31 km. The stream order shows the hierarchy that exists within stream segments and drainage networks.

The relief characteristics of the study are shown in Table 5. The lowest slope and runoff were observed the in the sub-basin A5 with the least basin relief value of 35.56, while the highest runoff was noticed in the A13 with the highest basin relief of 74.86. The least difference between maximum and minimum altitudes was observed in A13 with relative relief value of 0.001 while the highest was noticed in A14 with relative relief value of 0.018.

Table 3. Sub-basins stream length with order.

Sub basin	Order of stream				Total	Mean
	1st	2nd	3rd	4th		
	Length of stream (km)					
A2	13.53	11.84	7.04	3.46	35.87	8.97
A3	12.52	10.28	7.34	3.18	33.32	8.33
A4	14.41	6.41	3.29	8.12	32.23	8.06
A5	14.12	10.02	11.17	1.53	36.84	9.21
A6	16.18	11.49	5.49	0	33.16	8.29
A13	12.43	4.34	10.40	4.06	31.23	7.81
A14	8.01	9.10	11.55	3.95	32.61	8.15
A30	11.20	7.14	0	0	18.34	4.59
Total	102.40	70.63	56.29	24.29		
	Stream number					
A2	3	1	1	2	7	
A3	2	1	1	1	5	
A4	2	1	1	0	4	
A5	6	1	1	0	8	
A6	2	1	0	0	3	
A13	2	1	1	0	4	
A14	2	1	1	1	5	
A30	1	1	1	0	3	
Total	20	8	7	4	39	

Table 4. Computed topographic characteristics.

Sub basin	Area (km^2)	Perimeter (km)	Length of main stream (km)
A2	86.58	24.80	12.10
A3	14.64	19.05	3.18
A4	99.97	68.01	11.34
A5	161.32	139.85	23.31
A6	110.18	86.38	14.40
A13	44.78	54.62	9.10
A14	24.39	26.06	4.34
A30	40.05	25.42	4.24
Mean value	72.74	55.52	10.25
Total value	581.91	444.18	82.00

Table 5. Computed relief characteristics of the study area.

Sub basin	**Basin relief**	**Relative relief**	**Relief ratio**	**Ruggedness number**
A2	56.43	0.002	0.047	67.72
A3	67.05	0.035	0.021	93.87
A4	44.58	0.007	0.004	26.75
A5	35.56	0.003	0.002	28.45
A6	40.42	0.005	0.003	10.11
A13	74.86	0.001	0.008	52.40
A14	45.72	0.018	0.011	15.09
A30	37.26	0.015	0.009	33.53
Mean value	50.24	0.010	0.010	40.99
Total value	401.88	0.080	0.120	368.90

Catchment No. 2 has a maximum ratio of circulation of 1.77 and catchment No. 5 has the least value of 0.10. This implies that the basin may experience flash floods. The ratio of circulation of the basin indicates that the basin has elongation shape and with low runoff and high soil permeability as in the case of Romshoo *et al.* (2012). The form factor of 0.52 also corroborated the fact that the basin has elongated shape which is similar to what was observed in Salami *et al.* (2016). Flood flows of the elongated watersheds are easier to manage than circular watershed.

Estimated 0.15 km/km^2 value of the drainage density indicates a well-developed drainage system. The drainage density indicates the complexity and level of development of the basin's drainage characteristics. The average shape coefficient value of 0.13 revealed that the basin is not prone to low concentration times (Table 6). The compactness coefficient varied from 0.75 to 3.08 throughout the watershed while the average value is 1.79. This shows that the association between the perimeters of watershed and circle within the same basin is similar. This was corroborated by the coefficient of compactness of 3.42 which indicates that the basin has irregular shape. The concentration time ranged from 0.32 to 3.20 while, the average was 1.28. This value shows the time deviation from the onset of precipitation till the period in which the total area of the catchment contributed fully to the stream flow at the outlet. The average slope across the watershed varied between 0.000265 (0.0265%) to 0.90 (0.90%), with average slope of 0.003 (0.30%). This value has a direct link between infiltration and runoff.

Table 5. Computed areal characteristics of the study area.

Sub basins	Texture ratio (T)	Elongation ratio (R_e)	Circularity ratio (R_c)	Form factors ratio (R_f)
A2	0.81	0.1	1.77	1.16
A3	1.05	0.04	0.51	12.71
A4	0.29	0.11	0.27	0.19
A5	0.14	0.14	0.1	0.04
A6	0.23	0.12	0.19	0.01
A13	0.37	0.07	0.19	1.65
A14	0.77	0.05	0.45	8.27
A30	0.79	0.07	0.78	0.01
Mean value	0.56	0.09	0.53	3.01
Total value	4.45	0.71	4.26	24.04

The drainage characteristics of the stream from the catchment were found to be mainly of dendritic in nature, which revealed uniform flow pattern in the basin. Stream frequency for all the sub-watersheds ranged between 0.025 and 0.273 with an average of 0.097 (Table 6). These values are positively correlated with the drainage density of the areas. This indicated an increase in stream number due to increase in drainage density. The ratio of texture for all the sub-watersheds ranges from 0.14 to 1.05, while the average ratio of texture of the basin is 2.05. The nature of soil in the basin can be categorized as moderate. The ratio of elongation of the watershed is 0.02, this implies that there is very high relief in the basin terrain.

Synthetic unit hydrograph and estimated peak runoff for sub-basins

The computed sub-catchments synthetic unit and storm hydrographs for various return periods are presented in Figures 5 to 12. The synthetic unit and storm hydrographs of all the return **periods** follow similar patterns. It was observed that the runoff increases with in return period for all the sub-basins.

Table 6. Computed network characteristics of the study area.

Sub-basins	Drainage intensity (D_d)	Stream frequency (F_s)	Sinuosity factors (S)	Shape coefficient (K_f)	Compactness coefficient (K_c)	Concentration time (T_c)
A2	0.14	0.05	3.81	0.16	0.75	1.50
A3	0.22	0.27	1.00	0.03	1.39	0.32
A4	0.11	0.04	3.57	0.18	1.90	1.39
A5	0.14	0.02	7.34	0.30	3.08	3.20
A6	0.13	0.04	4.53	0.20	2.30	1.83
A13	0.20	0.09	2.87	0.08	2.29	1.08
A14	0.18	0.16	1.37	0.04	1.48	0.46
A30	0.11	0.10	1.33	0.07	1.12	0.45
Mean	0.26	0.25	8.39	0.23	3.04	2.17
Total	2.73	1.64	54.88	2.37	31.68	21.74

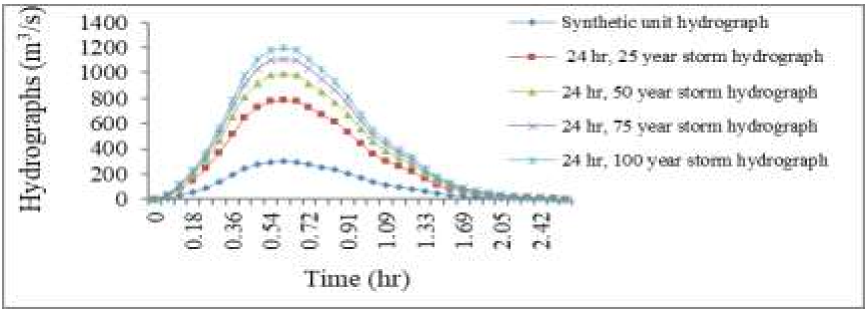

Figure 5. Hydrographs generated for different return periods for sub-basin 2.

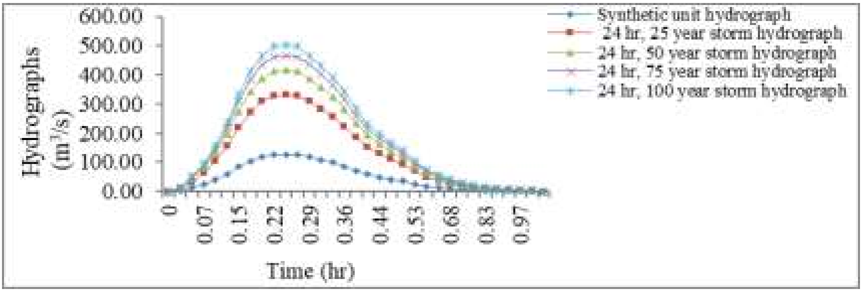

Figure 6. Hydrographs generated for different return periods for sub-basin 3.

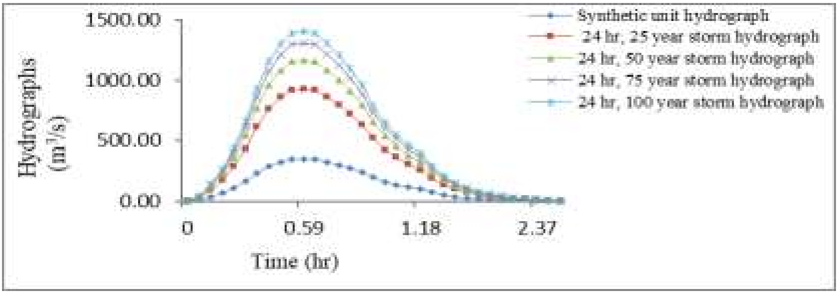

Figure 7. Hydrographs generated for different return periods for sub-basin 4.

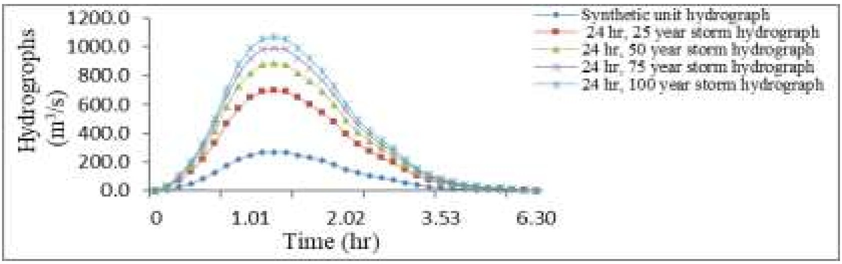

Figure 8. Hydrographs generated for different return periods for sub-basin 5.

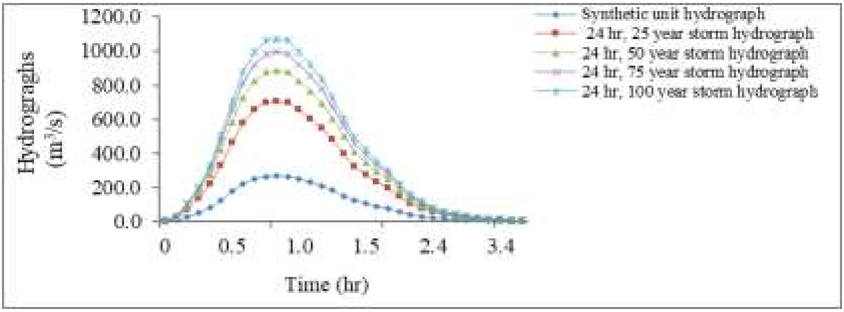

Figure 9. Hydrographs generated for different return periods for sub-basin 6.

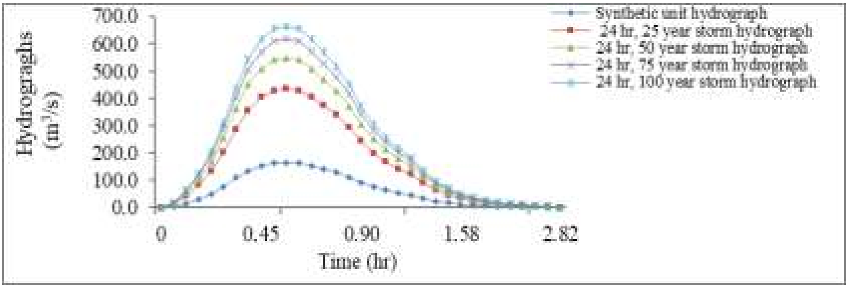

Figure 10. Hydrographs generated for different return periods for sub-basin 13.

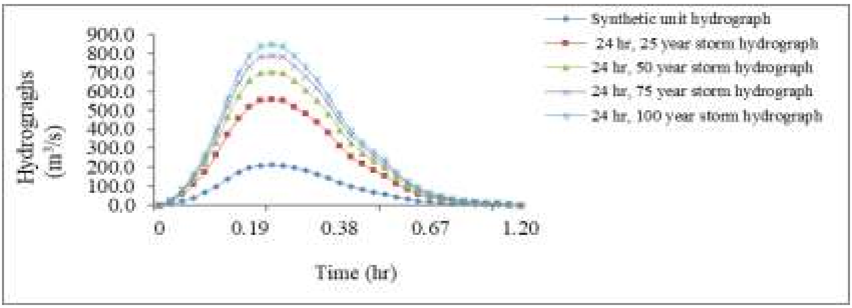

Figure 11. Hydrographs generated for different return periods for sub-basin 14.

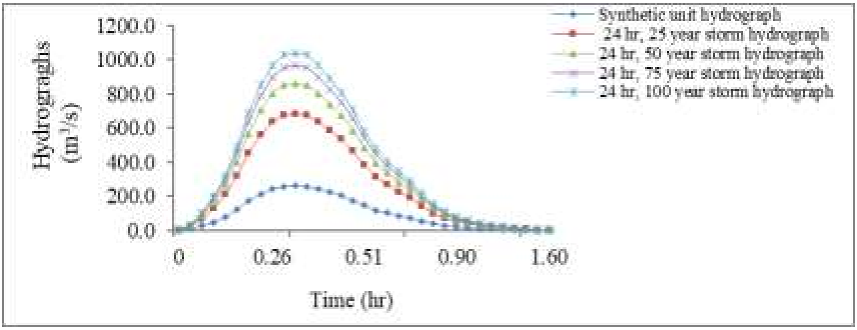

Figure 12. Hydrographs generated for different return periods for sub-basin 30.

The synthetic and storm hydrographs with various return periods estimated using morphometric characteristics for the sub-catchments as shown in Table 7. The hydrographs of peak runoff with return periods of 25 years ranged between 330.10 to 924.86 m^3/s, while the 50-year return period ranged between 416.83 to 1167.86 m^3/s (Table 7). The 75-year return period ranged from 467.04 to 1308.53 m^3/s and for the 100-year intervals ranged between 502.69 to 1408.40 m^3/s. The hydrographs of peak runoff could be adopted in designing and constructing hydraulic structures in the catchment especially in the sub-basin number 2 that was observed to be prone to erosion and flooding.

Table 7. Peak runoff for sub-basins (m^3/s).

Sub-basin	Peak runoff hydrographs for some return periods			
	25 yrs, 24 hrs	50 yrs, 24 hrs	75 yrs, 24 hrs	100 yrs, 24 hrs
A2	784.02	990.01	1109.25	1193.91
A3	330.10	416.83	467.04	502.69
A4	924.86	1167.86	1308.53	1408.40
A5	700.08	884.02	990.50	1066.10
A6	702.10	886.57	993.35	1069.17
A13	434.35	548.47	614.53	661.44
A14	557.42	703.87	788.65	848.84
A30	682.60	861.94	965.76	1039.47

CONCLUSION

The study area is a sub-basin in the lower Niger River basin of Nigeria with an estimated population of 178,840. The analysis of the various parameters that constitute a river watershed is of utmost important in river basin planning evaluation and management. It was observed that the basin has a low relief terrain which is elongated in shape and the drainage network is of dendritic type which implies its uniformity in soil texture. Generally, outcome of this research, most importantly, the morphometric parameters and the estimated peak runoffs can be adopted by stakeholders in water resources and environmental engineering in planning, designing and development of water infrastructure at the study area. An assessment of morphometric feature of catchment is very vital for sustainable planning and management of water system in a river basin. In this study, it was confirmed that morphometric data could play a role in the planning and execution of flood management system.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of Mr. Alhassan Danladi and staff of the **Department** of Civil Engineering, Kwara State University, Malete, Nigeria for the successful completion of this work.

Ethical statement
I declare that this study was carried out by the author(s) mentioned in this manuscript **and** the authors will bear any liability relating to claims coming from the content of this manuscript.

Conflict of interest
We have read the manuscript and we hereby affirm that the content of this manuscript or a major portion thereof has not been published in a refereed journal.

Contribution of authors
A.G. Adeogun (PhD) wrote the manuscript and computed the morphometric characteristics of the watershed. A. A. Mohammed (PhD) developed the hydrographs for **each** of the sub-basins and also revised the manuscript. H.O. Ganiyu (MSc) was involved in the GIS analysis of the watershed and the creation of some of the spatial images, and A.W. Salami (Professor) revised the manuscript.

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