Uniport Journal of Engineering and Scientific Research (UJESR)

Vol. 5, Issue 2, 2021, Page 38-50
ISSN: 2616-1192

(www.ujesr.org)

A GIS-Based Approach for Morphometric Characteristics and Development of Hydrographs for Landzu Watershed, Niger State, Nigeria

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Abstract

This work applied digital elevation model (DEM) for a hydro-morphometrical analysis of eighteen sub-catchments in Landzu watershed, Niger State, Nigeria. Eighteen sub-basins were considered in the watershed. Soil conservation service (SCS) approach was applied to determine hydrographs for the sub-basins. The study revealed that sub-catchment No. 4 has lowest concentration time and maximum discharge. Sub-catchment No. 8 has maximum ratio of circulation of 7.63. The sub-basin No. 8 has maximum flood hydrograph for the entire recurrent interval, while sub-basin No. 22 has the least value of hydrograph. The two sub-basins can be used in designing extreme scenarios for hydraulic structure in the basin.

Keywords: *Hydrograph, Landzu, Morphometric parameter, Watershed*

Received: 15th July, 2020 *Accepted: 23rd March, 2021*

1. Introduction

Hydromorphology is a terminology applied in water resources planning and management to describe hydrologic and geomorphologic processes. Proper planning and management of water resources in a basin involves reliable and current data on factors that affect river catchment. Morphometry is a study which includes the mathematical analysis and measurement of land forms, land shape and land surface dimensions. Morphometric analysis is very vital in investigating flood proneness and critical area susceptible to soil erosion within drainage basin. Prioritization of watershed on the basis of degree of erosion within river basin using different morphometric parameters can be performed using geospatial technology. Different watershed management treatment to prevent soil erosion can be performed on priority basis which prevent further degradation of critically eroded area (Bajirao *et al.*, 2019).

Floods are responsible for more over 30% of total cost estimate used in curbing disaster problems and over 70% of people affected by natural disasters (Ramshoo *et al.*, 2012). Many countries have measures in place to tackle flood problems. Quantitative analysis of catchment is vital for determining channel characteristics of a river basin (Soni, 2017). Morphologic characteristics of rivers are very useful in studying river basin system. There has been no study on morphometrical characteristics of Landzu sub-catchment in Niger State, Nigeria. The study assessed morphometric characteristics and developed runoff hydrographs for the watershed. The study is necessary for planning preventive measures to combat flooding with other problems that may arise in the catchment location. Study area is in Bida town of Niger State with Latitude $9^{\circ}05'$ N and Longitude $6^{\circ}01'$ E. It has catchment area of 51 km^2. Bida local government is the second biggest area in Niger State with population estimate of 178,840 (FGN, 2007). Map of Nigeria shows Niger State with catchment of the study area is shown in Fig. 1.

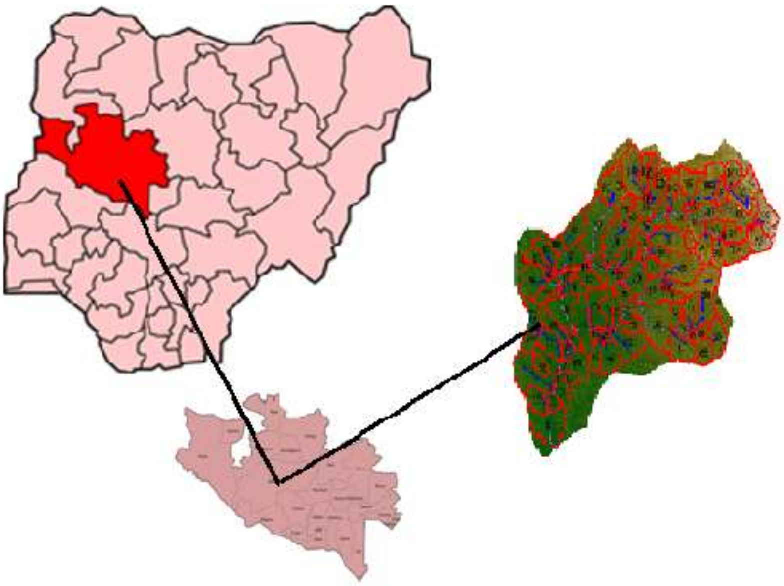

Fig. 1: Map of Nigeria depicting study area catchment

There were various studies on morphometric characteristics of watershed. Some of the previous works on the morphometrical characteristics of river catchments are reviewed here. Spatial information technologies, particularly Geographical Information System (GIS) and Remote Sensing (RS) are efficient tool in determining drainage basin and morphometric properties of water resources (Koshak and Dawood, 2011). Hydrologic response of a basin is defined as quantity of discharge against precipitation that is characterized by morphometric, soil and land use pattern. Soil properties and land terrain control percolation, distribution of excess precipitation as dictated by basin morphometric parameters (Ajibade *et al.*, 2010). Srivastava *et al.* (2014) applied morphometrical analysis to a catchment in India using DEM and GIS. The results revealed that ratio of bifurcation within consecutive stream orders were almost constant. Salami *et al.* (2016) assessed morphometrical characteristics of sub-lower Niger river catchment in Nigeria. It was observed that catchment number one had minimum time of concentration and maximum depth of runoff.

Rai *et al.* (2019) used geospatial approach to quantify river basin morphometry in India with GIS and DEM. Ratio of bifurcation of the basin revealed that it is normal and control the drainage orientation of the basin. Singh *et al.* (2013) assessed the morphometric characteristics of a river catchment in India with RS and GIS approaches. The results of ratio of bifurcation revealed that the catchment has elongated shaped. Waikar and Nilawar (2014) evaluated morphometrical characteristics of Charthana catchment in Maharashtra state of India using GIS. It was revealed that the catchment is of 4th order and drainage orientation is majorly sub-dendritic in nature. Kuntamalla *et al.* (2018) evaluated morphometric characteristics of a catchment in Rangareddy district in India with GIS. The results revealed that the drainage basin was characterized by dendritic drainage pattern.

Alfa *et al.* (2019) assessed the hydro-morphometrical properties of Ofu river sub-catchment in Nigeria with RS and GIS. The results indicated that the sub-catchment will have flat peak direct discharge for a longer period. Chadli and Boufala (2018) evaluated morphometrical characteristics of a catchment in Morocco with GIS and DEM approaches. It was noticed that large portion of the catchment had gentle gradient that is directed toward north-west. Thomas *et al.* (2012) studied the hydro-morphometrical characteristics of two river catchments in India. It was observed that the ratio of bifurcation of the basins did not highlighted structural control on drainage.

2. Materials and methods

The hydro-morphological variables used in this study were measured from DEM, network of streams and the watershed delineated using ArcGIS tools. The numbers of streams of various orders in the basin were counted and the lengths from mouth to drainage divide were measured with the GIS tool. Abel (2005) approach was modified and applied to characterize the catchment. Catchment segments were arranged numerically in accordance with (SCS, 2002) to determine the actual order of streams in the catchment. Bifurcation ratio was used to estimate ratio of stream segments of given order to the number of segments of the next higher order in the basins. The hydro-morphological characteristics of the sub-basins were determined using Equations (1) - (4).

2.1 Morphometrical characteristics of a basin

Morphometric characteristics of a watershed is majorly classified using: (i) association between number of streams in each order in a watershed as explained by (Strahler, 1964), (ii) mean stream length in each order, (iii) stream slope of each order, (iv) area of stream catchment for each order. The parameters are classified into four: topographic, areal, relief and network properties (Sreedevi *et al.*, 2004; Mesa, 2006; Nagaswera *et al.*, 2010; Navarro, 2011; Salami *et al.*, 2016). Various morphometrical parameters of a river basin applied in the study are present in Equations (1) to (4).

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

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

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

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

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

2.2 Estimation of peak runoff for sub-watershed

Runoffs for the sub-watersheds were estimated using Soil Conservation Service (SCS) method as explained in (Raghunath, 2006). The variables applied in developing unit hydrograph ordinates for SCS method are: peak discharge (Q_p), time to peak (t_p), lag time (t_l), time of concentration (t_c), quantity of runoff (Q_d) and slope of channel (S) as defined in Equations 5 to 10 in accordance with (Salami *et al.*, 2009) approaches. The runoff hydrograph was generated with hydrographic convolution as presented in Equation 11 (Sule and Alabi, 2013).

$$Q_p = \frac{0.208\, A\, Q_d}{t_p} \tag{5}$$

$$t_p = \frac{t_r}{2} + t_l \tag{6}$$

$$t_l = 0.6 t_c \tag{7}$$

$$t_c = 0.0195\left[\frac{L^{\,0.77}}{S^{\,0.385}}\right] \tag{8}$$

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) and t_l = Lag time (min).

$$Q_d = \begin{matrix} \frac{(P^* - I_a)^2}{P^* - 0.8S} & \text{for} & P^* > 0.2S \\ & \text{otherwise} & \\ Q_d & \text{for} & P^* \leq 0.2S \end{matrix} \tag{9}$$

$$S = \frac{25400}{CN} - 254 \tag{10}$$

$$Q_n = R_1 U_n + R_2 U_{n-1} + R_3 U_{n-2} + \cdots + R_n U_1 \tag{11}$$

where 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) and Q_n = Peak runoff (m^3/s).

3. Results

3.1 Morphometric characteristics of the basin

Digital elevation model of the basin is shown in Figure 2, while the sub-basin in the catchment area is presented in Figure 3. The results of topographic parameters of the sub-basins are presented in Table 1. Stream length of the sub-basins and order of basin streams are shown in Table 2. The topographic properties of the sub-basins are presented in Table 3, while the relief properties of the study area are shown in Table 4. Computed areal properties of the study area are shown in Table 5. The network properties of the sub-basins are shown in Table 6.

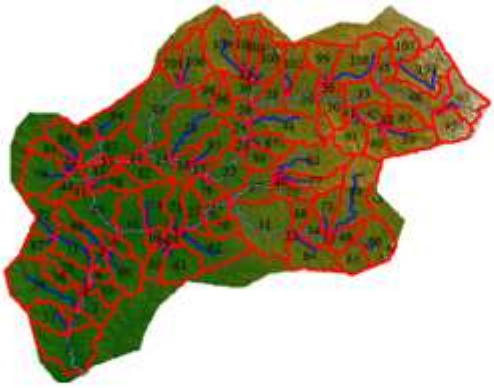

Fig 2: Digital elevation of the basin

Fig. 3: Sub basins of the study area

Table 1: Linear characteristic of the channel

River catchment	Stream order	Stream number (N_u)	Streams total length (L_u) (km)	Log N_u	Log L_u
Landzu Watershed	1	55	359.4	1.74	2.56
	2	23	206.83	1.36	2.32
	3	22	172.33	1.34	2.24
	4	9	46.42	0.95	1.67
		Bifurcation ratio			
1st order/2nd order	2nd order/3rd order	3rd order/4th order	average bifurcation ratio		
2.39	1.05	2.44	1.96		

Table 2: Sub-basin stream length with order

Sub basin	Stream order							Steam order				
	1st	2nd	3rd	4th	Total	Mean		1st	2nd	3rd	4th	Total
	Stream length (km)							Stream number				
A1	24.86	17.44	6.24	8.21	56.75	14.19		5	2	1	2	10
A2	41.36	22.58	8.25	5.77	77.96	19.49		12	2	1	1	16
A3	21.35	10.27	7.37	0	38.99	9.75		2	1	1	0	4
A4	33.56	9.71	5.98	0	49.25	12.31		6	1	1	0	8
A5	17.45	7.27	9.54	0	34.26	8.56		2	1	1	0	4
A6	14.36	8.25	5.26	0	27.87	6.97		2	1	1	0	4
A7	18.45	4.76	6.87	6.02	36.10	9.02		2	2	1	1	6
A8	21.34	8.46	12.61	0	42.41	10.60		3	1	1	0	5
A9	16.75	16.27	9.85	4.45	47.32	11.83		2	2	2	1	7
A18	15.25	14.52	14.11	2.63	46.51	11.63		2	1	1	1	5
A19	16.36	10.52	4.26	0	31.14	7.79		2	1	1	0	4
A21	15.64	19.29	8.21	0	43.14	10.79		2	2	1	0	5
A22	14.36	7.03	6.54	0	27.93	6.98		2	1	1	0	4
A25	10.59	18.62	7.84	0	37.05	9.26		1	2	1	0	4
A27	12.46	4.31	10.40	3.81	30.98	7.74		1	1	2	1	5
A37	17.56	14.64	14.63	2.94	49.78	12.44		2	1	2	1	6
A40	31.50	0.00	16.54	4.13	52.17	13.04		5	0	2	1	8
A81	16.20	8.26	17.83	0.00	42.29	10.57		2	1	1	0	4
Total	359.40	202.20	172.33	37.97			Total	55	23	22	9	109

Table 3: Computed topographic properties of the study area

Sub basins	Area (km^2)	Perimeter (km)	Length of main stream (km)
A1	130.35	27.06	13.53
A2	27.02	93.25	7.77
A3	44.83	72.02	6.00
A4	30.71	4.20	0.35
A5	70.81	21.18	1.77
A6	18.34	67.30	5.61
A7	18.85	72.22	6.02
A8	74.03	11.04	0.92
A9	27.39	53.41	4.45
A18	98.23	120.00	10.00
A19	13.70	51.14	4.26
A21	10.51	50.50	4.21
A22	1.03	13.69	1.14
A25	49.94	94.04	7.84
A27	32.27	124.84	10.40
A37	66.03	175.72	14.64
A40	5.89	29.05	2.42
A81	121.78	194.36	16.20
Mean value	46.76	70.83	6.53

Table 4: Computed relief properties of the study area

Sub basin	Basin relief (ΔH)	Relative relief (R_{hp})	Relief ratio (R_h)	Ruggedness number (N)
A1	68.67	0.003	0.005	82.40
A2	70.51	0.001	0.009	98.71
A3	42.23	0.001	0.007	25.34
A4	25.15	0.006	0.072	20.12
A5	30.14	0.001	0.017	7.54
A6	62.32	0.001	0.011	43.62
A7	46.56	0.001	0.008	15.36
A8	32.51	0.003	0.035	29.26
A9	30.85	0.001	0.007	26.53
A18	44.32	0.0004	0.004	11.08
A19	50.21	0.001	0.012	32.13
A21	47.36	0.001	0.011	17.05
A22	63.27	0.005	0.055	69.60
A25	83.36	0.001	0.011	65.85
A27	71.16	0.001	0.007	42.70
A37	62.98	0.000	0.004	56.68
A40	37.99	0.001	0.016	11.40
A81	47.54	0.000	0.003	17.11
Mean value	50.95	0.001	0.016	37.36

Table 5: Computed areal properties of the study area

Sub basins	Texture ratio (T)	Elongation ratio (R_e)	Circularity ratio (R_c)	Form factors (R_f)
A1	2.03	0.036	2.24	1.32
A2	0.59	0.016	0.04	0.40
A3	0.76	0.021	0.11	0.14
A4	13.10	0.017	2.88	0.50
A5	2.60	0.026	1.98	0.89
A6	0.82	0.013	0.05	0.72
A7	0.76	0.014	0.05	0.60
A8	4.98	0.027	7.63	0.66
A9	1.03	0.016	0.12	0.22
A18	0.46	0.031	0.09	0.68
A19	1.08	0.012	0.07	0.12
A21	1.09	0.010	0.05	0.98
A22	4.02	0.003	0.07	0.48
A25	0.58	0.022	0.07	0.72
A27	0.44	0.018	0.03	0.20
A37	0.31	0.026	0.03	0.15
A40	1.89	0.008	0.09	0.29
A81	0.28	0.035	0.04	0.20
Mean value	2.05	0.020	1.92	0.51

Table 6: Computed network properties of the study area

Sub basin	D_d	F_s	S	K_f	K_c	T_c
A1	0.10	0.07	38.66	0.50	0.66	1.71
A2	0.29	0.33	22.20	0.10	5.02	0.90
A3	0.13	0.20	17.15	0.17	3.01	0.67
A4	0.01	0.29	1.00	0.12	0.21	0.03
A5	0.02	0.13	5.04	0.27	0.70	0.16
A6	0.31	0.49	16.02	0.07	4.40	0.62
A7	0.32	0.48	17.19	0.07	4.66	0.67
A8	0.01	0.12	2.63	0.28	0.36	0.08
A9	0.16	0.33	12.72	0.10	2.86	0.47
A18	0.10	0.22	28.57	0.37	3.39	1.20
A19	0.31	1.61	12.18	0.05	3.87	0.45
A21	0.40	2.09	12.02	0.04	4.36	0.44
A22	1.11	0.21	3.26	0.00	3.78	0.10
A25	0.16	0.44	22.39	0.19	3.73	0.91
A27	0.32	0.68	29.72	0.12	6.15	1.26
A37	0.22	0.35	41.84	0.25	6.05	1.87
A40	0.41	0.39	6.92	0.02	3.35	0.23
A81	0.13	0.45	46.28	0.46	4.93	2.10
Mean value	0.25	0.49	18.66	0.18	3.42	0.77

D_d = Drainage intensity, F_s = Stream frequency, S = Sinuosity factors, K_f = Shape coefficient, K_c = Compactness coefficient, T_c = Concentration time

3.2 Synthetic hydrographs for sub-basins

The synthetic unit and storm hydrographs for various recurrent intervals at the sub-catchments are presented in Figures 4 to 10. Peak runoff hydrographs for the sub-basins are presented in Table 7.

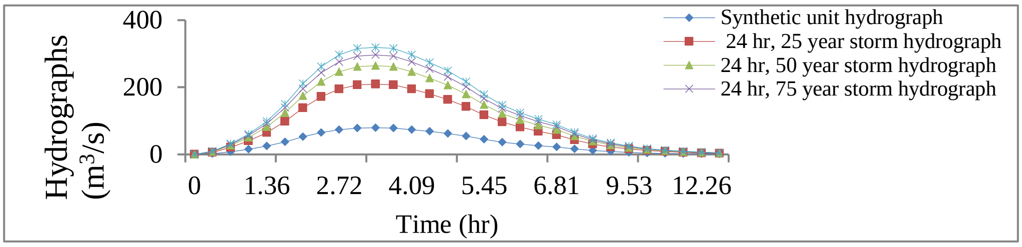

Fig. 4: Hydrographs generated for different return periods for sub-basin 1

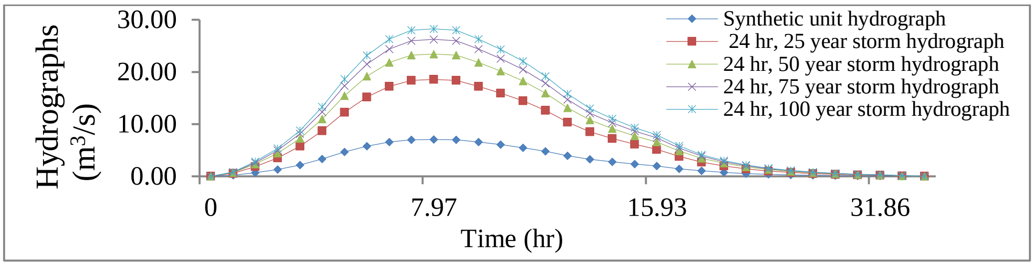

Fig. 5: Hydrographs generated for different return periods for sub-basin 2

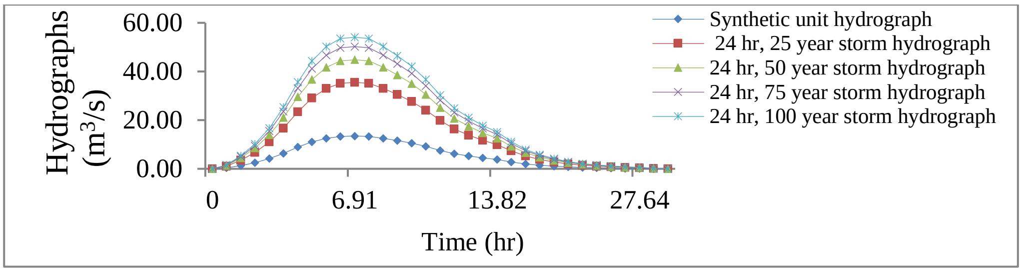

Fig 6: Hydrographs generated for different return periods for sub-basin 3

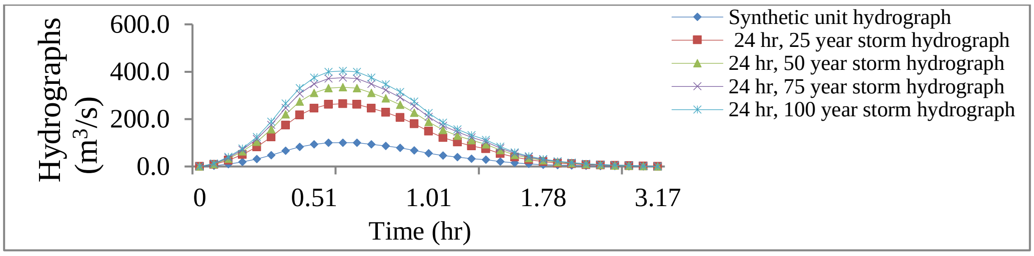

Fig. 7: Hydrographs generated for different return periods for sub-basin 4

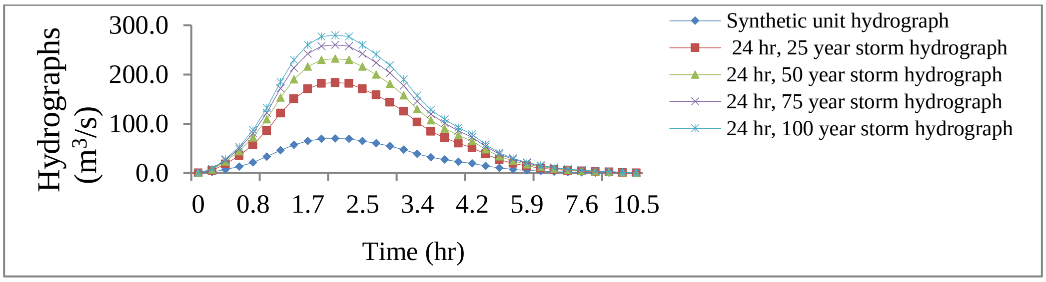

Fig. 8: Hydrographs generated for different return periods for sub-basin 5

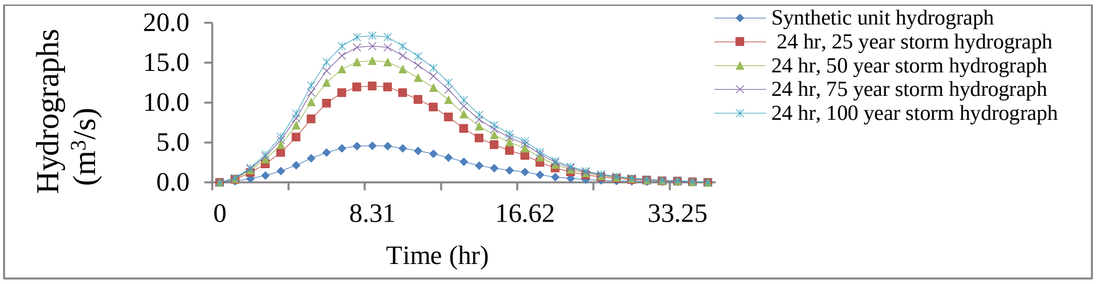

Fig. 9: Hydrographs generated for different return periods for sub-basin 6

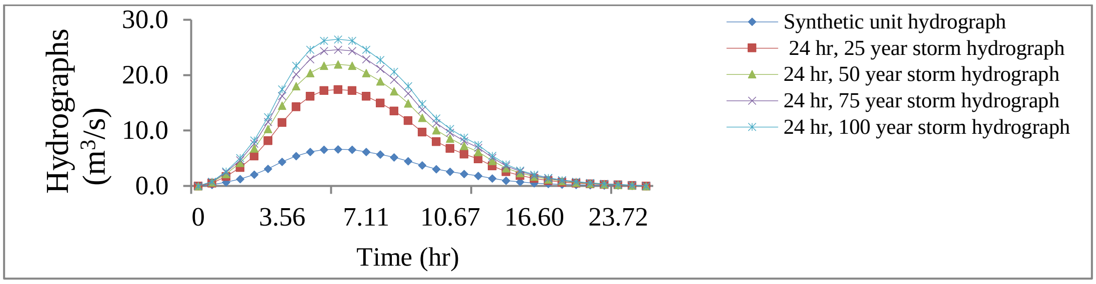

Fig. 10: Hydrographs generated for different return periods for sub-basin 7

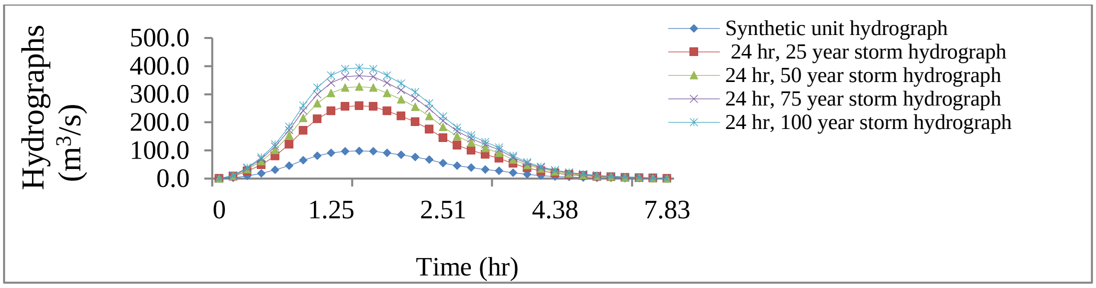

Fig. 11: Hydrographs generated for different return periods for sub-basin 8

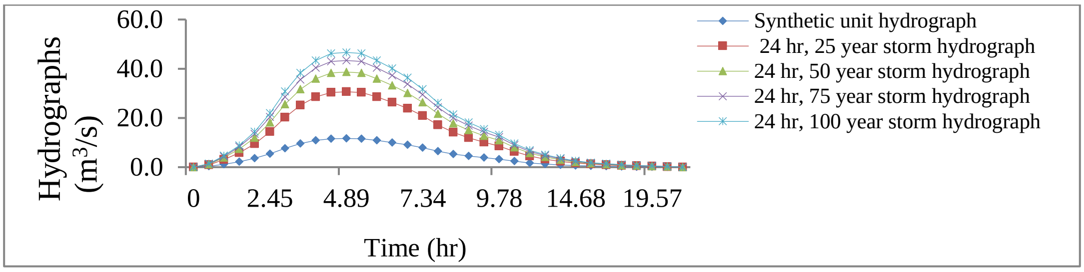

Fig. 12: Hydrographs generated for different return periods for sub-basin 9

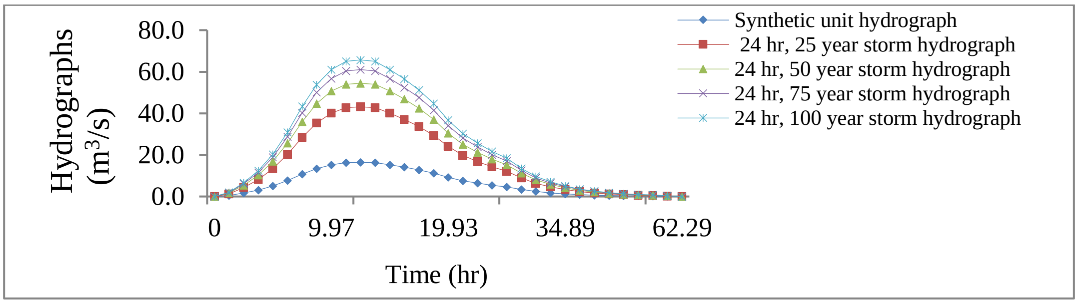

Fig. 13: Hydrographs generated for different return periods for sub-basin 18

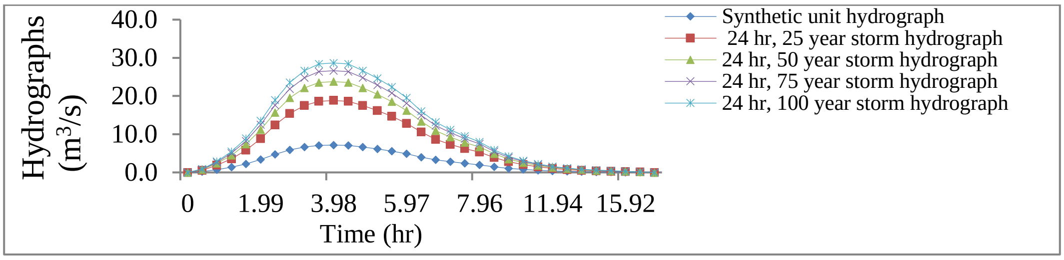

Fig 14: Hydrographs generated for different return periods for sub-basin 19

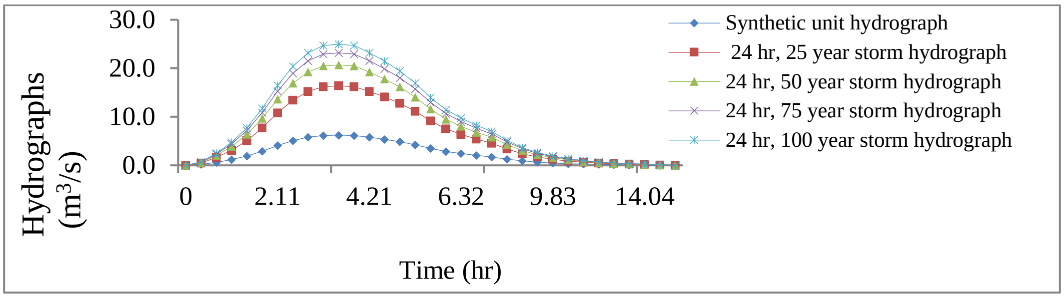

Fig. 15: Hydrographs generated for different return periods for sub-basin 21

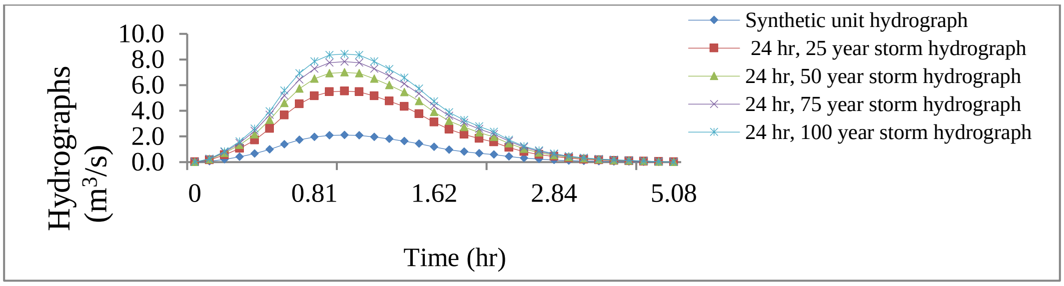

Fig. 16: Hydrographs generated for different return periods for sub-basin 22

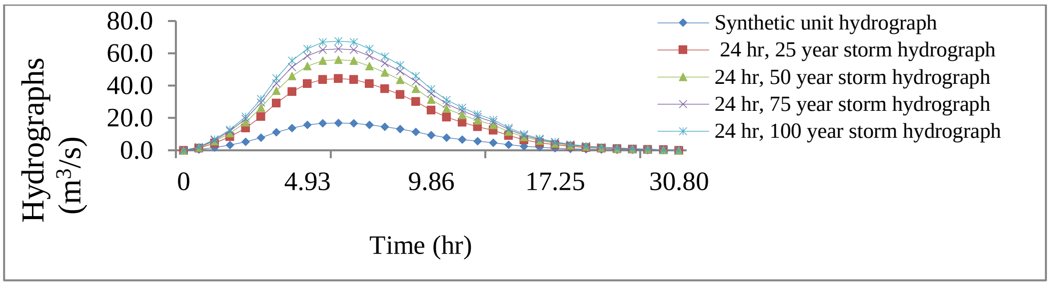

Fig. 17: Hydrographs generated for different return periods for sub-basin 25

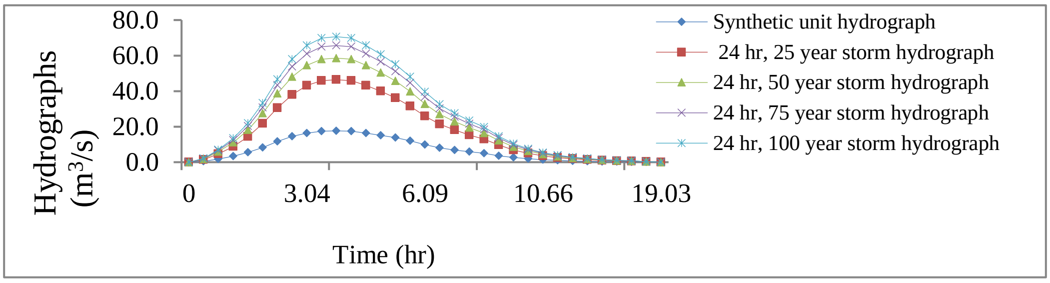

Fig. 18: Hydrographs generated for different return periods for sub-basin 27

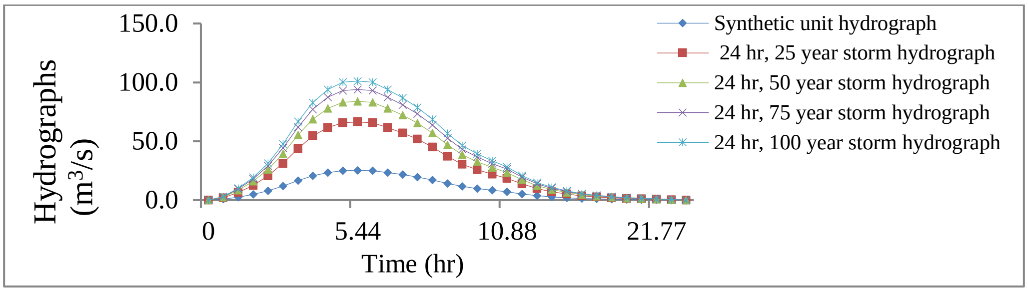

Fig. 19: Hydrographs generated for different return periods for sub-basin 37

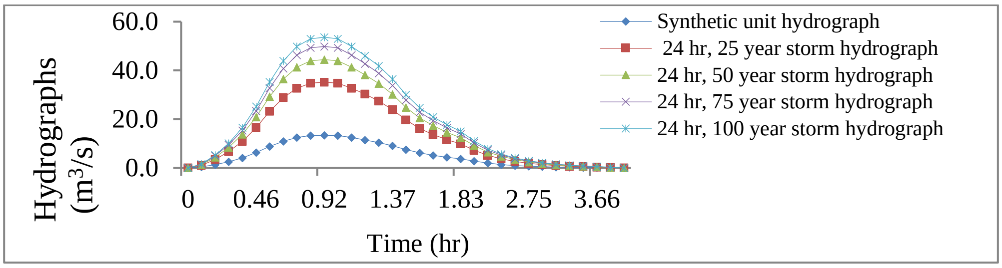

Fig. 20: Hydrographs generated for different return periods for sub-basin 40

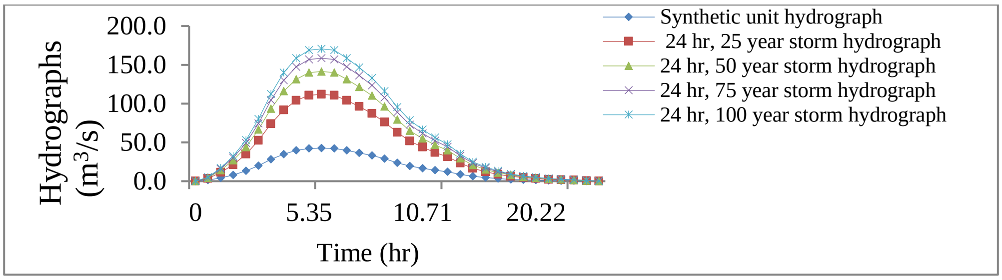

Fig. 21: Hydrographs generated for different return periods for sub-basin 81

Table 7: Peak runoff hydrograph 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**
A1	209.44	264.46	296.32	318.93
A2	18.55	23.43	26.25	28.25
A3	35.49	44.82	50.22	54.05
A4	264.84	334.43	374.71	403.30
A5	183.85	232.15	260.12	279.97
A6	12.07	15.24	17.08	18.38
A7	17.39	21.96	24.61	26.49
A8	258.64	326.59	365.93	393.86
A9	30.63	38.68	43.34	46.64
A18	43.13	54.46	61.02	65.68
A19	18.82	23.77	26.63	28.66
A21	16.38	20.68	23.17	24.94
A22	5.54	6.99	7.83	8.43
A25	44.35	56.00	62.75	67.54
A27	46.38	58.57	65.62	70.63
A37	66.38	83.82	93.92	101.09
A40	35.20	44.45	49.80	53.60
A81	112.00	141.43	158.47	170.56

4. Discussion

There are four stream orders in the basin as shown in Table 1. The 1st order streams total fifty-five with the overall length of 359.4 km; the 2nd order streams total twenty-three with length of 206.83 km; the 3rd order streams total twenty-two with a length of 172.33 km and the 4th order stream is only nine with a length of 46.42 km. The entire catchment area was divided into eighteen sub-basins as presented in Table 3; the sub-basin areas range from 1.03 to 130.35 km^2, while the catchment perimeters range from 4.20 to 194.36 km. The main stream length of the sub-basin, which is a significant hydro-morphometrical characteristic, ranges from 0.35 to 16.197 km.

The total stream segments are 109 as presented in Table 2; the first order streams total 55 segments and account for 50.46 %; the second order stream segments total 23 and account for 21.10 %; the third order stream segments total 22 and account for 20.18 %; the fourth order stream segment is 9 and accounts for 8.26%. The drainage patterns of the stream network from the basin have been observed to mainly be a dendritic type, which indicates the homogeneity in texture and the lack of structural control. The longer lengths of streams are generally indicative of flatter gradients. Generally, the total length of stream segments is the maximum in first order streams and decreases as the stream order increases. The stream lengths vary between 46.42 to 359.4 km at the fourth and first order respectively. Stream frequency for all the sub basins ranged from 0.069 to 1.606 with the average value being 0.49 which is similar to what was obtained in (Bajirao, *et al.,* 2019). This value exhibits a positive correlation with the drainage density value of the areas indicating the increase in stream number with respect to the increase in drainage density.

The texture ratio is an important factor in the drainage morphometrical analysis, which depends on the underlying lithology, infiltration capacity and relief aspect of the terrain. The texture ratio for all the sub basins varies between 0.28 and 13.10, while the average texture ratio of the basin is 2.05. The nature of soil in the basin can be categorized as moderate. The elongation ratio of the study area is 0.039, which indicates that there is very high relief of the terrain and is elongated in shape. Catchment No. 4 has the maximum circulation ratio of 2.87 and catchment No. 23 has the least value of 0.27. The basin has form factor of 0.96, this reveals that the basin is elongated in shape.

The mean bifurcation ratio of 1.960 indicates that the geology of the area have a significant impact on its drainage. The average shape coefficient for the watershed was 0.18, which indicates a watershed that is not prone to short concentration times. This reflects the relation between the average width of a basin and the length of the longest stream. The compactness coefficient varies from 0.21 to 6.15 throughout the watershed while average value is 3.42. This shows that the correlation between the perimeter of a watershed and circle with the same area of the watershed; gives idea on the regularity of its shape. The lower the value, the more regular the watershed perimeter and the more prone it is to present high runoff peaks. The concentration time ranges between 0.03 to 2.10, while the average is 0.77. This value represents time variation from the onset of precipitation till the time when the whole watershed contributes to the outlet runoff similar to what was observed in (Salami *et al.,* 2009). The average slope across the watershed varies between 0.00029 (0.029%) to 0.0103 (1.03%), with average slope of 0.0026 (0.26%).

5. Conclusions

The aim of this study was to assess the morphometric characteristics of River Landzu watershed in Niger State, Nigeria. The watershed channel processes as simplified by the morphometrical studies of the sub-basins and their contributions to flooding problems in the sub-basins. The watershed was sub-divided into eighteen sub-basins using DEM. The analysis of the various morphometric characteristics of the sub-basins that contribute to the river was carried out using DEM and remote sensing. Unit and flood hydrographs with 25, 50, 75 and 100% recurrent period were determined for the sub-basins using SCS method. The results revealed that the areas of the sub-basins vary from 1.03 to 130.54 km^2, while the length of the streams ranges between 4.20 and 194.36 km. The ratio of relief ranges between 0.003 and 0.072 m/km. It was also observed that the basin has a low dendritic drainage network. The topographic pattern of the basin shows the weathering characteristics of the study area. The sub-basin No. 8 has maximum flood hydrograph for the entire recurrent interval, while sub-basin No. 22 has the least value of hydrographs. The two sub-basins can be used in designing extreme scenarios for hydraulic structure in the basin. This study is very important to water resources practitioners and environmental managers for sustainable development and utilization of the water resources in this area.

Acknowledgements

The authors wish to thank the management of the Kainji Hydropower Station, Nigeria, for providing the data used in this study. The authors appreciate the management of NACHRED for providing enabling environment in the course of this work.

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