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DETERMINATION OF PEAK RUNOFF USING THE CATCHMENT CHARACTERISTICS ALONG FOMA BASIN ILORIN, NORTH CENTRAL NIGERIA

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Abstract: This paper presents the evaluation of the peak runoff for an ungauged catchment using the catchment characteristics. The study made use of Geographical Information System (GIS) to determine watershed features for the morphometric analysis of four sub-catchments within Foma sub-basin along Ilorin West and Ilorin South local government areas of Kwara State, North Central Nigeria. Morphometric parameter such as sub-basin characteristics which is an important factors in determining the runoff of an ungauged basin were computed and analysed. Soil Conservation Services (SCS) method of peak runoff estimation was used to determine peak runoff of the study area for five return periods. The results of the peak runoff estimation based on SCS method for the four sub-catchments for 20-year, 50-year, 100-year, 200 year and 500-year return periods are 234.01, 298.30, 357.12, 427.79 and 537. 99 m3/s respectively. The peak storm hydrographs developed for various return periods can be used in designing the hydraulic structures within the study area.
Keywords: Digital elevation model; Geographic information system; Morphometric parameters; Return periods; Runoff; Sub-basin; Sub-catchment

1. INTRODUCTION

The design of flood hydrograph and peak flow has always been of paramount importance in the feed of hydrology. Particularly, for ungauged basins that are often characterized by small contributing areas and short concentration times, hence posing problems for flood alert (Młyński et al. 2018). Indeed, runoff prediction in ungauged basins is an interesting area in the field of hydrology due to the challenges usually involved in obtaining suitable historical observations needed for advanced hydrological model calibration (Duan et al. 2006). Studies have proposed many indirect rainfall–runoff methods (Rational formula, Soil Conservation Service – SCS Method, regionalization approaches, and so on) to predict runoff in ungauged catchments (Chow 1964, Young 2006, El- Hames 2012). While different hydrological models were also used to simulate the rainfall–runoff relationship for estimating the peak flow in ungauged catchments (Iskender and Sajikumar 2016, Gumindoga et al. 2017, Ragettli et al. 2017, Xu et al. 2018, Tegegne and Kim 2018, Ouarda et al. 2018). Similarly, statistical regionalization methods have been among the most widely used to estimate discharge at ungauged or poorly gauged locations using data from gauged sites over the last decades (Merz and Blöschl 2004, Oudin et al. 2008, Samuel et al. 2011, Brunner et al. 2018). The majority of such studies highlighted the difficulty in calibrating the model parameters due mainly to lack of data.

Generally, peak flows determine the design specifications of structures such as embankments, channels, bridges, and dams. Similarly, peak flows also determine the capacity of the control sections of flow-through measurement systems, collection pipes and transfer conduits of volumetric collection vessels. In order words, some estimate of peak flows must be made before the design of these systems can be completed (Miller 1994). The design peak flows at a particular return periods, such as the maximum flow in 5, 10, 25, etc., years and design specifications are a balance between economic cost and the prevention of failure of the structure (Miller 1994).

Indeed, catchment characteristics add a lot to runoff volume. Generally, the basin size is the most important basin characteristic in determining the quantity and timing of surface runoff at the outlet. The larger the basin size, the greater the possibility of the amount of rainfall that can be captured and directed to the basin outlet. Basin size mostly controls the volume of runoff past the outlet. Basin shape and topography are key basin characteristics controlling the routing of runoff to the basin outlet, and mostly control the timing of the peak, and to a lesser degree, the extent of the peak flow. Soil properties control, to a large extent, the penetration rate, storage, and release of the rainfall from the overburden. Soils affect the quantity and type of vegetation, which also influence the infiltration rate. Similarly, land use and modifications to the natural surface by practices such as deforestation, mining, and farming, as well as structures such as dams, levees, bridges, channels, and pavement also can have a significant effect (Carluer et al. 2004).

Many hydrologic procedures are available for evaluating the peak flows from a basin. However, no single method can be said to be applicable to all basins (Donald and Richard, 2005). Evaluating the volume of

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runoff or the peak runoff rate is likely to occur from a specific watershed in response to a specific rainfall event is a very difficult challenge. The challenge has resulted to the need to define many critical relationships, and interrelationships between these processes for years by many Hydrologists. In 1972, USDA-SCS attempts to quantify a watershed's runoff response when they published what we know today as the SCS or Soil-Cover-Complex Method. While the second early method was known as the Rational Method. The Soil-Cover-Complex Method was initially developed to calculate the volume of runoff only. In recent years, this method has been developed to further yield the peak rate of runoff. On the other hand, the Rational Method is a simple equation that is only able to estimate the peak runoff rate. The Rational Method which estimates peak flows is a basic representation of the complex process whereby rainfall amount and strength, catchment conditions and size as well as human activity, determine runoff amount, but it is appropriate where the consequences of the failure of structures are limited.

However, a great number of research have been undertaken to develop hydrological models that can be able to predict runoff peak flows and volumes. Though, quite a number of the research are not suited for general use. Sometimes too complex, and often limited by the geographical localities and hydrological conditions within which the data were collected. In addition, many of such models are regression, and their value difficult to assess outside their own particular circumstances (Miller 1994).

Meanwhile, this study determined the basin characteristics using ARC GIS, historical rainfall data, rainfall intensity and the curve number. The watershed composition was used to determine the runoff along the river areas. The runoff dynamics have some peculiar characteristic that dictates the direction of flow of flood along the Foma river rather than just a prediction through generalization which may not be quite accurate. Foma areas was named after a River basin which spread between Ilorin west and South local government area of Kwara state, in North Central Nigeria (Agbabiaka, et al., 2012). The relevance of determining the peak runoff for the basin cannot be overemphasized as past events that showed Foma River had flooded at one time or another. In 2012 and 2017, Foma River flooded above the capacity of its channel taking over farm lands and houses across Foma , Oloje, Abata and Sobi areas, between Ilorin west and Ilorin south local government areas of Kwara state. The surface area from which runoff resulting from rainfall is collected and drained along Foma river areas are presented in the Figure 1.

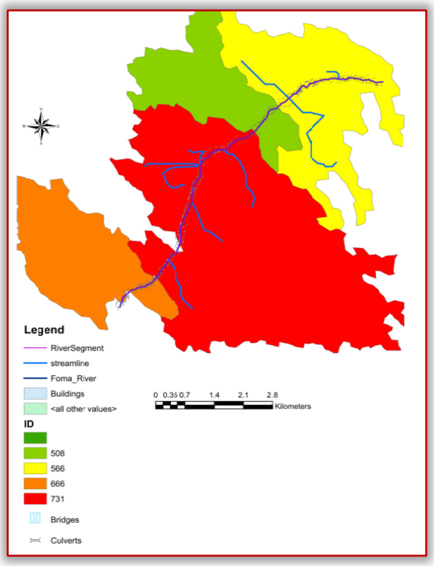

Figure 1. Foma river Watersheds

2. MATERIALS & METHODS

Description of the Study Area

The Foma River is a sub-basin along Ilorin West and Ilorin South local government areas of Kwara State, North Central Nigeria, which lies on latitude N08,49574 and longitude E004,5107, and a distance of 7 kilometres to the Emir palace Ilorin. The river is freely flowing during the raining season, while it is relatively quiet flowing during the dry season. The catchment area of the river is estimated to be around 303,309,421.02 m2. The river overflows its bank during the raining season, which over the years developed several kilometres stretch of floodplains. The human encroachment into the floodplain had resulted into several damages to buildings, institutions, and other social facilities in the affected communities (Chindo et al., 2019).

The basin areas consists of four sub-catchments and has two stream orders as shown in Figure 1. Table 1 shows the eight cross-sectional variables that were derived along the watersheds through GIS and site observation. Foma sub-basin and the stream order in the sub-basin spread across, College of Arabic and Islamic Studies area (CAIS), Apalara area, Okefoma area, Foma bridge, Ajetunmabi area, Oloje bridge, Abata Babaoyo area, Alagbado area and Sobi area. These areas spread across the Ilorin West and Ilorin South areas of Kwara State Nigeria.

Data Collection and Analysis

The drainage network of Foma sub-basin was delineated using ESRI Software Arc GIS 10.3. The steps followed include setting up work environment, creating a depression less Digital Elevation Model, creating

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a flow direction grid, creating a flow accumulation grid, creating outlet point, creating pour points, and then delineating the sub-basin. The parameters required for morphometric analysis are computed using ArcGIS software. Reflection Radiometer (ASTER) images were loaded onto Geographic Information Systems (GIS) environment. The remotely sensed data are geometrically rectified to digitize the pattern of sub-basin with the help of GIS software. The drainage patterns for the Foma sub-basin along with basin boundaries are digitized as a line feature giving a unique identity for each order of stream which was engendered from the DEM. The ArcGIS approach was used for drainage generation which is more coherent and reliable when compared to a manual approach. Based on the cumulative number of the upstream cells draining to each cell, flow accumulation, flow direction was defined. Also, a stream network in the watershed was defined.

Table 1. Cross-sectional Variables from Foma river Areas

Variable Name	Task	Values	Data Type
River Watershed	Input	Shed1, Shed2, Shed3, Shed4	Nominal
Drainage Density	Input	0.0001, 0.0002, 0.0005, 0.0007	Ordinal
Vulnerable Status of structures	Input	Not Vulnerable, Fairly Vulnerable, Highly Vulnerable	Ordinal
Types of Vulnerable Structures	Input	Hospital, Police post, Fishery ponds, Abattoir, Educational, Commercials, Slum, Agriculture, Residentials	Nominal
Bridges or Culverts	Input	CAIS, Apalara, Oke-foma, Foma-bridge, Ajetunmabi, Oloje-bridge, Abata Baba-oyo, Alagbado Bridge, Sobi-bridge	Nominal
Size of Bridges or Culvert (m)	Input	2.1, 4.5, 7.2, 11.2, 14.9, 15, 19.5, 60.8	Ordinal
River Point	Input	Source, Middle, Extreme, Terminal	Nominal
River Pollution	Input	Fair, High, Severe, Extreme	Ordinal
Magnitude of Flood	Target	Mild, Moderate, Severe, Extreme	Ordinal

The watershed area was evaluated by calculating the geometry of the derived watershed polygons, and length of the watershed was calculated by summing the length of the main stream channel and the distance from the top of the main channel to the watershed boundary. By summing the lengths of all stream segments in each sub-watershed, the total stream length was calculated, by using Strahler's ordering system, a stream segment with no tributaries that flows from the stream source is denoted as a first-order segment. A second order segment is created by joining two first-order segments. Foma sub-basin consists of four sub-catchments and has two stream orders as shown in Figure 1. Table 1 shows the cross-sectional variables along 530 structures of the river sub-catchments.

Estimating of Peak Runoff

— Theory on Unit hydrograph methods

The theories on the applied methods of unit hydrographs are described and were used to synthesize the peak runoff. The method used is Soil Conservation Service (SCS).

— Soil Conservation Service (SCS) method

In this method, the peak discharge and the time to peak can be determine in accordance to Viessman et al (1989), SCS (1972) and Ogunlela and Kasali (2002) using equations (1) and (2).

≡ Peak discharge

The peak discharge can be obtained through the equation (Remirez (2000)

$$Qp = \frac{2.08 * A}{t_p} \quad (1)$$

Where: Qp = peak discharge (m3/s), A = watershed area (km2), tp = time to peak (hr)

≡ Time to peak (tp) and lag time (tl)

$$tp = \frac{t_r}{2} + tL \quad (2)$$

or

$$tp = \frac{t_c + 0.133 t_c}{1.7} \quad (3)$$

where; tc= time of concentration (h); tr= storm duration (h); tL = lag time (h); tc = time of concentration (hr) (Kirpich's equation).

$$tc = 0.06628 \left\{ \frac{L^{0.77}}{S^{0.385}} \right\} \quad (4)$$

where: L = length of channel (stream) in km; S = Slope of channel (m/m)

Equation (3) was adopted in the estimation of the time of concentration for each of the sub-catchments. This was used to determine the values for both the peak discharge (qp) and time to peak (tp) which was applied to the dimensionless hydrograph ratios to obtain points for the unit hydrograph using equations 1

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and 3. The peak discharge, time to peak and lag time were determined in accordance to SCS (1972), Viessman et al. (1989) and Ogunlela and Kasali (2002). The parameters used for the analysis are as presented in Tables 2.

Table 2. Catchment characteristics of Foma river

Physical Characteristics	Numerical Values
Catchment Area	30.31 km2
Highest Elevation	346m
Lowest Elevation	269m
Length of Catchment	10.66m
Width of Catchment	4.41m
Slope of Catchment	0.722%
Elongation Ratio	0.33 : Elongated Basin
Drainage Density	0.00057:Low Drainage Density
Shape of Catchment	Long and Wide
Stream Order	First and Second Order

— Development of peak runoff or flood hydrograph

The estimated synthetic unit hydrograph from SCS method was used to develop the runoff hydrographs due to actual rainfall event over the watershed. The design runoff hydrographs for selected rainfall of recurrence interval 20, 50, 100, 200 and 500 years are developed through hydrograph convolution. Hydrograph convolution involves multiplying the unit hydrograph ordinates by increment rainfall excess, adding and lagging in a sequence.

≡ Hydrograph Convolution (Runoff hydrograph development)

The discrete convolution equation allows the computation of direct runoff Qn.

Let P = incremental rainfall excess (cm). U = unit hydrograph ordinate (m3/s/cm)

The first ordinate of the direct runoff hydrograph is due to the effective rainfall of P1, thus;

$$Q1 = P1\ U1$$

The second ordinate is due to the effective rainfalls of P1 and P2

$$Q2 = P1\ U2 + P2\ U1$$

The third ordinate is given by

$$Q3 = P1\ U3 + P2\ U2 + P3\ U1$$

While the fourth ordinate is given by

$$Q4 = P1\ U4 + P2\ U3 + P3\ U2 + P4\ U1$$

The peak runoff ordinate can be obtained using the fifth ordinate given by

$$Q5 = P1\ U5 + P2\ U4 + P3\ U3 + P4\ U2 + P5\ U1$$

≡ Estimation of Rainfall Excess

In the SCS method, the excess rain volume, Q, depends on the volume of precipitation, P, and the volume of the total storage, S, which includes both the initial abstraction, Ia, and the total infiltration F. The relation between rainfall excess and total rainfall (on twenty-four hour basis) is then (McCuen and Bondelid 1983).

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \quad (5)$$

$$P = \frac{P^*}{24} * P_T \quad (6)$$

where: P = accumulated rainfall (mm); PT = rainfall recurrence interval of the sub-basin (mm); P* = precipitation ratio; P*/24 = precipitation ratio dimensionless value in SCS type II for estimation of rainfall excess. S = volume of total storage (mm).

Note that equation (5) contains only one unknown, the storage parameter S. This parameter in (mm) can be obtained from

$$S = \frac{25400}{CN} - 254 \quad (7)$$

where: CN is runoff curve number

CN value of 75 was adopted based on the soil type which is particularly common in arid areas, in dry tropics and in mountain regions. Some parts of the Foma sub-basin contain Plinthic Ferric Lixisols which are strongly weathered soils from unconsolidated, strongly leached, finely textured materials from region of tropical warm temperate with pronounced dry season. They are often used for perennial crops or low volume grazing and these groups of soil are prone to erosion because of their unstable surface soil structure.

Therefore, the incremental rainfall excess resulting from a storm with effective rainfall of Pn during subsequent 24 hour interval is given in Table 3 for 20, 50, 100, 200 and 500 return periods

Table 3. Incremental rainfall excess (cm)

Return Period	Incremental rainfall excess (cm)				
	P1	P2	P3	P4	P5
20	5.30	2.73	1.00	0.67	0.53
50	6.97	3.36	1.22	0.81	0.65
100	8.48	3.90	1.41	0.94	0.75
200	10.22	4.15	1.62	1.07	0.86
500	12.96	5.44	1.95	1.29	1.03

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Table 4.24-hour storm hydrograph ordinate for various return period of the watershed

Time (hr)	Storm hydrograph ordinates				
	20	50	100	200	500
0	0.00	0.00	0.00	0.00	0.00
0.9	80.17	105.44	128.20	154.62	195.99
1.79	227.66	295.97	357.12	427.79	537.99
2.69	234.01	298.30	355.22	420.47	521.39
3.58	168.08	211.45	249.57	293.01	359.82
4.48	114.17	142.31	166.91	194.84	237.63
5.38	74.25	91.96	107.40	124.88	151.58
6.27	39.19	48.47	56.54	65.67	79.60
7.17	19.06	23.58	27.51	31.96	|38.76
8.06	9.33	11.54	13.47	15.65	|18.98
8.96	4.49	5.55	6.47	7.51	9.11
9.86	1.79	2.19	2.53	2.91	3.49
10.75	0.69	0.84	0.97	1.11	1.33
11.65	0.26	0.32	0.37	0.42	0.51
12.54	0.08	0.09	0.11	0.12	0.14
13.44	0.00	0.00	0.00	0.00	0.00

While the peak runoff ordinate for the watershed are summarized in Table 4 for 20, 50, 100, 200 and 500 return periods.

The storm hydrograph for returns periods 20, 50, 100, 200, and 500 years of the watershed is presented in Figure 2.

3. RESULTS AND DISCUSSIONS

The Foma River is a sub-basin along Ilorin West and Ilorin South local government areas of Kwara State, North Central Nigeria, which lies on latitude N08,49574 and longitude E004,5107, and a distance of 7 kilometres to the Emir palace Ilorin. SCS methods of peak runoff estimation was considered, the peak runoff values obtained for various return periods of 20, 50, 100, 200 and 500 are; 234.01, 298.30, 357.12, 427.79 and 537.99 m3/s respectively. Furthermore, the results show that the higher the return period the higher the value of the peak runoff.

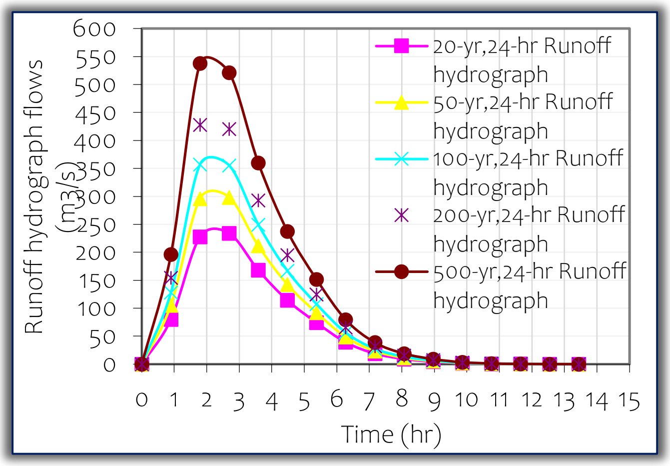

Figure 2: Storm hydrographs for Various Return Periods

4. CONCLUSION

In this study, physiography, and morphometric parameters of catchment area such as basin length, basin area, basin slope, soil distribution, land use were analysed. The parameters were used in estimating / predicting peak runoff for return periods of 20-years, 50-years, 100-years, 200 years, and 500-years using the SCS method. It can be established that catchment characteristics like area, length, slope etc. have a positive effect on the peak runoff of the sub-basin. The hydrograph developed will be useful in sizing or designing hydraulic structure like dam spillways, flood walls, culverts and bridges within the study area.

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