ANNALS OF FACULTY ENGINEERING HUNEDOARA
– International Journal of Engineering
Tome XI (Year 2013) – FASCICULE 4 (ISSN 1584 – 2673)

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DEVELOPMENT OF PEAK RUNOFF HYDROGRAPHS FOR SELECTED RIVERS IN SOME PARTS OF NIGERIA

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ABSTRACT: This paper presents the development of unit and runoff hydrographs for the Awun, Ogunpa and Wuruma Rivers. Unit hydrographs were developed based on the synthetic methods; Snyder, SCS and Gray. The SCS curve Number method was used to estimate the cumulative excess rainfall values for storm depth of different return periods. The peak runoff determined based on the ordinates from Snyder for 5-yr, 20-yr, 50-yr, 100-yr and 200-yr return period varies between 54.8m^3/s and 746.3m^3/s, the values of peak runoff based on the SCS varies between110.8m^3/s and 651.8m^3/s and those obtained based on Gray method varies between 87.4m^3/s and 453.1m^3/s for the three watersheds. The statistical analysis and graphical comparison inferred that SCS method can be used to estimate flow ordinate required for the development of peak runoff hydrograph of different return periods for the three river watersheds.
KEYWORDS: Synthetic unit hydrograph, runoff hydrograph, return period, river catchment and storm duration

INTRODUCTION

The design of hydraulic structures requires the knowledge of rainfall and runoff relationship in order to obtain the peak runoff from the rainfall of desired return periods. The peak runoff from rainfall can be estimated from storm hydrographs based on unit hydrographs established from synthetic methods and convolution process. Hydrograph can be defined as a continuous graph showing the properties of stream flow with respect to time, normally obtained by means of a continuous strip recorder that indicates stages versus time and is then transformed to a discharge hydrograph by application of a rating curve. Wilson (1990) observed that with an adjustment and well measured rating curve, the daily flow gauge readings may be converted directly to runoff volume. He also emphasized that catchment properties influence runoff and each may be present to a large or small degree. The catchment properties include area, slope, orientation, shape, altitude and also stream pattern in the basin. The unit hydrograph of a drainage basin, according to Varshney (1986) is defined as the hydrograph of direct runoff resulting from one unit of effective rainfall of a specified duration, generated uniformly over the basin area at a uniform rate. Arora (2004) defined 1-hr unit hydrograph as the hydrograph which gives 1 cm depth of direct runoff when a storm of 1-hr duration occurs uniformly over the catchment.

A vast amount of literature exists treating the various unit hydrograph methods and their development. Jones (2006) reported that Sherman in 1932 was the first to explain the procedure for development of the unit hydrograph and recommended that the unit hydrograph method should be used for watersheds of 5000 km^2 or less. Chow et al (1988) discussed the derivation of unit hydrograph and its linear systems theory. Further more Viessman et al (1989), Wanielista (1990) and Arora (2004) presented the history and procedures for several unit hydrograph methods. Ramirez (2000) reported that the synthetic unit hydrograph of Snyder in 1938 was based on the study of 20 watersheds located in the Appalachian Highlands and varying in size from 25 to 25000.0 km^2. Ramirez (2000) reported that the dimensionless unit hydrograph was developed by the Soil Conservation Service (SCS) and obtained from the UH's for a great number of watersheds of different sizes and for many different locations. It was also stated by Ramirez (2000) that the SCS dimensionless hydrograph is a synthetic UH in which the value of discharge is expressed as a ratio of discharge, Q, to peak discharge, Q_p and the value of time by the ratio of time, t, to time to peak of the UH, t_p. Wilson (1990) also reported that in 1938, Mc Carthy proposed a method of hydrograph synthesis but in that same year Snyder proposed a better known method by analyzing a larger number of basins in the Appalachian mountain region of the United States. Ogunlela and Kasali (2002) applied four methods of synthetic unit hydrographs *generation for an ungaged watershed. The outcome of the study revealed that both Snyder and SCS methods were not significantly different from each other.*

Salami (2009) evaluated three methods of storm hydrograph development for the catchment of lower Niger River basin at downstream of Jebba Dam. The methods considered are Snyder, SCS and Gray methods, the statistical analysis, conducted at the 5% level of significance indicated significant differences in the methods except for Snyder and SCS methods which have relatively close values. However, SCS method was recommended for use on this watershed since it incorporates most major hydrological and morphological characteristics of the basin such as watershed area, main channel length, river channel slope and watershed slope. Salami et al., (2009) presents the establishment of appropriate method of synthetic unit hydrograph to generate ordinates for the development of design storm hydrographs for the catchment of eight selected rivers located in the South West Nigeria. Unit hydrographs were developed based on Snyder, Soil Conservation Service (SCS) and Gray methods; while the SCS curve Number method was used to estimate the cumulative rainfall values for storm depth of different return periods. The peak storm hydrographs corresponding to the excess rainfall values were determined based on the unit hydrograph ordinates established. The peak storm hydrograph flows obtained based on the unit hydrograph ordinate determined by Snyder for 20-yr, 50-yr, 100-yr, 200-yr and 500-yr, return period varies from 112.6m^3/s and 1336.4m^3/s, while those based on the SCS varies from 304.4m^3/s and 646.6m^3/s and those based on Gray varies from 398.1m^3/s and 2607.4m^3/s for the eight watersheds. The analysis shows that the values of peak flows obtained by Gray and SCS methods for five watershed were relatively close, while the values of peak flows obtained by Gray and Snyder methods for two watershed were relatively close and the values of peak flows obtained by Snyder and SCS methods for only one watershed was relatively close. This inferred that SCS method can be used to estimate ordinate required for the development of peak storm hydrograph of different return periods for the river watersheds considered. Salami et al., (2011) estimated the peak flows for Asa, Oyun and Moro rivers in Awun drainage area. The value of peak flows obtained based on the unit hydrograph ordinate determined by Snyder for 5-yr, 20-yr, 50-yr, 100-yr and 200-yr return period varies from 230.0 m^3/s and 806.0 m^3/s, while those based on the SCS varies from 260.0 m^3/s and 1053.0 m^3/s and those based on Gray varies from 208.0 m^3/s and 861.0 m^3/s for the three rivers in the Awun drainage basin. The study revealed that the values of peak flows obtained by Snyder and Gray methods for Asa river is fairly close (6.0%), while the percentage difference shows that for Oyun river the values of peak flows obtained by Snyder and SCS methods is fairly close (7.7%) and the percentage difference shows that for Moro river the values of peak flows obtained by Snyder and Gray methods is fairly close (11.3%). This inferred that Snyder method can best be used to estimate ordinates required for the development of peak runoff hydrograph of different return periods.

This study applied Snyder, SCS and Gray methods to develop unit hydrographs and subsequently used to generate peak storm hydrographs of rainfall depth of various return intervals through convolution method. The peak flows obtained can be used for the design of hydraulic structures within the River Catchment.

MATERIALS AND METHODS - Study Area

The catchment of Wuruma River is located between latitude 9^{o}30' and 10^o north with longitude 3^{o}36' and 4^{o}12'east with total area as 109.62 km^2 and it lies within Kwara State with the length of main river channel of 15.89 km. Awun River catchment is located between latitude 8^o 28' to 9^o north and longitude 4^{o}30' to 4^{o}45' east with total area as 954 km^2 and it lies within Kwara State with the length of main river channel of 80.23 km. Ogunpa River catchment is located between latitude 7^{0}8' and 7^{0}29' north and longitude longitudes 3^0 50' and 3^{0}73' east with total area as 108.85 km^2 and lies within Oyo State with the length of main river channel of 22.87 km. Figure 1 is a map of Nigeria showing the location of the River catchment.

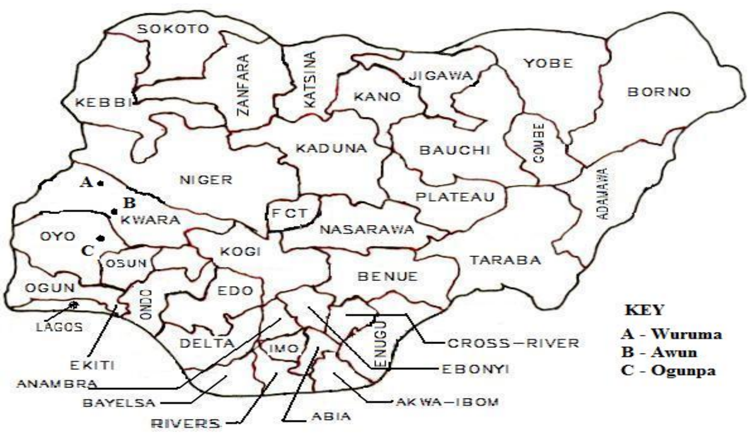

Figure 1. Map of Nigeria showing location of river catchments

Basic Theory

Theories on the unit hydrographs are described and were used to synthesize the peak runoff. The methods are; Snyder's, Soil Conservation Service (SCS), and Gray methods. Snyder's method can be used to determine the peak discharge, lag time and the time to peak by using characteristic features of the watershed. Ramirez (2000) reported that the hydrograph *characteristics are the effective rainfall duration, t_r, the peak direct runoff rate Q_p, and the basin lag time, t_l. From these relationships, five characteristics of a required unit hydrograph for a given effective rainfall duration may be calculated. The five characteristics are the peak discharge per unit of watershed area, q'_p , the basin lag t_p, the base time, t_b, and the widths, w (in time units) of the unit hydrograph at 50 and 75 percent of the peak discharge. The unit hydrograph parameters are estimated in accordance to Ramirez (2000) and Arora (2004).*

Soil Conservation Service (SCS) method, Raghunath (2006) reported that the US Soil Conservation Service in 1971 used many hydrographs from drainage areas of varying sizes and different geographical locations developed a dimensionless unit hydrograph. The peak discharge and the time to peak can be determined in accordance to Viessman et al (1989), Wanielista (1990), Ramirez (2000), SCS (2002), Ogunlela and Kasali (2002) and Raghunath (2006). The estimated values for both the peak discharge and time to peak were applied to the dimensionless hydrograph ratios in accordance to SCS and the points for the unit hydrograph were obtained (Raghunath , 2006) and used to develop the unit hydrograph curve. Gray's method, the discharge can be obtained through the dimensionalizing of the incomplete Gamma function Γ as revealed in Viessman et al 1989; Ogunlela and Kasali, 2002.

In development of unit hydrographs, the Snyder's method was used to compute the lag time (t_L), rainfall duration (tr), peak discharge(Q_p), and time base (t_b) by using the watershed characteristics obtained from the topographic map of the River catchment under consideration in accordance to Ramirez (2000) and Arora (2004). The parameters obtained are presented in Table 1. Where L is length of the river, L_c is length of the river from a point near the centroid of the catchment to the dam section, and A is the catchment area.

Table 1. Parameters for the generation of unit hydrograph (Snyder's method)

Watershed	L (km)	L_c (km)	t_L (hr)	t_r (hr)	Q_p (m^3/s)	t_b (hr)	A (km^2)
Awun	80.23	42.49	18.34	3.33	89.68	127.01	950.00
Ogunpa	22.87	13.19	8.87	1.61	21.15	98.61	108.85
Wuruma	15.80	8.61	6.99	1.27	27.05	92.96	109.62

The method of Soil Conservation Service (SCS) for constructing synthetic unit hydrographs was based on a dimensionless hydrograph, which relates ratios of time to ratios of flow, it involved determination of slope of the catchment S, concentration time t_c , the peak time t_p and peak flow Q_p, in accordance to Viessman et al., (1989) and Ramirez (2000). The parameters obtained are presented in Table 2.

Table 2. Parameters for the generation of unit hydrograph (SCS method)

Watershed	L (km)	t_c (hr)	t_L (hr)	t_p (hr)	S_c (%)	Q_p (m^3/s)	A (km^2)
Awun	80.23	25.87	15.52	16.935	0.12	117.20	950.00
Ogunpa	22.87	5.87	3.52	3.84	0.46	58.92	108.85
Wuruma	15.80	6.10	3.66	4.00	0.20	57.07	109.62

The Gray method requires the determination of period of rise P_R, and other parameters like rainfall duration D, the volume of the unit hydrograph V, and the volume of dimensionless graph V_D. The parameters were obtained in accordance to the procedure stated by Viessman et al (1989), Ogunlela and Kasali (2002) and presented in Table 3.

Table 3. Parameters for development of unit hydrograph (Gray method)

Watershed	P_R (hr)	P_R/γ (hr)	D (hr)	Σcfs (10^4)	$V=V_D$ (10^6 m^3)
Awun	73.38	24.31	18.35	1.30	24.22
Ogunpa	15.45	5.12	3.86	0.70	2.77
Wuruma	11.25	3.73	2.81	0.97	2.78

The parameters in Tables 1-3 were analyzed in accordance to procedure already established by Viessman et al (1989), Ramirez (2000), Ogunlela and Kasali (2002) and Arora (2004) to estimate the unit hydrograph flow presented in Figures 2, 3 and 4 for Awun, Ogunpa and Wuruma watershed respectively.

In the development of peak runoff hydrographs, the obtained unit hydrographs ordinates presented in Figures 2, 3 and 4 were used to develop the runoff hydrographs due to actual rainfall event over the watershed. Peak storm hydrographs for selected return periods (5yr, 20yr, 50yr, 100yr and 200yr) were developed through convolution. The discrete convolution equation allows the computation of direct runoff Q_n given excess rainfall P_m and the unit hydrograph U_{n-m+1}. The maximum 24-hr rainfall depths of the different recurrence intervals for the catchment under consideration are 85.0 mm, 107.0 mm, 125.0 mm, 140.0 mm and 155.0 mm, respectively (Olofintoye, et al 2009). The runoff hydrograph was derived from a multiperiod of rainfall excess called hydrograph convolution. It involves multiplying the unit hydrograph ordinates (U_n) by incremental rainfall excess (P_n), adding and lagging in a sequence to produce a resulting runoff hydrograph. The SCS type II curve (Viessman et *al,1989) was used to divide the different rainfall data into successive equal short time events and the SCS Curve Number method was used to estimate the cumulative rainfall for storm depths of 5yr, 20yr, 50yr, 100yr and 200yr return period. The incremental rainfall excess was obtained by subtracting sequentially, the rainfall excess from the previous time events. The equations that apply to the SCS Curve Number method are given in Eq. (1) and (2) (SCS, 2002).*

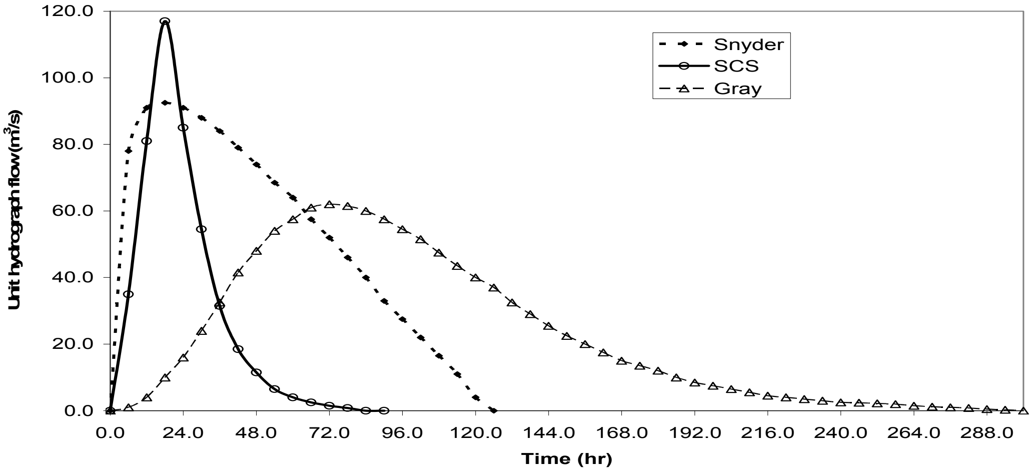

Figure 2. Synthetic unit hydrograph for Awun watershed

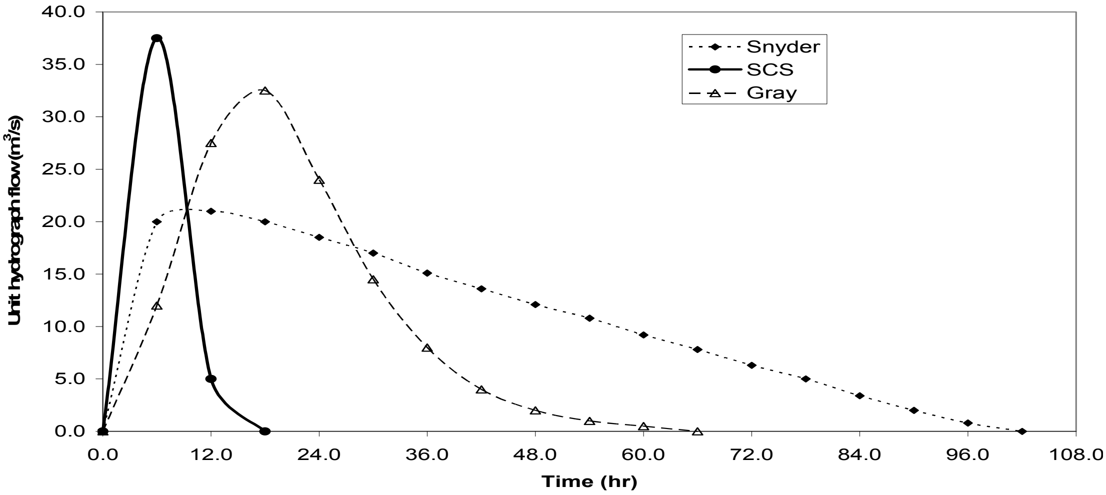

Figure 3. Synthetic unit hydrograph for Ogunpa watershed

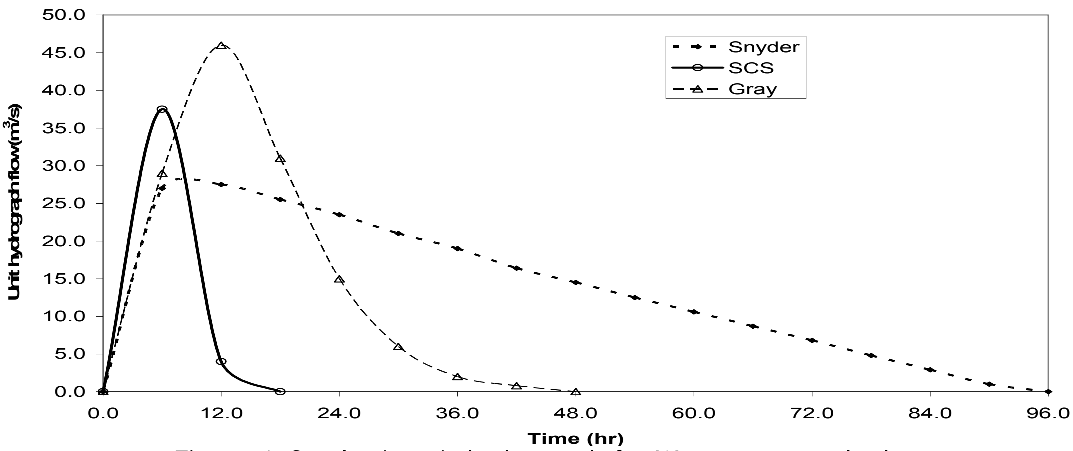

Figure 4. Synthetic unit hydrograph for Wuruma watershed

$$Q_d = \frac{\left(P^* - I_a\right)^2}{P^* + 0.8S} \; for \; P^* > I_a$$
$$Q_d = 0 \; for \; P^* \le I_a \qquad (1)$$

where; I_a = initial abstraction I_a = 0.2S, P = accumulated precipitation (mm), Q_d = cumulative rainfall excess, runoff (mm)*

$$S = \frac{25400}{CN} - 254 \qquad (2)$$

With the CN = 75 based on soil type, S is estimated as 84.67 mm, while I_a is 16.94 mm. This implies that any value of rainfall less than 16.94 mm is regarded as Zero.

The runoff hydrograph ordinates based on the rainfall depths of desired return periods were estimated from the unit hydrographs. The runoff hydrograph ordinates for the watersheds due to Snyder, SCS, and Gray methods are extracted and used to plot the runoff hydrographs as presented in Figures 5a-5c, 6a-6c and 7a-7c for Snyder, SCS and Gray methods, respectively.

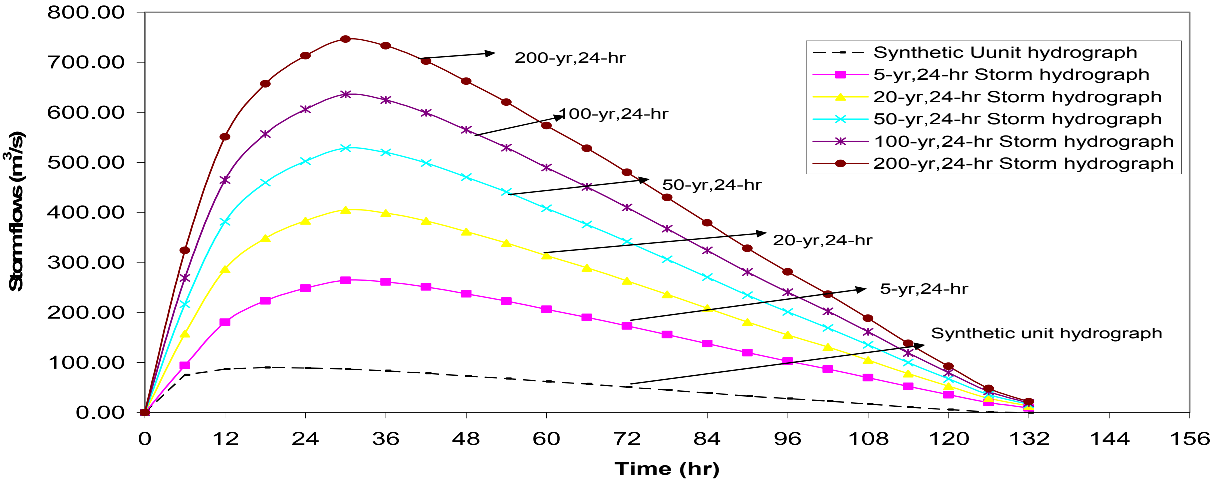

Figure 5a. Unit hydrograph with generated storm hydrograph of different return periods for Awun (Snyder method)

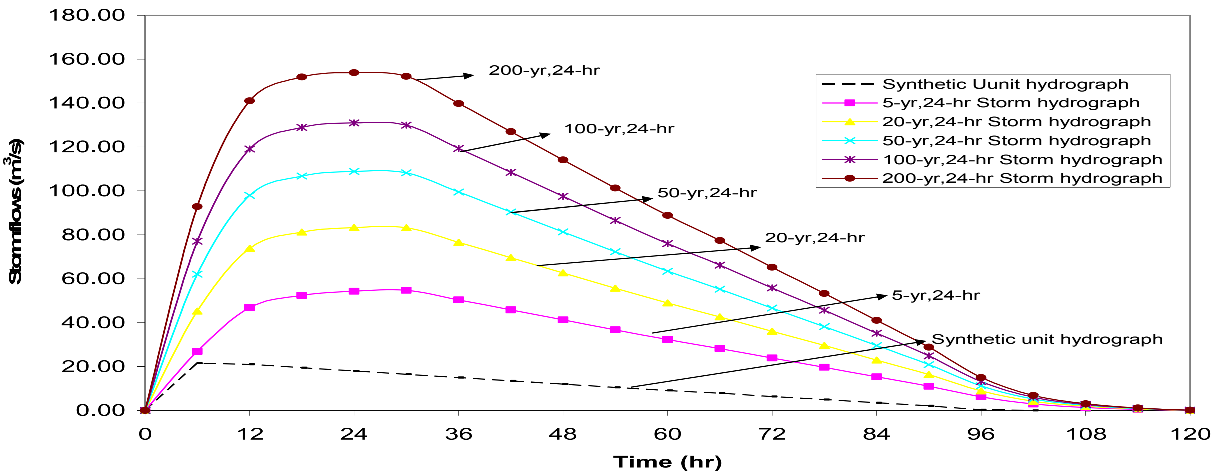

Figure 5b. Unit hydrograph with generated storm hydrograph of different return periods for Ogunpa (Snyder method)

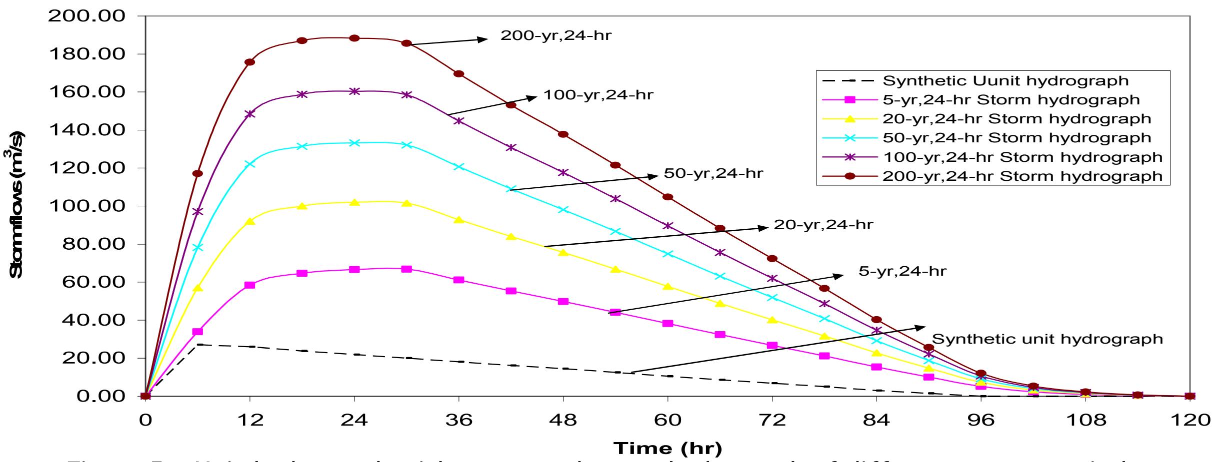

Figure 5c. Unit hydrograph with generated storm hydrograph of different return periods for Wuruma (Snyder method)

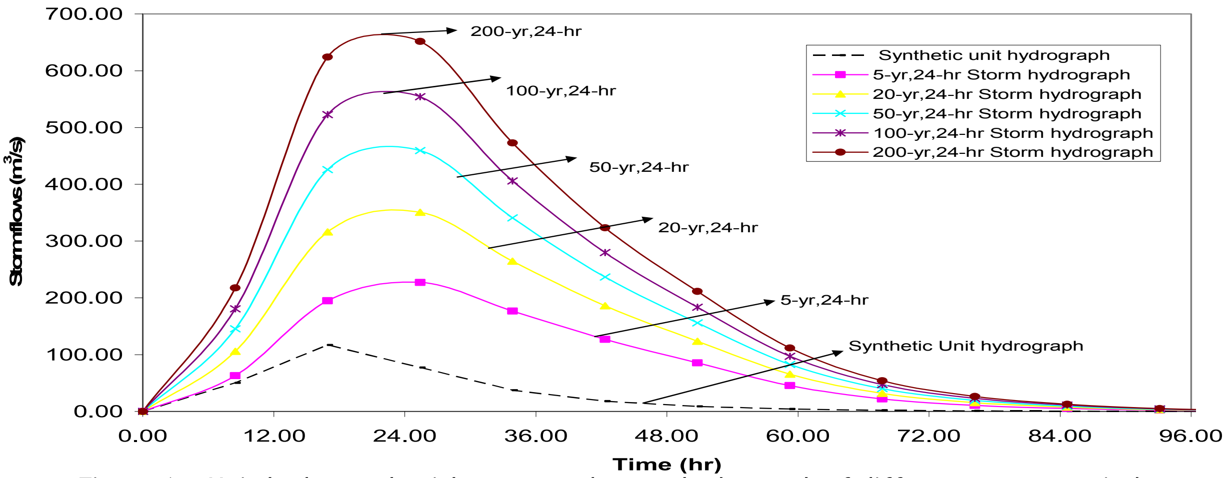

Figure 6a. Unit hydrograph with generated storm hydrograph of different return periods for Awun (SCS method)

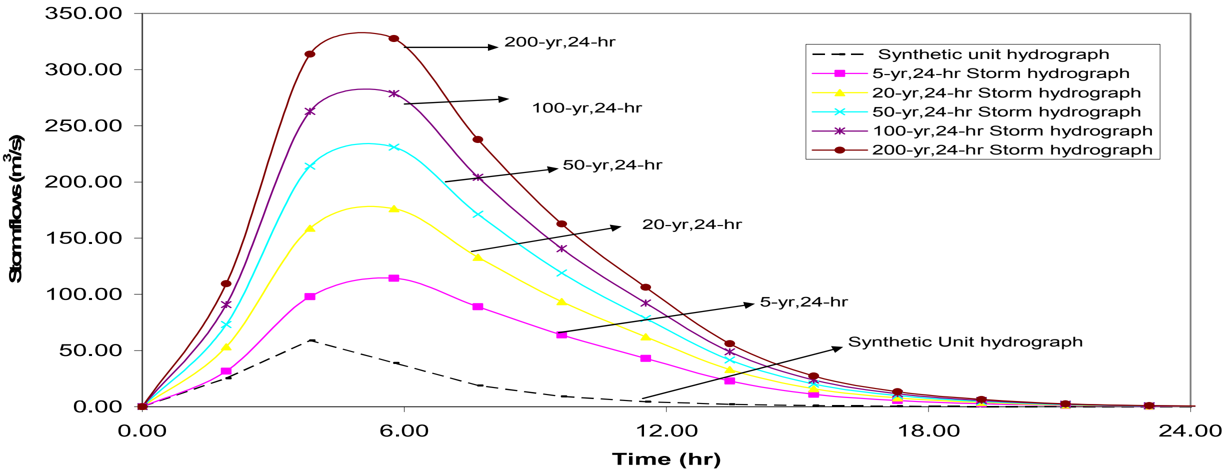

Figure 6b. Unit hydrograph with generated storm hydrograph of different return periods for Ogunpa (SCS method)

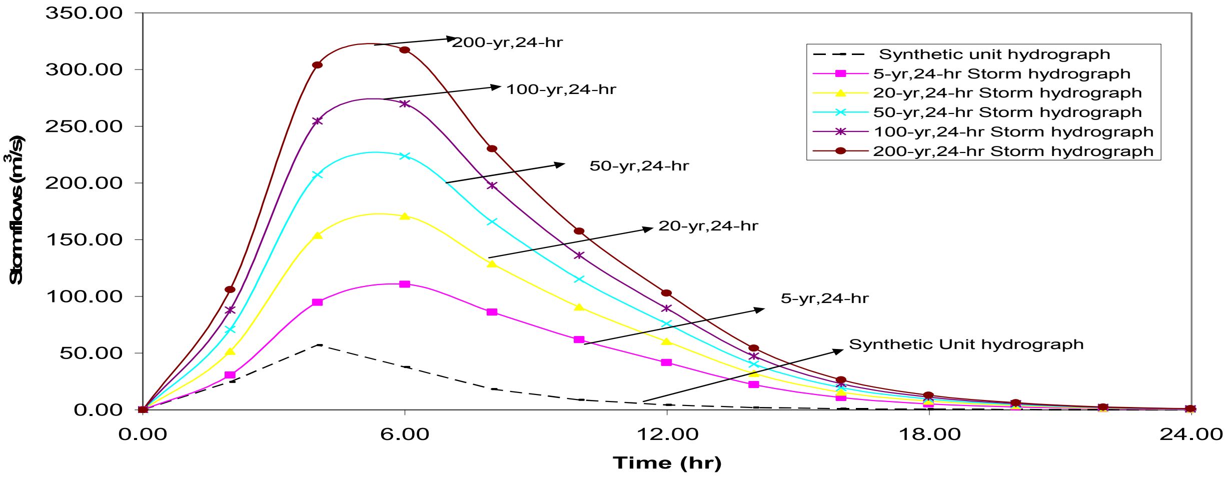

Figure 6c. Unit hydrograph with generated storm hydrograph of different return periods for Wuruma (SCS method)

The runoff peak flows for the catchments of Awun, Ogunpa and Wuruma based on the three methods of synthetic unit hydrographs and various return periods are presented in Table 4, 5, and 6, respectively.

Table 4. Runoff peak flows for Awun River watershed (m^3/s)

Method	Storm return period				
	5yr, 24hr	20yr, 24hr	50yr, 24hr	100yr, 24hr	200yr, 24hr
Snyder	264.44	404.85	528.43	635.78	746.27
SCS	227.42	350.77	459.54	554.23	651.74
Gray	160.59	245.83	320.83	385.94	453.06

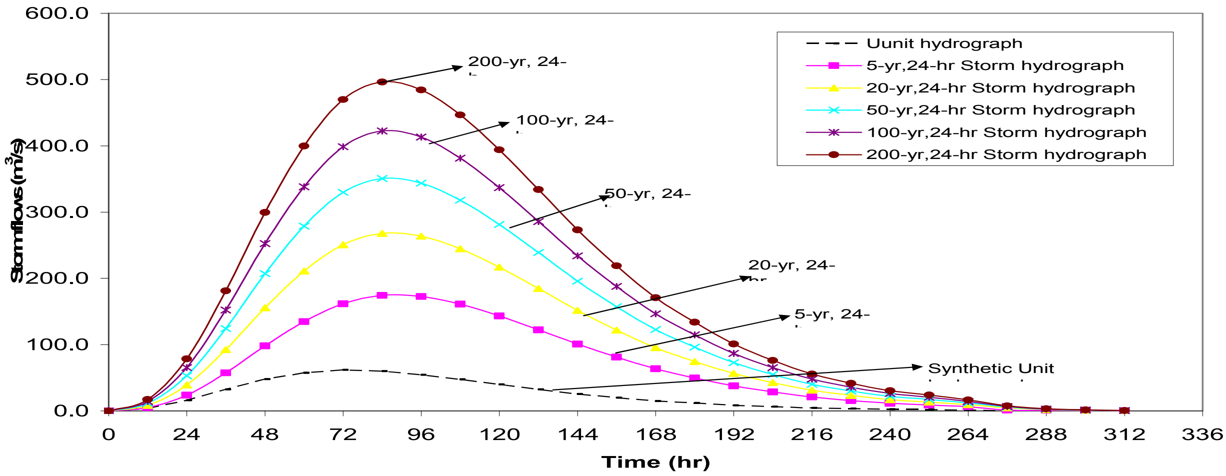

Figure 7a. Unit hydrograph with generated storm hydrograph of different return periods for Awun (Gray method)

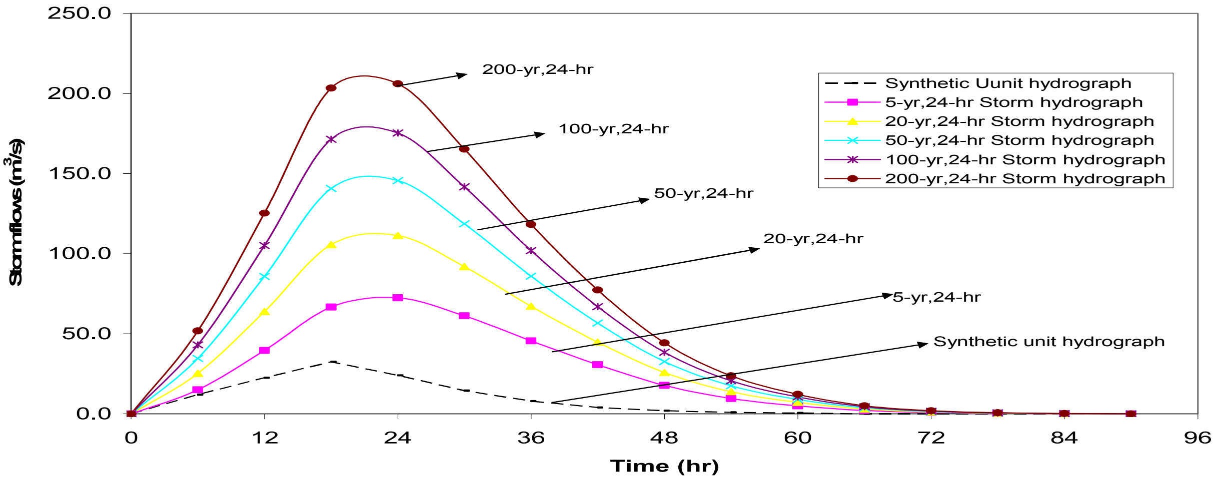

Figure 7b. Unit hydrograph with generated storm hydrograph of different return periods for Ogunpa (Gray method)

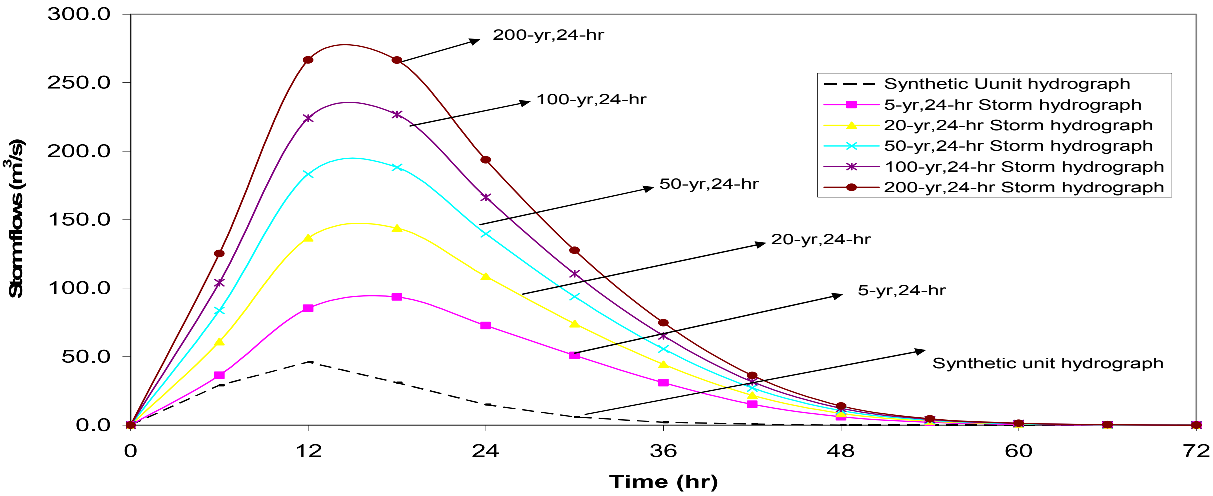

Figure 7c. Unit hydrograph with generated storm hydrograph of different return periods for Wuruma (Gray method)

Table 5. Runoff peak flows for Ogunpa River watershed (m^3/s)

Method	Storm return period				
	5yr, 24hr	20yr, 24hr	50yr, 24hr	100yr, 24hr	200yr, 24hr
Snyder	54.74	83.32	108.84	131.00	153.84
SCS	114.32	176.33	231.00	278.60	327.62
Gray	87.40	133.79	174.61	210.05	246.58

Table 6. Runoff peak flows for Wuruma River watershed (m^3/s)

Method	Storm return period				
	5yr, 24hr	20yr, 24hr	50yr, 24hr	100yr, 24hr	200yr, 24hr
Snyder	66.84	102.04	133.26	160.36	188.27
SCS	110.73	170.79	223.75	269.86	317.34
Gray	120.86	185.02	241.47	290.48	340.99

A statistical analysis known as Randomized Complete Block Design (RCBD) (Salako, 1989; Murray and Larry, 2000 and Oyejola, 2003) was adopted to evaluate the different methods of storm hydrograph development for the five return periods of 5-yr, 24-hr; 20-yr, 24hr; 50-yr, 24-hr; 100-yr, 24-hr and 200-yr, 24-hr. The table of observation was developed, the different methods are represented as treatments (T_1, T_2 and T_3) while the return periods are presented as blocks (B_1, B_2 , B_3, B_4 and B_5). The mean value for each of the storm flows of the methods were used to form Table 7 for Awun watershed. An analysis of variance table (ANOVA Table) for the Randomized Complete Block Design (RCBD) was constructed for the statistical analysis by calculating some parameters such as degree of freedom (d.f), sum of squares (SS), mean squares (MS), F-Ratio and Coefficient of variation (CV). These parameters were estimated in accordance to (Salako, 1989; Murray and Larry, 2000 and Oyejola, 2003) and presented in Table 8 for Awun watershed.

Table 7. Mean values for statistical evaluation (Awun watershed)

Methods (Treatments)	Return periods (Block)					Total
	5yr,24hr	20yr,24hr	50yr,24hr	100yr,24hr	200yr,24hr	
Snyder (T_1)	145.33	222.51	290.44	349.46	410.21	1417.96
SCS (T_2)	60.14	92.07	120.16	144.57	169.70	586.64
Gray (T_3)	64.76	99.17	129.45	155.76	182.85	632.00
Total	270.24	413.75	540.06	649.80	762.76	2636.60

Table 8. ANOVA Table for Randomized Complete Block Design (RCBD) Awun

Source of variation (SV)	Degree of freedom (df)	Sum of squares (SS)	Mean Square (MS)	F-Ratio
Treatment	2	87392.22	43696.11	37.17
Block	4	49861.06	12465.26	10.60
Error	8	9403.39	1175.42	
Total	14	146656.67	57336.80	

Coefficient of variation CV = 19.50 %

The tabular F is obtained from statistical Table (Adegboye, 1995). From the table the F- value for the treatment df (2) on the horizontal axis and error df (8) on the vertical axis at the 5% level of significance, is 4.46. Since this value is much lower than the calculated value (37.17). The coefficient of variation CV (19.50%) indicates the degree of precision and it is a good index of the reliability of the analysis. The same analysis was carried out for Ogunpa and Wuruma, the results follows the same trend like Awun River catchment and the CV values are 5.43% and 10.85% for Ogunpa and Wuruma respectively.

RESULTS AND DISCUSSION

Three methods of synthetic unit hydrograph were adopted to determine the ordinates of peak storm hydrograph for Awun, Ogunpa and Wuruma River catchments in Nigeria. The methods are Snyder, SCS and Gray. The synthetic unit hydrograph flows based on the three methods have been presented in Figures 2 to 4. The comparison of the unit hydrograph with the generated storm hydrographs of different return periods were presented in Figures 5 to 7 based on Snyder, SCS and Gray methods, respectively. The runoff peak flows (m^3/s) for the catchment of Awun, Ogunpa and Wuruma River based on the three methods were presented in Tables 4 to 6. The values obtained for Awun watershed based on Snyder method is higher by 13.18% and 39.28% than those of SCS and Gray method, respectively. While for Ogunpa watershed, the values obtained for Gray method is higher by 37.62% and 0.51% than those of Snyder and SCS method, respectively and for Wuruma watershed, the values obtained for Gray method is higher by 44.792% and 7.49% than those of Snyder and SCS method respectively.

However, the percentage difference shows that for Awun watershed the values of peak flows obtained by Snyder and SCS methods is fairly close (13.18%), while the percentage difference shows that for Ogunpa watershed, the values of peak flows obtained by Gray and SCS method is almost same (0.51%) and the percentage difference shows that for Wuruma watershed the values of peak flows obtained by Gray and SCS method is fairly close (7.49%). This inferred that Soil Conservation Service (SCS) method can be used to estimate ordinate required for the development of peak storm hydrograph of different return periods.

The mean storm flows obtained from the different methods were statistically evaluated using the Randomized Complete Block Design. The results indicated that there were significant differences in the methods, but based on the percentage difference, it can be summarized that the SCS method can be useful in the generation of unit hydrograph ordinates required for the development of storm hydrograph within the catchment under consideration.

CONCLUSIONS

Based on the results obtained, it could be observed that the generating of unit hydrograph using synthetic methods has been found useful and effective. The statistical evaluation of the storm hydrograph flows obtained from the three methods indicated that there were significant differences in the methods. In some cases two methods give very close values. This implies that those two methods are highly efficient in estimating the parameters of the watershed which are required in the development of the unit hydrograph for the catchment considered. Conclusively, SCS method is recommended for use on this watershed since it is most comparable to other methods. The established unit and storm hydrographs can be used to compute the peak flows for the design of hydraulic structures within the catchment. The selection of peak storm hydrograph flows of the desire return period depends on the type of required hydraulic structure. For example, peak flow of 100 yr return period is required for the design of bridge, while 20 yr return period can be adopted for drainage culverts and minor bridges.

ACKNOWLEDGEMENT

The authors acknowledged Lower Niger River Basin & Rural Development, Ilorin and Ogun- Osun River Basin, Abeokuta for providing the catchment characteristics of the rivers and rainfall data of Ilorin and Ibadan.

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