International Journal of Latest Engineering Research and Applications (IJLERA) ISSN: 2455-7137

Volume – 01, Issue – 03, June – 2016, PP – 07-16

DEVELOPMENT OF PEAK RUNOFF HYDROGRAPHS FOR OBA AND OTIN RIVERS IN OSUN STATE, NIGERIA

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Abstract: The unit and storm hydrographs for the catchments of Oba River and Otin River, Osun State, Nigeria were developed. Soil Conservation Service (SCS) and Snyder's unit hydrograph methods were used to develop synthetic hydrographs for the four catchments, while the SCS Curve Number method was used to estimate excess rainfall values from rainfall depth of different return periods. The peak storm flows obtained based on the unit hydrograph ordinates using convolution procedures determined by SCS for rainfall events of 10yr, 20yr, 50yr, 100yr and 200yr return periods for Oba River and Otin River vary from 336.12 m^3/s to 611.53 m^3/s while those based on Snyder's method vary from 142.31 m^3/s to 283.34 m^3/s for both Oba River and Otin River. The statistical analysis at 5% level of significance indicated that there were significant differences in the two methods. The analysis shows that the values of the peak flows obtained from SCS method is higher by about 58.11% and 54.08% than that of Snyder's method for both the Oba and Otin rivers respectively. SCS method was recommended for use on the four watersheds since it incorporates most major hydrological and morphological characteristics of the basins like the watershed area, main channel length, river channel slope and watershed slope.

Keywords: Synthetic unit hydrograph, design storm hydrograph, storm duration, River catchment and recurrence interval.

Introduction

Rainfall and runoff data are seldom adequate to determine a unit hydrograph of a basin or watershed in many parts of the world. This situation is common in Nigeria due to lack of gauging stations along most of the rivers and streams. Generally, basic stream flow and rainfall data are not available for planning and designing water management facilities and other hydraulic structures in undeveloped watersheds. However, techniques have been evolved that allow generation of synthetic unit hydrograph. This includes Snyder's method, Soil Conservation Service (SCS) method, Gray's method and Clark's instantaneous method. The peak discharges of stream flow from rainfall can be obtained from the design storm hydrographs developed from unit hydrographs generated from established methods.

Warren et al., (1972) described hydrograph 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 gauge readings may be converted directly to runoff volume. He also emphasized that catchment properties influence runoff and each may be presented to a large 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 of 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.

Many literatures exist 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 2000 square miles ($5000km^2$) or less. Chow et al., (1988) discussed the derivation of unit hydrograph and its linear systems theory. Furthermore, Viessman et al., (1988), Wanielista (1990), and Arora (2004) presented the history and procedures for several unit hydrograph methods.

Ogunlela (1996) developed a unit hydrograph for a small agricultural watershed at the University of Ilorin, using Clark’s method to route through an assumed linear reservoir, to account for the storage characteristics of the watershed. He obtained a unit hydrograph peak of 2.97 m^3/s at a time to peak of 0.33 hr, while for the 25-year, 24-hr and 100-year, 24-hr storm hydrographs, he obtained peaks of 4.53 m^3/s (at 0.58hr) and 6.23 m^3/s (at 0.58hr) respectively.

Ayanshola and Salami (2009) developed a unit hydrograph for the catchment of Asa River, based on Snyder, SCS and Gray methods. Ayanshola and Salami (2009) obtained 299.27m^3/s, 307.28m^3/s and 2083.40m^3/s as peak unit hydrograph values for Snyder, SCS and Gray methods respectively. The statistical analysis, conducted at the 5% level of significance indicated significant differences in the methods except for Snyder’s and SCS methods which were not significantly different from each other.

Ogunlela and Adewale (2009) developed synthetic hydrograph for the University of Ilorin Agricultural and Bio-systems Engineering field plot, using Clark’s Unit Hydrograph method. They obtained 2.4 x 10^4 m^3 and 1.02 m^3/s for runoff and peak discharge respectively. For the 24 hr, 100yr storm hydrograph the runoff volume was 5.23 x $10^4 m^3$ while the peak discharge was 2.15m^3/s.

Ogunlela and Kasali (2002), in their study, obtained an attenuation of 0.24 m^3/s for the 25-yr, 24-hr flow while 0.4 m^3/s attenuation was obtained for the 100yr, 24-hr flow. Maximum water elevations were 996.88m and 997.17m for the 25-yr and 100-yr flow respectively.

Salami (2009) evaluated methods of storm hydrograph for the catchment of Lower Niger River basin downstream of Jebba Dam. The methods considered are Snyder, SCS and Gray methods, the statistical analysis, conducted at 5% level of significance indicates significant differences in the methods except for Snyder and SCS methods which have relatively close values.

Salami et al. (2009) presented 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. The authors concluded that the values of peak flows obtained by Gray and SCS methods for five watersheds were relatively close, while values of peak flows obtained by Snyder and SCS methods for only one watershed were relatively close. The authors 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. The main objective of this study was to estimate design floods for selected rivers in Osun State, Nigeria.

2. Materials and Methods

2.1 Study Area

Osun State, where the catchments of the rivers under study are located is situated in the South West of Nigeria. The State is located between latitude 7^0 30’ and 7^0 55’ North, and longitudes 4^0 20’ and 4^0 40’ East. Osun State stands at 304.5 metres altitudes above sea level. The State covers an area of approximately 14,875 square kilometers, and is bounded by Ogun, Kwara, Oyo and Ondo states in the South, North, West and East respectively. Figure 1 presents the map of Nigeria showing the location of river catchments.

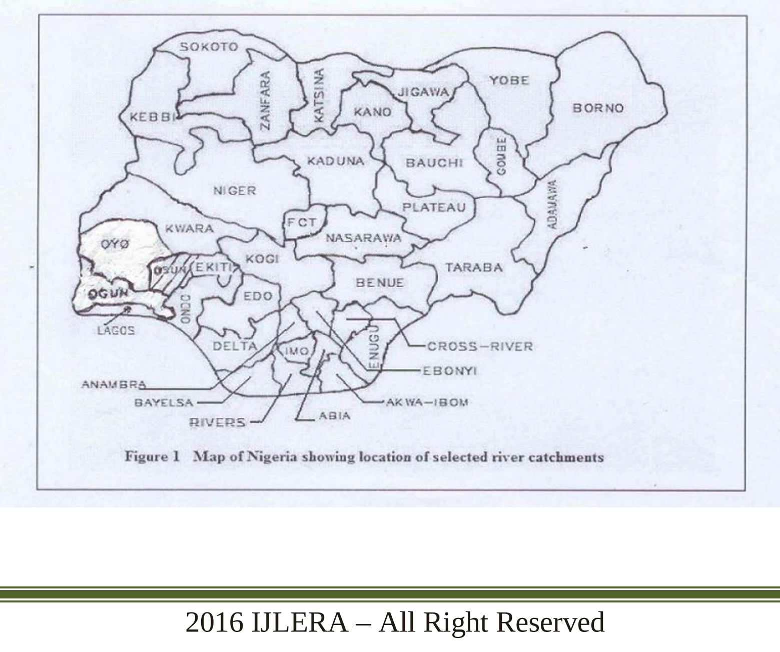

Figure 1 Map of Nigeria showing location of selected river catchments

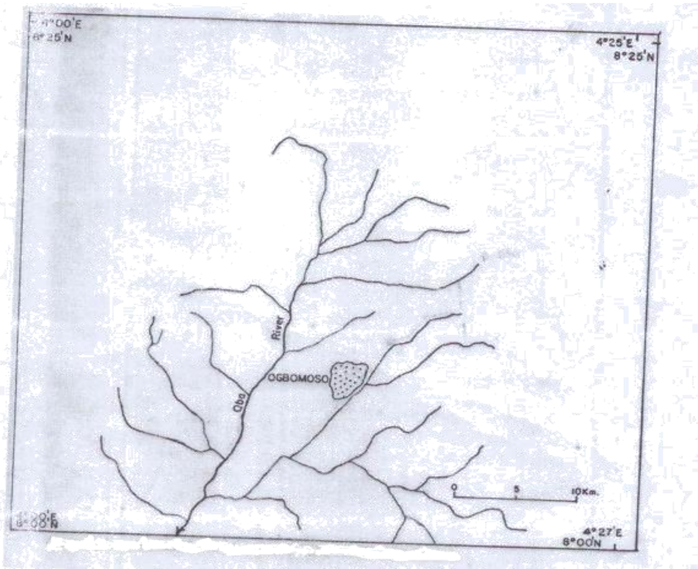

Figure 2. Map of Oba River catchment Area

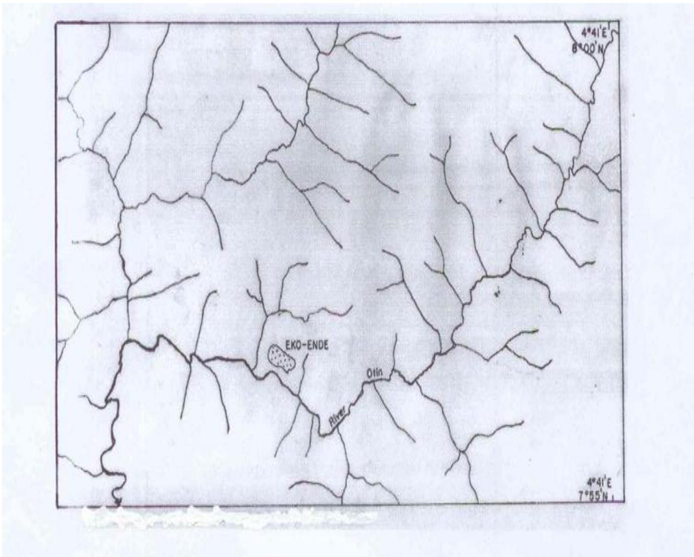

Figure 3. Map of Otin River Catchment Area

Table 1	**Catchment characteristics**				
Watershed	L (km)	L_c (km)	A(km^2)	Sc	
Oba River at Ogbomosho control station	23.5		10	375	0.00390
Osun River at Esa-Odo control station	36.0	16		475	0.00360

Where,

A= Area of the watershed; L = Length of the river;
L_c= Length of stream up to the centroid of catchment,
S_c= Watershed slope = $\frac{\text{Difference in levels}}{\text{length of watershed}} = \frac{\Delta H}{L}$

2.2. Development of Synthetic Unit Hydrograph

The two methods applied to develop the synthetic unit hydrographs were the SCS and Snyder's methods described in sections 2.2.1 and 2.2.2 respectively.

2.2.1. Development of Unit Hydrograph by SCS Method

The lag time, time to peak and peak discharge were determined in accordance to Viessman et al (1989), Waniesta (1990), SCS (2002) and, Ogunlela and Kasali (2002). This method was based on a dimensionless hydrograph, which relates ratios of time to ratios of flow Viessman et al (1989), and Ramirez (2000). The calculated values for parameters t_p and q_p were applied to the SCS dimensionless unit hydrograph to obtain the corresponding unit hydrograph ordinates.

Peak Discharge:

$$Q_p = \frac{(0.0208*A*Q_d)}{t_p} \quad (1)$$

Where:
Q_p = peak discharge (m^3/s); A =watershed area (km^2)
Q_d = quantity of runoff (1mm for unit hydrograph)
t_p = time to peak (hr)

Time to Peak:

$$\text{Time to peak, } (t_p) = (t_c + 0.133t_c) / 1.7 \quad (2)$$

$$\text{Time of concentration, } (t_c) = 0.0195 * \frac{L^{0.77}}{S^{0.385}} \quad (3)$$

L = length of channel (m)
S = slope of channel
Lag time, $(t_L) = 0.6t_c$

The values calculated for both the peak discharge and time to peak were applied to the dimensionless hydrograph ratios to obtain points for the unit hydrograph flow rate and its corresponding time (Tables 2 and 3).

2.2.2 Development of Unit Hydrograph by Snyder's Method

The method was used to determine the peak discharge, lag time and the time to peak by using characteristic features of the watershed.

Lag time:

$$\text{Lag time, } t_L = C_t\,(L.L_c)^{0.3} \quad (4)$$

Where t_L lag time (hr) and C_t = coefficient representing variation of water shed slopes and storage, (values of C_t range from 1.0 to 2.2, Arora (2004)). An average value of 1.60 is assumed for these catchments.

Unit-hydrograph duration, t_r (storm duration):

$$t_r = \frac{t_l}{5.5} \quad (5)$$

From equation (5), the duration of the storm was obtained. However, if other storm durations are intended to be generated for the watershed, the new unit hydrograph storm duration (t'_r), the corresponding basin lag time (t'_l), can be obtained from equation (5).

$t'_l = t_l + \frac{(t_r - t_l)}{4}$ (6)

Peak discharge:

$Q_p = \frac{(2.75 \times C_p \times A)}{t_L}$ (7)

C_p is the coefficient of accounting for flood wave and storage conditions.

Time to peak:

Time to peak, $t_p = (t_r / 2) + t_L$ (8)

Base time (days)

Base time, $T_b = 3 + 3 * \frac{t_l}{24}$ (9)

The time width W_{50} and W_{75} of the hydrograph at 50% and 75% of the height of the peak flow ordinate were obtained based on equations (8) and (9) respectively in accordance to U.S Army Corps of Engineer (Arora, 2004). The unit of the width is hr.

$W_{50} = \frac{5.9}{(q_p)^{1.08}}$ (10)

$W_{75} = \frac{3.4}{(q_p)^{1.08}}$ (11)

$q'_p = \underline{Q'_p}$ (12)

.

Table 2: Unit hydrograph by SCS method – Oba River

T (hr)	0.00	2.73	4.25	6.38	8.5	11.05	12.75	14.88	17.00	19.13	21.25
Q (m^3/s)	0.00	78.92	179.86	121.13	58.73	23.86	13.76	6.61	3.30	1.65	0.73

Table 3: Unit hydrograph by SCS method – Otin River

T (hr)	0.00	3.05	6.09	9.14	12.18	15.83	18.27	21.32	24.36	27.41	30.45	
Q (m^3/s)	0.00	69.76	162.23	107.07	51.91	21.09	12.17	5.84	2.92	1.46	0.65	

Table 4: Parameters for the generation of unit hydrograph (Snyder's method)

River Watershed	L (km)	Lc (km)	Tl (hr)	tr (hr)	Qp (m^3/s)	Tb (hr)	A (km^2)	S (%)
Oba River	23.50	10.00	8.23	1.49	77.69	44.89	375.00	0.0039
Otin River	36.00	16.00	10.77	6.62	75.2	58.75	475.00	0.0036

2.3. Development of Peak Storm Hydrograph

The established unit hydrographs were used to develop the storm hydrographs due to the extreme rainfall event over the watersheds. Design storm hydrographs for selected recurrence intervals (10yr, 20yr, 50yr, 100yr and 200yr) were developed through convolution. The maximum 24-hr rainfall depths of the different recurrence intervals for the catchments under consideration determined using Gumbel Extreme Value Type 1 distribution equation are 94mm, 104mm, 116mm, 126mm and 136mm (Adejumo, 2011). The storm hydrographs were derived from a multi-period of rainfall excess called hydrograph convolution. It involves multiplying the unit hydrograph ordinates (U_n) by incremental rainfall (P_n), adding and lagging in a sequence to produce a resulting storm hydrograph. The SCS type II curve was used to divide the different rainfall data into successive short time events and the SCS Curve Number method was used to estimate the cumulative rainfall excess. The incremental rainfall excess was obtained by subtracting sequentially, the rainfall excess from the previous time events.

Rainfall excess Q_d is given as follows (SCS, 2002):

$$Q_d=(P-I_a)^2/(P-I_a)+S, \quad (13)$$

If $P \leq 0.2S$, $Q_d = 0$.

$$Q_d = \frac{(P - I_a)^2}{(P + 0.8S)} \quad (14)$$

$I_a=0.2S$

Where ,

P = Accumulated Precipitation (mm)

Q_d = Cumulative rainfall excess, direct runoff depth (mm)

S = Maximum potential difference between rainfalls and runoff in mm starting at the time the storm begins. I_a = Initial abstraction.

$$S=(25400/CN)-254 \quad (15)$$

CN is the basin Curve Number

$I_a = 0.2S$

With CN = 75 based on soil group, small grain and good condition, S was estimated as 84.67mm, while Ia is 16.94mm. This implies that any value of rainfall less than 16.94mm is regarded as zero.

The storm hydrograph ordinates based on the rainfall depth of desire recurrence interval were estimated from the unit hydrographs, The storm hydrograph ordinates for the watershed due to SCS and Snyder's method were extracted and used to plot the storm hydrographs as presented in figures 4-7.

Table 5: Storm hydrograph peak flows for the two catchments based on the two methods and various return periods in m^3/s

Catchments	Methods	Storm Return Periods				
	SCS	**10yr,24hr**	**20yr,24hr**	**50yr,24hr**	**100yr,24r**	**200yr,24hr**
Oba river		336.12	414.71	514.55	601.63	691.38
Otin river		297.12	366.60	454.86	531.85	611.53
	Snyder's					
Oba river		142.31	175.59	217.87	254.74	292.91
Otin river		137.67	169.86	210.75	246.42	283.34

Table 6: Variation between SCS and Snyder's methods for the four catchments

Catchments	Total peak flows for different return periods		
	SCS (m^3/s)	Snyder's (m^3/s)	% Diff.
Oba river	772.61	323.60	58.11
Otin river	682.01	313.20	54.08

2.4. Statistical Evaluation of Storm Hydrograph Development

A statistical analysis known as Randomized Complete Block Design (RCBD) (Salako, 1989; Murray and Larry, 2000; Oyejola, 2003) was used to evaluate the two methods of storm hydrograph development for five return periods of 10- yr, 24-hr, 20-yr, 24-hr, 50-yr, 24-hr, 100-yr, 24-hr and 200-yr, 24-hr. The table of observation was developed, the two methods are represented as treatments (T_1 and T_2) while the return periods are represented as blocks (B_1, B_2, B_3, B_4 and B_5,). The mean value for each of the storm hydrograph flows of the methods were used to form tables of observation presented in tables 7 and 8.

Table 7: Mean values for statistical evaluation for Oba River at Ogbomoso station

Methods	Return Periods (Blocks)					Total
Treatment)	10-yr, 24-hr	20-yr, 24-hr	50-yr, 24-hr	100-yr, 24-hr	200-yr, 24-hr	
SCS (T_1)	102.40	125.77	155.40	181.21	207.89	772.67
Snyder's (T_2)	42.89	52.67	65.08	75.89	87.07	323.60
Total	145.29	178.44	220.48	257.10	294.96	1367.52

Table 8: Mean values for statistical evaluation for Otin River at Eko-Ende station

Methods	Return Periods (Blocks)					Total
(Treatments)	10-yr, 24-hr	20-yr, 24-hr	50-yr, 24-hr	100-yr, 24-hr	200-yr, 24-hr	
SCS (T_1)	90.39	111.02	137.17	159.95	183.48	682.01
Snyder's (T_2)	41.51	50.98	62.99	73.45	84.20	313.20
Total	168.02	206.36	254.98	297.32	267.75	995.21

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 variance (CV). These parameters were estimated in accordance to (Salako, 1989; Murray and Larry, 2000; Oyejola, 2003) and are presented in tables 9 and 10.

Table 9: ANOVA table for RCBD (Oba River at Ogbomoso Station)

Source of variation SV	Degree of freedom df	sum of squares SS	mean of squares MS	F-Ratio
Treatment	1	20166.37	20166.37	67.23

Block	4	7150.85	1787.73	
Error	4	1199.88	299.97	
Total	9	28517.10	22254.07	

Table 10: ANOVA table for RCBD (Otin River at Eko-Ende Station)

Source of variation SV	Degree of freedom df	sum of squares SS	mean of squares MS	F-Ratio
Treatment	1	13602.09	13602.09	67.28
Block	4	5891.34	1472.84	
Error	4	808.70	202.18	
Total	9	20302.13	15277.11	

The tabular F is obtained from statistical table in appendix E. From the statistical table, the F-value for the treatment df (1) on the horizontal axis and error df (4) on the vertical axis at the 5% level of significance, is 7.71. Since this value is much lower than the calculated values for the two catchments; 67.23 and 67.28, for Oba at Ogbomoso station and Otin at Eko-Ende station respectively. This indicates that the methods differ significantly from each other.

3.0. Results and Discussion

3.1. Results

The storm hydrograph peak flows for the two catchments namely; Oba river and Otin river at various return periods from SCS and Snyder's methods for the two methods are presented in Table 5. The comparison of unit hydrograph with generated storm hydrographs of different return periods for the catchments are presented in Figures 4 and 5, for the SCS method; while Figures 6 and 7 present that of Snyder's method. Table 6 shows the variation between the SCS and Snyder's method. Gumbel Extreme Value Type 1 distribution was used to obtain the storm depth values for 10, 20, 50, 100 and 200yrs return period with values 94, 104, 116, 126 and 136mm (Adejumo, 2011) respectively.

3.2. Discussion

Table 5 shows that the peak storm hydrograph estimate occurred at a short duration ranging from 336.12m^3/s – 691.76 m^3/s for Oba River at Ogbomoso control station and 297.12 m^3/s – 611.53 m^3/s for Otin river at Eko – Ende control station, using SCS method. The table also indicates that peak storm hydrograph, using Snyder's method, ranged from 142.31 m^3/s – 292.91 m^3/s for Oba River at Ogbomoso control station and 137.67 m^3/s – 283.34 m^3/s for Otin river at Eko – Ende control station. From the above, it is shown that for corresponding rivers for both methods, peak storm hydrograph estimate for Snyder's method is higher than that of SCS method. The results also indicated that runoff was generated at a short duration with low discharge magnitude for Oba River at Ogbomoso control station and Otin River at Eko – Ende control station.

The 10-yr, 24-hr storm hydrograph discharges are 336.12 m^3/s and 142.31 m^3/s for Oba River for both SCS and Snyder's methods while also for the same return period while 297.12 m^3/s and 137.67 m^3/s are the peak discharges for Otin River at Eko-Ende control station. The 20-yr, 24-hr storm hydrograph discharges are 414.71 m^3/s and 175.59 m^3/s for Oba River at Ogbomoso control station for both SCS and Snyder's methods also for the same return period while 366.60 m^3/s and 169.86 m^3/s are the peak discharges for Otin River at Eko-Ende control station. The 50-yr, 24- hr storm hydrograph discharges are 514.55 m^3/s and 217.87 m^3/s for

Oba River at Ogbomoso control station for both SCS and Snyder's methods while 454.86 m^3/s and 210.75 m^3/s are the peak discharges for Otin River at Eko-Ende control station. The 100-yr, 24-hr storm hydrograph discharges are 601.63 m^3/s and 254.74 m^3/s for Oba River at Ogbomoso control station for both SCS and Snyder's methods while 531.85 m^3/s and 246.42 m^3/s are the peak discharges for Otin River at Eko-Ende control station. The 200-yr, 24-hr storm hydrograph discharges are 691.76 m^3/s and 292.91 m^3/s for Oba River at Ogbomoso control station for both SCS and Snyder's methods while 611.53 m^3/s and 283.34 m^3/s are the peak discharges for Otin River at Eko-Ende control station.

The mean storm hydrograph flows obtained from the two methods were statistically evaluated using Randomized Complete Block Design. The results indicated that there were significant differences in the two methods. Table 5 also shows that the higher the return period, the greater the magnitude of the storm hydrograph generated, for both methods. However, the unit and storm hydrograph curves of figures 4 – 7 of various return periods for both methods show that the hydrograph pattern is the same with different peak values of storm hydrograph. The analysis, however, shows that the values of the peak flows obtained from SCS method is higher by about 58.11% and 54.08% than that of Snyder's method for both Oba and Otin Rivers respectively; these values are wide compared with each other, therefore poorly matched.

The peak flow values can therefore be useful in the study of flooding problems within the catchments. The results obtained can be used for flood forecasting, hydraulic structures, watershed simulation and comprehensive water resources planning.

4.0 Conclusions

The study shows that the watersheds under consideration have undergone notable eco-hydrological changes due to several developments along their courses. Hence, the natural beds of the rivers have been covered with grasses and have influenced their flow pattern. Statistical evaluation of the results using the Randomized Complete Block Design indicated that there were significant differences in the two methods. The analysis shows that the values of the peak flows obtained from SCS method is higher by about 58.11% and 54.08% than those of Snyder's method for both Oba and Otin Rivers respectively.

The peak flow values obtained can be used for flood forecasting, hydraulic structures, watershed simulation and comprehensive water resources planning. The two methods are efficient in estimating the parameters of the watershed which are required in the development of the unit hydrograph for the four catchments.

The established unit and storm hydrographs can be used to compute the peak flows for the design of hydraulic structures within the catchments. It can also be inferred that synthetic unit hydrograph methods are suitable for the estimation of ordinates for the development of storm hydrograph for rivers that have small watershed, because it was observed that the bigger the watershed area the more the differences between the values obtained with different methods using the same return periods. In conclusion, SCS method is recommended for use on these watersheds since it incorporates most major hydrological and morphological characteristics of the basins like the watershed area, main channel length, river channel slope and watershed slope.

The selection of peak storm flows of the desired return period depends on the type of hydraulic structure. For example, a peak flow of 200 yr return period will be required for the design of a bridge, while a 10 yr return period flow can be adopted for drainage culverts. Synthetic unit hydrograph methods are suitable for the estimation of storm hydrographs for rivers that have small watershed areas. The bigger the watershed area the more the differences between the values obtained from different methods for the same return periods.

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