International Electronic Engineering Mathematical Society IEEMS
http://www.ieems.net
International e-Journal of Engineering Mathematics: Theory and Application
http://www.ieems.net/iejemta.htm
ISSN 1687-6156
Volume (7), Sept., 2009, pp. 47-60

DETERMINATION OF PEAK STREAM FLOWS OF DIFFERENT STORM DURATIONS AND RETURN PERIODS FOR RIVER ASA CATCHMENT IN ILORIN, NIGERIA

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ABSTRACT

This report presents the development of unit and storm hydrographs for River Asa catchment. Unit hydrographs of different storm durations were considered and Snyder's method was used to develop the unit hydrographs, while the SCS curve Number method was used to estimate excess rainfall values from rainfall depth of different return periods. The design storm hydrographs corresponding to the excess rainfall values were determined based on the unit hydrograph ordinates established. The value of the peak unit hydrograph flows obtained for 1 hr, 2hr and 3hr storm duration is about 106m^3/s, 104m^3/s and 102m^3/s respectively. The design storm hydrograph flows obtained based on the 1 hr unit hydrograph ordinate for 10-yr, 25-yr, 50-yr, 100-yr and 200-yr return period varies from 480.0m^3/s and 980.0m^3/s. While the design storm hydrograph flows obtained based on the 2 hr unit hydrograph ordinate for 10-yr, 25-yr, 50-yr, 100-yr and 200-yr return period varies from 475.0m^3/s and 966.7m^3/s. Also the design storm hydrograph flows obtained based on the 3 hr unit hydrograph ordinate for 10-yr, 25-yr, 50-yr, 100-yr and 200-yr return period varies from 472.6m^3/s and 957.0m^3/s. The design storm hydrograph flows obtained based on 1 hr unit hydrograph ordinates for 10-yr, 25-yr, 50-yr, 100-yr and 200-yr return period gives the highest values and can be recommended for sizing hydraulic structures within Asa River catchment.

KEYWORDS: Synthetic unit hydrograph, design storm hydrograph, storm duration, River catchment and recurrence intervals

INTRODUCTION

In the design of dam, drainages, sewers, culverts, bridges, reservoirs, spillways and flood control structures, it is important and essential to know the precipitation and runoff relationship to get the peak discharges of stream flow from the peak rainfall for the design of the structures. 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 present to a large or small degree. The catchment properties include area, slope, orientation, shape, altitude and also stream pattern in the basin. Daniyan (1997) described unit hydrograph as represented by the surface runoff resulting from 1 cm of rainfall areas in excess of infiltration and other losses occurring in a unit time. 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 explained procedure for development of the unit hydrograph. Sherman recommended that the unit hydrograph method should be used for watersheds of 2000 square miles 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. 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 unit hydrographs generation to develop unit hydrograph for an ungaged watershed. The outcome of the study revealed that Snyder method was the most appropriate method. 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. In this study Snyder's method was applied to develop unit hydrographs of different storm durations and subsequently used to generate design storm hydrographs of rainfall depth of various return intervals for the design of hydraulic structures within the River Asa catchment. Figure 1 is the map of Nigeria showing Kwara State and the study area where the catchment area of River Asa situated.

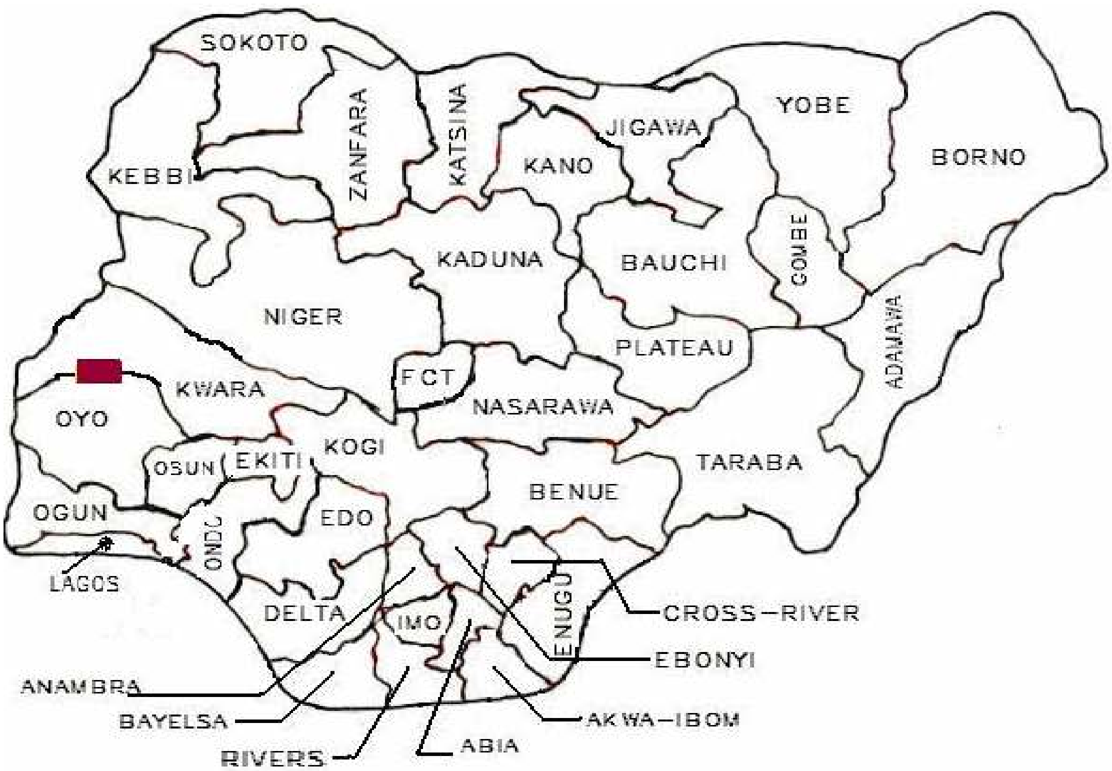

Figure 1 Map of Nigeria showing location of Asa river catchment

MATERIAL AND METHODS

Study area

The catchment of Asa River is located between latitude $8^0 36'$ and $8^0 24'$ North and Longitudes $4^0 36'$ and $4^0 10'$ east. Its total area is 906.0 km^2 and it lies within Kwara State and Oyo State with about one third of the basin area in Oyo State. The topography is a fair representative of surrounding plains which can be described as undulating with very broad and gentle slopes, laying at an attitude of between 457m and 265m above mean sea level (a.m.s.l). The eastern water divide is formed by a ridge of hill rising to almost 579m (a.m.s.l) but else where the catchment is gently undulating plain. The density of the drainage channels in the area is 0.956km of channel for every square surface with no visible drainage channels. The head waters of the river basin are situated in the south-west area located at an elevation of 396m to 457m (a.m.s.l). A large part of the catchment is above 376.5m (a.m.s.l). The lowest parts of the catchment which consist of the flood plain are below 274m (a.m.s.l). The stream has been serving as the town's main source of water for Ilorin.

DEVELOPMENT OF SYNTHETIC UNIT HYDROGRAPH

Snyder's method was used in the generation of unit hydrograph for River Asa watershed. The following parameters were determined based on Snyder's methods. The lag time, unit hydrograph duration, peak discharge, base time and hydrograph time widths corresponding to 50% and 75% of peak flow by using the watershed characteristics obtained from the topographic map. (Viessman et al, 1989; Ogunlela and Kasali, 2002 and Arora, 2004). The watershed characteristics include:Area of watershed, A = 906.0 km^2 ; length of main river channel, L = 57.5 km and the length along the main river channel from the outlet to a channel point nearest the watershed centroid, Lc = 30.31 km. The unit hydrograph parameters are estimated in accordance to Arora, (2004).

Lag time, t_p

$$t_p = C_t \left(L * L_c\right)^{0.3} \quad (1)$$

where t_p is lag time (hr) and C_t is a coefficient representing variations of watershed slope and storage. (Values of C_t range from 1.0 to 2.2, Arora (2004)). An average value of 1.60 is assumed for this catchment. Equation (1) gives the lag time, t_p as 15.02 hr.

Unit-hydrograph duration, t_r (storm duration)

$$t_r = \frac{t_p}{5.5} \tag{2}$$

From equation (2) the duration of the storm was obtained as 2.73hr. However, 1hr, 2hr and 3hr unit hydrograph storm durations are intended to be generated for the watershed, which can be used to establish the design storm hydrograph flow of different intensity for the watershed. For the new unit hydrograph storm duration (t'_r), the corresponding basin lag time ((t'_p) were obtained from equation (3)

$$t'_p = t_p + \left(\frac{t'_r - t_r}{4}\right) \tag{3}$$

Peak discharge, Q'_p

The peak discharge (**Q'_p**) based on different unit hydrograph durations and lag time were obtained from equation (4)

$$Q'_p = \frac{2.78 * C_p * A}{t'_p} \tag{4}$$

Where C_p is the coefficient accounting for flood wave and storage conditions.(Values of C_p range from 0.3 to 0.93, Arora (2004) with an average of 0.62 is assumed for this catchment).

Base time (days)

The base time was obtained from equation (5)

$$T_b = 3 + 3\left(\frac{t'_p}{24}\right) \tag{5}$$

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 (6) and (7) respectively in accordance to U.S Army Corps of Engineer (Arora, 2004). The unit of the time width is hr. Also the peak discharge per area (cumec/km^2) is given by equation (8)

$$W_{50} = \frac{5.9}{\left(q_p^{'}\right)^{1.08}} \tag{6}$$

$$W_{75} = \frac{3.4}{\left(q_p^{'}\right)^{1.08}} \tag{7}$$

$$q_p^{'} = \frac{Q_p^{'}}{A} \tag{8}$$

The parameters for the unit hydrograph of 1 hr, 2 hr and 3 hr storm duration respectively are presented in Table 1.

Table 1 Synthetic unit hydrograph parameters for different storm duration

t'_r (hr)	t'_p (hr)	Q'_p (m^3/s)	q'_p (m^3/s/km^2)	T_b (hr)	W_{50} (hr)	W_{75} (hr)
1.0	14.59	106.17	0.1172	116.00	59.76	34.15
2.0	14.84	104.38	0.1152	116.52	60.88	34.79
3.0	15.09	102.65	0.1133	117.27	61.99	35.42

The synthetic unit hydrograph for the storm duration of 1 h, 2 hr and 3 hr are presented in Figures 2, 3 and 4 respectively.

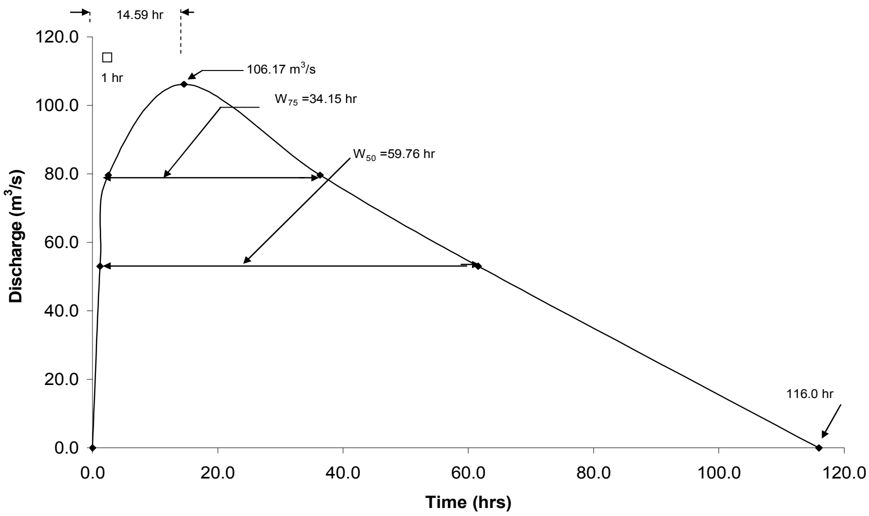

Figure 3 1-hr Unit hydrograph

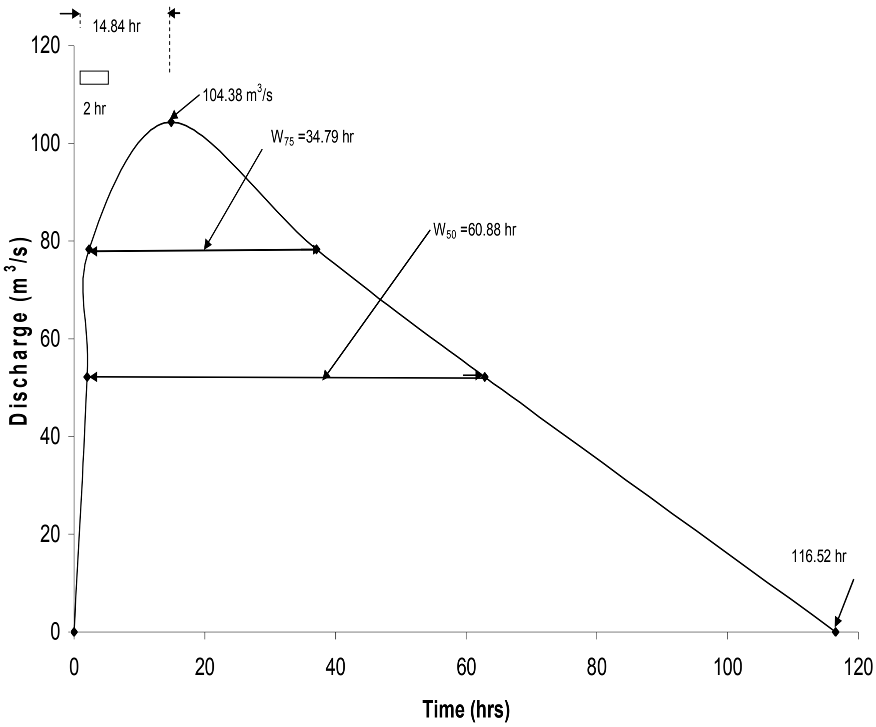

Figure 4 2-hr Unit hydrograph

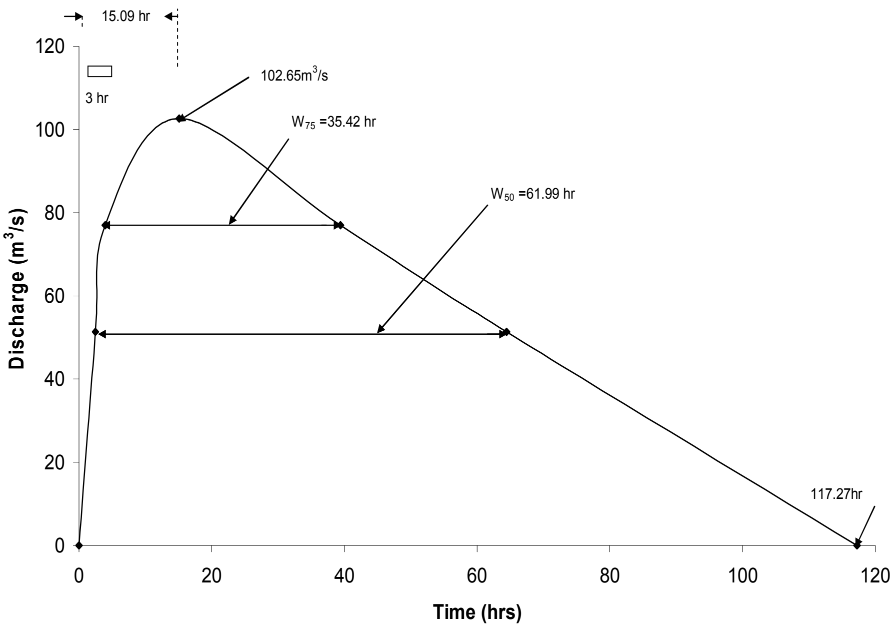

Figure 5 3-hr Unit hydrograph

DEVELOPMENT OF DESIGN STORM HYDROGRAPHS

The established unit hydrographs are used to develop the storm hydrographs due to actual rainfall event over the watershed. Design storm hydrographs for selected recurrence interval (10yr, 25yr, 50yr, 100yr and 200yr) were developed through convolution. The maximum 24-hr rainfall depths of the different recurrence interval for the catchment under consideration are 113.0 mm, 130.0 mm, 144.0 mm, 159.0 mm and 176.0 mm respectively (Olofintoye et al, 2009). The storm 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 storm hydrograph. The SCS type II curve 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 depth of 10yr, 25yr, 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 below (SCS, 2002).

$$Q_d = \frac{\left(P^* - I_a\right)^2}{P^* + 0.8S} \; for \; P^* > 0.2S \qquad (9)$$
$$Q_d = 0 \; for \; P^* \leq 0.2S$$

I_a = initial abstraction I_a = 0.2S

$$S = \frac{25400}{CN} - 254 \qquad (10)$$

With the CN = 75 based on soil group B, small grain and good condition, 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.

Where P* = accumulated precipitation (mm), Q_d = cumulative rainfall excess, runoff (mm) 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 1 hr, 2 hr and 3 hr storm duration are extracted and used to plot the storm hydrographs as presented in Figures 6 – 8.

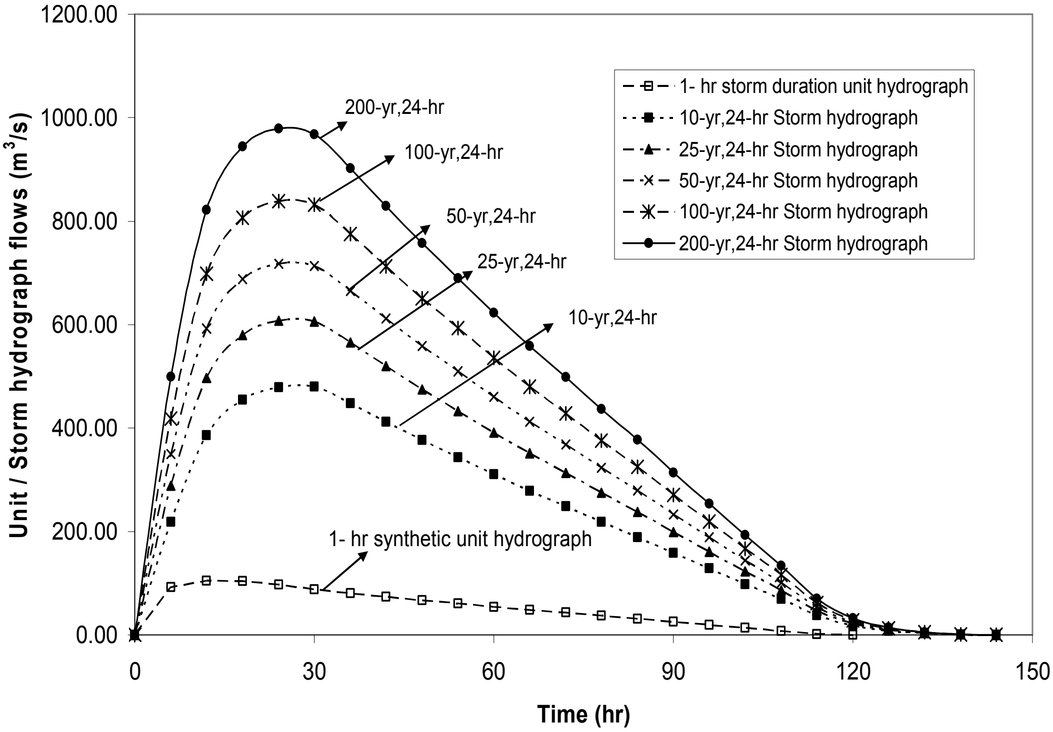

Figure 6 Comparison of one hour unit hydrograph with generated storm hydrographs of different return periods

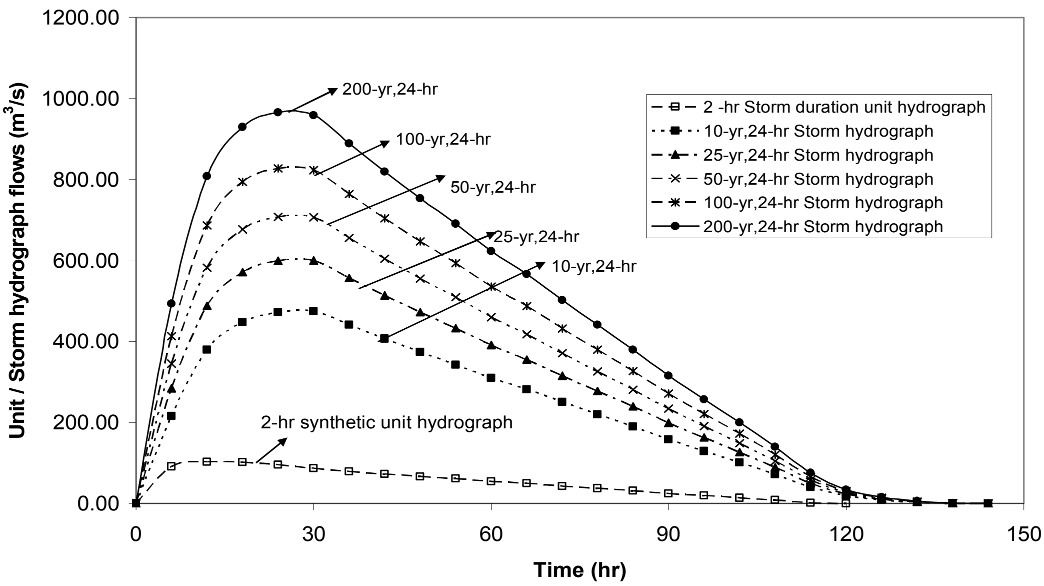

Figure 7 Comparison of two-hour unit hydrograph with generated storm hydrographs of different return periods

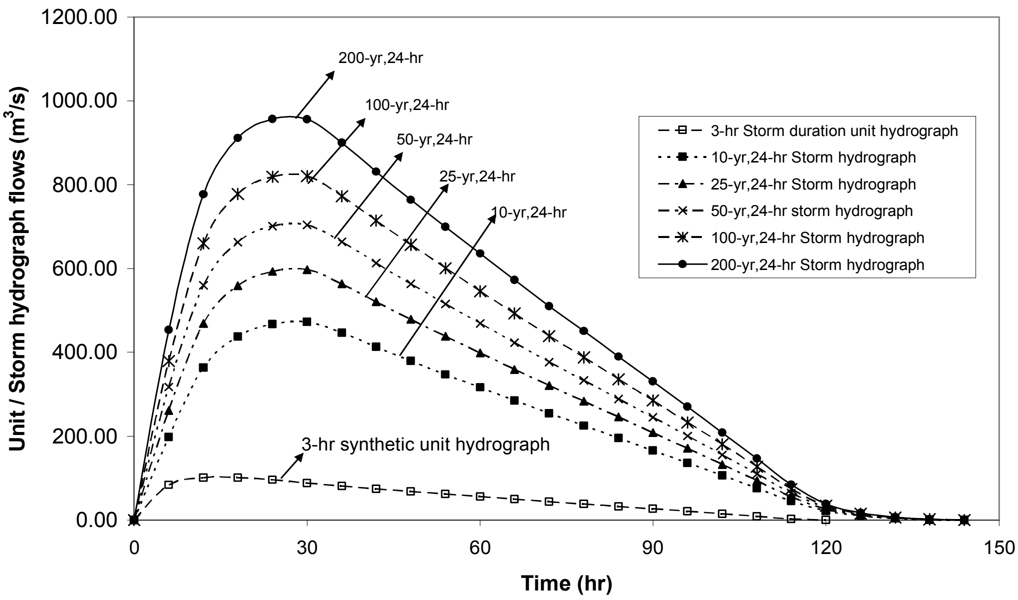

Figure 8 Comparison of three-hour unit hydrograph with generated storm hydrographs of different return periods

The relationship between the unit hydrograph ordinates and storm duration is presented in Figure 9, while the relationship between the predicted peak flows of different return periods and storm duration is presented in Figure 10. The graphs indicated a linear relationship, and a best fit was used to establish mathematical relationships presented in equations (11) to (16) along with the values of coefficient of determinations (R^2). Unit hydrograph ordinates and storm duration is presented in equation (11).

$$Q_p = -1.76t_r + 107.92 \qquad R^2 = 0.9999 \qquad (11)$$

While equation for the Prediction of peak flows of different storm duration for return periods of 10 yr, 25 yr, 50 yr, 100 yr and 200yr are presented in equations (12) to (16) respectively.

$$Q_p = -3.70t_r + 483.27 \qquad R^2 = 0.9605 \qquad (12)$$

$$Q_p = -5.00t_r + 611.70 \qquad R^2 = 0.9287 \qquad (13)$$

$$Q_p = -6.90t_r + 723.70 \qquad R^2 = 0.9700 \qquad (14)$$

$$Q_p = -9.25t_r + 847.67 \qquad R^2 = 0.9882 \qquad (15)$$

$$Q_p = -11.50t_r + 990.90 \qquad R^2 = 0.9919 \qquad (16)$$

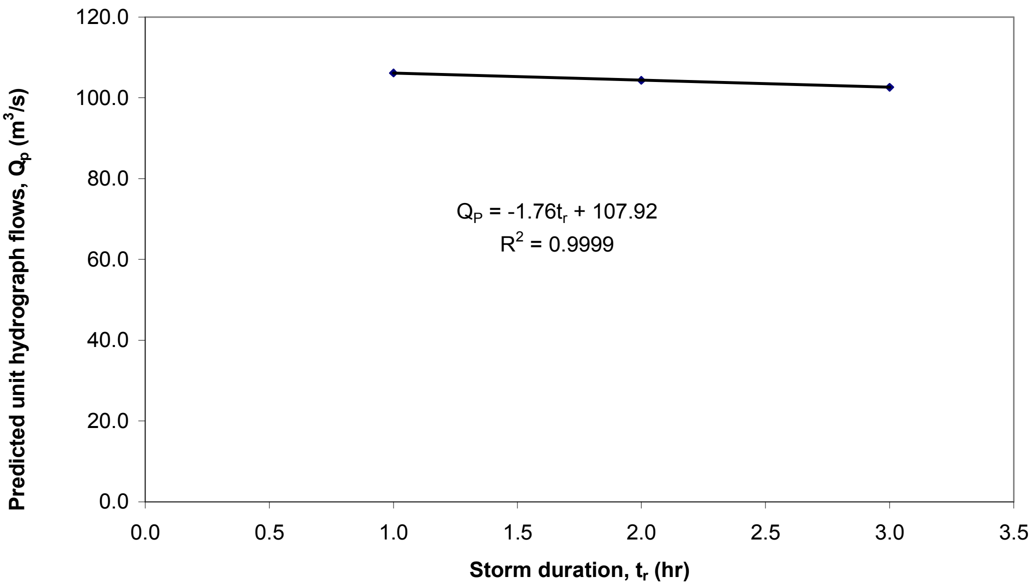

Figure 9 Variation of predicted unit hydrograph flows with storm durations

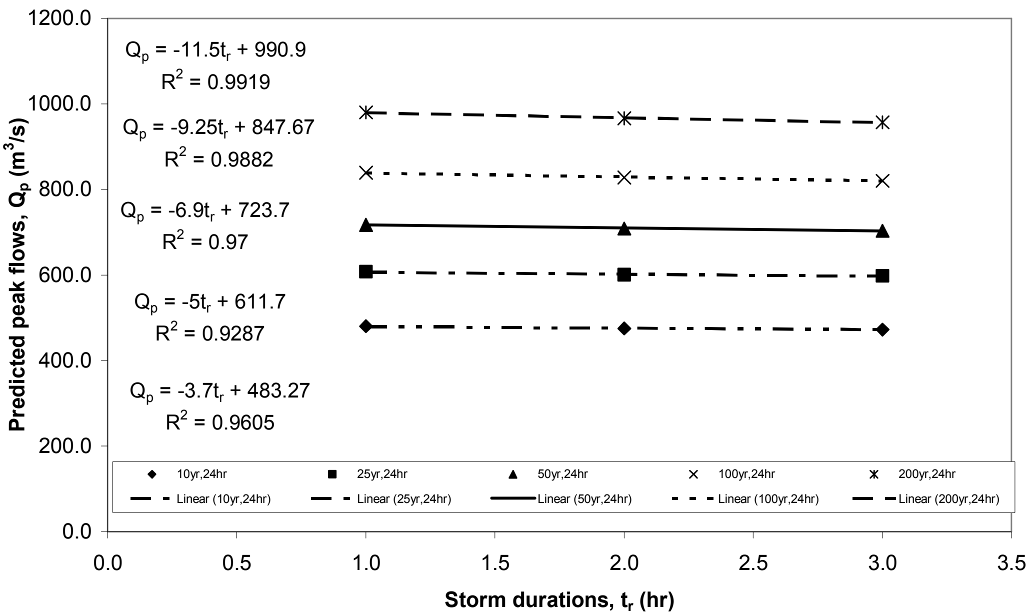

Figure 10 Variation of predicted peak flows of different return periods and storm durations

The established mathematical relationship for the unit hydrograph ordinate and storm hydrograph of different return periods based on 1hr, 2hr and 3hr storm durations were adopted to determine peak flow values for storm durations of 0.2hr, 0.4hr, 0.6hr, 0.8hr, 1.5hr, 2.5hr as presented in Table 2 along with those of 1hr, 2hrs and 3hrs storm durations. The peak flow values of shorter storm durations can be useful in the study of flooding problem within the Asa river basin.

Table 2 Synthetic unit and storm hydrograph peak flows (m^3/s) for River Asa watershed

Hydrograph	Storm duration (hr)								
	0.2	0.4	0.6	0.8	1.0	1.5	2.0	2.5	3.0
Unit hydrograph	107.6	107.2	106.9	106.5	106.2	105.3	104.4	103.5	102.7
Storm hydrograph									
10yr, 24hr storm	482.5	481.8	481.1	480.3	480.0	477.7	475.0	474.0	472.6
25yr, 24hr storm	610.7	609.7	608.7	607.7	607.5	604.2	600.1	599.2	597.5
50yr, 24hr storm	722.3	720.9	719.6	718.2	717.5	713.4	708.5	706.5	703.7
100yr, 24hr storm	845.8	844.0	842.1	840.3	839.0	833.8	828.0	824.5	820.5
200yr, 24hr storm	988.6	986.3	984.0	981.7	980.0	973.7	966.7	962.2	957.0

RESULTS AND DISCUSSION

The study revealed that the Asa River catchment area is about 906.0 km^2 with an elongated length of 50 km and width of 18 km. The length of the main stream is 57.50 km, while the length of the river channel from the outlet to a point nearest to the centroid of the basin was estimated to be 30.30 km. The synthetic unit hydrograph parameters based on the three storm durations are presented in table 1, while the unit and storm hydrograph peak flows for 1hr, 2hrs and 3hrs storm durations considered are presented in Table 2 along with those obtained with the mathematical relationship established. The result shows that the unit hydrograph peak flows for 1hr, 2hrs and 3hrs storm durations considered ranges between 102.0 m^3/s and 106.0m^3/s, while the time to peak ranged between 14.0 hr and 15.0 hr. This is an indication that the storms of lower duration results to high intensity and consequently generate high stream flows. Also from the results the values of the design storm hydrograph having return period of 10-yr, 24-hr has peak flows ranging from 470.0 m^3/s to 480.0 m^3/s, while the time to peak is 30 hr. For the 25-yr, 24-hr storm hydrographs, the peak flows ranging from 597.5 m^3/s to 607.5 m^3/s, while the time to peak ranging from 25 h to 30 hr. For the 50-yr, 24-hr storm hydrographs, the peak flows ranging from 703.7 m^3/s to 717.5 m^3/s while the time to peak is from 24 hr to 30 hr. For the 100-yr, 24-hr storm hydrographs, the peak flows ranging from 820.5 m^3/s to 839.0 m^3/s while the time to peak is from 24 hr to 30 hr. For the 200-yr, 24-hr storm hydrographs, the peak flows ranging from 957.0 m^3/s to 980.0 m^3/s while the time to peak is from 24 hr to 25 hr. The relationship between the unit and storm hydrographs of various return periods are presented in Figures 6 -8, where the values of the unit and storm hydrograph flows at any desire period can be estimated. More over, the established mathematical relationship given in equations (11) to (16) is reliable based on the fact that the values of coefficient of determination which is very close to one. Hence the equations can be used for prediction of peak flows of desired storm durations as can be observed in Table 2.

CONCLUSIONS

The Asa River catchment has experienced a lot of development in the recent years and this has replaced the natural ground surface with an impervious surface and this has resulted in high peak discharge. However, the established unit and storm hydrographs can be used to compute the peak flows for the design of hydraulic structures within Asa River catchment. The selection of peak storm hydrograph flows of the desire return period depend on the type of hydraulic structure in mind. For example, peak flow of 100 yr return period is required for the design of bridge, while 25 yr return period can be adopted for drainage culverts and minor bridges. The outcome of this study is recommended for use within Asa River catchment and nearby ungaged watershed.

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