Evaluation of Methods for Design Discharge Estimation in Ungauged Catchments, A case of Tigithe River catchment in Mara River Basin

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Abstract

Realistic design flood estimation, where the magnitude of a flood is associated with a level of risk (e.g. return period), is necessary in the planning, design and operation of hydraulic structures (e.g. bridges, culverts, dam spillways, drainage canals etc) for the preservation of human life and property. Standard technique for design flood estimation generally includes statistical analyses of observed peak discharges. However, observed streamflow data are often not available at the site of interest for most of the catchments in developing countries and rainfall event-based methods have to be used.

In this study, event based rainfall-runoff modelling technique was used to estimate design discharge for six sites in Tigithe River in Mara River basin. Three models were used namely, TRRL East Africa Model, Soil Conservation Service (SCS) unit hydrograph and Snyder unit hydrograph rainfall runoff model. The TRRL East African Model was developed by the UK Transport and Road Research Laboratory on the basis of rainfall-runoff studies for a range of selected East African catchments and applied to catchments up to 200km2. Catchment characteristics such as catchment area, length of the longest course, catchment slope and slope of the longest water course required by the models were derived from Digital Elevation Model (DEM) with 30-m resolution. Measured discharge values at a number of sites along Tigithe River were obtained from published reports provided. Also rainfall data from Tarime, Nyabirama and Gokona were obtained from the Tanzania Meteorological Agency (TMA). The data of interest to the study were the Annual Maximum Daily rainfall required to estimate peak flows at the drainage sites. The results from the frequency analysis of 24-hr Annual Maximum Rainfall values for the three stations provided the input values to the models

For all the drainages sites analyzed at different return periods, Snyder method had good agreement with TRRL East Africa Model developed for the East African catchments as compared to SCS method which was under-estimating the peak discharge for all the return periods.

Key words: Ungauged catchments, Design Discharge, Event-based rainfall-runoff modelling

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1. INTRODUCTION

Flood is a discharge wave moving downstream in a channel. The discharge and hence the water level, water surface slope and velocity are changing with distance and time. Realistic design flood estimation, where the magnitude of a flood is associated with a level of risk (e.g. return period), is necessary in the planning, design and operation of hydraulic structures (e.g. bridges, culverts, dam spillways, drainage canals etc) for the preservation of human life and property (Rahman *et al.*, 1998; Reis and Stedinger, 2005).

Various approaches have been used for estimation of flood peak discharges with different return periods. In catchments with sufficiently long gauge records, the design discharges can be obtained from the statistical frequency analysis of streamflow data. Design discharges for ungauged catchments can be obtained from prediction methods or a deterministic approach, in which rainfall is translated into a flood based on catchment descriptors, like area, slope, land use, and other physical or climatic characteristics. Hydrological models attempt to simulate the complex hydrological processes that lead to the transformation of rainfall into runoff, with varying degree of abstraction from these physical processes. These models have been applied to simulate a rainfall-runoff process in gauged catchments successfully for over 40 years, but the representation of flow in ungauged catchments remains a challenge (Darina, 2013). To overcome the difficulties, rainfall-runoff technique is used, in which catchment physical properties can be used as model parameters. Using this type of models, design rainfalls of different return period are input to a model.

The peak discharge of the obtained hydrograph is assumed to be design discharge with the same return period as its corresponding input design rainfall (Froehlich, 2012). In this study a comparative analysis is carried out to estimate design discharge using Soil Conservation Service (SCS), Snyder Unit hydrographs and TRRL East African Model methods. The TRRL East African Model was developed by the UK Transport and Road Research Laboratory on the basis of rainfall-runoff studies for a range of selected East African catchments. The method is commonly applied to catchments up to 200 km^2.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

Tigithe river catchment is located approximately between 1°25' – 1°42' S and 34°15' – 34°40'E. Tigithe river is one of the tributaries of Mara river on Tanzanian side (Figure 1). There are three air masses that influence the rainfall regime of the Tigithe river catchment. The apparent movement of the Inter-Tropical Convergence Zone (ITCZ) determines the seasons. The catchment is dominated by dry northeasterly winds from the Sahara Desert from November through March causing little rainfall. The short rains are experienced from November to December. The Southeast Trade winds from the Indian Ocean which influence rainfall pattern of the region between March and June, weakening considerably between June and October. The less dry months are January and February. The southwest trade winds, or sometimes known as the Congo air mass, which bring rain from the west in July with storms and hailstorms. Besides the variety of air masses, the rainfall amount and distribution are governed by altitudinal variations, giving rise to a bimodal rainfall pattern of wet and short rains. The north-south and east-west rainfall gradients are very sharp.

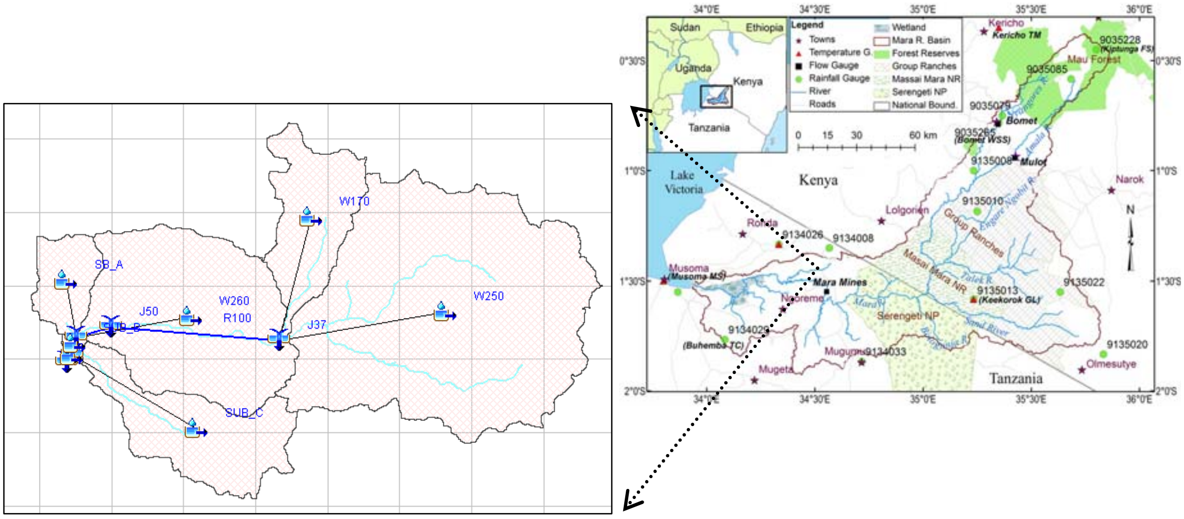

Figure 1: Location Tigithe River subcatchment

2.2 Data Availability

Measured discharge values at a number of sites along Tigithe stream were obtained from published reports. Rainfall data from Tarime, Nyabirama and Gokona (Table 1) were also used. The data of interest to the study were the Annual Maximum Daily rainfall required to estimate peak flows at the selected sites. Spatial data used were 30-m resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model, soil data from Food and Agriculture Organization of the United Nations (FAO, 1995); and landuse data from USGS Global Land Cover Characterization (GLCC) database.

Table 1: Annual Maximum Rainfall Data for Tarime, Nyabirama and Gokona

Tarime Station			**Nyabirama station**		**Gokona Station**	
S/N	**Year**	**AMR (mm)**	**Year**	AMR (mm)	Year	AMR (mm)
1	1970	58.9	2004	61.8	2005	44
2	1971	46.7	2005	40	2006	70
3	1972	75.2	2006	75.5	2007	68
4	1973	63.8	2007	68.5	2008	67
5	1974	83.5	2008	40.5	2009	45
6	1975	89	2009	48	2010	58
7	1976	79	2010	66	2011	50
8	1977	82.2	2011	44	2012	57
9	1978	61.4	2012	58		
10	1979	42.1				
11	1980	51.2				
12	1981	82.7				
13	1982	90.7				
14	1983	57.2				
15	1984	61.8				
16	1985	53.6				
17	1986	62.7				
18	1987	35.8				
19	1988	49.4				
20	1989	51.8				
21	1990	43.7				
22	1991	45.1				
23	1992	42.6				
24	1993	42.5				
25	1994	45.2				
26	1995	45.8				
27	1996	53.5				
28	1997	85.2				
29	1998	103.2				
30	1999	75.3				
31	2000	63.7				

2.3 Estimation of Design Rainfall

A frequency analysis of 24-hour Annual Maximum rainfall for three stations located in the Tigithe river catchment was carried out to determine rainfall magnitude of frequencies of occurrences of 10, 25, 50 and 100 year return periods. These values were required to generate peak flows at the selected sites.

2.4 Estimation of Design Flood

The transformation of rainfall into runoff to estimate the peak flood and the entire hydrograph at the section of interest, has been carried out developing the following three hydrological models:

- ✓ TRRL East African Model
- ✓ SCS UH rainfall-runoff model;
- ✓ Snyder UH rainfall-runoff model

The other approach could have been statistical analysis, but because of the fact that long term time series discharge data for Thigite River is not available, this method could not be used.

2.4.1 TRRL east Africa flood model

The TRRL East African Model was developed by the UK Transport and Road Research Laboratory on the basis of rainfall/ runoff studies for a range of selected East African catchments. The method is commonly applied to catchments up to 200 km^2. The model requires inputs of 24-hr Annual Maximum rainfall and catchment characteristics.

The model is made up of two parts, a linear reservoir model and a flood model. The linear reservoir part of the model describes the land phase of the flood cycle. This is the time between the rainfall reaching the ground and the water entering the stream system. The flood routing part of the model routes the flood down the water course to the catchment outfall. The model assumes that a storm rainfall of a given return period results in a peak flood of equal return period. The application of the model requires the selection of a range of parameters for each catchment which include:

(i) *Standard Contributing Area Coefficient, Cs* - the standard runoff factor for a wet zone grassed catchment. The coefficient varies with soil type and average catchment slope. The average catchment slopes have been classified according to the TRRL classification as follows: Moderate 1-4%, Rolling 4-10% and Hilly 10-20%. The soil characteristics have been classified in accordance with the TRRL classification as presented in Table 2 below.

Table 2: TRRL classification of soil characteristics

Soil Characteristic	**Description**
Impeded Drainage	Very low permeability Clay soils with high swelling potential Shallow soils over largely impermeable layer, very high water table
Slightly impeded Drainage	Low permeability. Drainage slightly impeded when soil fully wetted
Well Drained	Very permeable. Soil with very high infiltration rates such as sands, gravel and aggregated clays

Source: TRRL Laboratory Report 706, Transport and Road Research Laboratory, Department of Environment, UK, 1976

(ii) *The land use factor, C_L* - this factor adjusts the runoff factor according to land usage relative to a catchment with short grass cover

(iii) *The catchment wetness factor, C_W* - a measure of the antecedent wetness of the catchment

(iv) *Lag time, K* – the time for the recession curve of outflow from a linear reservoir to fall to one third of its initial value. This parameter is strongly dependent on the vegetation cover.

2.4.2 SCS unit hydrograph model

The unit hydrograph of a watershed is defined as the direct runoff hydrograph resulting from an excess rainfall (net rain) of unitary height, uniformly distributed over the drainage area at a constant rate for an effective duration. Thus, the unit hydrograph represents the response function of the basin to rainfall and reflects the unchanging characteristics of the watershed. The unit hydrograph is a simple linear model that can be used to derive the hydrograph resulting from any amount and duration of excess rainfall.

The synthetic unit hydrograph used by the SCS was developed averaging a large number of individual dimensionless unit hydrographs. The final product was made dimensionless by considering the ratios of q/q_p (flow/peak flow) on the ordinate axis and t/Tp (time/time to peak) on the abscissa, where the units of q and q_p are m^3/s/mm. Its shape is characterized by a time-to-peak located at approximately 20% of its time base and an inflection point at 1.67 times the time-to-peak. The design unit hydrograph of the basin of interest is obtained from the dimensionless one having scaled it by means of the unit peak discharge and time to peak calculated as follows:

$$q_p = \frac{2.08.A}{T_p} \tag{1}$$

$$T_p = \frac{D}{2} + t_{lag} \qquad (2)$$

Where

- q_p and T_p are the peak discharge and the time-to-peak, respectively;

- A = catchment area in km^2;

- D = duration (in hr) of the excess rainfall adopted for deriving the unit hydrograph (usually is the time step adopted in the simulation);

- t_{lag} is the time (in hr) elapsed from the centroid of the excess rainfall to the peak of the hydrograph and corresponds in the SCS to the 60% of the concentration time t_c.

The concentration time t_c has been evaluated by adopting the SCS equation (t_c in hr):

$$t_c = 0.00227.L^{0.8}.\left(\frac{1000}{CN} - 9\right)^{0.7} . \frac{1}{\sqrt{s}} \qquad (3)$$

Where:

- L = length of the main stream in meters;

- CN =curve number, i.e. the parameter of the model representing the soil type;

- s = average slope of the basin expressed in %.

The CN for a watershed was estimated as a function of land use, soil type, and antecedent watershed moisture, using tables published by the SCS.

2.4.3 Snyder unit hydrograph model

Like the SCS UH, the Snyder synthetic UH was derived by observations of watersheds varying in size from about 30 to 30,000 km^2. Snyder defined a standard case, for which the following is verified:

$$t_{lag} = 5.5.D \qquad (4)$$

The basin lag can be estimated by:

$$t_{lag} = C_1.C_t\left(L.L_c / \sqrt{S}\right)^N \qquad (5)$$

- C_1 = 0.75 adjusting coefficient:
- C_t = coefficient derived from gauged watershed; in case of lack of measures, it can be assumed in the range 0.4 – 2.2;
- L = length of the main stream in kilometres;
- L_c = hydraulic length, in km, of flow along the main stream, from the outlet to a point on the stream nearest to the centroid of the watershed area;
- N is an exponent, commonly taken as 0.33.

On the other side, the peak discharge per unit drainage area of the standard unit hydrograph is:

$$q_p = \frac{C_2.C_p}{t_{lag}} \qquad (6)$$

With q_p expressed in $m^3/s/km^2$

C_2 = 2.75 adjusting coefficient;

Cp = peaking coefficient derived from gauged watersheds; in case of lack of measures, it can be assumed in the range 0.4 – 0.8

2.4.4 Loss model

Since both SCS and SNYDER unit hydrographs need an excess rainfall as a necessary input, rainfall losses have to be taken into account. The evaluation of excess rainfall was performed by means of the Curve Number method of the Soil Conservation Service. According to this method, the excess rainfall is calculated by:

$$P_{excess} = \frac{(P(t) - 0.2S)^2}{P(t) + 0.8S} \qquad (8)$$

With:

- P_{excess}= cumulative excess rainfall at duration t in mm;
- P(t) = cumulative rainfall at duration t in mm;
- S = maximum potential abstraction, in mm, expressed as: 25400/CN – 254, where CN is the curve number, which is the parameter of the model representing the soil type.

2.4.5 Models Implementation

Convolution of both the SCS UH and SNYDER UH was performed inside HEC HMS program from USACE, which internally runs the above explained UHs and losses algorithms. A hydrologic system made of 6 contributing sub-basins inside the Thigite river catchment were created for better modelling the process of flood formation at the drainage sites; the adopted HEC HMS hydrologic scheme is shown in Figure 2.

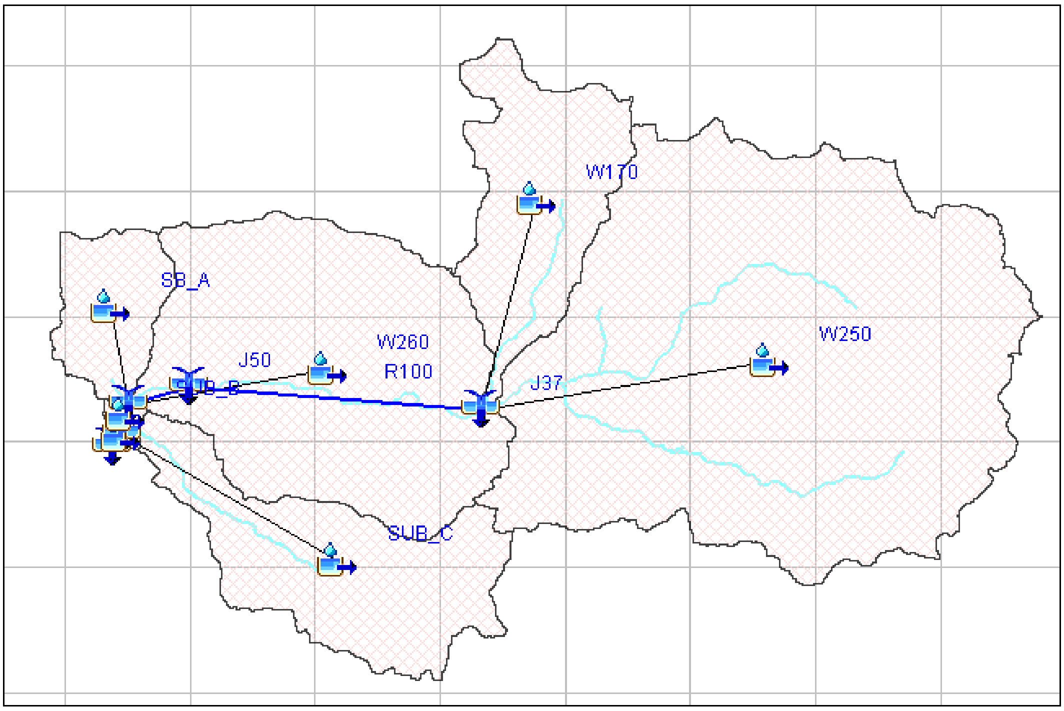

Figure 2: HEC-HMS Hydrologic scheme

The CN values for each sub-basin were estimated by means of the land cover map of the area (Figure 3). Each class has been joined with the table provided by SCS and spatially represented. The representative CN value for each basin comes from a weighted-average of the CNs falling inside the examined area.

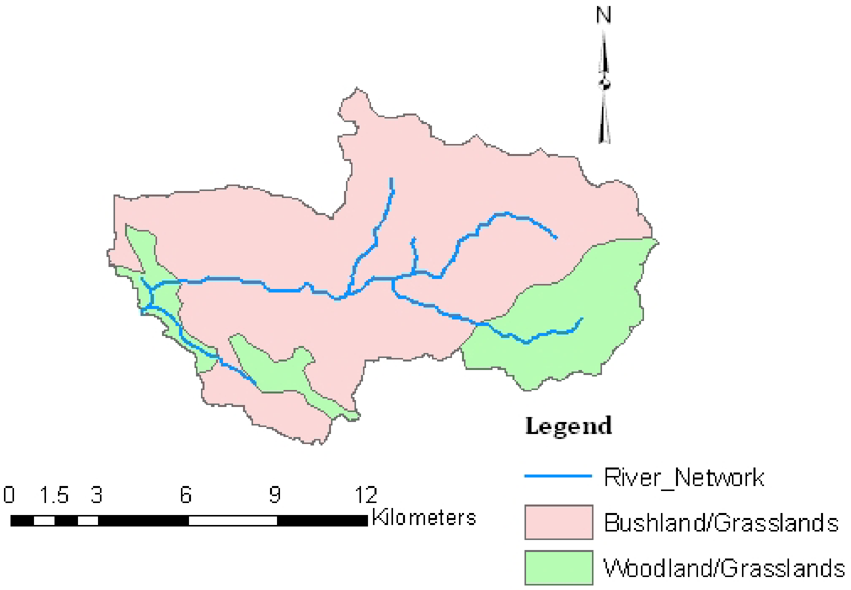

Figure 3: Land use/land cover map for Tigithe subcatchment

3. RESULTS AND DISCUSSIONS

3.1. Estimated Rainfall Design Storms

The results from the frequency analysis of 24-hr Annual Maximum Rainfall values for the three stations provided the input values to the Models. The derived frequency curves, using the Extreme Value type I (EV1) distribution, for the 24-hr Annual Maximum rainfall records for the three stations are presented in Figures 4 to 6 and the estimated design rainfall storm values are presented in Table 3. The determined rainfall values for Nyabirama and Gokona are very close in view of the fact that the stations are located close to each other. The values for Tarime are higher compared to the estimates for Nyabirama and Gokona. The values for Tarime were adopted in the study to estimate the peak flows at the selected sites in view of the fact that the data that was available for Tarime was fairly of long record compared to the other two. This is anticipated to give better estimates of the design storm values.

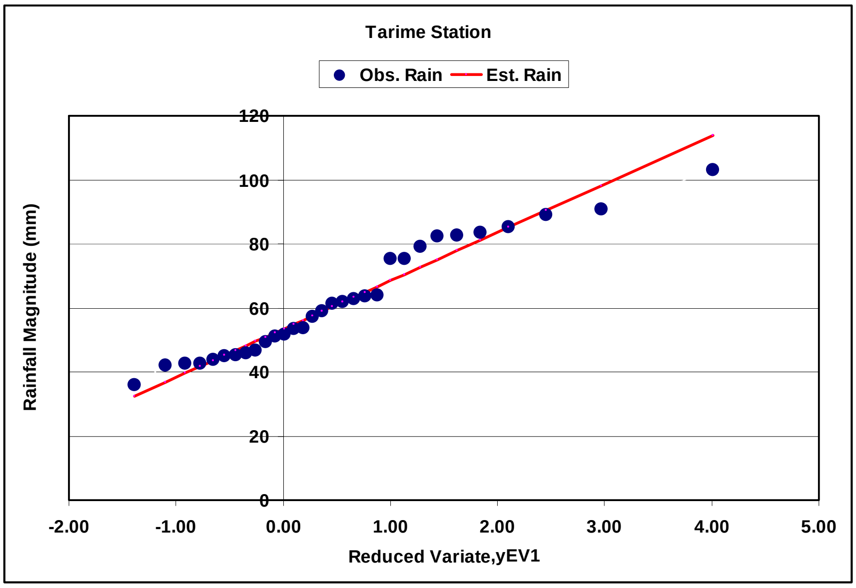

Figure 4: Frequency Curve of 24-hr Annual Maximum Rainfall for Tarime Station

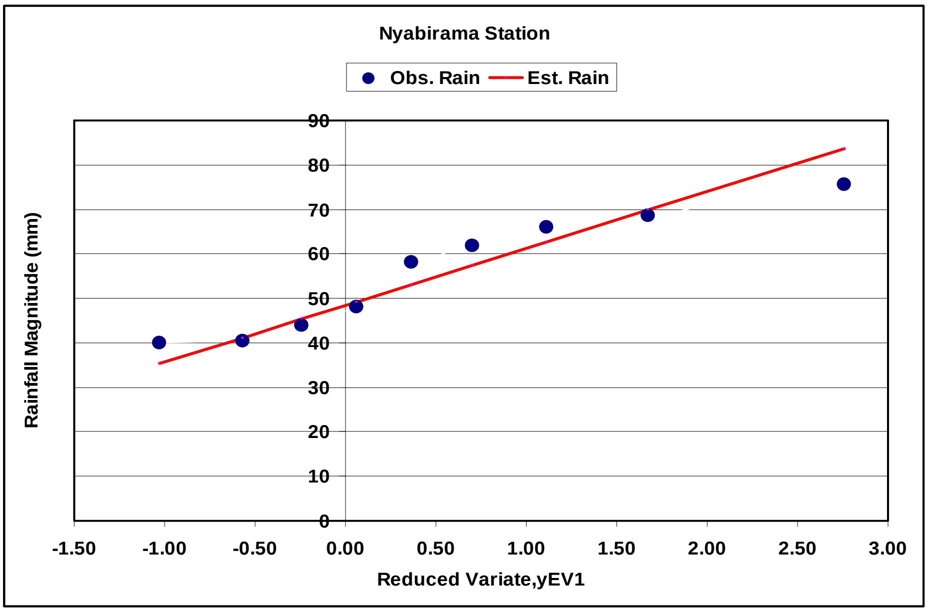

Figure 5: Frequency Curve of 24-hr Annual Maximum Rainfall for Nyabirama Station

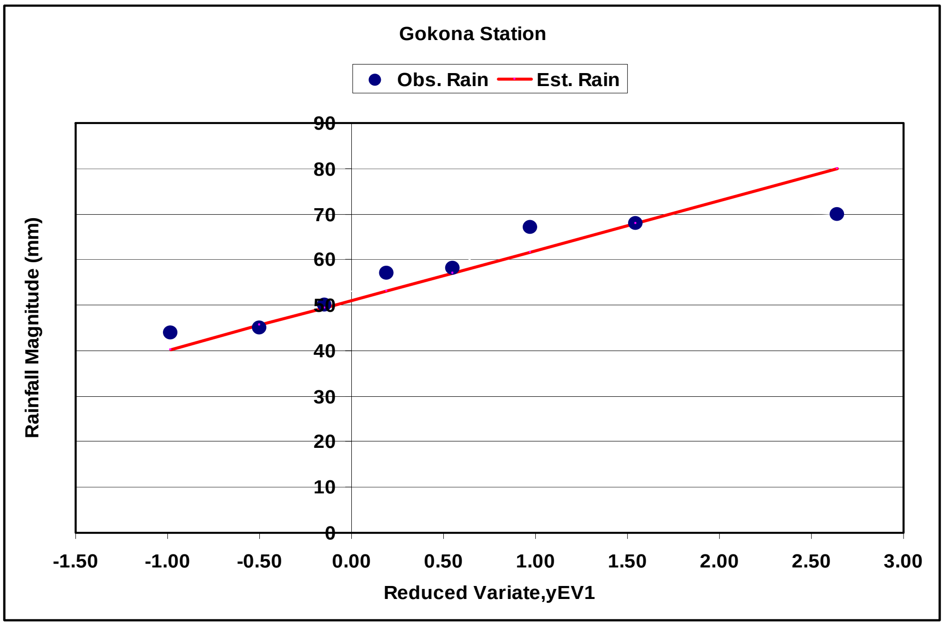

Figure 6: Frequency Curve of 24-hr Annual Maximum Rainfall for Gokona Station

Table 3: Estimated Rainfall Design storm values

Name of Station	Design storms for specified return period [mm]			
	T10	**T25**	**T50**	**T100**
Tarime	87	102	112	122.74
Nyabirama	77	89	98	107
Gokona	76	86	94	102

3.2. Estimated Design Discharges

The calculated parameters for the rainfall-runoff models, including the resulting curve number (CN) values and the adopted C_t and C_p coefficients, are summarized in Table 4 below.

Table 4: Parameters for synthetic Unit Hydrographs

		LOSS PARAMETERS			**SCS UH PARAMETERS**			**SNYDER UH PARAMETERS**						
Site	Area [km^2]	CN	S	I_a [mm]	L [km]	Slope	t_{lag} [hr]	C_1 [-]	C_t [-]	C_2 [-]	C_p [-]	L [km]	L_c [km]	t_{lag} [hr]
A	5	69	3.0	0.6	3.9	1.0	2.7	0.75	0.4	2.75	0.4	3.94	2.12	0.6
B	104	77	3.4	0.7	20.9	8.9	3.4	0.75	0.4	2.75	0.4	20.9	10.3	1.2
C	15	77	3.0	0.6	9.3	6.9	2.0	0.75	0.4	2.75	0.4	9.3	4.8	0.8
D	125	77	3.0	0.6	22.0	8.6	3.6	0.75	0.4	2.75	0.4	22.03	10.2	1.3
E	110	77	3.0	0.6	21.3	9.0	3.5	0.75	0.4	2.75	0.4	21.3	10.4	1.5
F	15	68	3.0	0.6	10.0	6.9	2.2	0.75	0.4	2.75	0.4	10.0	5.5	0.8

The estimated peak flows for the return periods of 10, 25, 50, and 100 years at the selected sites are tabulated in Table 5 and the hydrograph for site B is as shown in Figure 7. From the results it can be observed that the results for both SCS and Snyder methods are in close agreement with TRRL East Africa Model. TRRL East Africa model has been used as the basis for the comparison due to the fact that the model was developed based on experimental data from several East African catchments and hence the model represent fairly well the hydrology of these catchments. Another reliable and commonly used method for comparison is flood frequency analysis; however, in this case it was not possible as the catchments were not gauged. It can also be noted that the SCS-UH methods is slightly underestimating the peak discharge and the Snyder method is overestimating the peak discharge as compared to the TRRL model. It should be noted that the parameters C_t and C_p in the Snyder model are not physically based and therefore they were estimated by calibration of the model. The guiding principle in this case is that the values should be within the reported range from different catchments. Table 4 gives the best values for C_t and C_p parameters as estimated from calibration of the model.

Some studies (e.g. Packman & Kidd 1980; Guo 2001) showed that the design storm approach can produce peak discharges of desired return periods with the acceptable level of accuracy if used properly and these peak discharge are comparable to those obtained by continuous simulation approach or analytical probabilistic approach (Guo, 2001). The models used conceptualize complex spatially distributed processes in the catchment using relatively simple mathematic equations with parameters that do not often represent directly measurable entities. This may lead to uncertain parameter estimates and also the lumped nature of the models may not be able to reproduce well the spatial heterogeneities in the catchment (Beven, 1989). However, Hjelmfelt (1991) proved that HEC-HMS models can perform satisfactorily even with parameters obtained directly from catchment characteristics.

Table 5: Flood summary for different sites

	TRRL [m^3/s]	**SCS-UH [m^3/s]**	**Percentage difference from TRRL model**	**SNYDER UH [m^3/s]**	**Percentage difference from TRRL model**	**SITE**
T10	19	11	42.1	20	5.3	A
T25	22	14	36.4	25	13.6	
T50	24	16	33.3	28	16.7	
T100	27	18	33.3	32	18.5	
T10	280	220	21.4	289	3.2	B
T25	327	272	16.8	358	9.5	
T50	364	308	15.4	405	11.3	
T100	400	348	13.0	457	14.3	
T10	51	42	17.6	53	3.9	C
T25	60	53	11.7	67	11.7	
T50	66	60	9.1	76	15.2	
T100	73	68	6.8	86	17.8	
T10	310	244	21.3	325	4.8	D
T25	362	304	16.0	405	11.9	
T50	404	344	14.9	460	13.9	
T100	445	389	12.6	520	16.9	
T10	280	237	15.4	268	4.3	E
T25	328	291	11.3	330	0.6	
T50	365	329	9.9	372	1.9	
T100	402	370	8.0	418	4.0	
T10	51	41	19.6	50	2.0	F
T25	59	51	13.6	62	5.1	
T50	66	58	12.1	70	6.1	
T100	72	65	9.7	79	9.7	

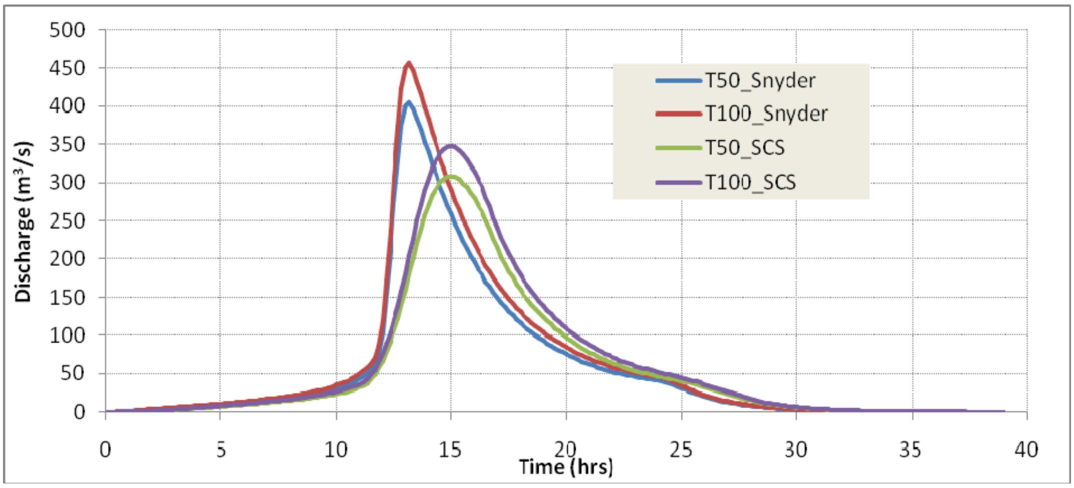

Figure 7: Hydrograph for the SCS-UH and Snyder UH methods for site B

From Table 5, it can be observed that the average percentage difference between TRRL method and the two methods, SCS and Snyder is 17.6% and 9.2%, respectively. The differences may be attributed to uncertain parameter estimates and also the lumped nature of the models which do not reproduce well the spatial heterogeneities in the catchment.

4. CONCLUSION

The study has shown that the approaches used for design discharge calculation is giving acceptable agreement with TRRL Model which has been developed for the catchments in East Africa. It is also found that the Snyder method is giving better results as compared to the SCS method. However, it is worth noting that the Snyder method is sensitive to two parameters C_t and C_p which are not physically based but estimated via calibration. Therefore the choice of the parameters affects the performance of the model.

The used synthetic unit hydrographs models conceptualize complex spatially distributed processes in the catchment using relatively simple mathematic equations with parameters that do not often represent directly measurable entities. This may lead to inaccurate estimation of peak discharge. Also the models are lumped and the average parameters may not reproduce well the spatial heterogeneities in the catchment. However, some other studies (e.g. Hjelmfelt (1991)), have shown that the selected models can perform satisfactorily even with parameters obtained directly from catchment characteristics. The models can therefore be satisfactorily applied for the estimation of design discharge in small ungauged catchments for planning, design and operation of hydraulic structures.

5. ACKNOWLEDGMENTS

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