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Validating the Soil Conservation Service triangular unit hydrograph (SCS-TUH) model in estimating runoff peak discharge of a catchment in Masvingo, Zimbabwe

Nhamo Luxon*, Manyamba Christopher and Chilonda Pius

International Water Management Institute (IWMI), Pretoria, South Africa.

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The knowledge of runoff discharged by a catchment at its outlet is important for water accounting and water allocation to competing uses. Runoff generated by a catchment is important in determining the catchment water balance, estimating pollutant loads, and quantifying sediment yield and delivery ratio. The Soil Conservation Service triangular unit hydrograph (SCS-TUH) model was used in this study to simulate water discharged into Siya Dam from Rosva River Catchment in Masvingo Province, Zimbabwe. The SCS-TUH model is preferred because it takes into consideration the physical and hydrological conditions of a catchment, as well, as the volume and flow variations of the entire rainfall event. The model simulates the peak runoff rate of a catchment using daily rainfall data. An overview of the methodology and the different steps followed are given. The model results were validated by comparing the simulated values with measured values recorded from a gauging station at the catchment outlet. The plotted hydrographs of both simulated and measured values coincided very well in height as well as in shape with great precision. The results showed that the SCS-TUH model can be used for simulating runoff discharge in ungauged catchments in the region.

Key words: Peak runoff rate, water availability, water allocation, water management, water balance.

INTRODUCTION

Most catchments in developing countries do not have gauging stations at their outlets to measure peak runoff rates. Yet the knowledge of water discharged into reservoirs on a daily basis is important in determining water allocation to the downstream uses. Regular recording of runoff discharge helps decision makers regarding water distribution to the multiple water uses as they know the amount of water entering a reservoir on daily basis. Therefore, the knowledge of runoff discharged by a catchment is an important part of water resource management (Manley, 1978; Young et al., 2000). With the declining rainfall amounts in recent years, there is a growing need for developing countries to increase land under irrigation in order to ensure food security for a growing population. Because most catchments are not gauged for water flow observation, this study evaluates the suitability of the triangular unit hydrograph (TUH) model in simulating runoff discharge at a catchment outlet.

In the absence of measured records, runoff discharge is usually estimated by using physical and/or statistical relationships between flow, climate and catchment characteristics (Holmes et al., 2002). Water discharge models range from simple water balance models for

*Corresponding author. E-mail: l.nhamo@cgiar.org. Tel: +27128459100. Fax: +27128056397.

mean discharge to complex physically based rainfall models designed to replicate the entire observed hydrograph (Manley, 1978; Institute of Hydrology, 1980; Moore, 1985; Gustard et al., 1992; Holmes, 2002).

This study, done in the Rosva River Catchment (RRC) in Masvingo Province of Zimbabwe, applies the Soil Conservation Service triangular unit hydrograph (SCS-TUH) model (Sherman, 1932, 1941; SCS, 1972; Fang et al., 2005) to simulate runoff discharge rate at the outlet of the catchment. The aim of the study is to evaluate the suitability of the SCS-TUH model in simulating runoff peak discharge of ungauged catchments. The simulated peak discharge rates of the studied catchment are compared with measured records in order to validate the model. Of the many unit hydrographs in literature, the SCS-TUH model is used in this study because it takes into consideration the physical and hydrological conditions of a catchment, as well, as the volume and flow variations of the entire rainfall event (Weaver, 2003; Durrans, 2003; Fang et al., 2005).

The maximum amount of flow discharged from a catchment at its outlet is related to the amount of time required for the entire catchment to be contributing to the flow (Durrans, 2003; Fang et al., 2007). A unit hydrograph (also called storm hydrograph) is a graph which shows the rate of water flow (river, canal, etc.) as a function of time at a determined section of a catchment (Ramirez, 2000). It is the integral expression describing the physiographic and climatic characteristics which control the relationships between precipitation and runoff in a catchment (Chow, 1994; Weaver, 2003).

MATERIALS AND METHODS

Study area

The Rosva River Catchment (RRC) is one of the catchments that supplies Siya Dam with water. Siya Dam, one of the major dams in Masvingo Province of Zimbabwe, is the main source of water for the various irrigation schemes and estates downstream, and also supplies water to the communities that live along the water canal that starts from the dam. Figure 1 is map showing the location, elevation and shape of RRC (31°24`-31°35` E, 20°08`-20°09` S). It is a sub-catchment of the Save Catchment in South East Zimbabwe. The average annual rainfall of the catchment is 650 mm. Rainfall is highly variable and occurs mainly during the summer, that is, from November to March. The catchment area is 198.9 km^2, with a broad and compact shape that make its tributaries to be few and long as shown in Figure 1.

It is mainly mountainous with isolated flat lands where agriculture is practised. Its average height is 1064 m. These geographic characteristics make the runoff to reach the catchment outlet quickly (Taffa, 2002). The soils are sandy loamy soils formed on granite rocks.

Data sources

Data that includes Landsat ETM satellite imagery, SOTER soil classification map (FAO, 2012), ASTER GDEM and weather data obtained from Siya Weather Station was used. The 30 m resolution ASTER GDEM was used to delineate the catchment boundaries and derive the river network using Geographic Information Systems (GIS). Landsat satellite imagery was used to generate the landuse/landcover map of the catchment, and the results were rectified using Google Earth. Measured daily runoff discharge recordings were obtained from the Zimbabwe National Water Authority (ZINWA), Station Number 114.

The geographic attributes (average height, length of longest river and catchment area, etc.) of the catchment, necessary for the calculation of the parameters important for estimating the peak runoff rates, were calculated using Geographic Information Systems (GIS).

The SCS-TUH model and method

The SCS-TUH (SCS, 1972; Sherman, 1932, 1941) analysis procedure is a widely used model among hydrology practitioners due to its predictability, and stability (Hann et al., 1982, 1996; Maidment, 1993; Chow et al., 1994; Viessman and Lewis, 2002; McCuen, 2005; Pongsai et al., 2010). The method takes into consideration the base time (T_b), that is, the time of the rise of the hydrograph (the time from the beginning of runoff to the time of peak runoff), and the area of the catchment and the runoff depth of a rainfall event (Ramirez, 2000).

The peak runoff rates (P_r) for 21 rainfall events that occurred within the catchment, and recorded within a period of 24 h were calculated using Equation 1, which is derived from the SCS-TUH analysis procedure (SCS, 1972; Huggins and Burney, 1992; Ponce and Hawkins, 1996; Hrissanthou, 2005). The peak runoff rate is calculated as:

$$P_r = \frac{0.278(AQ)}{T_b} \quad (1)$$

where, P_r is the peak runoff rate (m^3/s), A is the area of the basin (km^2), Q is the runoff depth (mm), and T_b is the base time, (h).

The Q for each rainfall event was calculated using the SCS Curve Number method (SCS, 1972; Ponce and Hawkins, 1996; Liu, 2008; Hawkins et al., 2009), expressed as;

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

where, Q is the runoff depth (mm), P is the daily rainfall (mm), S is the maximum retention capacity of soil (mm).

Equation 2 is only valid when $P >$ the initial abstractions (I_a) (that is, $P > 0.2S$). I_a is calculated as $I_a = 0.2S$. $P = 0$ when $P \leq 0.2S$ (Ponce and Hawkins, 1996; Durrans, 2003). The I_a is the total abstractions that occur before any runoff takes place. Selected days from 1997 to 2000 that had rainfall of more than the calculated I_a of 6.9 mm, were used to estimate the Q of each of the selected daily rainfall events. The I_a means that when rainfall is less than 6.9 mm, there is no runoff produced, thus it is used to determine rainfall events that produced runoff in that particular catchment.

The use of Equation 2 requires an estimate of the maximum retention capacity (S) which is also used to calculate the I_a. The S is a function of the curve number (CN) and is calculated using Equation 3 (SCS, 1972; Williams and LaSeur, 1976; Ponce and Hawkins, 1996):

$$S = 254\left(\frac{100}{CN} - 1\right), \text{ in mm} \quad (3)$$

The composite CN for the catchment is calculated as (Hawkins, 1993, 2009; Williams and LaSeur, 1976; Liu and Li, 2008; D'Asaro and Grillone, 2010):

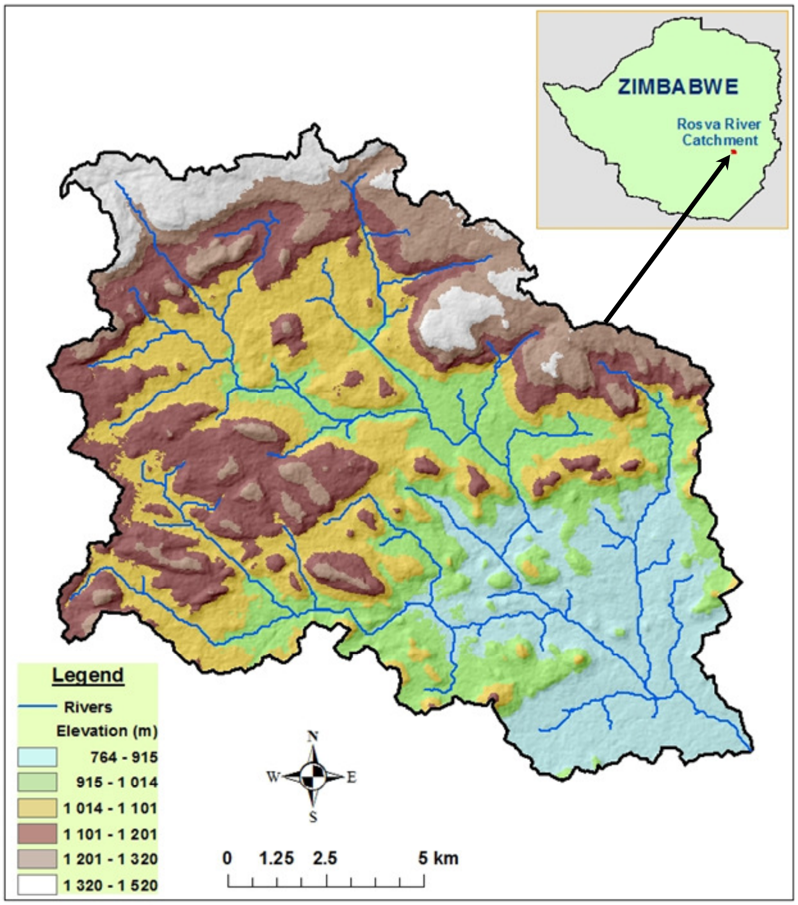

Figure 1. Location, elevation and shape of Rosva River Catchment.

$$CN = \frac{\sum_{i=1}^{n} CN_i A_i}{A}, \quad (4)$$

where, CN is the composite curve number of the catchment (dimensionless), A is the basin area (ha), CN_i is the curve number of each uniform plot of land within the catchment, and A_i is the area of each uniform plot within the catchment (ha). Using Equation 5, the composite CN for RRC was found to be 88.

The T_b for Equation 1 was calculated as a function of the time of concentration of the catchment. The Kirpich formula (Kirpich, 1940; Huggins and Burney, 1992; Xing et al., 2008) was used to calculate the T_b as a function of the time of concentration, which is expressed as:

$$T_b = 2.67\left(\frac{T_r}{2} + 0.6T_c\right) \quad (5)$$

where, T_b is the base time (h), T_r is the duration of the rainfall event, (h), which is 24 h in this case, T_c, is the concentration time (h), which is calculated as follows (Durrans, 2003; Xing et al., 2008):

$$T_c = \left(\frac{0.87L^3}{H}\right)^{0.385} \quad (6)$$

where, T_c is the concentration time (h), L is the length of the main river channel of the basin (km), and H is the difference in elevation (m). The method assumes that the maximum runoff rate of a catchment is reached when all parts of the catchment are contributing to the outflow. This happens when the T_c is reached (Dawod et al., 2011). The Kirpich method was originally developed for small catchments of less than 0.45 km^2; however, it has been applied to larger basins (Chow et al., 1994; Ponce and Hawkins, 1996; Watts and Hawke, 2003; Garen and Moore, 2005; Fang et al., 2007; Granato, 2012).

The flow of water originating from different locations in a catchment will have different travel times to the catchment outlet as some points are closer to the outlet than others (McGlynn et al., 2004). The two common measures of runoff travel times are time of concentration (T_c) and lag time (T_L). T_c is the time required for a drop of effective precipitation falling at the most remote point of a catchment to reach the catchment outlet (Ramirez, 2000; Durrans, 2003), whereas T_L is time from the centroid of rainfall excess to the time of peak runoff for a catchment (Green and Nelson, 2002; Wanielista et al., 1997). T_L and T_c are variables used to compute surface runoff using unit hydrograph methods, and there is no distinct advantage of one method over the other. In this study we used the T_c (Durrans, 2003; Ramirez, 2000; Granato 2012).

RESULTS AND DISCUSSION

Determination of model parameters

The input parameters for the model were derived from data collected from selected 21 rainfall events that

Table 1. Peak runoff rate input parameters for Rosva River Catchment.

Initial abstraction (I_a) (mm)	Maximum retention (S) (mm)	Curve number	Difference in elevation (m)	River length (Km)	Area (Km^2)	T_c (h)	T_p (h)	T_r (h)	T_b (h)
6.9	34.6	88	1064.17	27.62	198.88	3	14.2	24	38.3

Table 2. Comparison between measured and simulated discharge values, Rosva River Catchment.

Day	Rainfall (mm)	Evaporation (mm)	Effective rainfall (mm)	Runoff depth (mm)	Discharge (m^3/s)		Relative error (%)	Absolute error	Standard deviation
					Simulated	Measured			
18 Dec 1997	8.0	0.4	7.6	0.013	0.02	0.17	-88.87	0.15	0.11
19 Dec 1997	9.0	1.2	7.8	0.022	0.03	0.40	-92.12	0.37	0.26
19 Mar 1998	12.5	1.5	11.0	0.430	0.62	0.71	-12.50	0.09	0.06
08 Oct 1998	8.5	2.4	6.1	0.020	0.10	0.07	42.29	-0.03	0.02
01 Jan 1999	17.0	3.2	13.8	1.141	1.65	1.26	30.74	-0.39	0.27
02 Jan 1999	15.5	5.1	10.4	0.318	0.46	0.96	-52.18	0.50	0.35
03 Jan 1999	11.0	2.6	8.4	0.061	0.09	1.63	-94.62	1.54	1.09
21 Jan 1999	11.5	2.2	9.3	0.153	0.22	0.93	-76.22	0.71	0.50
22 Jan 1999	12.0	2.6	9.4	0.166	0.24	1.09	-78.03	0.85	0.60
23 Feb 1999	8.5	3.3	5.2	0.090	0.13	1.18	-88.99	1.05	0.74
04 Mar 1999	15.0	2.6	12.4	0.749	1.08	1.90	-43.07	0.82	0.58
06 Mar 1999	16.0	1.9	14.1	1.234	1.78	1.71	4.16	-0.07	0.05
09 Mar 1999	12.0	3.3	8.7	0.087	0.13	1.42	-91.15	1.29	0.92
24 Nov 1999	7.5	4.5	3.0	0.501	0.72	0.77	-6.10	0.05	0.03
09 Dec 1999	14.5	4.3	10.2	0.284	0.41	0.33	24.24	-0.08	0.06
01 Jan 2000	18.0	6.4	11.6	0.558	0.80	1.16	-30.61	0.36	0.25
11 Jan 2000	15.9	4.4	11.5	0.535	0.77	0.66	17.10	-0.11	0.08
23 Feb 2000	14.0	2.0	12.0	0.650	0.94	1.11	-15.42	0.17	0.12
24 Feb 2000	15.0	2.8	12.2	0.699	1.01	1.07	-5.69	0.06	0.04
17 Mar 2000	24.0	5.3	18.7	2.992	4.32	6.16	-29.88	1.84	1.30
10 May 2000	12.0	0.8	11.2	0.471	0.68	0.68	0.02	0.00	0.00

occurred between 1997 and 2000 as shown in Table 2. The calculation of the P_r using the SCS-TUH model relied mainly on the runoff depth (*Q*) of the rainfall event. The *Q* is a function of the amount of rainfall and the maximum retention capacity of the soil as given by Equation 2. The *Q* reflects the P_r potential.

According to the curve number (CN) and the maximum retention capacity (*S*) of the RRC, rainfall events produce runoff only if they are above the initial abstraction (I_a) of 6.9 mm as shown in Table 1. This means that the I_a is dependent on the CN of the catchment.

Table 1 gives the input parameters calculated for RRC and used to run the SCS-TUH model in the catchment. Table 1 also gives geographic attributes and the time variables estimated to calculate the runoff depth (*Q*) and the base time (T_b) according to Equations 2, 5 and 6 respectively.

The 21 rainfall events shown in Table 2 were recorded on a daily basis and at equal intervals, meaning that they had durations of 24 h each. The time of concentration (T_c) of 3 h was calculated using Equation 6. Using the calculated T_c and the duration of the rainfall event (T_r), the base time (T_b) was calculated as 38.3 h. The simulated P_r results shown in Table 2 were calculated from effective rainfall obtained from subtracting evaporation from total rainfall. Effective rainfall is the amount of rainfall that will eventually result in runoff. The simulated and measured peak discharge rates for the catchment range between 0.02 and 4.32 m^3/s, and between 0.07 and 6.16 m^3/s respectively. The measured rates tend to be higher than the simulated ones but the differences are minimal.

Model validation

In order to validate the SCS-TUH model output, the daily rainfall data of the 21 events that occurred in RRC were used to estimate the daily peak runoff rates (P_r). The validity and feasibility of the model was then verified by comparing the simulated P_r with measured values recorded from a gauging station located at the outlet of

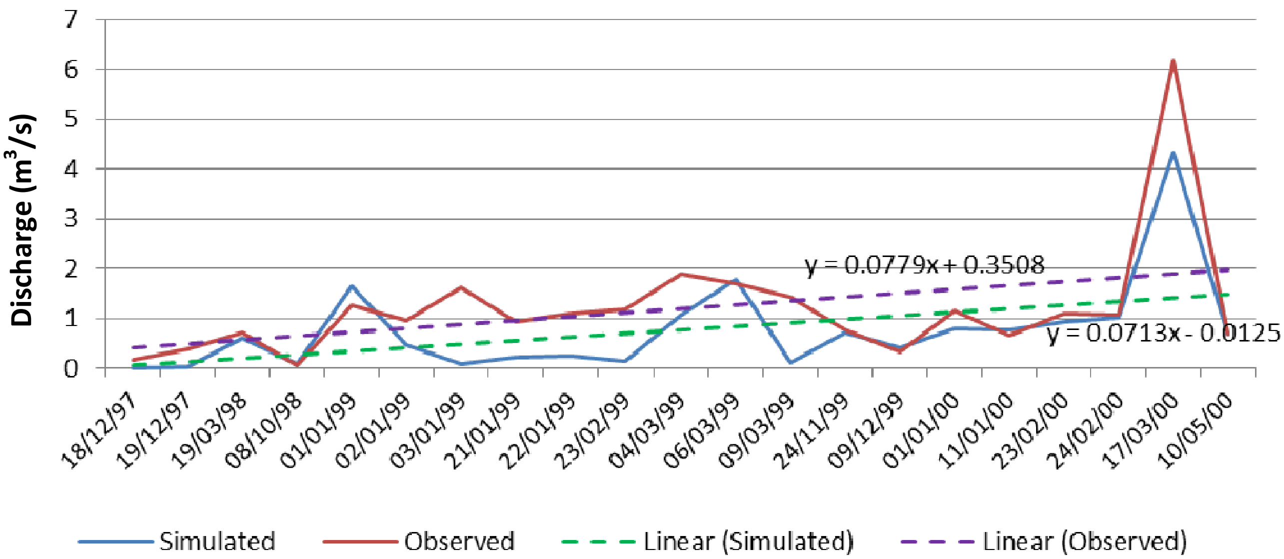

Figure 2. Comparison of measured and simulated discharge by the triangular unit hydrograph model.

the catchment. Table 2 shows both the simulated and measured runoff discharge rates as well as the statistical comparison between them.

The absolute errors between the simulated and measured discharge values range from 0 to 1.3 mm and the relative errors from -94.62 to 42.29% which are within the permissible limit. The standard deviation of the sample ranges from 0 to 1.3 and the group standard deviation averages 0.38, a low standard deviation indicating that the data points tend to be very close to the mean of the measured and simulated values. The correlation coefficient between the simulated and the measured discharge values is 0.88 (88%), implying a positive association between simulated and measured trends as the coefficient is close to the best fit of 1.

Figure 2 shows the hydrographs of both the simulated and measured data for the 21 rainfall events, and the linear estimate trend lines for the two sets of results. The hydrographs of both the simulated and measured discharge processes coincided very well in height as well as shape except for a single event (03/01/99). The linear estimate trend lines are close to each other and the equations are almost the same showing the closeness of both simulated and measured data. Generally, the results indicate that there is a minimal difference between the exact values and the approximation, a scenario that validates the SCS-TUH in estimating runoff discharge rates at the outlet of a catchment.

The analysis derived from both the hydrographs shown in Figure 2 and the data presented in Table 2 demonstrate that the simulated results of the SCS-TUH are consistent with the actual situation. Thus the SCS-TUH model could be applied to estimate runoff discharge for ungauged catchments as it has shown to be precise and practical.

Conclusions

This study used the SCS triangular unit hydrograph to estimate runoff discharge (peak runoff rate) at the outlet of Rosva River Catchment. The simulated results were compared with measured discharge data recorded from a gauging station located at the catchment outlet. The results of the analysis have shown that the simulated discharge results are in good agreement with measured data, and the simulated accuracy is over 88%, showing that the triangular unit hydrograph provides a powerful tool for runoff rate simulation for ungauged catchments.

The SCS Curve Number model and the Kirpich formula were used to estimate the runoff depth and the time of concentration respectively. These are very important parameters in the estimation of runoff rate using the triangular unit hydrograph. Therefore, the results of the analysis may also validate both the SCS Curve Number method and the Kirpich formula.

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