A rainfall-runoff model for two small ungauged catchment using the water balance of a reservoir for calibration.

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Abstract

In semi-arid regions, small artificial surface reservoirs are important to meet the domestic and agricultural water requirements of smallholder farmers. The research objective of the study was to determine the rainfall-runoff relation of two ungauged rivers using the measured water levels of the downstream reservoir. The study areas are the catchments of the upper Mnyabezi River (22 km^2) and upper Bengu River (8 km^2), which are tributaries of the Thuli River in southern Zimbabwe. The rainfall-runoff relationship is established with the SCS-Method. The catchments were each divided into sub-areas by Thiessen-polygons. For each polygon the amount of discharge was calculated based on the precipitation, land use, land treatment, antecedent moisture conditions and hydrological soil group. The summation of the calculated runoff per polygon formed the inflow variable for the reservoir models. The collected daily water level data from the period March -May 2007 were used to calibrate the rainfall-runoff model. The calibration process of the rainfall-runoff model resulted in an initial abstraction of 7.6 % of the actual retention. It is concluded that the SCS-method is a useful tool to simulate the rainfall-runoff relation of small ungauged catchments.

1. Introduction

Access to irrigation water for smallholder farmers in the Limpopo basin is limited (Love *et al.*, 2006). In the semi-arid regions of Zimbabwe, artificial surface water reservoirs usually meet the domestic and agricultural water requirements of smallholder farmers in dry periods. From this point of view, it is interesting to obtain more insight into the hydrological processes of catchments upstream of these reservoirs. Catchments where no runoff data are available are termed ungauged catchments. For these catchments, the parameters of rainfall-runoff models cannot be obtained by the calibration on direct runoff data and hence need to be obtained by other methods (Blöschl, 2006). This study concentrates on the hydrological processes occurring in the catchments of the upper Mnyabezi River and upper Bengu River, which are two small tributaries of the Thuli River (a tributary of the Limpopo River) in the semi-arid region of southern Zimbabwe. The research objective is to determine the rainfall-runoff relation of two ungauged rivers using the water levels of the downstream reservoir.

2. Study area

The river upstream of the Mnyabezi reservoir dam is about 8 km long and the study area covers approximately 22 km^2. The upper-Bengu River is about 2.5 km long and covers approximately 8 km^2. Figure 1 presents an overview of the location of both catchments. Both rivers are highly ephemeral, which means that they only flow after heavy rain events. The soil of both catchments consists of sandy loam and the underlying layer consists of weathered granite (Matura *et al*., 2007). The soil layer is shallow to moderately deep and is on average 0.5 m thick (Moyo, 2001). The land use is a mixture of agricultural fields, farmsteads and sparsely wooded degraded rangeland where cattle graze.

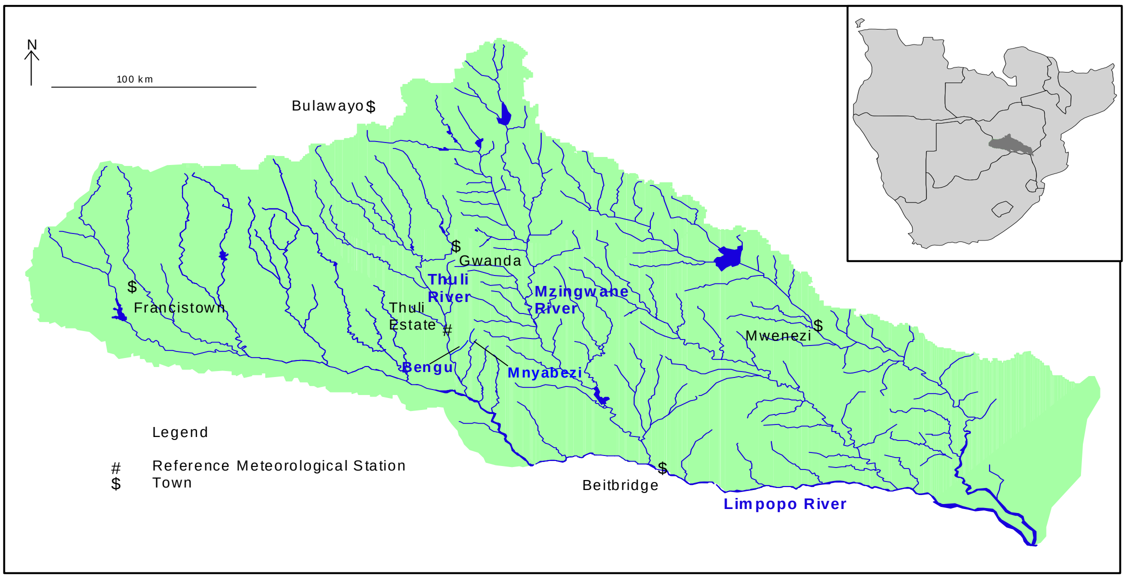

Figure 1: Location of Mnyabezi and Bengu rivers in the northern Limpopo Basin. Inset: location in southern Africa.

The rainfall in southern Zimbabwe is erratic and ranges between 150 and 630 mm·$year^{-1}$. The average rainfall is 385 mm·$year^{-1}$. The open water evaporation in southern Zimbabwe ranges from 96 mm·$month^{-1}$ in June to 240 mm·$month^{-1}$ in January. These values are based on data for 1987 – 2000 of the meteorological station at the Thuli Estate (Department of Meteorological Services Zimbabwe, 1981), which is approximately 20 km from the both catchments.

3. Methods

Earlier studies, which aimed to simulate the rainfall-runoff response of small catchments in semi-arid regions of southern Africa, used semi-distributed models such as Monash and Pitman (Hughes, 1995; Anderson, 1997). These models require many parameters, representing specific catchment characteristics. Due to the relative short period of data collection, this study used lumped parameters to simplify the hydrological processes. For small catchments, the most simple rainfall-runoff models are the Rational Method (Lloyd-Davies, 1906) and the SCS-method (USDA-SCS, 1986). The Rational Method is often applied in urban areas, and the SCS-method in sub-urban and rural areas (Dingman, 2002). For this reason, the SCS method has been applied to simulate the rainfall-runoff processes in the Mnyabezi and Bengu catchments. The method relates the discharge (*Q*) to total rainfall (*P*) and storage capacity via an empirical relation, presented in equations 1 and 2. The initial abstraction (I_a) is a lumped term for the interception of rainfall, depression storage and infiltration before the start of runoff. After runoff starts, all additional rainfall becomes either runoff or actual retention (*S*). The actual retention (*S*) is based on the CN-value, which is dependent on four characteristics: land use, land treatment, antecedent moisture conditions and hydrological soil group. The relations between these parameters are provided in tables.

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \qquad (1)$$

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

Where ,
Q [mm·day^{-1}] is the runoff,
I_a is the initial abstraction,
S [mm·day^{-1}] is the actual retention,
P [mm·day^{-1}] is the precipitation and
CN [-] is the curve number.

Table 1 provides an overview of the methods, locations and frequencies for all the measured parameters and variables in the Mnyabezi and Bengu catchments.

Table 1: Measuring strategy parameters and variables rainfall-runoff model

Parameter	Measuring Method	Location	Frequency
Precipitation rate [mm·day^{-1}]	7 standard rain gauges	Distributed over the catchments	Daily at 8 a.m.; in the period March – May 2007
Water level reservoir [mm]	Gauging plate	In both reservoirs	Daily at 9 a.m.; in the period March – May 2007
Area catchment [ha]	Topographical map	-	Once
Hydrological soil group	Sieving test	3 ground samples of soil	Once
Land use catchment area [ha]	Survey with GPS	Mnyabezi and Bengu catchment	Once
Land treatment	Observation field	Mnyabezi and Bengu catchment	Once
Hydrological condition	Observation field	Mnyabezi and Bengu catchment	Once
Initial abstraction [%]	Calibration	-	-

Since the Mnyabezi and Bengu rivers are ungauged, it is necessary to calibrate the rainfall-runoff model by using the water level of the reservoirs. By knowing the increase in water level after a rain event and the dimensions of the reservoirs, the amount of river inflow can be calculated. The initial abstraction was used as the fitting parameter for the calibration of the model, because this parameter is difficult to determine. In arid regions the initial abstraction can change during the year due to surface crust forming (FAO, 1991) and variable transmission losses of the alluvial aquifer (Anderson, 1997). These features make the normally used assumption of I_a = 20 % of the actual retention (S) not valid (USDA-SCS, 1972). Studies in southern Africa have used percentages of 10 % and less (Schulze et al., 1993; Hranova, 2006). To obtain the best fit, the initial abstraction was varied between 5.0 and 15.0 % of actual retention S.

4. Results field measurements

This paragraph presents the results of the field measurements in the Mnyabezi and Bengu catchment. The first sub-paragraph describes the results for the average CN-value and the second sub-paragraph the rainfall and water level outcomes. At last, the dimensions of the reservoir are presented.

4.1 Average CN-value

Thiessen polygons (Thiessen, 1911) have been used to divide the Mnyabezi and Bengu catchments into seven polygons (each rain gauge representing one polygon), see figure 2 and 3. For each polygon, a specific CN-value is calculated based on the land-use, land treatment, hydrological condition and antecedent moisture conditions.

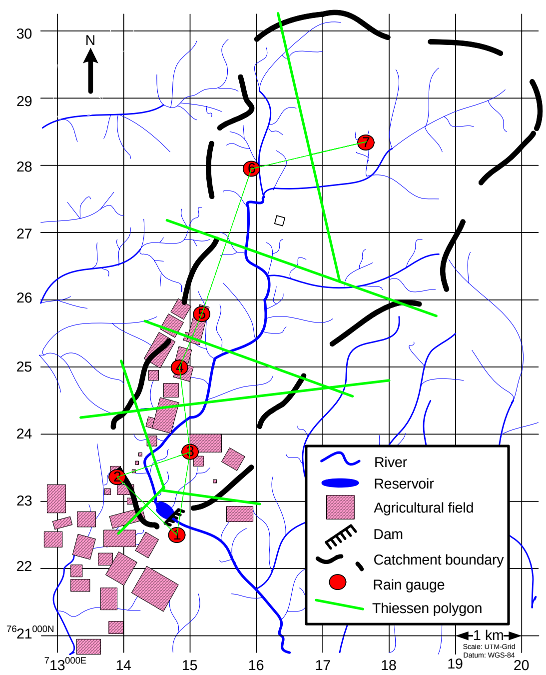

Figure 2: Thiessen polygons for the Mnyabezi catchment

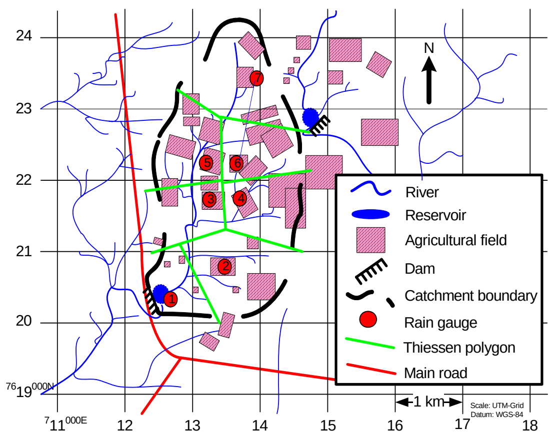

Figure 3: Thiessen polygons for the Bengu catchment

Field surveys have been done to map the land use and land treatment. The rangelands are classified as “pasture lands”. The hydrological condition depends on the intensity of grazing activities and vegetation coverage. In general, there is much activity near the reservoir (poor hydrological condition), which decreases upstream (good hydrological condition). The agricultural fields have been classified as "row crops" in poor hydrological conditions, because the maize is planted in rows far enough apart that most of the soil surface is directly exposed to rainfall. According to Moyo (2001), who has done soil analysis in the Fumukwe catchment (10 km away), soils in the area consist of loamy sand. The results of the sieving tests for soil from the Mnyabezi and Bengu catchments provide similar results. According to Maidment (1992), soils consisting of loamy sand result in hydrological soil group "A". Table 2 and 3 present the calculated average curve numbers per polygon for the Mnyabezi and Bengu catchments under normal antecedent moisture condition. The rainfall-runoff model calculated automatically the antecedent moisture conditions, which also has influence on the CN-value, based on the amount of rainfall in the preceding five days.

Table 2: CN-value of the Thiessen polygons for the Mnyabezi catchment

Polygon	Area [ha]	Rangeland [%]	fields [%]	Farmsteads [%]	Hydro. cond.	CN-value [-]
1	20	90	0	10 (2 farms)	Poor	67.1
2	50	88	2	10 (5 farms)	Poor	67.2
3	220	75	20	5 (5 farms)	Fair	54.1
4	150	80	18	2 (3 farms)	Fair	53.3
5	350	97	3	0	Fair	49.7
6	400	100	0	0	Good	39.0
7	1010	100	0	0	Good	39.0

Table 3: CN-value of the Thiessen polygons for the Bengu catchment

Polygon	Area [ha]	Rangeland [%]	fields [%]	Farmsteads [%]	Hydro. cond.	CN-value [-]
1	50	90	0	10 (5 farms)	Poor	67.1
2	130	76	20	4 (5 farms)	Poor	68.4
3	80	63	31	6 (5 farms)	Poor	68.7
4	100	48	50	2 (2 farms)	Poor	69.8
5	100	36	60	4 (4 farms)	Fair	63.2
6	90	37	60	3 (3 farms)	Fair	63.1
7	150	85	13	2 (3 farms)	Fair	52.2

4.2 Rainfall and water level

During the measuring period, rainfall events occurred on the 26th of February (20 – 40 mm), on the 29th of March (40 – 70 mm) and on the 5th of April (2.5 – 30 mm). The effect on the water level in the reservoirs of the first rain event has not been recorded with gauging plates, because they had not been installed yet. The heavy rain event of the 29th of March was followed by dam overflow at both catchments. The rainfall event on the 5th of April only leaded to water level rise in the Mnyabezi reservoir. Figure 4 presents the water level of the Mnyabezi and Bengu reservoirs, which has been measured with limnigraphs in both reservoirs.

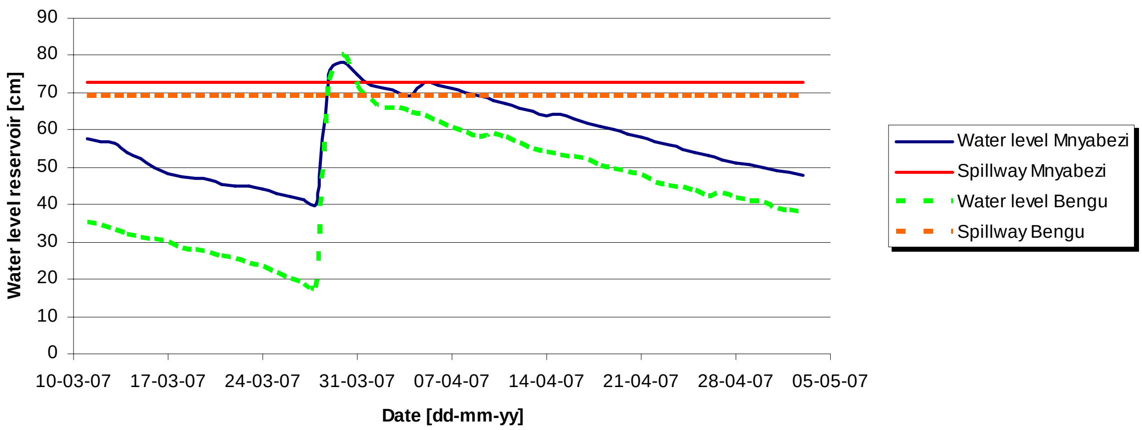

Figure 4: Water level Mnyabezi and Bengu reservoirs

4.3 Dimensions of the reservoirs

The dimensions of the Mnyabezi and Bengu reservoirs have been surveyed by use of a GPS-device and a dumpy level. Points have been marked where the height of the surface area equalled the height of the spillways. This resulted in the maximum dimensions of both reservoirs (see table 3). The reservoirs are simplified by a rectangular surface.

Table 3: Dimensions reservoirs used in the model

Parameter	Normal dimensions Mnyabezi reservoir [m]	Dimensions with a heightened spillway Mnyabezi reservoir [m]	Dimensions reservoir Bengu [m]
B	140	150	200
L	110	400	90
h_{max}	0.73	1.00	0.69

5. Calibration results

The water level records of the Mnyabezi and Bengu reservoirs have been used to calibrate the models. During the measuring period, three rainfall events occurred (see section 4.2). The calibration process has been started with the Bengu rainfall-runoff model. Next, the value found for the initial abstraction [% of actual retention] is used for the Mnyabezi reservoir model. During the calibration process, it has been assumed that both catchments have equal values for the initial abstraction. Since both catchments have the same meteorological conditions, land use and hydrogeological characteristics, this assumption seems to be justifiable. The best fit is obtained for both models, using an initial abstraction of 7.6% of the actual retention.

6. Uncertainties outcomes

It was extremely dry in southern Zimbabwe during the measuring period, which was caused by El Niño effects (FewsNet, 2006). Due to this drought, only three major rain events occurred. Since the rainfall events causing dam overflow could not be used for the calibration, the rainfall-runoff model has only been calibrated on one rainfall event in the Bengu and Mnyabezi catchments. This causes a large uncertainty in the outcomes of the rainfall-runoff model. Nevertheless, the results are in line with similar studies conducted in (semi-)arid regions in southern Africa (Schulze et al., 1993; Hranova, 2006).

Another uncertainty for the rainfall-runoff model lies within the model structure. At this moment, the complex hydrogeological relations are lumped in an equation to calculate the runoff, linking the parameters CN-value, initial abstraction and the variable precipitation. The CN-value and initial abstraction, which are sensitive parameters, have been assumed constant during the whole year. Nevertheless, the CN-value can vary in time due to change in land use or land treatment. The initial abstraction can vary in time due to crust forming on the surface or due to variable transmission losses of the alluvial aquifer. Another uncertainty refers to the dimensions of the reservoir in relation to the water level. At this moment, a simple rectangular shape simulates the dimensions of the reservoir. This can be improved by measuring the exact shape of the reservoir with a dumpy level when the reservoir is dry.

7. Conclusions

The objective of this study is to determine the rainfall-runoff relation of two ungauged catchments in the semi-arid region of southern Zimbabwe using the water levels of the downstream reservoir. It can be concluded that the SCS-method is a useful tool to simulate the rainfall-runoff relation of small ungauged catchments. The complex hydrogeological relations in the catchment are lumped, which provides results not as accurate as an advanced rainfall-runoff model. But for these models large quantities of data are necessary, which are most of the time not available in the rural areas of African countries. The strong point of the method is that a minimum amount of data is necessary to reach realistic results. Improvements to the model can be made by varying the CN-value and initial abstraction depending on the catchment characteristics per season. This will require a long measuring period to calibrate the model properly.

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