Application of the Soil Water Assessment Tool (SWAT) in Simiyu River catchment

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Abstract

The physically based Soil Water Assessment Tool (SWAT) model is applied on the Simiyu river catchment at Ndagalu outfall, Tanzania. Input data are spatially distributed data set such as topographical, land cover and soil data, climatic and river flow time series data. The model was calibrated for the period 1970-1974 based on the availability of coinciding climatic data and validated in the period 1976-1983. The calibration involved fine-tuning the land cover-soil parameters to match the observed discharge at Ndagalu flow gauging station. The weather generator tool of the SWAT was used to fill in the missing climatic data and enabled flow simulation in the periods with missing data. Several model fit techniques and water balance matching techniques were used to assess model performance. Results and analysis was presented to show model performances in calibration and validation periods. During model set-up it was found that the land use (especially vegetation types) classification was a sensitive issue for the river flow estimation. The study identified optimum parameters for better discharge simulations. However, since some model parameters were obtained manually by fine-tuning, in future study the more physical basis of the parameters need to be considered. Also, the analysis of observed and estimated hydrographs showed that the rainfall data used is not representative and more rainfall data is required especially in the headwaters of the catchment so as to have better rainfall representation, which may produce better model fits. Considering the good results of SWAT in this study and comprehensiveness of the model in land surface processes representation, the model is very promising for land and water management studies and expected to give valuable information to land and water resources managers.

Introduction

Background

The SWAT model (Arnold *et al.*, 1998) is a physically based model and requires data such as weather variables, soil properties, topography, vegetation and land management practices occurring in the catchment. The model was developed for continuous simulation, as opposed to single event models. The physical processes associated with water flow, sediment transport, crop growth, nutrient cycling, etc are directly modeled by SWAT using the above mentioned input data. Some of the advantages of the model includes: modeling of ungauged catchments, prediction of relative impacts of scenarios (alternative input data) such as changes in management practices, climate, vegetation on water quality, quantity or other variables. SWAT also has a weather simulation model that generates daily data for rainfall, solar radiation, relative humidity, wind speed and temperature from the average monthly variables of these data. This provides a useful tool to fill in missing daily data in the observed records.

Moreover, the model performs dormancy calculations properly set for simulations in tropical areas. Dormancy is a period in which a plant does not grow, awaiting for the necessary environmental conditions such as temperature, moisture and nutrient availability. The term also refers to condition of relative inactivity as applied to seeds, tubers and perennial plants during the winter. Since vegetation is an important part of water movement in land surface processes, appropriate dormancy calculations are important for estimating consumptive use of water by vegetation, which ultimately contributes to good match of the water balance.

As a semi-distributed model, SWAT is attractive for its computational efficiency as it offers some compromise between the constraints imposed by the other model types such as lumped, conceptual or fully distributed, physically based models (Watson *et al.*, 2003). SWAT incorporates a kinematic storage model for subsurface flow (Sloan *et al.*, 1983; Sloan and Moore, 1984).

Due to spatial variability, budget constrains or access difficulties, model input parameters always contain uncertainties (Lenhart *et al.*, 2002). This is pertinent for the Simiyu catchment where especially access difficulties into the game reserves headwaters and budget constraints - to conduct field studies - are persistent. This study will therefore identify parameters that can lead to a better understanding and to better estimated values of the parameters and thus to a reduced uncertainty. Also, SWAT has not been widely and critically applied in Tanzania for hydrological analysis. Consequently, this study will evaluate the model performance and its processes representation so as to assess its suitability for catchments such as the Simiyu catchment, taking into account limited data availability and access. Previous model applications based on system and conceptual type models in the catchment recommended, among other things, to carry out a study based on physically based distributed model in order to capture the speculated complex river flow phenomenon in the Simiyu River (Mulungu, *et al.*, 2003).

Objectives

The objective of the study is to establish baseline characteristics for the SWAT model development and application in Simiyu catchment. These characteristics will be used to provide information on the hydrological behaviour of the catchment when subjected to

climatic and land management forcing inputs. Moreover, the same tools can be applied to other catchments around Lake Victoria basin.

Research methodology

The Simiyu catchment

The Simiyu River catchment (Fig. 1) covers an area of about 11,000 km^2 to the outfall into the Lake Victoria and is located between 33^o 50' – 35^o 00' E and 2^o 40' – 3^o 30' S. The area of the Simiyu River catchment at Ndagalu gauging station (112012 at 33.568^{o}E 2.639^{o}S) is 5320 km^2. The map also shows the location of other hydro-climatic stations that were used in this study. The Simiyu River drains from the Serengeti National Park plains to the Lake Victoria. On the downstream, Duma River joins Simiyu River and form a main tributary. The Duma River is a result of the confluence of Ngasamo and Bariadi rivers on the upstream. In this study, model calibration was performed at the Ndagalu flow gauging station following previous data analysis and models application in the catchment.

The land cover in Simiyu catchment is dominated by grassland, woodland and cultivated land. The main soil types in the catchment are sandy loam, loam and sand clay loam but according to the United States Geological Survey (USGS) data, the soil can be categorized in only one hydrologic soil group (2 or B), which is either shallow loess or sandy loam or loamy. This soil group has moderate infiltration rates if thoroughly wetted and therefore has a moderate rate of water transmission. Based on the geological map of Tanzania (GURT, 1967), the Simiyu is dominated by granite (Syn-orogenic and Migmatite) and sedimentary and metamorphic rocks (Nyanzian). Volcanic rocks (Neogene) cover a small part of Simiyu catchment around the Serengeti plains.

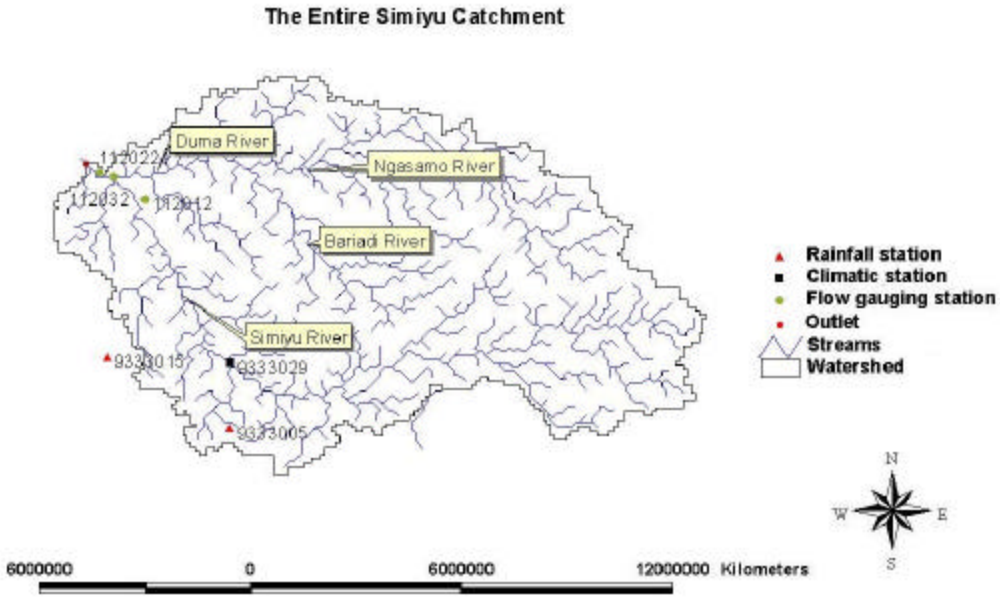


Fig. (1): Map of the Simiyu catchment

The topography of the Simiyu catchment, as analysed from a Digital Elevation Model (DEM), can be categorized as mild with minimum and maximum elevation ranging from 1143 m.a.s.l. on the catchment's most downstream points to 1927 m.a.s.l. on the catchment's headwaters respectively. Table 1 gives the Simiyu catchment topography derived data.

Table (1): Simiyu River tributary catchment physical (geometry) and topographic data

Parameter	*DEM estimate*
Area (sq. km)	5091
Average slope length (m)	121.0
Average slope (m/m)	0.011
Average elevation (m.a.s.l)	1387.79

Available data sets for the study

The spatial datasets included the Africa 1km x 1km data such as Digital Elevation Model (DEM), land cover and soil data from the United States Geological Survey (USGS). Climatological time series data such as daily rainfall, temperature, radiation, wind speed and relative humidity were obtained from the Tanzania Meteorological Agency (TMA) and river flow data from the Ministry of Water and Livestock Development (MWLD). The time series data coverage is summarized in the Table 2. The rainfall stations in the catchment are not uniformly distributed. There are two stations (09333005 at 33.767^{o}E 3.167^{o}S and 09333015 at 33.483^{o}E 3.000^{o}S) located around the downstream end of the catchment and the headwaters do not have a station at all (Fig. 1). Absence of rainfall data in the headwaters is likely to affect the accuracy of runoff simulations. From the climatological time series data (0933329 at 33.767^{o}E 3.017^{o}S), the weather simulation data (monthly averages) was calculated and used in SWAT to generate the missing data for the weather stations.

Table (2): Available data sets for rainfall (09333005), climatic (09333029) variables and River discharge data

Data set	*Data coverage*	*Mean*	*Std. deviation*	*% Missing*
Rainfall (mm/day)	Jan-1928 - Dec-1993	2.26	7.26	8.97
Min.Temp. (^{o}C)	Jan-1970 - Oct-1974	16.42	1.78	0.06
Max. Temp. (^{o}C)	Jan-1970 - Oct-1974	28.57	2.15	0.06
Radiation (Langleys/day)	Jan-1970 - Jul-1984	17.72	3.95	0.02
Wind speed (Km/day)	Jan-1970 - Apr-1984	1.58	0.63	0.02
Relative humidity (-)	Jan-1970 - Jun-1984	0.55	0.12	0.02
Discharge at 112012 (cumecs)	Jan-1970 - Dec-1996	11.82	36.92	0.00
Discharge at 112022 (cumecs)	Jan-1969 - Dec-2000	27.00	45.42	21.89
Discharge at 112032 (cumecs)	Jan-1970 - Sep-1978	13.35	35.53	0.00

Application of the SWAT in Simiyu catchment

Basin delineation

The Simiyu catchment at Ndagalu was delineated from a DEM and formed the base of all spatial data and SWAT model set-up. This location was strategically selected in order to use the observed river flows for comparison with the SWAT simulated flow during calibration. The land use and soil data were then clipped in the basin using the facility provided within the SWAT software (AVSWAT2000) (Di Luzio, *et al.*, 2002) operated under the ArcView 3.2 GIS platform.

Soil spatial data selection and analysis

The soil hydraulic properties are important for determination of the amount of water available for runoff and to the plants in the soil profile. The soil spatial data was related to the soil hydraulic properties that were taken from the United States Department of Agriculture (USDA) database. This was considered sufficient, as in the Simiyu catchment there is no detailed data for the subsurface layers. However, this is likely to bring some inaccuracy in the simulations and fine-tuning the parameters may not reflect the actual ground conditions. The key soil water parameters such as field capacity (q_{fc}), permanent wilting point (q_{wp}) and available soil water (S_{aw}), as presented in Table 3, were used to obtain soil type and properties data for the Simiyu catchment from the USDA database.

Table (3): Some typical available soil water for various textural classes of soils

Soil	q_{fc} *(vol.%)[pF=2]*	q_{wp} *(vol.%)[pF=4.2]*	S_{aw} *(vol.%)*	S_{aw} *(mm/m)*
Sandy	10-20	4-10	6-10	60-100
Sandy loam	15-27	6-12	9-15	90-150
Loam	25-36	11-17	14-20	140-200
Clay loam	31-41	15-20	16-22	160-220
Silty clay	35-46	17-23	18-23	180-230
Clay	39-49	19-24	20-25	200-250

(Source: Agricultural Compendium 1981: 75 Table 2.3/7)

Land use spatial data classification and analysis

With the Simiyu catchment divided into a single catchment that falls out at Ndagalu, the land use and soil distributed dataset were imported and overlaid. Since a dominant Hydrologic Response Units (HRU) distribution was used, only a single HRU was created to represent (comprise) a Grassland (RNGE) land use - Loamy soil combination for the Simiyu catchment at Ndagalu from the different land use classes shown in Table 4 and Fig. 2. This single lumped land area combination does not make the model to explicitly reflect differences in evapotranspiration and other hydrologic conditions for different land covers and soils. In the future studies, distributed combinations will be formed to provide a much better physical description of the water balance. Details of the model set-up and operation in Simiyu catchment can be found in the customized user manual / guideline (Bauwens and Mulungu, 2004).

Table (4): Simiyu Land use classes matched with the SWAT land use classes

USGS Land use Class	*SWAT Land use Class*	*% Total catchment area*	*Dominancy Rank*
Grassland	RNGE	82.89	1
Shrubland	RNGB	15.34	2
Deciduous Broadleaf Forest	FRSD	0.94	3
Dryland Cropland & Pasture	PAST	0.45	4
Cropland / Grassland Mosaic	AGRR	0.37	5

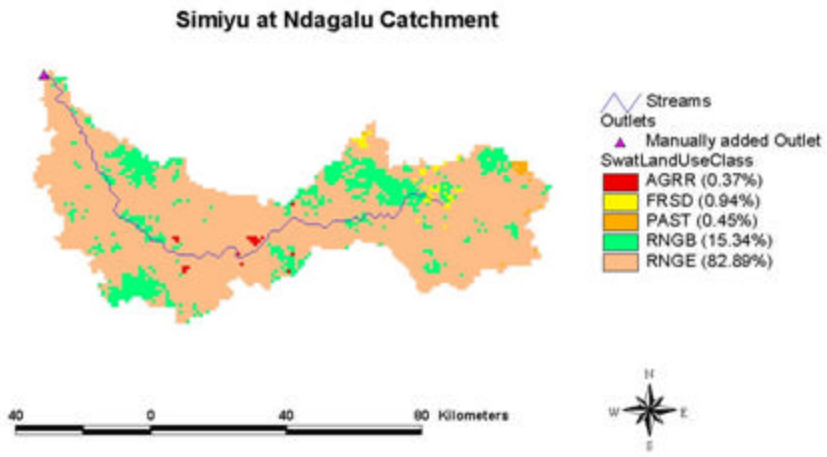


Fig. (2): Re-classed Land use data for the SWAT simulations

Model calibration, results and discussions

Optimum SWAT model parameters

The SWAT model was run on daily time step using the curve number method to simulate surface runoff and hence indirectly model the infiltration process. The water available for infiltration and subsequent percolation is obtained as the difference between the rainfall and surface runoff. The Muskingum scheme was used for river flow routing to the catchment outlet at Ndagalu. It is imperative to note that in the model set-up, attention should be on the classification of land use and soil type to match the SWAT's classification and type respectively. During model set-up, it was found that the land use classification (especially the vegetation types) was sensitive to the assigned SWAT land use classes for the river flow estimation.

The model was calibrated for the period 1970-1974 based on the availability of coinciding climatic data and validated in another period. Rainfall from the station 09333005 was used in the model simulations. The weather generator tool of the SWAT was used to fill in the missing climatic data and enabled flow simulation in the periods with missing data. The calibration involved fine-tuning the land cover-soil parameters to match the observed discharge at Ndagalu flow gauging station. One parameter was chosen at a time and tuned, then simulate the discharge. Several model fit techniques and water balance matching techniques were used to assess model performance. This was achieved by comparing of observed and estimated annual average water variables for total water yield, surface runoff and base flow. Also, plots of observed and estimated daily flow hydrographs were compared. When the best fit on annual and daily basis is obtained, the model parameters set were considered optimum and used to estimate the river discharge. Further check was carried out on the simulated potential evaporation if it is within the expected range in a semi arid region.

In modeling the ground water flow, the following considerations were made. Among the areas of the Lake Victoria basin, it seems that a large part of the Simiyu catchment has low ground water potential (World Bank and Danida, 1995). Also, the analysis of the flow duration curve at Ndagalu flow gauging station suggested that groundwater storage is not much released on the river discharge at Ndagalu station (Mulungu, *et al.*, 2003), implying

deep aquifer water storage. Consequently to account for the water movement (by evaporation and deep-rooted plants) from the saturated zone to the unsaturated zone through the capillary fringe, a low value of the GW_REVAP was used in the simulations. A value of 0 for the parameter restricts the movement from the shallow aquifer to the root zone while a value of 1 implies the movement nearly equals the potential evapotranspiration rate. Another parameter is REVAPMN, a value of zero (0) showed more or less good fit for the low flows. That is the movement of water from the shallow aquifer to the unsaturated zone or to the deep aquifer is allowed at any time. The following parameters were found to be very sensitive to the discharge simulations and Table 5 presents optimum parameters values for the model set-up. Other parameters were left at default values.

Table (5a): Optimum SWAT model parameters for Simiyu catchment

Parameter	*Description*	*Range*	*Database (input) file*	*Optimum value*
EPCO	Plant uptake compensation factor	0.00 – 1.00	.hru or .bsn	EPCO=0.000
ESCO	Soil evaporation compensation factor	0.00 – 1.00	.hru or .bsn	ESCO=0.000
CH_K1	Effective hydraulic conductivity in tributary channel alluvium (mm/h)	0.00 – 150.00	.sub	CH_K1=0.500
CH_K2	Effective hydraulic conductivity in main channel alluvium (mm/h)	-0.01 – 150.00	.rte	CH_K2=0.300
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0.00 – 5000.00	.gw	GWQMN=0.000
GW_REVAP	Groundwater “revap” coefficient (-)	0.02 – 0.20	.gw	GW_REVAP=0.1450
REVAPMN	Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur (mm)		.gw	REVAPMN=0.000
ALPHA_BF	Baseflow alpha factor	0.00 – 1.00	.gw	ALPHA_BF=0.0480

Table (5b): Optimum SWAT model parameters for Simiyu catchment

Parameter	*Description*	*Range*	*Database (input) file*	*Optimum value*
SOL_AWC	Available Water Capacity of the soil layer (-)	0.00 – 1.00	.sol	SOL_AWC=0.240 (for both layers)
SOL_K	Saturated hydraulic conductivity (mm/h)	0.00 – 2000.00	.sol	SOL_K=36.000
CH_N1	Manning’s “n” value for the tributary channels (-)	0.01 – 30.00	.sub	CH_N1=0.014
CH_N2	Manning’s “n” value for the main channel (-)	0.01 – 0.30	.rte	CH_N2=0.014
OV_N	Manning’s “n” value for overland flow (-)	0.01 – 30.00	.hru	OV_N=0.150
CN2	SCS runoff Curve Number for moisture condition II	35.00 – 98.00	.mgt	CN2=69.000
NLAYERS	Number of layers in the soil	1 - 10	.sol	NLAYERS=2
FFCB	Initial soil water storage expressed as a fraction of field capacity water content	0.00 – 1.00	.bsn	FFCB=0.000

Discharge simulation results

For the optimum parameters results above, the following results were obtained as shown in Table 6 and Figs. 3 - 6.

Table (6): Average annual water balance 1970-1974

Water variable	*Observed (mm)*	*Estimated (mm)*
Total Water Yield (WYLD)	63.45	67.89
Surface Runoff (SURQ)	37.24	39.03
Base flow (GWQ)	26.21	28.86

The comparison of the observed and estimated average annual water balance in the period 1970-1974 showed a good match. Therefore, for long term simulation the model showed that the water balance matches well.

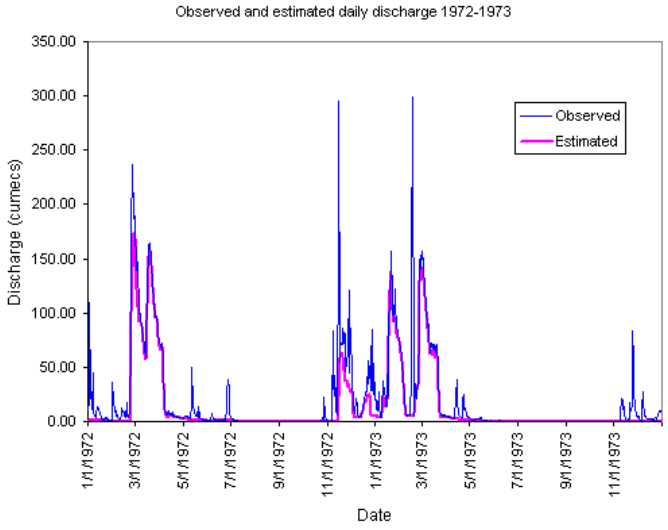


Fig. (3): Observed and estimated daily discharge 1972-1973 at Ndagalu

Peak flows seem to be underestimated because of the assumption of uniform soil texture and land use in the entire catchment, which does not reflect the reality. Also, some peak flows were not captured at all. This may be attributed to local rainfall storms that were not well represented by the rainfall data used in the hydrologic simulations. Another possibility is the decrease of catchment area from the published one to the DEM derived one (Table 1), which may affect the catchment's discharge peaks and timings.

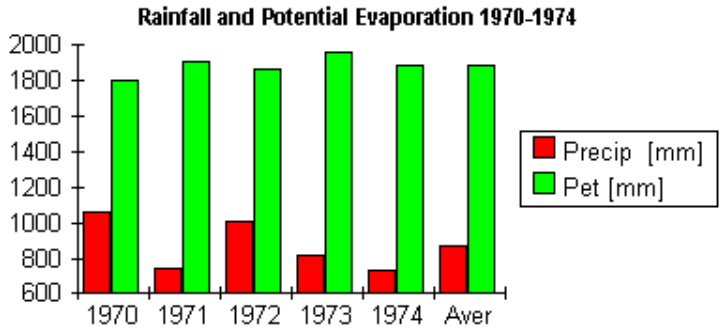


Fig. (4): Annual rainfall and potential evaporation 1970-1974

The plot of the annual rainfall and potential evaporation during the period 1970-1974 shows a more or less constant evaporation. This is an expected pattern as for semi arid areas, where the evaporation rate (atmospheric driven) in Tanzania is about 1800+ mm/y (FAO, 1986) and where it does not vary much throughout the year. The SWAT model therefore simulated the potential evaporation well.

Model validation

The period 1976-1983 was used for the model validation. Because of average poor daily fit during validation, annual data was used to explain the model performance. Figure 5 shows the comparison on an annual basis, where a fair match was observed. Poor matching was observed for the years 1977 and 1983. Part of the deviations might be due to the fact that the weather-generator was used to produce some of the weather data (see Table 2). The flow for year 1983 was high because of large underestimation of evaporation (see Fig. 6).

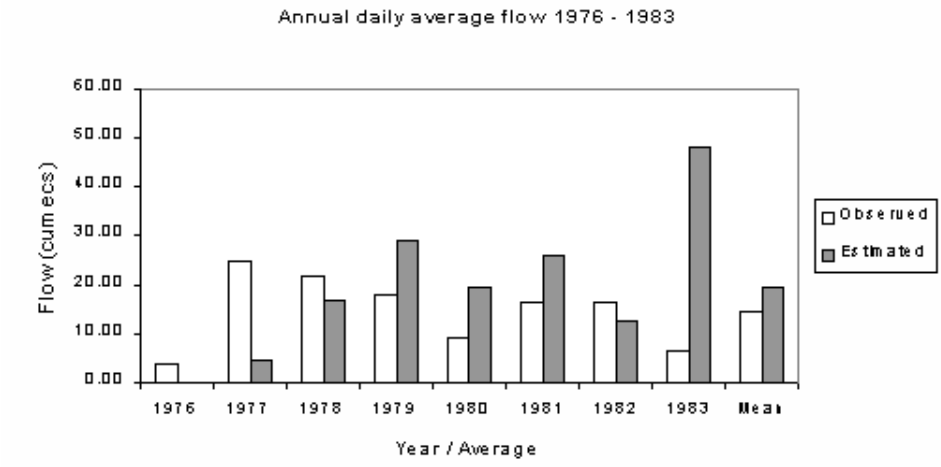


Fig. (5): Observed and estimated annual daily discharge 1976-1983 at Ndagalu

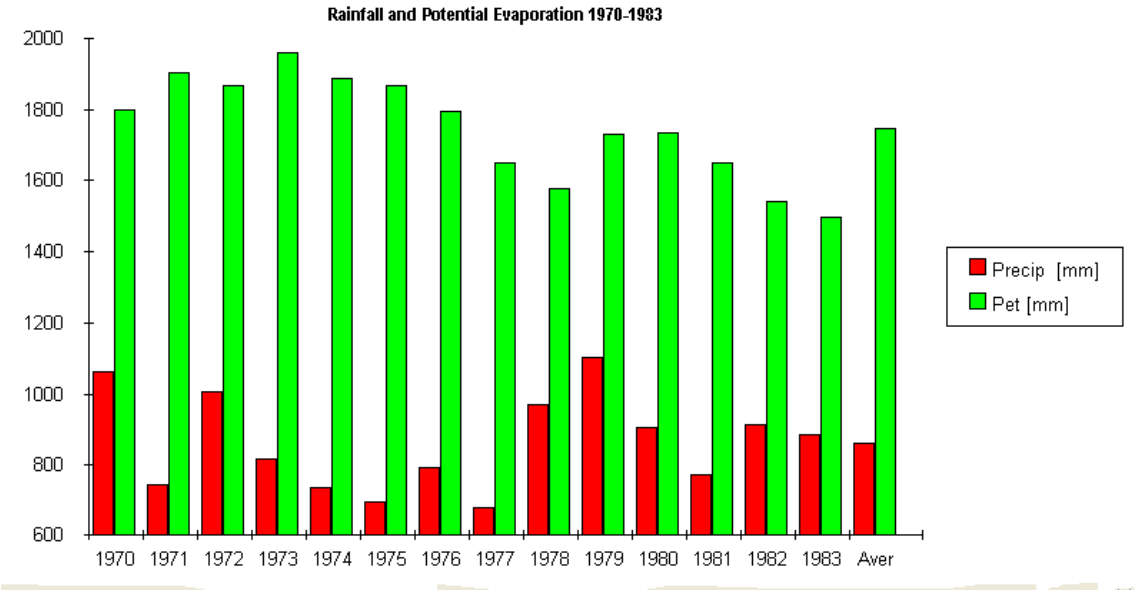


Fig. (6): Annual rainfall and potential evaporation 1970-1983

The annual potential evaporation from 1976 was below the threshold rate and also it can be speculated that the deviation might be due to weather-generated data. For example, the year 1976 is entirely missing rainfall data and the year 1977 followed with the large percentage (16.71%) of missing rainfall data in the period 1976-1983. Although the year 1983 had rainfall and other weather data intact, the missing temperature data could have impact on simulated water fluxes.

Conclusions and Recommendations

For this study, a SWAT model for the Simiyu river basin was set up, using a coarse spatial dataset from the USGS, point rainfall data, a dominant HRU combination and other physical information about the basin. It is imperative to note that in the model set-up, attention should be on the classification of land use and soil type to match the SWAT's classification and type respectively. During model set-up, it was found that the land use classification (especially the vegetation types) was a sensitive issue for the river flow estimation. The model was calibrated by manual fine-tuning of the parameters. The results show a good performance in the hydrologic simulations, especially during the calibration period. This indicates that the physical processes in Simiyu catchment are fairly well represented by SWAT. The model can therefore be evaluated to suit the Simiyu catchment hydrologic simulations taking into account limited data availability and access.

However, in a future study, it is recommended to use subbasin model set-up, more distributed HRU combinations and to avoid the use of the weather simulator for model validation. The study will also benefit much if efforts will be made to get rainfall data from the headwaters areas, although these data might be difficult to get because the area falls within the restricted wildlife parks. Satellite derived rainfall data may therefore be useful. Also, more consideration should be given to the physical basis of the parameters in future research.

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