Application of SWAT Model for Mountainous Catchment

Birhanu, B.Z, Ndomba, P.M and Mtalo, F.W.

University of Dar es Salaam, Water Resources Engineering

Abstract

A GIS based hydrologic model, SWAT (Soil and Water Assessment Tool) was applied for modeling the WeruWeru catchment at the foot slopes of Mt. Kilimanjaro in Northern Tanzania.

The catchment has an approximate drainage area of 101 km^2 and a mean annual precipitation between 1500mm and 3000mm. The water balance modeling was performed on annual and monthly bases using spatial and temporal data.

A statistical weather generator file WXGEN was prepared for ten years to generate climatic data and fill in gaps in the measured records of climatic data. Various GIS data preprocessor modules involving watershed delineation, input map characterization and processing, stream and outlet definition, the computation of the geomorphic parameters, and characterization of the landuse/land cover and soil were developed in the course of modeling. Surface runoff computation was done using Soil Conservation Service-Curve Number (SCS-CN) method; and Muskingum routing method was used for flow routing.

The Rainfall-Runoff modeling was based on a long term global water balance simulation for 15 years (1972-1986) and temporal calibration technique. The Nash and Sutcliff efficiency criterion (R^2) and the Index of Volumetric Fit (IVF) were adopted for the measure of efficiency of the performance of the model. An R^2 of 82% and 59% was obtained during calibration and verification periods respectively.

The predicted mean daily stream flow was found to be 1.92m^3/s exactly as observed during the water balance simulation. Besides, modeling result gave a total annual water yield of 597.1mm, from which the annual surface water component was 155.8mm and that of the base flow component was 441.4mm in the long term simulation period with IVF unity. While demonstrating the catchment is rich in ground water sources as a result of high magnitude of precipitation and good water retention capacity, this study shows that SWAT model can be a potential monitoring tool for watersheds in mountainous catchments.

Introduction

Kilimanjaro mountain catchments are located in Northern Tanzania which drive their water from the slopes of Mt. Kilimanjaro. These catchments are heavily populated and as a result water has become a limiting factor for life and development. Various hydrologic studies have been conducted by using different hydrologic models to simulate the catchments hydrology. For example, the use of a modified conceptual HBV model (Rinde, 1999) by Rohr (2003) to simulate Charongo, Ngomberi and 1DD1 catchments in the southern slopes of Mt. Kilimanjaro, and the use of a semi distributed hydrologic modeling system (HEC-HMS) by Moges (2003) to simulate the 1DD1 catchment are a few worth mentioning. The limitations applying these hydrologic models were also discussed by these studies. In Mt. Kilimanjaro catchments, the interaction

between precipitation, evapotranspiration, surface runoff, infiltration and spring discharge on the mountain slopes and the low- lying plains has been reported as complex by Rohr (2003). These components are all important and considerable factors in the local hydrological cycles (Rohr, 2003). The uncertainty in catchment hydrology can be solved with the use of hydrologic models by customizing to the region of interest. For example, in their study of sediment yield modeling for ungauged catchments in Tanzania, Ndomba *et al.,* 2005, recommended to customize the SWAT model in the local area for improved watershed management.

In recent years, SWAT model developed by Arnold *et al*., (1998) has gained international acceptance as a robust interdisciplinary watershed modelling. SWAT is currently applied world wide and considered as a versatile model that can be used to integrate multiple environmental processes, which support more effective watershed management and the development of better informed policy decision (Gassman *et al*., 2005). But little have been published on the applicability of SWAT model in the tropical catchments particularly in East Africa and Nile basin. In Tanzanian catchments, for example, there are few research studies using SWAT model (Birhanu, 2005; Ndomba *et al.,* 2005) which recommended further testing/customizing SWAT model for different climatic conditions. Thus this study examines the applicability of SWAT model for modeling mountainous catchments, focusing on WeruWeru catchment in the Kilimanjaro region of Northern Tanzania.

Description of the study area

The catchment is located between 37.25˚E - 37.33˚E and 3.08˚S -3.16˚ S with an approximate drainage area of 101 km^2. The minimum and maximum ground elevations in the catchment are 2001 and 4177meters a.m.s.l respectively, and the region receives heavy rains of about 1500mm-3000mm annually. Forest, bush land and scattered cropland are the main landuse/land cover forming (84.91%) of the area, other land covers are open woodland and scattered bushland (13.21%), and snow (1.89%). Sandy loam and loam soils are the dominant soil types in the area, according to the classification by Pauw (1984). The catchment was gauged from 1969 to 1986 and the gauge was re-sited making the rating curve unreliable then after. There are no meteorological stations in the study area, thus stations in the nearby area as shown in figure 1 were used.

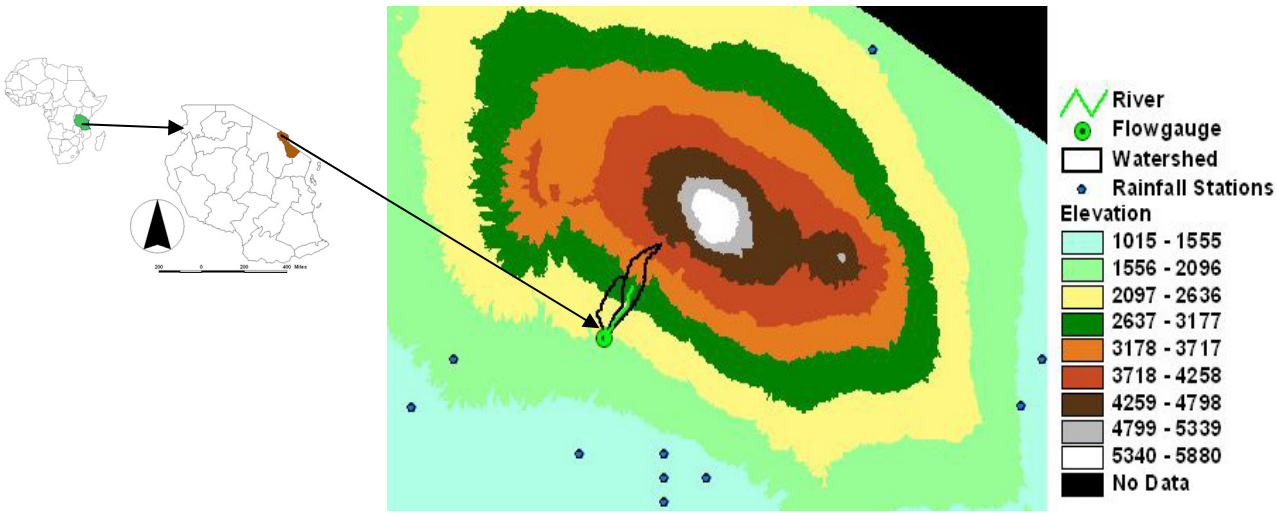


Figure 1: Weru Weru catchment

Methodology

SWAT is a physically based hydrologic model and requires physically based data (Jacobs and Srinivasan, 2005). Obtaining physically based data for hydrological modeling is often difficult, even in developed countries where data of high quality are generally collected and analyzed (Jacobs and Srinivasan, 2005). In this study various input data were collected from different sources: climatic input data were collected from meteorological office for neighboring stations outside the catchment. These include; daily precipitation, maximum/minimum air temperature, wind speed, and relative humidity. Spatial input data used are Digital Elevation Model (DEM), landuse/landcover, and Soil. DEM data was sourced from the US. Geological Survey's (USGS, 2006) public domain geographic data base HYDRO1K, the landuse and soil data were obtained from the Institute of Resource Assessment (IRA) based at the University of Dar es Salaam (UDSM). Further, the data base incorporated into the SWAT model was used for reclassifying the landuse and soil data. The input data were prepared to the required format for an input to the SWAT model. A statistical weather generator file WXGEN (Sharply and Williams, 1990) was prepared for ten years in order to generate climatic data and fill in gaps in the missing records from climatic data obtained from Moshi airport station (0973004).

The hydrological modeling using SWAT was based on the application of the Graphical User Interface (GUI) of AVSWAT2000 (DI Lizio,2002) which after being loaded is embedded into ArcView, and tools are accessed through pull down menus and other controls which are introduced in the various ArcView GUI and custom dialogs. The watershed and sub watershed boundaries, drainage networks, slope, soil series and text maps were generated under the GUI of AVSWAT2000. Various GIS data preprocessor modules which involve watershed delineation, input map characterization and processing, stream and outlet definition, the computation of the geomorphic parameters, and characterization of the landuse/landcover and soil were developed in the course of modeling the catchment. Interactions between surface flow and subsurface flow in SWAT are based on a linked surface-subsurface flow model developed by Arnold *et al.,* (1993).

The simulation option of the rainfall runoff modeling was performed which based on previous experience and modelling techniques published by various researchers (Birhanu, 2005; Ndomba, *et al.,* 2005; Val Leiw *et al.,* 2005; Ndomba, 2007). These include using a curve number method for calculating the surface runoff (SCS, 1972), a first order Markov Chain Skewed Normal to determine rainfall distribution, computing potential evapotranspiration by using Penman Monteith method, and Muskingum routing method for routing water through the channel networks. An automated base flow separation technique based on master recession curves developed by Arnold *et al*., (1995a) was used to separate the observed flow components into surface and base flow. This technique was successfully used by Arnold and Allen (1999) for estimating base flow and annual ground water recharge from stream flow hydrographs.

In this study, calibration and validation procedure presented in the SWAT user manual was followed (Neitsch *et al.,* 2002). Calibration for water balance and stream flow was first done for average annual conditions. Once the run was calibrated for annual conditions, we shifted to the monthly records to fine-tune the calibration. Parameters used for model calibration were the Curve Number (CN2), threshold depth of water in the shallow aquifer for water moving into the soil zones (REVAPMN), threshold depth of water for percolation to occur (GW_REVAP), soil

available water capacity (SOL_AWC), baseflow alpha factor (ALPHA_BF), and number of days of ground water delay (GW_DELAY). Calibration and verification was performed for the selected periods and the objective functions used to test the model performance were the Nash and Sutcliff efficiency criteria (R^2), and the Index of Volumetric Fit (IVF).

Results and Discussions

Data for the first three years (1969-1972) were used as a warm-up period for the model setup, and calibration was done for 15 years (1972 to1986). The calibration results for the surface and ground water components of the total water yield are shown in Table 1 and Figure 1, with an IVF unity (100%). The observed daily average flow for the simulation period is 1.92m3/s, and the simulated result from the model is 1.92m3/s, which shows good agreement of the water balance simulation in the long term bases.

Table 1: Long-term average annual volumes calibration results

	TOTAL WATER YIELD(mm)	BASE FLOW(mm)	SURFACE FLOW(mm)
Observed	597.2	438.4	158.8
Simulated	597.1	441.4	155.8

As shown in Table 1 the model overestimated the base flow and underestimated the surface flow with the same magnitude (0.5% of the total water yield). One would note that the discrepancy did not produce a significant change in the overall simulated water balance (597.1mm), which is an equivalent figure as the total observed water balance (597.2mm).

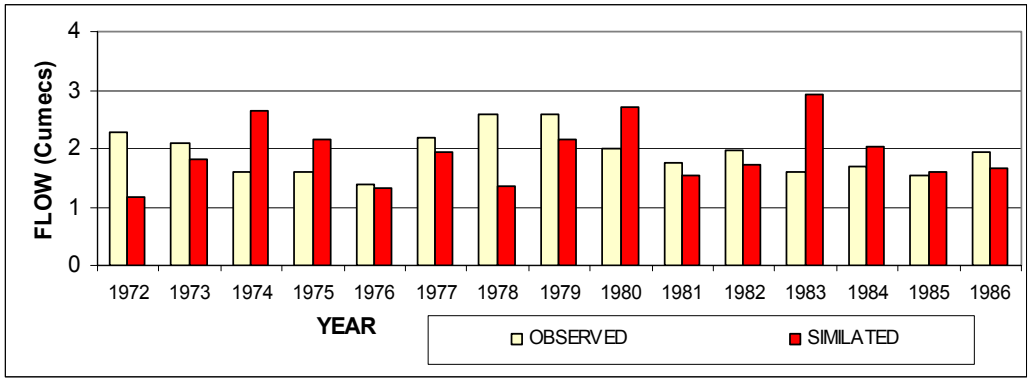


Figure 2: Long term average annual simulation results (Jan 1972-Dec 1986)

The trend followed by the observed and simulated average daily flow for the year is promising as shown in Figure 2 except flow was overestimated during 1974, 1980, and 1983. Close examination of the data reveal that rainfall records during these periods were high particularly in the rainy seasons (April 1974, May 1980 and May 1983). The doubt is that the flow data during these periods were not correctly recorded, as when the gauging station flooded, nobody came out to the station to take measurements. After the water balance was well simulated in the long-term simulation period, a seasonal calibration and verification on a monthly basis was done in the wet years of the data series. The calibration period was from March 1979 to February 1980 as shown in Figure 3, and the Nash and Sutcliff efficiency criteria (R^2) is 82 %. A validation period was between March 1982 and February 1983 with an R^2 59 %, which implied that the

predicted monthly flow data was in close agreement with the observed flow values in the validation period.

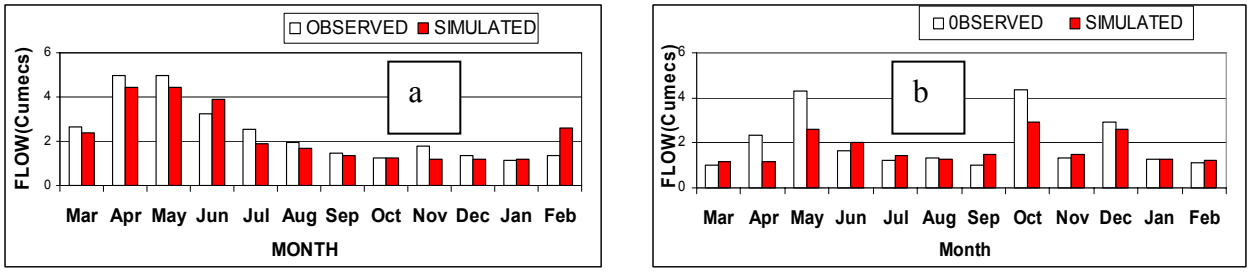


Figure 3: (a) Temporal calibration (March 1979 -Feb1980) and (b) Verification (March 1982-Feb 1983)

In addition to surface and base flow components, SWAT derived average annual basin outputs in mm. These are: Actual Evapotranspiration (AE =536), Potential Evapotranspiration (PE=1274), Lateral soil flow (49) and ground water from shallow aquifer (393). Rohr (2003) used Morton's complementary relationship to calculate the AE for Charongo (21 km^2) and Ngomberi (52 km^2) catchments in the southern slopes of Mt. Kilimanjaro and reported an AE of 597 mm and 783 mm respectively. Besides, the magnitude of infiltration (ground water recharge) computed by the water balance was reported as 291 mm and 510 mm respectively for these two catchments (Rohr, 2003). Thus, the authors of this research believe that the outputs from SWAT are reasonably comparable to the other catchment studies in the same geographical area.

Conclusions

The predicted mean daily stream flow was found to be 1.92 m^3/s exactly as observed during the water balance simulation. Besides, modeling result gave a total annual water yield of 597.1 mm, from which the annual surface water component was 155.8 mm and that of the base flow component was 441.4 mm in the long term simulation period with IVF unity. While demonstrating the catchment is rich in ground water sources as a result of high magnitude of precipitation and good water retention capacity, this study shows that SWAT model can be a potential monitoring tool for watersheds in mountainous catchments of the tropical regions.

References

Birhanu, B.Z (2005). Application of SWAT model in simulating the available water resources in Pangani river basin upstream of NYM reservoir. A case study of 1DD1 catchment. M.Sc Thesis, University of Dar es Salaam, Tanzania, 2005.

Arnold, J.G., P. M .Allen, and G. Bernhardt (1993). A comprehensive surface ground water flow model. Journal of Hydrology. 142:47-69.

Arnold, J.G., P. M .Allen, R .S. Muttiah, and G. Bernhardt (1995a). Automated base flow separation and recession analysis techniques. Ground water 33(6): 1010-1018.

Arnold, J.G., and P. M .Allen (1999). Automated methods for estimating base flow and ground water recharge from streamflow records. J. of. Amer. Water Res. Assoc. 35(2):411-424

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams, (1998). Large area hydrologic modelling and assessment part I:Model development. *J. of Amer. Water Res. Assoc.* 34(1): 73:89.

DI Luzio, M, Srinivasan R, and Arnold, J. G (2002) ArcView Interface for SWAT2000 User's Guide. Backland Research and Extension Center, Temple, Texas BRC Report 02-07. Published 2002 by Texas Water Resources Institute, College Station, Texas. TWRI Report TR-193.

Gassman, W.P., M.R. Reyes., C.H. Green and J.G. Arnold (2005). SWAT peer –reviewed literature: A review, Proceedings of the 3rd International SWAT conference, Zurich, 2005.

Jacobs, J.H., and R. Srinivasan (2005). Application of SWAT in developing countries using readily available data. Proceedings of the 3rd International SWAT conference, Zurich, 2005.

Moges, S.A (2003) Development of a decision support system for Pangani river basin. PhD Thesis (University of Dar es Salaam, Tanzania, 2003)

Neitsch, S.L, Arnold, J.G, Kiniry, J.R, Williams, J.R, King, K.W (2002) Soil and Water Assessment Tool, Theoretical Documentation and user's manual, Version 2000.

Ndomba, P.M, F.W. Mtalo and A. Killingtveit (2005). The Suitability of SWAT model in sediment yield modelling for ungauged catchments: A case study of Simiyu river basin catchments, Tanzania. Proceedings of the 3rd International SWAT conference, Zurich, 2005.

Ndomba, P.M (2007).Modelling of Erosion Processes and Reservoir Sedimentation in the Pangani River basin, Upstream of NYM Reservoir. A draft PhD Thesis submitted for examination at the University of Dar es Salaam.

Rinde, T (1999). Landpine: A hydrologic model for describing the influence of landuse on changes in runoff. Trondheim: SINTEF Bygg og miljoteknikk.

Rohr, P.C (2003). A hydrological study concerning the southern slopes of Mt. Kilimanjaro, Tanzania. Dr. Ing.- Thesis 2003:39, Norwegian University of Science and Technology.

Sharpley, A.N. and Williams, eds. (1990) EPIC Erosion Productivity Impact Calculator,1. model documentation. U.S Department of Agriculture, Agricultural Research Service, ARS-8.

Notes: