Problems and Prospects of SWAT Model Applications in NILOTIC Catchments: A Review

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Abstract

This paper highlights some problems and prospects of applying a complex Soil and Water Assessment Tool (SWAT) hydrologic model in catchments of Nilotic countries. SWAT is a semi-distributed physically based model which was originally developed by United States Department of Agriculture – Agricultural Research Service (USDA-ARS) to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large ungauged basins. The selected studies cover a range of applications, modeling techniques/efforts and catchment sizes. The calibration and verification periods ranged between 1 to 20 and 1 to 9 years, respectively. The model performance on a daily basis corresponded to Nash and Sutcliffe Coefficient of Efficiency (CE) of 13.7- 87%, coefficient of determination (R^2) between 26% and 72% and an Index of Volumetric Fit (IVF) of 98-143%. The number of sensitive parameters ranged between 2 and 19 and depended on the complexity of the hydrological features in the catchments and modeling efforts. Among the most sensitive parameters governing runoff generation process, in the studied catchments, were Soil Conservation Service runoff Curve Number (CN2), Soil Available Water Capacity (SOL_AWC) and Soil Evaporation Compensation factor (ESCO). The overall evaluation indicated that the SWAT model satisfactorily simulates river flows in the study catchments with limited data availability and where global spatial data are appropriate. The model is therefore recommended for applications in catchments within the Nile countries with similar data availability situations.

Key words: Hydrology, Modeling, Nilotic Catchments, Review, SWAT

1. INTRODUCTION

SWAT is the acronym for **S**oil and **W**ater **A**ssessment **T**ool; a river basin model developed by Dr. Jeff Arnold for the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) (Arnold et al., 1995). The current version of SWAT (SWAT2005) is a continuation of roughly thirty years of non-point source modeling experience. The model is comprehensive and was developed to assess the impact of land management practices on water, sediment and agricultural chemical yields in large complex basins with varying soil types, land use and management conditions. The inbuilt algorithms of SWAT model are useful tools for generating missing climate data for basins (Sharpley and Williams, 1990). The SWAT model is a physically based semi distributed hydrologic model requiring comprehensive input data which is difficult to obtain even in developed countries where data of high quality are generally collected and analyzed (Jacobs and Srinivasan, 2005). This shades doubt on its application in the catchments of Nilotic countries that have varying Physiographic and climatic characteristics with limited data availability.

Currently the model is being applied worldwide with reported success. Gassman *et al*. (2005) indicated that the use of SWAT model in USA, to support Total Maximum Daily Load (TMDL) analysis, as well as, in studies of climate change, hydrologic processes, land use change and water use and water quality applications, increased. They also indicated SWAT applications in Canada, Australia, India and in the European catchments for various purposes (Fohrer and Arnold, 2005; Mapfumo et al.,2005; Watson, et al.,2005; Gosian et al.,2005; Schmidt and Volk, 2005).

Recently, SWAT model has been applied in catchments of Nilotic countries including Tanzania, Kenya, Ethiopia, Rwanda, Uganda and Burundi for various applications. The main objective of this paper is therefore to provide the range of problems and prospects of the SWAT model applications in these countries. In order to achieve this, the paper analyses the model application techniques, Input data type and resolution requirements, purpose of applications, catchment characteristics, conclusions drawn and associated recommendations made in the past studies in order to provide the way for future SWAT model applications in catchments of Nilotic Countries .

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2. SWAT MODEL APPLICATIONS

A summary of SWAT model applications in selected catchments in Nilotic countries is presented in Table 1 with information of the country, case studies, catchment hydrological characteristics, purpose of model applications and the authors being indicated. The locations of the study cases are as shown on Figure 1.

Table 1 SWAT model applications

Country	Tanzania (TZ)				Kenya (KY)			Ethiopia (ET)			R, B, U, T*
Name of the Basin	Simiyu	Simiyu Ndagalu	1DD1	Weru Weru	Nyando	Sondu	Upper Tana	Lake Ziway	Hare River	Upper Part of Awash	Kagera River
Catchment Area (Km^2)	11,000 (5320 modeled)	10,659	7,280	101	3587	3050	10,000	7300	167	7240	57,364
Elevation/ Elevation Range (amsl)	1143 - 1927	1135-2021	900 - 5000	2001-4177	1100-3000	Not Given	730 - 4700	1636	1180-3480	Highlands (1800 to 3554) Lowlands (1550 to 1800)	1100-4500
Mean Annual Precipitation (MAP) (mm)	825	1000	Arid/Semi Arid (500-600). Humid (1000 - 2000)	1500-3000	1000-1600	Not Given	Up to 1800	650	890 at lowlands and 1430 at highlands	850 - 1000 on plain area and 1200 mountains	Upto 1800
Spatial Features	Arid	Arid	Semi-arid to Humid	Humid	Flood Prone	Mountainous	High Physiographic Variation	Semi Arid/Sub Humid	Steep Mountains and abrupt faults	Humid to Subhumid (highlands) and Semi arid to arid (lowlands	Diverse in Topography, Climate and Landform
Purposes of Application	Land and Water Management	Sediment Yield Study	Hydrology, Soil erosion and sediment yield	Water Resources Assessment	Landuse, Climate and Reservoir Storage Change	Landuse Change	Catchment Management	Climate change and Water Availability	Landuse/Land cover change	Hydrology and Soil Erosion	Water resources Management
Authors and year of publication	Mulungu and Munishi, (2007)	Ndomba et al.,(2005)	Ndomba et al.,(2007, 2008)	Birhanu et al.,(2007)	Sang (2005)	Jayakrishnan et al., (2005)	Jacobs and Srinivasan (2005)	Zeray et a., (2007)	Tadele and Forch (2007)	Chekole et al., (2007)	Didier (2007)

* R, B, U, T *refers to Rwanda, Burundi, Uganda, and Tanzania*

2.1 Descriptions of Selected Model Applications

The Simiyu Basin

The Simiyu river catchment in the Lake Victoria basin is an important source of agriculture, fishing and livestock production (Figure 1). Besides, there is an increased population pressure and the land and water resources in the area are under pressure (Mulungu and Munishi, 2007). The use of comprehensive hydrological model (SWAT) aimed at aiding management of land and water in the catchment.

Figure 1 Location of SWAT model applications in Nilotic Countries

The catchment is an arid catchment with altitude ranging between 1143 m and 1927 m, mean annual rainfall of 825 mm (Mulungu and Mkhandi, 2005) dominated by grassland, woodland and cultivated land. The catchment of the ephemeral River Simiyu is dominated by sandy loam, loam and sandy clay loam soils (Mulungu and Munishi, 2007). High resolution data such as landuse from 30 m LandSat TM Satellite, 90 x 90m Digital Elevation Model (DEM) and Soil data of Soil and Terrain Database for Southern Africa (SOTERSAF) were used to model Simiyu basin. Using high resolution data sets Mulungu and Munishi (2007) compared model efficiencies with previous studies in the same region (Mulungu and Mkhandi, 2005) which used the same model (SWAT) but less spatial resolution data. Previously 1 x1 km DEM and one type of soil profile Sandy Clay Loam (SCL-SCL) were used unlike the use of four soil profile classes in their present study: Clay Loam: CL-CL (two layers), Sandy Clay Loam: SCL-SCL (two layers), Fine Sand Loam: FSL-CL-SCL (three layers) and Loamy Sand: LS-S (two layers).

The Simiyu Ndagalu/ 1DD1 Kikuletwa Basin

The suitability of SWAT in modeling sediment yield in the data scarce area was assessed using SWAT model in Simiyu Ndagalu catchment as given in Table1 (Ndomba et al., 2005). The catchment dries up completely between July and October. The longest flow path of 222 km and 0.4% average slope steepness were estimated. The mean annual precipitation is 1000 mm and dominant land covers are pasture, cultivated land, and range land with 86% deep sandy soils (Ndomba et al., 2005). The study of sediment yield modeling was extended to the complex catchment of 1DD1- Kikuletwa subcatchment located in the foot slopes of Mount Kilimanjaro, in the northern-eastern part of Tanzania (Ndomba, et al., 2007). The study intended to predict long-term sedimentation rate and the remaining economic life of the reservoir downstream. In this study SWAT model was adequately calibrated and verified by field based data (Ndomba, 2007; Ndomba et al., 2008).

The Weru Weru Basin

A study on Water resources assessment was conducted on the Weru Weru catchment located along the slopes of Mt. Kilimanjaro. The study area lacks recorded meteorological data (Birhanu et al., 2007) and data in the nearby areas were used for SWAT hydrological modeling. Spatial input data used are Digital Elevation Model (DEM), landuse/landcover, and Soil. DEM data was sourced from the US. Geological Survey's public domain geographic data base HYDRO1K, the landuse and soil data was obtained from the Institute of Resource Assessment (IRA) based at the University of Dar es Salaam (UDSM). Furthermore;, 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 climate data and fill in gaps in the missing records from climate data obtained from Moshi Airport Station (0973004) (Birhanu et al., 2007). In the study data for the first three years (1969-1972) were used as a warm-up period for the model setup, and calibration was executted for 15 years (1972 to1986).

The Nyando/Lake Ziway/Hare River Basin

Application of SWAT model was extended to study the impacts of changes on landuse/climate on reservoir storage on flooding or water availability (Sang, 2005; Zeray et al.,2007, Tadele and Forch, 2007) in the Nyando/Lake Ziway/ Southern Rift Valley Lakes basins in Ethiopia and Kenya. The SWAT modeling study by Zeray et al.,(2007) aimed at quantifying the possible impacts of climate change on water resources availability from year 2001 to 2099 and to suggest possible adaptation measures against this impact. Modeling in Lake Ziway basin in Ethiopia, a base period (1981-2000) was chosen and four periods of 25 years climate change scenarios were developed between the years 2001 and 2099 for maximum temperature, minimum temperature and precipitation based on the Hadley Center Coupled Model, version 3 (HadCM3), and General Circulation Model (GCM). The respective changes of the scenario periods were determined as monthly temperature changes and monthly precipitation changes in percentages from the base years (Zeray et al., 2007). In the study of climate change scenario, the SWAT model was initially calibrated and validated for the base period (1981-2000) and computed the total inflow volume into the lake. The total inflow volumes of the future periods were simulated by applying future changes of temperature and precipitation using A2a and B2a scenarios (Zeray et al., 2007).

In another study, the dynamics of Landuse change in the Hare River basin located in the Southern Rift Valley Lakes Basin of Ethiopia (Tadele and Forch, 2007) was studied using SWAT model. The purpose of the study was to investigate the consequent impacts of landuse change on streamflow. The 1975 and 2004 landuse/land cover maps were used as an input to the SWAT model together with two sets of hydro-climatic data; 1975 landuse data corresponds to 1980 -1991 climatic data and the 2004 landuse data corresponds to 1992-2005 climatic data. Besides, the SWAT model was run using the two sets of landuse maps while setting all the other input variables constant. In the Awash River basin the catchment was delineated into 27 subbasins and further divided into 160 Hydrological Response Units (HRUs) with 2% landuse cover and 5% soil class cover.

The Sondu River Basin

The hydrologic modeling of Sondu River basin located in the Western Kenya draining into Lake Victoria aimed at assessing the environmental impacts of changes in landuse (Jayakrishnan et al., 2005). Digital Elevation Model (DEM) data, with resolution of 1x1 km and only one type of soil data, was available and used for the entire basin. Among the three World Meteorological Organization (WMO) weather stations (Kisumu, Kericho, and Kisii) in and around the basin, Jayakrishnan et al., (2005) used the station at Kericho that have data on precipitation, maximum and minimum temperatures for 21 years (1978-1997). The missing precipitation and temperature data at Kericho were filled using data from Kisumu and Kisii weather stations. Streamflow records for 18 years were available (1979-1996) with a high percentage of missing data. Days of missing records were neglected for computing mean monthly streamflow values. No sediment flow data was available to calibrate the sediment load simulation at the basin outlet. SWAT was calibrated on monthly basis for 10 years of data (1979 to 1988) using the current technology adoption scenario curve numbers. The calibrated model was validated for 9 years of data (1989 to 1997). Two model parameters, i.e. Soil Available Water holding capacity (SOL_AWC) and Soil Evaporation Compensation factor (ESCO) were used for model calibration.

The Awash River Basin

Assessment of the spatial distribution of water resources and evaluation of the impacts of different land management practices on hydrologic response and soil erosion in the upper part of the Awash River basin in Ethiopia (Chekol et al., 2007) was done using SWAT model. In the catchment farming activities are changing very rapidly due to population pressure (Chekol et al., 2007) and nine scenarios were developed to understand the effects of these changes on water quantity and sedimentation.

The Upper Tana River

The Masinga reservoir supplies water and provides 65% of Kenya's hydropower and is affected significantly by siltation and impaired by water quality due to unregulated deforestation to allow for agricultural expansion in marginal soils. The application of SWAT model in the Upper Tana River Basin of Kenya enabled the characterization of afforestation scenarios to reduce siltation and improve water quality to Masinga reservoir (Jacobs and Srinivasan, 2004). The various afforestation scenarios of the upper 1850-2000 m were evaluated and the implementation of complete afforrestation down to 1850 m resulted in a 7% decrease of sediment loading (Jacobs and Srinivasan, 2004). The data sets used during the modeling process include 100 m square grid Digital Elevation Model (DEM), gridded landuse and soil from the Kenyan 1:1 000,000 Soil and Terrain (KENSOTER) map. The data set spatial resolutions are course. Jacobs and Srinivasan (2004) represented the 9,752.82 km2 catchment area into 60 sub-basins for model simulations. However, among the modeling challenges was the lack of reliable observed streamflow and sediment data. In the simulation of the Upper Tana River basin, 18 years (1978-1995) were used to set up the SWAT model with the first 3 years used to warm up the model.

The Kagera Basin

In another application SWAT model was used to model Kagera River basin which is a sub-catchment of the Nile River basin distributed in four countries: Burundi, Rwanda, Tanzania and Uganda that are located in east-central Africa. The basin carries 34% of the annual inflow to the Lake Victoria and 75% of the land area of Rwanda and 52% of the land area of Burundi that lie in the basin. The basin is an important source for hydropower especially at Rusumo waterfall and around 14 million people, most of them being farmers, live within the catchment. This necessitates the development of a suitable hydrologic model to manage water resources in the area (Haguma, 2007). After three years (1971-1973) of warming up, six years monthly calibration (1974 - 1979) and five years (1980 - 1984) monthly validation was conducted at two gauging stations, Rusomo on Kagera River and Kigali on Nyabarongo River, of the Kagera river basin. It should be noted that, in this study case, globally available data was extensively used.

3. RESULTS AND DISCUSSIONS

3.1 Results

Table 2 provides the full range of the performances and suitable parameters developed in the course of SWAT modeling. Besides, Table 2 stipulates various simulation techniques used. Model calibration and validation periods vary based on data availability and purpose of application.

The Sondu River Basin

The Sondu River basin, calibration results indicated that the Nash and Sutcliffe Coefficient of Efficiency (CE) both in calibration and validation periods were poor. CE obtained were -69%, -72%, -69% (during calibration) and -8%, 10%, and -8% (during verification) for Traditional, Current adoption and Future adoption, respectively. The authors, Jayakrishnan, et al., (2005), attributed the poor performance of the model to inadequate rainfall and other model input data. In particular, limited digital data on landuse, soil and elevation were a challenge in the course of modeling. Simulations of traditional technology and future adoption scenarios involved differences of up to 19% in the mean monthly streamflow compared to the observed data, resulting in poor simulation efficiencies (Jayakrishnan, et al., 2005). Although, the CE of model calibration and validation were poor (Table 2), the hydrologic study in Sondu River basin showed that comparable water balance simulation was obtained. Better elevation data and subbasin delineation and more detailed soil and weather data combined with detailed parameter calibration efforts were recommended to improve the results. In conclusion, Jayakrishnan et al.,(2005) indicated that SWAT model, developed and widely applied in United States, can possibly be applied in the African catchments but with a higher input data collection effort for the model setup (Jayakrishnan. et al., 2005).

The Hare River Basin/Awash River Basin

The study in Hare River basin concluded, that the SWAT model satisfactorily predicted monthly and annual flows and the model is useful to analyze the impacts of landuse/land cover changes on streamflow even in basins with limited data (Tadele and Forch, 2007).The results of Upper part of Awash River basin case study concluded that the SWAT model accurately tracked the measured flows and simulated well the monthly sediment yield.

The Upper Tana River

The case-study of Upper Tana River basin demonstrated a successful application of SWAT with limited readily available data (Jacobs and Srinivasan, 2004). In the Nyando basin the performance of ten years (1971-1980) calibration of mean annual flow produced a coefficient of determination (R2) between 26% and 72%. And three years (1976-1978) daily flow calibration model performance (R2) was between 45% and 72%. The CE was between 48% and 75%. Lower R2 results were attributed to the lack of representative rainfall recording stations (Sang, 2005). Three (3) years (1986 to 1988) model validation produced an R2 between 6% and 77% and CE between 61% and 69% at four gauging stations (1GB05, 1GB03, 1GD07, and 1GD03).

Table 2 SWAT model application results

Name of the Basin	Type of data used	Mode of Calibration	Period of Calibration/ Simulation	Period of Validation	Performance Efficiency Adopted	Model Performance	Sensitive Parameters
Simiyu (TZ)	High resolution	Daily	5 (1976 - 1980)	3 (1981- 1983)	IVF ,CE	Calibration IVF=143%,CE=13.73%, Verification IVF=106% & CE=40.54%.	CN2, ALPHA_BF, SURLAG, ESCO, SOL_AWC, CH_K2, SOL_Z
Simiyu Ndagalu (TZ)	Coarse Resolution	Annual, Seasonal	1 (Seasonal), 20 (Annual)	Not Provided	IVF,CE	IVF=98% and CE(Calibration=58%)	CN2, SOL_AWC,CH_K2, REVAPMN, GW_REVAP,GW_REVAP, ALPHA_BF,SOL_AWC
1DD1 (TZ)	High/Coarse Resolution	Daily, Monthly	1977 - 1982	3 (1970 to 1972)	IVF, CE	Daily Calib (IVF=100%, CE=54.6%). Monthly Calib.(IVF=100%,CE=68%) Daily Verif (CE=68%)	CN2, SURLAG, GWQMN, RCHRG_DP, SLOPE, SOL_Z
WeruWeru (TZ)	Coarse Resolution	Annual, Monthly	15 (Annual) 1(Seasonal)	Seasonal (March 1982 to Feb 1983)	IVF, CE	IVF=100%, Calibration 82%, Verification 59%	CN2,REVAPMN,GW_REVAP, SOL_AWC, ALPHA_BF, GW_DELAY
Nyando (KY)	Good Resolution	Annual, Daily	10 (Annual) 3 (Daily)	3years (1986 to 1988)	R^2, CE	Annual R^2 26% to 72%. Daily R2 45% to 72%. CE 48% to 75%. And in verification R^2 from 6% to 77%, CE from 61% to 69%	SOL_AWC, CN2, ESCO, GWQMN,GW_REVAP,REVAPMN
Sondu (KY)	Course Resolution	Monthly	10 (1979-1988)	9 (1989-1997)	CE	Calib (-69% to -72%, Verif.(8% to 10%)	SOL_AWC, ESCO
Upper Tana (KY)	Course Resolution	Monthly	18 (1978-1995)	Not used	Not Reported	Not Reported	Not Reported
Lake Ziway (ET)	Good Resolution	Monthly	15 (1981 to 1995	5 (1996 to 2000)	R^2	Calib and Valid. 20% to 70%	CN2, GWQMN, ESCO, SLOPE, RCHRG_DP,GW_REVAP, GW_DELAY
Hare River (ET)	Good Resolution	Annual, Monthly	6 (1980 to 1985)	6 (1986 to 1991)	R^2,CE, RMSE	R^2 (72% to 92%); Annual CE (41% to 92%); Monthly CE(43% to 82%)	CN2, SOL_AWC,SOL_Z, SOL_K, ESCO, SLOPE, GW_REVAP, REVAPMN, ALPHA_BF
Awash River (ET)	Good Resolution	Daily, Weekly Monthly	4(1989 to 1992)	6 (1993 to 1998)	CE, R^2 Percent Difference (D)	Calibration 78% to 87% (daily CE), -3.22% to -3.3% (weekly D),78% to 87%(monthly R^2), Verification	CN2, SOL_AWC, SLOPE, SOL_K, ESCO, SOL_Z, CANMX
Kagera River (R,B,U,T)	Coarse Resolution	Monthly	6 (1974 to 1979)	5	CE	Using local data (63% Calib and -136% Verif. Using global data, (41% to 43% calib) and -1.19% to -21,03% verif)	Not Reported

The Kagera Basin

In Kagera River basin at Rusomo gauging station, using rain gauge data the CE was 63% and -136% during the calibration and validation processes, respectively. The CE varied between 41% and 43% and between -1.19% and -21.03% during the calibration and validation processes, respectively. The globally available data was used. The low performance during validation was attributed to a possible change in the flow regime. And the calibration and validation of SWAT at Kigali flow gauging station is poor and attributed to variability in topography, climate and geomorphology of the area (Didier, 2007). Modeling performance were poor and Didier (2007) attributed the poor performance of SWAT model to the coarse nature of the free accessible global data sets, model resolution, variability in topography and climate and landform of the study area. In most cases climatic global data sets have coarse resolution and have difficulties to represent climatic variability within catchments of small or medium size. Furthermore they cannot represent areas with specific physical processes such as Orographic precipitations (Didier, 2007). However, the observed and simulated hydrographs have the same trend except that the simulated streamflow peaks are higher. The results at the sub watershed indicated that the observed and simulated streamflows have good agreement both during the calibration and validation periods. The model predicted the base flow correctly and gave reasonable results for surface runoff. Didier (2007) recommended that modeling catchments, at sub watershed level, should be executed with high resolution data sets. In another study global data sets, that are available online (topographical data, SRTM; soil data, FAO soil maps; land use, global land use maps; climate data, precipitation, temperature, solar radiation etc.) did not produce promising results and Didier (2007) recommended the use of high resolution data sets.

The Weru Weru Basin

The long term water balance for Weru Weru catchment for 15 years (1972 to 1986) and temporal calibration and validation resulted promising results. It was reported that SWAT can be a useful tool to assess the water resources availability in small mountainous watersheds (Birhanu et al.,2007).

The Simiyu Basin

In the study of Simiyu River, the Sub-catchment Mulungu and Munishi (2007) reported that though the estimated long-term average water balance (1976-1983) showed a close agreement between the observed (74.56mm) and estimated (78.66) the Simiyu River catchment, modeling results showed that peak discharges were underestimated and some peak flows were not captured at all. Besides, the model performance efficiencies are not satisfactory. In the study, five years (1976-1980) calibration and three years (1981-1983) validation were performed at Ndagalu station and the CE and the Index of Volumetric Fit (IVF) results are 13.73%, and 143%, respectively, during calibration period, and 40.54% and 106%, respectively, during the validation period. The poor performance of the model were attributed to uneven rainfall stations distribution and poor representation of local rainfall storms by the rainfall data used in hydrological simulations (Mulungu and Munishi, 2007). In the study, though high resolution data was used, the simulation results were not satisfactory and it was concluded that the SWAT model fit results did not improve by increasing the spatial detail (Mulungu and Munishi, 2007).

The Simiyu Ndagalu

The study on sediment yield modeling in Simiyu Ndagalu river basin indicated that the observed and simulated annual volumes are comparable and better simulation of ground water component than surface runoff. However, some of runoff peaks were not captured properly (Ndomba et al., 2005). The study showed that parameters of water balance, estimated at one sub-catchment, with good data, was used in developing a sediment yield model for the entire basin and reasonable estimates of sediment load was obtained for the ungauged catchment despite the course resolution of spatial data (soil). The results indicated the suitability of the freely available geo-spatial data for the development of complex models like SWAT to use in estimation of hydrological variables in the ungauged catchments. From their results, Ndomba et al. (2005) recommended the application of the model in ungauged catchments (poor data regions).

1DD1 Kikuletwa Basin

Long-term sediment modeling in the 1DD1-Kikuletwa catchment indicated that estimated and observed annual total sediment loads were comparable. However, according to the Total Mass balance controller (TMC) as objective function the simulated loads overestimates the observed by 28.7%. In addition it was also reported that the SWAT model captured 56% of the variance of the observed daily sediment loads during calibration (Ndomba, 2007). The SWAT model application in longer period (i.e. 37 years), predicted well the reservoir sediment accumulation with a relative error of 2.6% and it was shown that such estimation accuracy can be attributed to both sound sediment sampling program design and well calibrated components of SWAT model (Ndomba et al., 2007). The study in 1DD1-Kikuletwa River basin indicated that the predicted and measured long-term sediment yields are comparable and for catchments, where sheet erosion, is dominant. SWAT model is a better substitute of the sediment-rating curve and long-term prediction of sedimentation rate that can be done with reasonable accuracy (Ndomba, 2007; Ndomba et al., 2007).

3.2 Discussions

In the critical review of SWAT model applications, Gassman et al., (2005) reported the results of various researchers that compared the performance of SWAT model with other hydrologic models like Dynamic Watershed Simulation Model (DWSM), Hydrologic Simulation Fortran-Program (HSPF), MIKE-System Hydrologic European (MIKE-SHE). Gassman et al., (2005) cited the work of Borah and Bera (2004) who reported that SWAT and HSPF are suitable for predicting yearly flow volumes, sediment loads, and nutrient losses for monthly predictions except for months having extreme storm events and hydrologic conditions and poor in simulating daily extreme flow events. Similar work showed that DWSM reasonably predict distributed flow hydrographs and concentrations or discharge graphs of sediment, nutrient, and pesticides at small time intervals. In addition, Gassman et al., (2005) reported the finding of El-Nasir et al. (2005) who reported that SWAT and MIKE-SHE simulated the hydrology of Belgium's Jeker River Basin in an acceptable way. However, MIKE-SHE, slightly, predicted the overall variation of river flow better.

It is to be noted that little effort was done in Nilotic countries catchments to compare application results between SWAT model and other hydrologic models such as DWSM, HSPF, and MIKE-SHE which have equal or better modeling efficiencies. These models have hydrology, sediment, and chemical routines applicable to watershed scale catchments. However, previous studies elsewhere by Borah and Bera (2003; 2004) indicated that the results of SWAT are promising for continuous simulations in predominantly agricultural watersheds than DWSM, HSPF.

Lack of available climate data was a challenge in SWAT modeling in the catchments of Nilotic countries (Mulungu and Munishi, 2007; Jacobs and Srinivasan, 2004; Sang, 2005; Birhanu et al., 2007; Ndomba et al., 2005; Ndomba et al., 2008). It implies that the scarcity of climate data was a setback for better hydrologic predictions even if high resolution spatial data was used. Besides, limited availability of spatial data produced unsatisfactory performance of SWAT model in some catchments such as Sondu River basin (Jayakrishnan et al., 2005). Besides Harmel et al. (2000) and Moon et al. (2004) indicated that SWAT hydrologic responses are sensitive to choice of climate inputs. Moreover; several hydrological model specialists demonstrated that the quantity and quality of the input data is often the limiting factor in successful model simulations (Ndomba et al., 2008; Hughes and Beater, 1989; Sorooshian, 1991).

4. CONCLUSIONS AND RECOMMENDATIONS

SWAT model has been applied in various catchments of Nilotic countries with varied Physiographic and climatic conditions. The climatic characteristics, of these catchments, ranged between arid/semi arid to humid. The applications covered small to large basins with areas between 101 km2 and 364 km2. SWAT model applications included climate change, landuse change, water availability, sediment yield and erosion modeling and water resources assessment/management.

Both manual or expert knowledge and automatic optimization tools have been used to calibrate the parameters. Data for calibration was split into two portions with nearly 70% for calibration and 30% for verification. Except in one of the applications, longer period was used for model calibration than validation. Seasonal calibration and validation were performed on daily or monthly basis after long-term annual water balance analysis. The calibration and validation periods ranged between 1 and 20 and 1 and 9 years, respectively. Long term simulations were conducted on annual basis. In these applications Curve Number (CN2), Soil Available Water Capacity (SOL_AWC), Ground water Slope (SLOPE), Soil hydraulic Conductivity (SOL_K), Soil Evaporation Compensation factor (ESCO), Soil depth (SOL_Z) were the most sensitive parameters. Input data of various types/quality such as coarse/high- resolution, measured and global internet spatial and climate data sets were used. The results of one of the studies indicated that the model performance efficiency is higher when coupled with the use of high-resolution data sets. However; the study at Simiyu River catchment indicated that higher resolution of spatial data, in larger catchments, does not necessarily improve the performance of SWAT model application.

It should be noted that the authors are aware that the performance of the SWAT model applications in the case studies can not be objectively compared because the performance is affected by modeling efforts/techniques, input data quality and catchment representation of important hydrological features. Regarding input data quality, an effort is required to be exerted to gather the required representative data, particularly precipitation, as it is a moisture input to most hydrologic models including SWAT. Our modeling experience with SWAT model applications suggests that poor catchment representation of important hydrological features may lead to poor performance of the model. However based on the review, SWAT model seems to perform satisfactorily in catchments of Nilotic countries and thus there exists prospects for its wide applications in the region. Since the basins are characterized by scarce data we propose the use of high resolution data for small basins. In order to improve the input data for SWAT model application and as a follow research we propose that the global climate data be validated using ground climate station data sets.

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6. REFERENCES

1. Arnold, J.G., Williams, J.R., and Maidment, D.R., (1995). *Continuous-time water and sediment-routing model for large basins,* Journal of Hydraulic Engineering Vol. 121(2): pp. 171-183.
2. Birhanu, B, Z., Ndomba, P.M and Mtalo, F.W. (2007). *Application of SWAT for Mountainous Catchment:* FWU Water Resources Publications. Volume No: 06/2007.ISSN No. 1613-1045, pp182-187.
3. Borah, D.K. and M.Bera.(2004). *Watershed scale hydrologic and nonpoint-source pollution models:Review and applications,* Trans. ASAE 47(3): 789-803
4. Borah, D.K. and M.Bera.(2003). *Watershed scale hydrologic and nonpoint-source pollution models:Review of mathematical bases.* Trans. ASAE 46(6): 1553-1566.
5. Bosch, D.D.,J.M.Sheridian, H.L.Batten, J.G. Arnold. (2004). *Evaluation of the SWAT model on a Coastal Plain Agricultural Watershed,* Trans.ASAE 47(5):1493-1506
6. Chekol, D.A., Tischbein, B., Eggers, H. and Vlek, P. (2007). *Application of SWAT for Assessment of Spatial Distribution of Water Resources and Analyzing Impact of Different Land Management Practices on Soil Erosion in Upper Awash River Basin Watershed*, FWU Water Resources Publications. Volume No: 06/2007,ISSN No. 1613-1045. pp 110-117
7. El-Nasir, A., J.G.Arnold., J.Feyen., and J.Berlamont., (2005), *Modeling the Hydrology of a Catchment using a Distributed and a Semi Distributed Model*, Hydrol.Process. 19(3):573-587.
8. Fohrer, N. and Arnold, J.G (2005). *Editors of SWAT 2000 Development and Application:* Jour. Of Hydrological Processes, Special Issue, Volume 19 Issue 3, Pages 563-859.
9. Gassman, P.W., Reyes, M.R., Green, C.H. and Arnold J.G. (2005). *SWAT Peer- Reviewed Literature: A Review,* 3rd International SWAT Conference. Pp 1-18 July 11-15, Zurich
10. Gosain, A.K., Rao,S.and Ray,D.B.(2005). *Vulnearability Assement of Climate Change Impact on Indian Water Resources using SWAT Mode*l, 3rd International SWAT Conference, Pp 231-240. July 11-15, Zurich
11. Haguma D.., (2007). *Development of a hydrologic model of Kagera River basin using remote sensing data,*. M.Sc Thesis, UNESCO-IHE Institute for Water Education, Delft, the Netherlands.
12. Hughes, D.A. and Beater, A.B. (1989).*The application of two single event models to catchments with different physical characteristics*, Hydrol. Sci. J., 34, 63-78
13. Jayakrishnan,R., Srinivasan, R., Santhi,C. and Arnold, J.G. (2005). *Advances in the Application of the SWAT model for water resources management,. Hydrol*. Process. 19, 749-762 (2005). Published online in Wiley InterScience (www.interscience.wiley.com).

14. Jacobs, J.H. and Srinivasan, R. (2005). *Application of SWAT in Developing Countries using Readily Available Data.* (3rd International SWAT Conference, July 11-15, Zurich).
15. Harmel,R.D., C.W. Richardson, and K.W.King. (2000). *Hydrologic Response of a small watershed model to generate precipitation*. Trans. ASAE 43(6):1483-1488.
16. Mapfumo,E., D.S. Chansyk. And W.D. Williams.(2004). *Simulating daily soil water under foothills fescue grazing with the soil and water assessment tool model (Alberta, Canada).* Hydrol. Process. 18:2787-2800.
17. Moon, J., R.Srinivasan, and J.H. Jacobs (2004). *Streamflow estimation using spatially distributed rainfall in the Trinty River Basin*, Texas. Trans. ASAE 47(5):1445-1451
18. Mulungu, D.M.M. and Mkhandi, S.H (2005). *Modeling Land-Water Interactions in Simiyu River Catchment Using the Soil and Water Assessment Tool (SWAT),* unpublished Paper.
19. Mulungu, D.M.M., Munishi, S.E. (2007). *Simiyu River Catchment Parameterization using SWAT model. Journal of Science Direct*. Physics and Chemistry of the Earth 32(2007) 1032-1039.
20. Ndomba, P.M.,Mtalo, F.W. and Killingtveit, A.(2005). *The Suitability of SWAT model in sediment yield modeling for ungauged catchments. A case of Simiyu subcatchment, Tanzania*. In: Proceedings of the 3rd International SWAT conference, 11th-15th July, EAWAG-Zurich, Switzerland, pp. 61 – 69. http://www.brc.tamus.edu/swat
21. Ndomba, P.M., Mtalo, F.W. and Killingtveit, A.(2007). *Sediment Yield Modeling Using SWAT model at Larger and Complex Catchment: Issues and Approaches. A Case of Pangani River catchment, Tanzania.* A paper presented at 4th International SWAT Conference, 4th-6th July, Institute for Water Education (UNESCO-IHE) Delft, The Netherlands. http://www.brc.tamus.edu/swat.
22. Ndomba, P.M. (2007). *Modeling of erosion processes and reservoir sedimentation upstream of Nyumba ya Mungu reservoir in the Pangani River Basin*. PhD. thesis (Water Resources Engineering), University of Dar es Salaam.
23. Ndomba, P.M.,Mtalo, F.W. and Killingtveit, A.(2008). *SWAT model application in a data scarce tropical complex catchment in Tanzania.* J. Phys. Chem. Earth (2008), doi: 10.1016/j.pce.2008.06.013
24. Sharpley, A.N. and Williams,eds.(1990). *EPIC-Erosion Productivity Impact Calculator, model documentation.* U.S. Department of Agriculture,Agricultural Research Service, Tech.Bul.1768
25. Sorooshian, S.(1991). *Parameter Estimation, Model Identification and Model Validation: Conceptual-Type Models. In:D.S.Bowles and P.E. O'Connel (Editors), Recent Advances in the Modeling of Hydrologic System*s, 3030, Kluwer, The Netherlands
26. Sang, J.K., (2005). *Modeling the Impact of Changes in Landue, Climate and Reservoir Storage on Flooding in the Nyando Basin, Kenya.* M.Sc Thesis Jomo Kenyata University of Agriculture and Technology.
27. Schmidt, G and Volk,M(2005). *Effects of Input Data Resolution on SWAT Simulations-A Case study at the EMs River Basin (North Western Germany).* 3rd Internation SWAT Conference, pp 241-250. July 11-15 Zurich.
28. Tadele Kassa and Forch Gerd (2007). *Impact of Landuse/ Land Cover change on streamflow: A case study of Hare watershed, Ethiopia.* FWU Water Resources Publications. Volume No: 06/2007. ISSN No. 1613-1045. pp 80-84
29. Watson, B.M., N. Coops., S.Selvalingam., M.Ghafouri.(2005). *Integration of 3-PG into SWAT to Simulate the Growth of Evergreen Forests.* 3rd International SWAT Conference.July 11-15, Zurich.
30. Zeray, L., Roehrig, J. and Chekol, D.A. (2007). *Climate Change Impact on Lake Ziway Watershed Water Availability, Ethiopia.* FWU Water Resources Publications. Volume No: 06/2007. ISSN No. 1613-1045. pp 18-23

7. LIST OF ABBREVIATIONS {PLEASE ADD THE UNITS OF THE SYMBOLS

ALPHA_BF	Baseflow Alpha factor (days)
CE	Nash and Sutcliffe Coefficient of Efficiency
CH_K2	Channel effective hydraulic conductivity (mm/hr)
CL	Clay Loam
CN2	Conservation Service runoff Curve Number (-)
DEM	Digital Elevation Model
DWSM	Dynamic Watershed Simulation Model
ESCO	Soil Evaporation Compensation factor (-)
ET	Ethiopia
FAO	Food and Agriculture Organization
FSL	Fine Sand Loam
GW_REVAP	Groundwater "revap" coefficient (-)
GWQMN	Threshold water depth in the shallow aquifer for flow (mm)
HSPF	Hydrologic Simulation Fortran-Program
IVF	Index of Volumetric Fit (%)
KENSOTER	Kenyan 1:1 000,000 Soil and Terrain map
KY	Kenya
LS	Loamy Sand
MAP	Mean Annual Precipitation (mm/year)
MIKE-SHE	MIKE-System Hydrologic European
RBUT	Rwanda, Burundi, Uganda, and Tanzania
RCHRG_DP	Deep Aquifer percolation (-)
REVAPMN	Threshold water depth in the shallow aquifer for "revap"(mm)
SCL	Sandy Clay Loam
SLOPE	Average slope steepness (m/m)
SOL_AWC	Soil Available Water Capacity (mmH_20/mm soil)
SOL_Z	Soil Depth (mm)
SOTERSAF	Soil and Terrain Database for Southern Africa
SRTM	Shuttle Radar Topography Mission
SURLAG	surface runoffs lag time (days)
SWAT	Soil and Water Assessment Tool
TMDL	Total Maximum Daily Load (t/day)
TZ	Tanzania
USDA-ARS	United States Department of Agriculture – Agricultural Research Service
WXGEN	Statistical weather generators file for SWAT

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