INTECH
open science | open minds

OPEN ACCESS
ARTICLE

International Journal of Water Sciences

Assessing the Potential Impacts of Four Climate Change Scenarios on the Discharge of the Simiyu River, Tanzania Using the SWAT Model

Research Article

Alain Lubini[1] and Jan Adamowski[2,*]

1 Department of Civil Engineering, Ecole Polytechnique de Montréal, Canada
2 Department of Bioresource Engineering, McGill University, Ste. Anne de Bellevue, Quebec, Canada
* Corresponding author E-mail: jan.adamowski@mcgill.ca

Received 13 Feb 2013; Accepted 26 Mar 2013

DOI: 10.5772/56453

Abstract The Soil and Water Assessment Tool (SWAT) was used to explore the potential impact of four climate change scenarios on discharge from the Simiyu River in Tanzania, located in the Lake Victoria watershed in Africa. The SWAT model used in this study was calibrated and verified by comparing model output with historic stream flow data for 1973-1976 as well as 1970-1971. SWAT was operated at daily and monthly time steps during both calibration and verification. For the daily-time step verification, the model had a Nash Sutcliffe coefficient of efficiency (NSE) of 0.52 and a correlation coefficient (R^2) of 0.72. For the monthly time-step verification, the recorded NSE and R^2 values were 0.66 and 0.70. In developing climate change scenarios within the general patterns defined by the Intergovernmental Panel on Climate Change, predicted increases in CO_2 concentrations were implemented within the constraints of the model's parameterisation by raising, in a seasonally-specific manner, the values of two proxy parameters: daily baseline temperature and precipitation. Under all scenarios, Simiyu River discharge increased (24-45%), showing the highest increase in the rainy season (March to May), with the greatest increase occurring during the rainy season (March to May). Discharge was influenced to a much greater degree by increases in precipitation rather than by temperature. The increase in river flow predicted by the model suggests that the potential increase in heavy flood damage during the rainy season will increase, which could, in turn, have significant adverse effects on infrastructure, human health, and the environment in the watershed. The SWAT predictions provide an important insight into the magnitude of stream flow changes that might occur in the Simiyu River in Tanzania as a result of future climatic change.

Keywords Climate Change, Modelling, River Flow, SWAT, Simiyu River, Africa

1. Introduction

From political and social scientists to engineers and hydrologists, the impact of global warming has demanded the attention of research communities around the world as well as of the general public. Climate change is characterized not only by rises in surface temperatures and sea-levels, but also changes in precipitation and decreases in snow cover (IPCC, 2007). Moreover, climatic shifts, as a result of global warming, have been linked to human health problems, water supply shortages, and biodiversity and ecosystem damage. These climatic shifts have already created problems related to human health, water supply shortages, and loss of biodiversity and ecosystem integrity. Many studies conclude that Africa is not only the continent that is the most vulnerable to the impacts of global warming, but also the one that is the least equipped (financially and managerially) to handle them (Perlis, 2009). The majority of Africa's population relies to a large extent on natural resources. This dependency, coupled with fragile governance capacities, could result in severe problems in addressing the challenges of climate change (IISD, 2009). This will necessitate effective and sustainable water resources management and adaptation strategies in the short, medium, and long-term.

In light of water's importance in agriculture, fisheries, and manufacturing, it is important to assess the potential impacts of climate change on the hydrological processes in a watershed. Therefore, the goal of this research was to use the Soil and Water Assessment Tool (SWAT) to measure the likely impacts of four climate change scenarios on the discharge in Tanzania's Simiyu River, located in the Lake Victoria watershed in Africa. Lake Victoria is not only the largest freshwater lake on the continent, but also one of the major sub-basins within the Nile basin. The Simiyu River was selected because of its economic, social, environmental, and political importance in eastern Africa and because few studies have been conducted in this area on this topic. In this study, the SWAT model was used to evaluate fluctuations in seasonal and annual discharges in response to four future climate scenarios in the Simiyu River. The model was calibrated and verified using historical climate and stream flow data in the Simiyu River.

1.1 Previous studies of climate change impacts in African watersheds

Apart from Tyson's (1991) early research, relatively little work has emerged on future climate change scenarios focused on Africa. Tyson's climate change scenarios for southern Africa were constructed using results from the first generation of GCM (General Circulation Model) equilibrium 2×CO_2 experiments. In a further development, Hulme (1994) presented a method for creating regional climate change scenarios combining GCM results with the newly published IPCC IS92 emission scenarios and demonstrated the application of the method in Africa. In Hulme's study, changes in mean annual temperature and precipitation under an IS92a emission scenario were predicted for the period of 1990 to 2050.

Hulme et al. (1996) took a more selective approach to the use of GCM experiments in describing the 2050 consequences of three future climate change scenarios for the Southern African Development Community (SADC) region of southern Africa. Three different GCM experiments, selected to span the range of precipitation changes predicted by the GCM for the SADC region, allowed for an assessment of some potential impacts and implications of climate change on agriculture, hydrology, health, biodiversity, wildlife and rangelands. However, considerable uncertainty remains regarding the large-scale precipitation changes simulated by GCMs for Africa. Based on such models, Joubert and Hewitson (1997) nevertheless concluded that, in general, precipitation would increase over much of the African continent by the year 2050. As a specific example, their model predicted that by 2050 parts of the Sahel might expect precipitation rates as much as 15% over 1961-90 means.

More recently, Jung et al. (2007) used the meso-scale meteorological model MM5 and the hydrological model WaSim to perform a joint regional climate-hydrology simulation to estimate the effects of anthropogenic influences on the water balance in the Volta Basin, located in West Africa. Their results indicated a decrease in rainfall at the beginning of the rainy season, an increase in rainfall at the height of the rainy season, and a clear increase in temperature.

Lumsden et al. (2009) assessed present, intermediate, and future climate scenarios for Southern Africa to evaluate potential changes in hydrologically relevant statistics of rainfall that could be observed this century as a result of climate change. The scenarios that were accounted for were developed by a downscaling technique simulated by GCMs. According to their study, more rainfall is projected in the east of the region, in the form of more rain days and more days with greater intensity rainfalls. At the same time, the results indicate less projected rainfall along the west coast and the adjacent interior, with the possibility of a slight increase in inter-annual variability.

Using the output data of GCMs in order to address the impacts of climate change in West Africa was studied by Ardoin-Bardin et al. (2009). Using four different models, they were unable to reproduce rainfall volumes in the Sahelian zone, and they had difficulty in simulating the seasonal dynamics of rainfall in the Guinean zone. Running the HadCM3 (Hadley Centre Coupled Model, version 3) model with new scenarios for future climate conditions, they came to the conclusion that the possible future changes in runoff are highly dependent on rainfall and, hence, on the quality of the output of a given GCM.

Milzow et al. (2011) explored the use of combined satellite radar altimetry, surface soil moisture estimates (SSM) and Gravity Recovery and Climate Experiment (GRACE) total storage change datasets for hydrological model calibration using a SWAT model in the poorly gauged Okavango watershed in Southern Africa. The study found that the use of the combination of the three data sets improved the parametrization of the model. The model showed poor performance at a daily time step due to absence of in-situ precipitation measurements and large variation in the three precipitation datasets, but performed well for long-term scenarios.

In the past decade, studies carried out in the Simiyu River watershed (the study site of the research described in this paper) of the Lake Victoria watershed of Tanzania, were mainly aimed at forecasting stream flow. A Geographic Information System (GIS) based distributed model developed by combining a grid-based water balance model and a flow accumulation/routing model, and operating on a monthly time step at a spatial grid cell resolution of 0°10′, performed reasonably well (± 3% error on an annual basis) in predicting stream flow in this river watershed (Moges, 1998), but fared poorly in simulating the timing and magnitude of hydrographs.

In a more recent study, Mulungu et al. (2007) explored discharge estimation in the Simiyu River watershed using the SWAT model. Using high resolution data, they used the model to estimate the discharge at Ndangalu gauging station (112012 at 33.568°E 2.639°S). Sensitivity and auto-calibration analysis showed that surface model parameters such as the curve number (CN2) and saturated hydraulic conductivity (SOL_K) were the most sensitive, with a low level of model performance for the verification period.

Rwetabula et al. (2007) used a spatially distributed model (WetSpa) to estimate daily river water discharge in the Simiyu River. Three years of daily observed discharge values measured at the mouth of the river at Lake Victoria were used to calibrate global parameters of the model. Results showed that 38.6% and 61.4% of the total runoff were provided respectively by surface runoff and interflow, while the groundwater flow contribution was nil. The model revealed that the total outflow to Lake Victoria occurs mainly in the wet season, from March to May and from November to January.

In other watersheds in Africa, Githui et al. (2007) used the SWAT model to investigate the impact of climate change on the runoff of the Nzoia River watershed in Kenya. The results showed an acceptable match between the measured and the predicted discharge ($R^2 > 0.7$), with an increase in rainfall, temperature and surface runoff for all the considered scenarios. The study suggested that the 2020s are likely to experience more flooding events as a result of increased rainfall than in the 2050s.

Doktorgrades (2009) studied the impact of climate change in the sub-surface hydrology of the Volta Basin using the MM5 mesoscale climate model and the hydrological WaSiM (Water Flow and Balance Simulation Model) model using the IPCC 2001 climatological data. In his detailed study, Doktorgrades found that the 2007 report of the IPCC lacked new information on African climate change (but highlighted model uncertainties, particularly over tropical Africa). He also found that the inconsistency of different model projections reflected in the low values of the regional climate change index in Giorgi (2006), which relies on regional temperature and precipitation changes in the IPCC multi-model ensemble framework. This model discrepancy clouds the interpretation of the results of uncertain model parameters, which may impact specifically on the simulation of African climate. In light of all of this, IPCC 2001 data was used in Doktorgrades' study to avoid model discrepancy and uncertainty in the interpretation of the model parameters for African climate simulations. For the same reason as the Doktorgrades (2009) study, our study also uses the IPCC 2001 climate data for simulations for studying the climate change impacts on the flow in the Simiyu River watershed.

Most recently, Mango et al. (2011) used the SWAT model to investigate the impacts of land use and climate change in the hydrology of the Mara River Basin in Kenya. Due to the scarcity of climate data in the region, rainfall estimates were derived from the remote sensing data provided by the Famine Early Warning System (FEWS). The NSE values for the observed and simulated flows using the RFE model was 0.43, while the R^2 value was 0.56. Though the correlation results were not sufficient to predict accurate flows in the watershed, the data can be used for better understanding of the hydrological processes in the watershed.

In the research described in this paper, the Soil and Water Assessment Tool (SWAT) was used to explore the potential impacts of four climate change scenarios on discharge from Tanzania's Simiyu River, located in the Lake Victoria watershed. The purpose of the research is to provide insight into the magnitude of stream flow changes that might occur in the Simiyu River watershed as a result of future climatic change, and to assess what variables affect discharge the most. This information is critical for a better understanding of the potential effects of climate change on the Simiyu River, including potential adverse effects on infrastructure, human health, and the environment. This information is also critical for the development of water resources strategies and policies as well as possible adaptation strategies.

2. Methods

2.1 The Simiyu watershed

Roughly 5320 km² in area, the Simiyu River watershed, located within the Mwanza, Kwimba and Mwasa districts of Tanzania, lies within the confines 33°15′—35°00′E longitude and 2°30′–3°30′S latitude (Figure 1). Arising in the Serengeti Plains at an altitude of about 1882 m AMSL, the river flows in a westerly direction and discharges into Lake Victoria. The water quality of Lake Victoria has been steadily declining due to point and non-point pollution sources from domestic, industrial and agricultural activities. Tanzanian river basins that pollute Lake Victoria are mainly the Mara, Kagera, and Simiyu watersheds (Crul, 1995). The Simiyu catchment is one of the main contributors to the deterioration of Lake Victoria, because it is relatively large, and has many agricultural activities that use agrochemicals (Ningu, 2000), generating high yields of sediments (Lugomela and Machiwa, 2002).

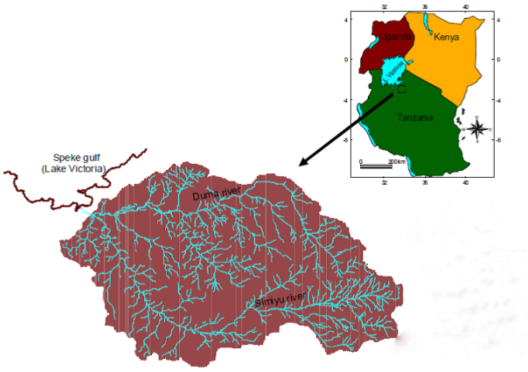

Figure 1. Simiyu Watershed (Rwetabula et.al, 2005)

The watershed is mainly dominated by granite (Syn-orogenic and Magmatite), sedimentary and metamorphic rocks (Nyanzian), with volcanic rocks (Neogene) only covering a small portion of the watershed around the Serengeti plains in north-central Tanzania. Covered by grasses and other herbaceous plants over most of its extent, the watershed's eastern and northern portions are dominated by an open cover of trees, where the crowns do not form a thickly interlaced canopy.

Characterized by a tropical wet and dry climate, the watershed is subject to two wet seasons: the short rains of October through December, and the long rains of March through May. The intermediate months of January and February represent a period of transition between the two. The dry season occurs between June and September. Mean annual precipitation generally varies between 750 mm and 1100 mm, the latter occurring in the upper part of the watershed. The historical maximum and minimum annual rainfalls are 1500 mm yr^{-1} and 400 mm yr^{-1}, respectively. Estimates of minimum and maximum mean actual evapotranspiration within the watershed range from 500 to 700 mm yr^{-1} and from 1200 to 2700 mm yr^{-1}. On average, the monthly discharge varies from 0 to 34 m³/s, while during the dry season (June to October), minimum or no discharge is sometimes recorded.

2.2 Data

Provided within the framework of the "Friends of the Nile" project, the data required to conduct this study included a digital elevation model, land use, and soil type maps, along with weather data. Daily data records for the climatic variables (precipitation, relative humidity, temperature, wind speed, solar radiation and potential evapotranspiration (ET_P), drawn from the two stations located downstream of the Simiyu River within the watershed, were checked for reliability, consistency and homogeneity. The SWAT model used in this study was calibrated and verified by comparing model output with historic stream flow data for 1973-1976 as well as 1970-1971 due to the availability of coexisting flow and climate data during the time period. Given that data series for the time period under concern were incomplete and of variable length, a need clearly existed for either applying some sort of patching technique or calculating an areal mean rainfall. Having chosen the latter approach, daily data from pair meteorological stations were used in a double mass curve analysis over a common period of time in order to assess the homogeneity of the rainfall data. Rainfall distribution was found to be homogeneous within the Simiyu region. However, the resulting distribution of residuals suggested that the outliers be removed in order to calculate the areal mean rainfall using the Thiessen polygon method.

2.3 Theoretical background

Developed by the USDA Agricultural Research Service (ARS) to predict the impact of land management practices on water, sediment and agricultural chemical yields over extended periods of time in large complex watersheds (e.g., on a watershed scale) of varying soil, land use and management conditions, the physically based and semi-distributed SWAT model operates on a daily time step (Neitsch et al., 2002). SWAT divides watersheds into sub-watersheds and attendant stream reaches; yields for each sub basin are then computed, routed through stream reaches and reservoirs, and combined as appropriate.

Input information for each sub-basin is grouped or organized into the following categories: climate;

hydrologic response units or HRUs; ponds/wetlands; groundwater; and the main channel, or reach, draining the sub-basin. Hydrologic response units are lumped land areas within the sub-basin that are comprised of unique land cover, soil, and management combinations. An assumption is made that there is no interaction between HRUs within a single sub-basin. Loading from each HRUs are calculated separately and then summed together to determine the total loadings from the sub-basin (Neitsch et al., 2002).

2.4 Hydrology

The hydrological processes in SWAT are simulated in two phases: land phase and routing phase, the former being based on the water balance equation, expressed in mm of water (Neitschet et.al, 2005):

$$SW_t = SW_0 + \sum_{i=0}^{i=n} (Rday_i - Qsurf_i - Ea_i - Wseep_i - Qgw_i) \quad (1)$$

where,
Ea_i is the amount of evapotranspiration on day *i*,
Qgw_i is the amount of return flow on day *i*,
$Qsurf_i$ is the amount of surface runoff on day *i* (mm),
$Rday_i$ is the rainfall depth on day *i*,
SW_t is the final soil moisture content (day *n*),
SW_0 is the initial soil moisture content (day 0), and
$Wseep_i$ is the amount of percolation bypass flow exiting the bottom of the soil profile on day *i* (mm H_2O).

To model this phase, SWAT requires climatic variables such as daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity.

Surface runoff can be estimated either by the SCS curve number procedure or the Green and Ampt infiltration method. The SCS curve equation is an empirical model developed to provide a consistent basis for estimating the amount of runoff under varying land use and soil types, and is given by:

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)} \quad (2)$$

where,
I_a represents the initial abstractions – including surface storage, interception and infiltration prior to runoff (mm)
Q_{surf} is the accumulated runoff and/or rainfall excess (mm)
R_{day} is the rainfall depth for the day (mm), and
S is the retention parameter (mm), which varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content. It is related to the curve number (*CN*) according to the relationship:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad (3)$$

The Green and Ampt equation was developed to predict infiltration based on the soil parameters. The method assumes that the soil profile is homogenous and antecedent moisture is uniformly distributed in the profile. The Green-Ampt Mein-Larson infiltration rate is defined as:

$$f_{inf_t} = K_e\,[1 + \frac{\Psi_{wf} + \Delta\theta_v}{F_{inf_t}}] \quad (4)$$

where,
f_{inf_t} is the infiltration rate at time *t* (mm hr^{-1}),
F_{inf_t} is the cumulative infiltration at time *t* (mm),
K_e is the effective hydraulic conductivity (mm hr^{-1}),
Ψ_{wf} is the wetting front matric potential (mm), and
$\Delta\theta_v$ is the change in volumetric moisture content across the wetting front (mm mm^{-1})

2.5 Climate change

Climate change simulations though SWAT can be carried out by manipulating the climate inputs such as precipitation, temperature, solar radiation, relative humidity, wind speed, ET_P and weather generator parameters that are fed into the model (Neitschet et al., 2005). For some parameters (e.g., CO_2 level and temperature) adjustments can be made within individual sub-watersheds by a simple percent increase or decrease in the particular parameter.

Changes in carbon dioxide levels are particularly critical because they have an impact on plant growth. As volume-based atmospheric carbon dioxide concentrations ($[CO_2]_{vol}$) increase, plant productivity increases and plant water requirements go down. Consequently, the canopy resistance term can be modified to reflect the impact of the change in $[CO_2]_{vol}$ on leaf conductance. Morison and Gifford (1983) found that when the initial $[CO_2]_{vol}$ ranged between 330 and 660 ppm, a doubling in CO_2 concentration resulted in a 40% reduction in leaf conductance. Consequently, Easterling et al. (1992) proposed the following modification to the leaf conductance term for simulating the effects of $[CO_2]_{vol}$ on evapotranspiration:

$$g_{\ell_{CO_2}} = g_\ell\left(1.4 - 0.4\,(\frac{[CO_2]_{vol}}{330})\right) \quad (5)$$

where $g_{l,\,CO2}$ is the leaf conductance modified to reflect CO_2 effects (m s^{-1}) and CO_2 is the concentration of carbon dioxide in the atmosphere (ppmv).

3. Calibration and verification

In order to assess the impact of climate change on discharge from the Simiyu River, the SWAT model had to first be calibrated and verified. The model was calibrated by comparing predicted and observed hydrographs for the period of January 1973 to December 1976.

The SCS CN method for partitioning of precipitation between surface runoff and infiltration, the variable storage method for channel routing, and the Hargreaves method for calculating ET_P were model options implemented through the study. These model options were suitable given the level of data availability; for example, the temperature time series was incomplete (maximum and minimum temperatures were only available from 1970 to 1974). Though the Penman Monteith method is more accurate when complete data is available, the Hargreaves method requires less data and can be applied in instances when some weather data are missing (Heuvelmans et al, 2005).

Along with the curve number, the fraction of available water (AW) is an important parameter in calibrating the surface runoff:

$$\mathrm{AW} = \frac{\theta_{\mathrm{m}} - \theta_{\mathrm{pwp}}}{\theta_{\mathrm{fc}} - \theta_{\mathrm{pwp}}} \qquad (6)$$

where,

θ_{fc} θ_{m} is the soil's volumetric soil moisture content at field capacity
θ_{fc} θ_{n} is the measured volumetric soil moisture content, and
θ_{pwp} θ_{pwp} is the soil's volumetric soil moisture content at the permanent wilting point.

Model performance during the calibration and verification phases was evaluated using both the correlation coefficient between measured and predicted parameter values (R^2) and the Nash-Sutcliffe coefficient of efficiency (*NSE*). The former measures the strength and direction of a linear relationship between two variables, thus representing the proportion of the variance of one variable that is predictable from the other variable; the latter indicates how well the plot of observed versus predicted data fits a 1:1 line. A perfect match of observed and predicted values would result in an *NSE* of 1.0, with values gradually approaching zero as the quality of the match deteriorates to the point ($NSE < 0.0$) where the mean observed parameter is a better predictor than the model (Singh et al., 2004). Values of $1.0 \geq NSE \geq 0.5$ are generally considered to represent good model performance.

3.1 Scenario baseline

A baseline scenario, assumed to reflect current conditions, was executed prior to performing scenario simulations, which were then run with modified climate inputs for the same simulation period in order to provide a consistent basis for the comparison of scenario impacts. The 4-year period from 1973 to 1976 was used as a baseline condition.

3.2 Climate change scenario

Various modeling techniques have been used to develop a wide range of climate change scenarios. Atmosphere-ocean general circulation model simulations (AOGCMs) are often used to help build these scenarios, as are regional climate models that use downscaled AOGCM simulated data. In addition to modeling techniques, scenario-building requires a physical understanding of the processes governing regional responses, as well as a comprehensive understanding of recent historical climate change events. Although the precise pattern of the changes in temperature, precipitation, and extreme events is not well known, simulations by global climate models have led to an agreement on the following trends: i) The global mean surface temperature is projected to increase between 1.1 °C and 6.4 °C by 2100; ii) Global sea levels are projected to rise by 18 to 59 centimeters by the year 2100. Furthermore, climate change scenarios for Africa indicate future warming across the continent, with decadal increases that range from 0.2°C (low scenario) to more than 0.5°C (high scenario) (Hulme et al. 2001; Desanker and Magadza 2001).

In order to examine the sensitivity of stream flow, both altered temperatures and rainfalls were used as a proxy for increases in $[CO_2]_{vol}$. To achieve year-long equivalents of rises in $[CO_2]_{vol}$ of 479, 492, 555 or 559 ppm relative to the baseline, in combination with temperatures being raised over the entire year by 1.5, 2.5, or 4.5°C, rainfall was increased to different degrees on a month-to-month basis (2, 3, 4, 5, 10, 15, or 20%) except in June through August when it remained unchanged (Table 1). The combined increases in temperature and precipitation of the four scenarios implemented were based on putative rises in $[CO_2]_{vol}$ and IPCC (2001) predictions of future warming across Africa. As discussed earlier, Doktorgrades (2009) found that the IPCC 2007 data for the African continent lacked new information, which was reflected in the inconsistent model projections during simulations. Hence, IPCC 2001 data was used in their study to avoid model discrepancy and uncertainty in the interpretation of the model parameters for African climate simulations.Data from the IPCC Third Assessment Report (2001) was also used throughout the present research project for the same reasons.

Based on the resulting rise in CO_2 the first scenario describes a future world with rapid change in economic structures alongside reductions in material intensity and the introduction of clean and resource efficient technologies. The second scenario is characterized by intermediate levels of economic development with less rapid and more diverse technological change than in the first scenario. The last two scenarios incorporate the rapid introduction of new and more efficient technologies and place a special emphasis on creating a balanced portfolio of energy sources (i.e., not relying too heavily on one particular source of energy). The third scenario in particular focuses on the use of non-fossil energy sources.

The four scenarios tested in this study were:

$S^{2.5}_{492}$ A 2.5°C rise in temperature over the entire year.

Increases in precipitation:
- Sept-Nov: 3%
- Dec-Feb: 5%
- Mar-May: 15%

Resulting Rise in $[CO_2]_{vol}$: 492ppm

$S^{1.5}_{479}$ A 1.5°C rise in temperature over the entire year.

Increases in precipitation:
- Sept-Nov: 1%
- Dec-Feb: 20%
- Mar-May: 5%

Resulting Rise in $[CO_2]_{vol}$: 479ppm

$S^{2.5}_{555}$ A 2.5°C rise in temperature over the entire year.

Increases in precipitation:
- Sept-Nov: 4%
- Dec-Feb: 15%
- Mar-May: 10%

Resulting Rise in $[CO_2]_{vol}$: 555ppm

$S^{4.5}_{559}$ A 4.5°C rise in temperature over the entire year.

Increases in precipitation:
- Sept-Nov: 2%
- Dec-Feb: 10%
- Mar-May: 20%

Resulting Rise in $[CO_2]_{vol}$: 559ppm

Season	$S^{2.5}_{492}$			$S^{2.5}_{555}$		
	ΔT (°C)	ΔP (%)	ΔCO_2 (ppm)	ΔT (°C)	ΔP (%)	ΔCO_2 (ppm)
Dec.-Feb.	2.5	5	492	1.5	20	479
Mar.-May	2.5	15	492	1.5	5	479
Jun.-Aug.	2.5	0	492	1.5	0	479
Sep.-Nov.	2.5	3	492	1.5.	1	479

$S^{2.5}_{492}$			$S^{4.5}_{559}$		
ΔT (°C)	ΔP (%)	ΔCO_2 (ppm)	ΔT (°C)	ΔP (%)	ΔCO_2 (ppm)
2.5	15	555	4.5	10	559
2.5	10	555	4.5	20	559
2.5	0	555	4.5	0	559
2.5	4	555	4.5	2	559

Table 1. Increases relative to the base scenario in air temperature (ΔT), precipitation (ΔP), and atmospheric carbon dioxide concentration (ΔCO_2) on a volumetric basis, for the four climate change scenarios investigated.

Over the interior, semi-arid regions of the Sahara and central-southern Africa, predicted rises in temperatures ranged from 1.5°C up to 4.5°C (IPCC 2001). Indeed, the intermodal range - an indicator of the extent of agreement between different GCMs - is smallest over North and Equatorial Africa and greatest over the interior of southern Africa. The scenarios described above are drawn from historical data that shows an increase of approximately 0.7°C in temperature across most of Africa during the 20th century, a decrease in rainfall over large portions of the Sahelian region, and an increase in rainfall in east central Africa.

Parameter	Description	Units	File type	Soil layer	Adjusted value
SOL_AWC	Soil available water capacity	mm H_20 mm^{-1}	.sol	1	0.12
				2	0.03
				1	0.03
				2	0.50
SOL_K	Saturated hydraulic conductivity (K_{sat})	mm hr^{-1}	.sol	1	20
				2	12
				1	7
				2	23
CN2	Curve number		.mgt		40
SLSUBBSIN	Mean slope Length	m	.hru		10
SLOPE	Mean slope Steepness	m m^{-1}	.hru		0.129
OV_N	Manning "*n*" Value		.hru		0.01
LAT_TIME	Lateral flow Travel	day	.hru		0.001
CH_N 1	"n" value for the tributary		.sub		29.9
CH_K 1	Effective hydraulic conductivityin tributary channel	mm hr^{-1}	.sub		11
CH_K 2	Effective hydraulic conductivity in main channel	mm hr^{-1}	.Rte		0.019
CH_N 2	Manning "n" value for the main channel		.Rte		0.05
CH_S 2	Average slope of main channel	m m^{-1}	.Rte		0.001
GW_DELAY	Ground water Delay	day	.GW		30
ALPHA_BF	Baseflow alpha factor	day	.GW		0.3
GWQMN	Threshold depth of water	mm water	.GW		2575
PND_FR	Fraction of subwatershed area that drains into ponds		.PND		0.09
PND_PSA	Surface area of ponds	ha	.PND		720
PND_K	Hydraulic conductivity through bottom of ponds	mm hr^{-1}	.PND		0.005
WET_FR	Fraction of subwatershed that drains into wetlands		.PND		0.05
WET_NSA	Surface area of wetlands at normal water level	ha	.PND		20
WET_MXSA	Surface area of wetlands at maximum water level	ha	.PND		700
WURC	Average daily removal from the reach for the month	m^3 day^{-1}	.wus		5×10^4 200×10^4

Table 2. SWAT model parameters after calibration and verification.

Future changes in mean seasonal rainfall in Africa are less well defined. Under the lowest warming scenario, up to 2050 few areas would experience changes in December through February, or June through August precipitation, exceeding two standard deviations of natural variability. However, in parts of equatorial East Africa, rainfall is predicted to increase by 5-20% from December through February, and decrease by 5-10%, from June through August (IPCC 2001b).

4. Results and discussions

In order to create an accurate simulation of the Simiyu River's flow using SWAT, it was necessary to adjust several model parameters to best match observed and simulated values (Table 2). Following this calibration, specific model parameters were set and remained unchanged for the verification period. The comparison between the predicted and observed flows was carried out for both daily and monthly time steps (Table 3).

Statistics*	Daily		Monthly	
	Calibration	Verification	Calibration	Verification
n	1461	730	48	24
Var Q_{obs}	403.66	1004.7	178755	447067
SSQ	278374	355262	2584101	3659731
R^2	0.73	0.72	0.83	0.83
NSE	0.53	0.52	0.70	0.66

**n*, number of values; Var Q_{obs},variance of the observed flow; SSQ, sum of square deviations between observed and predicted flow values; R^2, linear correlation coefficient between observed and predicted flow values; *NSE*, Nash-Sutcliffe coefficient of model efficiency.

Table 3. SWAT model accuracy statistics for calibration and verification phases for both daily and monthly time steps.

4.1 Daily Time step

4.1.1 Calibration

In general, the model was able to accurately simulate discharge rates below 80 m³/s, but it failed to simulate higher peaks. This may be partly attributable to inconsistencies in the data set, since some peaks are not explained by the magnitude of the precipitation recorded for the corresponding period. Furthermore, given that the river watershed is mainly dominated by sandy loam soil (which has a high infiltration rate even when thoroughly wetted), these results suggest that ground water storage may be abstracting water from either runoff or from the river itself.

A plot of predicted and measured daily stream flows (Figure 2) over the 4-year calibration period (1973-1976) shows that the model underestimated the flow for the years 1973 and 1974 by 18% and 23%, respectively, and overestimated it by 15% and 21% in 1975 and 1976.

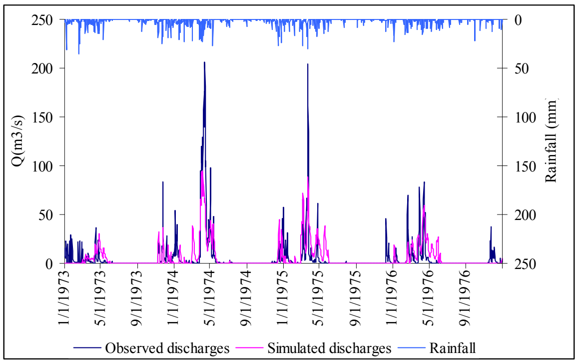

Figure 2. Sequential plot of the daily observed and modeled discharges and the rainfall at Ndagalu for the calibration period 1973-1976

The R^2 was 0.73, and the NSE was 0.53, for the calibration period as shown in Table 5.

Statistics	Daily time step	
	Calibration	Verification
N	1461	730
VarQobs	403.06	1004.68
SSQ	278374.3	355261.8
R	**0.7314**	**0.7232**
NSE	**0.5272**	**0.5156**

n, number of values; Var Q_{obs},variance of the observed flow; SSQ, sum of square deviations between observed and predicted flow values; R^2, linear correlation coefficient between observed and predicted flow values; *NSE*, Nash-Sutcliffe coefficient of model efficiency.

Table 5. Statistics for daily data

4.1.2 Verification

The verification period encompassed the hydrological years of 1970 and 1971; during this two-year simulation period, no changes were made to the calibrated parameters. The results show that the discharges predicted from the model were not very different from those observed during the calibration period (Figure 3). The calculated flow is less than what was measured for both years, the differences being 37% and 20% for 1970 and 1971, respectively. The R^2 was 0.72, and the NSE was 0.52, for the verification period as shown in Table 5.

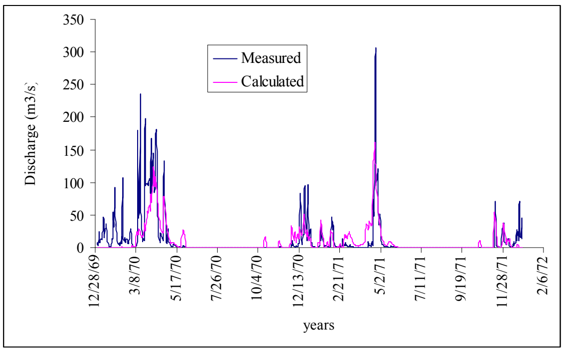

Figure 3. Predicted and simulated stream flow for the verification period 1970-1971

4.2 Monthly time step

4.2.1 Calibration

The monthly stream flow data that was collected during the four-year calibration period (1973-1976) revealed that predicted flows closely followed observed flows (Figure 4). The R^2 was 0.83, and the NSE was 0.70, for the calibration period as shown in Table 6.

Statistics	Monthly time step	
	Calibration	Verification
N	48	24
VarQobs	178754.96	447066.8
SSQ	2584100.52	3659731
R	**0.8346**	**0.8273**
NSE	**0.6988**	**0.6589**

n, number of values; Var Q_{obs},variance of the observed flow; SSQ, sum of square deviations between observed and predicted flow values; R^2, linear correlation coefficient between observed and predicted flow values; *NSE*, Nash-Sutcliffe coefficient of model efficiency.

Table 6. Statistics for monthly data

The time-series of predicted and monthly measured stream flows that were used to produce these results show that there was a slight over prediction during high flow months (i.e., March-May) in 1975 and a large under estimation during the same monthly period in 1974; this is most likely because of the uncertainties in the measured values. The data showed a remarkable difference in the magnitude of extreme events; for example, the recorded stream flow during March 1975 was 1176.2 m^3/s, while stream flows in March 1974 measured only 319.79 m^3/s.

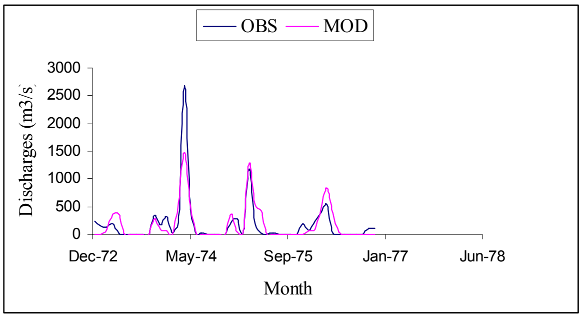

Figure 4. Monthly observed and calculated discharge for the calibration period January1973 - December 1976

4.2.2. Verification

When analyzing the performance on a monthly time-scale, the verification period shows that the model performed well, although it slightly under predicted the flow for the wet season. However, there was little difference between predicted and measured values for November and December 1970 or for January 1971 (Figure 5).

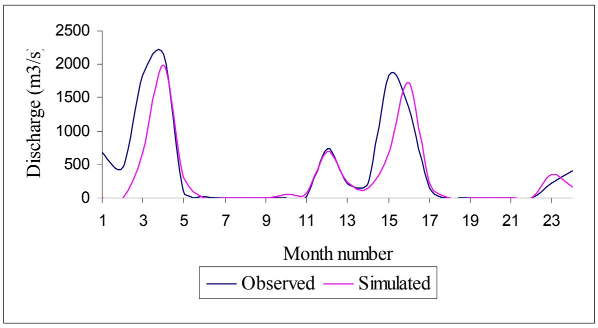

Figure 5. Monthly observed and calculated discharge for the verification period 1970/01 - 1970/12

Respective R^2 and NSE values of 0.83 and 0.66 (Table 6) confirm this conclusion as they are similar to corresponding values for the calibration period (R^2=0.83 and NSE=0.70). These verification results indicate that the SWAT model was able to accurately replicate monthly cumulative stream flow levels at the outlet of the watershed over the time period simulated.

In order to develop, verify, and improve the accuracy of the model, a sensitivity analysis was used to identify the factors that had the greatest impact on predicted river flow (see Appendix). These factors were found to be: i) Water capacity of the soil layer (SOL_AWC); ii) Mean slope length (SLSUBBSN); iii) Mean slope steepness (SLOPE); and iv) Threshold depth of water (GWQMN).

		Scenario			
Month	Baseline	$S^{2.5}_{492}$	$S^{1.5}_{479}$	$S^{2.5}_{555}$	$S^{4.5}_{559}$
Jan	1.32	1.67	2.86	2.44	2.05
Feb	0.97	1.28	2.54	2.09	1.67
Mar	19.40	22.87	21.59	22.35	24.27
Apr	26.84	32.45	29.24	30.95	34.40
May	12.15	14.90	13.38	14.25	16.25
Jun	0.27	0.42	0.31	0.36	0.48
Jul	0.01	0.01	0.01	0.14	2.39
Aug	0.00	0.26	0.67	0.76	0.80
Sep	0.00	0.00	0.00	0.00	0.87
Oct	0.00	0.93	0.84	1.49	2.90
Nov	2.29	3.14	3.99	4.37	4.26
Dec	3.68	6.03	7.71	7.22	6.62
Yearly cumulative	**66.95**	**83.96**	**83.14**	**86.42**	**96.95**

Table 4. Predicted relative changes in river flows (m^3 day^{-1}) for the 4 climate change and baseline scenarios.

In addition to the curve number, the fraction of available water (AW) is an important parameter in calibrating the surface runoff. For sandy loam soil, predicted river flow was very sensitive to AW; a 0.1 increase in the latter resulted in a 0.31-0.53 increase of the NSE that indicated a better fit, while R^2 remained quite stable. However, a similar change in AW for clay loam soil did not significantly affect the performance criteria. The optimal values of θ_m for sandy loam and clay loam soils were 0.6 and 0.5 respectively, both greater than the respective soil's θ_{fc}, indicating that one may expect significant percolation from the top layers to the underlying layers.

Comparatively, the following factors each had a lesser effect on overall model performance: the curve number (CN), base flow alpha factor (ALPHA_BF), ground water delay (GW_DELAY), saturated hydraulic conductivity (SOL_K), groundwater "revap" coefficient, and REVAPMN (threshold depth of water in the shallow aquifer for revap). For example, despite the hydrological response unit (HRU) chosen within the watershed, an increase in curve number from 35 to 79 resulted in neither the NSE nor the R^2 being drastically affected; with the NSE dropping from 0.53 to 0.51 and R^2 decreasing by 1%. An optimal CN value of 40 was obtained for soils allowing moderate water transmission and infiltration when thoroughly wetted (U.S Natural Resource Conservation Service Soil Hydrologic Group B).

4.3 Climate change

Cumulative monthly stream flows (Table 4) predicted under the four scenarios were 24% ($S_{479}^{1.5}$) to 45% ($S_{559}^{4.5}$) greater than those under the baseline scenario. The greatest increases occurred in the rainy season (March to May). Scenarios $S_{492}^{2.5}$ and $S_{555}^{2.5}$ had identical rises in temperature, but $S_{555}^{2.5}$ represented a greater equivalent rise in [CO_2] than $S_{492}^{2.5}$, while $S_{555}^{2.5}$ represented an overall greater increase in precipitation than $S_{492}^{2.5}$. Apart from the long rainy period, the predicted streamflow was greater under $S_{555}^{2.5}$ than $S_{492}^{2.5}$, indicating that the discharge was strongly influenced by the increase in precipitation. For all four scenarios, the magnitude of the discharges recorded during the dry period (June through August) increased slightly compared to the baseline despite the fact that the precipitations were held at 0 mm. An illustration of that increase occurred under $S_{559}^{4.5}$, where seasonal discharge [July-August] was 13-fold greater than the corresponding baseline. Under such circumstances, water shortage problems would be alleviated with possible benefits for agricultural activities.

This result is in accordance with the conclusions drawn from the study conducted by Githui et al. (2008) in western Kenya, which is in the same region as the Simiyu River watershed. They found that streamflow response was not sensitive to shifts in temperature with 6-115% change (in streamflow) when rainfall varied from 2.4-23.2%.

The predicted rise in river flow (Figure 6) indicates that the potential for heavy flood damage during the rainy season of March through May is possible. A comparison between the baseline and scenarios 1 and 4 suggests that there will be an increase of 17% and 22% of stream flow during this period. Stream flow is high as a result of an increase in rainfall; this implies high runoff due to the soil composition, which is mainly made of clay-loam (73.05%) and sand clay loam (25.73%) (Mulungu et al. 2007). The increase in flow as shown above will require adjustment from policy makers in order to address the risk related to more rainfall, with measures needing to be taken to protect cities against likely flooding and waterborne diseases (such as malaria, cholera, and dysentery).

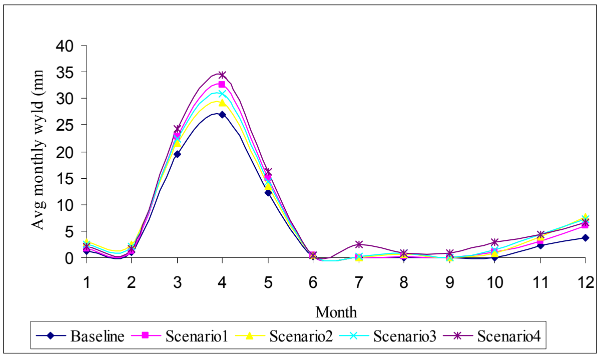

Figure 6. Change in average monthly stream flows predicted for scenarios 1 - 4 relative to the baseline over the 4 year simulation period

5. Conclusions and recommendations

Because of the strategic importance of the Simiyu River in relation to Africa's vulnerability to climate change, this study chose to analyze the impact of four possible future climate change scenarios on the discharge of the Simiyu River watershed, as measured at the Ndangalu gauging station. This study used a SWAT model that was based on a four year calibration period and a two year verification period, with both calibration and verification being performed on a daily and monthly basis. The simulated climatic scenarios used in this study were hypothetical in nature, and thus cannot be viewed as assessments of absolute future climatic conditions. Nevertheless, the SWAT predictions derived from this study provide insight into the potential magnitude of stream flow changes that could occur as a result of future climatic changes, and the calculated discharges may serve as a comparative baseline for various other climate change scenarios.

In this study, the most sensitive parameters identified were the SOL_AWC, SLSUBBSN, SLOPE, and GWQMN, and notwithstanding apparent inconsistencies in the data series used, the model was fairly accurate in predicting low flows, but did poorly in predicting extreme peak flow events. This is likely due to high annual and variability, which creates higher variance in the simulated streamflow. Even though sensitivity analyses on individual parameters were conducted, it would also be advisable to perform advanced uncertainty analysis in the future to decreasing the influence of parameter uncertainty on the modeling results. Both approaches should be considered during watershed delineation. Future studies using the SWAT model should also be done with longer time series in order to improve the output models for the watershed.

For each scenario, increases in precipitation had a greater impact on the river's discharge than increases in temperature, and this was found to be true on both a seasonal basis as well as over longer periods of time. This supports the findings of Wigley and Jones (1984), who evaluated the influences of precipitation changes and direct [CO_2] effects on stream flow and found that for most rivers in the world annual stream flow was more sensitive to precipitation changes than to the rate of evapotranspiration. The forecasted trends for the long rainy season that were produced during the different simulation scenarios indicated that under increased precipitation, flooding would intensify. The consequences of severe flood damage could negatively impact communication infrastructure, farms, human health, human settlements, and biodiversity. In some areas, commercial ranching may marginally improve as a result of increased rainfall, whereas communal ranching might be exposed to greater risk because of increased erosion and the incursion of woody weeds.

Predicting future rainfall patterns is extremely difficult and this created uncertainties in this study. This is due to the fact that the models used in this study did not account for the role of the El Nino southern oscillation (ENSO) or other atmospheric processes affected by land cover change and dust loadings. Such limitations make it difficult to quantify some of the impacts of climate change, which is why future research should focus on integrated approaches, as well as investigating the links between climate, hydrological, and ecosystem models. Furthermore, because climate change has very regional impacts, climate change scenarios generated by other climate models should be compared with scenarios set up by the GCMs because it will increase our understanding of potential impacts on water resources in Africa in the 21st century. There is a specific need to develop regional models that incorporate local climate aspects (from either sparse observations or low resolution numerical simulations) that can be used in constructing various climate change scenarios. Research should also focus on evaluating strategies to sustain and improve the development of the Simiyu River and its watershed in a changing environment. Strategies that incorporate climate change adaptation options will also enhance this process.

6. Acknowledgments

The advice of Prof. Willy Bauwens of Vrije University is appreciated. The financial assistance of the Flemish Interuniversity Council, the IUPWARE program, the Katholieke Universiteit Leuven, and an NSERC Discovery Grant held by Jan Adamowski are acknowledged.

7. References

[1] Ardoin-Bardin S., Dezetter A., Servat, E., Paturel J.E., Mahe G., Niel H., Dieulin C., (2009), Using general circulation model outputs to assess impacts of climate change on runoff for large hydrological catchments in West Africa, Hydrological Sciences 54(1), 77-89

[2] Crul, R.C.M., (1995), Limnology and hydrology of Lake Victoria. Verhandlungen Internationale Vereinigung Limnologie, 25, 39–48.

[3] Desanker P.V., Magadza C, (2001), Africa. In: McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Doken and K.S. White (eds.). Climate Change 2001: Impacts, Adaptation and Vulnerability. IPCC Working Group II, Third Assessment Report, Cambridge University Press.

[4] Doktorgrades D.E., (2009), Modelling impacts of climate change on water resources in the Volta Basin, West Africa, Diese Dissertation ist auf dem Hochschulschriften server der ULB Bonn. http://hss.ulb.uni-bonn.de/diss_online elektronisch publiziert

[5] Easterling W.E., Rosenberg N.J., McKenney M.S., Allan Jones C., Dyke P.T., Williams J.R., (1992), Preparing the erosion productivity impact calculator (EPIC) model to simulate crop response to climate change and the direct effects of CO2,Agricultural and Forest Meteorology, 59 (1992), pp. 17–34.

[6] Ficklin D. L., Luo Y., Luedeling E., Zhang M., (2009), Climate change sensitivity assessment of a highly agricultural watershed using SWAT, Journal of Hydrology, Volume 374, Issues 1–2, 30, Pages 16-29, ISSN 0022-1694.

[7] Githui F., Gitau W., Mutua F., Bauwens W., (2009), Climate change impact on SWAT simulated streamflow in western Kenya, International Journal of Climatology, 29, 1823–1834.

[8] Heuvelmans G., Garcia-Qujano J.F., Muys B., Feyen J., Coppin P., (2005), Modeling the water balance with SWAT as part of the land use impact evaluation in a life cycle study of CO2 emission reduction scenarios, Hydrological Processes 19, 729-748

[9] Houghton J.T., Ding Y., Griggs D.J., Noguer M., Van der Linden P.J., Dai X., Maskell K., Johnson C.A., (2001), Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. IPCC (Intergovernmental Panel on Climate Change), Cambridge University Press, Cambridge, New York

[10] Hulme M., (1994) Regional climate change scenarios based on IPCC emissions projections with some illustrations for Africa area, Blackwell Publishing on behalf of The Royal Geographical Society (with the Institute of British Geographers) 26(1): 33-34

[11] Hulme M., (1996), Climate change and southern Africa: an exploration of some potential impacts and implications in the SADC region, CRU/WWF, Norwich, UK, 104pp

[12] Hulme M., Doherty R., Ngara T., New M., Lister D., (2001), African climate change: 1900–2100, Climate Research, 17, 145–168

[13] IISD, (2009), Climate change and conflict: Lessons from community conservancies in northern Kenya, Conservation development centre, International Institute of sustainable development and saferworld.

[14] IPCC, (2001), Climate Change. The Physical Science Basis. Cambridge, UK: Cambridge University Press. 996 p.

[15] IPCC, (2007), Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on ClimateChange, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[16] Joubert A.M., Hewitson B.C., (1997), Simulating present and future climates of southern Africa using general circulation models. Prog Phys Geogr 21:51–78

[17] Jung G., Kunstmann H., (2007), High-resolution regional climate modeling for the Volta region of West Africa, Journal of Geophysics Research, 112

[18] Lugomela C., Machiwa J., (2002), Nutrient distribution, phytoplankton abundance and species composition in Magu bay following the principal rain season in 2001, in: In Nutrients, microalgae sedimentation and sediment associations at the mouth of Simiyu river (Magu bay of Speke gulf) Lake Victoria, Tanzania, Lake Victoria Environmental Management Project (LVEMP), Tanzania, 22–39,

[19] Lumsden T.G., Schulze R.E., Hewitson B.C., (2009), Evaluation of potential changes in hydrologically relevant statistics of rainfall in Southern Africa under conditions of climate change, Water SA 35(5), 649-656

[20] Morison J.I.L., Gifford R.M.. (1983), Stomatal sensitivity to carbon dioxide and humidity, Plant Physiology, 71: 789-796.

[21] Mulungu D.M.M., Munishi S.E., (2007), Simiyu River catchment parameterization using SWAT model, Physics and Chemistry of the Earth 32(15-18): 1032-1039

[22] Mango L. M., Melesse A. M., McClain M. E., Gann D., Setegn S. G., (2011), Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: results of a modeling study to support better resource management, Hydrology and Earth System Sciences, 15, 2245–2258.

[23] Milzow, C., Krogh P.E., Bauer-Gottwein P., (2011), Combining satellite radar altimetry, SAR surface soil moisture and GRACE total storage changes for hydrological model calibration in a large poorly gauged catchment, Hydrology and Earth System Sciences, Vol.15, 1729-1743.

[24] Moges, S., (1998), GIS-based distributed water balance model for Lake Victoria basin. University of Dar es Salaam Publication. 124p.

[25] Neitsch S.L., Arnold J.G., Kiniry J.R., Williams J.R., King K.W., (2002), Soil and Water Assessment Tool, Theoretical documentation. Version 2000, Texas Water Resources Institute, College Station, TWRI Report TR-192.

[26] Nietsch S.L., Arnold, J.G., Kiniry J.R., Williams J.R., King, K.W., (2005), Soil and Water Assessment Tool Theoretical Documentation. Version 2005, College Station, TX: Texas Water Resource Institute.

[27] Ningu J., (2000), An inventory of agro-chemicals in the Lake Victoria basin, Mwanza, Tanzania, Lake Victoria Environmental Management Project (LVEMP), Tanzania, 1–23.

[28] Rwetabula J., Desmedt F., Rebhun M., (2007), Prediction of runoff and discharge in the Simiyu River (tributary of Lake Victoria, Tanzania) using the wetspa model, Hydrology and Earth System Sciences Discussions, 4(2), 881-908.

[29] Singh J., Knapp H. V., Misganaw D., (2004), Hydrologic Modeling of the Iroquois River Watershed using HSPF and SWAT, Watershed Science Section, Illinois State Waters Survey.

[30] Tyson P.D., (1991), Climatic change in Southern Africa: past and present conditions and possible future scenarios climatic change, Global Change: Issues for the Southern Hemisphere, 18, 241-258