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Modelling Soil and Water Dynamics in the Black Volta Basin Using the Soil and Water Assessment Tool (SWAT) Model

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ABSTRACT

The study focused on the Black Volta Basin (BVB) which is one of the major sub-basins of the Volta River. A high dependency of the population on the basin resources and the lack of sufficient and informed data has led to the under management of its water resources. This research investigated how well the Soil and Water Assessment Tool (SWAT) model can be used to obtain modelled surface runoff flows in the BVB. Spatial data (land-use/land-cover, soil and DEM) together with daily weather data (temperature, precipitation, wind, relative humidity and solar radiation) were used to set-up and run the model. Sequential Uncertainty Fitting II (SUFI2) program was used to evaluate the sensitivity of parameters, and to calibrate the results. The model compared reasonably with observed discharges during calibration with a Correlation Coefficient (R^2) of 0.73. However, in the initial model run, a Nash Sutcliffe Efficiency (NSE) of -0.02 was obtained. Uncertainties pertaining to the conceptual framework of the model and the high frequency of missing data gaps resulted in the poor model performance.

Keywords: *Modelling, Watershed, Water balance, Black Volta Basin, SWAT and SUF2*

INTRODUCTION

Understanding the mutual relationship between soil and water is very essential in our everyday activities. Soil and water, the most fundamental of resources known to man, sustains our existence on earth (Schnabel et al., 2013). Soils offer services such as flood protection and the conservation of natural ecosystems, whilst water is essential for all facilitative, supportive and regulative services (Mace et al., 2012). Water that is stored in the soil has a dynamic characteristic that changes spatially in response to soil properties, topography and changes in the climate, and temporally because of changes occurring between water retention and recirculation (Ladesma et al., 2018). The sustainability of water resources is largely influenced by soils as the gravitational forces offered by these soils filter, retain and later discharge water through cracks and fissures to aquifers and surface waters (Mace et al, 2012).

Unsustainable management of most of Africa's trans-boundary water resources (Ali, 2011) has led to the under-development of these resources. The Volta basin is no different as most basins within the catchment are ungauged while others have insufficient weather stations (Codjoe, 2020).The basic issue of most water resources is not entirely as a result of water stress from the activities of the population but it is an issue that is related to the efficiency of the enabling environment to sufficiently manage these limited resources (Loucks and van Beek, 2017). Poor soil and water resource management has sustained and stimulated numerous negative effects relating to health, environment and socio-economic issues (Dungumaro and Madulu, 2002). From the initial production to final water usage, problems related to the management of these resources can be noticed at every stage (Saatsaz, 2020). Provision for sustainability is the key reason for water resources management (Braimah et al., 2016). Understanding soil and water dynamics is vital for the sustainable management of water resource and most of irrigated waters.

The management, design and planning of hydrological structures is made simple and efficient by modelling tools (Johnston and Smakhtin, 2014). The versatility and dynamic nature of most computer related models, such as SWAT and WEAP, qualifies them as one of the optimum tools for water resource's planning, management and conservation (Kwarteng et al., 2020). Over the past decade, the SWAT model has shown to be an effective tool for evaluating water resources issues (Himanshu et al., 2017). In Little Washita River Experimental Watershed in Oklahoma, Van Liew and Garbrecht (2003) assessed the capacity of the model to simulate discharges in the stream under varying climatic conditions. They found that the model performed better in drier years than in wetter years. Peterson and Hamlet (1998) suggested that the model was more suitable for long periods of simulation. In Alberta, Canada, Mapfumo (2004) confirmed the capacity of the model to predict soil-water patterns in small watersheds. The study found that the model under-predicted in saturated soils and over-predicted in unsaturated soils. However, the prediction of the soil-water patterns was achieved, and the model's adequacy was also attained. This research paper seeks to assess the performance of the SWAT model in predicting river flows within the BVB.

MATERIALS AND METHODS

Study Area

The Black Volta Basin is located in West Africa, and specifically in the north western part of Ghana (Figure1). Geographically, it lies between latitude 7°00'00''N and 14°30'00''N, and longitude 5°30'00''W and 10°30'00''W. The BVB constitutes approximately 32.6% of the Volta basin when some parts of Bamboi, which belongs to the lower Volta, is added to the basin (Barry et al., 2005) and covers an estimated area of approximately 142,056km².

The BVB is characterized by both the wet and dry seasons with annual average temperature of 28°C (Agorsah, 2003). The coolest month is August with the hottest months occurring within March and April. The entire West African region is affected by the Inter-Tropical Convergence Zone (ITCZ) which subsequently affects the BVB leading to a unimodal rainfall in the basin (Sultan et al., 2005). A range of relief values varying between 62m and 752m, with an average of 307m is noticed in the BVB (Abdollahi et al., 2017). The BVB is dominated by two (2) principal agro-ecological zones, which are the Sudan and Guinea savannahs. Agriculture is the main land-use in the BVB, with extensive bush fallow cultivation under food crops. A high intense urban land-use is being experienced in both Wa and Lawra whilst the activity of mining of gold in the Birimian rocks is up and rising in the region (Andah et al., 2003). In the BVB, the dominant geological formation in the region is granitoids which consist of granite, Voltarian and Tarkwanian formations, and Birimian (Gordon and Amatekpor, 1999). Acrisols, Cambisols, Nitosols and Luvisols are the main group of soils in the BVB.

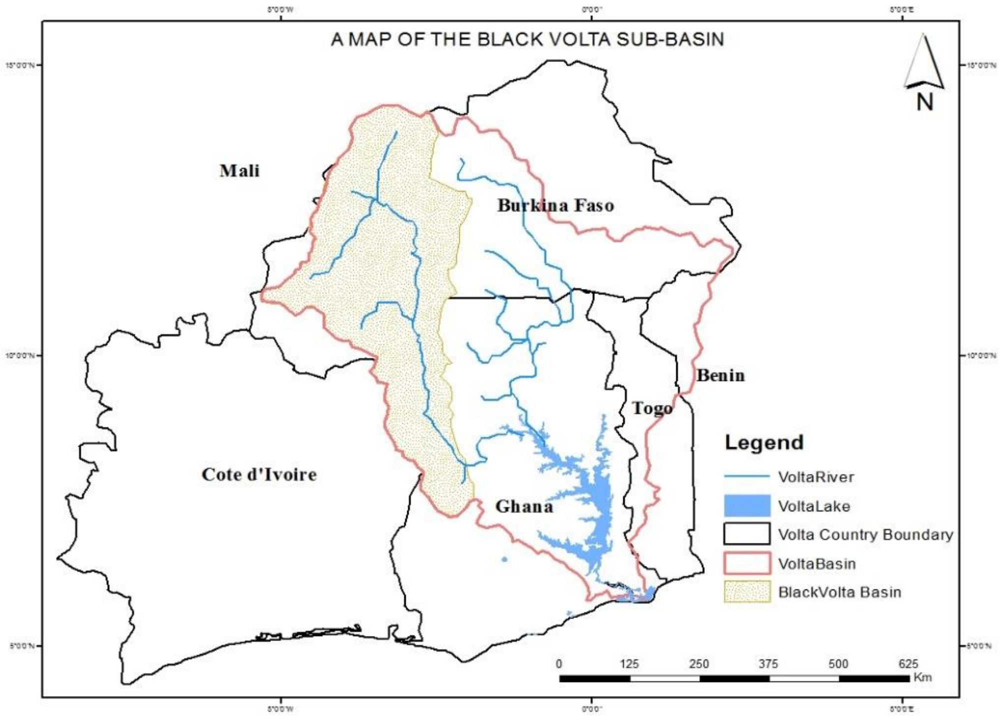


FIGURE 1. **Map of the Study Area**

Model Background

The Soil and Water Assessment Tool (SWAT) ® model is a Geographic Information System (GIS) – driven suite tool that can be used for distributed hydrological modelling (Mehdi et al., 2018). It is used as an extension in the Environmental Systems Research Institute (ESRI) ArcSWAT® program. SWAT is a physically-based, semi-distributed, conceptual river basin model. The model was developed by the Agricultural Research Service of United States Department of Agriculture (USDA-ARS) to sufficiently improve water resources management decisions to achieve an adequate supply of water (Arnold and Allen, 1996). The model runs on a daily time-step and uses input data that are easily accessible. It can predict the impacts of catchment land-use problems towards the yields of agricultural activities and sediment deposits, as well as on water (Melaku et al., 2018). Figure 2 outlines the processes and the components of the model which include parameters such as; agricultural management, plant growth, weedicides, nutrients, soil temperature, weather and hydrology (Neitsch et al., 2005).

Runoff Description in SWAT

The components of the hydrologic cycle can be sufficiently assessed using the water balance equation. The water balance equation is given as:

$$SW_t = SW + \sum_{i=1}^{t}\left(R_{day} - (Q_{surface} + ET + W + Q_{ground})\right)$$

Where SW is initial moisture content of the soil in day (mm); t is time (days)

R_{day} is daily precipitation (mm); $Q_{surface}$ is surface runoff (mm)

ET is daily evapotranspiration (mm)

Q_{ground} is daily groundwater flow (mm) and W is daily percolation (Du et al., 2019)

Either the Green Ampt Infiltration method or the Soil Conservation Service (SCS) runoff Curve Number (CN) method is used to simulate runoff in SWAT. Land-use, antecedent soil moisture conditions and soil permeability are the main parameters that are used in the SCS-CN method. Mathematically, the SCS-CN method is given as (Mishra and Singh, 2003):

$$Q_{surface} = \frac{(R_{day} - 0.2s)^2}{R_{day} + 0.8s_i}, \quad R_{day} > 0.2s$$

$$, Q_{surface} = 0$$

$$R_{day} \leq 0.2s, \; s = 25.4\left(\frac{100}{CN} - 10\right)$$

Where $Q_{surface}$ is daily surface runoff

R_{day} is daily precipitation

s is the retention parameter and

CN is curve number

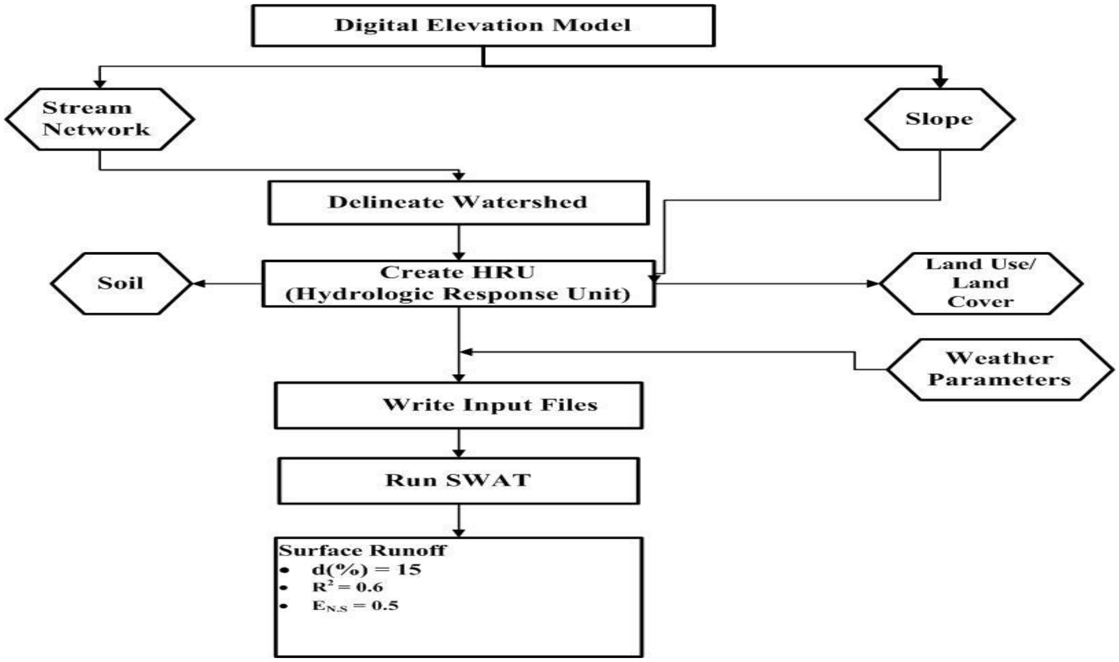


FIGURE 2. **A theoretical framework of SWAT**

Sequential Uncertainty Fitting Version 2 (SUFI2) Procedure

The SUFI2 procedure (Figure 3) is not applied to individual parameter values, but rather to a set of parameter values so that any interactions between the parameters are explicitly taken into account (Kumar et al., 2017). A set of parameter values are created from the Latin Hypercube sampling technique. In SUFI2, parameter uncertainties which account for all sources of uncertainties are expressed as 95PPU or 95% Prediction Uncertainty. The 95PPU, from definite parameter ranges, creates an envelope of good solution to find a good fit between observed and simulated outputs (Abbaspour et al., 2007).

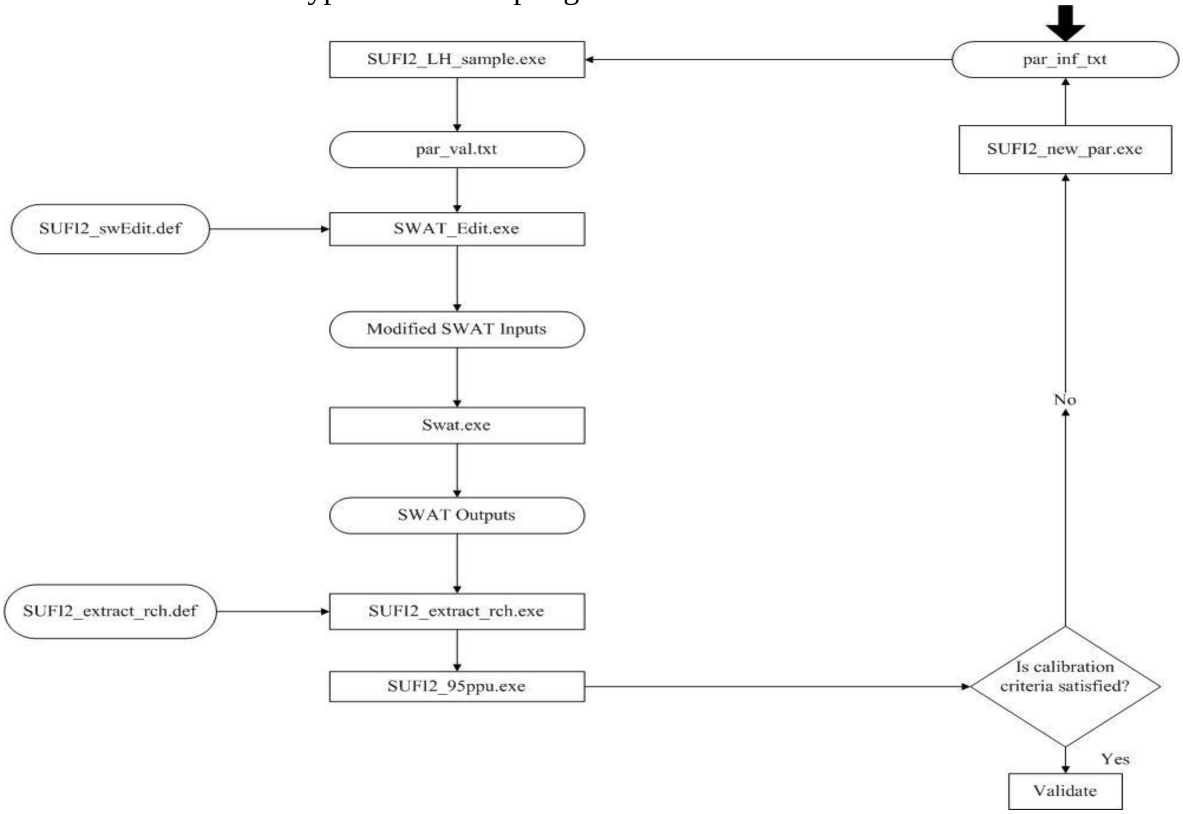


FIGURE 3. **A Detailed Framework of the SUFI2 Procedure**

Model Input Data

Spatial Data

A 30-m resolution Digital Elevation Model (DEM), which was obtained from USGS ASTER GLOBAL DEM, was used for the study. It was further processed to remove sinks and data errors. In SWAT, predicted hydrologic responses are very sensitive to land-use changes (Gessesse et al., 2019). A 30-m pixel resolution land-cover map was obtained from USGS Landsat 8 website for the year 2009. Ground-truth data was used to geo-reference the corresponding map.

SWAT® 2012 soil database was manually updated by using the FAO Soil Water database. Additional soil properties data were added to the soil database of SWAT for the whole world. The BVB soil map was developed from the Food and Agriculture Organization (FAO) Digital Soil Map. The soil map data was obtained in ESRI format to facilitate its effectiveness in ArcSWAT®®.

Climatic Data

Data on relative humidity, solar radiation, wind speed, precipitation and temperature (maximum and minimum) from four (4) weather stations located in Ghana were used as the climate inputs to run the SWAT model. The data were obtained from the Ghana Meteorological Services Department (GMet) and was cross-checked with climate data from the Global Weather Data. The data covered the period 1960-2013.

TABLE 1. **Climatic Stations Used for Modelling**

Station ID	Station Name	Data Type	Start Date	End Date
01018WEN	Wenchi	Precipitation and Temperature	1960	2013
01032SUN	Sunyani Airport	Precipitation and Temperature	1974	2013
07000BOL	Bole	Precipitation and Temperature	1960	2013
01013WA	Wa	Precipitation and Temperature	1960	2013

Discharge Data

Observed river flow data were obtained from the GRDC Runoff Database. Two (2) gauge stations of the BVB within Ghana were used for the simulations. The percentage of missing data proved to be significant. However, SWAT provided an interface where the missing data were replaced during the simulations.

TABLE 2. **GRDC Stations of the BVB in Ghana (Obtained from GRDC Runoff Database)**

Station	Latitude	Longitude	Catchment Area (km^2)	% of Missing Data
Bamboi	8.15	-2.0333	134200	35
Lawra	10.633	-2.9167	93820	25

RESULTS AND DISCUSSION

Topographic Report

The ArcSWAT®® interface produced a topographic report which is related to the general overview of the characteristics of the watershed; its topographic features, sub-basins and their respective HRUs, land-use, soils and slope distribution. Table 3a is a summary of a simple elevation report for the watershed which shows the minimum and maximum elevation of 77m and 873m, respectively. The report generates a line of data for each elevation value found within the watershed, and then lists them distinctly for each sub-basin (Teshager et al., 2016). It provides a value for the area below the represented elevation value and also the percentage of area the watershed covered by that particular value.

Table 3b on the other hand shows the minimum, maximum and mean elevation values of each sub-basin within the watershed. From this table, sub-basin 9, which is the main reach for all cumulative flows in the watershed, has a minimum and maximum elevation value of 77m and 476m respectively. It has the lowest minimum elevation in the watershed but a relatively considerable maximum elevation. The topographic nature of the sub-basin makes it a comparatively better accumulation point for all flows in the watershed.

TABLE 3a. **ArcSWAT®® Topographic Report on Elevation Values**

```
Elevation report for the watershed     1/1/0001 4:32:48 PM     7/8/2018 12:00:00 AM
----------------------------------------------------------------------------------------------------------
Statistics::  All elevations reported in meters
  Min.    Elevation: 77
  Max.    Elevation: 873
  Mean.   Elevation: 270.845933922914
  Std.    Deviation: 75.8652964703973
```

Elevation	% Area Below Elevation	% Area Watershed
77	.00	0
78	.00	0
79	.01	0
80	.01	.01

Based on the number of sub-basin outlets that were used in the watershed delineation process, ten (10) Sub-basins were created in the final ArcSWAT®® run. The outlet point in each sub-basin boundary marks the beginning of the flow point of the adjacent sub-basin, and the end of the reach of latter sub-basin. Meanwhile, the reach of sub-basin nine (9) marks the final accumulation point of all flows in the watershed into the main Volta River.

TABLE 3b. **ArcSWAT®® Topographic Report for Each Sub-Basin**

Sub-basin	Min. Elevation (m)	Max. Elevation (m)	Mean Elevation (m)
1	230	656	3.6.33
2	246	466	327.21
3	239	516	325.92
4	285	691	369.59
5	238	532	310.42
6	55	458	266.04
7	202	573	287.93
8	121	474	257.87
9	77	476	167.39
10	133	873	286.63

ArcSWAT®® Hydrological Results

A final ArcSWAT® model run was successful and produced an interface where the hydrological processes and its respective average and peak component values were provided (Fig 4).

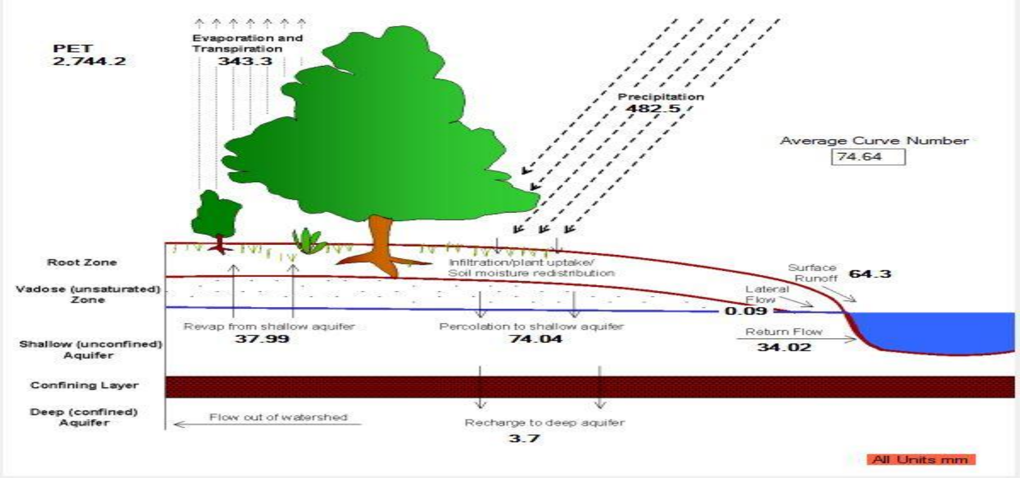


Figure 4. **Description of the Hydrology within the Watershed**

From the results, the average annual precipitation of 482.5mm was the major contributor to blue and green water flows, and also to the storage of green water. An average Curve Number (CN) value of approximately 75 indicates that anthropogenic activities have led to significant developments in the watershed.

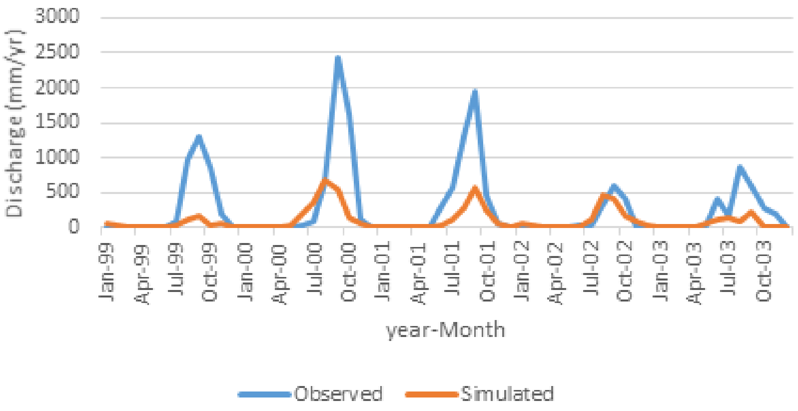
Characteristics of the Water Balance Components

The components of the water balance that were analysed in this study included soil moisture content (SW), evapotranspiration (ET), water yield (WYLD) and precipitation (PCP). Water yield, evapotranspiration and precipitation values were 176, 381 and 483 mm, respectively. These values indicate a relatively balanced hydrological system. CN values are usually an estimate of the surface runoff. The CN a measure of the infiltration capacity of soils (Lal et al., 2017). Percolation of 74mm in the watershed (Figure 4) indicates a moderate rate of water transmission within the soils in the watershed.

Higher temperatures experienced within the watershed together with a high savanna land-use type (Annor, 2012) accounts for the high evapotranspiration in the region. Potential changes in the water balance components are as a result of changes in precipitation. However, the patterns with which precipitation is distributed across the watershed is similar to that of evapotranspiration in contrast with soil moisture, with which it varies.

Initial Flow Results

Figure 5. **Automated Results for Average Monthly Observed and Simulated Discharges from 1999 – 2003**



Under the initial simulation, SWAT underestimated monthly average flows throughout the simulation (Figure 5), especially in the mid-to-late 2000s. The Nash Sutcliffe Efficiency (NSE) was -0.02 and the corresponding Correlation Coefficient (R^2) was 0.42. An NSE value of -0.02, which is far from 1.0, indicate a very systemic and large under-prediction. The R^2 value of 0.42 indicates that the simulated and the observed discharges are poorly matched. Model calibration is, however, required to provide a good fit between observed and simulated discharges.

Calibration of Flow Results

Before calibration, analysis of sensitive parameters were carried out in SWAT-CUP. This analysis was done to assess the influence of a set of parameters on flow output predictions. In the analysis, ten (10) parameters, out of fifteen (15) selected parameters, were found to be sensitive to the model outputs. Table 4 shows the ten (10) most sensitive parameters.

TABLE 4. **Ranking of the Sensitive Parameters**

Rank	Parameter	Description	Fitted Value
1	Alpha_bf	Baseflow alpha factor	0.035229
2	Gw-revap	Groundwater ‘revap’ coefficient	0.288669
3	Sol-k	Saturated hydraulic conductivity	912.942688
4	Gwqmn	Threshold water depth in the shallow aquifer	193.745561
5	Revapmn	Threshold depth of the water in the shallow aquifer for ‘revap’ to occur	194.026611
6	Cn2	Initial scs cn ii value	7.126283
7	Sol-awc	Available water capacity	0.791912
8	Esco	Soil evaporation compensation factor	1.414711

9	Rchrg-dp	Deep aquifer percolation fraction	-0.214465
10	Surlag	Surface run-off lag time	25.785385

A comprehensive calibration was performed for the BVB. Measures for assessing the performance of the model: R^2 and NSE, were evaluated to find reasonable goodness of fit. Figure 6 below shows the final hydrograph for the model calibration.

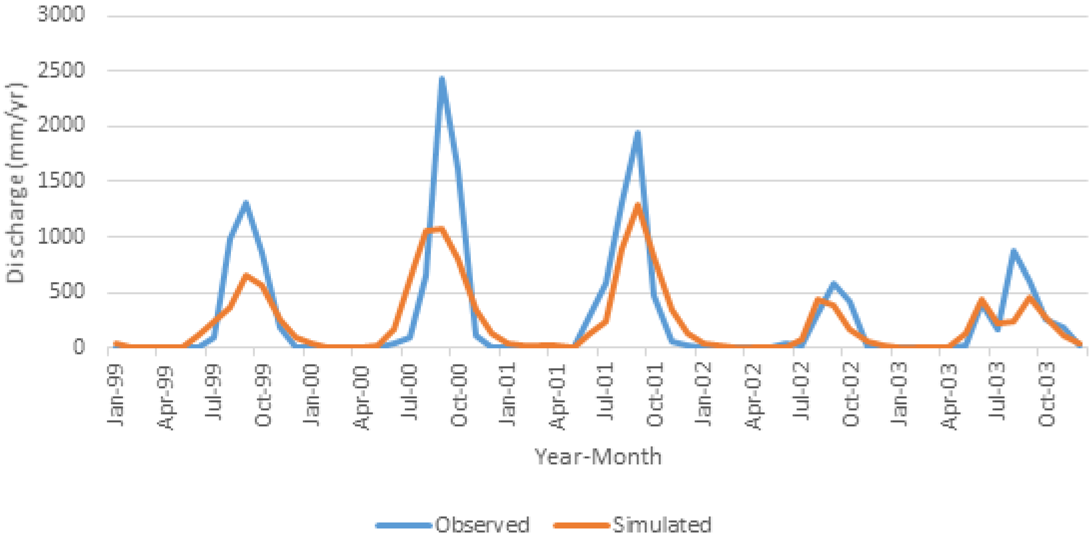


FIGURE 6. **Calibrated Results for Average Monthly Observed and Simulated Discharges**

The calibrated results (Figure 6) show that, the SWAT model underestimated observed discharge values for nearly all the rainy periods of the year, and overestimated observed flows for most of the early periods of the calibrated years. However, an interesting phenomenon occurs between January and late May in each of the years where the observed flows consistently and adequately compare well with the simulated flows. This indicates that the model was successful in predicting storage and infiltration losses. It is in these periods within the catchment where the relative temperature is very high (Andah and Guchuki, 2005). A relatively strong correlation ($R^2 = 0.73$) exists between the observed and simulated flows with a corresponding NSE value of 0.67. Furthermore, the simulated and observed flows follow arguably very similar curves, although the observed curves are consistently higher than the simulated curves.

CONCLUSION AND RECOMMENDATION

The SWAT model was used to predict river discharges in the Black Volta sub-basin, with the aim of determining the performance SWAT model in modeling surface water flows. The SWAT model, as a semi-distributed model, allows for the representation of the Spatio-temporal variability of climatic conditions up to the sub-basin level. It is an impressive tool for distributed modelling. Spatially available datasets including land-use and soil, as well as daily weather data were pre-processed using GIS to run the model.

A Correlation efficiency (R^2) of 0.73 was obtained after calibration with observed river discharge for the period 1999 to 2003. These performance values could be improved by using well-refined input data, particularly soil and land-use features, since globally available datasets were used in this study. This study demonstrates the capability of GIS to create, combine and generate all the relevant datasets required to set-up and run the model. The results also show the ability of SWAT to simulate the processes in the hydrological cycle occurring within the BVB and related semi-arid areas.

To ensure better performance of the application of SWAT model in the Black Volta sub-basin in future studies, a stream-flow gauge with a stable hydrologic control section should be installed, especially in the headwater areas of the watershed. This is needed to reduce the high frequency of missing data in the observed flows. The gauge is also reliable for measuring flows which exceed the height of the rating table, and thus, help reduce uncertainties in flow gauge measurements to a minimum.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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