

PREDICTION OF THE STREAMFLOW OF HADEJIA-JAMA'ARE-KOMADUGU-YOBE-RIVER BASIN, NORTH EASTERN NIGERIA, USING SWAT MODEL

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Abstract

Hadejia-Jama'are-Komadugu-Yobe River basin (HJKYRB) is one of the major river basins the water resources of which are vital to sustenance of the livelihood of the growing population in Northern Nigeria. It is however among those of which the proper management of the scarce resources among competing demands is of growing concern. The SWAT model which could potentially be useful as a decision support tool was therefore evaluated for applicability in the basin. Thirty years(1971 to 2000) of daily meteorological data of a station were used for the model sensitivity analysis. The model was calibrated and validated using in each case 12 years of observed stream flow data from a gauging station. The periods covered by the calibration and validation data were 1974 to1985 and 1989 to 2000 respectively. The sensitivity analysis identified 17 model parameters as important with Moisture Condition II Curve Number (CN₂) as the most sensitive. The coefficient of determination (R²) and Nash-Sutcliffe Efficiency(NSE) obtained during calibration were0.57 and 0.51 respectively. For the validation R²was 0.71 while NSE was 0.65. The values ofR²and NSE obtained were within the acceptable range in literature. It was concluded therefore that the SWAT model could be useful as a decision support tool for water resources management policies in the basin.

Key Words: SWAT, calibration, Hadejia-Jama'are-Komadugu-Yobe, stream flow

Introduction

The Hadejia-Jamare-Komadugu-Yobe Basin, (HJKYB) is a sub-catchment of the Chad basin. It is a very important catchment in Northern Nigeria supporting the competing water needs of a growing population of over 15 million people. Concerns have been expressed about possible future water scarcity in portions of the basin (Sobowale *et al.*, 2010) and the water resources potential per capita for the basin estimated as 376 m³ for 2010 and projected to decrease to 232 m³ by year 2030 is the lowest in the country (Japan

International Cooperation Agency, JICA, *et al.*, 2014). According to an earlier report by Barchiesi *et al.* (2011), inappropriate water management practices have resulted in changed seasonal river flows and widespread environmental degradation in the catchment. The report also highlighted fragmented and uncoordinated regulatory frameworks for agricultural and other competing water usage as factors responsible for growing tension and risk of conflict among water users in the catchment. It therefore suggested modalities and approaches for

the management that would scale up from local to regional integrated water resources management.

A feasible cost effective approach to integrated watershed management is the use of catchment simulation models as tools for the study of the effects of the interacting variables impacting on the quantity and quality of available water resources at both temporal and spatial scales. Such models are indispensable as predictive decision support tools in sustainable integrated water resource management. The Soil Water Assessment Tool (SWAT) is an example of such model (Srinivasan and Arnold, 1994; Neitsch *et al.*, 2011). The SWAT model is a continuous-time, semi-distributed, physically-based model which can predict the effects of alternative management decisions on water resources and nonpoint-source pollution in large river basins (Arnold *et al.*, 2012). The major components include those simulating weather, hydrology, soil erosion, sediment yield, vegetation and crop; nutrient and pesticide cycles; land management and, channel and reservoir routing. It divides a basin into sub-basins and Hydrologic Response Units (HRU). The HRUs are defined as lumped areas having unique land cover, soil and management combinations within the sub-basin. It has been reported to have a substantial reputation as a model to quantify the impact of land management practices in large, complex watersheds and to have been used in many developing countries and the United States of America (George and Leon, 2008). A review of its development history and applications has been provided by Saleh *et al.* (2009) while George and Leon (2008) described the Water Base Project of United Nations University, Macao, China which provided an open source Geographic Information

System (GIS) support and a setup interface for SWAT resulting in the tool known as MapWindow SWAT (MWSWAT). Data sources and procedures for using MWSWAT were also discussed by George and Leon (2008). SWAT is however being continuously improved and updated with better features and capabilities (Arnold *et al.*, 2012).

The applicability of the SWAT model to HJKYB however needs to be ascertained. Furthermore, on account of their limitations in the representation of complex natural processes, models such as SWAT require calibration before application. The aim of this study therefore was therefore the evaluation of the prediction of surface runoff by SWAT in HJKYB. The specific objectives were to determine the relative sensitivities of the model parameters important to runoff, calibrate the model for the basin, and compare the predicted runoff with observed historical data.

Materials and Methods

Model Description SWAT 2009 (Neitsch *et al.*, 2011) interfaced with MapWindow GIS version 4.8.6 (Schneider, 2011) was used for the study. The theory of the model has been outlined by Neitsch *et al.* (2011). According to them, the land phase of the hydrologic cycle is simulated based on the following water balance equation;

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (1)$$

where SW_t is the final soil water content (mm H₂O), SW_0 is the initial soil water content on day i (mm H₂O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H₂O), Q_{surf} is the amount of surface runoff on day i (mm H₂O), E_a is

amount of evapotranspiration on day i (mm H₂O), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H₂O) and Q_{gw} is the

amount of return flow on day i (mm H₂O). The options for estimating potential evapotranspiration are by the methods of Hargreaves *et al.* (1985), Priestly and Taylor (1972) and Penman-Monteith (Monteith, 1965); all as cited by Neitsch *et al.*, (2011).

Also, two methods are available for estimating surface runoff namely, as cited Neitsch *et al.* (2011), the Soil Conservation Service (SCS) (SCS, 1972) and the Green and Ampt (1911) procedures. The SCS procedure was described by the following equations;

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

where Q_{surf} is the accumulated runoff or rainfall excess (mm H₂O), R_{day} is rainfall depth for the day (mm H₂O), I_a is the initial abstraction (mm H₂O) and S is the retention parameter (mm H₂O) which varies both spatially, due to changes in soils, land use, management and slope; and temporally due to changes in soil water content. The retention parameter is given by

$$S = 25.4 \left(\frac{100}{CN} - 10 \right) \quad (3)$$

where CN is the curve number for the day. The initial abstraction, I_a , is approximated as $0.2S$.

Three antecedent soil water conditions (AMC) are recognized by the SCS method namely: I denoting dry i.e. wilting point, II for average moisture and III for field capacity. The curve number for AMC I is the lowest the value the curve number for the day can assume under dry conditions.

The curve numbers CN_1 for AMC I and CN_3 for AMC III are estimated from that for AMC II, that is, CN_2 , as follows;

$$CN_1 = CN_2 - \frac{20(100 - CN_2)}{100 - CN_2 + \exp [2.553 - 0.0636(100 - CN_2)]} \quad (4)$$

$$CN_3 = CN_2 \exp [0.00673(100 - CN_2)] \quad (5)$$

Details of the estimation procedures for all the variables in Equations (1) to (5) are described by Neitsch *et al.* (2011). Also described are the details of estimation of water yield of a river catchment from the sum of the surface runoff (mm H₂O), the lateral flow contribution to streamflow (mm H₂O) and the groundwater contribution to stream flow (mm H₂O) less the transmission losses (mm H₂O) from tributary channels in the HRUs. In addition, the several model parameters that are subject to adjustment during model calibration were also defined.

Description of study area

Hadejia-Jama'are-Komadugu-Yobe Basin (HJKYB) is located in the northeastern part of Nigeria and covers the whole of Jigawa and Kano and States. Parts of Bauchi, and Plateau and Yobe States also fall within the basin. It is bounded between latitude 10.036° N and 12.976° N and longitude 7.336° E and 11.631° E. It is about 54, 920 km² in area with a perimeter of 1,437 km. The highest point in the basin is about 1570m, while the lowest is 325m above sea level. About 54,105 km² representing 98.52% of the total area has it slopes within 0 to 10%, only about 814 km² representing about 1.48% of the total area has slope above 10%. The area covered by this study is dendritically drained by two major rivers namely the Hadejia and the Jama'are Rivers and their tributaries (Figure 1).

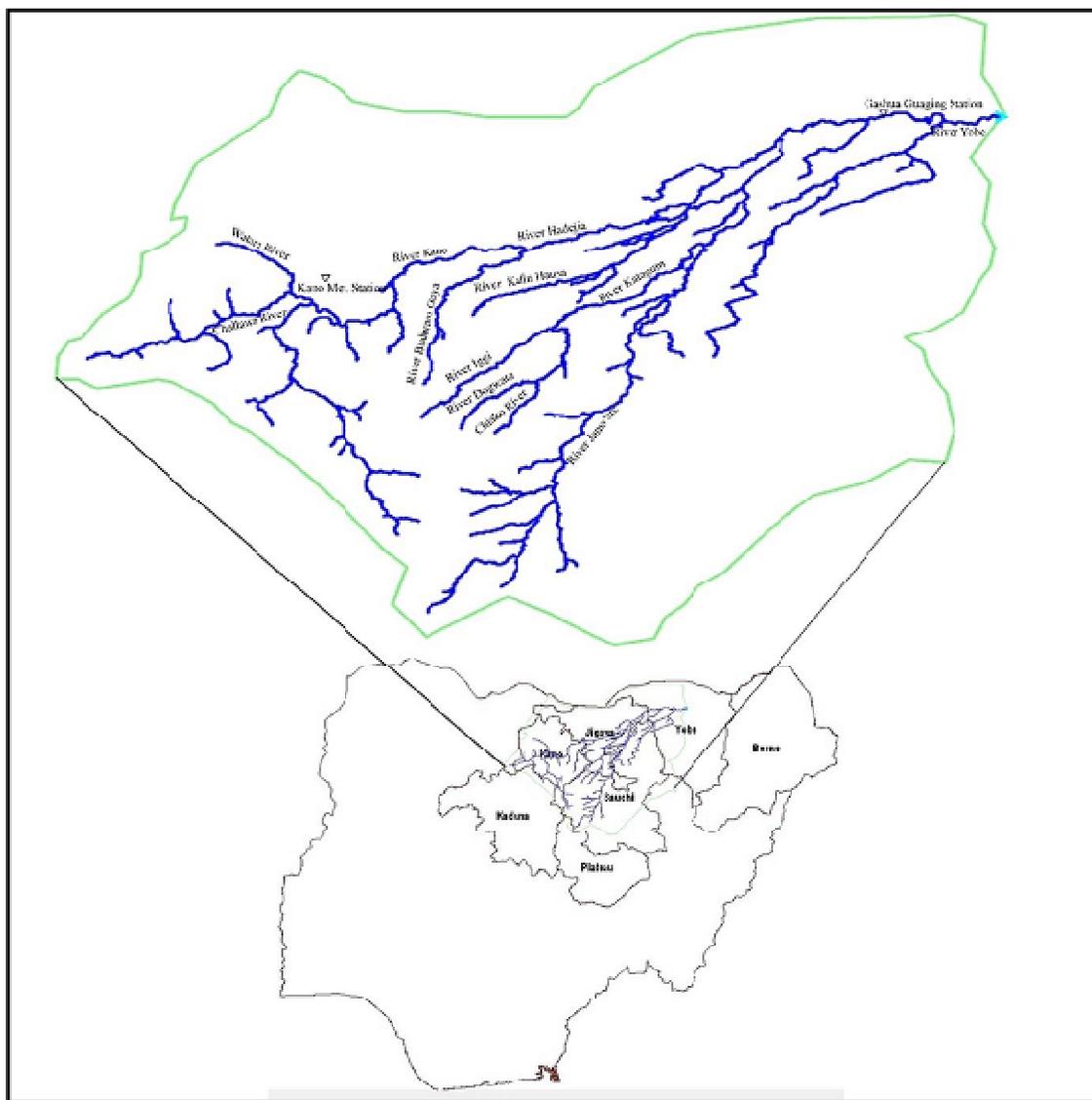


Figure1: Map of Nigeria showing Hadejia-Jama'are Komadugu Yobe Basin. (The states covered by the basin and the adjoining states are indicated)

Both rivers have the Jos plateau in Plateau State as their source and flow in the northeastly direction, eventually meeting in an extensive floodplain called Hadejia-Nguru Wetlands, west of Gashua town. The two rivers with the Yobe River after their confluence with the latter are collectively known as the Komadugu Yobe River which eventually empty into Lake Chad.

Data Collection and Analysis

The required input data include the Digital Elevation Model (DEM), land use and land cover map, soil map and meteorological data. The MapWindow GIS (Leon, 2014) interface of the MWSWAT was used to discretize the catchment area and extract the SWAT input files. The topography data used were that at 90m resolution extracted from the Shuttle Radar

Topography Mission (SRTM) version 4 (The Consortium for Spatial Information, CGIAR-CSI, 2012). The final DEM obtained for the basin was used for delineation and for obtaining topographical parameters such as overland slope, stream network and slope length for each sub-basin. The basin was delineated into 139 sub basins with Automatic Watershed Delineation (AWD) tool of the GIS interface using a threshold sub basin size of 200 km². The sub-basins were further divided into 289 HRUs.

Landuse and land cover map of the Global Land Cover Characterization, GLCC, database (United States Geological Survey, 2012) was used to estimate vegetation and other parameters representing the watershed area. The GLCC database has a spatial resolution of 1km and 24 classes of landuse representation (Loveland *et al.*, 2000). Digital soil data were extracted from the Food and Agriculture Organization's harmonized digital soil map of the world (HWSD) version 1.1. (Nachtergaele *et al.*, 2009). The database provides data for 16,000 different soil mapping units for two soil layers 0 - 30 cm and 30 - 100 cm depth. Soil data extracted from the database were supplemented with additional information gathered from the soil report and map of Federal Department of Agricultural Land Resources, FDALR, (FDALR, 1990). The weather data used were for Kano meteorological station obtained from Nigeria Metrological Agency for the period 1971 to 2000. They comprise daily data on rainfall, maximum and minimum temperatures. Run off data in terms of stream discharges were obtained from Nigerian Hydrological Services Agency for the Gashua gauging station for the periods 1974 to 1985 and

1989 to 2000 and employed in the model calibration and validation.

Model Application

The SCS curve number procedure (SCS, 1972; as cited by Neitsch *et al.*, 2011) was employed in surface run off estimation while the variable storage method (William, 1969; as cited by Neitsch *et al.*, 2011) was used for flow routing. The Hargreaves method was used for estimating potential evapotranspiration. Preparation of necessary input files and execution of the necessary steps in running the model were as outlined in Leon (2014) and Arnold *et al.* (2011). The model sensitivity analysis was performed using 30 years (1971 to 2000) of daily meteorological data. The MWSWAT interface which combines the Latin Hypercube (LH) and One-factor-At-a-Time (OAT) sampling (van Griensven *et al.*, 2006) was employed considering 42 parameters and 10 loops of simulations. This resulted in 430 simulation runs that included one baseline simulation per loop. Calibration was performed using the auto-calibration tool in MWSWAT and observed discharge data for the period 1974 to 1985 while those for 1989 to 2000 were used in the model validation. The indices used for the evaluation of the model calibration and validation results were coefficient of determination (R^2) and Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970), NSE , defined as follows;

$$R^2 = \frac{[\sum_i^n (Q_{m,i} - \bar{Q}_m)(Q_{s,i} - \bar{Q}_s)]^2}{\sum_i^n (Q_{m,i} - \bar{Q}_m)^2 \sum_i^n (Q_{s,i} - \bar{Q}_s)^2} \quad (6)$$

$$NSE = 1 - \frac{[\sum_i^n (Q_{m,i} - Q_{s,i})]^2}{\sum_i^n (Q_{m,i} - \bar{Q}_m)^2} \quad (7)$$

In Equations (6) and (7), $Q_{m,i}$ (m³/s) while $Q_{s,i}$ (m³/s) is the corresponding simulated flow. \bar{Q}_m and \bar{Q}_s are the means of the measured and simulated data respectively while n is the number of measured and simulated pairs of data compared.

Results and Discussion

Weather, Relief and Land cover

The rainfall and temperature records (Table 1) for the period covered by the model calibration and validation show that rainy period from April to October was the hotter part of the year with the most significant rainfalls occurring from June to September. The DEM obtained for HJKYB

and the delineated 139 sub-basins are shown in Figures 2 and 3 respectively. Savannah and Cropland wood mosaic categories dominate the land cover of the watershed constituting, respectively, 32203.74 km² or 58.64% and 21262.99 km² or 38.72 % of the total watershed area (Figure 4).

Table 1: Average daily air temperatures and monthly rainfalls for the period (1974 – 2000) of the model calibration and validation

Month	Daily temperatures (°C)		Rainfall (mm/month)
	Maximum	Minimum	
Jan	29.0	14.2	0.0
Feb	32.2	16.7	0.4
Mar	36.1	20.8	0.9
Apr	39.0	24.1	10.9
May	38.0	24.7	51.4
Jun	34.9	23.3	112.2
Jul	31.4	21.6	223.0
Aug	30.6	21.2	294.4
Sep	32.3	21.6	133.0
Oct	34.8	20.9	15.1
Nov	33.0	17.4	0.0
Dec	29.6	14.9	0.0

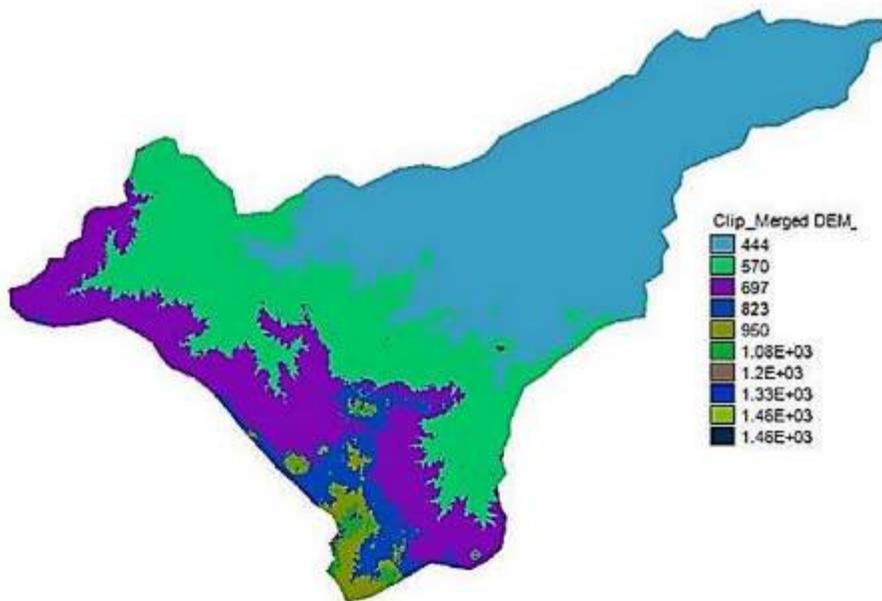


Figure 2: Digital Elevation Model of the Study Area (Elevations are in meters a.m.s.l.)

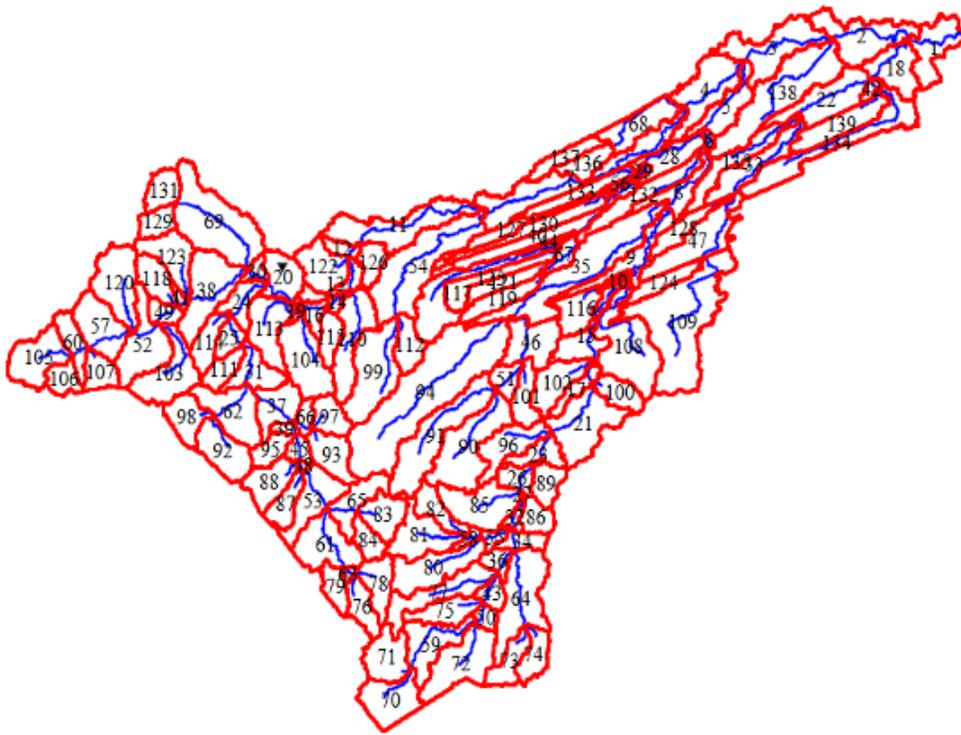


Figure 3: Delineation of the Study Area into Sub-basins

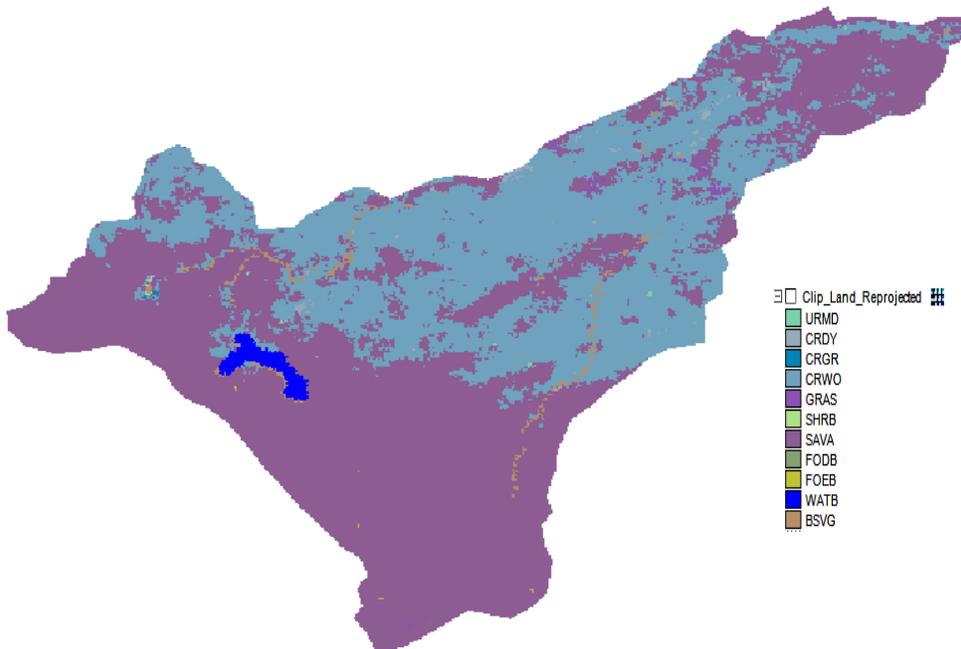


Figure 4: Land Use and land cover of the study area (URMD = Urban and Built-Up Land; CRDY = Dryland Cropland and Pasture; CRGR Cropland/Grassland Mosaic; CRWO = Cropland/Woodland Mosaic; GRAS = Grassland; SHRB= Shrubland; SAVA = Savannah; FOEB = Evergreen Broadleaf Forest; WATB =Water bodies; BSVG= Barren or Sparsely Vegetated)

Sensitivity Analysis

Seventeen model parameters were identified as sensitive from the analysis. The parameters are listed in Table 2 with their relative sensitivities on which was based the ranking presented in the table. The first ranked CN₂ could be categorized as ‘very important’ parameter and underlines the very important influence of land use and land cover on runoff generation. The parameters ranked 2 to 5

could be considered as ‘important’ and the remaining ones as ‘slightly important’ (van Griensven *et al.*, 2006). The result is similar to that of Adeogun *et al.* (2014) where CN₂ ranked first followed by those categorized as ‘important’ in this study though not in the similar order as in this study. The result is also comparable to those of other similar studies (Qiu *et al.*, 2012; Shawul *et al.*, 2013).

Table 2. The sensitive model parameters with their relative sensitivities and ranking

Parameter Code	Definition	Relative sensitivity	Rank
CN ₂	Moisture condition II curve number	1.250	1
GWQMN	Threshold depth of water in the shallow aquifer for base flow to occur (mm H ₂ O)	0.935	2
RCHRG_DP	Aquifer percolation coefficient	0.534	3
SOL_Z	Depth from soil surface to bottom layer (mm)	0.354	4
ESCO	Soil evaporation compensation coefficient	0.201	5
SOL_AWC	Soil available water capacity (mm/ mm)	0.054	6
CH_K2	Effective hydraulic conductivity of channel (mm/ hr)	0.027	7
BLAI	Maximum potential leaf area index	0.016	8
CANMX	Maximum canopy storage (mm H ₂ O)	0.011	9
SURLAG	Surface runoff lag coefficient	0.006	10
GW_DELAY	Delay time for aquifer recharge (days)	0.006	11
ALPHA_BF	Base flow recession constant	0.004	12
SLSUBBSN	Average slope length (m)	0.004	13
EPCO	Plant uptake compensation factor	0.004	14
SOL_K	Saturated soil hydraulic conductivity (mm/ hr)	0.002	15
SLOPE	Average slope of the sub-basin	0.002	16
CH_N2	Manning’s “n” for the main channel	0.002	17

Calibration and Validation

The comparisons between the measured and simulated discharges are presented in Figures 5 and 6 for the model calibration and validation respectively. The R² and NSE for comparisons were 0.57 and 0.51 respectively and for the calibration data set. The corresponding values for the validation set were 0.71 for R² and 0.65 for NSE. The performance of the model was considered to be good considering the limited data available for the study. Only a rainfall station with the relevant records related to the limited flow

data at a gauging station were used. The R² and NSE values obtained however exceeded 0.5 suggested by Moriasi *et al.* (2007) as the acceptable minimum. The calibration and validation results were also comparable to the acceptable results obtained by Abbaspour *et al.* (2015) in a continental-scale application of SWAT in Europe. It should be noted that in contrast with the performance during calibration, the model in validation under-predicted the peak flows by 18.1 to 34.6% in 9 out of the 12 hydrological years (Figure 5).

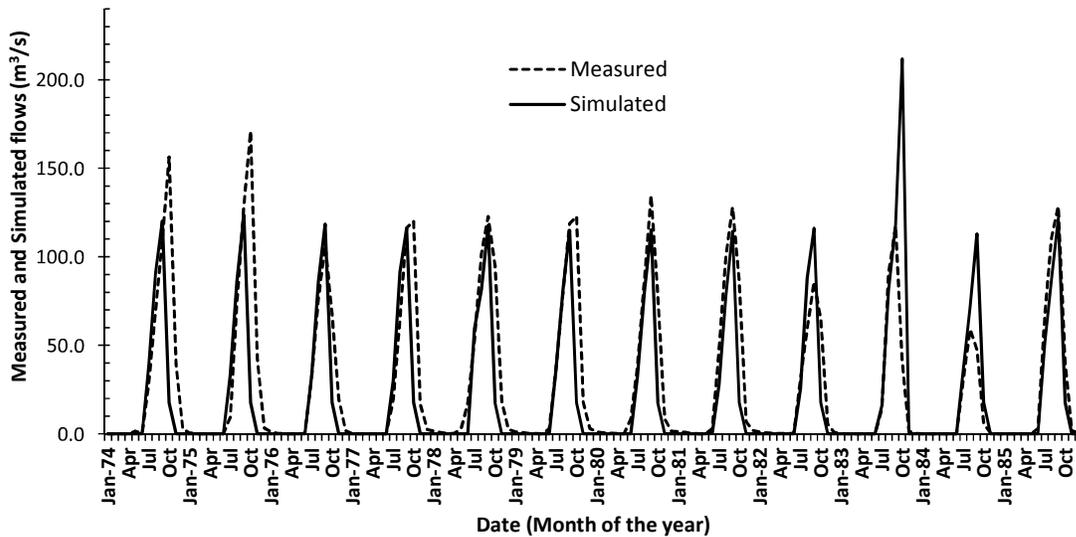


Figure 5: Measured average daily flows at Gashua and simulated flows obtained during model calibration

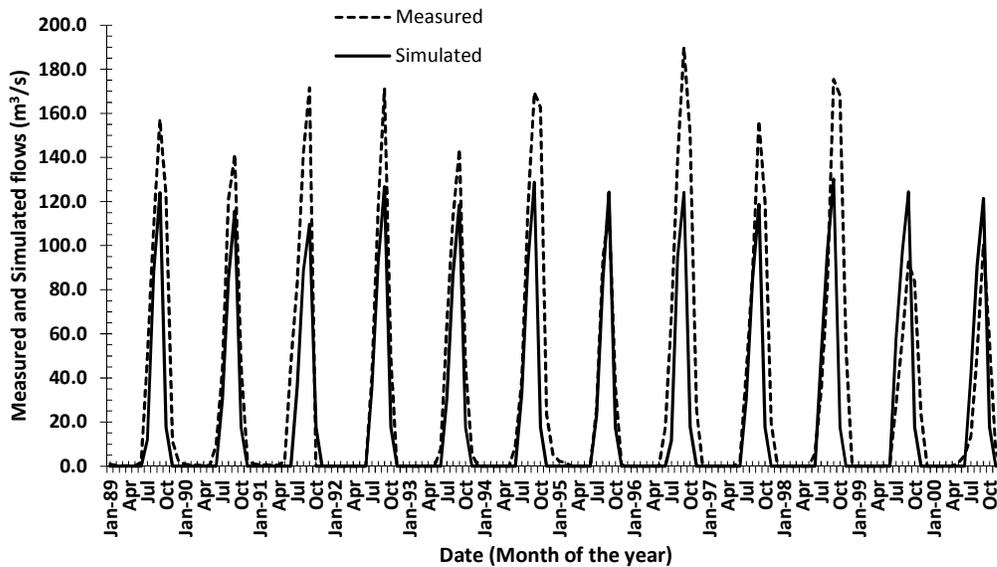


Figure 6: Measured average daily flows at Gashua and simulated flows obtained during model validation

This could be attributed to the higher number of relatively wetter years in the validation data set. With the most significant rainy period as June to September (Table 1) peak flows usually occurred in the month of September (Figure 5). The average total June to September rainfall for the 1974 to 2000 period was 762.6 mm. This average total

was exceeded by 14.3 to 130.7 % in the validation years in which the peak flow under-prediction occurred. The implication is that model may yield conservative estimates of available blue water (Hoekstra *et al.*, 2011) in years in which the seasonal rainfall is above average.

Conclusion

Based on the calibration and validation results the SWAT Model performed well in the simulation of runoff stream flow from the Hadejia-Jama'are-Komadugu-Yobe-River Basin. The good R^2 and NSE obtained suggest that SWAT could be useful as a decision support tool for water resources management policies in the basin. The most sensitive of the 17 important model parameters determined during calibration was CN_2 which relates to land cover and land use. The other 16 in order of decreasing sensitivity were GWQMN, RCHRG_DP, SOL_Z, ESCO SOL_AWC, CH_K2, BLAI, CANMX, SURLAG, GW_DELAY, ALPHA_BF, SLSUBBSN, EPCO SOL_K, SLOPE and, CH_N2. In view of the peak flow under-prediction identified during validation, resuscitation of stream flow measurements and increasing the number of functional rainfall and gauging stations would be necessary in the basin for the collection of more temporally and spatially extensive data necessary for the refinement of the results of this study.

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