EVALUATION OF THE SWAT MODEL IN SIMULATING CATCHMENT HYDROLOGY: CASE STUDY OF THE MODDER RIVER BASIN

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Abstract

This paper presents the set-up and the performance of the SWAT model in the Modder River Basin. Two techniques widely used, namely quantitative statistics and graphical techniques, in evaluating hydrological models were used to evaluate the performance of SWAT model. Three quantitative statistics used were, Nash-Sutcliffe efficiency (NSE), present bias (PBIAS), and ratio of the mean square error to the standard deviation of measured data (RSR). The performance of the model was compared with the recommended statistical performance ratings for monthly time step data. The model performed well when compared against monthly model performance ratings during calibration and validation stage.

Keywords: SWAT model, Modder River Basin, Hydrological models.

1. INTRODUCTION

Hydrological models aid in answering questions about the effect of land management practices on quantity and quality of runoff, infiltration, subsurface flow (both unsaturated and saturated) and deep percolation. The objective of hydrologic system analysis is to understand the system operation and predict its output (Chow et al., 1988). These hydrological models rely on observed (measured) data to produce hydrologic response of the catchment. Hydrologic models aid in answering questions about the effect of land management practices on quantity and quality of runoff (Hundecha & Bárdossy, 2004; Sahel & Du, 2004; Linard et al., 2009; Moriasi et al., 2012).

Hydrologic process of the C52B quaternary catchment was simulated using Soil and Water Assessment Tool (SWAT) model. The model (SWAT) set-up was followed by model evaluation in simulating stream flow and also on its possible use for similar purposes in the future.

The modelling system allows the user to estimate water quantities available for extraction at any point and time, and represent the dynamics of soil-water, which controls plant growth and chemical cycling (Schattenberg, 2011). In SWAT the catchment is divided into multiple sub-catchments which are further subdivided into hydrologic response units (HRUs) that consist of homogenous land use, management and soil characteristics.

The HRUs represent percentages of the sub-catchment area and are not identified spatially within a SWAT simulation. Alternatively, a catchment can be subdivided into only sub-catchments that are characterised by dominant land use, soil type, and management (Winchell et al., 2007; Gassman et al., 2007).

The SWAT model has been widely used and applied worldwide to address water quantity and water quality issues (Arnold & Allen, 1996; Butts et al., 2004; Bouraoui et al., 2005; Chaplot et al., 2005; Kim & Pachepsky, 2010; Oeurng et al., 2011). SWAT has also been applied in South Africa to model effect of land use change on hydrology of the catchment (Govender & Everson, 2005; Welderufael et al., 2013). Gassman et al. (2007) grouped SWAT applications under broad categories such as hydrologic only, hydrologic and pollutant loss or pollutant loss only to assess model efficiency in the reported studies.

In this study SWAT model was evaluated for simulating the monthly stream flow of the quaternary catchment C52B. Successful model evaluation comprises both operational and scientific examination (Willmott et al., 1985). Operational examination evaluates model's precision and accuracy. Accuracy is the extent to which model-predicted values approach a corresponding set of measured observations (Loague & Green, 1991; Legates & McCabe, 1999). Evaluation of model performance should include both statistical criteria and graphical displays. Moriasi et al. (2007) recommend the use of both graphical techniques and quantitative statistics in model evaluation. This combined assessment approach can be useful for making comparative evaluations of model performance between alternative/competing models (Loague & Green, 1991).

The objectives of this study are:

- To set-up the SWAT model for the catchment condition and run the model
- To calibrate and validate the SWAT simulation results.
- To assess the performance of the SWAT model using efficiency criteria.
- Material and methods

2.1 Description of the Modder River basin area

The whole Modder River basin is a large basin with a total area of 17366 km2. The study site is located within the Upper Orange Water Management Area to the east of the city of Bloemfontein (central South Africa).

The study site, C52B, is a sub-catchment of C52 catchment or its one of the quaternary catchments of C52. The area of the study site is 949 km2. The Mean Annual Evaporation (MAE) of C52B quaternary catchment is 1570 mm, Mean Annual Precipitation (MAP) of 563 mm and with Mean Annual Runoff (MAR) of 39x106 m3 (Midgley et al. 1994). The climate of the area is semi-arid.

2.2 Delineation of the catchment

The SWAT model can be applied with different spatial discretisation schemes, but most users apply it in a semi-distributed way, that is supported by ArcView interface (Neitsch et al., 2005). Catchment was delineated by following the five steps in ArcSWAT including digital elevation model (DEM) set-up, stream definition, outlet and inlet definition, and calculation of subbasin parameters. The study area was manually delineated by drawing the polygon around/masking the study area (Figure 1). In the SWAT model subbasins are calculated as contributing area to an individual stream channel. Threshold value of 930 hectares was used and 24 subbasins were created.

Streamflow network was edited by manually adding an outlet to the catchment at known location or at existing gauging station of the catchment which is useful for the comparison of the predicted and observed streamflow data. Lastly subbasin parameters were calculated.

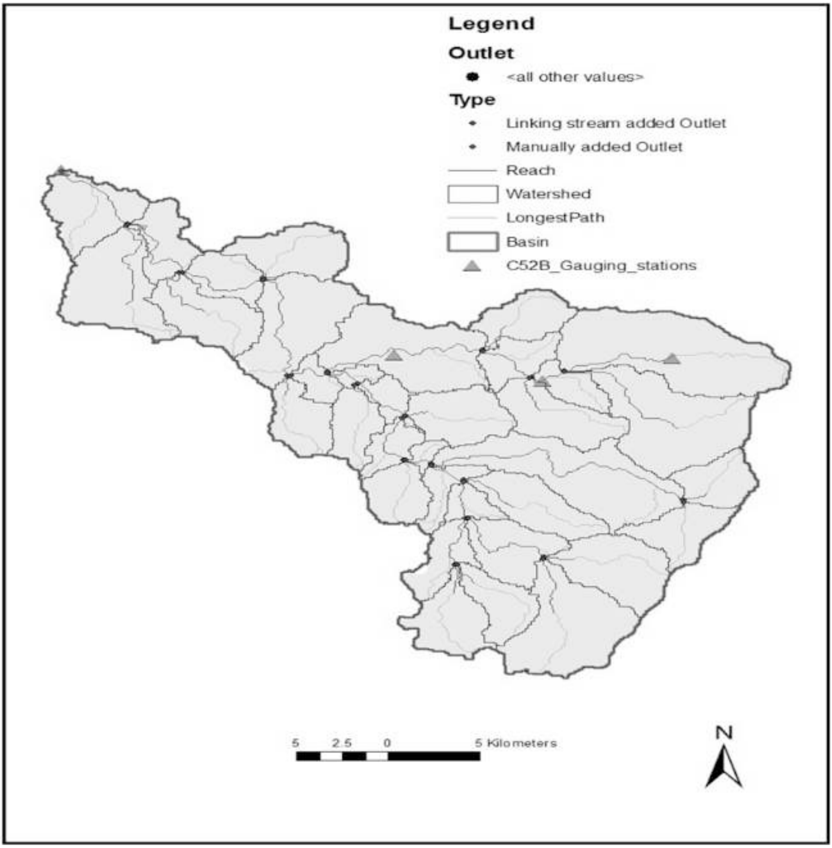


Figure 1. Delineated catchment.

2.3 Input data

The SWAT model, like any other model, requires large amounts of data, depending on the scale of the project. Data preparation is the most important aspect, but was the most time consuming process in this study. The Digital Elevation Model used in this project was for the whole C5 catchment. Daily weather data, such as measured precipitation, wind speed, maximum temperature and minimum temperature data was needed by SWAT model. One landtype (Dc 17) was adopted for the whole C52B because it was a dominant landtype in the subbasin. Observed monthly streamflow data was obtained for C5H003 gauging station.

2.4 Statistics for model evaluation

The NSE, RSR and Pbias, were calculated to evaluate the SWAT model's performance. The efficiency Nash and Sutcliffe (NSE) proposed by Nash and Sutcliffe (1970) is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation (Krause et al., 2005). The larger values in a time series are strongly overestimated whereas lower values are neglected (Legates & McCabe, 1999 cited by Krause et al., 2005). RSR is calculated as the ratio of the RMSE and standard deviation and optimal value is 0 (Moriasi, 2007). Percent bias (Pbias) measures the average tendency of the simulated data to be larger or smaller than their observed data (Moriasi, 2007).

3. RESULTS AND DISCUSSIONS

3.1 Model set-up

Original land use data obtained from land use map of 2000 was reclassified to fit the syntax and naming used by ArcSWAT hydrological model. The reclassified land use and the percentage cover area are shown in Table 1. Figure 2 is a graphical representation of the reclassified land use given in Table 1.

Table 1. SWAT Land use types and percentage area

LU SWAT	Area (%)
PAST (pasture: includes all grass lands)	81.6
AGRR (generic agricultural land)	5.3
WETN (wet land)	1.0
RNG (range land)	2.9
URBN (urban area)	8.7
FRSE (forest land)	0.1
WATR (water bodies)	0.3

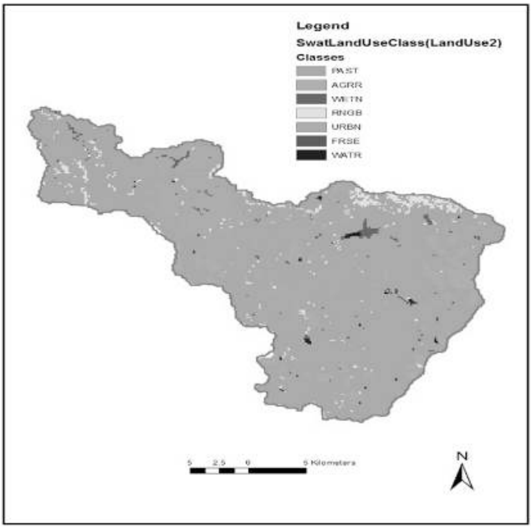


Figure 2. Land use map.

The digital elevation model, the land use and the soil map were used to delineate subbasins and HRUs. In ArcSWAT Multiple HRUs command was used to create HRUs for each subbasin in the hydrologic analysis. The threshold values used to create HRUs are 10% for land use, 0% for soil and 20% for slope in the HRU definition.

Model calibration involves adjusting model parameters to best fit between observed data and simulated data. The SWAT model contains many parameters which cannot be adjusted all at the same time. Therefore calibration procedure was performed by selecting most sensitive parameters to stream flow, namely soil parameters and curve number (CN) (Lenhart et al., 2002). Table 2 gives the top ten most sensitive parameters. Soil evaporation and curve number are the most sensitive parameters in this particular study.

Table 2. Parameters sensitivity analysis

Parameter	**Parameter Name**	**Rank**
Esco	Soil evaporation compensation factor	1
Cn2	Initial SCS CNII value	2
Sol_Awc	Available water capacity (mm H_2O/mm soil)	3
Sol_Z	Soil depth (mm)	4
Revapmn	Threshold water depth in the shallow aquifer for “revamp” (mm)	5
Gwqmn	Threshold water depth in the shallow aquifer for flow (mm)	6

Canmx	Maximum canopy storage (mm)	7
Alpha_Bf	Baseflow alpha factor (days)	8
Blai	Maximum potential leaf area index	9
Gw_Revap	Groundwater “revap[a]” coefficient	10

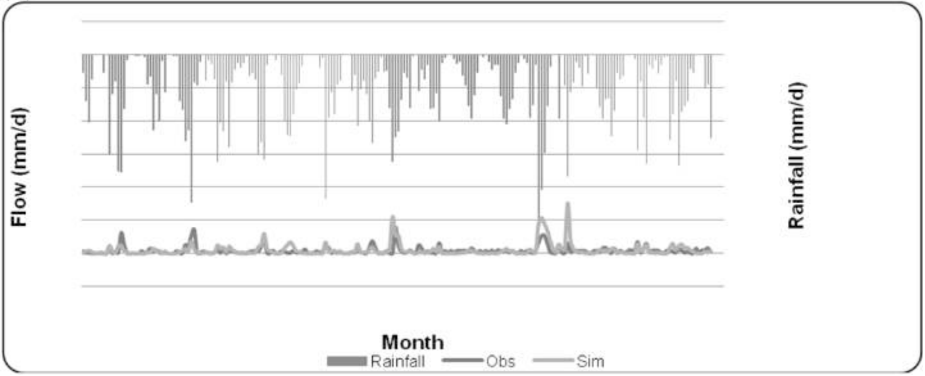
‘a’ Revamp: In SWAT model mean the movement into overlaying unsaturated layers as a function of water demand for evapotranspiration.

In the ArcSWAT interface auto-calibration and uncertainty input window, location of subbasin was specified where observed data will be compared against simulated output. The default value of 2000 for MAXN, the maximum number of trials allowed before optimization is terminated, was used. However optimization process stopped after 6730 trials because there was less than 1% change in the parameters. Streamflow parameters that were calibrated were selected with their default lower and upper calibration bounds. Model parameters were calibrated against measured data at a single gauge.

3.2 Simulation results

When model performance ratings were applied to the SWAT modelling of Modder river basin, C52B, the following results were obtained. Graphical representation of the monthly simulation result against observed flows for the period 1993 to 2010 before calibration is shown in Figure 3 (A). The model before calibration produced unsatisfactory results with high variation of minimum and maximum values in the flow pattern. The rate of change of the conditional mean simulated data with respect to observed data is equal to 0.848 and the correlation coefficient is equal to 0.29 (Figure 4: B).

(A)



(B)

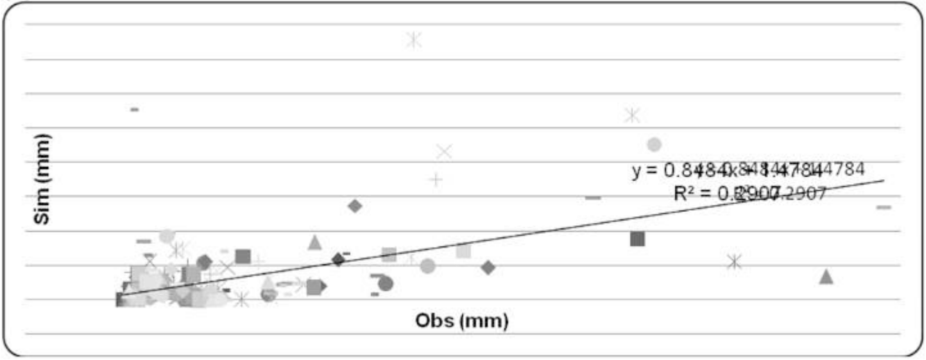
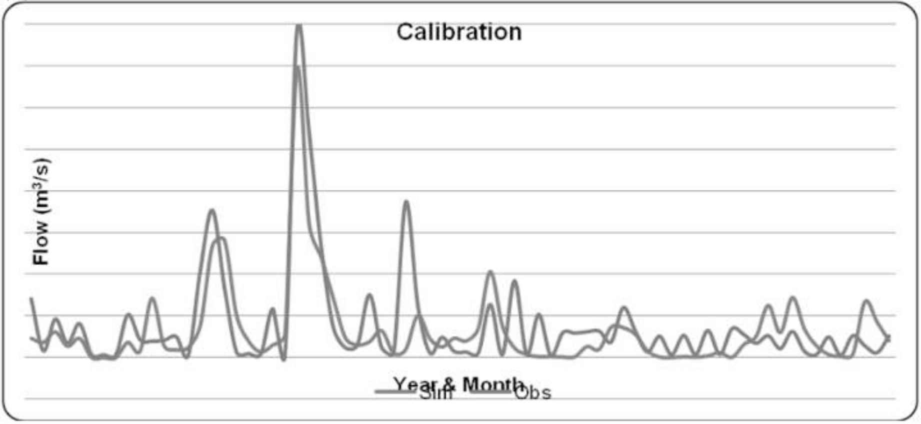


Figure 3. (A) Monthly streamflow hydrograph (1993-2010) and (B) linear regression of observed and simulated data before calibration.

The monthly predicted flows for calibration and validation stage (Fig.4.4: A & B) show that the model in general underestimate streamflow. This is also confirmed by the positive Pbias value during calibration and validation period, which indicates underestimation bias while negative value indicates overestimation bias by the model (Gupta et al., 1999; cited by Moriasi et al., 2007). In general calibrated and validated model results show a good comparison with the observed flow pattern.

(A)



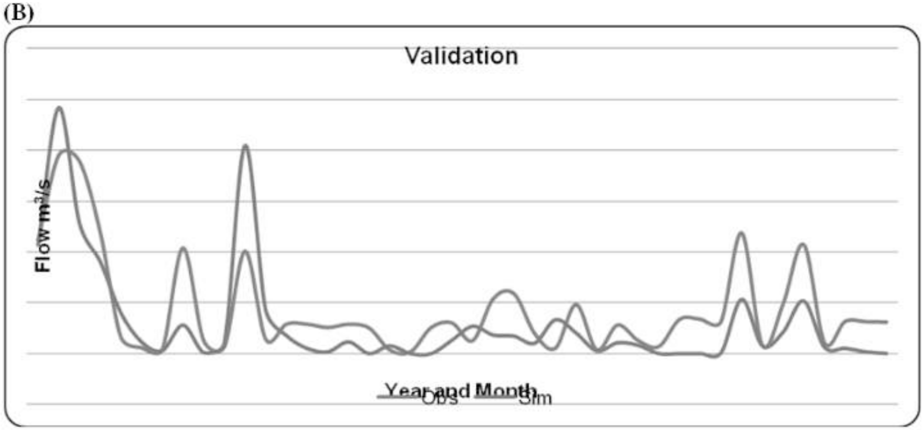
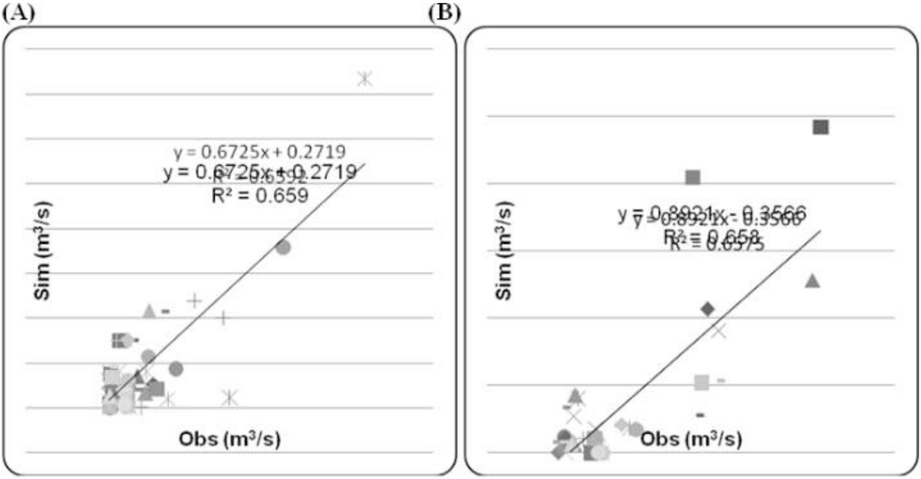


Figure 4. Monthly observed and simulated streamflow for (A) calibration stage and (B) validation stage.

Further graphical analysis of calibrated streamflow and validated streamflow, the accuracy of the model can be demonstrated (Figure 5: A & B). For monthly time step, the correlation of simulated streamflow and observed streamflow during calibration stage is R^2 value of 0.659 and R^2 value of 0.658 during validation stage. The yearly time step produced better correlation values, R^2 value of 0.840 during calibration stage and R^2 value of 0.994 during validation stage.



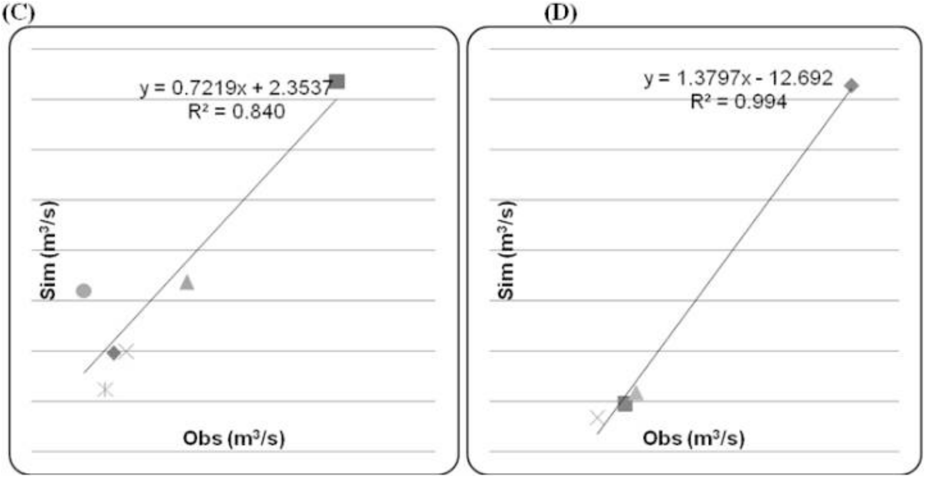


Figure 5. Observed and simulated data for (A) calibrated monthly flows, (B) validated monthly flows, (C) calibrated yearly flows, and (D) validated yearly flows.

Summary of the statistics of uncalibrated model, calibrated model and validated model for monthly and yearly time step are presented in Table 3. When comparing the model's performance against the model evaluation guidelines (Moriasi et al. 2007) presented in chapter 2 for monthly time step, SWAT2005 simulated the streamflow trends good to very good. RSR value of 0.4 gives the model performance rating of very good, NSE value of 0.65 gives the model performance rating of good and Pbias is equal to positive 15 indicating underestimation of the streamflow by the model but good performance rating during calibration stage. The underestimation might be because of the possible influence of inaccurately generated data or inconsistency in data for precipitation and temperature. Welderufael et al., (2013) reported Nash and Sutcliffe efficiency (NSE) of 0.57 for monthly streamflow and 0.68 for coefficient of determination (R^2) for daily streamflow of the Modder River at the outlet of a 419 Km^2 sub-catchment within C52A quaternary catchment, in central region of South Africa. Jha (2011) reported R^2 of 0.86 and NSE of 0.85 for calibrated monthly flows, and for validation the following monthly flows statistics was reported R^2 of 0.69 and NSE of 0.61. Srinivasan et al., (2010) reported R^2 of 0.75 and NSE of 0.74 for calibrated monthly flows, and for validation the following monthly flows statistics was reported R2 of 0.58 and NSE of 0.69. Bouraoui et al., (2005) reported R^2 of between 0.62 and 0.84 and NSE of between 0.41 and 0.84 for calibrated monthly flows. Coefficient of determination (R^2) value of 0.5 or greater for monthly time step calibrations is regarded as satisfactory model performance (Gassman et al., 2007), and for this study the R^2 is 0.66 and NSE is 0.65.

During validation stage the model performed well overall. The statistics at this stage for monthly time step are, RSR value of 0.5 which gives the model performance rating of very good, NSE value of 0.5 gives satisfactory model performance rating, and Pbias value of 31 shows that the model still underestimate streamflow. There was an improved performance by the model in representing the true system during calibration and validation stage from initial simulation, reaching acceptable performance level. Many reported that the SWAT model had shown better performance to the monthly time step simulation than the daily (Welderufael et al., 2013; Wang & Melesse, 2005). Wang & Melesse (2005) reported that SWAT model had a good performance in simulating the monthly, seasonal, and annual mean discharges, and results of this research project confirm those findings.

Table 3. Summary of statistics for ArcSWAT simulated versus observed data

Statistics	**Uncalibrated monthly**	**Calibrated monthly**	**Calibrated yearly**	**Validated monthly**	**Validated yearly**
NSE	-0.8	0.65	0.77	0.5	0.98
Pbias	-19	15	15	31	31
RSR	1.8	0.4	0.2	0.5	0.0
R^2	0.29	0.66	0.84	0.66	0.99
Slope	0.848	0.673	0.7219	0.892	1.380
Y-Intercept	1.478	0.272	2.354	-0.357	-12.692

The NSE indicates how well the plot of observed versus simulated data fits 1:1 line. The value between 0 and 1 are generally accepted levels of performance (Moriasi et al., 2007). RSR is calculated as the ratio of the RMSE and standard deviation, and optimal value is 0. Percent bias (Pbias) measures the average tendency of the simulated data to be larger or smaller than their observed data (Moriasi et al., 2007). RSR value between 0 and 0.5 is considered very good performance by the model.

3.3 Model limitations and performance

The limitation of SWAT in predicting daily flow is probably due to use of the curve number (CN2) method. A major limitation of the CN2 method is that rainfall intensity and duration are not considered, only total rainfall volume (Rallison & Miller; 1981 cited by Saleh & Du; 2004). The following are the reasons why curve number method was chosen over infiltration equation (Arnold et al., 1996):

a) Less than one day rainfall is not always available and difficult to process.
b) Often subbasins tend to be several km^2 when simulating large watersheds. It is easy to obtain weighted curve number and realistically simulate runoff.
c) Soils data is often available with insufficient spatial detail to justify using infiltration equation.
d) It relates runoff to soil type, land use, and management practices.

Calibration and validation results indicate that SWAT model is an effective watershed management tool that can be run with available data. The model demonstrated a satisfactory level of performance in modelling hydrology of this watershed. Harmel et al. (2006) highlighted inaccuracies in streamflow data as a major factor affecting SWAT hydrological output. Saleh & Du (2004) found model efficiencies to be higher for monthly predictions than for daily predictions.

4. CONCLUSIONS

The results suggest that SWAT model can be a useful tool, which once calibrated effectively, can produce meaningful catchment predictions to aid management decisions. The research used the model evaluation techniques graphical and statistical methods, to evaluate the performance of SWAT model in the study area. The hydrographs and the quantitative statistics NSE, RSR, and Pbias were used. The model performed well for the monthly time step simulation. During the calibration period the monthly stream flow gave the values for NSE, Pbias and R2 as 0.65, 15, and 0.66, respectively. The SWAT model also performed well during the validation period for the monthly streamflow simulation giving NSE, Pbias and R2 as 0.56, 31 and 0.66, respectively. But, it is recommended that further studies at various catchments in South Africa are needed to evaluate uncertainties in the model that affect model performance and the sensitivity of the distributed hydrologic simulations to different calibration schemes.

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