HYDROLOGIC RESPONSE MODELLING IN LUTANANDWA RIVER CATCHMENT, LIMPOPO, SOUTH AFRICA, USING SOIL WATER ASSESSMENT TOOL (SWAT) MODEL

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doi:10.37017/jeae-volume5-no1.2019-1

Publication Date: 30 September 2019

ABSTRACT

Flow simulation is important in planning and design of engineering hydraulic structures. The purpose of this study is to predict flow in the Lutanandwa river catchment in the Luvuvhu river basin, Limpopo, South Africa. The input data needed for SWAT model set up included Digital Elevation Model (DEM), hydro meteorological data, land cover and soils data acquired from various institutions in South Africa. The DEM was processed from contours in the Department of Hydrology and Water Resources, University of Venda. Meteorological data was acquired from the South African Weather Service (SAWS). Observed daily stream flow data was obtained from the Department of Water Affairs and Sanitation. Land cover data was acquired from processed satellite imagery obtained from the department of Environmental Affairs and ground truthing carried out to verify the land cover information. Soils information was obtained from the Agricultural Research Council – Institute of Soil, Climate, and Water (ARC-ISCW). The soils data was obtained in the form of geo referenced land type map. Based on assessment of the data status, the period 2002 to 2014 was selected for modeling. The meteorological data processed for this period was prepared in the appropriate format for model set up. Soil water characteristic calculator was used to estimate the soil properties required as input to SWAT model. The land cover types in the study area was converted to corresponding SWAT land use types. The statistical parameters required as input to the weather generator in the SWAT model was calculated using the pcpSTAT programme which was used to compute the parameters using weather information. All input data was processed and prepared in the appropriate format for model set up. The processed input data was loaded into the Geographic Information Systems (GIS) interface of the SWAT model to enable model set up for flow simulation.

Keywords: Data preparation, Model set up, hydrologic response

INTRODUCTION

Stream flow hydrographs measure the hydrologic response of catchments to the incident rainfall. Information on runoff is important in design of engineering hydraulic structures used in soil and water conservation, flood control, water storage and hydroelectric power generation. Modeling stream flow is important as it enables prediction of stream flow hydrographs. The ability to predict stream flow is needed in predicting impact of climate change and land use on catchment hydrologic response. Such prediction is important in water resources planning and management. While recognizing the importance of stream flow in information provision on problems related to design, Asati and Rathmore (2012) demonstrated the role of hydrological modelling as a means of comparing performance of various models in runoff prediction. This was accomplished by testing the models of interest on data set from the same watershed. Model comparison has been used in assessing suitability of models and conditions for their applicability to a catchment
Modelling stream flow allows for prediction of flow at outlets of ungauged catchments where such information is important in water resources planning and management. The Soil Water Assessment Tool (SWAT) model selected for use in this study is physically based and able to simulate stream flow to a high level of spatial detail through watershed division into sub basins (Santhi et al., 2006). It has been used for applications that include simulation of stream flow and sediment discharge under various land used and management practices world over with notable success (Ndomba and Birhanu, 2008) including simulation of the effect of climate change (Githui et al., 2008) and land use (Odira et al., 2010) on hydrologic response. It has been adapted to catchments of various sizes. The SWAT model has gained publicity worldwide as excellent assessment model for hydrological modelling and water resource management (Vilaysane et al., 2015). The purpose of this study is to demonstrate the role of SWAT model in predicting hydrologic response in the Lutanandwa river catchment, Limpopo, South Africa.

METHODOLOGY

Study area

The study was conducted in the Lutanandwa river catchment, a sub-catchment of the Luvuvhu river basin. The catchment lies between latitudes 22°59’12”S and 23°05’30”S and longitudes 30°09’58” 30°21’58”E and occupies an area of about 132.4km², a mean annual rainfall and evaporation of 1287mm and 1200-1600mm respectively. Rainfall is seasonal occurring mainly in the summer months being October to March strongly influenced by the Southernsberg Mountains. Temperature varies varies from 2 to 34°C with a mean value of 18°C. The catchment is dominated by sandy clay loam soil. Land use activities in the catchment mainly consist of forestry and agriculture in the upper reaches, and rural settlements downstream. The detailed description of the quaternary catchment designated A91D is presented by Odiyo et al., (2012) and illustrated in the Figure 1. The predominant land cover types in the catchment are shown in Figure 2.

![Figure 1](image_url): Location of the study area in Luvuvhu river catchment, rainfall stations, stream gauges and weather stations (Adapted from Odiyo et al., 2012)
Figure 2: Land use types in the Lutanadwa river catchment

Brief Model description

SWAT model is a process based, continuous physically based distributed parameter river basin model that simulates water, sediment and pollutant yields used to assist water resources managers assess impact of land use management on water, and diffuse pollution for large ungauged catchments with different soil types, land use and management practices (Levesque et al., 2008). A detailed review of the SWAT model and its historical development and applications of the SWAT model is comprehensively documented in Gassman et al., (2007). The model has been used for a wide range of applications for reasons that include its computational efficiency and flexibility on input data requirements (Stehr et al., 2008). Outputs from the model simulation include such hydrological variables as Stream flow, ground water flow, evapotranspiration, sediment yield, surface runoff among others.

Digital elevation model development

The Digital Elevation Model (DEM) was derived from digitized contours using appropriate tools in ArcGIS software. Figure 3 shows the DEM derived from the contours. The DEM was processed at the department of Hydrology and Water Resources, University of Venda.

Hydro meteorological data acquisition and processing

Stream flow data

Daily flow data was acquired from the department of Water Affairs and Sanitation for the station designated A9HO27. The station was damaged by floods in the year 2000 during when it was out of operation for a period of two years. This resulted into a break in the data collection.
for the period 2000 to 2002. Hence the period considered for modeling commenced from the year 2002 during when discharge data was continuously recorded to date. During the period 2002 and 2014, the daily flow data had had no gaps making it ideal for model calibration and validation purposes.

Weather data
This was acquired in the form of daily rainfall data and other weather information including daily maximum and minimum temperature, solar radiation, dew point temperature, relative humidity and wind speed acquired on a daily time step. The data was obtained from rainfall stations as well as automatic weather stations in the vicinity of the catchment. Sources of the weather information included the South African Weather Service (SAWS) and the Agricultural Research Council – Institute of Soil, Climate, and Water (ARC-ISCW), South Africa. The period chosen for simulation was 2002 to 2014 during when data was available continuously as required by the SWAT model. The weather data was used to compute the statistical parameters required as input to the SWAT model GIS interface. The statistical parameters computed for rainfall is tabulated below (Table 1). Similar parameters were computed for the other weather elements including temperatures (maximum and minimum), wind speed, solar radiation and relative humidity.

Statistical Analysis of Daily Precipitation Data (2002 - 2012)
Input Filename = rain0212.txt
Number of Years = 11
Number of Leap Years = 3
Number of Records = 4018
Number of NoData values = 200
Table 1 Statistical parameters for precipitation used as input data for the weather generator in the SWAT model GIS interface

| Month | PCP.MM | PCPSTD | PCPSKW | PR_W1 | PR_W2 |
|-------|--------|--------|--------|-------|-------|
| Jan.  | 251.62 | 20.4343| 4.5004 | 0.2717| 0.6561| 14.27 |
| Feb.  | 138.93 | 13.2570| 5.2289 | 0.2825| 0.5746| 12.18 |
| Mar.  | 207.87 | 20.0245| 5.3895 | 0.2914| 0.6627| 15.09 |
| Apr.  | 76.24  | 6.9295 | 5.0593 | 0.1705| 0.6460| 10.27 |
| May   | 20.26  | 3.4449 | 8.3582 | 0.0822| 0.4286| 4.45  |
| Jun.  | 32.12  | 4.6497 | 7.8605 | 0.1041| 0.5082| 5.55  |
| Jul.  | 30.07  | 4.5771 | 8.3984 | 0.0972| 0.4340| 4.82  |
| Aug.  | 22.40  | 2.8726 | 6.5043 | 0.1219| 0.4194| 5.64  |
| Sep.  | 35.67  | 3.2729 | 5.0687 | 0.1240| 0.6477| 8.00  |
| Oct   | 90.65  | 7.1653 | 4.2074 | 0.2677| 0.6154| 13.00 |
| Nov.  | 152.37 | 12.5932| 4.8265 | 0.2737| 0.6424| 13.73 |
| Dec.  | 194.53 | 14.0872| 4.0563 | 0.2895| 0.7354| 17.18 |

PCP.MM = average monthly precipitation [mm]
PCPSTD = standard deviation
PCPSKW = skew coefficient
PR_W1 = probability of a wet day following a dry day
PR_W2 = probability of a wet day following a wet day
PCPD = average number of days of precipitation in month

Soil data acquisition and processing

The soils information was obtained from the land type maps acquired from Agricultural Research Council – Institute of Soil, Climate, and Water (ARC-ISCW), in which fifteen land type units were identified. Figure 4 shows the various land types in the study area. The soil texture for the land types in the study area was determined based on the detailed description of the land types provided with the soils data. Specific soil properties are required as input to the SWAT model during the model set up. The Table 2 shows the estimated soil properties based on the use of Soil Water Characteristics Calculator which uses soil texture to estimate the properties based on the use of pedotransfer functions developed by Saxton et al., (2006).
**Figure 4:** Land types in the study area obtained from soils information acquired

**Table 2** Estimated soil properties derived from soil texture for the land types in the Lutanandwa river catchment

| Land type | Approx. Texture | Soil properties |
|-----------|-----------------|-----------------|
|           | Depth (mm)      | Ave. % clay (given) | % silt | % sand | TEX | Bulk density | Ks (mm/h) | AWC (cm/cm) | ROCK % | OM % | C |
| lb304     | 389             | 15.0             | 83.0    | 2.0    | S-L  | 1.59       | 1.88      | 0.22       | 5       | 0.0  | 0.0 |
| Ab109     | 1004            | 34               | 21      | 45     | S-C-L | 1.54       | 2.38      | 0.12       | 3.7     | 0.1  | 0.058 |
| Ab108     | 1016            | 33               | 22      | 45     | S-C-L | 1.55       | 2.63      | 0.11       | 3.0     | 0.1  | 0.058 |
| Ab173     | 807             | 36               | 19      | 45     | S-C   | 1.53       | 1.86      | 0.12       | 0.0     | 0.1  | 0.058 |
| lb440     | 389             | 15.0             | 83.0    | 2.0    | S-L   | 1.59       | 1.88      | 0.22       | 5.0     | 0.0  | 0.0 |
| Ab111     | 887             | 33               | 22      | 45     | S-C-L | 1.55       | 2.67      | 0.12       | 13.0    | 0.1  | 0.058 |
| Ab179     | 1058            | 25               | 30      | 45     | L     | 1.59       | 6.01      | 0.12       | 11.0    | 0.1  | 0.058 |
| Fa331     | 738             | 20               | 2       | 78     | S-L   | 1.64       | 5.83      | 0.06       | 1.7     | 0.0  | 0.0 |
| Ae260     | 981             | 30               | 25      | 45     | S-C-L | 1.57       | 3.64      | 0.12       | 0.1     | 0.0  | 0.0 |
| Bd48      | 580             | 14               | 3       | 83     | S-L   | 1.63       | 39.12     | 0.05       | 0.9     | 0.0  | 0.0 |
| Ab107     | 763             | 32               | 23      | 45     | S-C-L | 1.56       | 2.98      | 0.12       | 1.7     | 0.1  | 0.058 |
| Bb128     | 518             | 15               | 2       | 83     | S-L   | 1.63       | 35.72     | 0.05       | 0.0     | 0.1  | 0.058 |
| Ca91      | 568             | 18               | 30      | 52     | S-L   | 1.62       | 13.31     | 0.11       | 0.0     | 0.1  | 0.058 |
| Fa306     | 183             | 15.0             | 83      | 2.0    | S-L   | 1.59       | 1.88      | 0.22       | 0.0     | 0.0  | 0.0 |
| Fa308     | 443             | 17.0             | 3       | 80     | S-L   | 1.64       | 27.66     | 0.06       | 0.0     | 0.0  | 0.0 |
Based on the soil properties estimated from soil texture for each land type, the estimated soil properties are recorded into the GIS interface of SWAT by incorporating the land type and properties into the interface as shown in Figure 5.

**Land use data acquisition and processing**

The land cover information was obtained from the department of Environmental Affairs website. The land cover information was derived from processed satellite image. The land cover types were then converted to the equivalent SWAT land use types as shown in Table 3.

![Figure 5: ArcView interface of SWAT illustrating incorporation of soil properties](image)

**Table 3** Conversion of land cover to SWAT land use types

| land use                                      | SWAT land use              | SWAT land use code |
|-----------------------------------------------|---------------------------|--------------------|
| Thicket and bush land                         | Range-grasses             | RNGE               |
| Forest plantation                             | Mixed forest Land         | FRST               |
| Unimproved grassland                          | Bermuda grass             | BERM               |
| Forest                                        | Evergreen Forest Land     | FRSE               |
| Cultivated: Temporary – semi commercial/subsistence dryland | Agricultural Land-Generic | AGRL               |
| Cultivated: permanent – commercial dryland    | Orchard                   | ORCD               |
| Urban/built-up: residential                   | Residential-Medium density| URMD               |
| Degraded: Forest and Woodland                 | Mixed forest Land         | FRST               |
| Forest and Woodland                           | Forest-deciduous          | FRSD               |
Model set up

The automatic delineation dialogue box embedded in the GIS interface of SWAT was used to load the input data that included DEM, to carry out stream definition, addition of catchment outlet and catchment delineation into sub basins and hydrologic response units. Based on the DEM and subsequent stream definition, the watershed was automatically delineated into seven sub basins from a manually digitized masked area derived from the DEM boundary. In the HRU definition, the dominant land use option was used resulting into a single HRU for each sub-basin. The input weather data included the daily rainfall, maximum and minimum temperature. Inputs to the weather generator included daily rainfall, temperatures, solar radiation, wind speed and relative humidity. The trial simulation run was performed on a daily and monthly time steps within the period 2002 to 2014 selected on the basis of availability of stream flow data on a continuous basis devoid of breaks or gaps in data acquired a requirement for calibration and validation processes.

RESULTS AND DISCUSSION

Preliminary simulation of hydrologic response

Daily flow simulations

Flow simulation was carried out after model set up. The year 2002 was used skipped for model warm up. The period 2003 to 2014 was then used for model simulations. A preliminary comparison of observed and simulated daily flow was performed in the period 2004 to 2008 to make a preliminary assessment of the model performance. This period was chosen being when the land cover was considered to be representative. Figure 6 show the hydrographs of observed and simulated total flow during this period.

Figure 6: Observed and simulated daily flow during the period 2008 to 2012
The hydrographs of simulated and observed flows tend to follow the same pattern. In general, the model seems to over predict the high flows especially the peak flows but under-predict low flows. Possible reason for over-prediction may be attributed to the differences in the model approach to flow determination and that used in flow observation. Observation of flow is instantaneous reading while the prediction is based on average daily flow. Considering the small size of the catchment, possibility could be that the observations were made when the peak flow has already passed the catchment outlet so that a lower value than the actual peak flow is recorded when reading is taken. The extent to which the low flows are under predicted does not appear to be as pronounced as that to which the high flows are over predicted to the extent that the predicted and observed low flow almost fit. The timing of the peak flows is the same in most instances, i.e. the hydrographs are not out of phase. Figure 7 shows the comparison of observed and simulated flows based on scatter plots and using linear regression for model evaluation.

Based on this initial simulation run, prior to model calibration, the value of coefficient of determination $R^2 = 0.30$ ($r = 0.55$) while that of the Nash Sutcliffe Efficiency (NSE) = -0.64, a reflection of unsatisfactory performance based on this preliminary assessment. Values of other performance measures e.g. Root mean square error (RMSE) = 32.15 and the ratio of RMSE and the standard deviation of measured data (RSR) =1.28 also reflected unsatisfactory performance in this first instance. Reasons for unsatisfactory results are partly attributed to the assumption of a single Hydrologic Response Unit (HRU) for each sub-basin during the HRU definition in model set up. Such an assumption results into a poor representation of the sub-basin characteristics also observed by Vilaysane et al., (2015) who points out that multiple scenarios would give a better stream flow estimation. Other possible reasons include poor representation of rainfall for the area in question. Over estimation or under-estimation of rainfall may cause discrepancies in runoff prediction. SWAT model allocates rainfall to a location based on the rain gauge nearest to it according the Thiesen polygon approach to areal rainfall determination which also ignores relief effects. Rainfall varies significantly spatially even within short distances, hence there is possibility of assigning more rainfall that would have occurred resulting into over-prediction of daily stream flow. However, improved performance is expected for monthly flow simulations.

![Figure 7: Scatter plot for Observed and predicted daily stream flow based on linear regression](image-url)
Monthly flow simulation

Subsequent to the daily simulations, flow simulation was carried out for the same period as was done for daily flow i.e. 2008 to 2012. Figure 8 show the monthly flow hydrographs for the simulated and observed flows during this period.

It is evident from the monthly flow hydrographs that the model over predicts high flows. This is also supported by the value of deviation volume (Dv) calculated to be -122.50 which measures the extent to which a model over-predicts the observed values indicating gross over prediction. The flow patterns are however similar. The high peak values are over-predicted. However, the simulated flows closely match the observed flows during the low flows, except for a few isolated instances when there is a slight under-prediction of the low flows e.g. during the period July to October 2009 and also in the period September to October 2011. Figure 9 show the scatter plot between the observed and predicted average daily flow in month for the same period.

![Figure 8: Observed and simulated average daily stream flow in month during preliminary simulation](image1)

![Figure 9: Comparison of observed and simulated average daily flow in month based on scatter plot](image2)
Based on the coefficient of determination $R^2 = 0.62$ ($r=0.78$), the model performance is satisfactory (>0.5) and therefore acceptable. Values of other performance measures however indicated otherwise.

The NSE = -8.15 PBIAS = -128.9 (>25), RMSE (=10.36>0.7) and RSR (= 3.03>0.7) also reflected unsatisfactory performance ((Moriasi et al., 2007. Unsatisfactory performance is partly attributed to uncertainty on input rainfall data. There are instances where high rainfall is recorded resulting into high runoff response and predicted stream flow, however the observed flows shows no such response. This may be associated with uncertainty of the rainfall data due to possible errors or misrepresentation of the rainfall in the area in question by the selected rain gauge record. Other factors could be the poor prediction of the soil properties. Such properties are required as input to SWAT model, however they were not available and had to be estimated based on soil texture information. Such estimation is approximate based on use of pedotransfer functions. Poor estimation of, say, Available Water Capacity will overestimate or underestimate the soil storage capacity and hence the amount of water available as runoff during rain storms and subsequently yield poor prediction of stream flow. Runoff is sensitive to land cover characteristics which influence the curve number (CN) values. The land cover types had to be converted to corresponding SWAT land use types during model set up. Such approximations of land use may not be representative of the actual land cover type thereby influencing the predicted stream flow. This is more pronounced with high flows that produce runoff and high stream flow. Poor representation of topographic graphical characteristics resulting from unrepresentative DEM may also cause discrepancies in stream flow prediction. Table 4 presents a summary of the performance measures during the preliminary simulation run. Unsatisfactory performance is expected during preliminary simulation runs since no adjustment has been made with regard to the sensitive model parameters. Improved performance is expected during calibration and validation processes.

The model shows promise of good performance in simulation of stream flow especially with respect to improved value for coefficient of determination ($R^2$) during monthly flow simulation. Also, the fact the patterns of flow are fairly well simulated except that the high flows are grossly over-predicted. The model also simulates the low flow fairly well judging from the reasonably close-fitting hydrographs for the low flows both in the case of daily and monthly flow simulations. The model shows promise for use in low flow simulation.

Table 4 Measures of model performance in stream flow prediction during preliminary flow simulation

| Time step | Performance Measures |
|-----------|----------------------|
| R² | RMSE | RS | V | PBIAS | NSE |
| Daily | 0.30 | 32.15 | 1.28 | -25.54 | -25.6 | -0.64 |
| Monthly | 0.60 | 10.4 | 3.02 | -122.5 | -128.9 | -0.85 |

CONCLUSION

The model was able to simulate hydrological stream flow during preliminary simulation run after model set up. The initial performance of the SWAT model in simulation of hydrologic response based on the daily flow simulation is unsatisfactory in this first instance. Several reasons are associated with this performance which includes the uncertainty associated with respect to daily flow simulations owing to the differences in which the model predicts flow and the manner in which observations are made to obtain measured flows. Assumption of single HRU per sub basin during model set up was identified as another possible reason. Improved simulation is also achievable through the more representative approach to model set up which includes use of multiple scenarios in HRU definitions as opposed to the assumption of single HRU per sub basin. Other reasons cited for poor model simulation included poor rainfall
representation or uncertainty with rainfall data, used of unrepresentative land use description, estimation of soil properties etc. Improved simulation performance based on the coefficient of determination ($R^2$) was observed during monthly flow simulations. Better performance is expected in the subsequent calibration and validation periods. The model shows promise for use in stream flow prediction in the catchment.

ACKNOWLEDGEMENTS

The author wishes to thank the University of Venda through which funding for this project was obtained through the Directorate for Research and innovation. Special thanks to the support obtained from staff at the department of Hydrology and Water Resources for processing some of the input data for model set up. I also wish to acknowledge support obtained from various institutions in South Africa who provided the raw data for this research and included the South African Weather Service (SAWS), Department of Environmental Affairs, Department of Water and Sanitation (DWAS), ESRI South Africa for training in GIS and Agricultural Research Council – Institute of Soil, Climate, and Water (ARC-IS CW).

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