# Application of SWAT model for simulation of runoff in micro watersheds of lower Himalayan region of India



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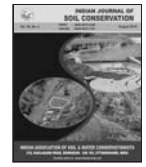
*Vol. 44, No. 2, pp 133-140, 2016*
Indian Journal of Soil Conservation
Online URL:http://indianjournals.com/ijor.aspx?target=ijor:ijsc&type=home



# Application of SWAT model for simulation of runoff in micro watersheds of lower Himalayan region of India

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**ARTICLE INFO**

***Article history :***
Received : October, 2014
Revised : December, 2015
Accepted : April, 2016

***Key words:***
AVSWAT-X,
Calibration,
Micro watershed,
Runoff,
SWAT model,
Validation

**ABSTRACT**

The physically based Soil and Water Assessment Tool (SWAT) was applied to two micro watersheds of lower Himalayan region of India. Areas of the micro-watersheds are 21 ha (*Choe* watershed) and 70.45 ha (W3B watershed), respectively, with the land use of range brush and mixed forest. Nine years and twelve years monthly rainfall data, respectively were used to simulate the hydrological behaviour of these watersheds. In order to establish the effectiveness of model to simulate hydrological responses to climatic variations, the simulated values were subjected to rigorous calibration with observed runoff data on a monthly time scale. The model was calibrated for the period 1973-1978 and 1971 to 1980, respectively for monsoon months and validated for the period 1979-1981 and 1982-1984, respectively for micro watersheds, *Choe* and W3F. Both, calibration and validation outputs were found to be reasonably acceptable with Nash Sutcliffe efficiency (NSE) as 66.4 and 80.2% for calibration period for *Choe* and W3B watersheds, respectively. NSE values for validation for *Choe* and W3B watersheds were also found to be 73.3 and 72.1%, respectively suggesting better parameterization and simulation performance. Since the database on SWAT model's potential in simulation performance on micro watershed scale is scanty, this paper was successful in showcasing the potential of SWAT in simulating the runoff of micro-watersheds of lower Himalayan regions.

## 1. INTRODUCTION

The SWAT is a river basin model that was developed jointly by the United States Department of Agriculture-Agricultural Research Services (USDA-ARS) and Agricultural Experiment Station in Temple, Texas (http://www.brc.tamus.edu/blackland/). SWAT has been extensively used since 1993 mainly by Hydrologists for watershed hydrology related issues. Application of SWAT can broadly be grouped in four classes. These are (i) Climate change and land use impact studies; (ii) hydrologic studies; (iii) comparison of SWAT with other models; and (iv) water quality studies. This paper mainly deals with hydrologic studies. Some of the hydrologic studies using SWAT were carried out by Arnold *et al*. (1996); Srinivasan *et al.* (1998); Arnold *et al.* (1999a); Arnold *et al.* (1999b); Spruill *et al*. (2000); Chanasyk *et al.* (2003); Tripathi *et al.* (2004); Afinowicz *et al*. (2005); Cao *et al.* (2006); Kannan *et al*. (2007); Liu *et al.* (2008); Rostamian *et al*. (2008); Rossi *et al.* (2008); Schuol *et al*. (2008); Wu and Johnston (2008); Jadhao and Tripathi (2009); Jain *et al*. (2010); Agrawal *et al.* (2011); Jha (2011); Akiner and Akkoyunlu (2012); Kushwaha and Jain (2013).

SWAT, a river basin model is currently one of the world's leading spatially distributed hydrological models. It is continuous time model developed originally by the USDA-ARS and Texas University (Arnold *et al*., 1996, 1998). It divides a watershed into smaller discrete calculation units for which the spatial variation of the major physical properties are limited, and hydrological processes can be treated as being homogeneous. The total watershed behaviour is a net result of several small sub-basins. The soil map and land use map within sub-basin boundaries are used to generate a homogeneous physical property, *i.e.* Hydrological Response Unit (HRU). The water balance for HRUs is computed on a daily time step. Hence, SWAT subdivides the river basin into units that have similar characteristics in soil and land cover and that are located in the same sub-basin. SWAT model has been tested for predicting runoff (Srinivasan and Arnold, 1994). Data of several years is required for development of a long term plan for homogeneous watersheds. The hydrologic component of SWAT is based on the following water balance equation:

$$Sw_t = SW + \sum_{i=1}^{t} (R_i - Q_i - Et_i - P_i - QR_i) \quad ...(1)$$

Where, $SW_t$ = final soil water content (mm), $SW$ = water content available for plant uptake, defined as the initial soil water content minus the permanent wilting point water content (mm), $t$ = time in days, $R$ = rainfall (mm), $Q_i$ = surface runoff (mm), $ET_i$ = evapotranspiration (mm), $P_i$ = percolation (mm) and $QR_i$ = return flow. SWAT incorporates some of the most common hydrological equations for the simulation of flow. For accurate implementation of these equations, detailed input data are needed. Some important information for simulation is the Digital Elevation Model (DEM) of the watershed, the soil and land use data and the weather data of the area. The importance of land uses in the operation of the model lies mainly in the computation of surface runoff with SCS curve method. The model includes in its database 102 different land use types, each one assigned respective CNII value (Curve Number for hydrological condition II). The user is required to link each of the land uses that appear in the watershed, to the ones that the model can identify. The success of the simulation depends highly on the accuracy of soils and land uses.

In India, like most of the developing countries in the world, the majority of the basins are either sparsely gauged or not gauged at all. This necessitates the application of a robust model for estimation of runoff. Literature on application of SWAT for simulating runoff from micro-watersheds in developing countries is limited. In the present study the main objective was to evaluate the applicability and performance of SWAT model in predicting monthly runoff for two lower Himalayan micro-watersheds and to identify most sensitive parameters for prediction of runoff. In order to achieve the objectives calibration, validation and sensitivity analysis, were carried out.

## 2. MATERIALS AND METHODS

### Study Area

SWAT was applied to two micro-watersheds of lower Himalayan region of India. These micro watersheds are named as *Choe* and W3B, respectively. Area of selected micro-watersheds is 21 and 70.45 ha, respectively. The annual average rainfall of micro-watersheds is 1100 and 2073 mm, respectively. Details of watershed parameters of both the watersheds along with the landuse are given in Table 1. Loamy sand is the dominant soil types in *Choe* watershed. However, alluvial medium texture is the dominant soil types in W3B watershed. Meteorological station is located near the micro watershed in both cases. Surface runoff occurs in these micro-watersheds during rainy season (June to September). For *Choe* micro watershed, nine years (1973-81) monthly data was taken up to model the hydrological output. The model was calibrated for the period from1973 to1978 using the parameters based on sensitivity analysis and validated for the period from 1979 to1981. For W3B watershed, twelve years (1971, 1973-80 and 1982-84) monthly data was taken up to model the hydrological output. The model was calibrated for the period for 1971 and 1973-1980 using the parameters based on sensitivity analysis and validated for the period from 1982 to 1984.

### Digital Elevation Model

The DEM was from Triangulated Irregular Network (TIN) created from contours of the spot elevation surveyed for the whole watersheds. The drainage Networks traced using the GPS was merged and burnt on the DEM data to exactly align the watershed outlets. DEM of both watersheds are shown in Fig.1. The salient morphological features of the study watersheds are shown in Table 1.

### Landuse Data

The predominant land use and land cover of the micro watersheds Choe and W3B are range brush and forest,

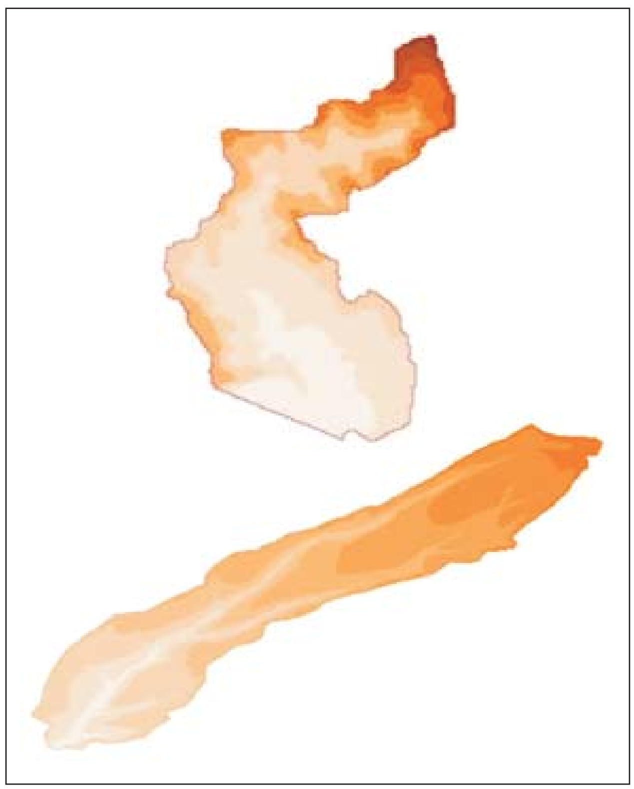

**Fig. 1. DEM of *Choe* and W3B watersheds**

**Table: 1**
**Morphological characteristics of micro-watersheds**

| Watershed Parameters | *Choe* | W3B |
|---|---|---|
| Area, ha | 21 | 70.45 |
| Length width ratio | 1.33 | 7.60 |
| Length of main drain, m | 1080 | 2289 |
| Average slope, % | 10 | 6 |
| Relief, m | 81 | 50 |
| Time of concentration, min | 11.43 | 32.65 |

respectively and the details were derived using the google earth high resolution imageries and GPS reconnaissance in the watersheds. The classification schemes were adopted using the threshold visual colour separation techniques identical to colour signatures of the land use codified using the GPS data of the geo rectified google earth images (jpeg images) captured from the GE interface. The classification was carried out using ERDAS imagine corrected to merge the unclassified cells into the nearest neighbourhood cells. The classified land use map is shown in Fig. 2 and other details are shown Table 2.

### Weather Data

Weather data such as daily precipitation, maximum and minimum air temperatures, wind speed and relative humidity were collected from the nearby meteorological observatory located in the vicinity of the watersheds.

### Soil Database

The SWAT database compatible soil input parameters were collected from various sources. The basic soil parameters were analysed for texture and other relevant physico-chemical parameters. Some parameters were generated using pedo-transfer functions software SOILWATER (Saxton *et al*., 1986). A series of attributes were assigned to type of soil, namely depth, saturated hydraulic conductivity and content of sand, silt and clay. Soil classification of the watershed is important for the model as soil in combination with land use determines the HRUs of the watershed.

### Model Setup

The SWAT model was setup using Arc View-SWAT interface (AVSWAT-X version 2005) for both the watersheds. The DEM processing was done by burning the actual drainage networks and Sub-basins were delineated. Mapping the soil and land use, the HRUs were also prepared after assigning appropriate memberships of land use, soil and slope characteristics. The details of the delineation are as shown in Table 3.

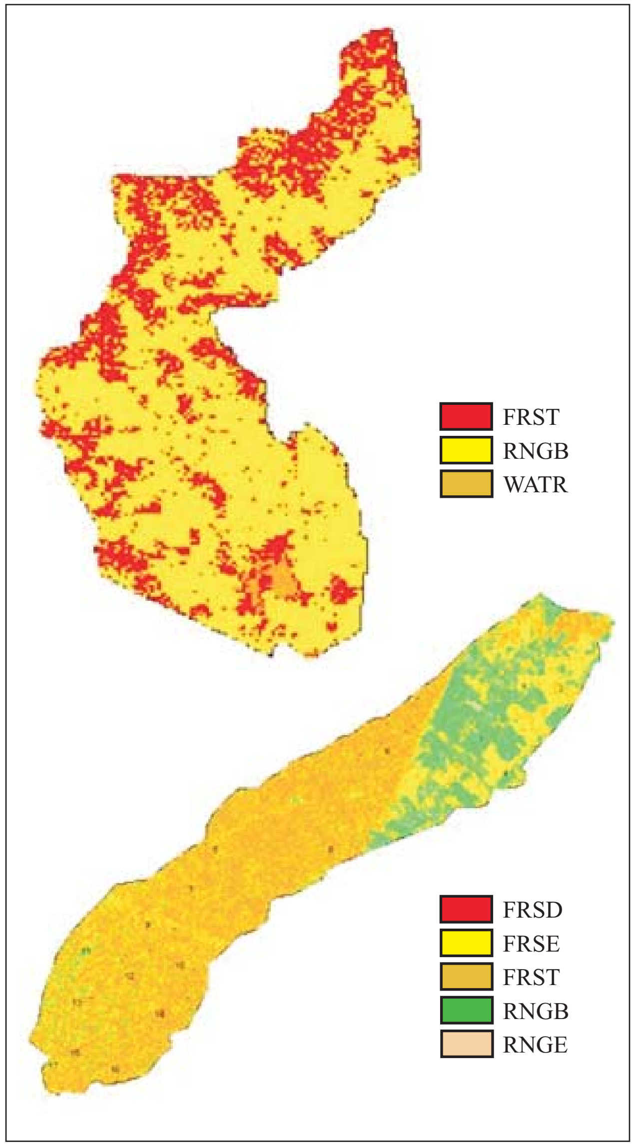


**Fig. 2. Land use map of *Choe* and W3B watershed**

**Table: 2**
**Location and land use details of micro-watersheds**

| Micro-watersheds | Latitude-N | Longitude-E | Elevation, m | Land use | SWAT code | % area |
|---|---|---|---|---|---|---|
| 1. *Choe*, near Chandigarh | 34.74 | 76.86 | 350 | Water | WATR | 1.94 |
| | | | | Mixed forest | FRST | 27.48 |
| | | | | Range brush | RNGB | 70.58 |
| 2. W3B, near Dehradun | 30.35 | 77.89 | 550 | Mixed forest | FRST | 29.46 |
| | | | | Evergreen forest | FRSE | 53.39 |
| | | | | Deciduous forest | FRSD | 1.62 |
| | | | | Range brush | RNGB | 15.42 |
| | | | | Range grass | RNGE | 0.11 |

**Table: 3**
**Sub-Watershed delineation with HRU characteristics**

| Name of the watersheds | No. of Sub-basins | No. of HRUs |
|---|---|---|
| *Choe* | 25 | 46 |
| W3B | 17 | 38 |

## Model Calibration and Validation

SWAT-CUP 2009 version was used to calibrate the model using Sequential uncertainty fitting (SUFI ver2) (Abbaspour *et al.,* 2007). SUFI-2 is one of five different modules (SUFI2, ParaSol, GLUE, MCMC and PSO) that are linked with SWAT in the package called SWAT Calibration Uncertainty Programs (SWAT-CUP). Its main function is to calibrate SWAT and perform validation, sensitivity and uncertainty analysis for a watershed model created by SWAT. The model was calibrated for the period 1973-1978 and 1971-1980, respectively for monsoon months and validated for the period 1979-1981 and 1982-1984, respectively for study areas.

## Model Performance Indicators

The objective functions, used to test the model performance were the Root Mean Square Error (RMSE), Nash Sutcliffe Efficiency (NSE) and percentage bias (PBIAS). These functions are given as follows:

$$RMSE = \left(\sum_{i=1}^{t} (Q_i^{obs} - Q_i^{sim})^2/n\right)^{1/2} \quad ...(2)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})^2}{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{mean})^2} \quad ...(3)$$

$$PBIAS = \frac{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})}{\sum_{i=1}^{n} Q_i^{obs}} \quad ...(4)$$

Where, $Q_i^{obs}$ = $i^{th}$ observation for the constituent being evaluated, $Q_i^{sim}$ = $i^{th}$ simulated value for the constituent being evaluated, $Q_i^{mean}$ = mean of observed data for the constituent being evaluated, and $n$ = total number of observations.

RMSE shows the measure of mean residual variance. The NSE is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") (Nash and Sutcliffe, 1970). In this criterion, a perfect agreement between the observed and estimated output yields an efficiency of 1.0. For a zero agreement, all the estimated value must be equal to the observed mean and a negative efficiency represents a lack of agreement. PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed values (Moriasi *et al.,* 2007). Positive values of bias indicate that underestimation by model whereas negative value indicates that overestimation by model (Gupta *et al.*, 1999), the optimal value of PBIAS being zero.

## 3. RESULTS AND DISCUSSION

### Analysis of Model Parameterisation

The identification of critical model parameters affecting the model prediction was done by sensitivity analysis. Sensitivity analysis was performed involving the parameters, deep aquifer percolation (RCHRG_DP), minimum depth of water in soil for base flow to occur, (GWQMN), initial SCS-CN for AMC-II (CN2), available water capacity of soil layer (SOL_AWC) *etc.* (Fig. 3 and Fig. 4) manually and by auto-calibration using SWAT CUP software version 3.1.3. Base flow parameter for bank storage (ALPHA_BNK) and saturated hydraulic conductivity (SOL_K) were found to be most sensitive parameters for *Choe* watershed; however, base flow parameter (ALPHA_BF) and Manning's roughness coefficient were the most sensitive parameters for W3B watershed. Ranges of parameters used for modeling are shown in Table 4 and Table 5, respectively for *Choe* and W3B watersheds.

Monthwise simulation was carried out for both watersheds for different periods. Calibration and validation

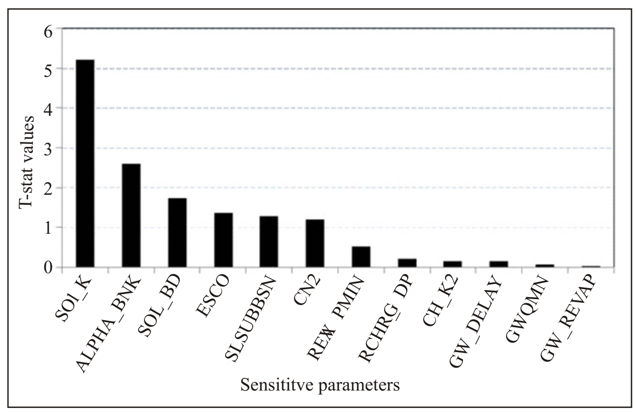


**Fig. 3. SWAT parameters considered for sensitivity analysis in *Choe* watershed**

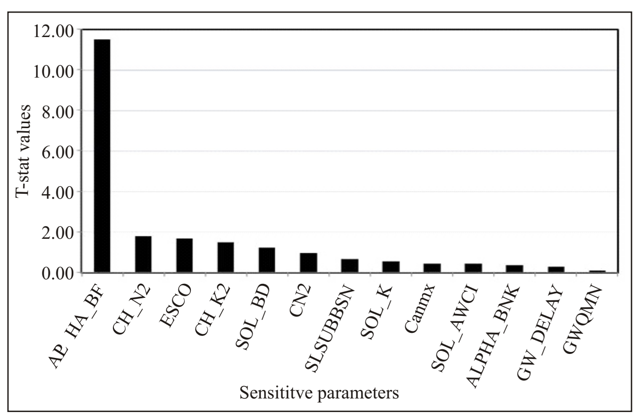


**Fig. 4. SWAT parameters considered for sensitivity analysis in W3B watershed**

**Table: 4**
**Range of parameter values used for modeling of *Choe* watershed**

| Sl. No. | Parameter code | Description | Fitted value | Min. Value | Max. Value | Location |
|---|---|---|---|---|---|---|
| 1 | SOL_K | Saturated Hydraulic Conductivity (mm $hr^{-1}$) | 0.8957 | 0.64 | 0.95 | *.sol |
| 2 | ALPHA_BNK | Base flow alpha factor for bank storage | 0.2707 | 0.17 | 0.30 | *.rte |
| 3 | SOL_BD | Soil Bulk density | 0.4187 | 0.34 | 0.43 | *.sol |
| 4 | ESCO | Soil Evaporation Compesation Factor | 0.0412 | .03 | 0.06 | *.bsn |
| 5 | SLSUBBSN | Average slope length of basin | 0.2550 | 0.18 | 0.30 | *.hru |
| 6 | CN2 | SCS Runoff Curve Number | 0.4025 | 0.37 | 0.47 | *.mgt |
| 7 | REVAPMIN | Threshold depth of water in the shallow aquifer for"revap" to occur | 1.6575 | 1.50 | 2.20 | *.gw |
| 8 | RCHRG_DP | Deep Aquifer Percolation Factor | 0.6087 | 0.54 | 0.65 | *.gw |
| 9 | CH_K2 | Effective hydraulic conductivity of main channel | 193.725 | 150.0 | 203.0 | *.rte |
| 10 | GW_DELAY | Ground Water Delay (days) | 63.025 | 61.0 | 70.0 | *.gw |
| 11 | GWQMN | Threshold depth of water in the shallow aquifer for flow to occur (mm) | 2128.75 | 1980.0 | 2150.0 | *.gw |
| 12 | GW_REVAP | Ground Water "Revamp" Coefficient | 2.545 | 2.50 | 3.10 | *.gw |

**Table: 5**
**Range of parameter values used for modeling of W3B watershed**

| Sl. No. | Parameter code | Description | Fitted value | Min. value | Max. Value | Location |
|---|---|---|---|---|---|---|
| 1 | ALPHA_BF | Base flow alpha factor | 0.0065 | 0.00097 | 0.009 | *.gw |
| 2 | CH_N2 | Manning's "n" value for the main channel | 0.08419 | 0.07500 | 0.11 | *.rte |
| 3 | ESCO | Soil Evaporation Compensation Factor | 0.2111 | 0.1800 | 0.2200 | *.bsn |
| 4 | CH_K2 | Effective hydraulic conductivity of main channel | 179.8425 | 100.0 | 209.0 | *.rte |
| 5 | SOL_BD | Soil Bulk density | 0.5901 | 0.56 | 0.60 | *.sol |
| 6 | CN2 | SCS Runoff Curve Number | 0.1220 | 0.12 | 0.15 | *.mgt |
| 7 | SLSUBBSN | Average slope length of basin | 0.6734 | 0.63 | 0.68 | *.hru |
| 8 | SOL_K | Saturated Hydraulic Conductivity | 0.4832 | 0.40 | 0.50 | *.sol |
| 9 | CANMX | Maximum canopy storage | 25.2125 | 23.0 | 28.0 | *.hru |
| 10 | SOL_AWC | Available water capacity of soil | 0.0944 | 0.05 | 1.0 | *.sol |
| 11 | ALPHA_BNK | Base flow alpha factor for bank storage | 0.292 | 0.2 | 0.3 | *.rte |
| 12 | GW_DELAY | Ground Water Delay (days) | 74.06 | 67.0 | 75.0 | *.gw |
| 13 | GWQMN | Threshold depth of water in the shallow aquifer for flow to occur (mm) | 1942.355 | 1928.0 | 1950.0 | *.gw |

of SWAT model output with observed values are shown for each watershed in Fig. 5a to Fig. 8b.

Results show that for *Choe* watershed, mean runoff (% of rainfall) was 7 and 11% for calibration and validation

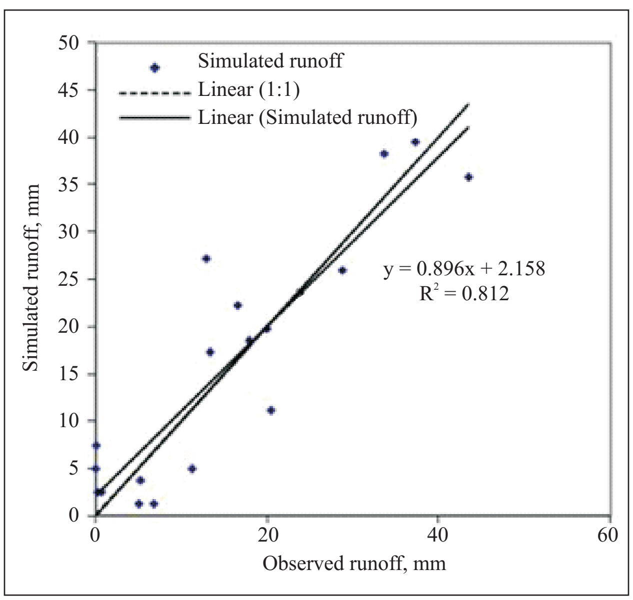


**Fig. 5a. Calibration of model output with observed values (1973-78) for *Choe* watershed**

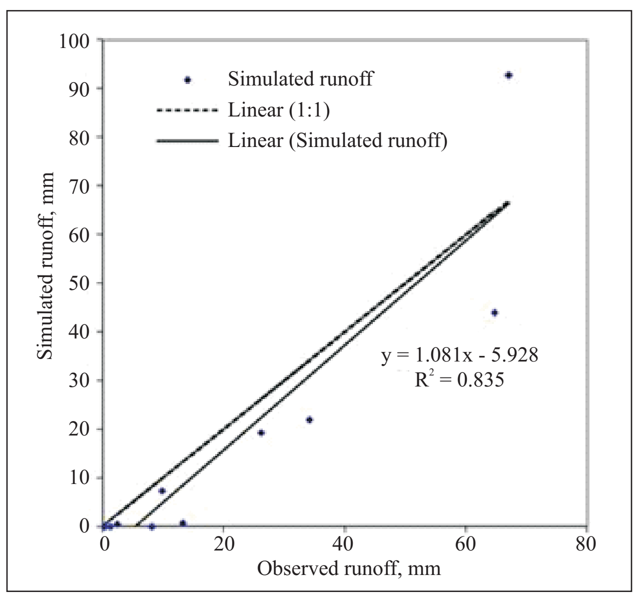


**Fig. 5b. Validation of model output with observed values (1979-81) for *Choe* watershed**

period, respectively whereas for W3B watershed, it was 16 and 7%, respectively for calibration and validation. Data further reveals that during validation period trend of runoff has changed which could be attributed to changing land use in both the micro watersheds. Calibrated and validated SWAT model outputs were found to be reasonably simulating the observed runoff values. Regression slope and coefficient of determination $R^2$ (Fig. 5a and Fig. 5b) being close to 1 indicate that there is close relationship between observed and simulated runoff. Coefficient of determination ($R^2$) was obtained as 0.81 and 0.83, respectively for calibration and validation period, respectively. NSE was found to be 80.2% for calibration and 73.3% (Table 6) for validation, as such, these values can be considered reasonably well for any model. Similarly, RMSE was calculated as 5.8 and 12.3, respectively for calibration and validation. PBIAS was found as 3.9 and 17.9, respectively for calibration and validation.

Similarly, for W3B watershed, calibrated and validated SWAT model outputs were found to be reasonably simulating the observed runoff values. Regression slope and coefficient of determination $R^2$ (Fig. 6a and Fig. 6b) being close to 1 indicate that there is close relationship between observed and simulated runoff. Coefficient of determination was obtained as 0.67 and 0.76, respectively during calibration and validation period. NSE was found to be 66.4% for calibration and 72.1% for validation, respectively which is considered as satisfactory for any model. Similarly, RMSE was calculated as 25.7 and 11.2, respectively for calibration and validation. PBIAS was found very good (PBIAS  10) as the values range between 3.6-7.0 both for calibration and validation (Table 6).

Fig.7(a) and Fig.7(b) show variation of observed and simulated runoff with respect to rainfall both for calibration

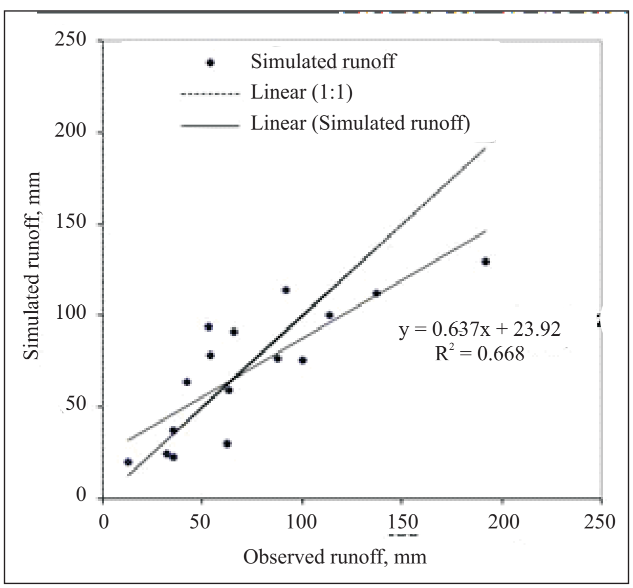


**Fig. 6a. Calibration of model output with observed Values (1971 to 1980) for W3B watershed**

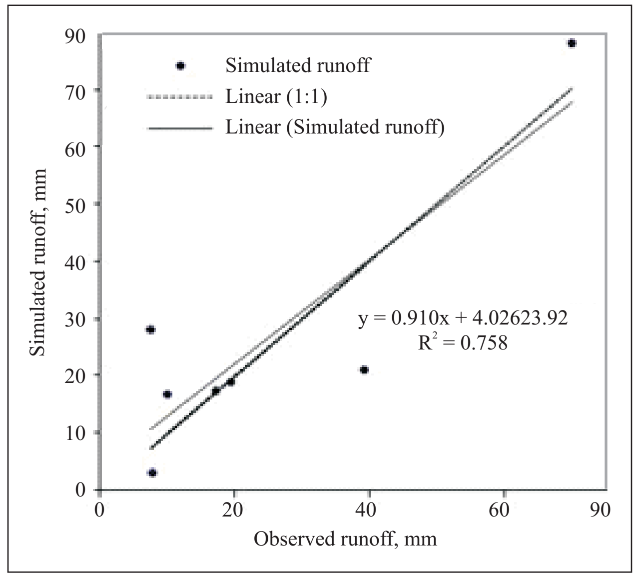


**Fig. 6b. Validation of model output with observed values (1982 to 1984) for W3B watershed**

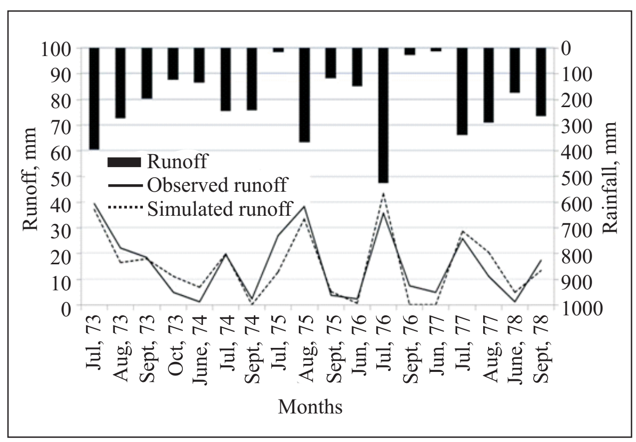


**Fig.7a. Simulated and observed runoff for Calibration period for *Choe* watershed**

**Table: 6**
**Performance evaluation of model for calibration and validation for different micro-watersheds**

| Performance evaluation measure | *Choe* watershed | | W3B watershed | |
|---|---|---|---|---|
| | Calibration | Validation | Calibration | Validation |
| Nash and Sutcliffe Efficiency (NSE), % | 80.2 | 73.2 | 66.4 | 72.1 |
| RMSE | 14.6 | 25.4 | 25.7 | 11.2 |
| PBIAS | 3.9 | 17.9 | 3.6 | - 7.0 |
| Coefficient of determination ($R^2$) | 0.81 | 0.83 | 0.69 | 0.76 |

and validation period respectively during different months of monsoon season for *Choe* watershed. Figures indicate that simulated runoff matches well with the observed values. Similarly Fig. 8(a) and Fig. 8(b) show variation of observed and simulated runoff with respect to rainfall during different months of monsoon season both for calibration and validation period for W3B watershed. In this case also there is very little difference between observed and simulated runoff.

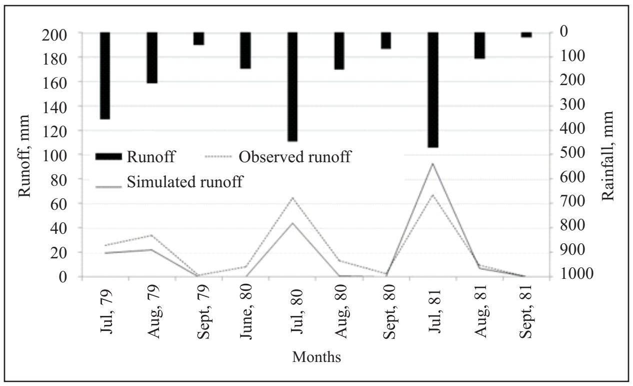


**Fig. 7b. Simulated and observed runoff for Validation period for *Choe* watershed**

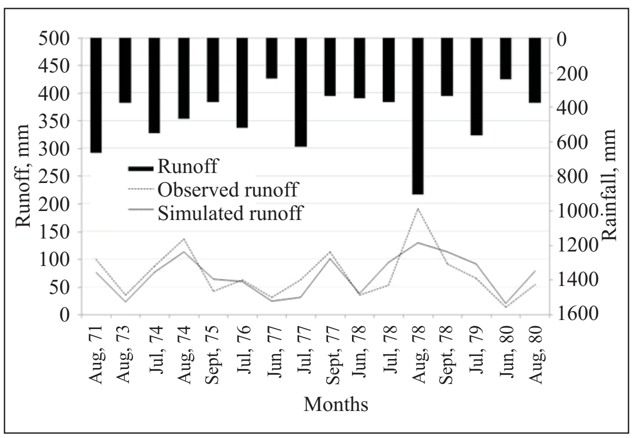


**Fig. 8a. Simulated and observed runoff for Calibration period for W3B watershed**

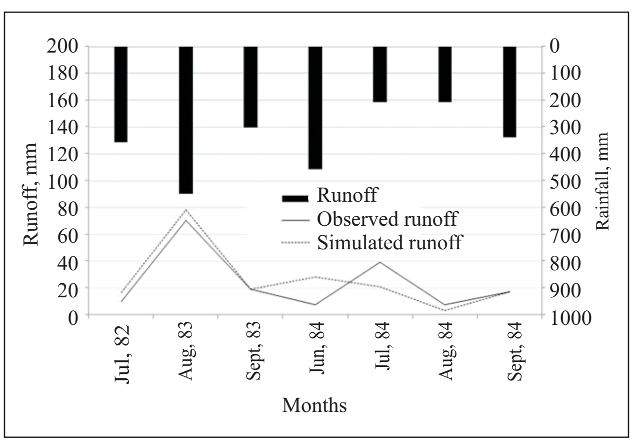


**Fig. 8b. Simulated and observed runoff for Validation period for W3B watershed**

## 4. CONCLUSIONS

SWAT was selected for estimation of runoff. The sensitive parameters were used to find the most reasonable parameter values for optimum estimation of runoff. The analysis shows that base flow parameter for bank storage and saturated hydraulic conductivity were found to be most sensitive parameters for *Choe* watershed, whereas base flow parameter and manning's roughness coefficient were more sensitive parameters in case of W3B micro watershed. The model generates detailed outputs at the spatial and temporal scale; however, in the present analyses only runoff has been considered and reported. The application of SWAT model in generation of crucial information such as water and sediment can be used.

Model performance was tested through various evaluation parameters and was found to be good in simulating surface runoff during calibration and validation period in case of W3B and *Choe* micro-watersheds. Evaluation statistics for simulating monthly runoff for both the micro-watersheds showed that simulated runoff matched well with the observed data. Simulated runoff is well to very good as NSE varies from 66.2 to 80.2% for both micro watersheds. Thus the study indicates that SWAT model can produce reliable estimate of monthly runoff even for micro watersheds to a larger extent having similar agro climatic condition.

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