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Calibration and Validation of Swat Model for Kunthipuzha Basin Using SUFI-2 Algorithm

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A B S T R A C T

Calibration and validation are the two important processes needed to perform for physically based distributed watershed models before their use for hydrologic calculations. The present study was conducted to calibrate the SWAT model for Kunthipuzha basin using SUFI-2 algorithm in SWAT-CUP package. SUFI-2 algorithm accounts for most sources of uncertainties and it is also easy to handle. By considering these advantages and based on recommendation of many researchers, Sequential Uncertainty Fitting procedure (SUFI-2) was selected in this study for sensitivity analysis, calibration and validation of the model. SUFI-2 also got provision for performing both type of sensitivity analysis such as one-at-a time and global sensitivity analysis. In this study, both one-at-a time and global sensitivity analysis was conducted. Calibration was done for a period of 7 years starting from 2000 to 2006, whereas, validation was done for a 3 year period starting from 2007 to 2009. The values of statistical indices such as NSE and R^2 were 0.81, 0.82 for calibration period and 0.73, 0.88 for validation period respectively which indicates the "very good" performance of the model in simulating hydrology. The p-factor and r-factor were 0.69 and 0.47 for calibration period, 0.57 and 0.51 for validation period respectively. SUFI-2 was found to be very convenient and easy to use than the other automatic calibration techniques.

Introduction

Model calibration is a process in which a generalized model is adjusted to represent the site specific process and conditions more realistically. Validation is the process of running a model with the parameters that were determined during calibration process with a data set which is not used for calibration. Validation should be carried out in order to build confidence whether the model represents the real system accurately or not. Calibration

can be done either manually or by using auto calibration tools like SWAT-CUP. User's experience in modelling and recognizing parameters are the two main significant skills to achieve success in manual calibration. Whereas, automatic calibration requires only input files to be filled out once (Eckhardt and Arnold. 2001). SWAT CUP is a generic interface and stand-alone program developed for SWAT model calibration (Abbaspour *et al.,* 2007). SWAT CUP includes several techniques such as PSO, SUFI-2, GLUE,

Parasol and MCMC. SUFI-2 is very convenient to use, but it needs good knowledge on the parameters and their effect on outputs (Yang *et al.,* 2008). Sequential Uncertainty Fitting Algorithm (SUFI-2) is very advantageous since it combines optimization with uncertainty analysis and can handle large number of parameters (Abbaspour, 2004). This study aims to calibrate the SWAT model for Kunthipuzha basin using SUFI-2 algorithm and to validate the model with calibrated parameters.

Materials and Methods

Description of the study area

Kunthipuzha River is an important tributary of Bharathapuzha river basin, the second largest river basin in Kerala. Kunthipuzha sub basin lies in the North East part of the Bharathapuzha river basin. The sub basin lies in the latitude longitude range of 100 53'N, 760 04'E to 110 14'N, 760 41'E and has a total catchment of 940 km^2 at the confluence point with the main river. Catchment area at Pulamanthole river gauging station (100 53' 50'' N, 760 11'50''E) manned by Central Water Commission, India is 822 km^2. Elevation of the catchment varies from 20 to 2300m. Mean annual rainfall of the area is 2300mm. About 80% of the total rainfall is received during June to September, 15% from October to November and about 5% during December to May. Mean temperature of the area is 27.3^{o}C. The location map of study area was shown in figure 1.

Software used

ArcGIS 10.3

ArcGIS is a proprietary Geographic Information System used to display the geographic information on a map and provides a common frame to work with different spatial data obtained from various sources. ArcGIS 10.3 released in 2015 was used for changing the projections and to work with spatial data.

SPAW software

SPAW, a daily hydrologic model which was developed by Keith Saxton, USDA-ARS was used for calculating some of the soil characteristics required for the SWAT model.

SWAT model

It is a physically based semi distributed hydrologic model which can operates on different time steps. It is a comprehensive tool that enables the impacts of land management practices on water, sediment and agricultural chemical yields for the watersheds with varying soils, land use and management practices. SWAT divides the basin into sub basins using digital elevation model and then each sub basin is further discretised into hydrological response units based on soil and land use information. Simulation of soil water content, surface runoff, nutrient cycles, sediment yield, crop growth and management practices will carry for each HRU and then aggregates for the sub basin by a weighted average. The two major components of watershed hydrology are land phase and routing phase. The land phase controls the quantity of water, sediments, nutrients and pesticide loadings to the main stream in each sub basin whereas the routing phase controls the movement of water, sediments etc through the channel network to the catchment outlet (Arnold *et al.,* 2012).

SWAT model uses the water balance concept to simulate the hydrology of watersheds which is shown below:

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

Where,

SW_t= final soil water content (mm H_2O)

SW_o= initial soil water content on day i (mm H_2O)

R_{day} = amount of precipitation on day i (mm H_2O)

Q_{surf} = amount of surface runoff on day i (mm H_2O)

E_a = amount of evapotranspiration on day i (mm H_2O)

w_{seep} = amount of water entering the vadose zone from the soil profile on day i (mm H_2O)

Q_{gw} = amount of return flow on day i (mm H_2O)

SWAT model was used for the study to simulate the hydrological process in the watershed.

SWAT-CUP

The calibration/uncertainty or sensitivity program can easily be linked to SWAT through a generic interface called SWAT-CUP. SWAT CUP is an interface that provides sensitivity analysis, calibration and validation of SWAT models. Recent version SWAT CUP 2012 version 5.1.6 was used for the study to carry out calibration and uncertainty analysis. In this study, SUFI 2 was employed to perform parameter sensitivity analysis, calibration and validation. Sequential Uncertainty Fitting Algorithm (SUFI-2) is very efficient not only in terms of localizing an optimum parameter range but also in terms of number of simulations (Schuol *et al.,* 2008). SUFI-2 is very convenient to use but the only drawback is, it is semi-automated and requires the interaction of the modeller to check a set of suggested posterior parameters which needs a good knowledge of the parameters and their

effects on the output. This drawback may add additional error called "modeller's uncertainty" to the list of other types of uncertainties (Yang *et al.,* (2008)

Preparation of databases

SWAT model requires input data such as DEM, land use map, soil map, meteorological and daily flow data. SRTM DEM of 30 m resolution was downloaded from the earthexplorer.usgs.gov.in website. Land use map derived from the LISS (III) imagery of IRS P6 satellite of 2008 was used for this study. The Soil map and the morphological characteristics of the soil collected from the Directorate of Soil Survey & Soil conservation of Kerala State were used for running the SWAT model. All the data sets were transformed into WGS_1984_UTM_ZONE_43N coordinate system in ARCGIS before feeding into the model. Both the Land use map and soil maps were rasterised in ARCGIS to use in SWAT model.

SWAT model also requires text tables such as land use and soil look up tables for converting the land use cover and soils into SWAT codes. Gauge location table and their daily values in the form of ASCII text format should be prepared to feed into the model for defining the weather conditions. SWAT-CUP allows the daily observed flow data in the form of observed_rch file. Observed_rch file required by the SWAT-CUP was prepared in excel.

SWAT model set up

The ArcSWAT 2012 was used to set up the model. On the basis of DEM, stream network and by selecting the watershed outlet, the entire basin was divided into 24 sub basins. In HRU analysis, by feeding land use, soil maps and by defining HRU'S with threshold percentage, a total of 129 HRU's were

formed. After watershed delineation and HRU analysis, weather data was fed to the model and simulation was done from 1st January 1997 to 31st December 2011 with a 3 year warm up period**.**

Sensitivity and uncertainty analysis

Calibrating a model with more number of parameters is a difficult task. Hence, to reduce the calibration effort sensitivity analysis was done. The parameter selection for sensitivity analysis was done based on characteristics of the study area as well as literature review.

For applying parameter identifiers, the changes made to the parameters should have physical meanings and should reflect the physical factors such as land use, soil, elevation etc., hence the following scheme has been suggested (Abbaspour, 2015).

x_<parname>.<ext>_<hydrogrp>_<soltext>_ <landuse>_<subbasin>_<slope>

Where,

x_ indicates the type of change to be applied to the parameter

v_ means the existing parameter value is to be replaced by the given value

a_ means the given value is added to the existing parameter value

r_ means the existing parameter value is multiplied by (1+ a given value)

<parname> = SWAT parameter name

<ext> = SWAT file extension code for the file containing the parameter

<hydrogrp> = (optional) soil hydrological group i.e., 'A', 'B', 'C', 'D'

<soltext> = (optional) soil texture

<landuse> = (optional) name of the landuse category

<subbsn> = (optional) subbasin number(s)

<slope> = (optional) slope

Any combination of the above factors can be used to describe a parameter identifier which provides the opportunity for a detailed parameterization of the system. Omitting the optional identifiers such as <hydrogrp>, <soltext>, <landuse>, <subbsn> and <slope> allows global assignment of parameters.

In SUFI-2, uncertainty of input parameters is depicted as a uniform distribution, while model uncertainty is quantified at the 95 PPU. The p_factor is the fraction of measured data (plus its error) bracketed by the 95 PPU band and r_factor is the ratio of average thickness of 95 PPU band to the standard deviation of the corresponding measured variable. A p_factor of 1 and r_ factor of zero represents a perfect model simulation considering the uncertainty and exactly corresponds to the measured data (Abbaspour *et al.,* 2015).

SWAT-CUP provides two types of sensitivity analysis; one-at-a time sensitivity analysis and global sensitivity analysis. Both the analysis have their own advantages and disadvantages.

Based on the results of one-at-a-time sensitivity analysis and then performing global sensitivity analysis, the limited dominant parameters that affect the output of the model was ranked and used for calibration. Initially 20 parameters were chosen based on characteristics of the study area and previous research. In one-at-a time sensitive analysis, 13 parameters are identified as sensitive to flow. Finally, in global sensitivity analysis, after performing one iteration of 500

simulations each, 7 most sensitive parameters which are sensitive to flow are selected and used for calibration.

Methodology for calibration in SWAT-CUP using SUFI2 technique

Create a new project and import a swat TxtInOut directory into the project.

Select the calibration method to be used for the project. After saving, the program creates a project directory and copies the TxtInOut files from the indicated location into SWAT-CUP directory.

Edit the files such as Par_inf.txt, SUFI2_swEdit.def, observation. Rch, extraction and objective function files under calibration inputs.

In Par_inf.txt, the number of parameters to be optimized and number of simulations to make in the current iteration should be specified. SUFI2 is iterative i.e., each iteration consists number of simulation, around 500 simulations in each iteration and 4 iterations are sufficient to reach an acceptable solution (SWAT-CUP documentation).

In SWAT_swEdit.def file, the beginning and ending simulation numbers should be mentioned.

In observation.rch file, the observed data that will be used to compare with the output. rch file should be copied and pasted here. Edit the information under this section such as number of observed variables, name of the variable and sub basin number to be included in the objective function and number of observed data points.

Under Extraction two files need to be modify such as Var_file_rch.txt and SUFI2_extract_rch.def files. In Var_file_rch.txt, the file names of the observations defined in the "observed_rch.txt" should be defined. In SUFI_extract_rch.def, how the variables should be extracted from the output.rch file should be defined.

Under objective function, there are two files which are needed to define such as observed, txt and Var_file_name.txt. In observed.txt, the same information as in "Observation_rch.txt" and some additional information for calculating objective function should be defined. In Var_file_name.txt, all the variables that should be included in the objective function should be defined.

Once the above steps are completed, by selecting the "Execute all items" under calibrate wheel the simulation process starts and after the completion of process the iteration can be saved under which all the calibration outputs are saved. Iterations should be continued by adjusting the parameters until an acceptable solution is reached. Based on the new parameters obtained from the last iteration (New_par.txt) and by observing the 95 PPU plot, the parameters need to be adjusted can be known. Generally 4 iterations with 500 simulations each will be sufficient to reach acceptable solution.

Results and Discussion

SWAT model set up

The elevation of the watershed was varying from 0 to 2330m. 18.95 % of the area was within the elevation band 0 to 50 m. Land use map shows that major land cover of the area was Plaintains (31.53 %) followed by Rubber trees (19.98 %) and Forest evergreen (12.37%). The model was run from 1st January 1997 to 31st December 2011 with a 3 year warm up period with default parameters. The result of the model simulation with the pre calibrated model is shown in figure 2 as a

comparison between simulated and observed annual river flow values. Marked deviation can be seen between the observed and simulated and this reveals the importance of model calibration in order to obtain satisfactory prediction accuracy. The NSE and R^2 values for the simulation were 0.75 and 0.76 respectively.

Sensitivity analysis

The results of sensitivity analysis carried out on the 20 sensitive parameters are presented in table 1. The most sensitive factor is ALPHA_BF followed by CH_K2, CN2, SOIL_Z and SURLAG. Many other studies (Sathian, 2010; Sathian, 2012; Sandra and Sathian, 2016; Varughese, 2016) for the region have also reported similar or comparable results.

The most predominant factor of river flow for the Kunthipuzha sub basin is base flow and therefore, the appearance of base flow alpha factor as the first ranking sensitive parameter is justifiable.

Similarly, the most important surface runoff influencing factor CN2 has come as the third sensitive factor also goes with the logic. High channel hydraulic conductivity suggest that drainage channels can assist both ground water discharge and recharge depending upon

the relative elevation between the water table and channel bottom.

Dotted plots

Dot plots are the plots of parameter values or relative changes versus objective function which shows the distribution of sampling points as well as parameter sensitivity. Dot plots for the seven sensitive parameters are shown in figure 3. The dotted plots also indicate that the most sensitive parameter is ALPHA_BF.

Calibration of the model

Out of 15 years of data, keeping 3 years as warm up period, the balance 7 years of data was used for calibration and the last 3 years for validation. Calibration was done from 1st January 2000 to 31st December 2006. Initially, the SWAT model assigns "0" as default value for CH_K2 which means that there is no loss of water expected from the stream bed but in case of humid and semi-arid tropics this will not be the case, there will be loss of water from the stream bed. Based on the Sensitivity analysis, CH_K2 has emerged as the second most sensitive parameter and hence the value of this parameter was increased based on the suggested value ranges. The sensitive parameters and their fitted range of values after calibration were shown in table 2.

Table.1 Sensitive parameters and their ranking for Kunthipuzha basin

Sensitivity rank	Parameter	Description	t-value	p-value
1	ALPHA_BF.gw	Base flow alpha factor	16.64	0.00
2	CH_K2.rte	Effective hydraulic conductivity of main channel	-2.03	0.04
3	CN2.mgt	Curve number	1.94	0.05
4	SOL_Z.sol	Depth from soil surface to bottom of layer	1.70	0.08
5	SURLAG.bsn	Surface lag coefficient	-1.48	0.13
6	RCHRG_DP.gw	Deep aquifer percolation fraction	-1.01	0.31
7	ESCO.hru	Soil evaporation compensation factor	0.93	0.34

Table.2 Sensitive parameters with their default and fitted range of values

Sensitive parameter	Default parameter range	Parameter range after calibration
v_ALPHA_BF.gw	0 to 1	0.04 to 0.38
v_CH_K2.rte	5 to 130	25.11 to 76.59
r_CN2.mgt	-0.2 to 0.2	-0.18 to -0.01
r_Soil_Z.sol	-0.8 to 0.8	-0.35 to 0.73
v_SURLAG.bsn	0.05 to 24	9.39 to 22.59
v_RCHRG_DP.gw	0 to 1	0 to 0.07
v_ESCO.hru	0 to 1	0.89 to1.0

Table.3 Performance indices during calibration and validation periods

Statistical criteria	After calibration	During validation
NSE	0.81	0.73
R^2	0.82	0.88
P-factor	0.69	0.57
R-factor	0.47	0.51

Fig.1 Location of Kunthipuzha basin

DEM of Kunthipuzha basin
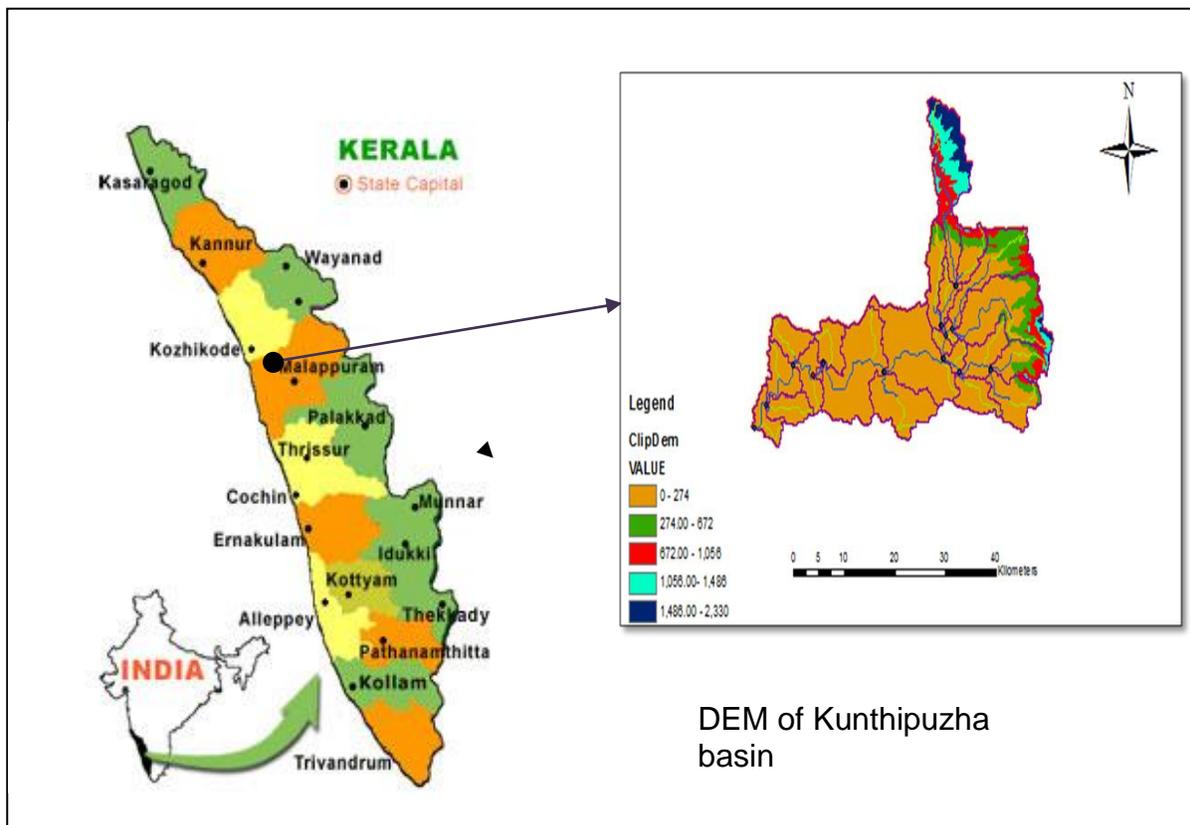
Fig.2 Average annual observed and simulated flow of Kunthipuzha river basin using pre-calibrated model
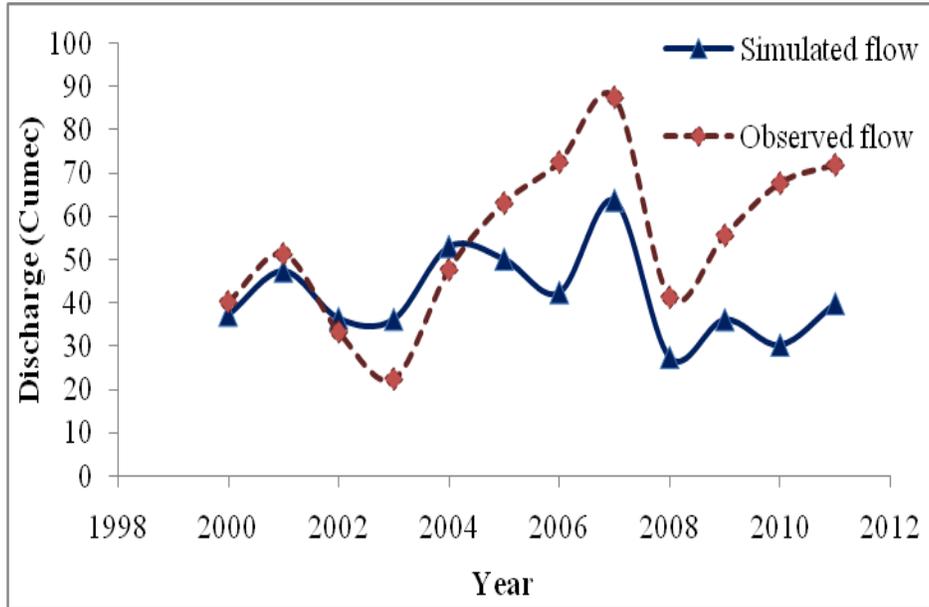
**Fig.3** Dot plots of sensitive parameters

1: V_ALPHA_BF.gw

2: V_CH_K2.rte

3: R_CN2.mgt

4: R_SOL_Z.sol

5: V_SURLAG.bsn

6: RCHRGE_DP.gw

7: V_ESCO.hru
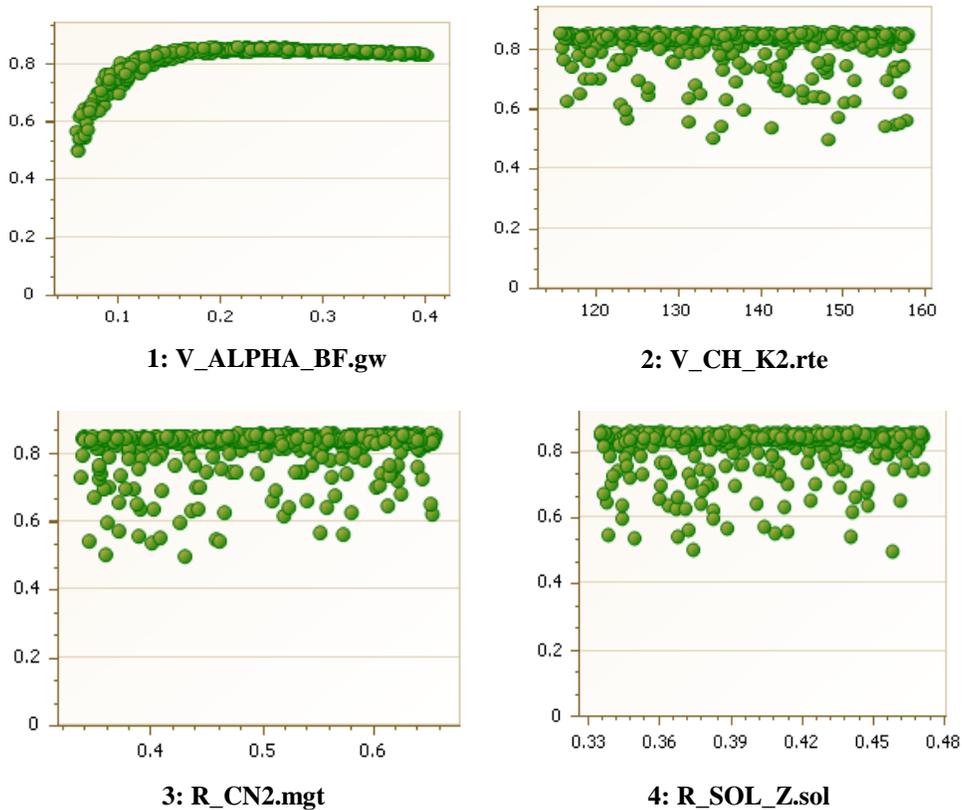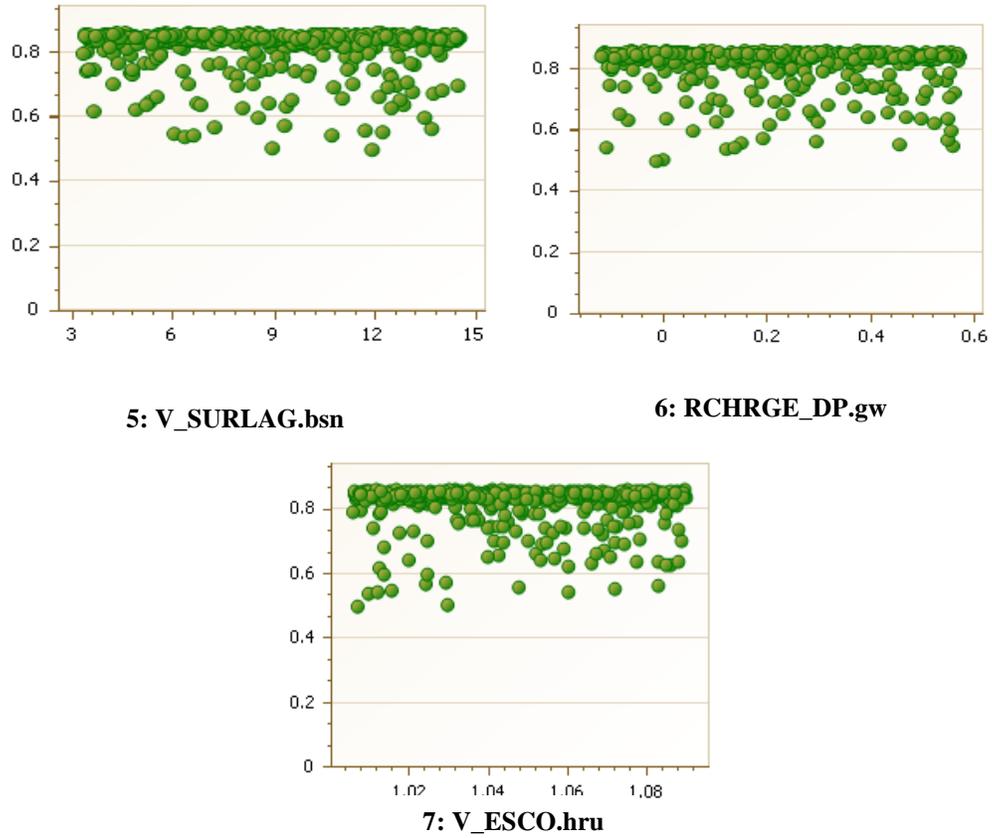
**Fig.4** Best simulated discharge with 95PPU for calibration period using SUFI-2
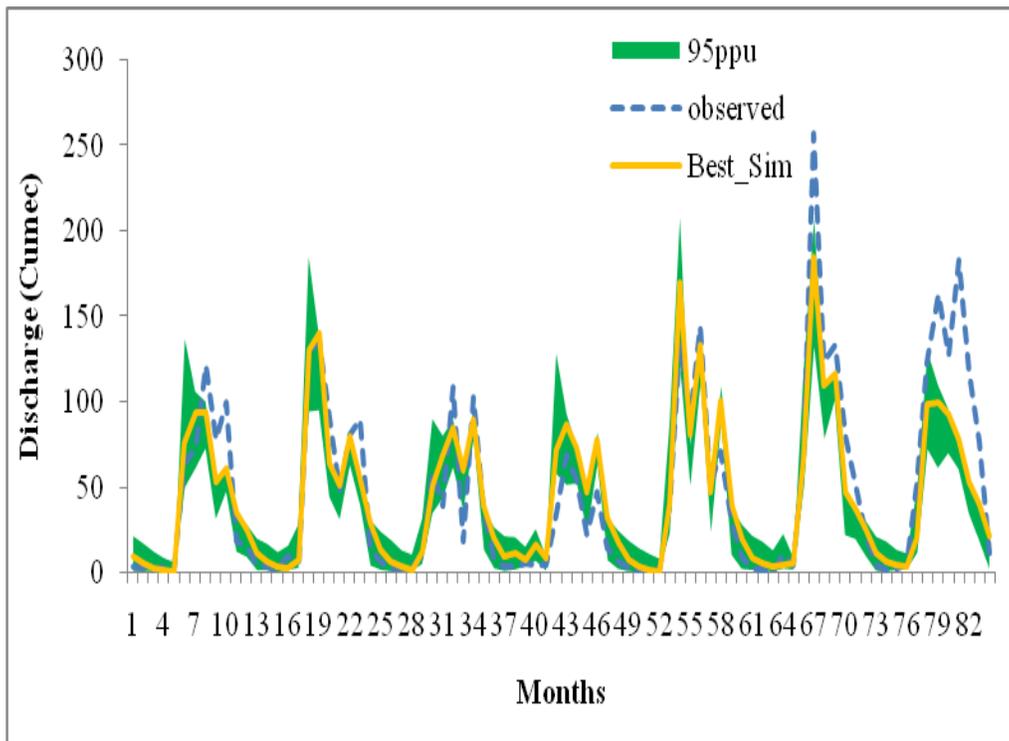
Fig.5 Best simulated discharge with 95PPU for validation period using SUFI-2
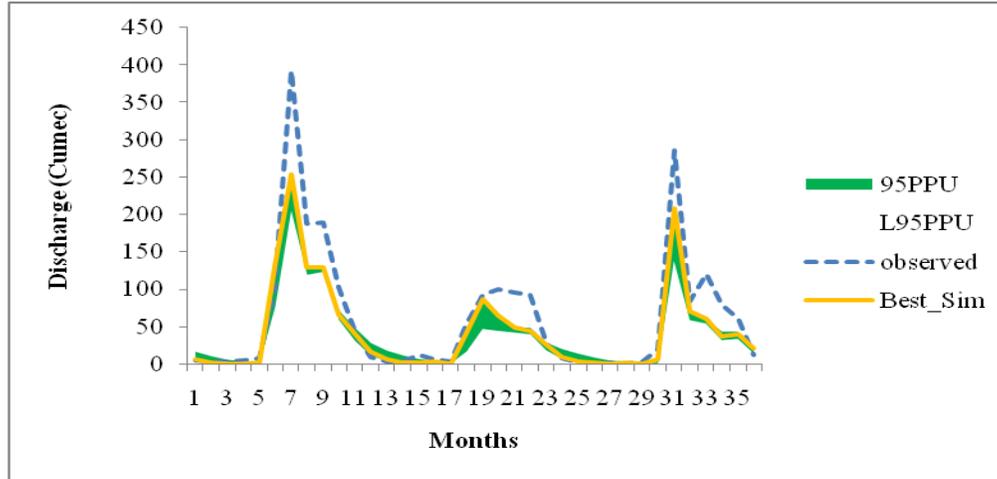
Model evaluation using performance indices

In order to evaluate the model performance, comparison of observed and simulated flow using statistical criteria such as NSE, Coefficient of determination were used.

The model evaluation statistics for the calibration and validation period was shown in table 3. and the results showed good performance of model prediction over the entire catchment. Before calibration, the values of NSE, R^2 were 0.75 and 0.76 which shows the predictive ability of the model even without calibration.

After the calibration, the values of NSE and R^2 were 0.80 and 0.81 which shows further improvement in the model prediction. From the figures 4 and 5, it was clear that after calibration, the variation between simulated and observed peak reduced considerably. However, even after the model calibration, some of the peak flows were under estimated by the SWAT. These discrepancies may be due to inaccurate meteorological data obtained, errors in other input data sets such as land use and soil maps and also errors during data preparation and processing. These

uncertainties in model can also be accounted for great variations in topography and rainfall both spatially and temporally. The other causes of these discrepancies may be due to dependency of SWAT model entirely on an empirical method known as SCS Curve number method for calculating runoff which does not consider duration and intensity of precipitation.

Validation of the model

Model validation was performed with an independent data set starting from 1st January 2007 to 31st December 2009. The values of model evaluation statistics such as NSE and R^2 during validation period were 0.73 and 0.88 respectively and it indicates that the calibrated model is good for prediction during the period which is outside the purview of calibration.

In the present study, SUFI-2 was used for calibrating the model and it was found very convenient to use. Parameters and their ranges were selected based on the characteristics of the study area, new parameter ranges suggested by the model and by observing 95 PPU plot. Since, SUFI-2 is iterative, more number of simulations should be done. Some

of the peaks were not well simulated by the model even after calibration and hence there is need to improve the SWAT model in simulating peak flows.

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