APPLICATION OF A PROCESS BASED HYDROLOGICAL MODEL FOR SIMULATING STREAM FLOW IN AN AGRICULTURAL WATERSHED OF INDIA

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ABSTRACT

In the present study, Soil and Water Assessment Tool (SWAT), a river basin or watershed scale model was used to predict the monthly stream flow of the Nagwa watershed in Eastern India. The model was calibrated and validated based on measured stream flow and quantification of the uncertainty in SWAT model output was assessed using Sequential Uncertainty Fitting Algorithm (SUFI-2). Weather and monthly stream flow data from meteorological station near the outlet of the watershed (1991 to 2007) were used for model set up, calibration and validation. ArcGIS 9.3.1 was used to prepare spatial input data such as digital elevation model, land use land cover and soil maps. Results indicate that coefficient of determination (R^2) and Nash-Sutcliffe simulation efficiency (NSE) values for SWAT model were found to be 0.77 and 0.75 during calibration and 0.70 and 0.67 during validation respectively. The value of R-factor in the SWAT model was found to be 1.26 which indicates a wider prediction interval. The values of P-factor show that the percentage of observed stream flow values bracketed by the 95PPU and SWAT model successfully captured 87% of the measured stream flow. In other words, the SWAT model estimates the stream flow values accurately and with less uncertainty.

Keywords. *SWAT, SUFI - 2, Measured stream flow, Simulation, Modeling.*

INTRODUCTION

Improved agricultural practices and lowering the stream flow discharges are the obvious solution of the non point source pollution problem because high level of discharges is derived from agricultural fields where fertilizers and pesticides are applied. The United States Environmental Protection Agency (USEPA) reported that the routine agricultural activities are responsible for more than 60 per cent of the surface water contamination [1]. In India, high consumption of nitrogenous fertilizers and the resulting 30-50% losses of nitrogen are reported to contaminate the surface and ground water bodies [2]. Since the hydrologic responses of the watersheds vary spatially and temporally, an intensive study of the individual watershed is necessary for developing the management practices and also for applying the results from one watershed to another watershed with same characteristics. Many water quality computer simulation models have been developed to simulate complex hydrologic processes and determine surface flow from agricultural watershed [3]. These models are classified as lumped or distributed parameter models. A model can provide the basis for developing policy intervention and sound watershed management scheme that ensures environmental protection and economic sustainability. Hydrological models nowadays are being used as an important management tool for taking up appropriate soil and water conservation measures. There are many process based hydrological models but in the present study, Soil Water Assessment Tool (SWAT) was selected. The SWAT model is recognized by the USEPA and has been incorporated into the EPA's BASINS (Better Assessment Science Integrating Point and Non-point Sources) [4]. The SWAT model was chosen because the model itself remains independent of GIS. The model interfaced with geographical information systems (GIS) facilitates pre and post processing such as watershed delineation, manipulation of the spatial and tabular data. Early origin of SWAT model can be traced to previously developed models by United States Department of Agriculture. These models are the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model [5], the Groundwater Loading Effects on Agricultural Management Systems (GLEAMS) model [6] and the Environmental Impact Policy Climate (EPIC) model [7]. Many researchers have calibrated and validated the SWAT model for various watersheds and proved the effectiveness of the SWAT model in simulating hydrological processes [8, 9, 10].

As process based watershed models are increasingly being applied to take decisions about alternative land management strategies, it is obvious for these models to go through a careful calibration and uncertainty analysis. Sources of model structural uncertainty include processes not accounted for in the model such as unknown activities in the watershed, and model inaccuracy due to over-simplification of the processes considered in the model. Input uncertainty is often related to imprecise or spatially interpolated measurements of model input or initial conditions. Other uncertainties in distributed models may also arise due to the large number of unknown parameters and the errors in the data used for parameter calibration [11]. Several uncertainty analysis techniques have been developed for watershed models. These include the Markov Chain Monte Carlo (MCMC) method [12]; Generalized Likelihood Uncertainty Estimation (GLUE) [13]; Parameter Solution (ParaSol) [14]; and Sequential Uncertainty Fitting (SUFI-2) [15]. Few hydrological modeling using SWAT model have been carried out in different watersheds of Damodar-Barakar catchment of Jharkhand [16, 17, 18]. Estimating uncertainties in the outputs of SWAT model has been the main focus of this paper. In the current study, we have applied SUFI-2 for a combined calibration and uncertainty analysis of our SWAT model.

MATERIALS AND METHOD

Description of the study area

The Nagwa watershed, located in Damodar Barakar Catchment under the Damodar Valley Corporation, Hazaribagh Command, Jharkhand, India, is approximately 92.46 km^2 of which about 30-40% is under shrubs and forest and the remaining area under cultivation. The average elevation of the command area is 540m from the mean sea level. The topography of the watershed is undulating with flat land in major parts. The average annual rainfall of the area is 1200 mm of which more than 80% occurs during the monsoon months from June to October and the rest in the winter months. The overall climate of the area is classified as sub-humid sub-tropical. The study area comes under the Sub-humid tract of Eastern Plateau in the 12th Agro-Ecological zone of India. The texture of red and yellow soils of the watershed ranges from sandy loam to clay loam. Soil structures vary from moderately fine to coarse sub angular blocky. It is bounded by latitudes of 23^0 59' 08" N to 24 ^{0} 05' 41" N and longitudes of 85 ^{0}16' 35" E to 85 ^{0}23' 45" E.

SWAT model description

The SWAT model is a physically based, semi-distributed parameter and watershed-scale model that works on a continuous daily time step. It simulates hydrological processes, sediment yield, nutrient loss, and pesticide losses into surface and groundwater and the effects of agricultural management practices on water in large watersheds [19]. SWAT incorporates the effects of weather, surface runoff, evapotranspiration, crop growth, irrigation, groundwater flow, nutrient loading, pesticide loading and water routing as well as the long-term effects of varying agricultural management practices [20]. In the hydrologic component, runoff is estimated separately for each sub-watershed or hydrological response unit (HRU) of the total watershed area and routed to obtain the total runoff for the watershed. Runoff volume is estimated from daily rainfall using modified SCS-CN (Curve Number Method) and Green–Ampt methods. Sediment yield is estimated from the Modified Universal Soil Loss Equation (MUSLE). The model requires spatial input of DEM, land use and soil maps as well as weather data such as daily rainfall and temperature. In the SWAT model, the watershed is divided into small sub-basins that are further subdivided into HRUs based on unique land cover, soil and topographic conditions. The hydrology component of the model determines a soil water balance at each time step based on daily data of rainfall, runoff, evapotranspiration, percolation, and base flow. Sediment yield from each HRU is computed with the MUSLE. The MUSLE approach of estimating sediment yield makes the sediment computation a non-linear function of the HRU area. Simulations are performed at the HRU level and summarized in each sub-watershed. The simulated variables are routed through the stream network to the watershed outlet. The MUSLE equation is given below:

$$sed = 11.8\left(Q_{surf}.q_{peak}.area_{hru}\right)^{0.56}.K_{USLE}.C_{USLE}.P_{USLE}.LS_{USLE}.CFRG^{0.56} \quad \text{………(1)}$$

where, sed is sediment yield for a given day in metric tons, Q_{surf} is surface runoff volume (mm/ha), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of HRU (ha), K_{USLE} is the USLE soil erodibility factor, C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor and $CFRG$ is the coarse fragment factors. Further details of ULSE factors are available in [20].

Preparation of spatial input data

The satellite data obtained from Thematic Mapper sensor for path no. 141 and row no 043 (spectral band: 0.45 - 2.35 µm) for October 14, 2006 was used to prepare the land use land cover (LULC) maps of the Nagwa watershed. All the layers were stacked and area of interest was taken out. Supervised method of classification was applied to classify the land uses. The maximum likelihood was used as a parametric rule while performing the classification. The land use classes mainly include agriculture, dense forest, water, fallow land and urban settlement. Classification accuracy was estimated by using a maximum likelihood report module, which simply compared ground truth pixels with the classified pixels through a confusion matrix. Kappa coefficient was used for measuring overall accuracy. It was computed for each pixel class based on difference between the actual agreement of the classification and reference data through formation of confusion matrix. The overall classification accuracy of 96.23% and Kappa coefficient of 0.94 were achieved. ArcGIS 9.3.1 was used for the analyses of satellite digital data, digitization of contours, construction of Digital Elevation Model (DEM), automatic extraction of watershed parameters and interpretation of results. The extracted watershed information was used to generate the input parameters of ArcSWAT 2009.93.4. The required rainfall and stream flow data were processed with the MS Excel 2003^{TM}.

Calibration of SWAT model

Latin Hypercube One–factor-At-a-Time (LH-OAT) method of the sensitivity analysis was used in this study which has been implemented in SWAT. The parameters affecting stream flow were tested such as base flow alpha factor, channel effective hydraulic conductivity (mm/hr), curve number, plant uptake compensation factor, soil evaporation compensation factor, groundwater "revap" coefficient, threshold water depth in the shallow aquifer for "revap" (mm), available water capacity (mm/mm), saturated hydraulic conductivity of soil (mm/hr) and surface runoff lag time (days). SWAT model was run for several simulations with different values of the input parameters to get an adequately calibrated model. All the values of the input parameters were chosen within the defined limit of the parameter values. The ArcSWAT 2009.93.4 interface for SWAT 2009 consists of a number of tools that can be used to evaluate the sensitivity of parameter, aid in model calibration and assess parameter uncertainty. The sensitivity analysis tool in the ArcSWAT Interface helps to identify parameters that improve a particular process or characteristic of the model, and identifies the parameters that are affected by the characteristics of the study watershed and those to which the given project is most sensitive [21].

The monthly calibration and validation of the SWAT model for stream flow were performed after conducting sensitivity analysis. Manual and automatic calibration methods were used for calibration. The sensitivity analysis and calibration currently available in the SWAT-CUP (SUFI 2 method) were performed to determine optimal parameter values for output variable based upon observed data collected at a single gauge outlet of the watershed. Seventeen years of meteorological and measured stream flow data were used for calibration and validation. The periods 1991- 2004 and 2005-2007 were used for calibration and validation respectively including two years of warm-up period (1991 and 1992). The warm-up period minimizes the effect of the estimated initial state variables such as soil water content and surface residue. After each parameter adjustment, the simulated and measured stream flow was compared to judge the improvement in the model prediction. The performance of the model for simulating hydrologic variables was evaluated with the help of statistical tests such as coefficient of determination (R^2) and Nash-Sutcliffe model efficiency (NSE).

Sequential Uncertainty Fitting ver. 2 (SUFI2)

There are three major sources of uncertainty in the outputs of a hydrological model: structural uncertainty, input uncertainty and parameter uncertainty. In SUFI-2, parameter uncertainty accounts for all sources of uncertainties such as uncertainty in driving variables, conceptual model, parameters and measured data. The program SUFI-2 was used for calibration and uncertainty analysis. This program is linked to SWAT in the calibration package SWAT-CUP (SWAT Calibration Uncertainty Procedures). SUFI-2 is able to handle a large number of parameters and observed data from many gauging stations simultaneously and also SUFI-2 requires much fewer simulations than other methods while producing similar NSE and R^2 values when the best calibration and validation results were compared with observed data.

The uncertainties are quantified by a measure referred to as the P-factor, which is the percentage of observed data bracketed by the 95% prediction uncertainty (95PPU). The 95PPU is calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable obtained through Latin hypercube sampling. This is calculated by the 2.5^{th} and 97.5^{th} percentiles of the cumulative distribution of every simulated point. As all forms of uncertainties are reflected in the measurements, the parameter uncertainties, generating the 95PPU, account for all uncertainties. The goodness of fit is assessed by the uncertainty measures calculated from the percentage of measured data bracketed by the 95PPU band and the average distance *d* between the upper and the lower 95PPU can be determined from:

$$\bar{d}_x = \frac{1}{k}\sum_{l=1}^{k}\left(X_U - X_L\right)_l \qquad \text{.......(2)}$$

where, k is the number of measured data points. The best result shows 100% of the measurements are bracketed by the 95PPU and $\bar{d}$ is close to zero. Another measure quantifying the strength of an uncertainty analysis is the R - factor, which may be defined as the average thickness of the 95PPU band divided by the standard deviation of the observed data [22]. The R-factor expressed as:

$$R - factor = \frac{\bar{d}_x}{\sigma_x} \qquad \text{.....(3)}$$

where, σ_x is the standard deviation of the measured variable *x*. A value of less than 1 is a desirable measure for the R-factor. The goodness of fit and the degree to which the calibrated model accounts for the uncertainties are assessed by the above two measures. Theoretically, the value for P-factor ranges between 0 and 100%, while that of R-factor ranges between 0 and infinity. A P-factor of 1 and R-factor of zero is a simulation that exactly corresponds to measured data. Further goodness of fit can be quantified by the R^2 and NSE coefficient between the observations and the final best simulation [23].

Model evaluation techniques

The most widely used statistics reported for hydrologic calibration and validation are the R^2, NSE and RMSE. It is recommended that both graphical techniques and quantitative statistics to be used in model evaluation [24]. R^2 values range from 0 to 1. Higher values indicate less error variance and normally values greater than 0.5 are considered acceptable [25]. If it is found lesser than zero, it indicates that the mean observed value is a better predictor than the simulated value. The R^2, NSE and RMSE can be determined with the following equation.

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - \bar{Y}_i^{obs}\right)\left(Y_i^{sim} - \bar{Y}_i^{sim}\right)}{\sqrt{\sum\left(Y_i^{obs} - \bar{Y}_i^{obs}\right)^2}\sqrt{\sum\left(Y_i^{sim} - \bar{Y}_i^{sim}\right)^2}}\right] \qquad \text{.....(4)}$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - \bar{Y}_i^{obs}\right)^2}\right] \qquad \text{........(5)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i^{sim} - Y_i^{obs}\right)^2}{n}} \qquad \text{..... (6)}$$

where, Y_i^{sim} is the i^{th} simulated value for the constituent being evaluated, Y_i^{obs} is the observed values, $\bar{Y}_i^{obs}$ and $\bar{Y}_i^{sim}$ are the mean of observed and n simulated values.

RESULTS AND DISCUSSION

The rainfall has direct bearing on the stream flow monitored at the outlet of the watershed. Rainfall and stream flow are mainly contributing factors for the detachment, transport and deposition of sediment particles. The model parameterization was derived using the ArcGIS interface for SWAT2009 and initially the whole watershed was divided into 19 sub-basins based on DEM. The parameterization of the stream reaches and the geomorphology of sub-basin were carried out by the interface. The land use and soil maps were then overlaid and hydrologic response units were generated with the help of the interface. Dominant land use more than 5% and soil type within each sub-basin were considered during HRUs generation. The major parameters affecting stream flow were modified to increase agreement between the simulated and observed monthly stream flow. During the calibration processes the curve number was adjusted within the range of ±10% from the curve number value for moisture condition II. These curve numbers were also adjusted for slopes greater than 4%. For simulation of the base flow in the watershed, the base-flow recession constant was adjusted to 0.05. It is directly proportional to groundwater flow response to changes in recharge. Groundwater delay time was adjusted to 42 days. This represents the lag between the times that water exits the soil profile and enters the shallow aquifer. This slightly reduced the overall stream flow and shifts the monthly timing. Groundwater revap coefficient that indicates the rate of transfer of water from the shallow aquifer to the root zone was adjusted to 0.02. The soil evaporation compensation factor was adjusted to 0.70. The calibrated values represent the response of land cover, land management practices, soil properties, and topographic condition of the watershed. The calibration process significantly reduced the difference between the measured and simulated stream flows. These parameters were adjusted to the level where they could represent the characteristics of the existing land use and topographic condition of the watershed. The final fitted values are listed in Table 1.

Table 1. Sensitive parameters for stream flow simulation and calibrated values.

Parameter	Lower Bound	Upper Bound	Calibrated Value
Sub Initial SCS CN II value, CN2	-25	25	17.63
Baseflow alpha factor [days], Alpha_Bf	0	100	43
Plant uptake compensation factor, EPCO	0	1	0.73
Soil evaporation compensation factor, ESCO	0	1	0.87
GW_REVAP Groundwater "revap" coefficient	-0.036	0.036	0.002
REVAPMN Threshold water depth in the shallow aquifer for "revap" [mm]	-100	100	79.38
SOL_AWC Available water capacity [mm/mm]	-25	25	2.53

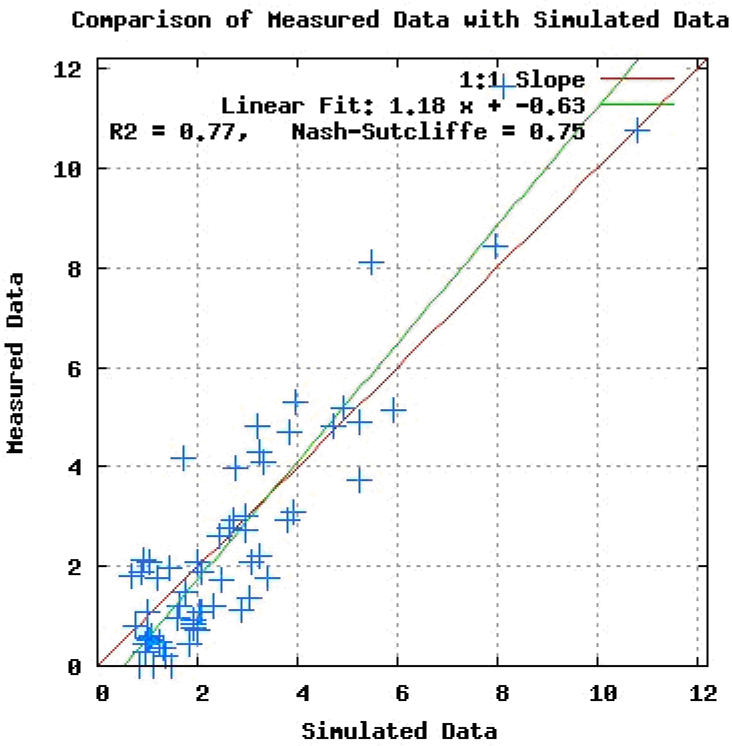
The Hargreave method of evapotranspiration estimation and Muskingum method of routing have been found to give best performance during calibration of the SWAT model under sub-humid region. It is observed that the simulated stream flow follows the trend of the observed stream flow. The magnitudes of the simulated stream flow are lower than that of observed stream flow for most of the years during high rainfall events. In case of normal rainfall events the prediction matches with the measured values. As initially the soil was dry and major portion of rainfall was retained in the cultivable land, the runoff was generated less in the beginning of the monsoon season. It is observed that the stream flow mainly depends on the nature of rainfall. Heavy and continuous rainfall in a short span of time produces more runoff. The observed as well as simulated high runoff during July, August and September months of high rainfall are ascribed to slower recharge process. The scatter plots of the observed and simulated monthly stream flow for the calibration period during June to October has been shown in Fig. 1 (top). The major portion of the scatter plot is well distributed about the regression line indicating the model capability of estimating stream flow for well-distributed normal rainfall events. The R^2 value during the calibration period shows a good correlation between observed and simulated values of stream flow. The R^2 and NSE values were found to be as 0.77 and 0.75 respectively. Low NSE obtained might be due to underestimated precipitation to the dominant soil type which is different from the four most frequent types and therefore whose attributes are not explicitly calibrated.

The SWAT model over predicted almost all the years of validation except in 2007 when rainfall received was highest (Fig. 1 (down)). This year has seen more frequent and intense rainfall as compared to remaining years. Most of the compared points are unevenly distributed around the regression line except a few events of lower magnitudes of stream flow. The SWAT did not perform very well during validation period. This may be due to inconsistency in terms of normal, wet and dry year and anomalies in the observed data. SWAT model simulated stream flow as 2.58 m^3/s against the observed average stream flow of 2.43m^3/s during the calibration periods 1993-2004. During validation periods of 2005-2007, SWAT model simulation of stream flow of 3.44m^3/s was found to be overestimated.

While we have compared the observed stream flow with the best simulated stream flow. This is the result of only one of many similarly good simulations. It is appropriate to show the 95% model prediction uncertainty (95PPU) intervals of the last iteration. It is quite reasonable to judge the performance of the model as represented by the P-factor and the R-factor. In average 87% of the measured monthly stream flow values could be bracketed by the 95PPU and the average R-factor was 1.26 during calibration of SWAT model and P – factor and R – factor were found to be as 27% and 0.51 during validation. Few observed values were bracketed with 95PPU during validation periods. Fig. 2 shows two criteria for calibration as well as the validation periods. Large uncertainties are, however, seen in the years of high rainfall. There are still many other influencing processes which were neglected (e.g., water use, irrigation) or simplified (e.g., assigning the dominant soil and land use to represent the whole subbasin, and using generated daily weather parameter except rainfall and temperature) due to the limited available information. SWAT does not simulate groundwater flow appropriately. Groundwater recharge is important in these regions. If base flow were better simulated, a larger P - factor as well as a smaller R -factor could be achieved for an overall calibration result. Therefore, parameters that account for less well understood processes, such as groundwater recharge and groundwater–river interaction, were important and dominated the flow processes.

CONCLUSIONS

The SWAT model is a physically based and computationally efficient model which uses spatial and temporal data as inputs to study long-term impacts of management practices. Monthly simulations show good agreement between measured and simulated flows. The value of R-factor in the SWAT model was found to be as 1.26 which means a wider prediction interval. The value of P-factor in SWAT model was observed as 87% which indicates that the model has been able to bracket 87 of the measured stream flow data within 95PPU. Overall, the SWAT model offers the most comprehensive representation of hydrological processes that can be of great help to take decisions on the land use management alternatives impacting water quality. The findings of the result can be very applied to simulate similar watershed under the same agro-ecological zone in India



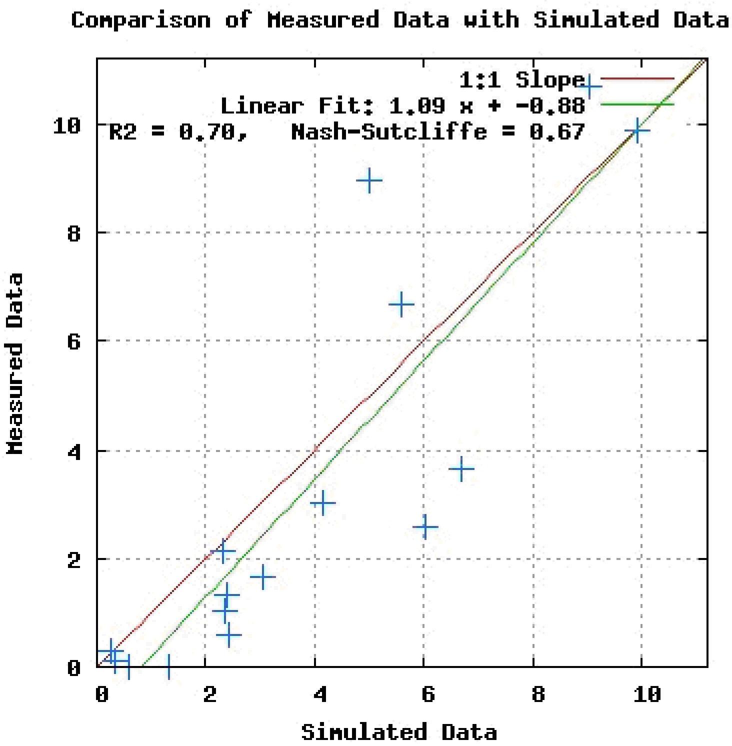
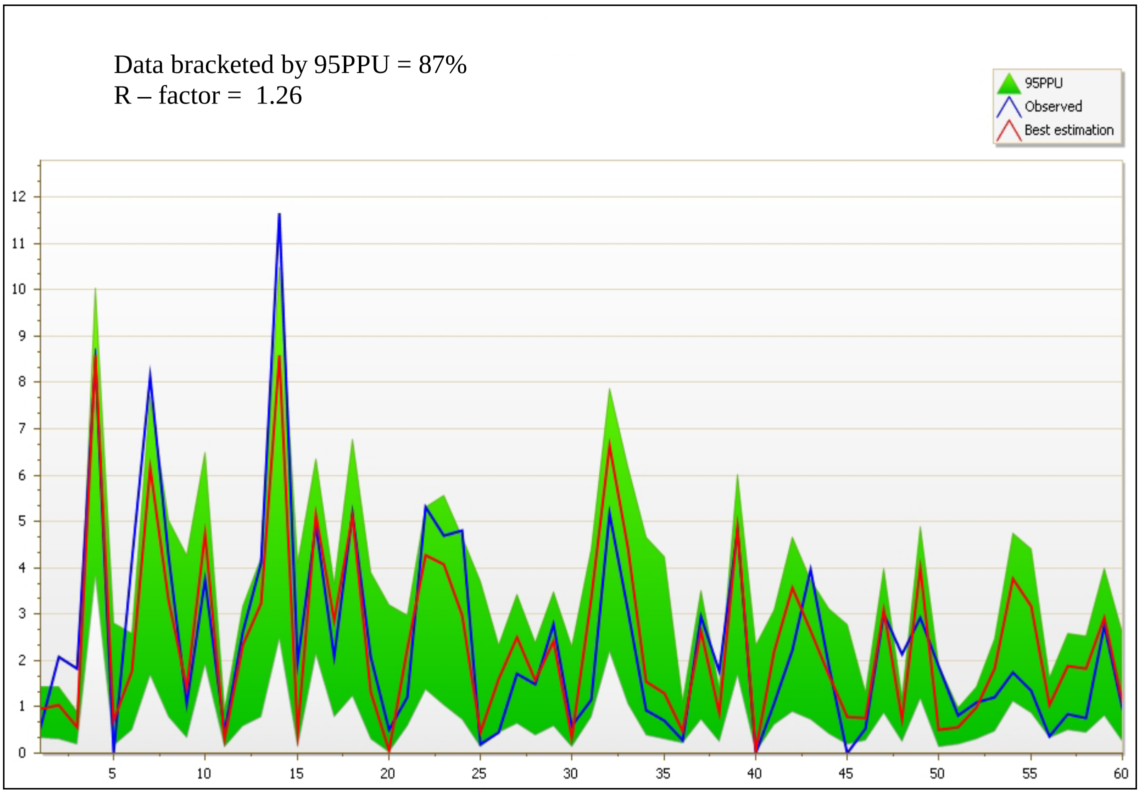


Fig. 1 Scatter plots of monthly measured and SWAT simulated stream flow (m^3/s) for calibration periods (top) and validation period (down)



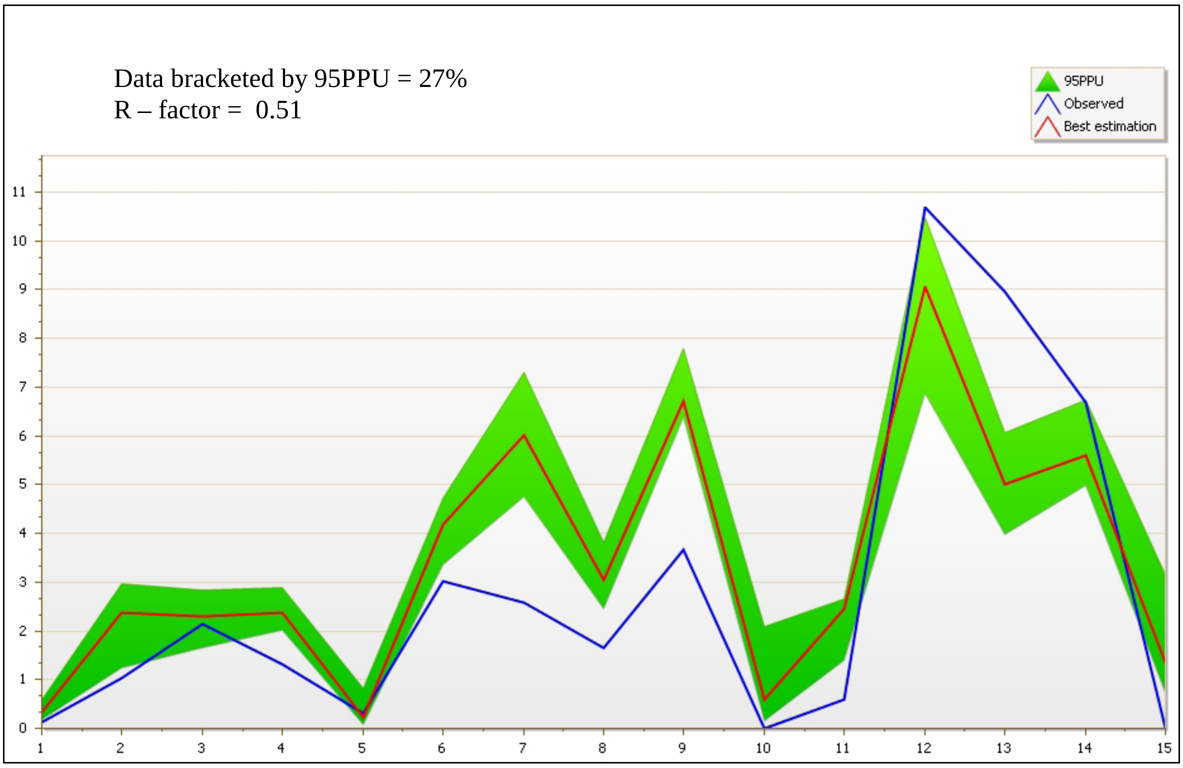


Fig. 2 Extracts of the monthly calibration (top) and validation (bottom) results showing the 95% prediction uncertainty intervals along with the measured and simulated stream flow for SWAT Model.

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