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[Research]

Runoff simulation using SWAT model and SUFI-2 algorithm (Case study: Shafaroud watershed, Guilan Province, Iran)

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ABSTRACT

Reliable estimates of runoff are required as a part of the information sets that help watershed managers make informed decisions on water resources planning and management. This study was carried out in Shafaroud watershed located in the north of Iran. In order to achieve the best runoff simulation in the study area, first rainfall data of four stations during 1998 to 2011 were collected and combined with other maps of the study area, such as Digital Elevation Model (DEM), land use and soil as input data in the form ofSoil and Water Assessment Tools (SWAT) model. After running the model, the Sequential Uncertainty Fitting (SUFI-2) algorithm in SWAT calibration and uncertainty program (SWAT-CUP) were used to evaluate the data uncertainty and the most accurate simulation. The first three years (1998-2000) of rainfall data for warm-up and the next 7 years (2001-2007) for the calibration and final 4 years (2008-2011) were used for the validation period. Finally, with multiple simulations, the uncertainty of the parameters was assessed with P-factor, R-factor, R^2 and NS coefficients. The results of validation period (R^2=0.85, NS=0.74) confirmed the potential of SUFI-2 algorithm of SWAT-CUP program for simulating runoff data in the study area.

Key words: Shafaroud watershed, Simulation, SUFI-2, SWAT-CUP.

INTRODUCTION

More detailed information on the status of rainfall runoff also facilitate decisions on future programs for watershed managers, a step towards the preservation of natural resources for sustainable development. Recently, rainfall-runoff models are widely used with hydrologists to simulate watersheds runoff and play a key role in water resources management (Bilondi *et al.* 2013). In other hand, several programs and techniques have been developed to reduce parameters uncertainty and achieve to best fit of parameters in the hydrological modeling (Singh *et al.* 2013).

The SWAT model (Arnoled *et al.* 1998) is a continuous-time semi-distributed hydrological model for application at the watershed scale (Krysanova & Srinivasan 2015). This model has been widely used to land use change effect assessment (Shen *et al.* 2010; De Girolamo & Lo Porto 2012; Yang *et al.* 2012; Du *et al.* 2013; Huang *et al.* 2013; Niu & Sivakumar 2014; Lin *et al.* 2015), sediment prediction(Shen *et al.* 2012; Rostamian *et al.* 2013), climate change (Andersson *et al.* 2006; Zhang *et al.* 2012; Huang *et al.* 2015), water quality (Debele *et al.* 2008; Zhang *et al.* 2011) and simulation of evapotranspiration (Wang *et al.* 2006). Many computer programs have been developed by hydrologists for parameters uncertainty analysis in river basin model, such as, generalized likelihood uncertainty estimation (GLUE; Beven & Binley 1992), sequential uncertainty fitting (SUFI-2; Abbaspouret *et al.* 2004), parameter solution (ParaSol; Van Griensven & Meixner 2006) and Markov chain Monte Carlo (MCMC; Kuczera & Parent 1998; Vrugt *et al.* 2008).

The SWAT-CUP (Abbaspour *et al.* 2007b) is a computer program that links the Sequential Uncertainty Fitting (SUFI-2) algorithm to SWAT model.

Up to now, researchers used SUFI-2 algorithm for model calibration and uncertainty analysis of parameters of SWAT model. Narsimlu *et al.* (2015) in Kunwari River basin applied SUFI-2 algorithm in 19-year period (1987-2005) for model calibration, sensitivity and uncertainty analysis. Fukunaga *et al.* (2015) investigated application of the SWAT hydrologic model to a tropical watershed at Brazil. Nyeko (2015) assessed the capabilities and limitations of SWAT model in modeling watershed that has limited field and hydrologic data for possible use in water resources management. Romanowicz *et al.* (2005) investigated Sensitivity of the SWAT model to the soil and land use data in the Thyle catchment of Belgium country. Schuol & Abbaspour (2006) used SWAT to simulate water quantity of the four million km^2 area in West Africa and applied Sufi-2 algorithm on parameters uncertainty. Defersha & Melesse (2012) applied SWAT to evaluate the impacts of land use changes on runoff and sediment yield in the Mara River basin, Kenya. Krysanova & Srinivasan (2015) assessed five projects of different applications of SWAT covering the following themes: impacts of climate change, impacts of land cover change and combined impacts of climate change and human intervention in water management. Bossa *et al.* (2012) applied the SWAT model in the Republic of Benin, West Africa to evaluate the effects of different soil databases on modeling of hydrological processes and sediment yield. Vilaysane *et al.* (2015) applied SWAT model to test the capability of the model for predicting stream flow and also used SUFI-2 algorithm for calibration and uncertainty analysis in Xedone river basin. Singh *et al.* (2013) used GLUE and SUFI-2 algorithms to simulate daily and monthly streamflow for the period 1993–2002 in the Krishna River basin. Their study revealed excellent correlation during monthly calibration, and good model match between the observed and simulated streamflows. Lin *et al.* (2015) in their study investigated the effects of land use and land cover changes on runoff response using SWAT model.

They used two different landuse scenarios (1985 and 2006, with reduced forest and increased cropland and urbanized area) in Jinjiang catchment. Shen *et al.* (2012) used SWAT model to simulate sediment and streamflow in Three Gorges reservoir basin. Their research showed that sediment simulation presented greater uncertainty than streamflow. Yang *et al.* (2008) tried to find the best uncertainty analysis techniques in Chaohe basin. They compared five algorithms (e.g. GLUE, ParaSol, SUFI-2, MCMC and PSO) to a distributed watershed model (SWAT) in north China. In this study, we focused on application of SUFI-2 algorithm for prediction of stream flow and uncertainty analysis in the Shafaroud watershed. The main objective of this study is to test feasibility and capability of the SUFI-2 algorithm for runoff simulation of the study area, which will contribute to the preservation of natural resources in the Shafaroud watershed and thereby is useful for sustainable development.

MATHERIALS AND METHODS

Study area

Shafaroud watershed is located in Guilan Province at north of Iran, between longitudes 48° 39´ 34˝ and 49° 8´ 11˝ East and latitudes 37° 24´ 58˝and 37° 34´ 18˝ north with a drainage area of 336.89 km^2 (Fig. 1). The altitude of the catchment ranges from 168 m to 2895 m. The main river with a total length about 40.95 km and located in the north of the catchment.

The numbers of meteorology stations were four stations and discharge data was measured at one gauge, located at the outlet.
The majority of land is used for forest, agriculture and pasture.

SWAT and SWAT-CUP

Soil and water assessment tools (SWAT) is a semi-physically based model for assessing the impact of management and climate on water supplies, sediment, and agricultural chemical yields in catchments (Narsimlu *et al.* 2015). In SWAT, a catchment is divided into multiple sub-catchments whit hydrologic response units (HRUs) that consist of homogeneous land use, management, topographical, and soil characteristics (Abbaspour *et al.* 2007a). Each sub-catchment is split into multiple hydrological response units (HRUs) based on topography, management, land use and soil types (Wang & Kalin 2011).
SWAT-CUP is a computer program for calibration of SWAT models. It enables sensitivity analysis, calibration, validation, and uncertainty analysis of SWAT models (Abbaspour *et al.* 2007b).

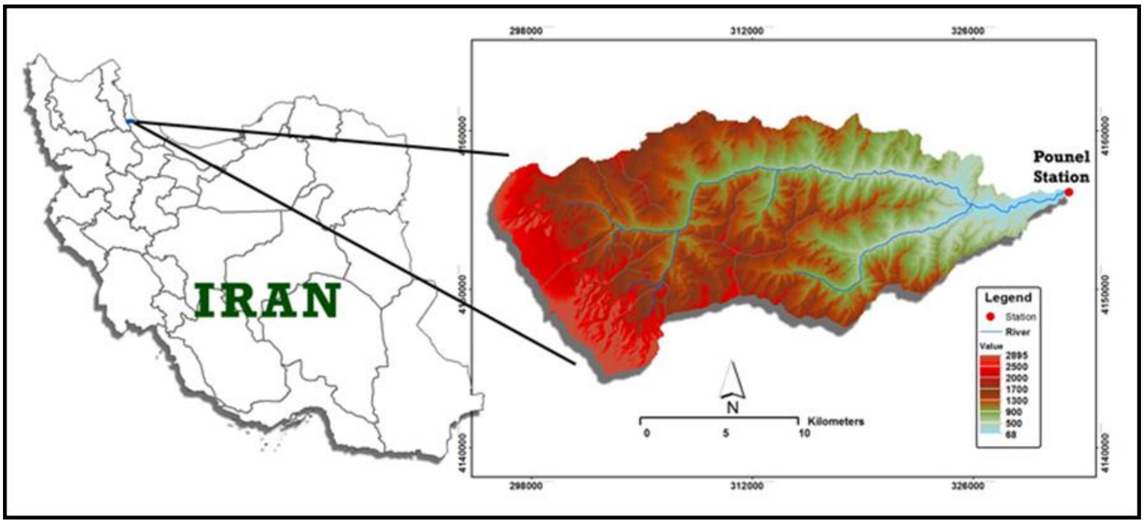

Fig. 1. Location of Shafaroud Watershed.

SUFI-2 Algorithm

Uncertainty in Sequential Uncertainty Fitting (SUFI-2) algorithm is defined as the difference between simulated and observed variables (Rostamian *et al.* 2013). The uncertainty is determined by the 95% prediction uncertainty band calculated at the 2.5% and 97.5% levels of the output variables (Abbaspour *et al.* 2004, 2007b).

P-factor

The P-factor (percentage of measured data bracketed by the 95% prediction boundary) often named 95PPU (Percentage Prediction Uncertainty). 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 (Abbaspour 2011). The range of the P-factor varies from 0 to 1, with values is close to 1 indicating good fitness between simulated and observed values (Yang *et al.* 2008).

R-factor

Another measure quantifying the strength of a calibration/uncertainty analysis is the R-factor, which is the average thickness of the 95PPU band divided by the standard deviation of the measured data. The calibrated parameter ranges can be generated with an acceptable value of the R-factor and P-factor.

The R-factor is given by Eq. (1) (Yang *et al.* 2008; Narsimlu *et al.* 2015):

$$R - factor = \frac{\frac{1}{n}\sum_{t_i=1}^{n}\left(\gamma_{t_i,97.5\%}^{M} - \gamma_{t_i,2.5\%}^{M}\right)}{\sigma_{obs}} \text{Eq. (1)}$$

Where $\gamma_{t_i,97.5\%}^{M}$ and $\gamma_{t_i,2.5\%}^{M}$ are the upper and lower boundaries of the 95UB and σ_{obs} is the standard deviation of the observed data.

NS objective function

Nash-Sutcliffe function has been used for assessment of model performance. This Function is calculated by using the following equation Eq. (2) (Nash & Sutcliffe 1970):

$$NS = 1 - \frac{\sum_{i=1}^{n}\{y_i - x_i\}^2}{\sum_{i=1}^{n}\{x_i - \bar{x}\}^2} \text{Eq. (2)}$$

Where $\mathbf{x_i}$ is the ground-based measurements; $\mathbf{y}_i$ is the model predicted data and $\bar{\mathbf{x}}$ is the mean of the ground-based measurements.

$\mathbf{R^2}$Coefficience

The range of determination coefficient ($\mathbf{R^2}$) is 0 to 1 that explain the relationship between Observed variance and simulated values. The $\mathbf{R^2}$ is given by Eq. (3) (Pluntke *et al.*, 2014):

$$R^2 = \frac{\left[\sum_i \left(Q_{Ob,i} - \bar{Q}_{Ob}\right)\left(Q_{S,i} - \bar{Q}_S\right)\right]^2}{\sum_i\left(Q_{Ob,i} - \bar{Q}_{Ob}\right)^2 \sum_i\left(Q_{S,i} - \bar{Q}_S\right)^2} \text{Eq. (3)}$$

Where Q_{Ob} and Q_S are the observed and simulated values, respectively.

RESULTS

Setup SWAT Model

According to the Soil and Water Assessment Tools (SWAT) model, the following main data was used: landuse, soil characteristics, topography and climate data. First, the raster maps (e.g. topography, landuse, soil) were imported in ArcSWAT 2012 interface.

In the next step, soil and landuse characteristics were overlaid for each sub-catchment. In addition, the weather data were defined. Finally, it was ran and simulated a 14-year period with 3 years warm-up from 1998 through 2011.

Calibration and Sensitivity Analysis

For calibration model we used SWAT-CUP program with SUFI-2 algorithm which can read output data from ArcSWAT interface. In this section, fourteen parameters were selected for calibration that influence streamflow. Sensitively analysis was performed and its results indicated the most sensitive parameters that illustrated in Table 1. According to Table 1, the most sensitive parameters are soil bulk density (SOL_BD) and SCS curve number for moisture condition II (CN2) because of P-value close to 0 and t-stat bigger than other parameters.

In the next step, model simulated and compared monthly simulated and observed streamflows using SUFI-2 algorithm. We calibrated a 7-year period from 2001 to 2007 and validated a 4-year period from 2008 to 2011. Analysis of hydrographs indicates that the calibrated model slightly underestimate the peak runoff (Fig. 2). The size of uncertainty band (95PPU) is shown in Fig. 2 which confirms the uncertainty is very high. After defining the initial values of the fourteen parameters, it was specified for selecting appropriate parameters ranges. It could be reduce the band of uncertainty. Furthermore, after three iterations with 500 model runs, the best calibration illustrated in Fig. 3, where R^2 value was 0.86, P-factor of 0.51, R-factor of 0.54 and NS was 0.77. With this calibration, the best ranges of parameters were obtained (Table 2). According to the last calibration, the best parameters values were imported (Table 2) in SWAT model and validated using data set for the period of 2008 to 2011and compared the plot of observed and simulated data.

Table 1. Sensitively analysis of parameters.

Index	Parameter	Definition	t_stat	p-value	Process	Sensitivity
1	ALPHA_BF	Base-flow alpha factors (1.days^{-1})	0.29	0.77	Groundwater	very low
2	GWQMN	Threshold depth in shallow aquifer (mm)	0.53	0.60	Groundwater	↑
3	HRU_SLP	Average slope steepness (m.m^{-1})	0.66	0.51	Geomorphology	
4	OV_N	Manning's n value for overland flow*	0.73	0.47	Geomorphology	
5	SOL_Z	Soil depth (mm)	0.79	0.43	Soil	
6	CH_K2	Channel effective hydraulic conductivity (mm.hr^{-1})	1.02	0.31	Channel	
7	GW_DELAY	Groundwater delay (day)	1.19	0.23	Groundwater	
8	CH_N2	Manning's n value for main channel*	1.22	0.22	Channel	
9	SOL_AWC	Available water capacity of the soil layer (mm.mm^{-1})	1.38	0.17	Soil	
10	SOL_ZMX	Maximum rooting depth of soil profile (mm)	1.54	0.12	Soil	
11	ALPHA_BNK	Base flow alpha factor for bank storage (days)	1.68	0.09	Channel	
12	SOL_K	Soil conductivity (mm.hr^{-1})	1.69	0.09	Soil	
13	CN2	SCS curve number for moisture condition II*	2.75	0.01	Runoff	↓
14	SOL_BD	Soil bulk density (g/cm^3)	5.59	0.00	Soil	very high

*dimensionless

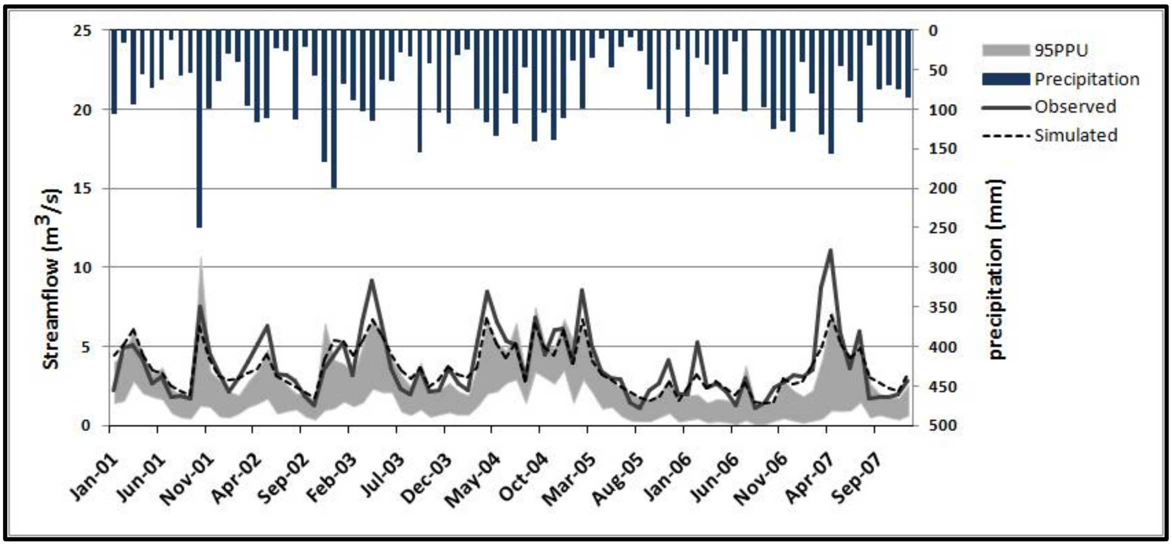

Fig. 2. 95% probability of uncertainty plot and comparing observed and simulated streamflow before calibration.

Table 3 illustrates the values of P and R factors, R^2 and NS in calibration (2001 to 2007) and validation (2008 to 2011) periods. Taking an analysis of the catchment at the outlet had a positive correlation with surface runoff, with R^2 of 0.85, while P-factor, R-factor and NS were 0.63, 0.49 and 0.74 respectively (Fig. 4).

In other words, the evaluation of the hydrograph plot showed good model match in validation period. Also coefficient of determination (R^2) value of calibration and validation period showed a good correlation between observed and simulated values (Fig. 5).

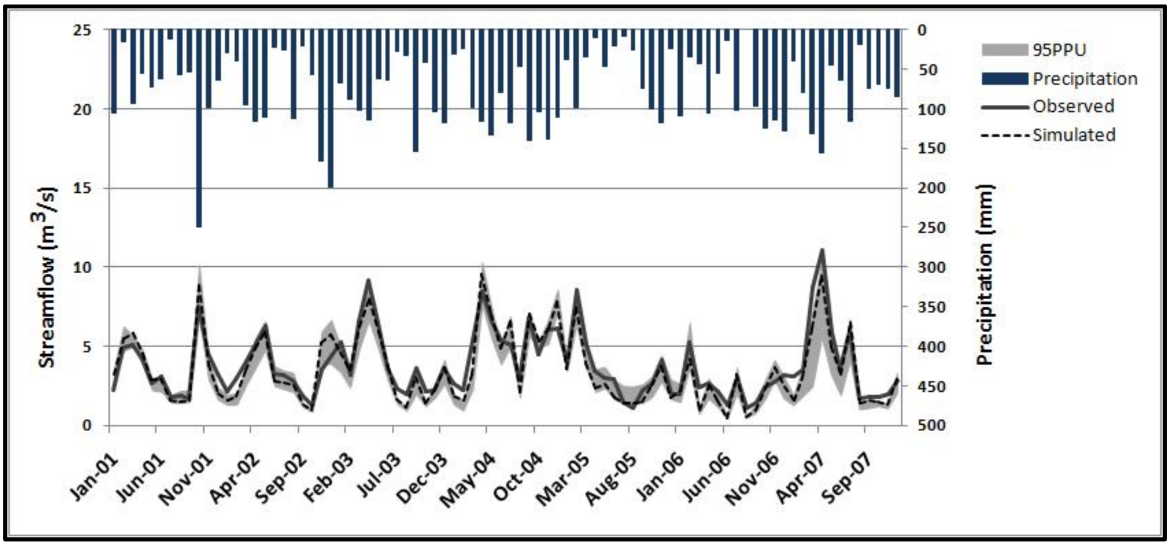

Fig. 3. 95% probability uncertainty plot and comparison observed and simulated streamflow after calibration (2001-2007).

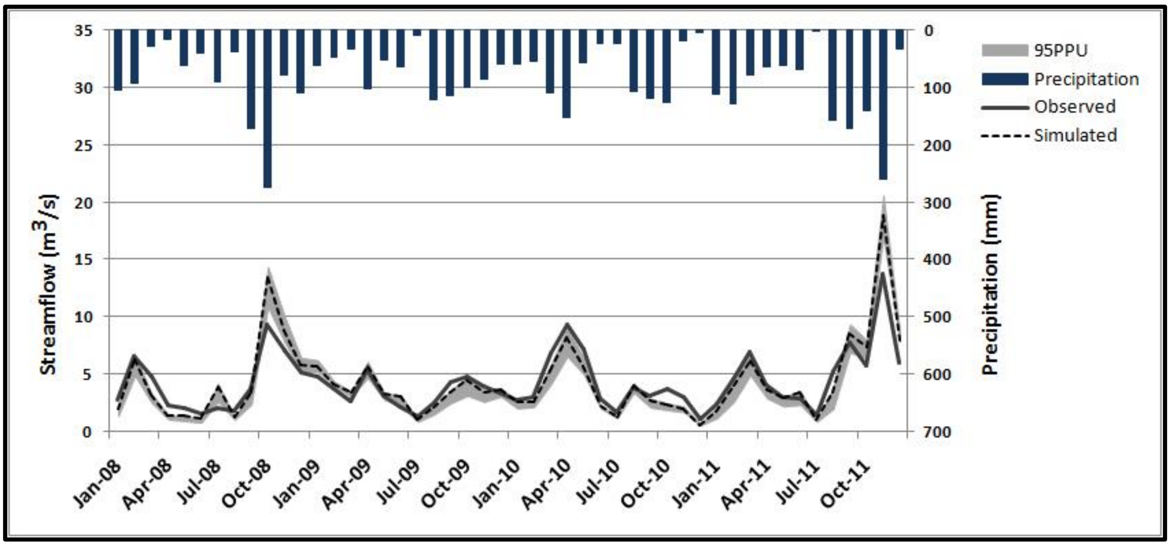

Fig. 4. 95% probability uncertainty plot and comparison observed and simulated streamflow in validation period (2008-2011).

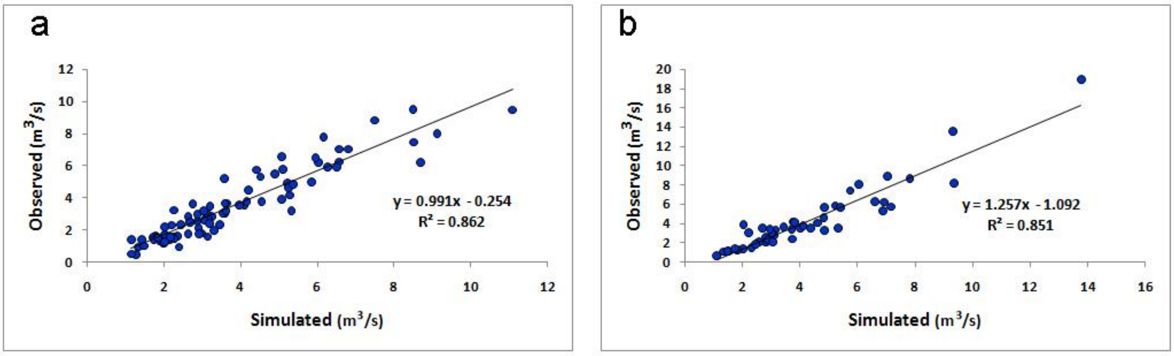

Fig. 5. Scatter plot of river streamflow for (a) calibration period (2001-2007) and (b) validation period (2008-2011).

Table 2. Optimum ranges of parameters.

Parameter_name	Fitted_value	Min_value	Max_value
CN2	0.233	0.193	0.272
ALPHA_BF	0.240	0.171	0.297
GW_DELAY	130.159	121.893	167.1877
GWQMN	-0.734	-0.783	0.238
CH_N2	0.222	0.204	0.245
CH_K2	159.381	133.678	165.119
ALPHA_BNK	0.763	0.609	0.910
SOL_ZMX	108.031	66.609	162.382
SOL_Z	365.522	315.512	506.027
SOL_AWC	0.074	0.010	0.089
SOL_K	0.440	0.434	0.884
SOL_BD	0.431	0.333	0.671
HRU_SLP	0.066	0.044	0.093
OV_N	-0.196	-0.199	-0.168

Table 3. Statistical Analysis of runoff simulation.

	Variable	P-factor	R-factor	R^2	NS
Before Calibration	FLOW_OUT	0.35	0.84	0.53	0.28
After Calibration	FLOW_OUT	0.51	0.54	0.86	0.77
Validation	FLOW_OUT	0.63	0.49	0.85	0.74

CONCLUSION

Many hydrologic studies and applications has been used SWAT model and SWAT-CUP program for calibration and validation data with decreasing uncertainty (Schuol & Abasspour 2006; Stedinger *et al.* 2008; Alibuyog *et al.* 2009; Li *et al.* 2010; Gosling *et al.* 2011; Du *et al.* 2013; Lin *et al.* 2015; Nyeko 2015).

Hosseini *et al.* (2011) applied SUFI-2 algorithm to simulate streamflow in Taleghan basin with an area of 800km^2. Fukunaga *et al.* (2015) investigated runoff simulation in the tropical watershed at Brazil using SUFI-2 algorithm. Their results revealed SUFI-2 algorithm performance was satisfactory in hydrology modeling. Vilaysane *et al.* (2015) applied SWAT model to test the capability of the model for predicting stream flow and also used SUFI-2 algorithm for calibration and uncertainty analysis in Xedone river basin. Pagliero *et al.* (2011) used SWAT model to predict surface water flow and nutrient loads in the Danube basin with an area of 803000 km^2. They applied SUFI-2 algorithm to reduce parameters uncertainty.

In SUFI-2 algorithm, all the uncertainties are combined and expressed through the P-factor, which is the percentage of measured data bracketed by the 95% prediction uncertainty (95PPU) with ranges from 0 to 1. Also, in uncertainty analysis used the R-factor, which is the average thickness of the 95PPU band divided by the standard deviation of the measured data (Yang *et al.,* 2008; Abbaspour 2011; Narsimlu *et al.,* 2015). In this study, It is calibrated fourteen parameters (e.g. CN2, ALPHA_BF, GW_DELAY, GWQMN, CH_N2, CH_K2, ALPHA_BNK, SOL_ZMX, SOL_Z, SOL_AWC, SOL_K, SOL_BD, HRU_SLP and OV_N) and tried to finding the best range of parameters with the most appropriate values of P-factor and R-factor (Table 3) that shown successfully efforts for decreasing uncertainty. In SWAT-CUP program, the Sequential Uncertainty Fitting (SUFI-2) algorithm try to predict all uncertainties (input data, parameters, model structure, output data) by finding the best amount of parameters uncertainty (Abbaspour *et al.* 2004, 2007b). The measured data uncertainty should be considered and the repeat of performance calibration can be obtained the best goodness fit if the rating of P-factor, R-factor, R^2 and NS are relaxed (Abbaspour *et al.* 2007a). Table 3 illustrates the values of P and R factors, R^2 and NS in calibration (2001 to 2007) and validation (2008 to 2011) periods.

The P-factor values close to 1 indicating a very high model performance, while the R-factor is the average width of the 95PPU band (Abbaspour *et al.* 2007b; Yang *et al.* 2008). According to Table 3, after calibration and validation periods the P-factor was obtained close to 1 with 0.51 and 0.63 respectively and thickness of the 95PPU band (R-factor) was lower than prior. These values confirm the accuracy of runoff simulation processes to decreasing data uncertainty. In other hand, according to Moriasi *et al.* (2007) classification, who defined a ''good model simulation'' with NS values from 0.65 to 0.75 and a ''best model simulation'' with NS values greater than 0.75, the calibration and validation model show better performance of model with Nash and Sutcliffe efficiency (NS) value of 0.77 and 0.74 respectively. Also coefficient of determination (R^2) value of 0.86 for calibration and 0.85 for validation period showed a good correlation between observed and simulated values (see Fig. 5).

These results to confirm the potential of SUFI-2 algorithm of SWAT-CUP program for simulating runoff data in Shafaroud watershed and matched well with those of the other authors (Tang *et al.* 2012; Rostamian *et al.* 2013; Singh *et al.* 2013; Vilaysane *et al.* 2015; Narsimlu *et al.* 2015). It is suggested in future studies, to use SUFI-2 algorithm in model parameters sensitivity and uncertainty analysis.

Also this algorithm can be used in further evaluation of land use change, sediment, climate change, water quality and evapotranspiration effect assessment on water resources.

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شبیه سازی رواناب با استفاده از مدل SWAT و الگوریتم SUFI-2
(مطالعه موردی: حوزه آبخیز شفارود، استان گیلان، ایران)

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چکیده

برآوردهای معتبر و دقیق از میزان دبی رواناب به مدیران حوزه‌های آبخیز در اتخاذ تصمیمات آگاهانه در مباحث مدیریت و برنامه‌ریزی منابع آب کمک می‌نماید. این تحقیق در حوزه آبخیز شفارود در شمال ایران انجام شده است. به منظور دستیابی بهینه به میزان رواناب، ابتدا داده‌های بارندگی چهار ایستگاه بارندگی در طی سال‌های ۱۹۹۸ تا ۲۰۱۱ جمع‌آوری شد و به همراه سایر نقشه‌های تهیه شده از منطقه مورد مطالعه همچون DEM، کاربری‌اراضی و خاکشناسی به عنوان داده‌های ورودی در قالب مدل SWAT به نرم‌افزار داده شد. پس از اجرای مدل، به منظور بررسی عدم قطعیت داده‌ها و دستیابی به دقیق‌ترین شبیه‌سازی از الگوریتم SUFI-2 در نرم‌افزار SWAT-CUP استفاده شد. بدین ترتیب که سه سال اولیه (۱۹۹۸-۲۰۰۰) از داده‌های بارندگی برای warm-up و ۷ سال بعدی (۲۰۰۱-۲۰۰۷) برای مرحله اعتبارسنجی و ۴ سال انتهایی (۲۰۰۸-۲۰۱۱) نیز برای مرحله صحت‌سنجی در نظر گرفته شدند. در نهایت با انجام شبیه‌سازی‌های متعدد، عدم قطعیت داده‌ها با مقادیر به دست آمده برای فاکتورهای P-factor وR-factor و ضرایب R^2 و NS مورد ارزیابی قرار گرفت. نتایج دوره صحت‌سنجی (R^2=۰/۷۵ و NS=۰/۷۴)، پتانسیل الگوریتم SUFI-2 در برآورد میزان رواناب در حوزه مورد مطالعه را تایید نمود.

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