Suitability of SWAT Model for Simulating of Monthly Streamflow in Lam Sonthi Watershed

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Abstract

The purpose of this study was to simulate the hydrologic processes from a watershed using the "Soil and Water Assessment Tool" (SWAT) model approach. The model was evaluated with the purpose to simulate the streamflows in an agricultural watershed in central Thailand. The results showed that the coefficient of correlation (R^2) and the Nash-Sutcliffe coefficient (E_{NS}) values were raised above 0.7, and the deviation of runoff volumes (D_v) was also acceptably accurate. Some months of simulated flows were overestimated but most simulated flows were close to observed flow by both the graphic and the statistical approaches. Although the model was evaluated using limited data and some of the model's algorithms for calculating flows might not be appropriate for tropical conditions like the watershed, overall prediction results were within acceptable levels for estimating monthly flows. This led to the conclusion that the SWAT model can reliably predict monthly streamflows on any other agricultural watershed in tropical climates with conditions similar to the watershed studied.

Keywords: streamflow prediction, soil and water assessment tool, hydrologic model, agricultural watershed, Thailand.
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1. Introduction

Understanding and predicting the hydrologic processes in a watershed are the challenging tasks of hydrologists and engineers. As the natural, complex processes in watershed scale are difficult to understand and simulate, for the past decade a number of watershed scale hydrologic models have been developed to predict such processes.

Hydrologic models capable of predicting the complex nature of processes are powerful aids to understanding such processes. They are also effective tools to assess the effect of land use changes, water management for agriculture, as well as best management practices in a watershed.

Among the commonly used hydrological watershed models is the "Soil and Water Assessment Tool" (SWAT), a robust hydrologic model successfully employed in a number of watersheds. SWAT is a public domain watershed scale model developed by the Agricultural Research Service of the United States of America's Department of Agriculture (USDA). The model was developed to predict the effects of land management on water, sediment, nutrients, pesticides, and agricultural chemicals in small to large complex basins.

Applications of SWAT have expanded worldwide over the past decade, especially in the United States and the European Union [1-4], but there is little SWAT research on predicting streamflows in the tropical climatic conditions of Thailand. The reason may be scarce data, not only temporal but also spatial scale for modeling in watershed hydrology. However, accurately assessing the hydrological processes in Thailand is a very important task because clearly understanding and predicting them is essential for appropriate watershed management.

The aim of this study was to better understand the hydrologic processes occurring in a watershed and to evaluate the performance of the SWAT model by comparing observed streamflows with predicted streamflows at the drainage outlet of an agricultural watershed in Thailand.

2. Materials and Methods

2.1 The Study Watershed

The Lam Sonthi Watershed (357 km^2), a sub-watershed of the Pasak Watershed, is located in central part of Thailand (Fig. 1). The watershed outlet is located at Ban Tha Yiam in Lop Buri province, 153 kilometers from Bangkok. The topography is mountainous along both sides of the watershed while the middle and the lower portions of the watershed are quite flat. The altitude of the watershed varies from 100 m in the lower area to approximately 700 m above mean sea level for the upper portion.

In the study area, the climate is characterized as sub-humid tropic. The wet season ranges from May to October and the dry season from November to April. The mean annual precipitation of the area is 1134 mm and the mean annual temperature ranges between 19.2 and 35.8 $^{\circ}C$. Maximum daily evaporation is 10.94 mm per day in April. Minimum evaporation is 0.34 mm per day in June.

The land use and land cover of the study watershed comprises 59.3 percent under forest, 37.7 percent under agriculture (corn as major crop), and 3 percent under grasses and others. The soils of the watershed are silt loam, loamy sand, silty clay, loam, clay, and sandy loam covering 48.3, 24.5, 11.4, 6.4, 4.7, and 4.7 percent of the watershed respectively.

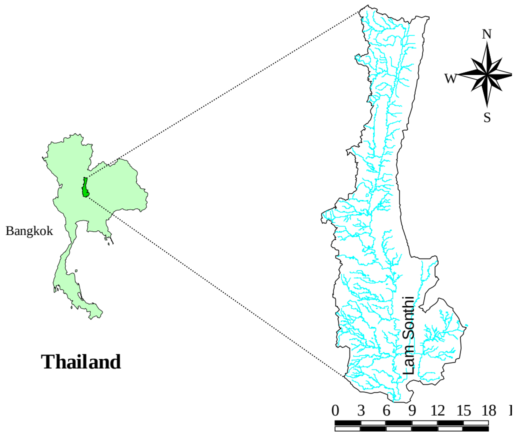


Fig. 1 The study area: Lam Sonthi River Watershed in Thailand.

2.2 Overview of the SWAT Model

The major components of SWAT are climate, hydrology, erosion, land cover/plant growth, nutrients, pesticides, and land management [5]. The SWAT was used to simulate the hydrologic processes of the study watershed. The processes are calculated based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right) \quad (1)$$

Where SW_t is the final soil water content (mm), SW_0 is the initial soil water content (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), w_{seep} is the amount of percolation and bypass flow exiting the soil profile bottom on day i (mm), and Q_{gw} is the amount of return flow/baseflow on day i (mm).

Surface runoff volume is calculated by using a modification of the SCS curve number approach. Peak runoff is computed by a modification of the rational method. Runoff routing in the channel is estimated by Muskingum routing method. The potential evapotranspiration are based on the Hargreaves' approach. The model calculates the amount of percolation and bypass flow through the soil layers by using a storage routing technique [5,6]. The shallow aquifer means an unconfined aquifer that contributes to flow to the main channel or river reach in sub-watershed. The deep aquifer is a confined aquifer and the entering water is assumed to contribute to streamflow somewhere outside of the watershed. A full explanation of SWAT theories and structure are given by [5].

2.3 Model Building

SWAT requires extensive data on meteorology, topography, land use, soil series, and land management as input. The weather data, which includes daily precipitation and maximum-minimum temperature were archieved from Thai Meteorological Department (TMD). The terrain elevation data was obtained from the Royal Thai Survey Department (RTSD) in digital form. Such data was used for delineating the study watershed into sub-watersheds. Digital land use data was acquired from the Land Development Department (LDD). It was processed and reclassified to match the SWAT model land use code. Ten classes of land use in the study area were used for SWAT processing. Soil profile and soil type were collected from LDD. There were fourteen types of soil found in the study area. These data were then converted and reclassified to match SWAT formats in order to support the model's requirements. Planting and harvest dates for crops were obtained from a local agent (the provincial agricultural office) and it were also scheduled and used to build the SWAT management input file.

2.4 Model Calibration

A traditional split-sample technique was conducted against observed streamflows of the watershed outlet gauging station (S.13). The hydrologic module of SWAT was calibrated and validated using data collated between 1999 and 2002.

The relevant model parameters (Table 1) were manually adjusted within a reasonable range suggested by [5] during the calibration period until the predicted monthly streamflows were in acceptable agreement with the observed ones. The model parameters used for calibration consist of two sub-modules that are the base flow module and the surface runoff module.

Two model parameters involve the base flow processes were calibrated. One of base flow parameter is the threshold water level in shallow aquifer required for return flow to occur (GWQMN). Another base flow parameter is the ground water revap coefficient (GW_REVAP). For the surface runoff processes, three parameters were adjusted in this study. These included the available water capacity of the first soil layer (SOL_AWC), SCS runoff curve number (CN2), and the Manning's "n" for the main channels (CH_N2). All of these parameters were calibrated in order to represent the hydrological processes of the study watershed.

2.5 Model Performance Evaluation

Model evaluation is a procedure to test whether the model can represent the physical processes occurring in a watershed. Coefficient of correlation (R) is one statistical measurement widely used to test the linear relation between two variables. The correlation equation is computed as:

$$R = \frac{\sum_{i=1}^{n}(O_i - O_{mean})(P_i - P_{mean})}{\sqrt{\left(\sum_{i=1}^{n}(O_i - O_{mean})^2\right)\left(\sum_{i=1}^{n}(P_i - P_{mean})^2\right)}} \quad (2)$$

where O is the observed data; P is the model simulated data for the time period entered for evaluation.

According to American Society of Civil Engineers (ASCE) [7], Nash-Sutcliffe coefficient, E_{NS} [8] and the deviation of runoff volume (D_v) were recommended. The E_{NS} is determined as:

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}(Q_{mes} - Q_{sim})^2}{\sum_{i=1}^{n}(Q_{mes} - Q_{mean})^2} \quad (3)$$

where Q_{mes} is the measured monthly discharge (m^3/s); Q_{sim} is the computed monthly discharge (m^3/s); Q_{mean} is the average measured discharge (m^3/s); and n is the number of monthly discharge values.

The deviation of runoff volumes, D_v may be expressed as:

$$D_v(\%) = \frac{V_{mes} - V_{sim}}{V_{mes}} \times 100 \quad (4)$$

where V_{mes} is the measured monthly or seasonal runoff volume; and V_{sim} is the model computed monthly or seasonal runoff volume.

In this study, the predicted monthly streamflows were calibrated to match observed monthly flows at the watershed outlet station and were satisfied if the R^2 reached above 0.6 and $E_{NS} > 0.5$ as recommended by [9]. In addition, ASCE [7] noted that D_v can take any values but in this study the smaller values of D_v were satisfied.

3. Results

The predicted values were plotted against the observed values through the calibration and validation period (Fig. 2, 3 and 4). The initial and final values of model parameters for calibration and validation procedures are shown in Table 1, while Table 2 presents the statistical indicators for both calibration and validation.

3.1 Model Calibration Results (1999-2000)

During the calibration period, the model simulated flows that matched observed flows with moderate accuracy. The simulated flows were substantially overestimated for 1999 but quite accurately predicted for 2000. The predicted peak discharge closely matched observed values in 2000, differing by only 0.2% but overestimated by 84% in 1999. The simulated monthly flows from the SWAT model reached the high value of both R^2 and the E_{Ns} -- more than 0.8 (R^2=0.805 and E_{Ns}=0.848). The scatter plot for model calibration (Fig. 3a) showed the uniform scatter of points above the 1:1 line for low flows, while for the peak flow it plotted very close to the 1:1 line.

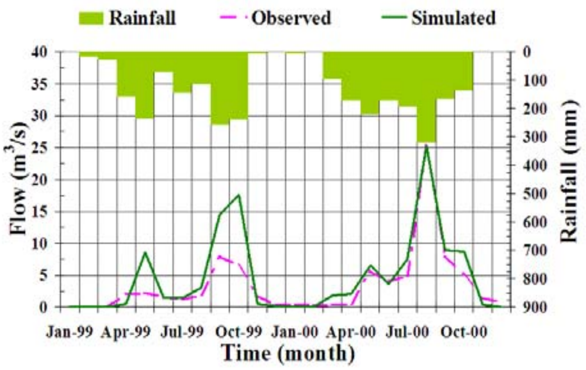
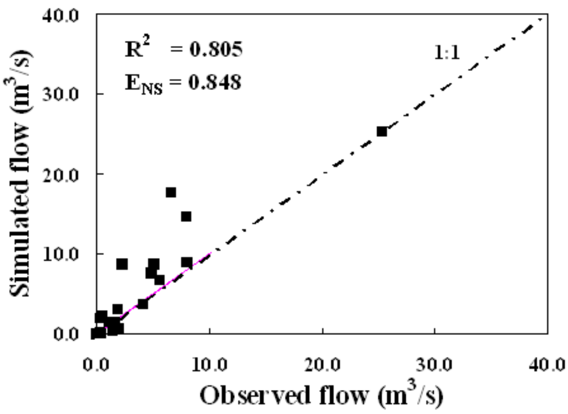


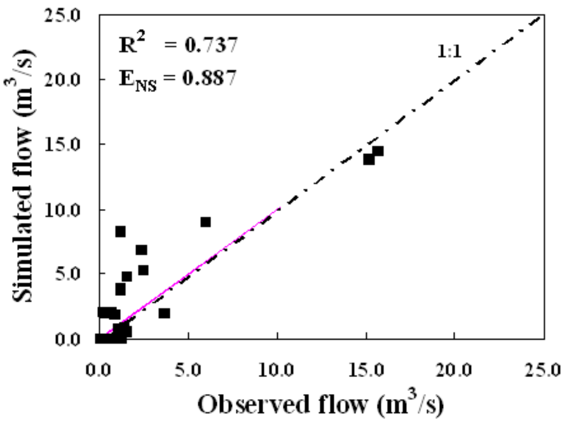
Fig. 2 Simulated versus observed monthly flows at the watershed outlet for model calibration.

3.2 Model Validation Results (2000-2002)

In the validation period, the predicted peaks flows and the time to peaks matched well with the observed flows. The peak flows in both 2001 and 2002 were underestimated by 9.1% and 8.2%, respectively. Fig. 3b, most of the points were evenly distributed along the 1:1 line, especially the peak flows in both 2001 and 2002. The simulated flows showed good agreement with observed flows by the high values of R^2 (0.737) and E_{Ns} (0.887).



(a) Calibration



(b) Validation

Fig. 3 Scatter plots of model: (a) Calibration and (b) Validation.

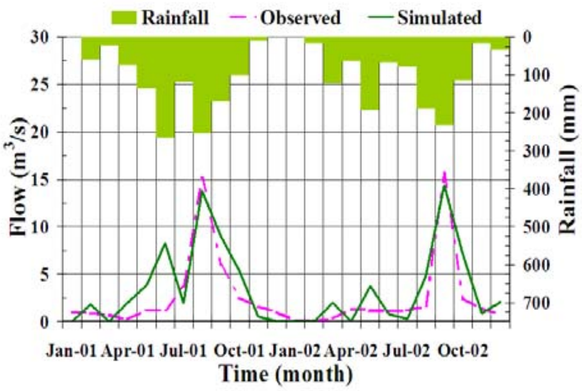


Fig. 4 Simulated versus observed monthly flows at the watershed outlet for model validation.

3.3 Comparing the Model Performance Between Wet and Dry Seasons

In most instances, monthly streamflows were reasonably predicted by the SWAT model for the study watershed in evaluation stages. However, streamflows were quite overestimated in the summer months through the four years of model evaluation. To reconcile this error, streamflows both in the wet and dry conditions were investigate using three statistical methods.

The results showed that in summer months the low values of R^2 fell below 0.425, whereas in monsoon months they reached above 0.757. In the same trend as R^2, the higher value of E_{NS} was obtained (0.904) in monsoon months but the lower value was met in summer months (0.516).

In addition, the predicted volume for D_v was overestimated by only 29.715 percent in the monsoon season, but largely overestimated in dry months with the high value of D_v at 66.705 percent. This implies that the streamflows were well predicted by the model in wet conditions but unsatisfactorily in dry conditions.

Table 1 The adjusted variables for model calibration.

Notation	Range* (Unit)	Adjusted value
GWQMN	0-100 (mm)	100
GW_REVAP	0.02-0.20	0.05
SOL_AWC	-	0.5
CN2	± 10%	+10%
CH_N2	0.01-0.30	0.03

*The initial ranges are based primarily on recommendations given in the SWAT User's Manual [5]

4. Discussion

Results found from this study when calibrating the SWAT model to study site in tropical conditions. Based on the statistical evaluation, it was found that the model performed reasonably well in predicting streamflow for both the calibration and validation periods. However, the model was not well simulated in dry condition. Overestimation of streamflow in the dry period has also been reported by any other applications of SWAT [2-4,10]. For this study, possible reasons for the differences between predicted and observed flows can be discussed several ways.

Table 2 The goodness-of-fit of monthly flow for model calibration and validation.

Statistical Test	Calibration		Validation	
	Obs.	Sim.	Obs.	Sim.
Average (m^3/s)	3.4	4.7	2.6	3.4
Peak flow (m^3/s)	25.3	25.3	15.7	14.4
Volume ($10^6 m^3$)	214	293	161	213
R^2	0.81		0.74	
E_{NS}	0.848		0.887	
D_v (%)	37.33		32.24	

Obs. = observed flow and Sim. = simulated flow

First, approximately forty percent of the study site is dominated by agriculture supported by water from small-scale irrigation systems. However, information about the water used by these systems, such as pumping for irrigation and water diverted directly from the streams, was unavailable. During the simulations, this missing data resulted in larger predicted streamflow than observed values throughout the calibration and validation period, particularly during dry seasons.

Second, the SWAT model employs a number of empirically-based algorithms for modeling. Some of the original parameters of the model, however, may be unsuitable for tropical regions where the hydrologic conditions are relatively different in comparison to the United States where the model was originally developed. For streamflow predictions, the SCS curve number method was used for estimating direct runoff in the study watershed. The method was developed using regional data from the mid-western United States; therefore, the shortcomings in predicting streamflow may be due to the empirical nature of the relationships developed mainly in the country. Some caution has been also recommended for implementing the method in different land uses [2] and climatic regions [11]. Consequently, such empirical bases should be modified to suite the environmental conditions of this region in order to improve predictions made by the model.

Another possible of the model lower perform in the dry condition than in the wet condition may cause from the model's parameters were unchangeable. The SWAT allows only the same set of input parameters through the calibration and validation periods. For example, in this study SOL_AWC, which is one of the most sensitive parameter in runoff simulation [12], was fixed throughout the evaluation periods in both wet and dry conditions. This may involve that the available water in soil layer may have taken place too quickly in wet condition whereas may have not occurred fast enough in the dry condition. Therefore, this study suggested that changeable of model parameters in different hydrological conditions and field survey to obtain seasonal soil moisture may improve model performance.

In case of model parameters adjustment, after the parameters that involved physical characteristics of the study watershed as GWQMN, GW_REVAP, SOL_AWC, CN2, and CH_N2 were fine-tuned. It was found that these adjusted parameters could improve the overall model performance which indicated by increasing the statistical values of R^2 and E_{NS} by 5.9% and 76.2%, respectively while D_v decreased by 49.5%. In addition, these parameter values were also found within the acceptable ranges suggested by previous researches [2,9,13]. However, these parameters are site specific so they can be largely differed on another watershed. It is important that such model parameters need to be examined when they are applied on another study site.

According to the scant data for this study, only four years data (1999-2002) were possible for model calibration and validation that data did not up to date for the current situation. This is because some model's parameters can be varies when watershed conditions such as land use are changed. Therefore, this study suggested that parameter as CN2 that more sensitive when land uses are modified. Such parameter needs to be re-calibrated when other simulation periods are considered in this study site.

5. Conclusions

The ability of the SWAT model to simulate streamflow in an agricultural watershed was evaluated with the overall goal of improving and understanding hydrologic processes. Model performance was tested on the Lam Sonthi River Watershed by use of extremely limited data in terms of quantity and quality. The discrepancies were found in streamflow predictions for some years during the dry months. Further improvement in the accuracy of the model is recommended to suit different geographical and climatic conditions.

Although the model used severely limited data and there were some shortcomings in output during the model simulation, the overall predictions of estimated monthly flow were within the acceptable ranges used as criteria for this study. Consequently, the SWAT model can be used confidently to predict monthly streamflow on any other agricultural watersheds in tropical regions with conditions similar to the watershed studied.

6. Acknowledgments

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