EVALUATION OF SWAT MODEL PERFORMANCE TO HYDROLOGIC CYCLE SIMULATION IN THE CONG WATERSHED, VIET NAM

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Abstract: *In this study, performance of semi-distributed hydrologic model, namely Soil and Water Assessment Tool (SWAT), was evaluated for hydrologic cycle simulation in the Cong Watershed.. The model parameters were calibrated and validated using meteorological data observed at five gauges and runoff data observed at Tan Cuong Station between 1961 and 1975. Quantitative statistical criteria such as Nash-Sutcliffe Efficiency (NSE) and Coefficient of determination (R^2) were used to evaluate the model performance on daily river flow simulations. As a result, the calibrated model performed well in hydrologic cycle simulations in the Cong Watershed, suggesting the applicability of the SWAT model to the target watershed. Subsequently, the calibrated SWAT model was utilized for further assessment of hydrologic cycle in the Cong Watershed under different conditions of 1966 - 1975 and 2001 - 2010 periods. For this purpose, the watershed's hydrologic cycle was assessed with regard to scenarios of climate variability, land use change, and reservoir operation.*

Keywords: hydrologic cycle, watershed, hydrologic response unit, calibration, validation

1. INTRODUCTION

There are a lot of hydrologic models developed to simulate the hydrologic cycle at a watershed scale. The results of model provide river flow characteristics which are of great importance for decision makers issuing appropriate water-related policies according to their local conditions. Among a wide variety of models, the Soil and Water Assessment Tool (SWAT: Arnold et al., 1998) has been used widely and successfully in many countries for assessing watershed hydrology. The SWAT offers convenient tools to define model structure and input data. It can operate on a daily time step, computes efficiently and lumps many detailed processes into simplified prediction. In Vietnam, there have been a few applications of SWAT model to simulate hydrologic cycle in Vietnamese watersheds. Raghavan et al. (2012), Khoi and Suetsugi (2012), and Viet Bach Tran et al. (2017) presented a reasonable performance of the calibrated SWAT model in the hydrologic simulation for the Be, Sesan, and Cau River basins, respectively.

In this study, after the SWAT model was successfully calibrated and validated for daily hydrologic simulation over the Cong watershed from 1961 to 1976, it further applied for assessing variability of hydrologic cycle within the Cong Watershed between the period 1966 – 1975 and the period 2001 – 2010 with respect to scenarios of climate variability, land use change, and reservoir operation.

2. METHODS

2.1. Description of SWAT model

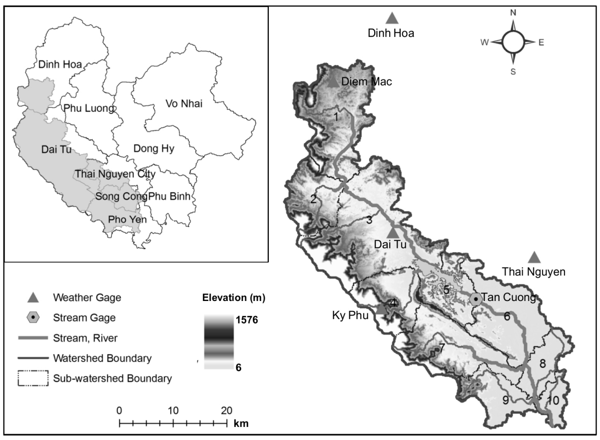

Fig 1. Location of the Cong watershed

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In SWAT, water balance is the driving force behind all the processes that happen in the watershed. With the purpose of accurately modeling the movement of water, pesticides, sediments or nutrients, the hydrologic simulation of a watershed can be separated into two phases: land phase and in-stream (or routine) phase. The land phase controls the amount of water, sediment and pesticide loadings to the main channel in each subwatershed, whereas the in-stream phase can be defined as the movement process of water, sediments, and nutrients through the channel network of the watershed to the outlet. Daily water budget components, including precipitation, evapotranspiration (ET), percolation, surface flow and baseflow, are calculated for each HRU based on physical environment and management practices that are required as model input. Subpartitioning a watershed into HRUs allows the model to simulate differences in ET for multiple crops and soils, using either of the Priestly-Taylor method (Priestly and Taylor, 1972), Penman-Monteith method (Monteith, 1965) or Hargreaves method (Hargreaves, 1975). On a subwatershed scale, the percolation from bottom of the root zone is calculated using storage routing method and the baseflow is simulated based on the amount of water stored in the shallow aquifer and recession constant. The delineation of in-stream phase is accomplished by applying either variable storage coefficient method (Williams, 1969) or Muskingum river routing method (Overton, 1966).

2.2. Description of the Cong watershed

The Cong watershed is situated to the west of Thai Nguyen province and is a sub-basin of the Cau River basin, one of the largest basins in Northern Vietnam. In the Cong watershed, the main river (i.e. the Cong River) originates from mountainous area of Bac Kan Province and flows into the Cau River at Da Phuc Bridge. It runs through the area of 869 km^2 and is approximately 100 km in length. Topographic slope dips gently from north to south (Fig. 1). In the watershed, there are five precipitation gauges, of which two gauges, namely Thai Nguyen and Dinh Hoa, observe other climatic data such as wind speed, solar radiation, relative humidity, etc. For river flow, only one gauge was placed on the Cong River to observe runoff data for the period from 1961 to 1975. According to the surveys of Ministry of Agriculture and Rural Development (MARD) since 1960, there are 12 soil types defined for the watershed.

2.3. Input data

Elevation, land use and soil type of the Cong watershed were obtained as GIS data at a 90 m resolution. Based on a threshold value of 45 km^2 and the DEM, the watershed was delineated into 10 subwatersheds (Fig. 1). These 10 subwatersheds were then subdivided into 242 HRUs on the basis of unique combinations of land use, soil type and topographic slope. The percentage thresholds for land use, soil type and slope to define HRUs were set at 5%, 10% and 10%, respectively. Daily meteorological data (precipitation from 5 gauges as well as maximum and minimum air temperature, wind speed, relative humidity from 2 gauges) and monthly meteorological data (solar radiation from 2 gauges) for the period from 1961 to 1975 and the period from 2000 - 2010 were used for the model simulation. The location of meteorological gauges used in this study is shown in Fig.1. Monthly solar radiation data were used to generate daily data using the Hargreaves method (Hargreaves and Samani, 1982) with power regression (Baigorria et al., 2004; Fukuda et al., 2008). The daily river records observed at the Tan Cuong station for the period from 1961 to 1975 and the daily outflow data released from the reservoir for period from 2000 to 2010 were collected from Thai Nguyen Irrigation Management Company for the purpose of hydrologic cycle assessment in the study.

2.4. Evaluation of model performance

The SWAT model simulates the land phase of hydrologic cycle based on the water balance equation as below (Arnold et al., 1998). Water yield, including surface flow and baseflow, generated in each subwatershed during land phase contributes to river flow in the reach and then flows to the outlet of watershed.

The SWAT model was calibrated for 1961 – 1969, in which the year of 1961 was considered as a warm-up period to make the hydrologic cycle fully operational. Following the calibration guidelines (Arnold et al., 2011; Arnold et al., 2012), baseflow separation of the observed river flow data at the Tan Cuong station was first examined using the baseflow filter program (Arnold and Allen, 1999) to estimate the relative contribution of surface flow and baseflow to total river flow of 54% and 46% in the respective calibration time. This information was additionally used during the calibration.

Model parameters were calibrated by considering surface, subsurface and basin responses until simulated values reached a good agreement with observation data. Subsequently, the model was validated for 1970 – 1975, while the model parameters were held at the calibrated values. The model performance was evaluated on daily runoff simulation with two statistical criteria, namely Nash-Sutcliffe efficiency (NSE) and coefficient of determination (R^2).

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{\mathrm{obs},i} - Q_{\mathrm{sim},i}\right)^2}{\sum_{i=1}^{n}\left(Q_{\mathrm{obs},i} - \overline{Q}_{\mathrm{obs}}\right)^2} \quad (1)$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(Q_{\mathrm{obs},i} - \overline{Q}_{\mathrm{obs}}\right)\left(Q_{\mathrm{sim},i} - \overline{Q}_{\mathrm{sim}}\right)\right]^2}{\sum_{i=1}^{n}\left(Q_{\mathrm{obs},i} - \overline{Q}_{\mathrm{obs}}\right)^2 \sum_{i=1}^{n}\left(Q_{\mathrm{sim},i} - \overline{Q}_{\mathrm{sim}}\right)^2} \quad (2)$$

where $Q_{\mathrm{obs},i}$ is the observed flow at time i (m^3/s), $Q_{\mathrm{sim},i}$ is the simulated flow at time i (m^3/s), $\overline{Q}_{obs}$ is the mean observed flow (m^3/s) and $\overline{Q}_{sim}$ is the mean simulated flow (m^3/s), and n is the number of pairs of observed and simulated values.

Table 1. Impact scenarios setting for hydrologic simulation

	Simulation period	Description
Baseline	1966 - 1975	The period 1966 - 1975 conditions
Scenario 1	2001 - 2010	Climate variability from the period 1966 - 1975
Scenario 2	2001 - 2010	Climate variability and land use change from the period 1966 - 1975
Scenario 3	2001 - 2010	Climate variability and land use change from the period 1966 - 1975, and Nuicoc Reservoir's operation

Table 2. Calibration of the SWAT model and calibrated parameter values

Parameter	Description	Units	Default value	Adjusted range		Adjusted value	Calibrated value
				Lower range	Upper range		
Surface water response							
CN2	SCS runoff curve number	none	varies among HRUs	-25%	25%	-23.5%	varies among HRUs
SOL_AWC	Available soil water capacity	mm/mm	varies among HRUs	-25%	25%	+25%	varies among HRUs
ESCO	Soil evaporation compensation factor	none	0.95	0.5	1	0.70	0.70

Subsurface water response							
GW_DELAY	Groundwater delay	days	31	-24	24	-24	7
ALPHA_BF	Base flow alpha factor	days	0.048	-0.012	0.012	0.00	0.048
GWQMN	Minimum threshold depth of water in the shallow aquifer required for return flow occurring	mm	0	0	3500	250	250
GWREVAP	Groundwater revap coefficient	none	0.02	0.02	0.2	0.15	0.15
REVAPMN	Minimum threshold depth of water in the shallow aquifer for "revap" occuring	mm	1	0	500	1	1
RCHRG_DP	Deep aquifer percolation fraction	fraction	0.05	0	0.5	0.25	0.25
Basin response							
SURLAG	Surface runoff lag time	none	4	0.05	10	0.50	0.50
CH_K2	Channel hydraulic conductivity	mm/h	0	0	50	10.0	10.0

2.5. Assessment of hydrologic cycle with different scenarios

After the model calibration and validation achieved satisfaction in the hydrologic simulation, the calibrated model was further applied to the assessment of hydrologic cycle alteration under the variability of watershed conditions as shown in Table 1.

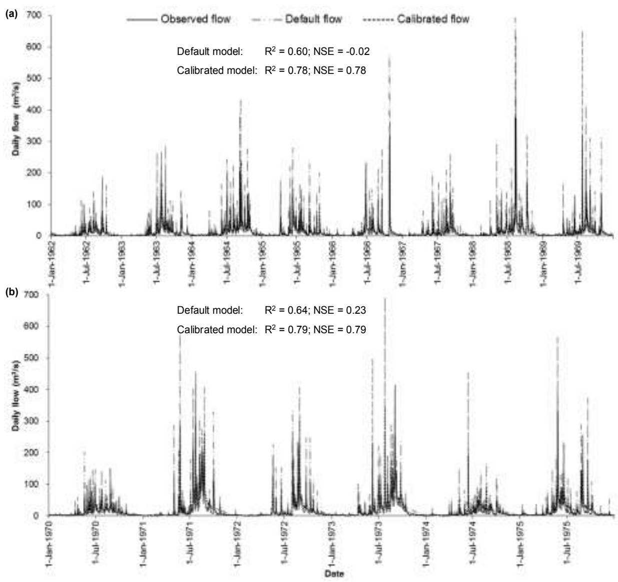

Fig 2. Comparison of daily flow simulations between the default and calibrated SWAT models: (a) calibration period (1962-1969) and (b) validation period (1970-1975)

Concerning the temperature comparison, the mean monthly temperature of the period 2001 – 2010 consistently increased by from 0.3 to 1.6^{o}C as compared with that of the period 1966 – 1975. In comparison with the first period, the mean monthly precipitation in the second period was characterized by both increasing and decreasing trends. However, the increasing rate (from 3.2 to 32.6%) tended to be lower than the decreasing rate (from 10.4 to 51.1%) of the mean monthly precipitation. It resulted in the falling trend of annual precipitation in the second period as compared with that in the first period.

The land use change assessment in the Cong Watershed between1966 - 1975 and 2001 - 2010 was conducted based on the summary of land use categories' areas in the watershed after HRU definition by SWAT model. The significant change was the decrease of the forest areas and the increase of the agricultural and residential areas in the latter period as compared with the former period. In the second period, the percentage of forest areas reduced by about 5% when it was changed into agricultural purpose and residential purpose.

The alteration of natural river flow regime on the Cong River was expected along with the occurrence of the Nui Coc Reservoir in 1980. The reservoir's operations were regulated with the purpose of flood control and water supply water for the downstream areas. This caused the seasonal change of the downstream flow as compared with antecedent flow regime. In this section, the influence of the reservoir operation on temporal variability the stream flow at the watershed outlet was assessed using the measured daily outflow from the Nui Coc Reservoir for 2001 – 2010.

3. RESULTS

3.1. Calibration and validation

The model parameters calibrated for the Cong watershed are summarized in Table 1. Most parameters were calibrated closely to the range bound in order to obtain the best accuracy after calibration. Model performance on the river flow using the default and calibrated model in the calibration and validation period can be observed through graphical and statistical evaluation (Fig. 2, Table 2). Fig. 2 depicts a reasonable agreement between observed and simulated hydrographs on daily step for both calibration and validation period after calibration, while the default SWAT model overestimated the flow. The result confirmed a better performance of the calibrated model as compared with the default one.

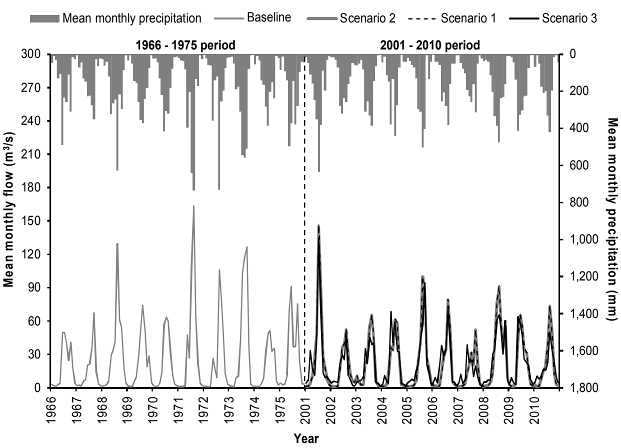

Fig 3. Comparison of monthly flow between baseline and scenarios at the watershed outlet

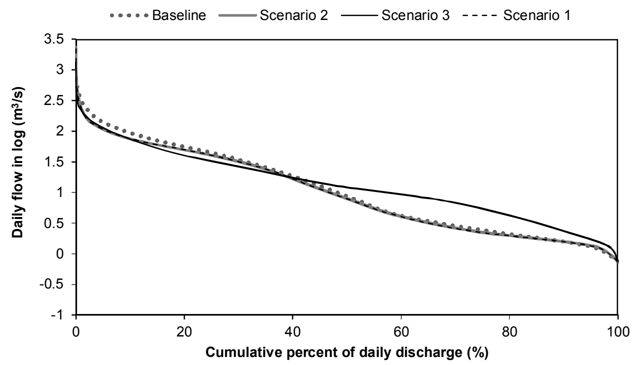

Fig 4. Comparison of daily flow between baseline and scenarios at the watershed outlet

For both the calibration and validation period, the NSE and R^2 indicated higher performance of the calibrated model in comparison with the default model. The default model poorly performed in both simulation periods with NSE ranging from –0.02 to 0.23 for daily simulations. After calibration, model performance showed a substantial improvement with NSE ranging from 0.78 to 0.79 for the period of calibration and validation, respectively.

In the study, 9 out of 11 parameter considered in the calibration process adjusted their default values to achieve the best calibration and validation in the hydrologic simulation at the daily time step. Despite the high performance, some peaks and baseflow portions in the daily hydrographs were simulated unreasonably (Fig. 2). This may be partially due to the lack of hourly rainfall data as well as some simplifications or limitations of the SWAT model. Such problems can be partially solved by accumulating observation data and/or by adding modules describing detailed processes related to watershed hydrology.

3.2. Assessment of hydrologic cycle with different scenarios

The monthly and daily river flow simulations at the watershed outlet regarding to three different scenarios of the period 2001 - 2010 were conducted and then were compared with the simulations for 1966 - 1975 through hydrographs (Figs 3-4). Generally, in comparison with the base line simulation, the river flow at the watershed outlet in the second period declined as a result of falling trend in precipitation in the scenario 1. The slight difference in river flow between the scenarios 1 and 2 revealed that the impact of land use change between two periods on the downstream flow was insignificant. Conversely, the influence of the reservoir operations to the downstream flow variability was quite remarkable when the simulations between the scenarios 2 and 3 were compared. The simulations of the scenarios 3 resulted in the higher flow and lower flow values under the releasing and stored stages of reservoir as compared with the river flow of the scenario 2.

For the hydrologic cycle assessment in the Cong Watershed, the distribution of hydrologic components, namely the mean annual precipitation, evapotranspiration, surface flow, and baseflow normalized by its area, at a subwatershed scale were presented for 1966 – 1975 and 2001 – 2010 (Fig. 5). In response to the precipitation distribution over the watershed, there was more water evaporated and generated in the downstream subwatersheds than that in the upstream subwatersheds.

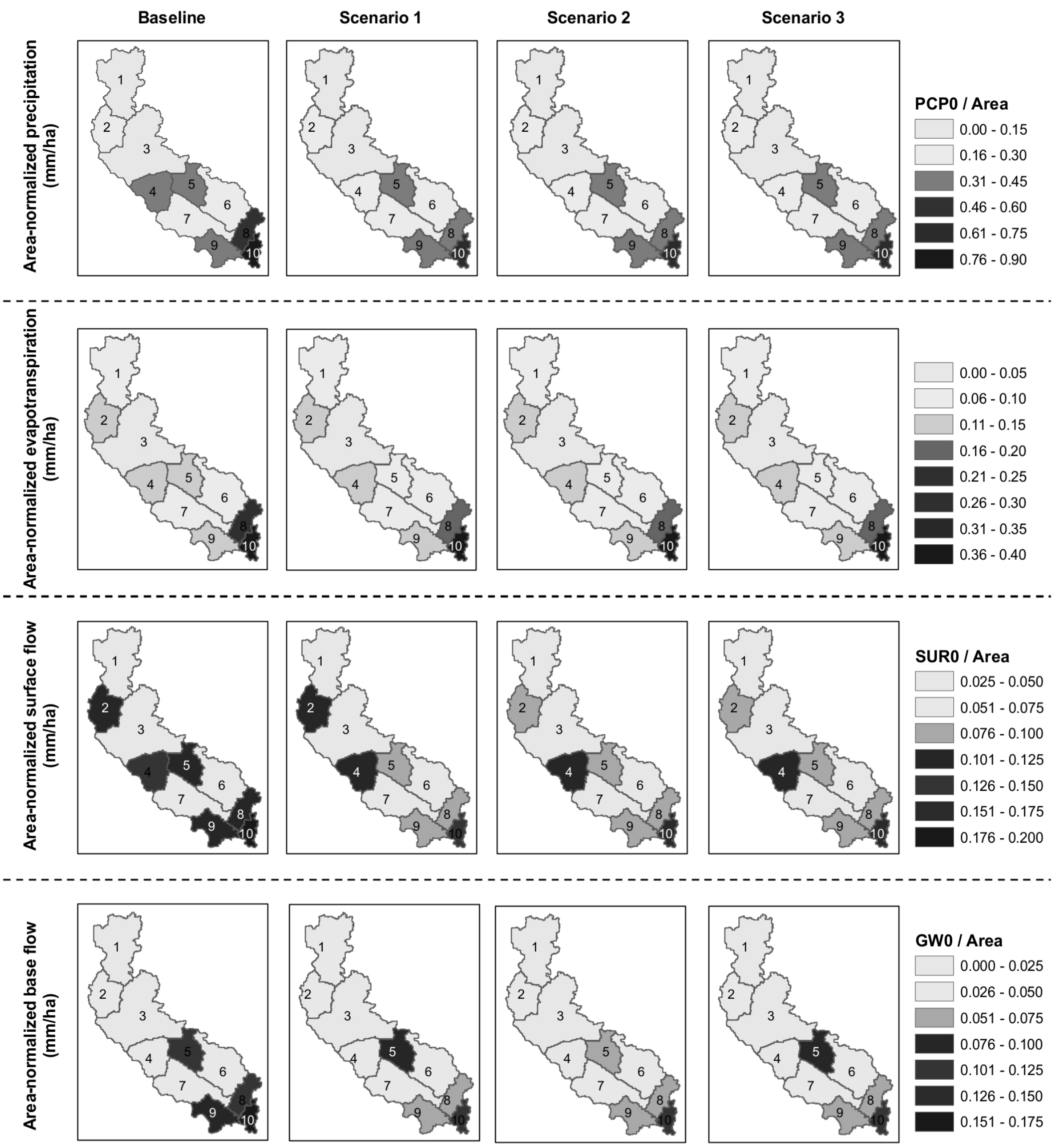

Fig 5. Comparison of the hydrologic components variability between the baseline and three scenarios

It can be seen that the alterations to the Cong River flow regime at the watershed outlet mostly came from the effect of climate variability between two periods and the Nui Coc Reservoir operations, while the impact of land use change in this case was minor. According to the precipitation variability, the river flow varied randomly between the increasing and the decreasing trends of the river flow. In contrast to river flow alteration caused by the climate variability, the seasonal impact of the reservoir operations on the river flow regime can be clearly seen with more water releasing to the downstream flow for agricultural irrigation and more water storing in the reservoir for flood control during the dry and flood seasons, respectively. It led to the increase in low flow portion and the decrease in high flow portion of river flow regime as shown in Fig. 4.

By assessing the impact of climate variability between two periods, the comparison between the base line and scenario 1 revealed that a decreasing trend in the latter 10-year period was observed for mean annual evapotranspiration, surface flow and base flow at most of the subwatersheds. Such phenomena were associated with the reduction of precipitation over the watershed in the second period as compared with the first period. Similar to the hydrologic alterations in the river flow regime, the influence of the land use change to the variability of hydrologic component was insignificant upon the comparison between the scenarios 1 and 2. It can be explained by the fact that the conversion of the forest areas to other purposes was scattered over the watershed. Accordingly, such change was not large enough to cause remarkable change to hydrologic circulation of the watershed. Only minor differences can be identified between the scenarios 1 and 2. As compared with the scenario 2, the scenario 1 generated more surface flow and baseflow at the subwatersheds 2 and 5, respectively. As the land use change, portion of the fallow area in the subwatershed 2 was changed into agricultural purpose with more density of vegetative cover, resulting in the decresing surface flow to some extent. Concerning the subwatershed 5, the conversion of a part of forest areas into agricultural purpose was a reason for the reduction of the baseflow generation. As illustrated in Fig. 5, the reservoir operations did not have much effect on the variability of hydrologic components at the subwatershed scales when the results in the scenario 3 were almost the same with that in the scenario 2. These results were expected because the Nui Coc Reservoir was built on the Cong River and thus its operation only affected to the river flow regime. The unique change came from the baseflow generation in the subwatershed 5 which generated more baseflow amount in the scenario 3 than the scenario 2. It can be explained by the water storage in the Nui Coc Reservoir, which resulted in more water recharged to the shallow aquifer and then flow to the river flow as the baseflow contribution.

4. CONCLUSIONS

The study revealed that, the calibrated SWAT model could simulate hydrologic cycle in a high accuracy after it was calibrated. Such confirmation was supported by the model performance evaluation since NSE and R^2 obtained their high values for both the calibrated and validated periods.

Application of the calibrated model to assess impact of climate variability, land use change and reservoir operations on the hydrologic cycle between the period 1966 – 1975 and the period 2001 – 2010 indicated seasonal alteration of hydrologic regime between two periods. According to the spatial simulation of water generated from the land phase, the critical sources of water over the watershed was identified, and such information can be useful for decision makers when designing a land use plan and an agricultural management strategy. Further test on model performance should be conducted using more observation data under varying conditions of the watershed, based on which complex characteristics of the watershed can be better understood and illustrated.

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Tóm tắt:

ĐÁNH GIÁ KHẢ NĂNG CỦA MÔ HÌNH SWAT TRONG MÔ PHỎNG CHẾ ĐỘ THỦY VĂN Ở LƯU VỰC SÔNG CÔNG, VIỆT NAM

Nghiên cứu này nhằm đánh giá khả năng của mô hình thủy văn bán phân bố, cụ thể là mô hình SWAT trong mô phỏng chế độ thủy văn ở lưu vực sông Công. Bộ thông số của mô hình được hiệu chỉnh và kiểm định dựa vào các tài liệu khí tượng của 5 trạm trên lưu vực và tài liệu dòng chảy từ trạm đo thủy văn trên sông Công với liệt tài liệu từ năm 1961 đến năm 1975. Khả năng mô phỏng chế độ dòng chảy trên lưu vực ở các thời đoạn ngày, tháng năm được đánh giá thông qua các chỉ số thống kê như chỉ số hiệu quả Nash-Sutcliffe và chỉ số tương quan (R^2). Kết quả đánh giá cho thấy mô hình SWAT sau khi được hiệu chỉnh đã mô phỏng tốt chế độ dòng chảy đã đo đạc trên sông Công và như vậy mô hình có thể áp dụng để mô phỏng chế độ thủy văn trên lưu vực nghiên cứu. Mô hình sau đó tiếp tục được sử dụng để mô phỏng đánh giá chế độ thủy văn trên lưu vực ứng với các điều kiện khác nhau giữa giai đoạn 1966 - 1975 và giai đoạn 2000 - 2010. Nội dung nghiên cứu này tập trung đánh giá chế độ thủy văn cho các kịch bản biến đổi về điều kiện khí hậu, thay đổi sử dụng đất và vận hành hồ chứa.

Từ khóa: chế độ thủy văn, lưu vực, đơn vị thủy văn, phân tích độ nhạy, hiệu chỉnh, kiểm định.

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