Analysing the impact of hydropower dams on streamflow in the Be river basin

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Abstract:

The aim of the present study is to assess the effect of hydropower dams on the streamflow in the Be river basin using the Soil and Water Assessment Tool (SWAT). Model calibration and validation of SWAT were conducted using the historical data collected from two stream gauges, namely Phuoc Long and Phuoc Hoa, and the obtained results indicated that SWAT shows a good reliability in reproducing streamflow with R^2>0.90 and NSE>0.70 for both periods of calibration (1980-1990) and validation (1991-1993). Considering the results of SWAT's calibration, the hydrological impact on the streamflow needs to be taken into consideration. The study results show that the separate impact of each hydrological dam (Thac Mo reservoir, Can Don reservoir, and Srok Phu Mieng reservoir) significantly increases streamflow in the dry season (89-101%) and decreases it in the wet season (6-33%). Moreover, there is a considerable rise in the dry season (89%) and a significant decline in the wet season (33%) of streamflow under the combined impact of the three dams.

Keywords: **Be river basin, hydrological dams, streamflow, SWAT model.**

Classification numbers: **2.3, 5.1**

Introduction

Changing climate is identified as one of the crucial challenges facing humanity in the 21st century. The mitigating measures for global warming require renewable energy sources to meet the increasing demand of energy consumption, which is mainly driven by factors contributing to population growth and economic development. Hydrological dams used as renewable energy sources represent a high potential for the reduction of greenhouse gases. Additionally, these dams contribute to meeting socio-economic development requirements, which is why the construction and development of dams have greatly increased in river basins.

The construction of dams has negative effects on hydrological regimes, sedimentation, ecosystems, fisheries, and the daily livelihoods of the surrounding and downstream inhabitants [1]. Specifically, an artificial reservoir affects the natural water quality, as well as the hydrological regimes of the river that depend on storage capacity and operation [2]. Hence, assessing the effect of hydrological dams on streamflow in the river basin is necessary for supporting management and providing useful information on scientific aspects.

The Be river basin has been established as a potential development site for a large number of hydrological dams. The cascade hydropower plant is relatively far in its development in this basin, which includes stages at the Thac Mo reservoir, Srok Phu Mieng reservoir, Can Don reservoir, and irrigation systems in Phuoc Hoa. There have been several studies assessing the water resources in this area, however, almost all of them concentrate on the impact of changing climate and land use [3, 4], and none of them take the effects of hydrological dams on streamflow into consideration. Therefore, the aim of the present study is

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to investigate the effect of dams on the streamflow in the Be river basin. For this purpose, the modelling approaches, particularly the SWAT model, were selected due to their effectiveness and their wide popularity for simulating river basins.

Study area

The Be river basin is one of the four largest tributary basins of the Dong Nai river system, stretching from latitudes $11^0$10’-$12^0$16’ N to longitudes $106^0$36’-$107^0$30’ East (Fig. 1). The total catchment area is larger than 7800 km^2 and the area had a population of about 1.5 million in 2010. It includes three provinces: Binh Phuoc, Binh Duong, and Dak Nong. The basin has a tropical monsoon climate with has two individual seasons, including wet season (lasting from May to October) and dry season (November to April). In the wet season, the flood peak occurs in September and October, with the precipitation accounting for about 85-90% of the total annual rainfall in this basin [3].

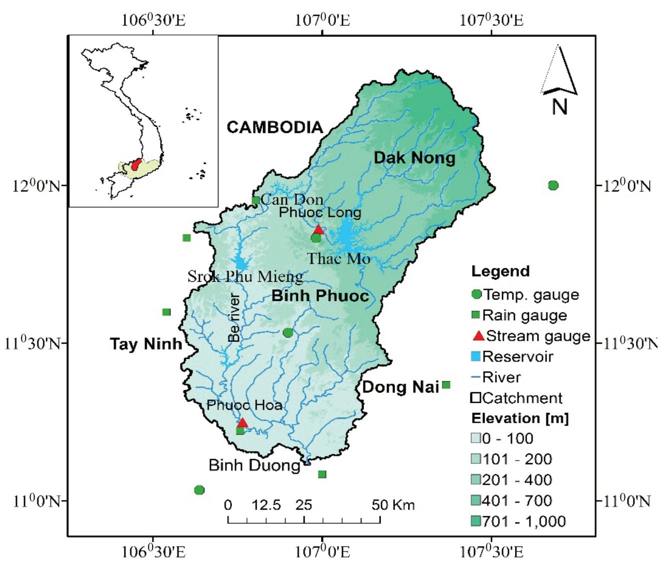

Fig. 1. Location of the Be river basin.

The terraced morphological structure of the Be river basin brings about considerable potential for hydrological dams. In the recent past, three reservoirs have been operated in the Be river, including Thac Mo (1995), Can Don (2004), and Srok Phu Mieng (2006), all of which were responses to the growing demand for electricity from the thriving southern economy (Fig. 1). The current capacity of hydropower reaches 1 billion kWh/year and is continuously increasing. In addition to these three dams, an irrigation system has been constructed in Phuoc Hoa to regulate the streamflow in the basin.

Materials and methods

SWAT model

SWAT, which is a distribution model based on physical processes, was chosen to simulate the streamflow in the Be river basin. The model was established by the United States Department of Agriculture (USDA) in the early 1990s to estimate the impact of land management practices and climate change on water, sediment, and nutrient over large spatial areas and long time periods. One of the main principles of this model is to simulate streamflow from rainfall and other regional physical characteristics [5].

To analyse large catchment areas in SWAT, the areas are partitioned into various sub-watersheds, which are then further subdivided into hydrological response units (HRUs) with homogeneous characteristics concerning soil, land use, and slope. Each HRU of the SWAT model simulates its hydrological cycle according to the following water balance equation [5]:

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

wherein SW_t [mm] is the total soil water content, SW_0 [mm] is the initial soil water content, t [d] is the time, R_{day} [mm] is the precipitation, Q_{surf} [mm/d] is the surface runoff, E_a [mm] is the amount of ET (evapotranspiration), W_{seep} [mm] is the amount of water entering the ground layer, and Q_{gw} [mm/d] is the parameter for the groundwater discharge.

In the SWAT model, the reservoir is one of the main tributaries of the basin area. The reservoirs water balance is evaluated based on the following equation:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep}, \quad (2)$$

wherein V [m^3] is the final water volume at the end of the day, V_{stored} [m^3] is the initial water storage at the beginning of the day, V_{flowin} [m^3] is the water volume flowing into the reservoir, $V_{flowout}$ [m^3] is the surface runoff, V_{pcp} is the precipitation volume of reservoir in day (m^3 H_2O), V_{evap} [m^3] is the evaporation volume of the reservoir, and V_{seep} [m^3] is the water loss volume from leakage.

SWAT model set-up

The simulation process on the Be river basin is implemented via ArcSWAT, which is an updated version of the SWAT model. In order to set up the SWAT model, there are five steps as follows: (1) data preparation (Table 1), (2) delineation of the sub-basin, (3) Hydrologic Response Unit (HRU) definition, (4) weather data input, and (5) calibration and validation using sequential uncertainty fitting with the SUFI - 2 algorithm. Then, the model is run under reservoir scenarios.

Table 1. Data collection in this study.

Data type	Description	Source
DEM	Elevation, slopes and lengths, a spatial resolution of 90 m	USGS-Hydro-SHEDS
Land use	Land use types in 2005	Sub-National Institute of Agricultural Planning and Projection (Sub-NIAPP)
Soil	Soil type, a spatial resolution of 1 km	Food and Agriculture Organization (FAO)
Weather	Daily precipitation (mm) and temperature (^{0}C) during 1978-2013 at 9 meteorological stations	Hydro-Meteorological Data Centre (HMDC)
Hydrology	Daily streamflow (m^3/s) at Phuoc Long and Phuoc Hoa stations	Hydro-Meteorological Data Centre (HMDC)
Reservoir	Reservoir parameters and discharge flow at three hydropower: Thac Mo, Can Don and Srok Phu Mieng	The hydropower in Thac Mo, Can Don and Srok Phu Mieng

The simulation result of the SWAT model is compared against the monitoring data using statistical parameters such as the coefficient of determination (R^2), Nash-Sutcliffe (NSE), and error percentage (PBIAS). The assessment standard is based on the study of [6] as described in Table 2.

Table 2. Model performance evaluation criteria for streamflow.

Effective simulation	R^2	NSE	PBIAS
Very good	0.85-1.00	0.80-1.00	≤±5%
Good	0.75-0.85	0.70-0.80	±5-10%
Satisfactory	0.60-0.75	0.50-0.70	±10-15%
Not satisfactory	≤0.60	≤0.50	>±15%

Result and discussion

Calibration and validation of the SWAT model

SWAT was established for the study area, and calibration results were simulated for the periods without the impact of a reservoir before 1993. The most sensitive parameters were selected for calibrating the streamflow in accordance with the study of [4]. Table 3 illustrates the SWAT-calibrated parameters for simulating streamflow.

Table 3. SWAT parameters calibrated for simulating streamflow.

No.	Parameter	Description	Min-Max value	Calibrated value
1	v_EPCO	Factor of compensation of water consumption by plants	0-1	0.77
2	r_SOL_K	Saturated soil hydraulic conductivity (mm h-1)	-0.25-0.25	-0.19
3	v_CH_N2	Manning coefficient for the main channel (s m-0.33)	-0.01-0.3	0.17
4	v_GW_REVAP	Coefficient of water rise to saturation zone (dimensionless)	0.02-0.2	0.19
5	v_CH_K2	Effective hydraulic conductivity of the channel (mm h-1)	-0.01-500	203.95
6	r_SOL_ALB	Soil Albedo (dimensionless)	-0.1-0	0.03
7	r_CN2	Number of the initial curve for the moisture condition AMCII (dimensionless)	-0.5-0.13	-0.21
8	v__GWQMN	Water limit level in the shallow aquifer for the occurrence of base flow (mm)	0-500	2296.71
9	v__GW_DELAY	Time interval for recharge of the aquifer (days)	0-500	23.79
10	v_ALPHA_BF	Baseline flow recession constant (days)	0-1	0.99

v: replaced value, r: ratio value.

Figures 2 and 3 compare simulated and observed daily streamflow for the calibration (1980-1990) and validation (1991-1993) periods. The results show an agreement between the observed and simulated data, shown in Table 4. However, the simulated streamflow value on the flooding and dry season, as well as the peak flood, does not fit with the observed value. This is caused by an uneven spatial rain gauge distribution and errors during the measurement process. Evidently, the range of R^2 varied from 0.90 to 0.91, NSE varied from 0.77 to 0.80, PBIAS varied from -14% to 9% for the calibration period, and the range of R^2 varied from 0.91 to 0.93, NSE varied from 0.82 to 0.86, PBIAS varied from 4% to 10% for the validation period. In general, the results of the calibration and validation steps indicate that SWAT can simulate streamflow in the Be river basin, the results of which could be used for investigating the impact of hydropower and reservoir on the streamflow.

Table 4. The calibration and validation result of streamflow at two stations.

Station	Calibration (1980-1990)			Validation (1991-1993)		
	R^2	*NSE*	*PBIAS*	*R^2*	*NSE*	*PBIAS*
Phuoc Long	0.90	0.80	9%	0.91	0.82	10%
Phuoc Hoa	0.91	0.77	-14%	0.93	0.86	4%

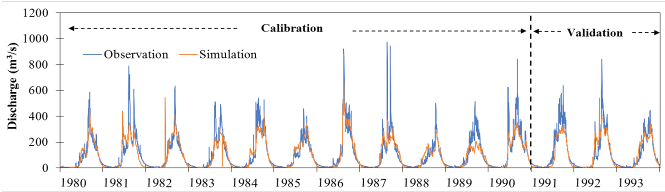

Fig. 2. The comparison between simulated and observed daily streamflow at the Phuoc Long station for the calibration period (1980-1990) and the validation period (1991-1993).

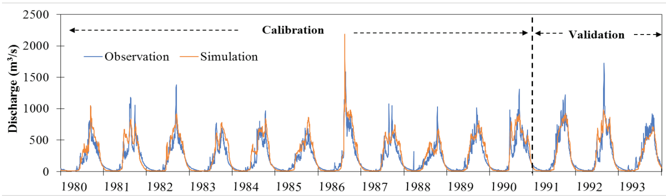

Fig. 3. The comparison between simulated and observed daily streamflow at the Phuoc Hoa station for the calibration period (1980-1990) and the validation period (1991-1993).

The impact of hydropower on streamflow

After the calibration and validation steps for streamflow without the impact of hydropower (1980-1993), the reservoir parameters involving discharge were used to evaluate the change of streamflow under reservoir impact. Figs. 4-6 illustrate the flow discharge simulation results at the Phuoc Hoa station, and show that they are affected by the three hydropower plants Thac Mo (in operation since 1995), Can Don (in operation since 2004), and Srok Phu Mieng (in operation since 2006). Considering the simulation results of the SWAT model, it is recognized that the SWAT model with the reservoir module satisfactorily simulate streamflow in the Be river basin under the impact of hydropower. The resulting statistical parameters concerning the effectiveness of the SWAT model's simulation are shown in Table 5.

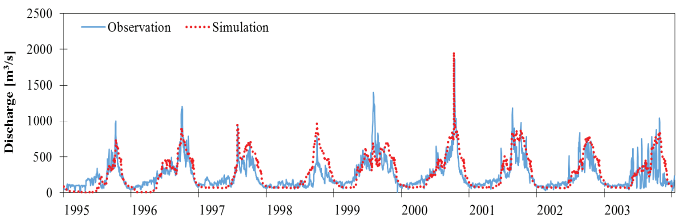

Fig. 4. The comparison between simulated and observed daily streamflow at the Phuoc Hoa station under Thac Mo hydropower operation (1995-2003).

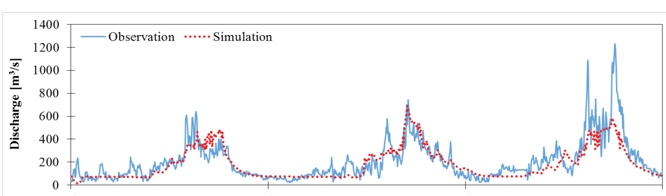

Fig. 5. The comparison between simulated and observed daily streamflow at the Phuoc Hoa station under Thac Mo and Can Don hydropower operations of (2004-2006).

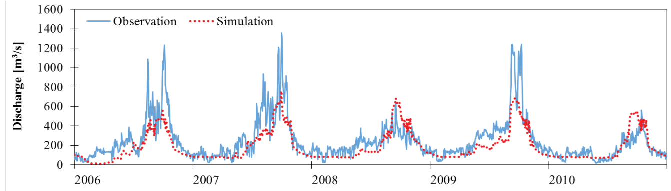

Fig. 6. The comparison between simulated and observed daily streamflow at the Phuoc Hoa station under the Thac Mo, Can Don, and Srok Phu Mieng hydropower operations of (2006-2010).

Table 5. The effectiveness of streamflow simulation at the Phuoc Hoa station under the hydropower scenarios.

Station	Thac Mo (1995-2003)			Thac Mo and Can Don (2004-2006)			Tha Mo, Can Don and Srok Phu Mieng (2006-2010)		
	R^2	*NSE*	*PBIAS*	R^2	*NSE*	*PBIAS*	R^2	*NSE*	*PBIAS*
Phuoc Hoa	0.77	0.42	-9%	0.81	0.64	11%	0.80	0.55	23%

With the streamflow simulation results under the impact of hydropower being satisfactorily reliable, the study investigates the impact of hydropower utilization on the Be river streamflow during the period of 2006-2013 under three scenarios: Scenario (1) - without hydropower, Scenario (2) - only one hydropower plant (Thac Mo, Can Don, or Srok Phu Mieng), and Scenarios (3) - the combination of the three hydropower plants.

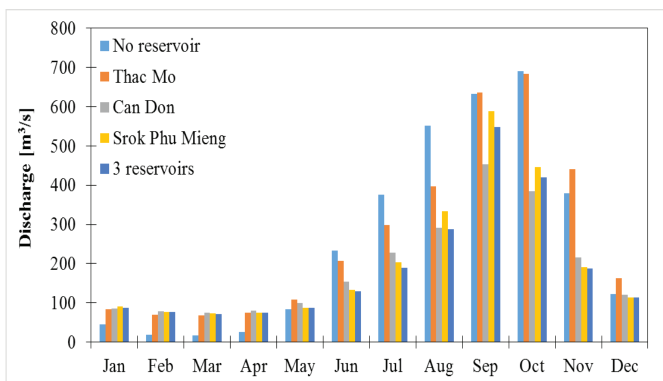

Fig. 7. Average monthly water discharge for three simulation scenarios during the period of 2006-2013.

Figure 7 illustrates the average monthly water discharge for the three scenarios. The result shows that streamflow in the dry season (December to May) is higher than normal conditions when the interventions of hydropower are operated to regulate water in the entire basin, contributing significantly to water scarcity during this period. By contrast, in the rainy season, the water discharge on river could be reduced in hydropower scenarios due to the storage volume of the reservoirs.

Table 6. The change in percentage ratio of streamflow under hydropower scenarios in Be river basin during 2006-2013 periods.

Season	Trend	Thac Mo	Can Don	Srok Phu Mieng	Three hydropower
Dry	Increase	101%	93%	89%	87%
Rainy	Decrease	6%	38%	33%	37%

Based on the quantified results seen in Table 6, the study indicates that dams regulate water in the lower river leading to an increased streamflow by 101, 93, and 89%, at the Thac Mo, Can Don, and Srok Phu Mieng stations, respectively, and 87% for the combined three hydropower plants, in comparison to the scenario without hydropower use in the dry season. On the other hand, the role of the hydropower dams in regulating flooding, and, as a result, mitigating its damage in the lower river could be significant if they are managed accordingly. When hydro-electric plants such as Thac Mo, Can Don, and Srok Phu Mieng begin operating, the water discharge in the rainy season decreases gradually by 6, 38, and 33%, respectively, and the three-dam scenario declines by 37% in comparison to the scenario without the use of hydropower.

Conclusions

In this study, the impact of hydropower reservoir operation on streamflow was investigated using the SWAT model. The results can be briefly described as follows: (1) SWAT could simulate the streamflow for the Be river basin with the satisfactory accuracy; (2) considering the separate effect of hydropower reservoir operation (Thac Mo, Can Don, and Srok Phu Mieng), streamflow discharge in the dry season increases by 89-101% and decreases by 6-33% in the rainy season; (3) streamflow increases by 89% in the dry season and decreases by 37% in the wet season.

In addition to the obtained results, there is a limitation related to the unavailability of discharge data from reservoirs. Thus, collection of this additional data should be considered to improve the results of the model. In general, the study results could be used for reference purposes aimed to support local authorities for sustainable water resource management through the enhanced understanding of the impacts of hydropower reservoirs on the streamflow in the study area. There are also suggestions for further research related to the separate and combined impacts of climate change, land use change, and potential development of hydropower in the Be river basin.

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The authors declare that there is no conflict of interest regarding the publication of this article.

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