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Research Article

Applying the variable infiltration capacity (VIC) model to reconstructing streamflow data in the Da River basin at Muong Te hydrological station

Khuong Van Hai[1]*, Giang Nguyen Tien[2], Do Thi Ngoc Bich[3]

[1] Center for Water Resources Software technology; khuongvanhai@gmail.com
[2] Faculty of Hydrology, Meteorology and Oceanography, University of Science, Vietnam National University, Hanoi; No. 334 Nguyen Trai Street, Thanh Xuan District, Hanoi, Viet Nam; nguyentiengiang@hus.edu.vn; giangnt@vnu.edu.vn
[3] Water Resources Institute, Ha Noi, Viet Nam; No. 8 Phao Dai Lang, Lang Thuong, Dong Da, Ha Noi, Viet Nam; bichdam555@gmail.com; dtnbich@monre.gov.vn

*Corresponding author: khuongvanhai@gmail.com; Tel.: +84–974183835

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Abstract: Reconstruction of streamflow in transnational river basins is of great significance in water resource planning and management in Vietnam. Among the ten biggest river basins (each having a total basin area of greater than 10,000 km^2) there are eight transnational river basins, and Vietnam is located downstream in the five basins of those eight. These include the Mekong River with 92% of the area belonging to foreign countries; the Red River with 51% located abroad, mainly China; the Dong Nai River with 17% belonging to Cambodia; the Ma River with nearly 38% belongs to Laos and the Ca River with 35% belongs to Laos. This study uses numerical modeling methods to reconstruct the streamflow from China to Vietnam in the Da River basin at Muong Te hydrological station. The VIC model was applied with daily climate data (rain, wind speed, maximum and minimum temperature) from 1981 to 2020 to reconstruct streamflow at Muong Te station in the Da River basin. Combining the VIC Model and the Shuffled Complex Evolution method to determine the most suitable set of parameters for the Da River basin creates a powerful tool for studying hydrological processes on river basins. Research results also show that the streamflow reconstruction for the period before 2008 when the upstream reservoirs were not yet in operation is highly reliable.

Keywords: VIC; Da river; Muong Te; SCE.

1. Introduction

Streamflow reconstruction is an important issue in hydrology, especially in data-deficient river basins that lack/have no gauging stations. Data-deficient basins, data-scarce basins and basins without gauging stations are basins with limited meteorological and hydrological data [1]. Therefore, studies on water resources and flood and drought forecasts in such basins often have low reliability. The International Association of Hydrological Sciences (IAHS) in the years 2003-2012 initiated research related to hydrological forecasting for basins lacking gauging stations (prediction in ungauged basins - PUB) considering uncertain factors [1]. Most of the studies related to PUB were carried out after 2003. An example of previous studies [2], performed estimation of hydrological model parameters based on classification basins according to similarities in basin characteristics and geomorphological topography, instead of traditionally used methods, such as regression equations.

The small number of hydrological gauging stations creates challenges related to forecasting inaccuracy of streamflows. Regardless of the forecasting method used, streamflow forecast results need to be verified against observed/gauge data [3]. Therefore, to be able to identify accurate forecast results for locations without gauging stations, gauge data at neighboring locations are often required to compare with simulation results [4]. One of the commonly used approaches recently is to use data in many neighboring basins combined with regionalization methods to forecast runoff for data-deficient basins [5]. The effectiveness of this approach has been demonstrated when applying streamflow forecasts to basins lacking gauge data using large datasets such as CAMELS-US with 671 basins in the United States [6] or CAMELS GB with 671 catchments in the UK [7]. Regionalization methods can be used to interpolate the hydrological characteristics of data-deficient catchments based on the characteristics (geology, geomorphology, spatial meteorology) of neighboring catchments [8].

The VIC model [8–10] is a macroscale hydrological model that addresses the full energy and water balance, originally developed by Xu Liang at the University of Washington. VIC is a research model and in many different forms, it has been applied to most major river basins in the world, as well as globally. This is a grid-based semi-distributed hydrological model that quantifies the main hydrometeorological processes occurring at the atmospheric land surface. Typically, mesh resolution ranges from 1/8 to 2 degrees. The VIC model was first described as a single soil layer model [11]. The single-layer soil model requires three parameters: permeability parameter, evaporation parameter, and baseflow recession coefficient. In 1994, Liang et al generalized the two-layer VIC model (VIC-2L) to include multiple spatially varying soil and vegetation layers and evaporation within a single grid cell. In VIC-2L, infiltration, drainage from the topsoil to the subsoil, and surface and subsurface runoff are calculated for each vegetation cover (in addition to the statistical parameter of heterogeneity) of infiltration and flow processes in a vegetated cover existing in the original VIC model). VIC-2L was later modified to allow moisture diffusion between soil layers, and there was an additional 10cm thin layer of soil on top of the previous topsoil layer. In this way, the three-layer VIC model (VIC-3L) [9, 11–14] was created and the VIC-3L frame has been used since then. The model now allows for more than three soil layers if desired. Such a model was used in this study.

The issue of monitoring cross-border water resources has become increasingly challenging in recent years, as water resources become scarcer due to the need to exploit them to serve socio-economic goals within each country sharing the river basin. The Da river plays a vital role in Vietnam's socio-economic development and water-food-energy security nexus. It houses three of the largest reservoirs in the country - Lai Chau, Son La, and Hoa Binh - which provide ample water supply for the Red River delta and Hanoi, the capital and the economic and political center of Vietnam. Monitoring streamflow from abroad into Vietnam within the Da River basin faces several difficulties due to the current flow data measurement practice that relies primarily on technology dating back to the late 20th century. Additionally, the manual methods used for data collection require significant human resources, infrastructure, and investment in monitoring equipment. The situation is further compounded at the Da river’s border with China, where monitoring and measuring streamflow is even more challenging, with most of the streamflow remaining unmeasured. While Ka Lang water resources station, which was built in 2016, uses automatic technology to measure flow, it is currently inactive. The Keng Mo station has been measuring and collecting flow data since 2020, but as it is a station built and managed by EVN, it presents difficulties in terms of accessibility, and the observed dataserie is not long enough. Moreover, there is currently no discharge gauging station on the mainstream of the Da river located upstream of the Lai Chau hydropower plant to monitor streamflow timeseries of sufficient length. Therefore, within the scope of this article, a modeling method has been applied to restore the streamflow at the Muong Te hydrological station, result of restore the streamflow supports effective management of the amount of water flowing into Vietnam from the up basin of the Da River through the country border.

2. Materials and Methods

2.1. Description of the study area

The Da River originates in Yunnan, one of China's southern provinces, and flows into the Red River delta in Vietnam, where it merges with two other tributaries, the Lo River and the Thao River (Figure 1). The Red River then continues to Hanoi, the capital of Vietnam,

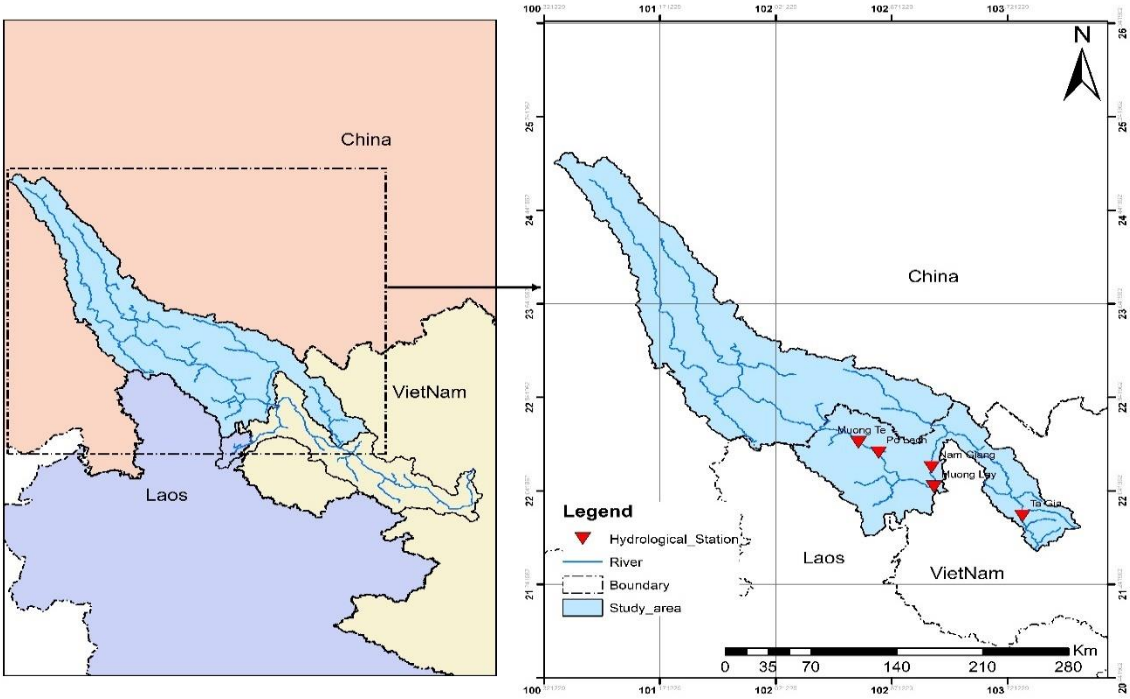

Figure 1. Map of the study area.

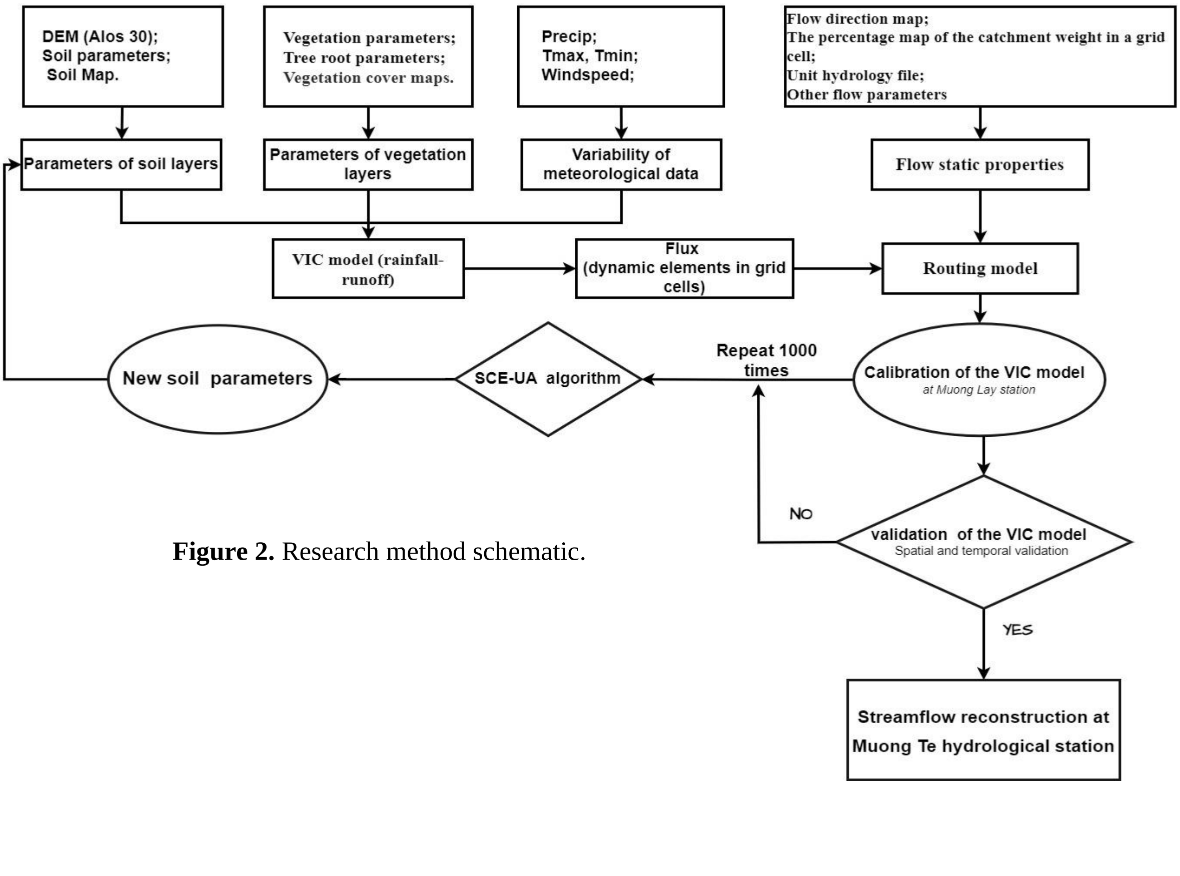

Figure 2. Research method schematic.

before flowing southeast to the East Sea. Numerous human interventions occur in and around this river without proper assessment or monitoring. Changes in land use as well as reservoir construction have a significant impact on this catchment area. The Da River generates substantial hydroelectric power, with dozens of dams in Yunnan and three large hydroelectric plants in Vietnam (EVN). However, the operating rules of the upstream dams are not publicly available. While there are hydrological and meteorological gauging stations in both country parts of the Da River catchment, little data from these stations is shared. A hydrological model has been used in this study to reconstruct the streamflow time series in the upstream part of the basin in Vietnam's territory.

2.2. VIC model

2.2.1. VIC model overview

Before intervening in a water system, it is crucial to model the system to evaluate potential impacts. This process, which involves modeling a catchment's physical characteristics and its rainfall-runoff processes, is referred to as hydrological modeling [15]. In this study, the VIC model will be used to simulate the Da River basin for several reasons:

(1) The VIC model is fully distributed and physically based, taking into account the spatial variability of inputs in great detail.

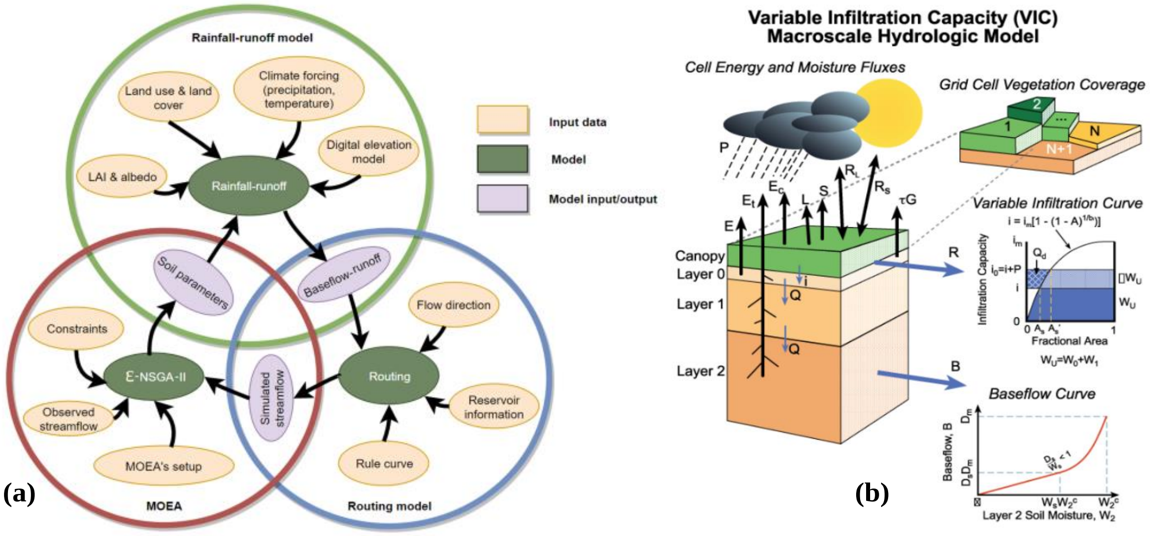

Figure 3. (a) Schematic overview of the VIC-model framework [16]; (b) Schematic overview of the mechanics behind the rainfall-runoff model. (https://www.hydro.washington.edu/Lettenmaier/Models/VIC/).

(2) The VIC model is a hydrological land surface model, which means it employs quantitative methods to simulate the exchange of water, energy, and momentum fluxes between the land surface and the atmosphere.

(3) Human interventions, such as reservoirs and changes in land use and land cover, can also be simulated.

The VIC hydrological model is typically implemented using a framework consisting of three components, as illustrated in Figure 3a [17]. The rainfall-runoff model [18] serves as the foundation for simulating interactions between the atmosphere, land, and water flow. The mechanics of this part of the model are shown in Figure 3b. It utilizes climate forcings and the area's physical properties as inputs, producing gridded baseflow and runoff as outputs. The routing model [19] is performed separately and accumulates the gridded baseflow and runoff to determine streamflow at a selected outlet. This study utilizes the SCE-UA optimization algorithm instead of the NSGA multi-objective genetic algorithm for model calibration as depicted in Figure 3a [20].

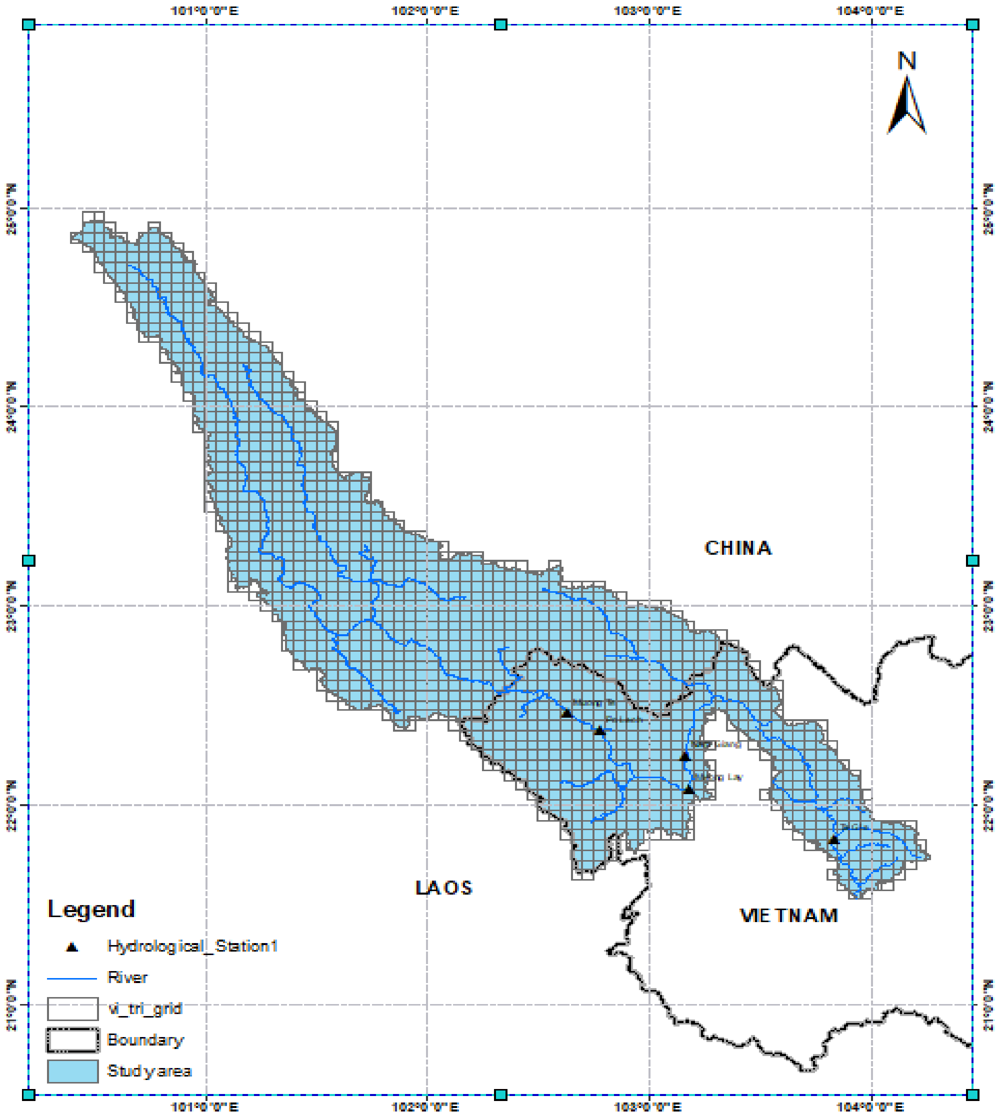

Figure 4. Set up VIC model for Da River.

2.2.2. Set up of the VIC model for the Da River basin

Simulation domain: The modeled Da River basin is divided into two regions including:

Region 1 from upstream to the Vietnam - China border to Muong Lay station (Lai Chau Province).

Region 2 is the Nam Mu River basin containing two lakes, Ban Chat and Hoi Quang.

Simulation grid: The Da River basin is digitized into the VIC model with 3 soil layers, with a resolution of 0.05 degrees, the entire study area is divided into 16,146 points (78×69), including 4,134 simulation points (Figure 4).

2.3. Data collection

In this study, land use and land cover maps are employed, along with various vegetation properties such as LAI, albedo, and global and regional meteorological forcing time series. Additionally, a digital elevation model, flow direction map, flow characteristics, soil map with soil properties, and observed streamflow time series are utilized. To provide a clear overview of the sources for these datasets, Table 1 lists the datasets used, and a short description for each of these is given in the following subsections.

Table 1. Overview of the used datasets and their sources.

Datasets	Period	Purpose	Source
Station streamflow Vietnam	1981-2020	Discharge time series	Vietnam Meteorological and Hydrological Administration
Grid precipitation Vietnam (VnGP)	1981-2020	VIC model input	The Vietnam Gridded Precipitation (VnGP) Dataset: Construction and Validation [18]
Grid precipitation China (CHM)	1981-2020	VIC model input	The China Hydro-Meteorology dataset (Beijing Normal University) [19]
Grid wind speed and min/max temperature	1981-2020	VIC model input	ECMWF - EU [20]
Digital Elevation Model (DEM)	-	Set up the VIC model	ALOS30 [21]
Soil map & Soil properties	-	Set up the VIC model	FAO - Unesco, "Soil map of the world" [22]
Land Use & Land Cover maps	1992-2020	Set up the VIC model	Land Cover CCI Product User Guide Version 2 [23]

2.3.1. Meteorological forcing data files

The VIC model is capable of processing either daily (precipitation, T_{max}, T_{min}, windspeed) or sub-daily meteorological data inputs, or a combination of both. VIC offers the flexibility of utilizing different variables and variable combinations as per the user's requirements. The global parameter file must contain a comprehensive description of the contents and formats of the meteorological data files.

2.3.2. Soil parameter file

The soil parameters for the VIC model are provided in a single ASCII file, where each row represents a unique grid cell. The fields in the file contain different parameter values for each cell. The soil parameter file serves three primary purposes: Firstly, it assigns a unique cell ID number to each grid cell, which acts as a database key to link the cell to its parameters in other parameter files. Secondly, it defines the soil parameters for each grid cell along with the geographic information such as the latitude and longitude of the grid cell center. Lastly, it defines the initial soil moisture conditions for use in the absence of an initial state file (Figure 5a).

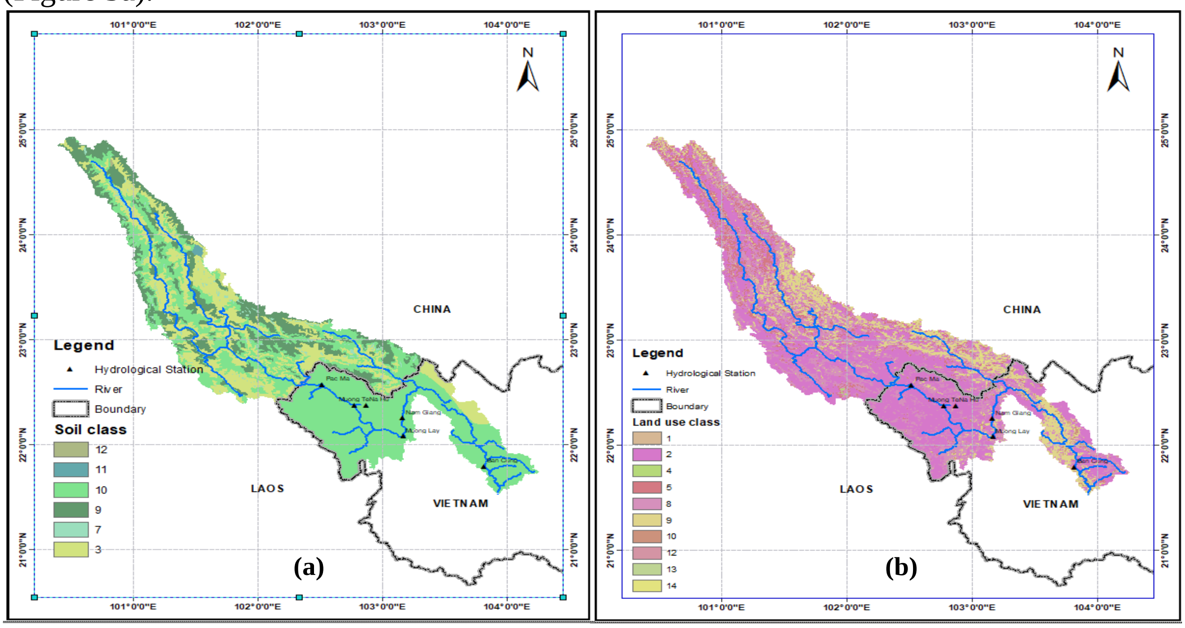

Figure 5. (a) Map of soil properties, (b) Land use and land cover maps.

2.3.3. Vegetation parameters and vegetation library

The vegetation parameters and vegetation library provide pertinent information regarding the number of vegetation types present in each grid cell, their partial coverage, and the required vegetation parameters for each vegetation type utilized in the VIC model. This information is presented in a columnar format as an ASCII file. Each grid cell is represented by a separate row, with each field containing a distinct parameter value.

2.3.4. Flow Direction

The flow direction file is a critical component of the routing model used in hydrological studies to establish connectivity between individual grid cells generated by the VIC model. The flow direction file provides header information to the model that knows the lower left latitude and longitude, the number of rows and columns, and grid cell resolution. Each grid cell in the file is assigned a number that represents the flow direction in the river and stream network.

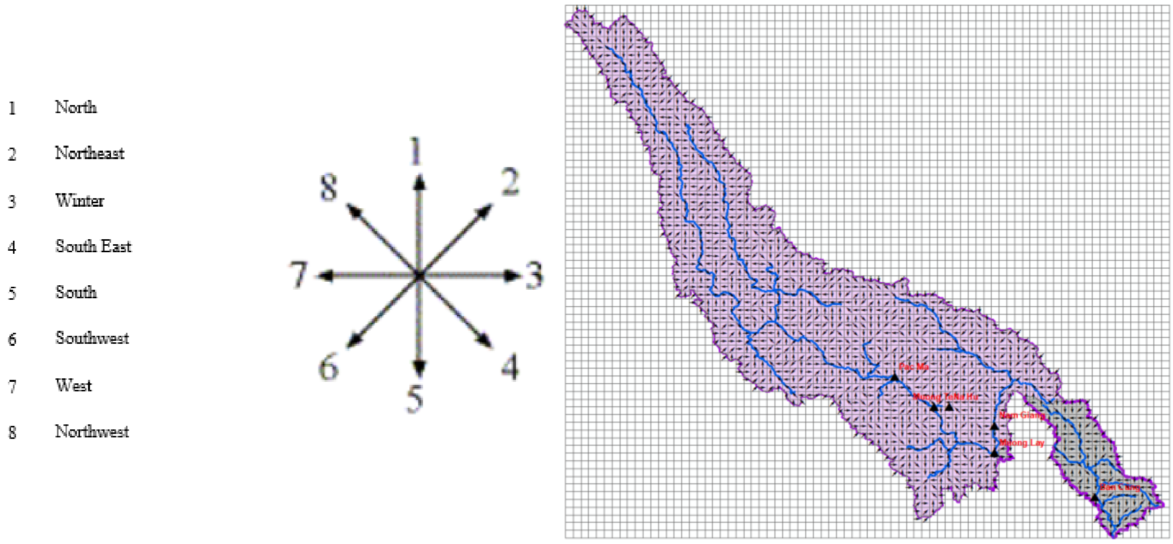

Figure 6. The flow direction map in the Da River basin.

3. Results and discussion

3.1. Calibration and validation of the VIC model

3.1.1. Calibration of the VIC model

The determination of six soil parameters (bin, Ds, Dmax, Ws, D2, D3) is a challenging task, given their conceptual nature and the lack of observable, physical quantities [24, 25].

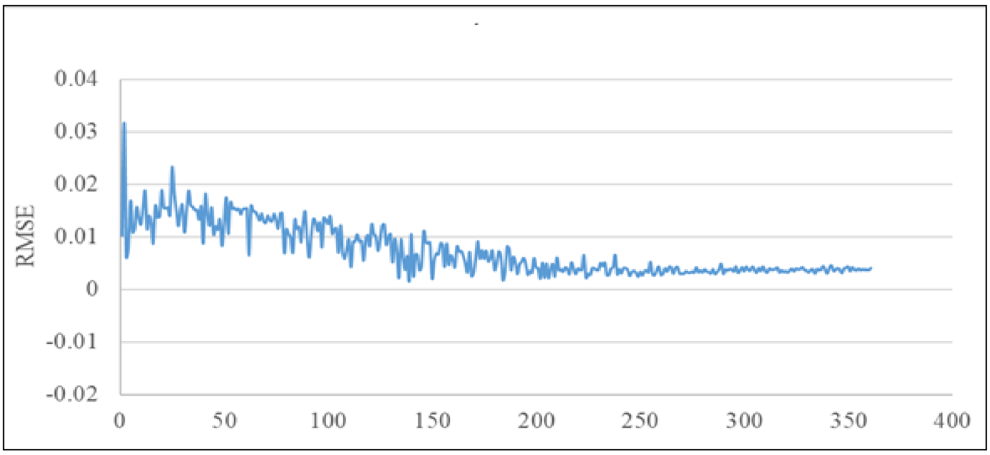

Figure 7. RMSE index convergence process using the SCE-UA algorithm (unit run-off is mm).

To address this issue, a calibration procedure was developed that utilizes an autocalibration script and the Shuffled Complex Evolution method, which was chosen for its ability to identify global optima with the right algorithmic parameters [26]. The calibration framework follows the VIC hydrological model [27], except for the parameter generation algorithm shown in Figure 2. The autocalibration script was run using a spatial resolution of 0.05°, which was a suitable resolution to mimic the Da River basin. Upon obtaining the optimal parameter set, the performance of the model was assessed using key performance indicators, specifically the NSE, BIAS, and RMSE.

The calibration of the VIC hydrological model employed the RMSE objective function to optimize six parameters, which were selected based on the RMSE index between observed discharge and simulated discharge at Muong Lay station during the years 1981-1995. The Shuffled Complex Evolution method was initially set up with 1000 iterations. After eliminating local disturbances, the RMSE indexes displayed an evolution of 380 RMSE indexes, showing the convergence of the simulated data series approaching the actual measured data series asymptotically. The convergence process of the objective function is illustrated in Figure 7. The results of the calibration process are provided in Table 2 and Figure 8.

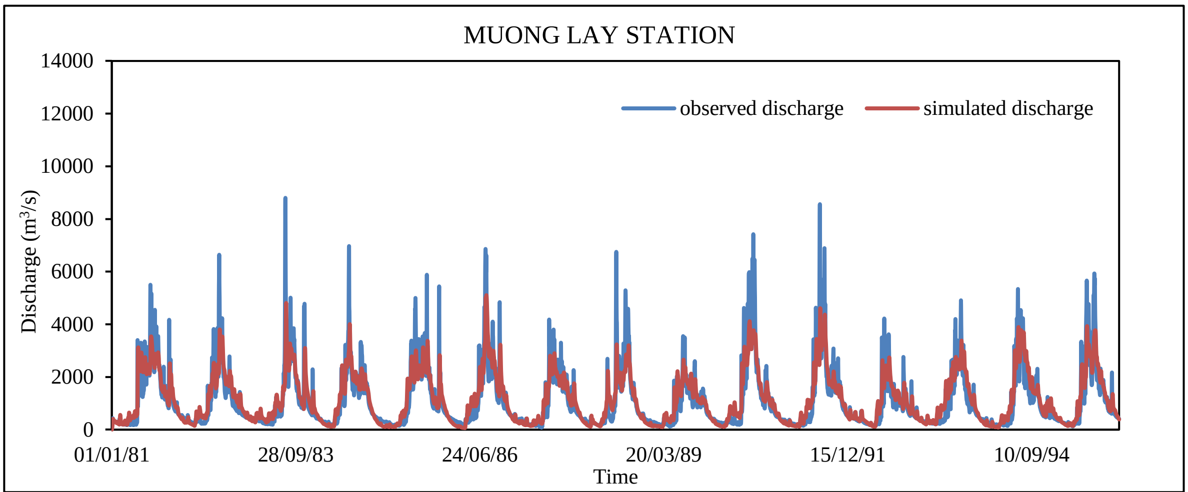

Figure 8. Simulated and observed daily discharge at Muong Lay station in the calibration period 1981-1995.

Table 2. Results of VIC model calibration of NSE, R^2, RMSE, BIAS index.

Hydrology stations	NSE	R^2	RMSE	BIAS
Muong Lay	0.78	0.86	444.3	114.9

The results of calibrating the VIC model show that the simulated discharge at Muong Lay station in the Da River basin is relatively consistent with the actual observed value, the reliability according to the NSE index is 0.78, the correlation coefficient is 0.86; the BIAS index is 114.9. The results of the adjusted simulation show that the VIC model parameters after adjustment are in close agreement with reality, which also means that the parameters after adjustment have relatively appropriately reflected the observed discharge from 1981-1995 in the Da River basin.

Table 3. VIC model calibration parameters.

No	Parameter	After calibration	Calibration range	
1	bin	0.3151	0.002	0.495
2	Ds	0.7065	0.019	0.875
3	Dsmax	27.1525	2.653	29.983
4	Ws	0.7170	0.1	0.984
5	D_2	0.3242	0.3	1.5
6	D_3	1.4995	0.3	1.5

3.1.2. Spatially validation of the VIC model

Upon completion of the calibration process, it is imperative to verify the stability and suitability of the parameter set as outlined in Table 3. This study conducted an independent spatial validation at Nam Giang station during the years 1981-1995. The results are shown in Figure 9a and Table 4.

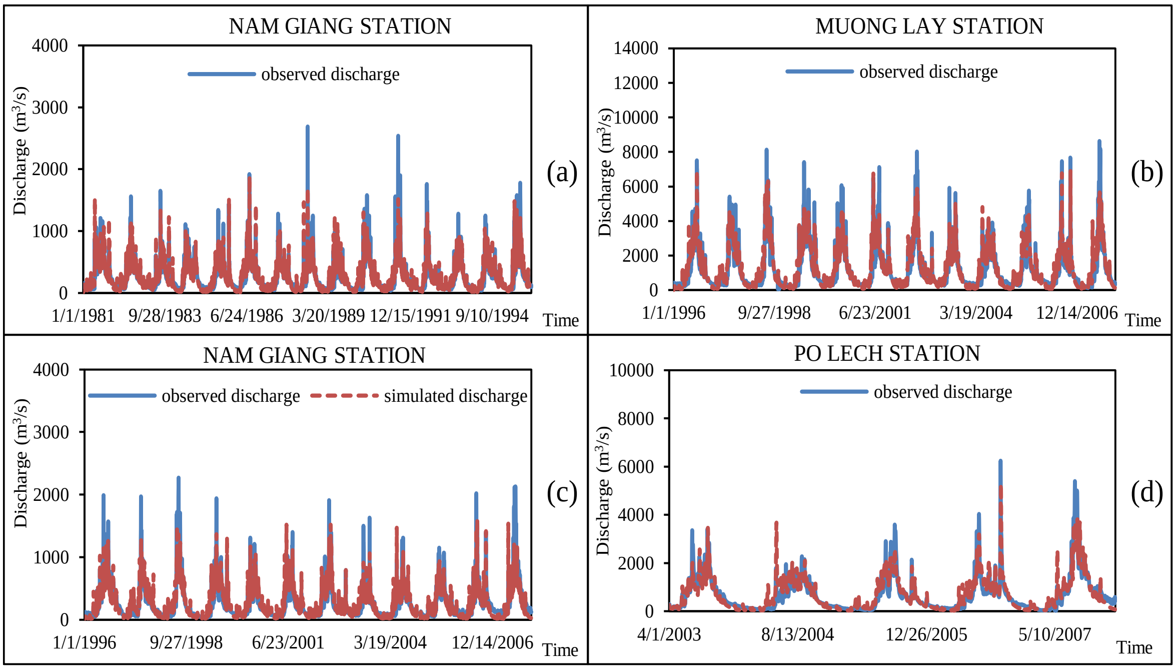

Figure 9. Simulated and observed discharge timeseries at: (a) Nam Giang station in the period 1981-1995; (b) Muong Lay station in the period 1996-2007; (c) Nam Giang station in the period 1996-2007; (d) Po Lech station in the period 2003-2007.

Table 4. Spatial independent validation results of NSE, R^2, RMSE, BIAS index.

Hydrology stations	NSE	R^2	RMSE	BIAS
Nam Giang	0.74	0.74	136.5	-8.9

After performing calibration and spatial validation on the VIC model, it was found that the simulated streamflow value at the Nam Giang station on the Da River basin is consistent with the observed value. The model's reliability, as determined by the NSE index, is good at 0.74, while the correlation coefficient is also 0.74. However, the BIAS index is negative at -8.9.

Based on the results of spatially independent validation, it has been found that the VIC model parameters are in close agreement with reality. This also indicates that the calibration parameters reflect the relatively well-observed discharge from 1981 to 1995 in the Da River sub-basins. Therefore, the set of parameters mentioned in Table 3 is deemed qualified for conducting spatial and temporal independent validation. This will confirm the stability of the VIC model parameters for the Da River basin.

3.2. Spatial and temporal validation of the VIC model

The study aimed to validate selected model parameters using discharge observations in the Da River basin at three stations - Muong Lay, Nam Giang, and Po Lech. The six parameters selected for validation are listed in Table 3 for the three stations - Muong Lay, Nam Giang (1996-2007), and Po Lech (2003-2007). The results of spatial and temporal independent validation are presented in Figure 9b-9d and Table 5.

Table 5. Spatial and temporal independent validation results of NSE, R^2, RMSE, BIAS index.

Hydrology stations	NSE	R^2	RMSE	BIAS
Nam Giang	0.78	0.8	134.6	-8.7
Muong Lay	0.85	0.86	488.5	33.0
Po Lech	0.81	0.81	323	8.0

The VIC model's spatial and temporal independent validation results indicate that the discharge values at certain locations in the Da River basin are consistent with the actual observed values. At the Nam Giang station, the NSE index is 0.78, which is a good grade, the correlation coefficient is 0.8, and the BIAS index is -8.7. At the Muong Lay station, the NSE index is 0.85, which is a good grade, the correlation coefficient is 0.86, and the BIAS index is 33.0. At the Po Lech station, the NSE index is 0.81, which is a good grade, the correlation coefficient is 0.81, and the BIAS index is 8.0.

The validation results indicate that the model parameters are consistent with reality, which implies that the validated parameters reflect the actual discharge from 1996 to 2007 in the Da River basin. Therefore, the parameters in Table 3 are qualified to simulate and reconstruct the flow from China to Vietnam on the Da River basin.

3.3. Streamflow reconstruction at Muong Te hydrological station

The reconstruction of streamflow data at Muong Te station for the period before and after large upstream reservoirs came into operation from 1981 to 2020 was done using the VIC model and the set of parameters selected in Table 3. The results of this simulation are presented in Figure 10.

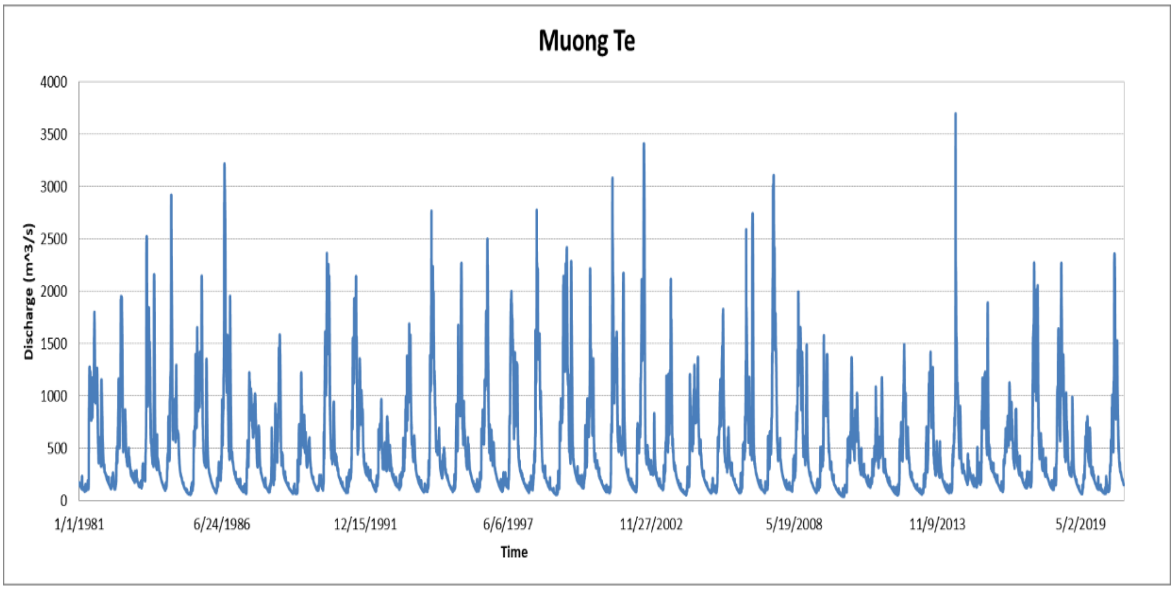

Figure 2. Results of streamflow reconstruction at Muong Te station in the period (1981-2020).

The results of streamflow reconstruction when considering correlation with the observed water level at Muong Te Station have a large decline in the period after 2007, Figure 11. For the period before 2008, the correlation coefficient between reconstructed streamflow and the actual water level observed is 0.78. In the period from 2008 to 2015, the correlation coefficient between the streamflow reconstruction and the actual observed water level decreased to 0.73. This result shows that the set of parameters in Table 3 is suitable for the reconstructed natural flow in the Da River basin. This recovery data plays an important role in researching and designing regulation reservoirs in the Da River basin and assessing the effects of water regulation reservoirs in Vietnam and China.

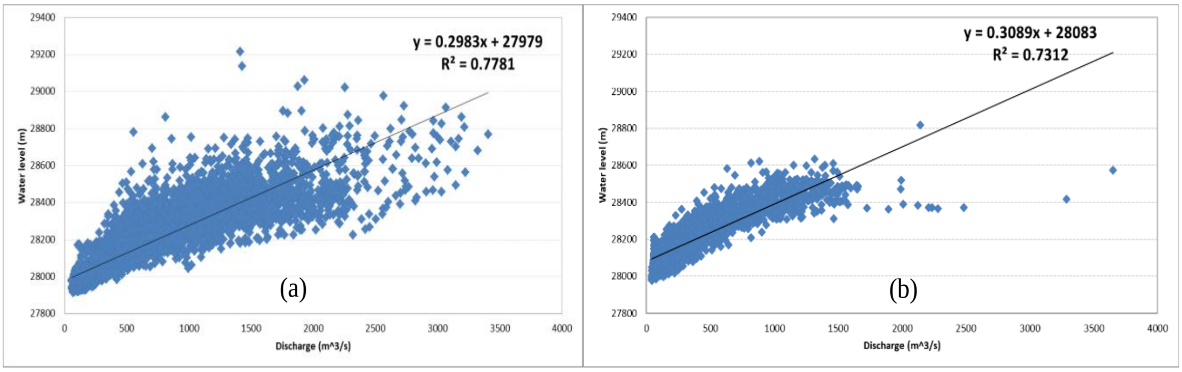

Figure 3. The correlation coefficient between streamflow reconstruction and actual water level observed at Muong Te station in the period before and after 2007.

3.4. Discussion

Da River and Red River are important in Vietnam's water resource security. Thus, there have been many studies applying simulation models on Da River and the Red River basins. The study [28] used the HEC-HMS model to simulate flow from 2003 to 2019, and simulation results were evaluated through 2 gauging stations (Ta Bu and Muong Lay) with Nash index ranging from 0.711 to 0.818; Study [29, 30] simulated daily streamflow on the Red River from 2005 to 2014, the simulation results were evaluated through 4 hydrological stations (Lao Cai, Yen Bai, Son Tay, and Hanoi) with Nash index ranging from 0.113 to 0.487; Yungang Li and his colleagues simulated the daily flow of the mainstream of the Red River on the Chinese side from 1961 to 2012. The simulation results were evaluated with the Nash index ranging from 0.85 to 0.89 [31]. In this study, the authors synchronized real observed rain data from China and Vietnam as input to the VIC model. To improve the simulation quality, the perturbed complex evolutionary algorithm [20, 32] was applied to calibrate the model's parameter set. The daily streamflow simulation results were evaluated with the Nash index ranging from 0.74 to 0.85 (Section 3.2), which shows a remarkable improvement compared with the previous studies conducted in Vietnam, and almost as good as the study conducted in China for the Red River. It is worth noting that Yungang Li and his colleagues used the observed meteorological and hydrological data, whereas this study utilized only measured discharge.

4. Conclusion

The monitoring of the discharge of water from China to Vietnam in the upstream area of Da River is challenging due to technological, economic, and natural conditions. As a result, discharge data is often incomplete or non-existent, making it difficult to plan and manage water resources in the basin. To address this, the VIC land surface hydrological model was used to simulate flow in the Da River basin by selecting appropriate parameters and data. The VIC model was combined with the Shuffled Complex Evolution method to determine the best set of parameters for the basin, creating a powerful tool for studying hydrological processes in river basins.

The research results showed that the streamflow at Muong Te station in the Da River basin between 1981 and 2020 was accurately restored using the VIC model. The streamflow reconstruction was exceptionally reliable for the period before 2008 when the upstream reservoirs were not yet put in operation. However, after 2008, the streamflow of the Da River was influenced by the regulation activities of flow-regulating reservoirs in China. Therefore, in-depth research is required to reconstruct the streamflow time series during this period by considering the hydrological processes in the basin and the regulation of reservoirs.

Author contribution statement: Designed the study conception: K.V.H.; collected data: G.N.T., K.V.H.; developed the theoretical research: G.N.T., K.V.H.; processed the data and performed the simulations: K.V.H.; analyzed the data: K.V.H.; contributed largely to revising the final manuscript: G.N.T., K.V.H., D.T.N.B.

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Competing interest statement: The authors declare no conflict of interest.

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