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Evaluation of the extended applicability of a simulated hydrological Tank model at the Ca River Basin sub-catchments

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ABSTRACT

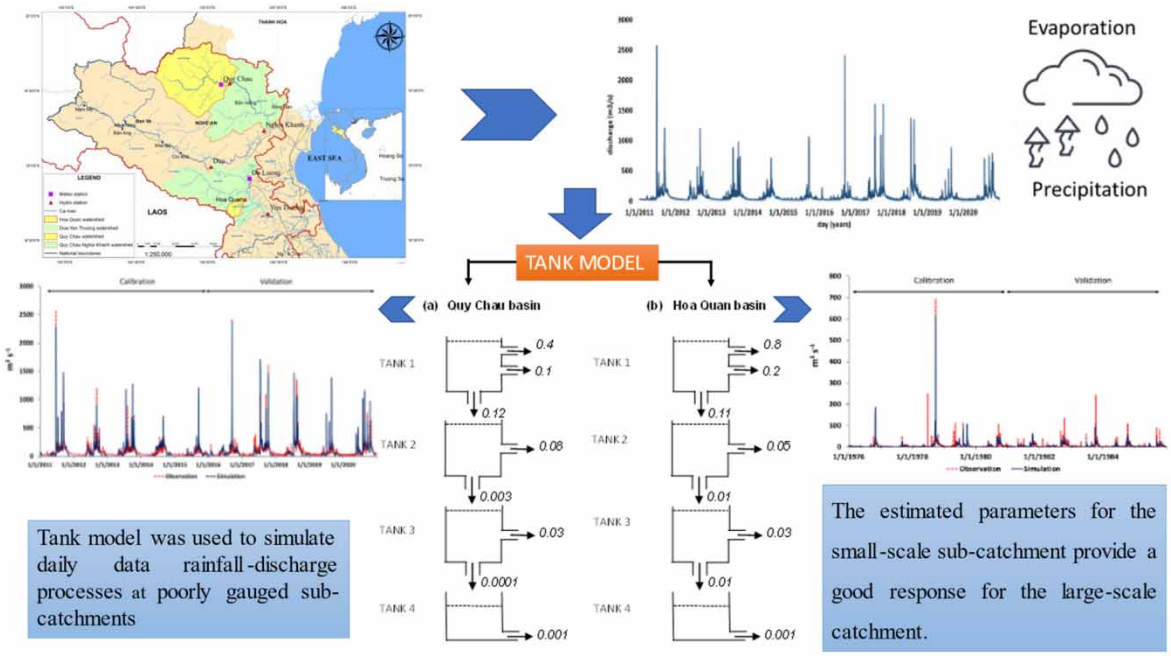
For the majority of the world, most drainage basins are poorly gauged or simply ungauged. The estimation of the hydrological parameters in sub-catchments of large basins is a very difficult task but is frequently required in hydrological analyses. Estimating runoff from ungauged or sparsely gauged catchments is a serious challenge in developing countries like Vietnam. The Ca River Basin is the most extensive system in the North Central region of Vietnam but contains very limited hydrological gauging stations. Therefore, this study aims to investigate the extended applicability of a simulated hydrological Tank model at the Ca River Basin sub-catchments. The daily Tank model was calibrated in gauged sub-catchments: Quy Chau in northern-side and Hoa Quan in southern-side sub-catchments. The extended applicability of calibrated parameter sets was verified by data from the continuously gauged stations of Nghia Khanh, Dua, and Yen Thuong. According to the findings of this study, the use of parameters identified in small sub-catchments can be used to calculate the flow processes in similar, but larger catchments in the Ca River Basin. The simulated Tank model parameters can be applied to calculate discharge at ungauged locations within the study area for a variety of purposes.

Key words: Ca River, discharge, poorly gauged basin, sub-catchments, Tank model

HIGHLIGHTS

- The Tank model was used to simulate daily data rainfall-discharge processes at poorly gauged sub-catchments.
- The Tank model consisting of four serial storage tanks is commonly used for long-term hydrological simulations.
- The estimated parameters for the small-scale sub-catchment provide a good response for the large-scale sub-catchment.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Runoff is a combination of random spatially distributed processes that determine the structure, characteristics, and dynamics of riverine ecosystems (Zeiringer *et al.* 2018). The flows at any given point in a river are necessary data for forecasting floods, predicting sediment loads, evaluating the effects of climate change on water resources, assessing environmental quality, and managing water resources. However, the majority of the world's watersheds, flow reaches, and river systems are ungauged or poorly gauged (Sivapalan 2003; Young 2006). Estimating runoff in ungauged or poorly gauged watersheds is considered a particular challenge in many hydrological studies (Sivapalan 2003; He *et al.* 2011; Razavi & Coulibaly 2013). There are two general approaches used for predictions in ungauged basins: the first approach estimates model parameters based on selected optimal variables from calibrated model parameters (Wagener & Wheater 2006; Azmeri *et al.* 2012; Betterle *et al.* 2018; Yang *et al.* 2018; Arsenault *et al.* 2019), while the second approach is model-independent, utilizing streamflow signatures to establish constraints to define the physical and climatic features of watersheds (Wagener & Montanari 2011). The first approach allows applying model parameters using for areas that have similar hydrological regions. Hydrological similarity presupposes that watershed behavior maintains a certain level of organization and predictability, despite the complexity of basin responses caused by heterogeneity and variation in hydrological processes (Grimaldi *et al.* 2016). This concept enables the transfer of hydrological data from a reference basin to an ungauged basin (Betterle *et al.* 2018; Loritz *et al.* 2018).

The hydrological Tank model, which is designed and implemented by a Japanese scientist (Sugawara 1979), is a conceptual rainfall-runoff model that is widely applied for different purposes such as flood control (Chen *et al.* 2014), runoff prediction (Oeurng *et al.* 2011), water resource management (Wickramarachchi & Wijesekera 2022), estimation of external nutrient loading for a lake (Le Tien *et al.* 2020), and assessing historical runoff variation (Phuong *et al.* 2018). The hydrological Tank model can display flow distribution for each layer of the watershed area at a specific time (Arifjaya *et al.* 2011). Many studies have been published on the Tank model's ability to demonstrate the performance and accuracy of the hydrological processes of a variety of watersheds in Asian countries such as Japan (Basri *et al.* 1999), Malaysia (Kuok *et al.* 2010), Nepal (Pradhan 2001), Bangladesh (Mondal *et al.* 2009), Korea (Kang *et al.* 2013), Indonesia (Kadarisman 1993; Purwanto 1999; Azmeri & Herissandy 2012), Sri Lanka (Wickramarachchi & Wijesekera 2022), and Vietnam (Ngoc *et al.* 2011; Udo & Mano 2012). The advantages of Tank models include the representation of flow distributions over time for each layer of the watershed area, which is commonly used for long-term historical runoff estimation (Arifjaya *et al.* 2011). The model was also used to simulate hydrological processes in single-tank watersheds, and calibrated parameters could be transferred from gauged to ungauged sub-catchments, thus, providing a valid

technique for runoff simulations of ungauged watersheds (Kang *et al.* 2013). Furthermore, the Tank model requires little data to simulate the hydrological process via tank cascade systems, which is widely applied in various regions from arid to humid areas and from tropical to snow-covered areas (Pradhan 2001). Based on the above review of the literature, it is clear that studies have used a rainfall-runoff model to estimate total long-term system inflows and to evaluate different potential future scenarios, particularly in areas with limited hydrological data availability. However, studies that simulate the parameters of the Tank model from small catchments to apply to larger catchments have not been fully documented. Therefore, the application of the Tank model needs to be performed with small- to large-scale sub-catchments in combination with simulation daily time steps in order to successfully identify parameters.

The Ca River Basin is an international river and one of the main river systems of Vietnam. It is located at 18°15′00″ N to 20°10′30″ N and 103°45′20″ E to 105°15′20″ E and occupies an area of 27,200 km^2, of which 17,730 km^2 in Vietnam and 9,470 km^2 in Laos. The basin is located in a tropical climate with two distinct seasons: a dry season from November to April and a rainy season from May to October. The Ca River Basin is the largest system in the central northern region of Vietnam. However, the number of gauging stations is limited with only seven managed hydrological gauging stations along the Ca River. This leads to a challenge in flow estimation in ungauged sub-catchments. Therefore, this study primarily focuses on a hydrological Tank model for streamflow estimation in gauged catchments in order to extend the investigation to a continuous large catchment that lacks data.

2. STUDY AREA, DATA COLLECTION, AND METHODS

2.1. Study area and data collection

The study examined the sub-basins of the Ca River, which is the third-largest river in North Central Vietnam (Figure 1). The selected sub-catchments for the Tank model simulation are the Hieu River Basin at the Quy Chau station, which covers an area of 2,084 km^2, and the Trai River Basin at the Hoa Quan station, which covers an area of 119 km^2 (Table 1). These areas were selected for two distinct reasons: (1) there are available data for Tank model simulation and (2) the research results were expected to be expandable to calculations for larger basins. When the runoff of given basins can be determined, it can serve as a variety of useful purposes, including the calculation of pollutant or sediment loads, which are some of the issues of concern in the Ca River Basin.

Figure 1 | Study area.

Table 1 | Dimensions of the target sub-catchments

Sub-catchments	Sub-catchment area (km^2)	Average slope (%)	Average Altitude (Min–Max) (m)	Forested area (km^2)
Quy Chau sub-catchment	2,084	15.68	594.71 (53–2,421)	77.4
Hoa Quan sub-catchment	119	14.99	230.64 (6–1,007)	70.4

The Hieu River Basin is the largest tributary on the left bank of the Ca River. There are two hydrological stations located in this basin: Quy Chau (105°08′20″N, 19°23′30″E) and Nghia Khanh (105°20′00″N, 19°26′00″E) stations. Hydro-meteorological monitoring daily data are available at Quy Chau station, including rainfall, evaporation, and discharge data since 1961. In this study, the hydro-meteorological daily data during the periods from 2011 to 2020 at the Quy Chau station were collected for simulating the Tank model (Table 2). The collected data revealed that average annual rainfall and discharge at Quy Chau were 1,717 mm/year and 2,377 million m^3/year, respectively.

Table 2 | Hydro-meteorological data for Tank model simulation at sub-catchments

Station name	*X* coordination	*Y* coordination	Period	Minimum	Maximum	Average
Meteorological station (mm/year)						
Do Luong	105°17′60″N	18°53′60″E	1976–1985	1,446	3,105	2,226
Quy Chau	105°05′52″N	19°32′41″E	2011–2020	1,325	2,048	1,717
Hydrological station (million m^3/year)						
Hoa Quan	105°15′43″N	18°46′45″E	1976–1985	81	367	197
Quy Chau	105°08′20″N	19°23′30″E	2011–2020	1,443	3,324	2,377

The Trai River Basin is a tributary on the right bank of the Ca River, and the Hoa Quan hydrological station (105°15′43″N, 18°46′45″E) has been located on this tributary from 1976 to 1985. Therefore, hydrological daily data are available for this period, which were collected for the model simulation (Table 2). The average annual discharge at Hoa Quan was 197 million m^3/year. The meteorological data at the Do Luong station (105°17′60″N, 18°53′60″E) were used as input to simulate the Tank model for the Hoa Quan sub-catchment. The annual rainfall at the Do Luong station was 2,226 mm/year.

2.2. Methods

This study's research method is briefly illustrated in Figure 2. Daily discharge, precipitation, and evaporation were used as input data for the hydrological Tank model consisting of four storage tanks. The model applied the initial parameters based on the suggestions of Sugawara (Sugawara 1995). Four evaluation indicators including the coefficient of determination (R^2), the Nash–Sutcliffe efficiency coefficient (NSE), the percentage of bias (PBIAS), and the root mean square error (RMSE)-observation standard deviation ratio (RSR) were used to evaluate model performance. The calibrated parameters at the small catchment were used for the larger catchment in order to evaluate the extended applicability of a simulated hydrological Tank model at the Ca River Basin sub-catchment. Detailed information on the model and evaluation parameters are described in the next sections of this study.

2.2.1. Tank model structure and parameters

The hydrological Tank model is a conceptual model, which was initially proposed by Sugawara & Funiyuki (1956) and Sugawara (1995). The model simulates the watershed by describing aquifers in layers with a series of vertical tanks. The number of storage tanks depends on land use (Basri *et al.* 1999), the catchment area (Pradhan 2001), and the time interval used in the modeling (Mondal *et al.* 2009; Kuok *et al.* 2010; Phuong *et al.* 2018). Typically, the Tank model is composed of three or four storage tanks (Sugawara 1979). The Tank model version with four storage tanks is used in the case of large basins with long-term simulations with daily data and forested areas in which the low flows are significant (Sugawara 1995; Le Tien *et al.* 2020). For this reason, the hydrological Tank model consisting of four serial storage tanks was used to simulate the rainfall-discharge processes with daily data in this study. The designed Tank model consists of a surface tank (Tank 1), intermediate tank (Tank 2), sub-base-tank (Tank 3), and base-tank (Tank 4) (Figure 3). River discharge can be simulated as the sum of outputs from the side outlets.

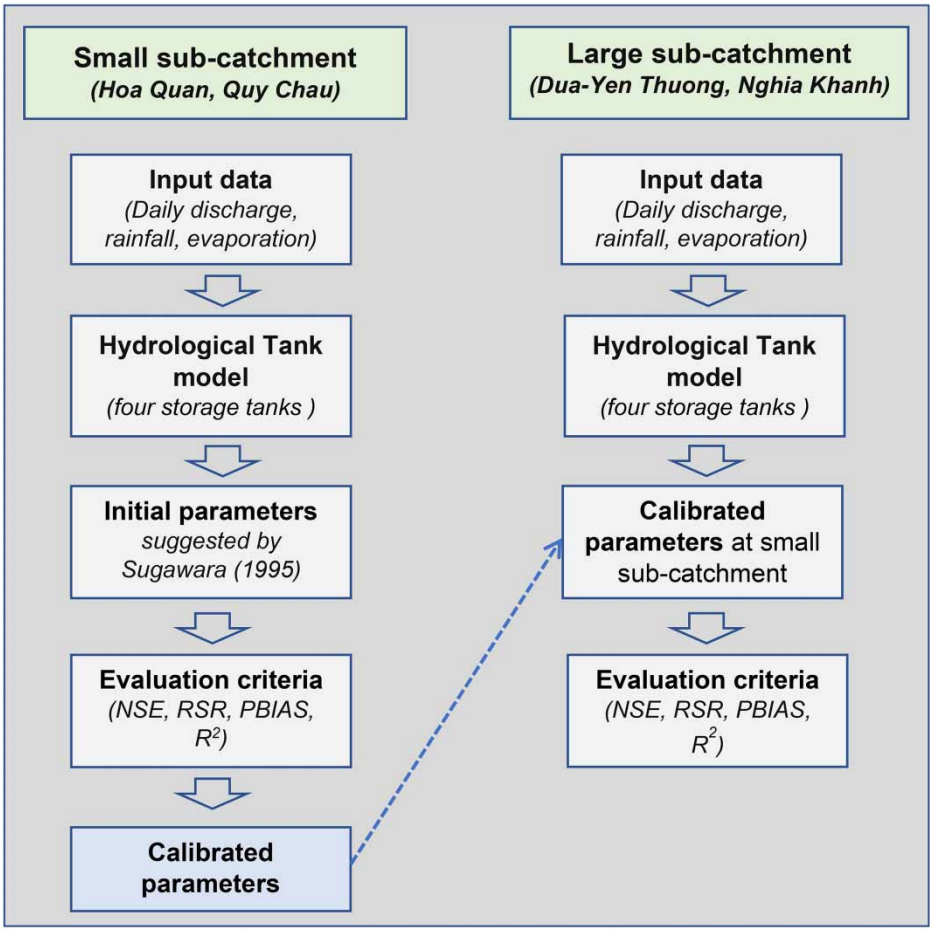


Figure 2 | Flowchart illustrating the methodology of the current study.

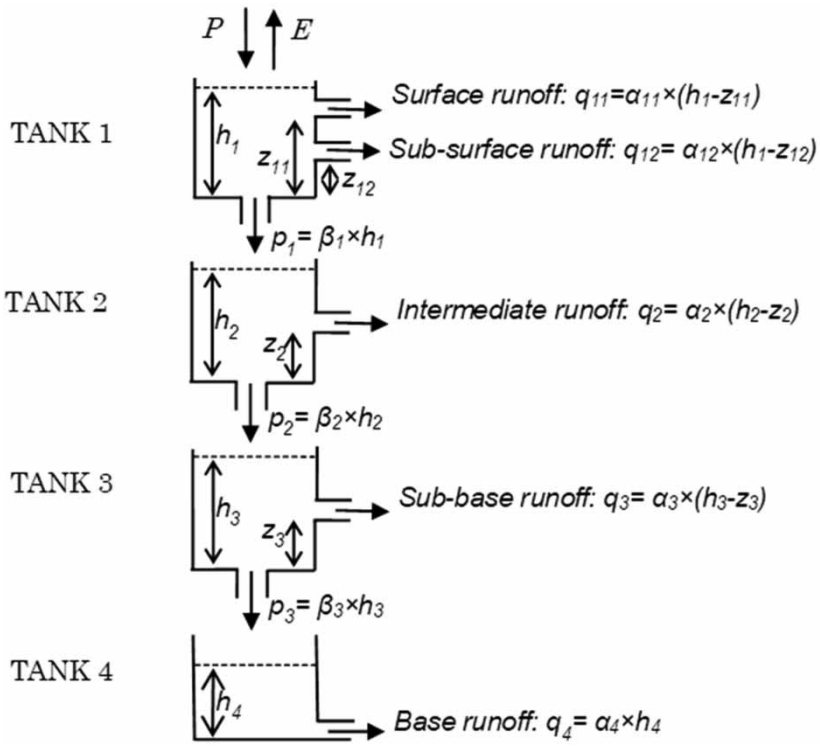


Figure 3 | Hydrological Tank model structure.

The runoff from side outlets of a storage tank is proportional to the water head over the outlet of tanks and defined as the surface runoff (q_{11}), sub-surface runoff (q_{11}), intermediate runoff (q_2), sub-base runoff (q_3), and base runoff (q_4). The discharge at the bottom hole of each tank is considered the infiltration (p_1), percolation (p_2), and deep percolation (p_3) flows into lower soil layers, which is proportional to the water depth.

Water balance and its constituents can be defined as follows:

$$\frac{Q}{A} = q_{11} + q_{12} + q_2 + q_3 \tag{1}$$

$$dh_1/dt = P - E - q_{11} - q_{12} - p_1 \tag{2}$$

$$dh_2/dt = p_1 - q_2 - p_2 \tag{3}$$

$$dh_3/dt = p_2 - q_3 - p_4 \tag{4}$$

$$dh_4/dt = p_3 - q_4 \tag{5}$$

where Q is the discharge ($m^3\ s^{-1}$); A is the drainage zone (km^2); p and q are the infiltration and discharge (mm); P and E are the precipitation and evaporation (mm); and h_i is the water depth of the *ith* tank.

The runoff or infiltration through an outlet can be expressed as follows:

$$q_{11} = \begin{cases} \alpha_{11} \times (h_1 - z_{11}) & h_1 > z_{11} \\ 0 & h_1 < z_{11} \end{cases} \tag{6}$$

$$q_{12} = \begin{cases} \alpha_{12} \times (h_2 - z_{12}) & h_2 > z_{12} \\ 0 & h_2 < z_{12} \end{cases} \tag{7}$$

$$q_2 = \begin{cases} \alpha_2 \times (h_2 - z_2) & h_2 > z_2 \\ 0 & h_2 < z_2 \end{cases} \tag{8}$$

$$q_3 = \begin{cases} \alpha_3 \times (h_3 - z_3) & h_3 > z_3 \\ 0 & h_3 < z_3 \end{cases} \tag{9}$$

$$q_4 = \alpha_4 \times h_4 \tag{10}$$

$$p_1 = \beta_1 \times h_1 \tag{11}$$

$$p_2 = \beta_2 \times h_2 \tag{12}$$

$$p_3 = \beta_3 \times h_3 \tag{13}$$

where α_{11} is the coefficient of the top side outlet of tank 1, α_{12} is the coefficient of the lower side outlet of tank 1, α_2 is the coefficient of the side outlet of tank 2, α_3 is the coefficient of the side outlet of tank 3, α_4 is the coefficient of the side outlet of tank 4, β_1 is the coefficient of the bottom outlet of tank 1, β_2 is the coefficient of the bottom outlet of tank 2, β_3 is the coefficient of the bottom outlet of tank 3, z_{11} is the height of the top side outlet of tank 1, z_{12} is the height of the lower side outlet of tank 1, z_2 is the height of the side outlet of tank 2, z_3 is the height of the side outlet of tank 3, h_1, h_2, h_3, and h_4 are the initial heights of water in tank 1, tank 2, tank 3, and tank 4, respectively.

2.2.2. Tank model initial parameter values

The Tank model is calibrated to determine 16 parameter values (α_{11}, α_{12}, α_2, α_3, α_4, β_1, β_2, β_3, z_{11}, z_{12}, z_2, z_3, h_1, h_2, h_3, and h_4). These parameters vary from one basin to another due to different characteristic properties such as climatic conditions, land use, soil type, watershed geomorphology, and hydrograph response (Arifjaya *et al.* 2011). Thus, in order to calibrate the Tank model, it is important to determine the initial parameters representing the physical natural component processes of the target basin. Parameter ranges are generally roughly estimated due to the lack of knowledge concerning the physical settings of a local catchment (Wu *et al.* 2017). Table 3 shows the range and initial values of parameters suggested by Sugawara (1995), which were used in the calibration trials in this study. The initial values of the storage parameters in the top tank, second tank, third tank, and fourth tank are 0, 0, 10–100, and 100–1,000 mm, respectively (Suryoputro *et al.* 2017). Parameters of the Tank model are optimized by manual trial and error. The optimal parameter set is ascertained by comparing the fitness of simulated data with observed hydrograph data. However, the optimal processes of the Tank

model need to follow certain principles. Specifically, the sum of the runoff and infiltration coefficients of each tank must be less than or equal to one (e.g. $\alpha_{11}+\alpha_{12}+\beta_1 \leq 1$; $\alpha_2+\beta_2 \leq 1$) (Sugawara 1979; Basri *et al.* 1999). The height of the top side outlet must be bigger than the height of the lower side outlet in the first tank ($z_{11} < z_{12}$) (Chen *et al.* 2014).

Table 3 | Initial parameters of the Tank model suggested by Sugawara (1995)

Parameters	Min–Max	Initial
Runoff		
α_{11} (day^{-1})	0–1	0.1
α_{12} (day^{-1})	0–1	0.1
α_2 (day^{-1})	0–1	0.03
α_3 (day^{-1})	0–1	0.006
α_4 (day^{-1})	0–1	0.001
Infiltration		
β_1 (day^{-1})	0–1	0.2
β_2 (day^{-1})	0–1	0.06
β_3 (day^{-1})	0–1	0.012
Outlet heights		
z_{11} (mm)	5–15	15
z_{12} (mm)	25–60	25
z_2 (mm)	0–30	15
z_3 (mm)	0–30	15

2.2.3. Model evaluation criteria

In order to calibrate the Tank model, several well-known quantitative criteria were used in this study for evaluating model performance. The four criteria include R^2, NSE, PBIAS, and RSR as recommended by Krause *et al.* (2005) and Moriasi *et al.* (2007).

The R^2 value (Equation (14)) describes the degree of co-linearity between simulated and observed data. R^2 ranges between 0 and 1 and values greater than 0.5 are considered acceptable (Golmohammadi *et al.* 2014). As the model conformity improves, R^2 approaches unity.

Meanwhile, the NSE (Equation (15)) is a normalized statistic that determines the relative magnitude of the residual variance ('noise') compared to the measured data variance ('information') (Nash & Sutcliffe 1970). The NSE ranges from $-\infty$ to 1, with the NSE by one being the optimal value. Values less than 0 occur ($-\infty < \text{NSE} < 0$) when the mean value of the observed data is a better predictor than the model, which indicates unacceptable performance (Krause *et al.* 2005).

The PBIAS (Equation (16)) measures the average tendency of the simulated data to be larger or smaller than their observed ones. The optimal value of PBIAS is 0, with low-magnitude values indicating accurate model simulation. A positive value indicates a tendency to underestimate and a negative value indicates a tendency to overestimate.

The RSR (Equation (17)) is a ratio of RMSE to the standard deviation of the observed data. The RSR incorporates the benefits of error index statistics and includes a scaling/normalization factor, so that the resulting statistic and reported values can apply to various constituents. The optimum value of the RSR is 0 and a higher value indicates lower model performance (Shrestha *et al.* 2018).

$$R^2 = \left(\frac{\sum_0^n (Q_{\text{obs}} - \bar{Q}_{\text{obs}})(Q_{\text{sim}} - \bar{Q}_{\text{sim}})}{\sqrt{\sum_1^n (Q_{\text{obs}} - \bar{Q}_{\text{obs}})^2 \sum_1^n (Q_{\text{sim}} - \bar{Q}_{\text{sim}})^2}} \right)^2 \tag{14}$$

$$\mathrm{NSE} = 1 - \frac{\sum_{1}^{n} (Q_{\mathrm{obs}} - Q_{\mathrm{sim}})^2}{\sum_{1}^{n} (Q_{\mathrm{obs}} - \bar{Q}_{\mathrm{obs}})^2} \tag{15}$$

$$\mathrm{PBIAS} = \frac{\sum_{1}^{n} (Q_{\mathrm{obs}} - Q_{\mathrm{sim}})}{\sum_{1}^{n} Q_{\mathrm{obs}}} \times 100 \tag{16}$$

$$\mathrm{RSR} = \frac{\mathrm{RMSE}}{\mathrm{STDEV}^{\mathrm{obs}}} = \frac{\sqrt{\sum_{1}^{n} (Q_{\mathrm{obs}} - Q_{\mathrm{sim}})^2}}{\sqrt{\sum_{1}^{n} (Q_{\mathrm{obs}} - \bar{Q}_{\mathrm{obs}})^2}} \tag{17}$$

where Q_{obs} and Q_{sim} are the observed and simulated flow, $\bar{Q}_{\mathrm{obs}}$ and $\bar{Q}_{\mathrm{sim}}$ are the mean observed and simulated daily discharge, and n is the total number of observations.

The river discharge prediction can be evaluated as 'Satisfactory', 'Good', 'Very good', and 'Unsatisfactory' for a daily time step according to the obtained model evaluation values (Table 4) (Moriasi *et al.* 2007).

Table 4 | Performance rating of the various statistical performance indicators (Moriasi *et al.* 2007)

Performance	R^2	NSE	RSR	PBIAS
Satisfactory	$0.50 < R^2 \leq 0.65$	$0.50 < \mathrm{NSE} \leq 0.65$	$0.60 < \mathrm{RSR} \leq 0.70$	$\pm 15\% \leq \mathrm{PBIAS} \leq \pm 25\%$
Good	$0.65 < R^2 \leq 0.75$	$0.65 < \mathrm{NSE} \leq 0.75$	$0.50 < \mathrm{RSR} \leq 0.60$	$\pm 10\% \leq \mathrm{PBIAS} \leq \pm 15\%$
Very good	$0.75 < R^2 \leq 1.00$	$0.75 < \mathrm{NSE} \leq 1.00$	$0.00 \leq \mathrm{RSR} \leq 0.50$	$\mathrm{PBIAS} < \pm 10\%$
Unsatisfactory	$R^2 \leq 0.5$	$\mathrm{NSE} \leq 0.50$	$\mathrm{RSR} > 0.70$	$\mathrm{PBIAS} \geq \pm 25\%$

2.2.4. Extension of the calibrated hydrological Tank model to larger catchments

The calibration period was 5 years from 2011 to 2015, and the validation period was 5 years from 2016 to 2020 at the Quy Chau sub-catchment. The same parameters were simulated at the Quy Chau sub-catchment, with an area of just 2,084 km^2, and were verified for use at the larger catchment area, Nghia Khanh, which has an area of 4,084 km^2 (Figure 1). The runoff data at Nghia Khanh cover the period from 2011 to 2015.

Similarly, the calibration period was 5 years from 1976 to 1980, and the validation period was 5 years from 1981 to 1985, at the Hoa Quan sub-catchment. The same parameters calibrated at the Hoa Quan sub-catchment with an area of 119 km^2 were verified for use at the catchment between Dua (105°02′20″N, 18°59′20″E) and Yen Thuong (105°23′00″N, 18°41′10″E) stations, which have an area of 2,000 km^2 (Figure 1). The runoff data at Dua and Yen Thuong stations for the period of 1976–1985 were collected corresponding to the simulated period.

In order to verify the Tank model for the catchment between Dua and Yen Thuong and the catchment at the Nghia Khanh station, meteorological data were used at the Do Luong station and the Quy Chau station, respectively. All necessary hydro-meteorological data were provided by the North Central Hydro-meteorological Centre, Vietnam.

3. RESULTS

3.1. Calibration and validation of the hydrological Tank model at the Quy Chau sub-catchment

The calibration and validation analysis of the parameters is critical to the successful application and performance of hydrologic models. Daily data from 2011 to 2020 were used to simulate the model at Quy Chau (Figure 4). Model evaluation criteria found that the NSE, RSR, and PBIAS indices were 0.85, 0.06, and −5.7% for the calibration period (2011–2015) and 0.86, 0.01, and 1.4% for the validation period (2016–2020), respectively (Table 5). A comparison of the discharge result from the simulated and the measured runoff shows $R^2 = 0.75$ for the calibration period and $R^2 = 0.78$ for the validation period. The graphical results during the study period indicate that

the simulated runoff corresponds well with the observations, and the performance is 'very good' (NSE, RSR, and PBIAS indices) according to the guidelines recommended (Moriasi *et al.* 2007). R^2 can be judged as 'good' ($0.65 < R^2 \leq 0.75$). Therefore, the set of parameters identified in Figure 6(a) can be optimally used to calculate the flow process in Quy Chau in the Hieu River areas, although the model has a minor degree of underestimation bias (PBIAS < 0). A previous analysis of the Tank model (Phuong *et al.* 2018) was done using two tanks and monthly data for simulating the Upper Hieu River Basin and presented NSE values of 0.895 (for the period of 1984–1998) and 0.92 (for 1999–2014), which are higher than our calibration. Normally, hydrological modelers frequently prefer to calibrate across a longer time period rather than a shorter, daily time period (Ficchi 2017; Adla *et al.* 2019). The monthly parameters of a hydrological model were considered due to their better calibration performance and lower computational requirements, as well as the lack of reliable observed discharge data across shorter time periods, especially in developing countries (Adla *et al.* 2019). As a result, the hydrographs simulated by daily- and monthly-calibrated models differ substantially.

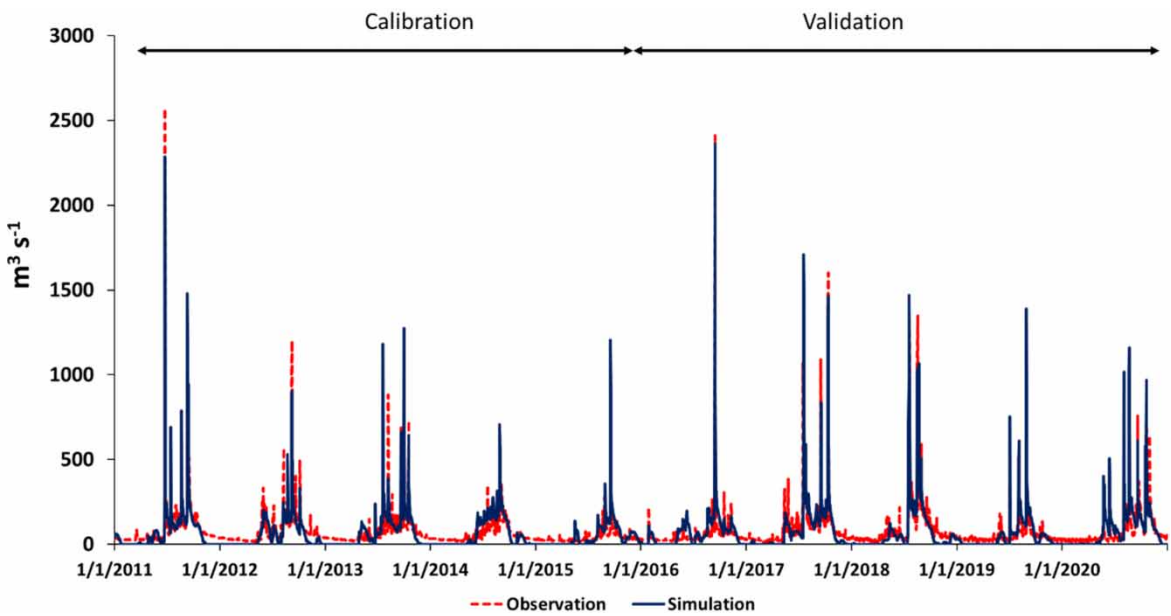


Figure 4 | The daily Tank model application at the Quy Chau sub-catchment.

Table 5 | Daily calibration and validation results at the Quy Chau sub-catchment

Indices	NSE	RSR	PBIAS%	R^2
Calibration (2011–2015)	0.85	0.06	− 5.7	0.75
Validation (2016–2020)	0.86	0.01	1.4	0.78
Total period (2011–2020)	0.85	0.02	− 1.8	0.77

3.2. Calibration and validation of the hydrological Tank model at the Hoa Quan sub-catchment

A Tank model was set up to evaluate the long-term daily inflow discharge (1976–1985). The calibration period was from 1976 to 1981, and the validation period was from 1982 to 1985 (Figure 5). Statistical analysis revealed that the performance of the Tank model was acceptable during the calibration period at the Hoa Quan station (NSE = 0.78, RSR = 0.05, PBIAS = 4.8%, $R^2 = 0.78$). The NSE, RSR, PBIAS, and R^2 values during the validation period were 0.52, 0.01, 1.3%, and 0.4, respectively (Table 6). The NSE value in the validation period (0.52) was lower than that for the calibration period (0.78) as all of the statistics computed for this period were more deficient than those computed for the calibration period, but the value was acceptable. A bias of 4.8% was found for the calibration period, whereas the validation period had a bias of 1.3%. This indicates that there

was an overestimation bias for the calibration period and the validation period. The calculated discharge at the Hoa Quan station differs from the observed peak discharge measured from 1978 to 1979. This could be due to the representativeness of the meteorological station, given that the measuring station is located downstream, while there is abnormal rainfall in upstream areas, which could not be fully recorded and tracked. In a nutshell, the hydrological Tank model at the Hoa Quan station was performed with acceptable computed data as compared to the observation data. The calibrated parameters at the Hoa Quan sub-catchments are shown in Figure 6(b).

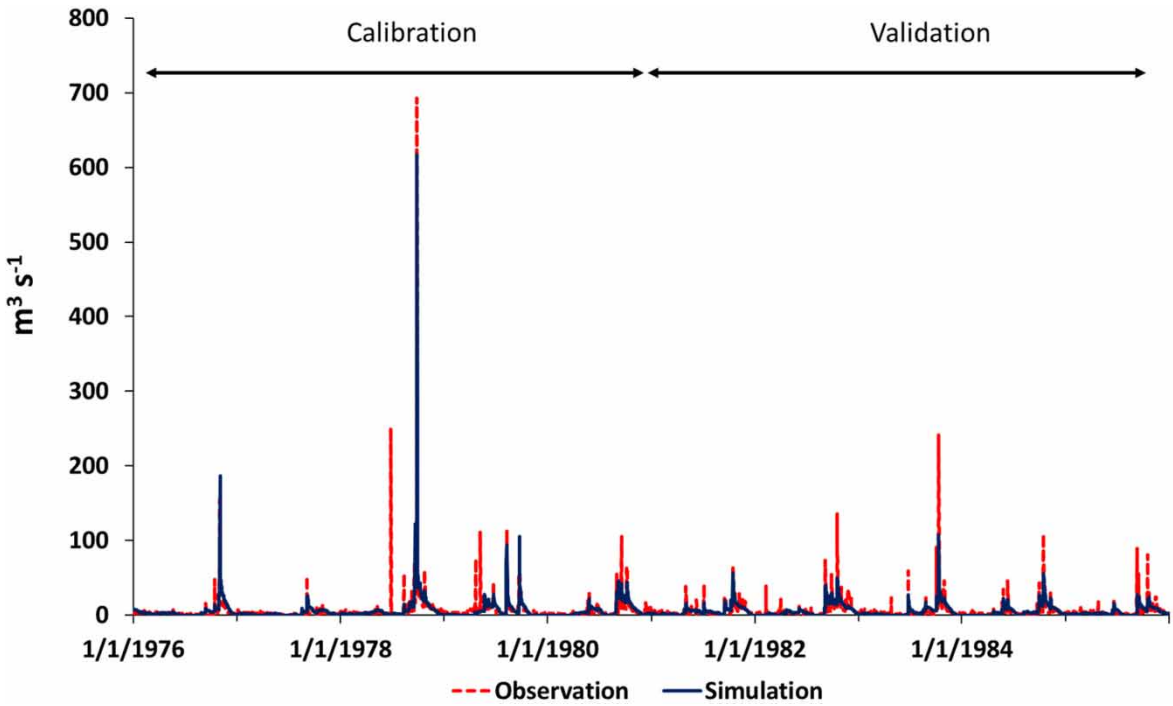


Figure 5 | The daily Tank model application at the Hoa Quan sub-catchment.

Table 6 | Daily calibration and validation results at the Hoa Quan sub-catchment

Indices	NSE	RSR	PBIAS%	R^2
Calibration (1976–1981)	0.78	0.05	4.8	0.78
Validation (1982–1985)	0.52	0.01	1.3	0.4
Total period (1976–1985)	0.73	0.03	3.2	0.69

3.3. The applicability of the calibrated Tank model at Quy Chau to Nghia Khanh

The simulated Tank model at Quy Chau was applied to extend the calculation to the area of Nghia Khanh. The observed and simulated daily flows are presented in Table 7 and Figure 7. The R^2, NSE, RSR, and PBIAS values during the calculation period were 0.6, 0.79, 0.11, and 11.7%, respectively. In general, the simulated discharge accurately matched the measured discharge. The model performance indicators exhibited from 'satisfactory' to 'very good' for the Nghia Khanh sub-catchment according to the guidelines recommended by Moriasi *et al.* (2007). The results suggested that Quy Chau station's parameters could be used for the larger area from Quy Chau to the Nghia Khanh sub-catchment.

3.4. The applicability of the calibrated Tank model at Hoa Quan to Dua-Yen Thuong

The same process was also applied to the Dua-Yen Thuong sub-catchment. The simulated Tank model at Hoa Quan was applied to extend the calculation to the area of Dua-Yen Thuong. The simulated data produced by the model were compared to observation data at the Yen Thuong station. The R^2, NSE, RSR, and PBIAS

values during the calculation period were 0.94, 0.89, 0.02, and −2.7%, respectively (Table 8 and Figure 8). The NSE, RSR, and PBIAS values calculated at the Dua-Yen Thuong area achieve 'very good' performance (Moriasi *et al.* 2007). The results from the Hoa Quan station suggest that the parameters at this station could be used for the larger area from the Dua to the Yen Thuong sub-catchment.

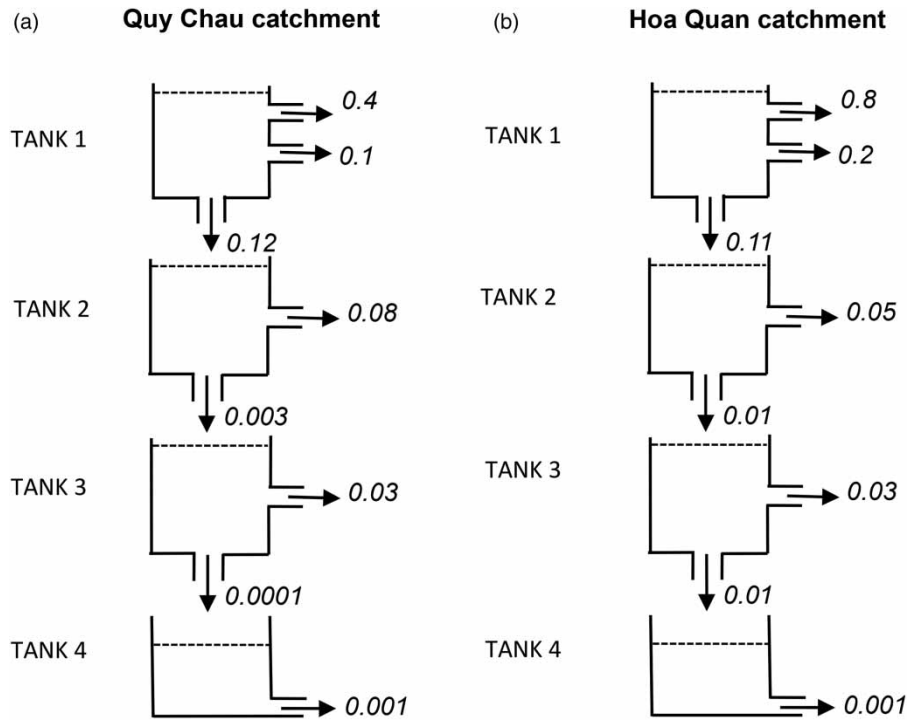


Figure 6 | Calibrated parameters at Quy Chau (a) and Hoa Quan sub-catchments (b).

Table 7 | Daily model results at the Nghia Khanh sub-catchment

Indices	R^2	NSE	RSR	PBIAS%
Period (2011–2015)	0.6	0.79	0.11	11.7

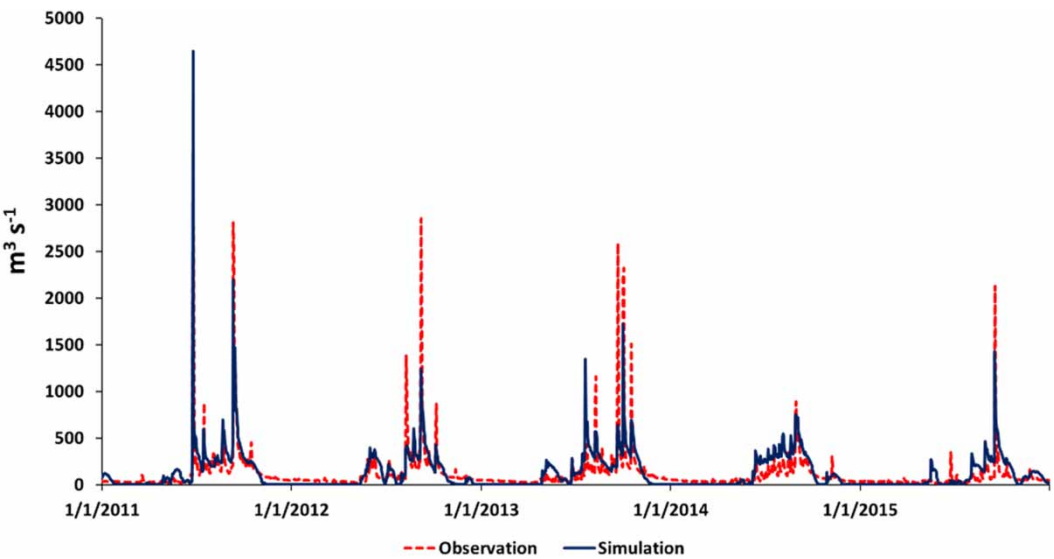


Figure 7 | The daily Tank model application at the Nghia Khanh sub-catchment.

Table 8 | Daily model results at the Dua–Yen Thuong sub-catchment

Indices	R^2	NSE	RSR	PBIAS%
Period (1976–1985)	0.94	0.89	0.02	– 2.7

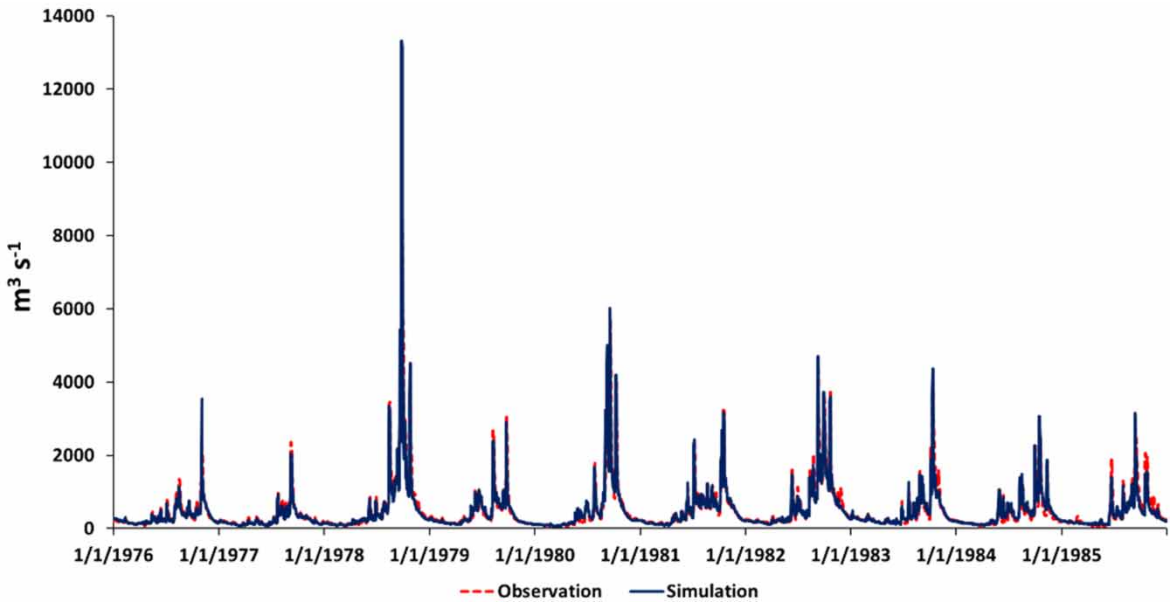


Figure 8 | The daily Tank model application at the Dua–Yen Thuong sub-catchment.

4. DISCUSSIONS

Previous studies on the Tank model used historical hydro-meteorological data in the basin with the aim of finding a representative set of parameters for that river basin. Several authors simulated the Tank model for basin areas with a range from 1 to 100 km^2, which include the Ciriung watershed with an area of 1.2 km^2 in Indonesia, the Terauchi watershed with an area of 50.55 km^2 in Japan (Setiawan *et al.* 2003), the Bedup watershed with an area of 47.5 km^2 in Malaysia (Kuok *et al.* 2010), and the Cisadane Upper Catchment with an area of 18 km^2 in Indonesia (Arifjaya *et al.* 2011). The others developed the Tank model for the basin with an area less than 1,000 km^2 including the Namatala River Catchment (155 km^2) in Eastern Uganda (Okiria *et al.* 2020) and the Nilwala River at Pitabeddara (291.4 km^2) in Sri Lanka (Wickramarachchi & Wijesekera 2022). There are also few authors who investigated the Tank model for a large basin with up to thousands of square kilometers, such as the Upper Dau Tieng River Basin in Vietnam with 2,700 km^2 (Ngoc *et al.* 2011). In fact, it will not be easy to determine representative parameters of large river basins or basins lacking hydro-meteorological data. Applying calibrated parameters from a gauged watershed to similar watersheds can be a solution to calculate discharges for watersheds lacking data. Pradhan's study is one of the few studies focusing on the applicability of the same set of model parameters to sub-basins (Pradhan 2001). Pradhan simulated the Tank model for the Jhikhu River watershed, a small-scale watershed (111.41 km^2), and the Sun Kosi River watershed (4,882 km^2), a larger watershed. The study indicated that in the case of small watersheds, parameters estimated for one sub-catchment did not match the next sub-catchment response. However, in the case of larger catchments, the estimated parameters for one large-scale sub-catchment give an accurate response for the next large-scale sub-catchment. Pradhan concluded that if the basin was large, the effects of random hydrological phenomena would cancel each other out and the change would be minimal. However, in a small basin, these effects of random hydrological and geomorphological phenomena may cause instability in predictions. Their study, on the other hand, developed a model to estimate the neighborhood catchment, whereas our study uses a calibrated model for small catchments and then extends that to larger areas of similar hydrological conditions. The simulated parameters could be applied to calculate discharge at ungauged locations within the study area. However, this study has some limitations related to hydrological data in the Hoa Quan sub-catchment, where the hydrological station has been inactive since 1986.

In addition, the measured meteorological data are quite sparse, which are the causes of the model-reduced effectiveness.

5. CONCLUSIONS

- This study assessed the applicability of a Tank model to simulate the river discharge of two poor gauged sub-catchments in the Ca River Basin.
- The model was first simulated by fitting observed and simulated daily runoff data for the Quy Chau and Hoa Quan sub-catchments, then the obtained model parameters were used for verifying the daily flow of Nghia Khanh and Dua–Yen Thuong sub-catchments, respectively.
- The model evaluation criteria at Quy Chau performed 'good' to 'very good' for the calibrated period of 2011–2015 and 'very good' for the validated period of 2016–2020.
- The model evaluation criteria at Hoa Quan performed 'very good' for the calibrated period of 1976–1981 and 'satisfactory' to 'very good' for the validated period of 1982–1985, except for the R^2 index. The effectiveness of the model in the Hoa Quan sub-catchment is limited by the lack of meteorological and hydrological data.
- The simulated daily time step Tank model parameter sets were applied to larger sub-catchments. The model performance indicators indicated 'satisfactory' to 'very good' for the Nghia Khanh sub-catchment and 'very good' for the Dua–Yen Thuong sub-catchment.
- The results of this study indicated the potential for using parameters identified in a local basin to calculate the flow process in similar, larger locations in the Ca River Basin sub-catchments. As such, the model can be used to simulate runoff from watersheds, and the simulated inflow data have the potential to benefit watershed management.
- Further studies could include simulations for large sub-catchments and an effectiveness assessment for small sub-catchments.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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