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A Hydrological Tank Model Assessing Historical Runoff Variation in the Hieu River Basin

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Abstract: The Hieu River is the largest tributary on the left bank of the Ca River, which is one of the large basins in north-central Vietnam. Here, we use cumulative anomaly tests and Pettitt tests to ascertain the turning points in annual rainfall and discharge during the time period 1962–2014. The results of our statistical analysis reveal a breaking point in 1982 for the rainfall time series and in the late 1970s and late 1990s for the discharge time series. A storage-type hydrological model is used to determine runoff processes for different periods corresponding to detecting points of rainfall and discharge. The results of our model simulation confirm that a two-tank model with monthly input data is the most appropriate tank model for the Hieu River. The difference between the hydrographs improved when we used a rain factor function. A comparison between the observed and calculated runoff revealed a drastic decrease between 1999 and 2014. The rate of discharge loss in the Lower Basin was approximately six times higher than that in the Upper Basin, a finding potentially due to reservoir construction and intensive water use for agricultural and residential purposes.

Key words: Hydrological tank model, Ca river basin, monthly data input, runoff variation.

Introduction

A hydrological cycle describes a water cycle, balance or budget within a drainage basin or on a global scale. Such a cycle can be affected by both natural and anthropogenic factors (Liu and Zheng, 2002; Vörösmarty et al., 2000; Wang et al., 2012; Yao et al., 2015; Zhang et al., 2001). As an inductive approach, statistical analyses and a hydrological model are effective tools to assess the impacts of natural and anthropogenic factors on the natural water cycle of the catchment. Among hydrological models, the tank model simply consists of several storage tanks arranged vertically in a series, representing a zonal structure of groundwater in the objective catchment (Sugawara et al., 1995). This study mainly focuses on the rainfall-runoff relation, and the tank model is applied to determine the runoff process that is a part of the hydrological cycle. The objective of this study was to calibrate a tank model in the large catchment lacking meteorological data. We then investigated runoff variation upstream of the Hieu River basin between 1962 and 2014 by applying the calibrated tank model.

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Study Area and Data Source

Study Area

The Hieu River Basin is located at 19°20′N–19°50′N and 104°30′E–105°20′E, and it is the largest tributary on the left bank of the Ca River in Vietnam (Figure 1). The catchment area is 5,340 km^2 and 228 km long, and it originates from the Pu Hoat Range with an elevation of 2,025 m on the Laos-Vietnam border. It flows into the Ca River at Anh Son. The mean slope is 1.3 ppt, and the average riverbed width is 30–35 m; the river network density is 0.71 km/km^2. The river basin is located in the northwest of Nghe An Province, where climatic conditions are characterized by two distinct seasons: the wet season (May to October) and the dry season (November to April). This study investigates the transition of flow regime at the Quy Chau and Nghia Khanh hydrological stations located in the Upper Hieu River. The areas of Quy Chau and Nghia Khanh are 1,960 and 4,024 km^2, respectively (Chikamori et al., 2012).

Data

Discharge data exist beginning from 1962 at the Quy Chau hydrological station and from 1973 at the Nghia Khanh hydrological station. Meteorological data at Quy Chau include precipitation and evaporation collected over the course of 53 years (1962–2014). All of the data were provided by the *North-Central* Hydro-meteorological *Centre, Vietnam*. Evaporation at the station was measured using a Piche tube, but evaporation data are missing for several years. Piche evaporation (E_m) is converted into potential evaporation (E_p) by multiplying by factors of k_1 = 1.263 and k_2 = 1.107, where k_1 converts from Piche evaporation to *GGI-3000 evaporation* according to data from Vinh station from 1961–2000 and k_2 converts from *GGI-3000* to actual evaporation of the water surface (Cung, 1979; ENV, 2001). To calculate the actual evaporation of the basin, we assume that evaporation on rainy days was negligible. Therefore, the monthly actual evaporation (E_a) was calculated by multiplying E_p by the ratio of the number of sunny days to the number of total days over a month. However, sunny day data have been available only since 1996. Therefore, the correlations among available meteorological data were investigated to extend the actual evaporation measurements from 1962–2014.

The collected data revealed that the average annual precipitation and Piche evaporation at Quy Chau station were 1,668 mm and 732 mm, respectively, over 1962–2014. The highest annual precipitation was 2,482 mm in 1978, and the lowest annual precipitation was 1,102 mm in 1976. The mean annual flow was 77 m^3/s between 1962 and 2014 at Quy Chau station and 126 m^3/s between 1973 and 2014 at Nghia Khanh station.

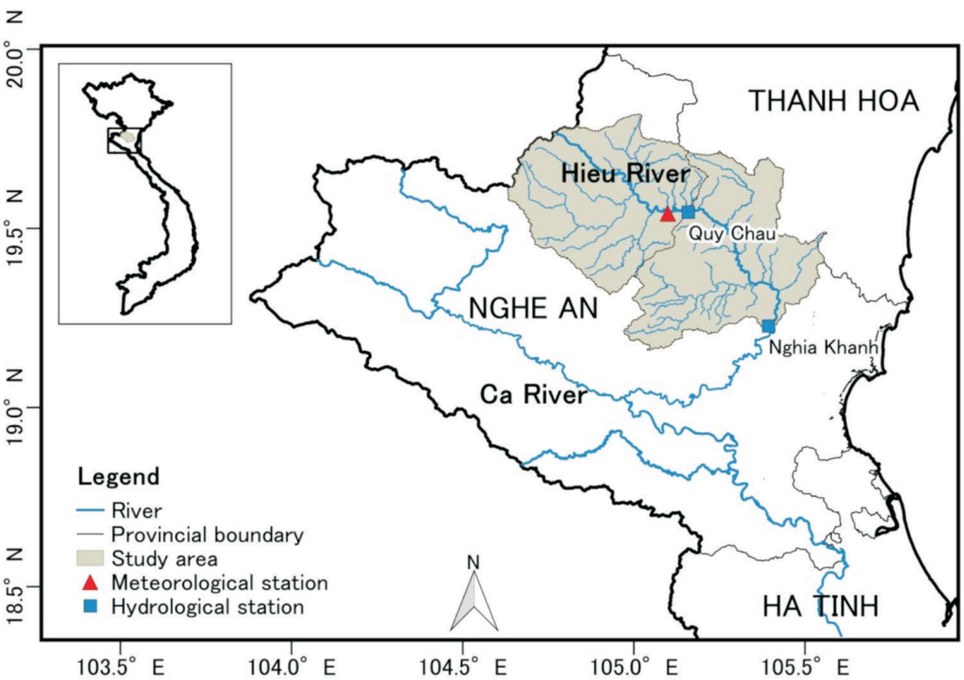


Figure 1: Location of the Hieu River Basin.

The annual discharge at Nghia Khanh was higher than that at Quy Chau by an average of a factor of 1.6. The average monthly flow varied from 15–312 m^3/s at Quy Chau station and from 42–334 m^3/s at Nghia Khanh station. The average monthly discharge of Nghia Khanh was higher than that of Quy Chau, particularly during the flood season.

Methods

Rainfall-runoff Analysis

Tank Model

The tank model is a conceptual representation of hydrological processes in the unit area of the basin, and it simulates wetness of several soil layers using tanks arranged vertically in a series. This kind of model typically consists of three or four storage tanks. Precipitation is the input of the model, and it enters into the top tank.

Some of the accumulated water flows through the side outlet of a tank and some of it infiltrates down into the second lower tank. The process repeats for every lower tank. Evapotranspiration is incorporated via subtraction from the tank. The runoff from the side outlet of a storage tank (q) is proportional to the water head over that outlet, and the infiltration (p) is proportional to the water depth. These relations can be expressed as:

$$q = a(h - z),\ p = bh \quad (1)$$

where h is the tank depth, z is the height of the discharge outlet from the base of each tank, a is the runoff coefficient and b is the infiltration coefficient.

In this study, the tank model with three storage tanks consisted of a surface tank, an intermediate tank, and a base tank (Figure 2). The two side outflows from the surface tank are regarded as the surface runoff (q_{11}) and the sub-surface runoff (q_{12}), the side outflow from the intermediate tank is regarded as the intermediate runoff (q_2) and the outflow from the third tank is regarded as the base runoff (q_3). The total outflow from the side outlet (Q) from each tank is regarded as the accumulation of the outflows from a system in the watershed, as given by the following equation:

$$\frac{Q}{A} = q_{11} + q_{12} + q_2 + q_3 \quad (2)$$

where A is the watershed area.

The tank model introduced by Sugawara for humid regions includes four tanks used to analyze daily discharge from daily precipitation and evaporation

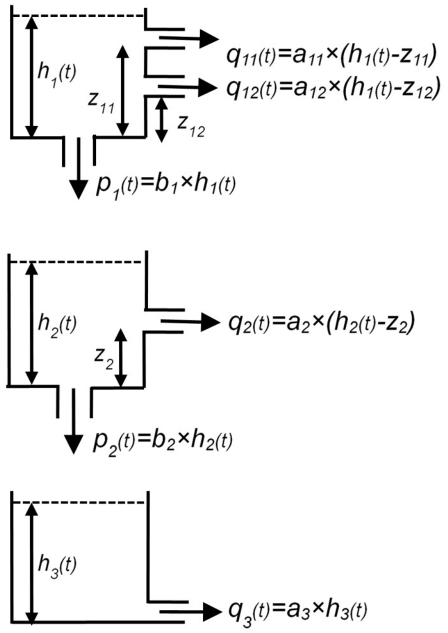


Figure 2: Structure of the tank model.

inputs (Sugawara et al., 1995). For flood analysis, the tank model includes two tanks, and the inputs are typically precipitation and the outputs are hourly discharge. Many types of tank models have been developed for humid regions using daily and hourly data. Nyadawa et al. (1996) proposed a modified tank model that explicitly simulates surface runoff phenomena. These authors verified the model using data from several basins in Kenya. Kuok et al. (2011) ascertained the best number of tanks in the tank model to provide reliable and accurate estimates of runoff for a rural catchment in a humid region.

Mondal et al. (2009) applied the tank model taking into consideration soil-moisture component. Nearly all studies estimating the amount of runoff originating from the catchment area for short-term analysis using daily and hourly input data have made use of a tank model. In this study, we have simulated a tank model for long-term analyses with monthly data. A tank model using monthly data might be associated with less-complex parameters and less difficulty when considering input data for a basin lacking meteorological stations.

Calibration of the Tank Model

We optimized the parameters of the tank model manually using a trial-and-error method. The value of each parameter was successively changed, and the fitness of the simulated hydrograph compared with the observed result was evaluated using the Nash-Sutcliffe efficiency (NSE):

$$NSE = 1 - \frac{\Sigma(Q_{obs} - Q_{cal})^2}{\Sigma(Q_{obs} - \bar{Q}_{obs})^2} \quad (3)$$

where Q_{obs} represents the observed monthly streamflow, $\bar{Q}_{obs}$ represents the observed monthly mean streamflow and Q_{cal} signifies the calculated monthly streamflow. In addition, the *coefficient* of determination (R^2) was also used to evaluate the tank model.

To search for the optimal set of parameters, several principles related to the runoff and infiltration coefficients were considered. First, the sum of runoff principles related to the runoff and infiltration coefficients were considered. The sum of the runoff and infiltration coefficients of a tank has to be less than unity (e.g., $a_{11}+a_{12}+b_1 < 1$ in the case of the top tank). In other words, the runoff depth from a single tank during a time increment should not exceed the water storage depth of that tank (*h*) (Sugawara et al., 1995; Basri, 2013). Second, the runoff and infiltration coefficients of the lower tank must be smaller than those of the upper tank (i.e., $a_{11}>a_{12}>a_2$). Therefore, the discharge from the lower tank is less than that from the upper tank, which reflects the fact that the discharge from a lower aquifer is typically less than that from an upper aquifer.

Assessment of Hydrological Regime Change

Cumulative Anomaly

The cumulative anomaly is a statistical method for the visual identification of a variable tendency of discrete data (Wang et al., 2012), and it is used extensively in meteorology. For a discrete series x_i, the cumulative anomaly (X_t) for a data point x_t can be expressed as

$$X_t = \sum_{i=1}^{t}(x_i - x_m),\ t = 1, 2,\ldots, n, \quad (4)$$

where $$x_m = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (5)$$

x_m denotes the mean value of the series x_i and n represents the number of discrete data points. The cumulative anomaly method can be used to analyze the inflection extent of a discrete data series.

Pettitt Test

The Pettitt test is a nonparametric method that is widely applied to detect abrupt changes in water discharge (Yao et al., 2015). We employed the Pettitt test using software (R; https://www.r-project.org/). For a given time series X ($x_1, x_2,\ldots, x_N$) divided into two samples $x_1, x_2,\ldots, x_t$ and $x_{t+1}, x_{t+2},\ldots, x_N$, the Pettitt test uses a version of the Mann-Whitney statistic $U_{t,N}$ calculated as

$$U_{t,N} = U_{t-1,N} + \sum_{j=1}^{N} \mathrm{sgn}(x_t - x_j),\ t = 2, 3, .., N \quad (6)$$

where

$$\mathrm{sgn}(x_t - x_j) = \begin{cases} 1, & x_t > x_j \\ 0, & x_t = x_j \\ -1, & x_t < x_j \end{cases} \quad (7)$$

The breakpoint is defined to be where $|U_{t,N}|$ reaches its maximum value:

$$K_N = \mathrm{Max}|U_{t,N}|,\ (1 \le t \le N). \quad (8)$$

The significance level associated with K_N is determined approximately as the following

$$p \cong 2\exp\left[\frac{-6(K_N)^2}{(N^2 + N^2)}\right]. \quad (9)$$

If $p < 0.05$, a significant change point exists.

Results

Evaporation Data Extension

Before applying the tank model, it is important to calibrate the model, which is viewed as exhibiting superior matching between the calculated and observed runoff. Success in calibrating the tank model depends strongly on data quantity and data quality, challenging aspects in the case of the Upper Hieu River due to the lack of meteorological data. Several years of measured evaporation data are missing: 1962, 1963, 1966, 1967, 1976 and 1977. To infill the missing evaporation data, we investigated the relation between available measured evaporation and precipitation. Figure 3 shows the relation between average monthly measured evaporation (E_m) and average monthly precipitation (P) over the course of 1962–2014. This figure shows that the ratio of E_m/P and P are negatively correlated. When the precipitation exceeds 50 mm from May through October, the ratio of E_m/P is less than unity. In April and November, the monthly precipitation is approximately 50 mm and the ratio of E_m/P is close to unity. From December through March, the ratio of E_m/P is higher than unity. The strong correlation ($R^2 = 0.97$) of E_m/P and P in Figure 3 can be used to extract the missing monthly evaporation data from the available monthly precipitation data.

Monthly actual evaporation E_a was converted from monthly potential evaporation E_p by multiplying E_p by the ratio of the number of sunny days in a month to the total number of days in a month. However, data pertaining to sunny days were only available from 1996–2014. Therefore, the average monthly fraction of sunny days from 1996–2014 was used to extend E_a over 1962–1995. After conducting this extension, we then investigated the correlation between annual E_a and annual E_p for the entire period of 1962–2014. The strong correlation ($R^2 = 0.94$) of E_a and E_p indicated that extended E_a can be used as input data to calibrate the tank model in this study.

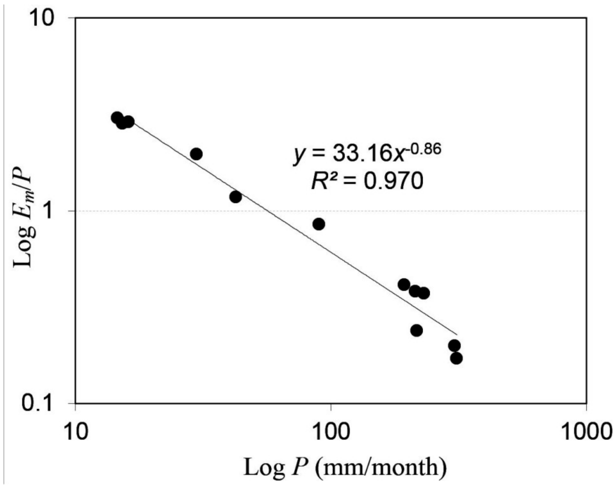


Figure 3: Correlation between mean monthly E_m/P and mean monthly P between 1962 and 2014.

Change Points of Annual Precipitation and Discharge

To determine the turning points of the annual rainfall and discharge from 1962–2014, we used the cumulative anomaly test and the Pettitt test. According to the Pettitt test results, there was no change-point year detected at $p = 0.05$. However, change points of annual rainfall series were detected at $p = 0.48$ in 1982. The annual discharge series at Quy Chau station was detected at $p = 0.21$ in 1977. The annual discharge series at Nghia Khanh station was detected at $p = 0.64$ in 1996. In accordance with the Pettitt test results, the cumulative anomaly test results showed that the turning point of annual rainfall series occurred in 1982 (Figure 4a). The turning points of annual discharge series were in 1977 and 1997 at Quy Chau station (Figure 4b), and the turning points of annual discharge series were in 1977 and 1996 at Nghia Khanh station (Figure 4c).

At the breaking point of 1982, the mean annual rainfall decreased from 1,767 mm from 1962–1982 to 1,602 mm from 1983–2014. However, the discharge series increased after 1977 and then subsequently decreased after 1997 at both stations.

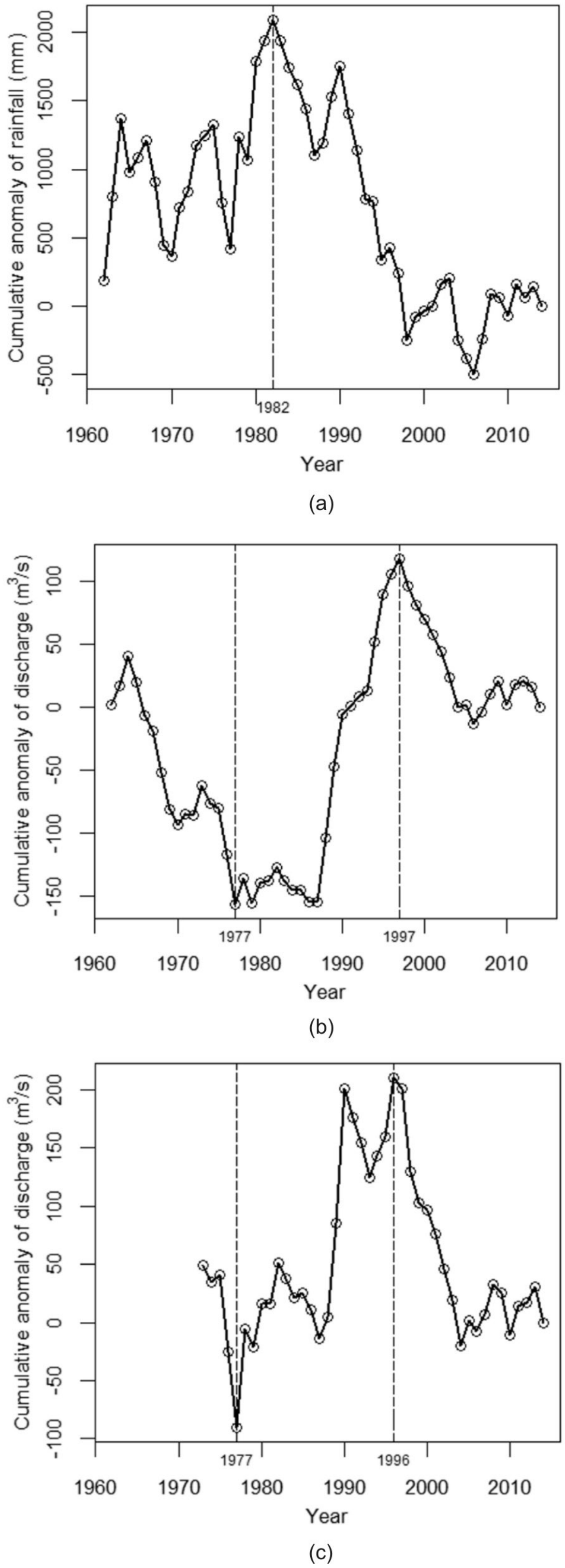


Figure 4: Cumulative anomaly test results of annual rainfall (a), annual discharge at Quy Chau station (b) and annual discharge at Nghia Khanh station (c).

Trial of Tank Model Calibration for the Whole Period of 1962–2014

Prior verification of the annual water balance was conducted for the long-term analyses before calibrating the tank model. In a catchment, the water input and the output must be balanced. However, in the research area, there was only a single meteorological station used for the input data. Therefore, the precipitation might not be representative of the entire catchment. This research assumes that monthly precipitation multiplied by the precipitation factors approximates the annual water balance. In addition, in order to simplify the tank model calibration, the actual evaporation was assumed to be accurate for this study. Consequently, the annual water balance can be expressed as $P \times C_P = Q + E_a$, where C_P is a precipitation factor (Sugawara et al., 1995).

At the Quy Chau hydrological station, the precipitation factor was 1.13 for 1962–2014. At the Nghia Khanh hydrological station, C_P was close to unity for 1973–2014. We used adjusted precipitation ($P \times C_P$), actual evaporation (E_a) and discharge (Q) to calibrate the tank model. The calibration results of the tank model show that the base flow of the calculated discharge was consistently smaller than that of the observed discharge for 1984–1998 at both stations. Breaking points of the base flow were close to breaking points of precipitation and discharge detected by the cumulative anomaly test and the Pettitt test.

Tank Model Calibration for the First Period (1962–1983) at Quy Chau station

The study was divided into three time periods for additional study: pre-1984 (period 1), 1984–1998 (period 2) and post-1998 (period 3). We first simulated the tank model for period 1 and then applied the simulated parameters for periods 2 and 3. The value of the precipitation factor during each period was estimated using the annual water balance equation of $P_i \times C_{Pi} = Q_i + E_{ai}$, where C_{Pi} is a precipitation factor during each period and i = 1, 2, 3 denotes the first, second and third periods, respectively. At Quy Chau, the results of C_{Pi} were 1.01 for the first period, 1.38 for the second period and 1.10 for the third period. At Nghia Khanh, the corresponding C_{Pi} values were 0.92, 1.08 and 0.96, respectively. The relative change in precipitation was calculated as $(C_{Pi} - 1) \times 100\%$. We found a significant lack of precipitation, with 38% at Quy Chau and 8% at Nghia Khanh during period 2.

The rainfall data at Quy Chau station were appropriate for catchment representation for periods 1 and 3, however insufficient to meet the water budget for period 2. Adjusting the precipitation by multiplying by a precipitation factor is apparently a simple method used for long-term analyses. However, the precipitation factor also shows a seasonal change (Sugawara et al., 1995). Therefore, using a precipitation factor that varies by month might yield better calibration results. In this case, the precipitation factor is described as $C_P(M)$, where M is the month index (Sugawara et al., 1995). In this study, $C_P(M)$ was calibrated by the number of trials.

The tank model was calibrated for period 1 (1962–1983) corresponding to two trials.

(1) Trial No. 1: Precipitation adjusted by multiplying by a constant precipitation factor. However, C_P at Quy Chau during 1962–1983 was close to 1.0. Therefore, the precipitation did not change.
(2) Trial No. 2: Precipitation was adjusted by precipitation factor $C_P(M)$ (Sugawara et al., 1995). The available precipitation data were adjusted taking into consideration a high peak discharge.

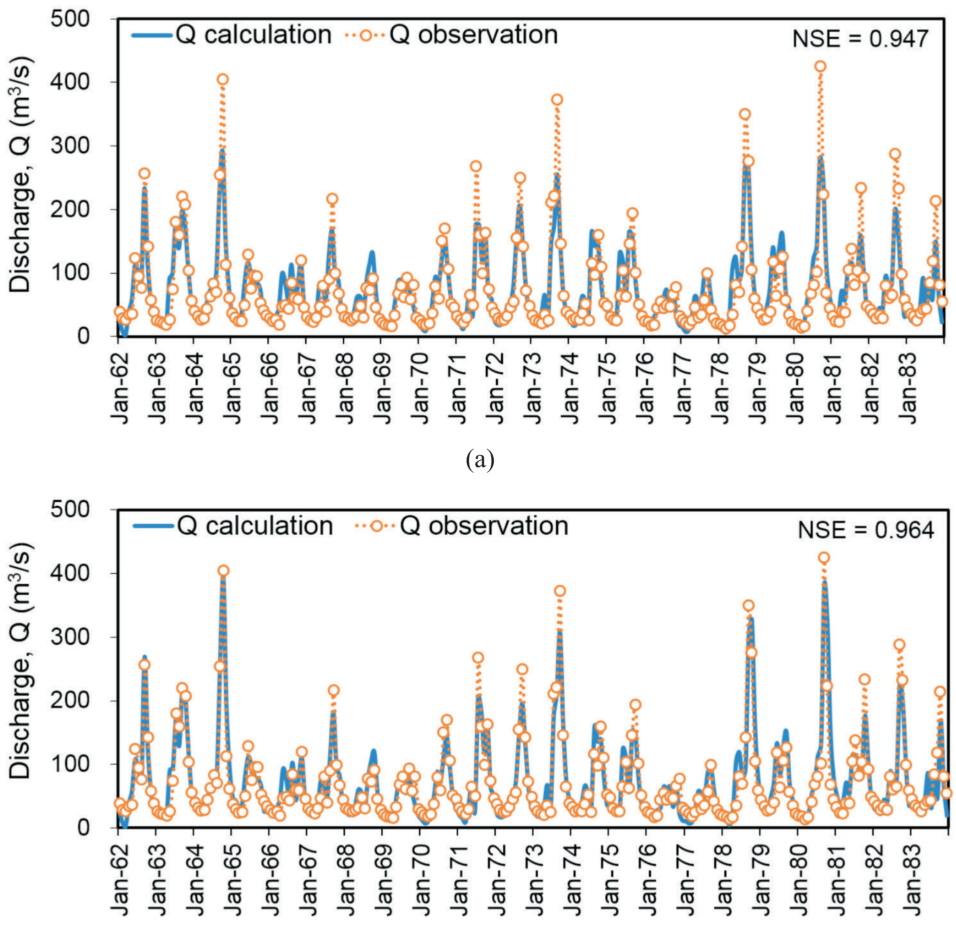
After the trials, the appropriate values of $C_P(M)$ were changed corresponding to different range of discharge. When the monthly discharge exceeded 400 m^3/s, the precipitation was multiplied by $C_P(M) = 1.5$. If the monthly discharge was between 200 and 400 m^3/s, the precipitation was multiplied by $C_P(M) = 1.2$. If the monthly discharge was less than 38 m^3/s, the precipitation was not changed. The precipitation factor for the other months was 1.0.

In Figure 5, we show the results of tank model calibration for the two trials at Quy Chau station. The NSE and the *coefficient* of determination (R^2) of trial No. 1 are 0.947 and 0.846, respectively. The *coefficients* of trial No. 2 are 0.964 and 0.884, respectively. Figure 6 shows the improvement in trial No. 2 (b) compared with trial No. 1 (a) based on the better fit of the duration curve.

Tank Model Calibration for the First Period (1973–1983) at Nghia Khanh Station

The tank model calibrated for 1973–1983 at Nghia Khanh made use of the same method as that applied to Quy Chau station. The appropriate values of $C_P(M)$ must be changed to correspond to a different range of monthly discharges. When the monthly discharge exceeds 400 m^3/s, the precipitation is modified by multiplying it by $C_P(M) = 1.4$. If the monthly discharge is less than 64 m^3/s, the precipitation was left unchanged. The precipitation factor for the remaining months was 0.92.

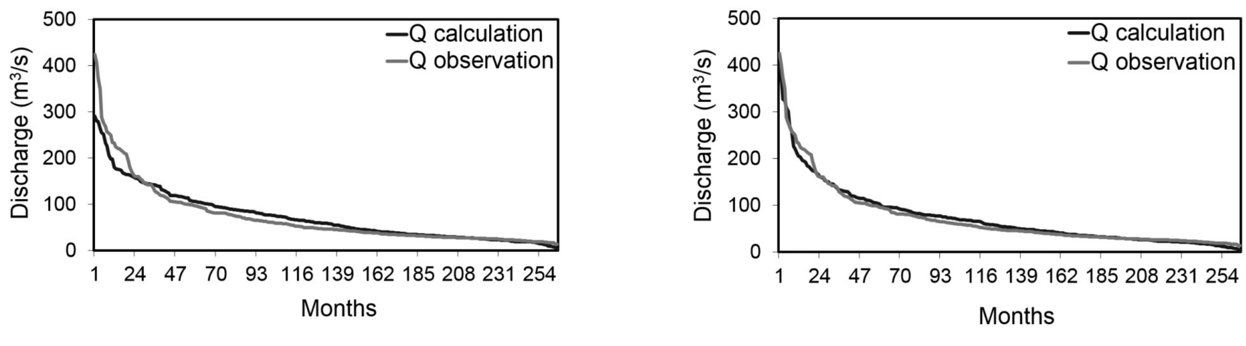
The results of the tank model calibration of the two trials at Nghia Khanh station are shown in Figure 7. The



(a)

(b)

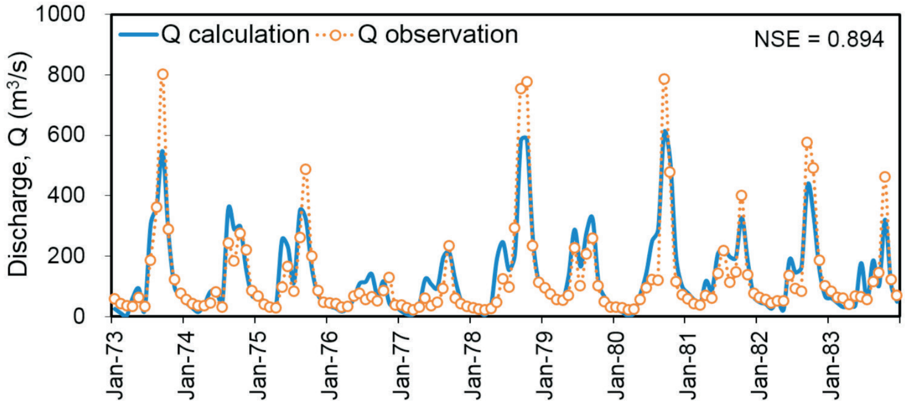
Figure 5: Calibrated tank model at the Quy Chau gauging station from 1962–1983: (a) trial No. 1 and (b) trial No. 2.



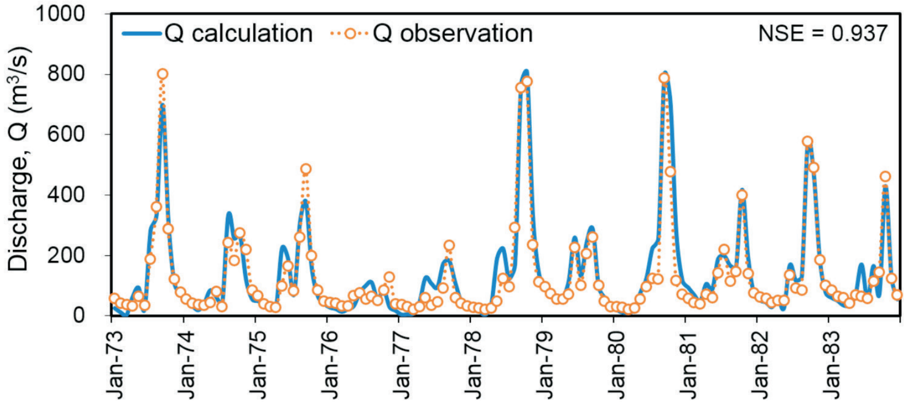
(a) (b)

Figure 6: Duration curves at Quy Chau station from 1962–1983: (a) trial No. 1 and (b) trial No. 2.

NSE and R^2 values of trial No. 1 were 0.894 and 0.821, respectively. The corresponding values for trial No. 2 were 0.937 and 0.905, respectively. An improvement in calibration was noted for trial No. 2 compared with trial No. 1 (Figure 8). These results indicate that a precipitation factor that varies with the month is useful for obtaining better calibration results. A month that has higher precipitation (discharge) necessitates a higher precipitation factor, which means that rainfall density might lead to a change in the relation between rainfall and infiltration, as well as surface runoff in the watershed (Basri, 2013).

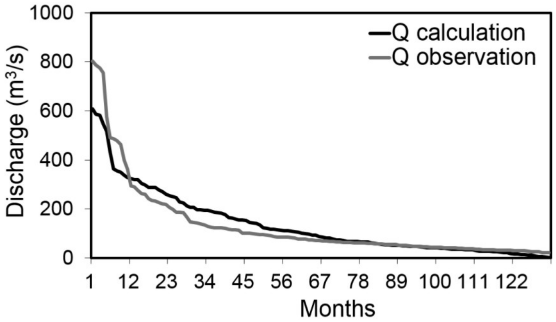


(a)



(b)

Figure 7: Calibrated tank model at Nghia Khanh station from 1973–1983: (a) trial No. 1 and (b) trial No. 2.



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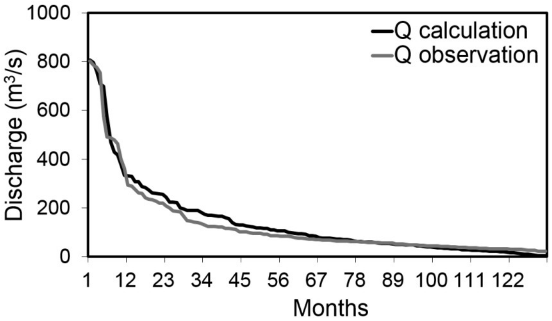


(b)

Figure 8: Duration curves at Nghia Khanh station from 1973–1983: (a) trial No. 1 and (b) trial No. 2.

Tank Model Validation

The calibrated parameters in Figure 9 were applied to periods 2 and 3. A similar $C_p(M)$ was applied for periods 2 and 3 as for period 1 (trial No. 2). The model evaluation statistics for different periods are listed in Table 1. Our results indicate that the tank model applied for period 3 had better results of the NSE and R^2 values than for period 2 at both stations. A significant effect was noted for the natural hydrological cycle of the basin during period 2. The results of the NSE and R^2 values for periods 2 and 3 in this study were in line with the findings of Giang et al. (2014) (Table 1). These authors applied the SWAT model to the Upper Ca River. They found that, compared with the calibration period (1971–1995), the simulated discharge during the validation period (1996–2010) more closely followed the corresponding observed discharge; it underestimated the peak-flow months less and overestimated the low-flow months less.

Table 1: Nash-Sutcliffe efficiency (NSE) and the coefficient of determination (R^2) results for different time periods

Stations →	*Quy Chau (1,960 km²)*		*Nghia Khanh (4,024 km²)*		*Yen Thuong (23,000 km²) (Giang et al., 2014)*	
Periods	1984–1998	1999–2014	1984–1998	1999–2014	1971–1995	1996–2010
NSE	0.895	0.920	0.892	0.896	0.86	0.89
R^2	0.665	0.830	0.762	0.815	0.87	0.89

Discussion

Tank Model Calibration Using Monthly Input Data

The tank model was calibrated for period 1 at the Upper Hieu River using the three-tank structure (Figure 2). However, the side outlet and infiltration coefficients for the third tank had very little effect on the simulation results. Therefore, the tank model composed of two tanks using monthly data was the most appropriate for simulating the Upper Hieu River Basin. The set of simulated parameters of trial No. 2 at each station is shown in Figure 9.

Previous researchers have investigated the most appropriate number of tanks for the tank model. For example, Kuok et al. (2011) investigated three-tank, four-tank and five-tank models to ascertain the most appropriate tank model configuration for the southern region of Sarawak in Malaysia. These authors revealed that the four-tank model yielded the best runoff forecasting result. Kadarisman (1993) applied the tank model for the Babak River Basin, Lombok Island, Indonesia and concluded that the tank model with three tank components was unsuitable for use in low-flow analysis. The tank model with three tank components can be used for normal and high-accuracy analysis in cases in which the low flows are not significant. Basri (2013) used the tank model with various types of land as a reference to determine the preferred number of tanks.

This author advised using tank models of different types based on land use (e.g., four tanks for a forest, three tanks for a garden or vacant lot, two tanks for a paddy and one tank for a settlement). The number of tanks therefore depends on the catchment area. Pradhan (2001) reported that the number of tanks necessary for the tank model increases for larger-scale catchments to ensure better performance of the model. In nearly all earlier studies, daily data were used to calibrate the tank model (Kuok et al., 2011; Mondal et al., 2009; Pradhan, 2001). In this study, monthly data were used as the input for the tank model. We found that a two-tank model with monthly input data was the most appropriate tank model for the Upper Hieu River.

Temporal Change of Runoff at the Upper Hieu River

The temporal change in runoff upstream of the Hieu River Basin was investigated for three time periods: prior to 1984, 1984–1998 and after 1998. Figure 10 shows the results of double mass curves of precipitation-calculated discharge and precipitation-observed discharge. These data indicate that the increment of

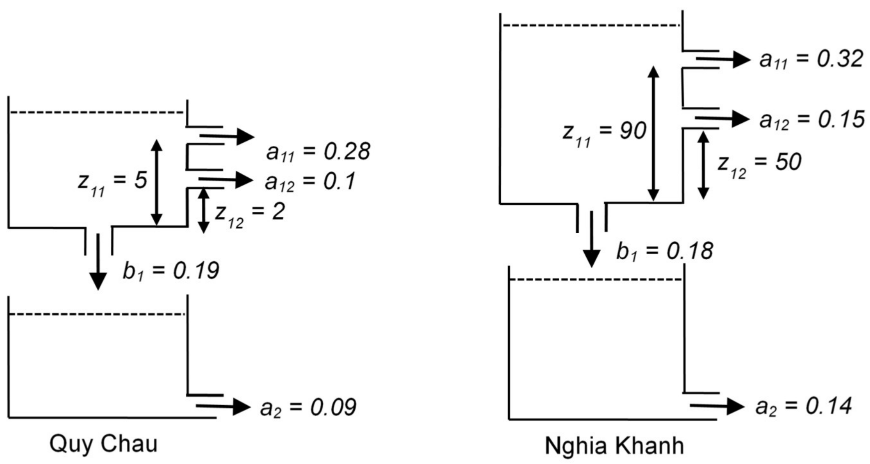
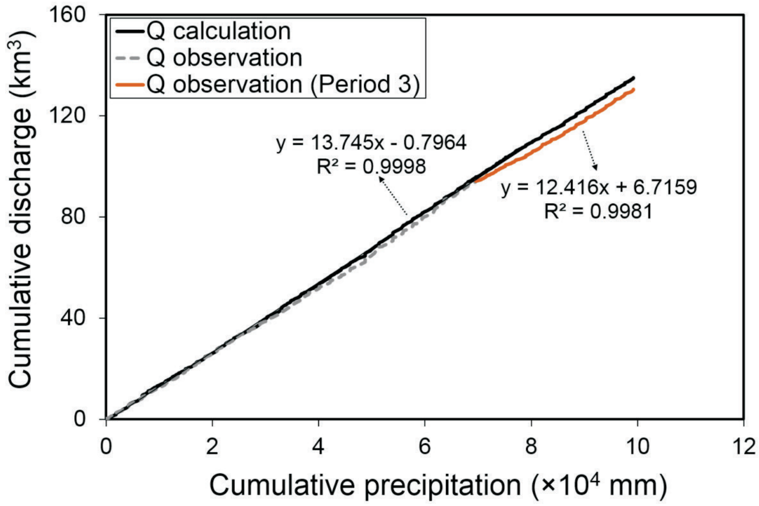
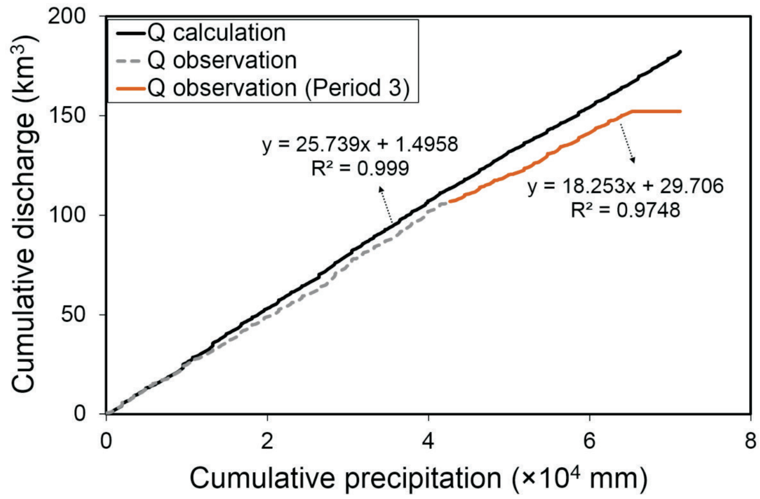


Figure 9: Calibrated parameters of the tank model using monthly data.



(a)



(b)

Figure 10: Double mass curves of precipitation and discharge: (a) Quy Chau and (b) Nghia Khanh.

observed discharge was less than the increment of calculated discharge during period 3. The annual loss in discharge was 0.2×10^9 m^3 at Quy Chau and 1.5×10^9 m^3 at Nghia Khanh between 1999 and 2014. This finding means the rate of discharge loss in the Lower Basin (between Quy Chau and Nghia Khanh) was approximately six times higher than that in the Upper Basin (upstream of Quy Chau).

It has been reported that the annual runoff of many rivers around the world has decreased remarkably during recent decades (Shiklomanov, 1993). The decrease in precipitation and/or the increase in evapotranspiration are considered to be factors that directly influence runoff decrease (Wang et al., 2012). The decrease in runoff might also result from anthropogenic influences in the catchment (e.g. population growth, river regulation, dam construction, irrigation) (Vörösmarty et al., 2000; Yao et al., 2015). At the research site, the actual evaporation that we found also exhibited an increasing trend for the last 53 years, which resulted in *reduction in runoff*. In addition, many reservoirs have been constructed and operated at upper Quy Chau since 2005 (e.g., Ban Kok, Sao Va and Nhan Hac, which have electricity generation capacities of 18, 3, and 45 MW, respectively).

There are two major reservoirs between Quy Chau and Nghia Khanh: Sao-River reservoir and Ban Mong reservoir. Construction of the Sao River reservoir, with a gross capacity of 5.1×10^7 m^3, started at the end of 1999 and finished in 2003. It was designed to provide irrigation water for 6,200 ha of land for rice cultivation, commercial crops and water reserves. Ban Mong reservoir, with a gross capacity of 2.5×10^8 m^3

and a power generation capacity of 42 MW, was first started in 2010 and ultimately completed in 2012. The reservoirs provide power generation, and water supply for residential and farming areas in the region. Moreover, they reduce flooding of the Hieu River downstream.

All of the water used for agricultural and residential purposes, in addition to the water stored in the reservoirs, resulted in a marked decrease in the river runoff in the Hieu River Basin beginning in 1998, particularly at Nghia Khanh. In addition, the reservoir might engender increased potential evaporation and leakage losses, resulting in decreased runoff (Gao et al., 2011).

Conclusions

We have used a tank model calibrated with monthly input data to assess the temporal variation in river flow at the Upper Hieu River Basin in Vietnam during the time period 1962–2014. With cumulative anomaly tests and Pettitt tests, we detected turning points in annual rainfall and discharge. Our results reveal turning points in annual rainfall series in 1982 and turning points in the annual discharge series in 1977 and 1997 at Quy Chau. At Nghia Khanh, we noted turning points in the annual discharge series in 1977 and 1996. In addition, we calibrated the tank model at both stations for the 53 years of observations. The base flow of the calculated discharge was less than that of the observed result from 1984–1998. We assessed the flow variation for three time periods: 1962–1983 (period 1), 1984–1998 (period 2) and 1999–2014 (period 3).

The value of the precipitation factor during each period was estimated by checking the annual water balance. The tank model was simulated for period 1. Then, we applied the calibrated parameters to periods 2 and 3. The precipitation and evaporation used as input data for calibrating the tank model came from a single meteorological station model with a catchment area of 1,960 km^2 at Quy Chau and 4,024 km^2 at Nghia Khanh. The results of tank model calibration indicated that the hydrographs improved when we used a precipitation factor as a function of the month. In addition, our results confirmed that a two-tank model with monthly input data is the most appropriate tank model for the Upper Hieu River.

We used the set of calibrated parameters applied to periods 2 and 3 to ascertain the temporal variation in the flow on the Upper Hieu River. The temporal variation of river flow was investigated by comparing the increase in calculated and observed discharges with increases in precipitation. A marked decrease in runoff has occurred since 1999, particularly at Nghia Khanh station. The rate of discharge loss in the Lower Basin was approximately six times higher than that in the Upper Basin, a finding likely due to reservoir construction and water being intensively used for agricultural and residential purpose.

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