QUANTIFYING NATURALIZED STREAMFLOW ENTERING VIET NAM FROM THE UPPER RED RIVER BASIN USING THE VIC-3L MODEL

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Abstract: *The Red River Basin is an important transboundary river system, with the upstream area in China contributing substantially to water resources in Viet Nam. However, quantifying natural transboundary inflows remains challenging because of limited observations and increasing human impacts on water resources. This study applied the VIC-3L model to reconstruct naturalized streamflow in the main tributaries of the Red River Basin flowing into Viet Nam during 1981-2020. The model was calibrated and validated at the Muong Lay, Lao Cai, Dao Duc, and Bac Me stations using the SCE-UA optimization algorithm. Results show that the model accurately reproduced monthly streamflow, with Nash-Sutcliffe efficiency (NSE) values ranging from 0.91 to 0.95. Total annual runoff from the three upstream catchments in China (the Yuanjiang, Lixian, and Panlong rivers) decreased from 53.67 km³ during 1981-2004 to 48.14 km³ during 2005-2020, representing a decline of approximately 10.3%. At Lao Cai station, the naturalized streamflow was 19.62 km³/year, whereas the observed streamflow was only 13.07 km³/year, indicating a difference of about 6.55 km³/year. The larger reduction in observed streamflow compared with naturalized streamflow suggests that, in addition to reduced precipitation, upstream reservoir regulation, inter-basin water diversion, and water usage may have contributed to changes in streamflow entering Viet Nam. The study demonstrates the applicability of the VIC-3L model for reconstructing naturalized streamflow and assessing transboundary water resources, providing a scientific basis for sustainable water resources management in the Red River Basin.*

Keywords: *VIC-3L, Red River basin, naturalized streamflow, transboundary water resources, streamflow variation.*

1. Introduction

The Red River Basin is one of the largest transboundary river systems in Southeast Asia, with approximately 48% of its catchment area located in China and a substantial proportion of runoff generated upstream before entering Viet Nam [1]. Water resources originating from the upstream basin are essential for socio-economic development, agricultural production, hydropower generation, and water security in Northern Viet Nam. However, increasing water abstraction, reservoir development, inter-basin water transfer projects, and climate variability have raised concerns about changes in water availability and transboundary flow regimes.

Previous studies have documented significant changes in streamflow across the upper Red River Basin. Li et al. (2008) analyzed hydrological characteristics in the Yuanjiang, Lixian, and Panlong river basins and showed that streamflow trends vary considerably among sub-basins because of differences in climate and topography [2]. Tran Thanh Xuan et al. (2012) quantified runoff contributions from the Chinese part of the basin and highlighted their importance to Viet Nam's water resources [1]. Ha Van Khoi and Vu Thi Minh Hue (2012)

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reported that cascade reservoirs constructed in Yunnan Province have altered flow regimes in the Da and Thao rivers since the late 2000s [3]. More recently, Do Huy Cuong et al. (2020) assessed the impacts of upstream water use and reservoir development on water resources in the transboundary Red River system [4]. These studies have provided valuable information on streamflow variability and water-resource changes in the basin.

Nevertheless, quantifying the amount of water that would naturally enter Viet Nam from the upstream basin remains challenging. Observed streamflow records reflect not only climatic variability but also the combined effects of reservoir operations, water withdrawals, and inter-basin water transfers. Consequently, observed discharge alone cannot fully represent the natural hydrological conditions of the transboundary tributaries entering Viet Nam.

Physically based hydrological models provide an effective approach for reconstructing naturalized streamflow under conditions where observations are affected by human activities. Among these models, the Variable Infiltration Capacity (VIC) model has been widely applied for water balance assessment, streamflow simulation, and hydrological studies in large river basins worldwide [5]. The VIC model has also been successfully applied in several river basins in Viet Nam, demonstrating its capability to reproduce streamflow under diverse hydro-climatic conditions.

Therefore, this study applies the VIC-3L hydrological model to reconstruct naturalized streamflow in the major transboundary tributaries of the Red River Basin entering Viet Nam during 1981-2020. The reconstructed naturalized streamflow is compared with observed discharge records to evaluate long-term changes in transboundary inflows and provide updated information on water resources originating from the upstream basin. The results contribute to the assessment of transboundary water resources and support water-resources planning and management in the Red River Basin.

2. Data and Methods

2.1. Study area

The Red River Basin is a transboundary river basin covering approximately 169,020 km² across Viet Nam, China, and Laos. The Chinese portion accounts for about 48% of the basin area, while Viet Nam and Laos occupy 51.35% and 0.65%, respectively. The basin is formed by three major tributaries, the Da, Thao, and Lo rivers, which converge at Viet Tri before discharging into the East Sea [1], [3], [4].

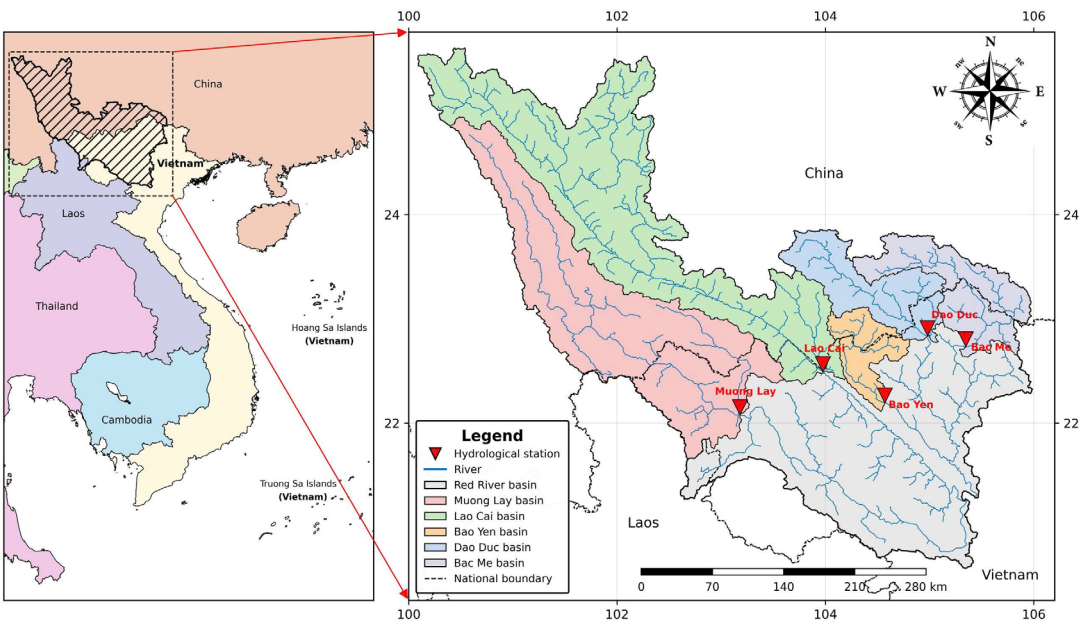


Figure 1. Map of the study area

This study focuses on the major transboundary tributaries flowing from China into Viet Nam, including the Da, Thao, Lo, and Gam rivers. Four hydrological stations were selected for streamflow reconstruction and model evaluation: Muong Lay (Da River), Lao Cai (Thao River), Dao Duc (Lo River), and Bac Me (Gam River) (Figure 1). These stations represent key control points for quantifying streamflow entering Viet Nam from the upstream basin.

The basin is characterized by steep mountainous terrain and a complex monsoon climate, resulting in pronounced spatial variability in precipitation and runoff. The long-term mean annual runoff of the basin is approximately 135 km³, of which about 38.9% originates from the Chinese part of the basin [1]. In recent decades, water resources in the upstream basin have been influenced by reservoir development, water withdrawals, and inter-basin water transfer projects. These factors, together with climatic variability, have contributed to changes in transboundary flow regimes entering Viet Nam.

2.2. VIC-3L hydrological model

The Variable Infiltration Capacity (VIC) model is a semi-distributed, physically based hydrological model widely used for streamflow simulation and water balance assessment in large river basins [5]. In this study, the VIC-3L version was employed to reconstruct naturalized streamflow in the major transboundary tributaries of the Red River Basin entering Viet Nam.

The VIC-3L model represents the soil profile using three layers corresponding to the surface layer, root zone, and deep soil layer. Gridded meteorological forcing data, including precipitation, air temperature, and wind speed, were used to drive the model. Simulated runoff and baseflow generated at each grid cell were subsequently routed through the river network to estimate streamflow at the selected control stations.

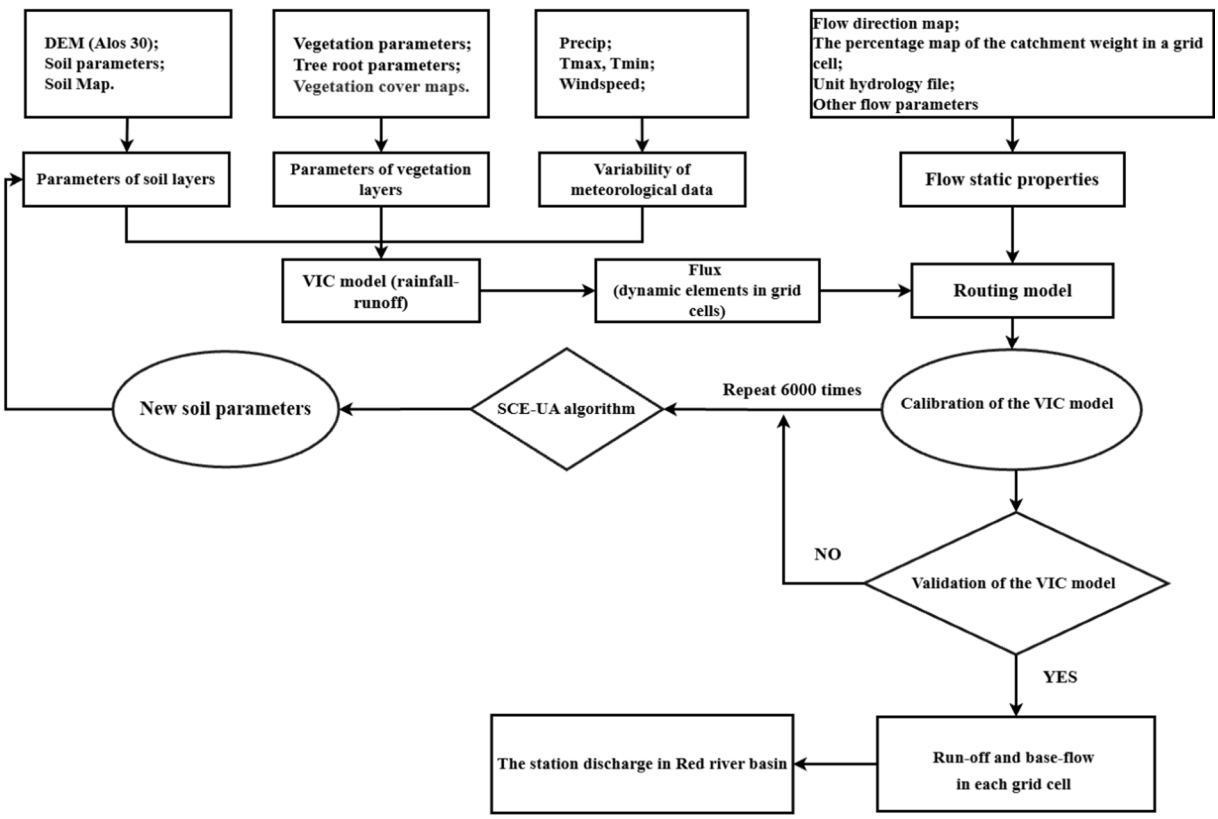


Figure 2. Workflow for reconstructing naturalized streamflow in the major transboundary tributaries of the Red River Basin

The model was calibrated and validated using observed streamflow records at the Muong Lay, Lao Cai, Dao Duc, and Bac Me hydrological stations. Model parameters were optimized using the Shuffled Complex Evolution algorithm (SCE-UA) [6,7]. The resulting simulations were used to reconstruct naturalized streamflow and evaluate long-term changes in transboundary inflows entering Viet Nam.

Figure 2 summarizes the modelling framework adopted in this study. The workflow consists of three main steps: (i) simulation of runoff and baseflow at the grid-cell scale using VIC-3L; (ii) routing of generated runoff through the river network to the control stations; and (iii) model calibration and validation using the SCE-UA optimization algorithm and statistical performance metrics [6], [7]. The final output is a continuous time series of reconstructed naturalized streamflow for the major tributaries entering Viet Nam.

2.3. VIC-3L model configuration

The VIC-3L model was configured for the major transboundary tributaries of the Red River Basin, including the Da, Thao, Lo, Gam, and Chay rivers. To facilitate hydrological simulation and runoff routing, the study area was divided into 17 relatively homogeneous zones based on hydrological stations, reservoir locations, and hydraulic control points.

The model was implemented at a spatial resolution of 0.05°. The Da River basin comprises 4,224 grid cells, of which 1,231 are active computational cells. The Thao River basin contains 5,330 grid cells with 1,502 active cells, while the Lo and Gam river basins contain 704 and 840 grid cells, respectively, corresponding to 356 and 384 active cells. The spatial configuration of the model domain is shown in Figure 3.

Meteorological forcing datasets, including precipitation, temperature, and wind speed, were combined with digital elevation, soil, and land-cover data to construct the model input files. Streamflow observations at the four control stations were used for model calibration and validation. Following model evaluation, the calibrated VIC-3L model was used to reconstruct naturalized streamflow throughout the period 1981-2020.

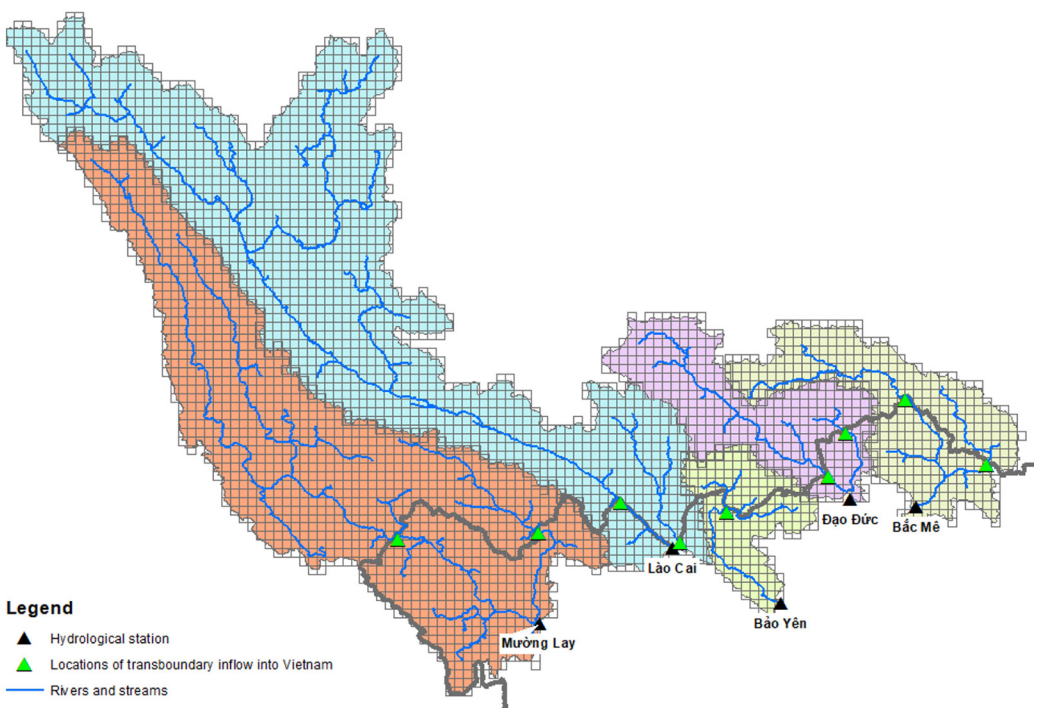


Figure 3. Spatial configuration of the VIC model for five major transboundary tributaries of the Red River Basin

2.4. Data

Meteorological, topographical, soil, land-cover, and hydrological datasets were used to configure, calibrate, and evaluate the VIC-3L model for the major transboundary tributaries of the Red River Basin. Gridded precipitation, air temperature, and wind speed data were used as meteorological forcing inputs, while digital elevation, soil, and land-cover datasets were used to define the physical characteristics of the model domain. Observed streamflow records at the selected hydrological stations were employed for model calibration and validation.

Table 1. Overview of datasets utilized in the setup and evaluation of the VIC-3L model[18]

Dataset	Time Period	Application Purpose	Source
Streamflow at Vietnamese Hydrological Stations	1981-2020	Model calibration, validation, and evaluation	Viet Nam Meteorological and Hydrological Administration
Viet Nam Gridded Precipitation	1981-2020	VIC model forcing input	Viet Nam Gridded Precipitation Dataset (VnGP) [8]
China Gridded Precipitation	1981-2020	VIC model forcing input	China Hydro-Meteorology dataset (CHM) Dataset (Beijing Normal University) [9]
Gridded wind speed, min/max temperature	1981-2020	VIC model forcing input	ECMWF - EU [10]
Digital Elevation Model (DEM)	-	VIC model configuration	ALOS30 [11]
Soil maps and properties	-	VIC model configuration	FAO [12]
Land use and land cover maps	1992-2020	VIC model configuration	Land Cover CCI Product User Guide Version 2 [13]

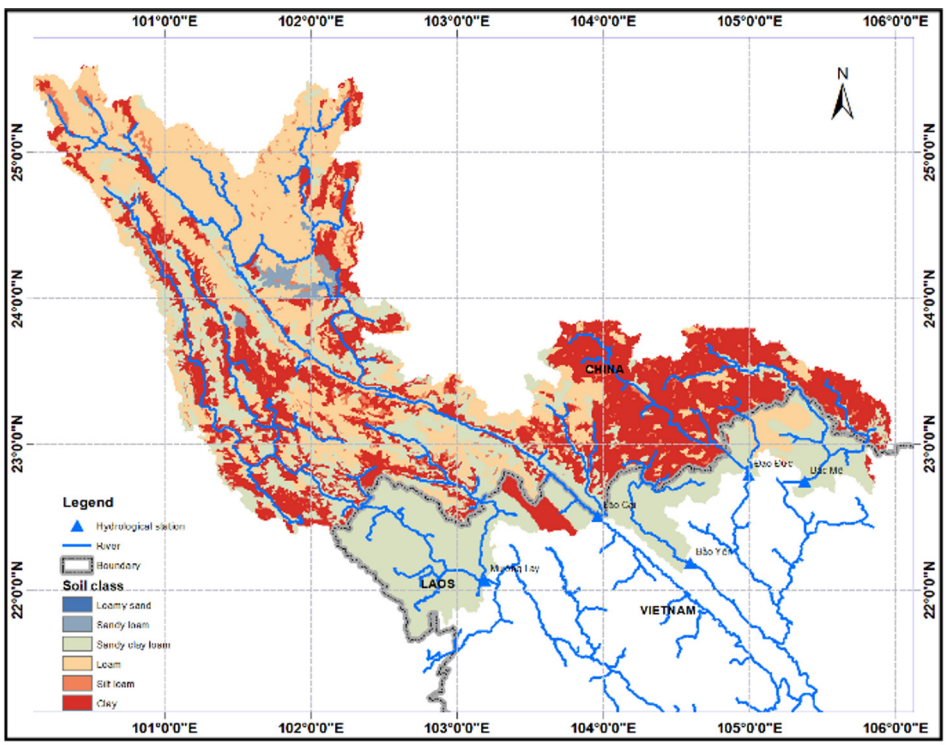


Figure 4. Soil map and properties used in the VIC-3L model setup

The datasets were selected to ensure spatial consistency and long-term temporal coverage throughout the study period (1981-2020), particularly for upstream catchments located outside Viet Nam where hydrometeorological observations are limited. Table 1 summarizes the datasets and their sources.

Figure 4 presents the soil map and soil properties used in the VIC-3L model configuration. Meteorological forcing data consisted of the Viet Nam Gridded Precipitation (VnGP) dataset, the China Hydro-Meteorology dataset (CHM), and gridded temperature and wind-speed data obtained from ECMWF. Basin characteristics were represented using the ALOS 30 m digital elevation model, FAO soil maps and associated soil properties, and ESA land-use and land-cover datasets. Streamflow observations at the Muong Lay, Lao Cai, Dao Duc, and Bac Me stations were obtained from the Viet Nam Meteorological and Hydrological Administration.

3. Results and Discussion

3.1. VIC model calibration and validation

The VIC-3L model satisfactorily reproduced monthly streamflow at the four control stations located on the major tributaries of the Red River Basin entering Viet Nam. Simulated hydrographs closely matched the observed seasonal flow regime, capturing wet-season peak flows, dry-season recession characteristics, and interannual variability, as illustrated by representative hydrographs at Lao Cai and Dao Duc stations (Figures 5 and 6).

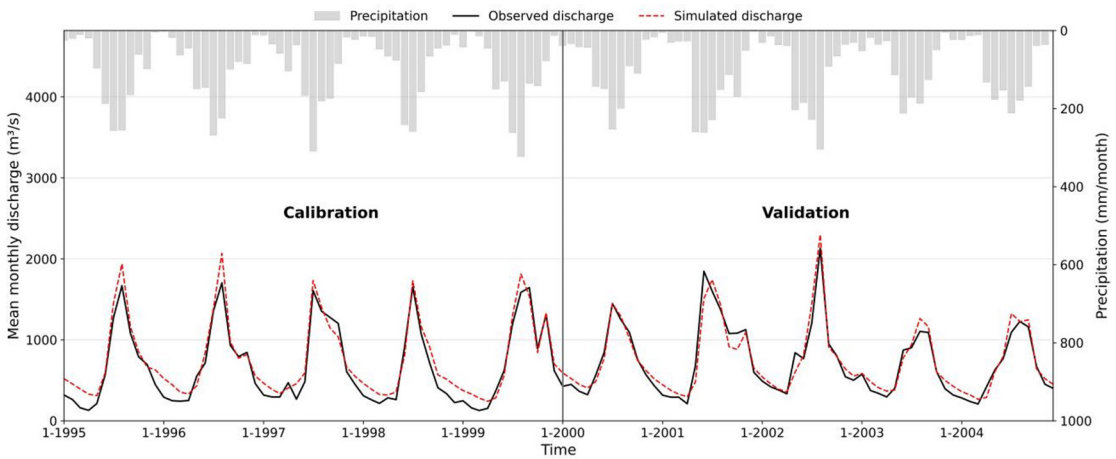


Figure 5. Simulated and observed mean monthly discharge at Lao Cai station

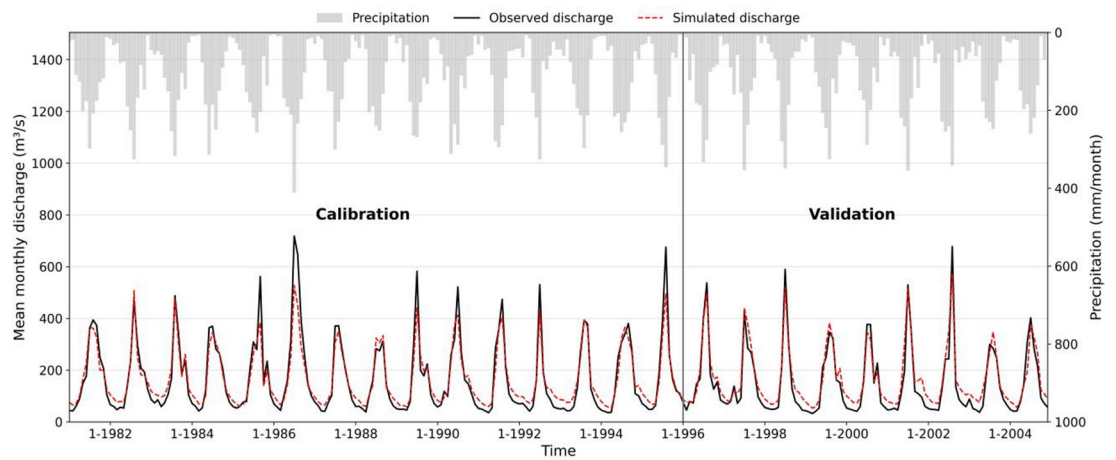


Figure 6. Simulated and observed mean monthly discharge at Dao Duc station

Table 2. Calibration and validation metrics of the VIC-3L model at control stations

Hydrological Station	Calibration				Validation			
	Period	NSE	R^2	Bias (m^3/s)	Period	NSE	R^2	Bias (m^3/s)
Muong Lay	1981-1995	0.918	0.926	17.054	1996-2004	0.925	0.934	-65.888
Lao Cai	1995-1999	0.914	0.949	89.153	2000-2004	0.934	0.938	25.738
Dao Duc	1981-1995	0.907	0.943	1.873	1996-2004	0.908	0.939	20.448
Bac Me (Simulated)	1997-2000	0.712	0.933	112.640	2001-2004	0.742	0.95	112.378
Bac Me (Adjusted)	1997-2000	0.931	0.933	0.908	2001-2004	0.949	0.95	0.946

Model performance statistics are summarized in Table 2. At Muong Lay, Lao Cai, and Dao Duc stations, calibration NSE values ranged from 0.907 to 0.918, while validation NSE values ranged from 0.908 to 0.934. Corresponding R^2 values exceeded 0.92 during both calibration and validation periods, indicating strong agreement between simulated and observed streamflow.

Initially, model performance at Bac Me station was lower than at the other study stations, with NSE values of 0.712 and 0.742 during the calibration and validation periods, respectively. This is likely associated with the well-developed karst system in the Gam River Basin [19], where complex infiltration processes, surface water-groundwater exchanges, and subsurface water losses play an important role. These processes are not explicitly represented in the VIC-3L model, which may contribute to the relatively lower simulation performance. Following parameter calibration, the NSE values increased to 0.931 and 0.949, respectively, while the Bias was substantially reduced, demonstrating a significant improvement in simulation accuracy.

Overall, the VIC-3L model demonstrated robust and consistent performance across the study area. The achieved NSE and R^2 values are comparable to, and in several cases higher than, those reported in previous VIC and HEC-HMS applications in the Red River Basin [15-17]. These results provide confidence in the reconstructed naturalized streamflow used for subsequent analyses of transboundary water resources.

Table 3. VIC model calibration parameters

No.	Parameter	Lixian River	Yuanjiang River	Panlong River	
				Lo river	Gam river
1	bin	0.3151	0.002356	0.054973	0.038563
2	Ds	0.7065	0.1014	0.080374	0.090474
3	Dsmax	27.1525	23.37628	27.9623	29.16091
4	Ws	0.7170	0.906078	0.808518	0.97494
5	D 1	0.3	0.292541	0.296788	0.247116
6	D 2	0.3242	1.485837	1.499957	1.160419
7	D 3	1.4995	0.778616	0.818899	0.9262
8	Velocity	1.2	1.979848	2.344727	2.103492
9	DIFF	800	800	800	2573.16
10	XMASK	12500	12500	12500	24320.95

3.2. Changes in runoff generated from upstream Chinese catchments

To investigate long-term changes in water resources originating from the Chinese headwaters, the study period was divided into two phases: 1981-2004 and 2005-2020. This division is consistent with previous assessments of hydrological changes in the upper Red River Basin and allows comparison between periods before and after major developments in the upstream basin [14].

The estimated mean annual runoff generated from the Yuanjiang, Lixian, and Panlong river basins is presented in Table 4. The results indicate a consistent decline in runoff across all three upstream catchments during the latter period. Total annual runoff decreased from 53.67 km^3 during 1981-2004 to 48.14 km^3 during 2005-2020, corresponding to a reduction of 5.53 km^3 (10.3%).

Among the three catchments, the Lixian River contributed the largest volume of runoff to the transboundary system. Mean annual runoff decreased from 24.98 to 22.43 km^3, representing a reduction of 2.55 km^3 (10.2%). The Yuanjiang River exhibited the largest relative decline, with runoff decreasing from 20.44 to 17.76 km^3, equivalent to a reduction of 2.68 km^3 (13.1%). In contrast, the Panlong River showed a smaller reduction, declining from 8.25 to 7.95 km^3 (3.6%).

The estimated runoff volumes are generally consistent with values reported by Tran Thanh Xuan et al. (2012), Li et al. (2008), and Do Huy Cuong et al. (2020), despite differences in study periods and methodologies. In particular, the estimated total runoff during 2005-2020 (48.14 km^3/year) is close to the values reported by Tran Thanh Xuan et al. (2012) (48.80 km^3/year) and Do Huy Cuong et al. (2020) (47.14 km^3/year). These results provide additional confidence in the reconstructed naturalized runoff and indicate a persistent decline in water resources generated from the Chinese headwaters of the Red River Basin during recent decades.

Table 4. Mean annual total runoff from upstream sub-basins into Viet Nam and comparative analysis with previous studies (km3/year)

River Basin	Simulated Results (this study)		Tran Thanh Xuan (2012)	Do Huy Cuong (2020)	Li (2008)
	1981-2004	2005-2020	1960-2009	1956-2017	1956-2000
Yuanjiang River	20.44	17.76	15.8	14.9	14.61
Lixian River	24.98	22.43	24.1	22.84	22.27
Panlong River	8.25	7.95	8.9	9.4	8.03
Total Volume	53.67	48.14	48.80	47.14	44.91

3.3. Comparison between naturalized and observed runoff

Figure 7 compares naturalized runoff, observed runoff, and basin-average precipitation at annual, rainy-season, and dry-season scales for the four transboundary catchments during the two study periods. Overall, basin-average precipitation and naturalized runoff decreased consistently across all catchments during 2005-2020 relative to 1981-2004, reflecting the influence of climatic variability. However, the magnitude of change in observed runoff differed substantially among catchments and between seasons, indicating varying degrees of anthropogenic regulation in the upstream basins.

At the annual scale, the Da River catchment upstream of Muong Lay station showed only minor differences between naturalized and observed runoff. Basin-average annual precipitation decreased from 1,691 to 1,616 mm, while naturalized runoff declined from 36.52 to 33.23 km^3 and observed runoff from 36.98 to 34.16 km^3. The close agreement between the two runoff series suggests that streamflow variability was largely controlled by climatic conditions. In contrast, the Thao River catchment upstream of Lao Cai station exhibited the largest divergence.

Although basin-average annual precipitation decreased by only 8.7% (from 1,122 to 1,024 mm), naturalized runoff declined by 13.3%, whereas observed runoff decreased by 40.7%, from 22.03 to 13.07 km³. Consequently, the difference between naturalized and observed runoff increased from 0.59 km³ during 1995-2004 to 6.55 km³ during 2005-2020, indicating that factors beyond precipitation variability, such as upstream reservoir regulation and water abstraction, substantially altered streamflow entering Viet Nam. The Lo River catchment upstream of Dao Duc station displayed a similar but less pronounced pattern, while the Gam River catchment upstream of Bac Me station experienced only a slight reduction in observed runoff despite decreases in precipitation and naturalized runoff, suggesting a different hydrological response to upstream regulation.

At the rainy-season scale, reductions in basin-average precipitation were accompanied by decreases in naturalized runoff in all four catchments. However, observed runoff declined more rapidly than naturalized runoff in the Thao and Lo rivers. At Lao Cai, rainy-season observed runoff decreased from 14.63 to 9.02 km³, compared with a reduction in naturalized runoff from 14.17 to 12.07 km³, indicating that most of the annual reduction in streamflow occurred during the wet season. A similar but weaker response was observed at Dao Duc, where observed runoff declined from 3.72 to 2.75 km³, while naturalized runoff decreased only from 3.58 to 3.27 km³. In contrast, the differences between naturalized and observed runoff remained relatively small at Muong Lay and Bac Me, implying comparatively limited human alteration of wet-season flows.

The dry-season results reveal contrasting hydrological responses among the catchments. At Muong Lay, dry-season precipitation increased slightly (from 380 to 398 mm), and observed runoff increased from 8.70 to 10.74 km³, despite a small decline in naturalized runoff, suggesting that upstream reservoir operation may have enhanced dry-season releases. A similar increase in observed dry-season runoff was found at Bac Me, where observed runoff increased from 1.32 to 1.66 km³, while naturalized runoff remained nearly unchanged (2.75 to 2.69 km³). In contrast, the Thao River experienced substantial reductions in both naturalized and observed dry-season runoff, with observed runoff decreasing from 7.40 to 4.05 km³, considerably exceeding the decline expected from precipitation changes alone.

Overall, the seasonal analysis demonstrates that the impacts of upstream human activities are not uniformly distributed throughout the year. The largest divergence between naturalized and observed runoff occurs in the Thao River, particularly during the rainy season, whereas the Da and Gam rivers exhibit evidence of enhanced dry-season flows, consistent with reservoir regulation that redistributes runoff from the wet season to the dry season rather than simply reducing annual water availability. This seasonal contrast cannot be identified from annual statistics alone and provides additional evidence of the differing hydrological effects of upstream water regulation among the transboundary catchments.

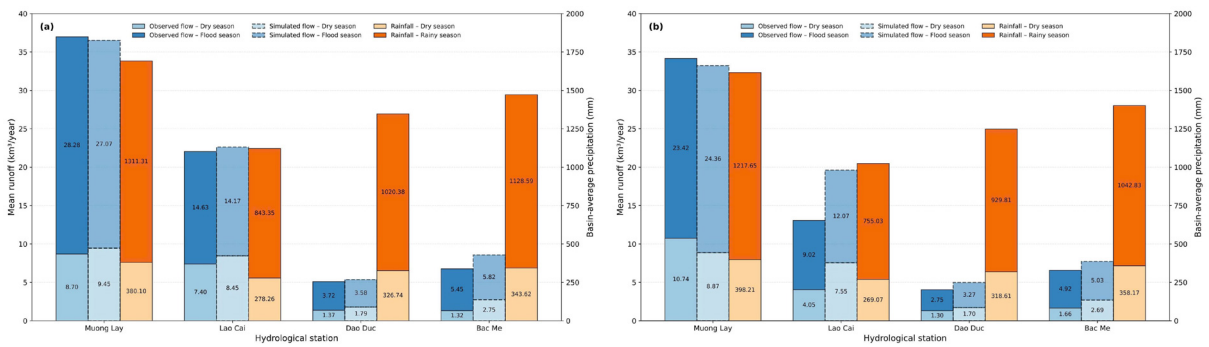


Figure 7. Comparison of naturalized runoff, observed runoff, and basin-average annual precipitation during the two study periods

4. Conclusion

This study applied the VIC-3L hydrological model to reconstruct naturalized streamflow and quantify transboundary water resources entering Viet Nam from the upper Red River Basin during 1981-2020. Model calibration and validation results demonstrated satisfactory performance at the selected control stations, with NSE values generally exceeding 0.90, providing confidence in the reconstructed naturalized runoff used for subsequent analyses.

The results indicate a decline in water resources generated from the Chinese headwaters of the Red River Basin during recent decades. Total annual runoff from the Yuanjiang, Lixian, and Panlong river basins decreased from 53.67 km^3 during 1981-2004 to 48.14 km^3 during 2005-2020, representing a reduction of approximately 10.3%. Among the three catchments, the Yuanjiang River exhibited the largest relative decline (13.1%), followed by the Lixian River (10.2%) and the Panlong River (3.6%). These results are generally consistent with previous studies and suggest a reduction in naturally available water resources entering Viet Nam.

A key finding of this study is the increasing divergence between naturalized and observed runoff at several transboundary control stations, particularly at Lao Cai on the Thao River. During 2005-2020, naturalized runoff at Lao Cai averaged 19.62 km^3/year, whereas observed runoff averaged only 13.07 km^3/year, resulting in a difference of 6.55 km^3/year. Observed runoff was therefore approximately 33.4% lower than the estimated naturalized runoff. This discrepancy was substantially larger than that observed during the earlier period and suggests that streamflow changes at the Viet Nam-China border cannot be fully explained by precipitation variability alone.

The observed divergence between naturalized and measured runoff may reflect the combined influence of upstream reservoir regulation, inter-basin water transfers, water withdrawals, and other human activities in addition to climatic variability. However, quantifying the relative contribution of these factors requires further investigation using dedicated attribution approaches and additional information on upstream water-resource development and operation.

The proposed modelling framework provides a practical approach for reconstructing naturalized streamflow and assessing transboundary water resources in data-scarce river basins. The results contribute to improved understanding of hydrological changes in the upper Red River Basin and provide scientific information to support water-resources assessment, drought monitoring, and transboundary water-management planning in Viet Nam.

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Conflicts of Interest: *The authors declare no conflicts of interest regarding the publication of this paper.*

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