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Quantifying the impacts of hydraulic infrastructure on tropical streamflows

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Abstract

Hydraulic infrastructures, such as reservoirs and water diversion channels, cause altered streamflow worldwide. Therefore, this study aimed to assess the coupled impacts of reservoir operations and water transfer on downstream streamflow over 42 years (1979–2020) for a tropical river in Vietnam, the Vu Gia Thu Bon (VGTB). We also quantified variations in the multi-sub-basin contributions to the water budget associated with hydraulic structure development. Therefore, a semi-distributed hydrological model, SWAT (Soil and Water Assessment Tool), was developed for the entire VGTB basin considering two plausible scenarios: with a dam and without a dam. In this study, reservoirs substantially affected the streamflow during the 2011–2020 period when 12 cascading hydropower dams were constructed in the Vu Gia sub-basins. The cascading reservoirs across the Vu Gia River reduced the annual average streamflow by 28.1% during this period, whereas their influence was augmented by 13.9% at reaches further downstream. In contrast, the local reservoir and flow diversions created on the Thu Bon River resulted in a 6.5% increase in streamflow. The upstream reservoir operation significantly increased streamflow at the mid-stream stations by 27.8% compared to the no-dam period. The streamflow decreased in the dry season by 5.6% in the Vu Gia sub-basins and increased by 61.7% in the Thu Bon sub-basins. However, the impacts decreased in the wet season by 41.3% due to the operation of reservoirs, in which Dak Mi 4 had the most significant influence. It was found that the water diverted to the Thu Bon River was governed and reduced by the cascading hydropower dams. Therefore, the operation of 11 reservoirs has partially compensated for the lost water in the Vu Gia sub-basins, to which the Dak Mi 4 plant has transferred 19.7 m^3/s (14%). Our findings classify the impact of cascading dams and diversion structures and their interaction with climate change.

KEYWORDS

reservoir, SWAT, tropical streamflow, tropics, Vu Gia Thu Bon River basin, water diversion

1 | INTRODUCTION

Hydrological cycles within river basins play a key role worldwide, providing streamflow to downstream deltaic systems (Oki & Kanae, 2006; Tran, Nguyen, Vo, et al., 2023). The duration and intensity of streamflow depend fundamentally on climatic variables, such as precipitation (Ahn & Merwade, 2014; Souvignet et al., 2014) and on the operation of basin-wide infrastructures such as hydropower dams, storage reservoirs, and water diversion structures (Ribbe et al., 2017). Most rivers worldwide are interrupted by dammed reservoirs (Zhou et al., 2016). The increase in reservoir construction has occurred particularly in regions with emerging economies, such as Southeast Asia (SEA), for flood control, irrigation, drinking water, hydropower generation, and hydrological hazard control in tropical river basins with complex climate characteristics (Zarfl et al., 2015). However, despite their benefits, reservoirs remain controversial due to their potentially negative impacts by altering the natural flow regime (Binh, Kantoush, & Sumi, 2020; Mittal et al., 2016). Furthermore, hydrological extremes can be intensified by ineffective management of reservoir water, which can sometimes have an impact greater than climate change (Di Baldassarre et al., 2018; Vu et al., 2017). Therefore, there is a need to evaluate the effects of reservoir operations on streamflow in specific multi-basin catchments.

The Vu Gia Thu Bon River (VGTB) basin in Central Vietnam and its water resources have been developed for various purposes, including energy, agriculture, flood mitigation, water supply, and saltwater intrusion control (Firoz et al., 2018; Ribbe et al., 2017; Viet, 2014). However, the basin faces challenges in securing water supply and mitigating severe flooding due to climate change and the rapid development of artificial hydro-structures (B. Q. Nguyen et al., 2023). Since 2007, 18 hydropower dams have been built, of which 12 are on the Vu Gia River, 6 are in the Thu Bon River, and a diversion channel carries water and sediment from the Vu Gia to the Thu Bon River (Figure 1a). Four large reservoirs, namely A Vuong, Song Bung 4, Dak Mi 4, and Song Tranh 2, have the greatest influence on the effectiveness of downstream flood control (T. H. Nguyen, 2020). The number of dams is projected to reach 58 by 2030 (ICEM, 2008). These cascaded reservoirs can alter the hydrological regime of rivers by changing seasonal flow (Ngo et al., 2018). Adaptations to the hydrological system often negatively affect seasonal downstream discharge (e.g., flood, drought, salinity intrusion, etc.). Firoz et al. (2018) observed the seasonal change in drought occurrences, from spring to summer, at most stations on the VGTB River. The downstream saltwater intrusion responds rapidly to changes in reservoir operation. The length of saltwater intrusion varies according to the alterations of the flow regime upstream and the tides. Therefore, addressing the complex interactions between reservoir operations and natural hydrological processes is essential for better water resources and environmental management.

Various approaches have been used to examine and quantify the effects of hydraulic infrastructure on runoff. Popular methods include streamflow time-series studies that look at monthly, seasonal, annual, and frequency changes to determine the anthropogenic effects on streamflow (Binh, Kantoush, Saber, et al., 2020; Binh, Kantoush, & Sumi, 2020; Y. Zhang et al., 2018) and relationships between runoff and climate variables (Johnson et al., 1991; D. Wang & Hejazi, 2011; H. Wang et al., 2016). The fundamental analysis of the hydro-climatic time series can provide the first insight into hydrological systems. However, they may be incapable of capturing the nonlinear nature of hydrological systems (Firoz et al., 2018). Another popular method is the use of hydrological models for hydrological reconstruction using models and is helpful for studying changes in water resources (Sorooshian et al., 2008). Hydrological models are advantageous because they can simulate scenarios with and without dams and extract the results at various stream locations, where it is possible to evaluate a group of cascading dams separately. The combination of

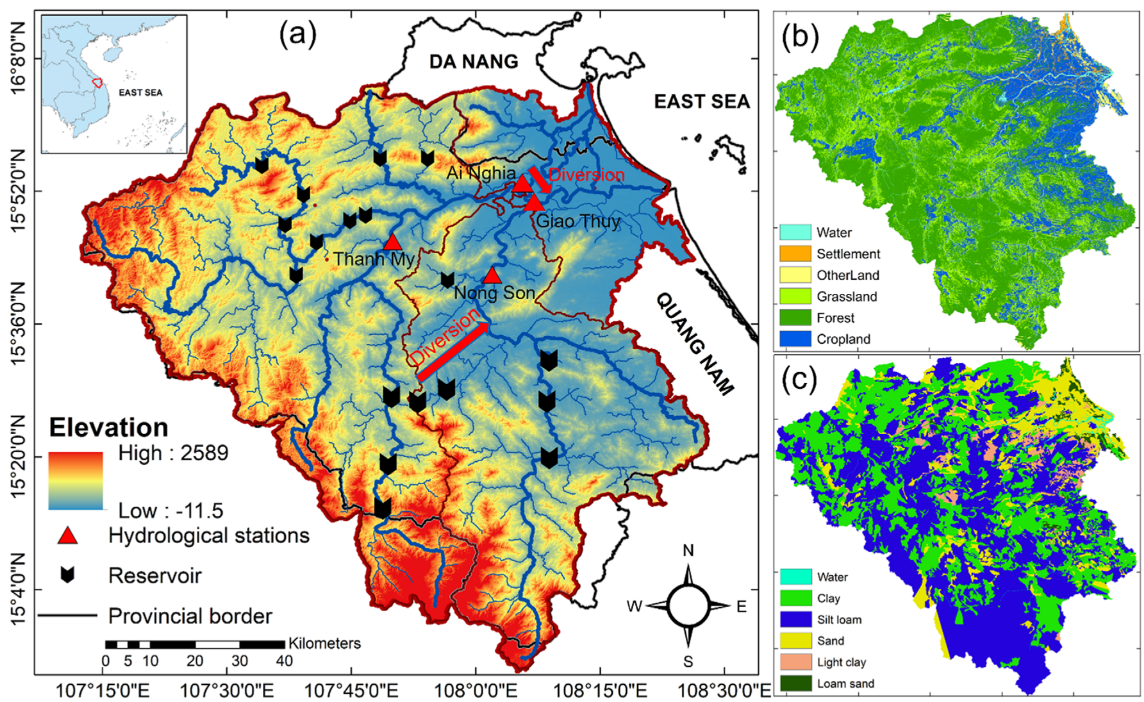

FIGURE 1 (a) Spatial coverage of the VGTB River basin. Locations of meteorological and hydrological stations and dams. (b) Land use map, and (c) soil map collected from the Lucci project.

hydrological models, water diversion, and reservoir operation is a promising method used in this study. A semi-distributive hydrological model, SWAT, can simulate the hydrological characteristics of the basin integrated with the basic reservoir operation (Carvalho-Santos et al., 2017; Chhuon et al., 2016; Loi et al., 2019; L. H. Nguyen & Fukushi, 2019; Shrestha et al., 2018; Tran, Nguyen, Zhang, et al., 2023; Vale & Holman, 2009; G. Wang & Xia, 2010). The advanced model incorporates a hydrological, reservoir operation, and water diversions module. Therefore, we can quantify the contribution of each group of dams on downstream flow alterations and the contribution of each sub-basin to the downstream flow discharge with a high confidence level.

Several studies have adopted numerical models to investigate the hydrological regimes of basins. However, previous studies have not considered the combination of reservoir operation and diversion and have only used short study periods (Firoz et al., 2018; Loi et al., 2019; Nauditt et al., 2017; H. T. Nguyen et al., 2020; Vu et al., 2017). Firoz et al. (2018) quantified the effects of only 8 of the 18 dams for 5 years after the beginning of their operation. This means that the impact of newly built dams has not been studied for a longer period. The authors used two models to establish the VGTB basin during 1980–2013. Just Another Modelling System (JAMS)/J2000 was used to simulate the basin streamflow and HEC-ResSim was used to simulate the operations of eight reservoirs and to reconstruct the streamflow for the main rivers. Furthermore, these studies did not combine the hydrological module with the reservoir operation module; instead, they simulated them separately. Using two models for a watershed may lead to discontinuous simulation and other possible errors. Therefore, it is impossible to properly capture the impact of all reservoirs on basin flow. Many other researchers (e.g., Loi et al., 2019 used SWAT; H. T. Nguyen et al., 2020 used HEC-RAS; Vu et al., 2017 used MIKE SHE) have not considered reservoir operations in their models to forecast flow and floods in the basin. Therefore, these studies could not correctly capture the impact of reservoir operation on streamflow.

Another issue is that only two stations (Thanh My on the Vu Gia sub-basins and Nong Son on the Thu Bon sub-basins) monitor discharge. Previous studies which analysed historical data at these two stations, could not reveal dam impacts on streamflow; thus, a more advanced methodology was required (Loi et al., 2019; Vu et al., 2017). Another knowledge gap is that previous studies have not quantified the contribution of each sub-basin and the diversion channel's role in the hydrological processes of the VGTB basin. Therefore, this study aims to fill these knowledge gaps by assessing changes in streamflow at multiple spatial locations (i.e., upstream, midstream, and downstream) of different groups of cascading dams (18 dams) and quantifying the effect of the diversion channel. We will quantify the effects of hydraulic infrastructures by comparing the basin's natural and anthropogenic streamflow, distinguish the effects of major reservoir operations on downstream flow, and quantify the flow contribution of the sub-basins to 2020 by the SWAT model, which were not adequately understood before. These primary findings presented a good approach for understanding the comprehensive cascading reservoir and inter-basin water diversion.

The main objective of this study was to quantify the coupled impacts of reservoir operation and water transfer on streamflow and water balance in the VGTB basin at various locations. The hydrological semi-distributed model was selected to simulate the streamflow from 1979 to 2020 and the effects of cascading hydraulic structures. The principal research aims were to: (1) model the basin's natural streamflow, (2) quantify the effects of hydraulic infrastructures, (3) distinguish the effects of four major reservoir operations on downstream flow, and (4) quantify the flow contribution of the sub-basins. The findings of this study will provide a detailed understanding of the effects of hydraulic infrastructures, such as hydropower reservoirs and water diversion structures on downstream flow. Our findings provide a comprehensive approach to quantifying the impact of cascading dams and diversion structures and distinguish their impacts from those of the effect of climate change. Furthermore, the insights gained from the effects of the hydraulic infrastructure of this basin can help water managers in Vietnam and other tropical monsoon regions.

2 | STUDY AREA

The VGTB River basin (approximately 10 350 km^2) is in the central region of Vietnam and represents approximately 2.5% of the total water volume in Vietnam (RETA, 2011) (Figure 1a). The topography of the VGTB basin is varied. From west to east, it changes from high mountains to undulating hills, with a slope of 20%–30%. Altitude, steep terrain, and significant rainfall provide great potential for hydropower energy in the upstream part of the basin. The primary land cover is forest (62.05%), and the predominant soil type is clay and silt loam (accounting for 83.33%) (Figure 1b,c). Agriculture is an important economic activity in the basin. Paddy rice is the most important agricultural crop, comprising approximately 70% of irrigated agriculture (Viet, 2014).

The characteristics of the sub-basins are shown in Figure 2a and Table 1. There are five main sub-basins from the headwater to the Ai Nghia station in the Vu Gia River (Con, A Vuong, Bung, Giang, and Dak Mi Rivers). From upstream to the Giao Thuy station in the Thu Bon River, there are also five major sub-basins (the Khe Dien River, Que Lam River, Truong River, Tranh River, and Khang River). In the VGTB basin, the inter-basin water diversion from the Vu Gia to the Thu Bon River occurs in both the upstream and downstream sections through the Dak Mi 4 plant and the Quang Hue channel, respectively (Figure 1a).

Data obtained over 42 years (1979–2020) show that the average annual rainfall of the entire basin is 2863 mm, varying significantly from 2184 mm in the lowlands to over 4188 mm in the southern mountainous areas (Figure 2a). Precipitation varies by season, with 48 to 81% of annual rainfall concentrated between September and December. The average temperature of the basin is 25.2°C, with the lowest temperatures in December or January and the highest in June and July (B. Q. Nguyen et al., 2022) (Figure 2b). The streamflow varied considerably between seasons, and the flood season from October to December corresponded to the heaviest rainy period. The flow in this

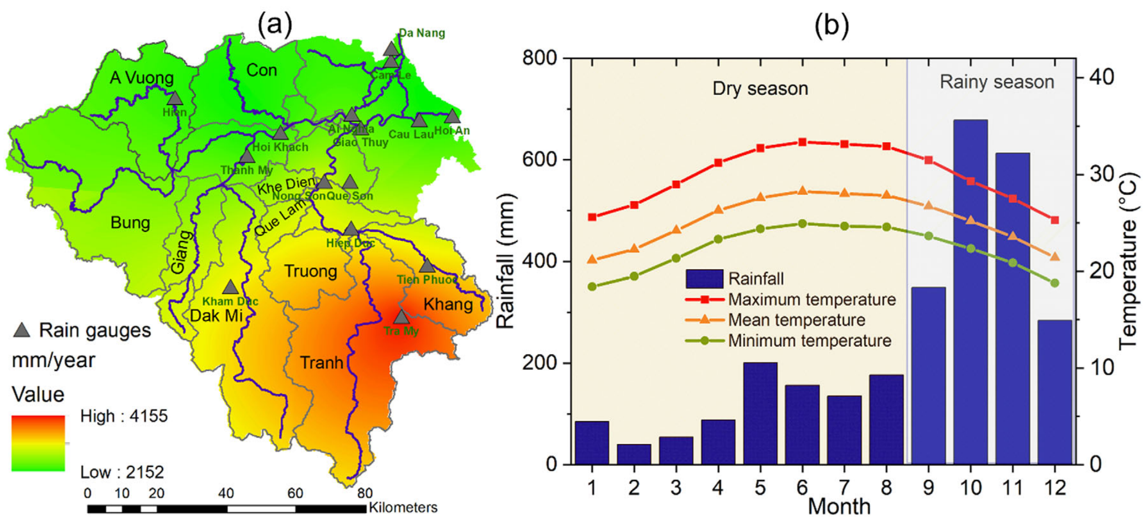

FIGURE 2 (a) Sub-basins and spatial variations of rainfall from 1979 to 2020 in the VGTB basin. Data interpolated from 15 rain gauges according to the Kriging method on ArcGIS 10.4. (b) Average monthly rainfall, minimum temperature average temperature, and maximum temperature of the VGTB basin.

TABLE 1 Characteristics of the sub-basins on the Vu Gia and Thu Bon rivers.

Basin	Sub-basin	Catchment area (km^2)	Percentage area, compared to Ai Nghia station (%)	Percentage area, compared to Giao Thuy station (%)	Reservoir
Vu Gia	Con River	634.5	11.94		2
	A Vuong River	769.4	14.48		3
	Bung River	1462	27.52		4
	Giang River	490.6	9.24		-
	Dak Mi River	1394	26.24		3
Thu Bon	Khe Dien River	135.8		3.86	1
	Que Lam River	131.9		3.75	-
	Truong River	430.9		12.26	2
	Tranh River	1649		46.90	3
	Khang River	584.8		16.63	-

period accounted for approximately 62.5% to 69.2% of the total annual flow. April is the driest month, accounting for only 2% to 3% of annual flow (RETA, 2011).

3 | METHODOLOGY AND MATERIAL

3.1 | SWAT model

The SWAT model was developed by Arnold and Srinivasan, researchers of the United States Department of Agriculture Research Service (USDA-ARS) and Texas AgriLife Research, respectively. It comprises a comprehensive computer simulation tool for watershed-scale studies that integrates multiple components, such as climate, hydrology, land cover, reservoir operation, and management practices (Arnold et al., 1998; Keitzer et al., 2016). The model divides the watershed into sub-basins. These sub-basins are further subdivided into soil characteristics, and the land use and slope units are known as hydrological response units (HRUs). The SWAT model was integrated with the GIS software. The model comes in many versions, such as ArcSWAT, MWSWAT, and QSWAT. For this study, SWAT version 1.9 was used with QGIS 2.6.1.

3.2 | Input data

Data plays a crucial role in hydrological models. We collected streamflow, rainfall, temperature, topography, land use, soil map, and dam data in the entire VGTB basin to establish, calibrate, and validate the SWAT model.

3.2.1 | Streamflow

Daily streamflow data at Thanh My and Nong Son stations during 1979 to 2020 were used to calibrate and validate the results of the SWAT model (Figure 1a). Data were collected from the Mid-Central Regional Hydro-Meteorological Center (MCRHMC, 2022). The monthly discharge volume released from the reservoirs from 2017 to 2020 was collected from the Natural Disaster Prevention and Control of Quang Nam Province (NDPAC, n.d.).

3.2.2 | Meteorology

We collected daily rainfall data from 15 stations distributed throughout the VGTB basin from 1979 to 2020, including 9 stations in mountainous areas and 7 stations in lowland areas. Daily temperature data were collected at 2 stations, Da Nang (lowland area) and Tra My (mountain region) (Figure 2a).

3.2.3 | Topography

In this study, topographic data (DEM) benefitted from the 'Land Use and Climate Change Interaction in Central Vietnam' (Lucci) project (www.lucci-vietnam.info), using a 30 m × 30 m spatial resolution (Figure 1a). The DEM was created by combining Shuttle Radar Topography Mission (SRTM) data and isolines (ISO 19115:2003 for geographic information metadata). The DEM map was formatted as a Type A spatial representation grid and coordinate system Universal Transverse Mercator (UTM) zone 48 N with a reference date of 2014.

3.2.4 | Land use and soil map

Land use and soil map data were also collected from the Lucci project with a resolution of 30 m × 30 m (Figure 1b,c). Land use was created based on Landsat images, SPOT images, and field survey data. The soil map was digitized using the National Institute of Agriculture Planning and Protection (NIAPP). The dataset reference dates for land use and soil maps were obtained in 2013 and 2011, respectively.

3.2.5 | Dams

Eighteen reservoirs in the SWAT model were collected from Decision 1865/QD-TTg: Procedures for operating reservoir systems in the VGTB River basin (Government of Vietnam, 2019). The characteristics of the dams (volume, year of construction, water release, and operating rules) were collected from the Natural Disaster Prevention and Control of Quang Nam Province and are shown in Table 2 (NDPAC, n.d.).

3.3 | Simulation scenarios

We evaluated the long-term alteration of streamflow in the VGTB basin over 42 years by analysing observational data, as well as related factors such as reservoir operation, rainfall, and land use. In this study, the flow alterations depended mainly on the operation of the reservoir and water transfer. Therefore, this study evaluated the operation of the reservoir and water transfer effects on streamflow. The model was simulated for two scenarios during the 42 years of 1979–2020, and emphasized the period 2011–2020 when large reservoirs started operating and had a significant impact on the downstream (Table 2): (a) without-dam and (b) with-dam. The model parameters were equal for both scenarios. The reservoir component was inactivated when simulating the flow under natural conditions (without-dam).

All reservoirs were considered in the study, and the impacts of the largest reservoirs (A Vuong, Song Bung 4, Dak Mi 4, Song Tranh 2) were evaluated. Each reservoir was independently established and released (the other reservoirs were inactive). The flow contribution rates of the sub-basins were evaluated in two cases: with and without-dam.

3.4 | Model setup

The basin was divided into 153 sub-basins and 2580 HRUs. The sub-basins were divided based on slope classes (0–5, 5–10, 10–20, 20–30, and >30°), six land classes (Figure 1b), six soil classes (Figure 1c), locations of hydrological stations and dams, water transfer and receiving sites, and uniform size distribution between sub-basins. The water transferred from the Vu Gia sub-basins to the Thu Bon sub-basins through the Dak Mi 4 plant and Quang Hue channel was also established. The transfer via Dak Mi 4 was determined for each month as the average daily value (WURESN, the average amount of water withdrawn from the reservoir each day in the month for consumptive water 10^4 m^3). Downstream, the water transferred by the Quang Hue channel was determined for each month as the average daily water (WURCH—average daily water removal from the reach for the month 10^4 m^3/day). From field surveys and other data, the percentage of runoff transferred to the Thu Bon River from 1979 to 2000 and from 2001 to 2020 was 13% and 43%, respectively.

3.5 | Calibration and validation processes

The model was simulated during the period 1979–2020. The year 1979 was used to warm up the model. The calibration period was 1980–1995, whereas two periods were used to validate the model;

TABLE 2 Profile of 18 hydropower dams in the VGTB River basin (Government of Vietnam, 2019; ICEM, 2008; MOIT, 2015).

Name	Catchment area	Dam height	Dead water level (DWL)	Normal water level (NWL)	Flood design water level (FWL)	Total storage	Active storage	Dead storage	Turbine dis-charge	Capacity	First year of operation
Unit	km^2	m	m	m	m	10^6 m^3	10^6 m^3	10^6 m^3	m^3/s	MW	Year
A Vuong	682	80	340	380	382.2	343.55	266.48	77.07	78.4	210	2008
A Vuong 3	258.4	22.9	551.6	552.5	559.45	2.94	0.44	2.5	22.7	1.04	2016
Song Tranh 2	1100	96	140	175	178.51	729.2	521.1	208.1	245	190	2011
Song Tranh 3	1450	36.5	70.5	71.5	75.9	34.1	3.1	31	301.6	62	2013
Song Tranh 4	1610	25	45.5	46.5	-	24.81	3.32	21.49	298	48	2020
Dak Mi 2	445	30	624	630	635.19	1.611	0.692	0.919	44.36	98	2019
Dak Mi 3	612	30	353	359	363.96	5	2.304	2.696	76	63	2017
Dak Mi 4	1125	90	240	258	260.33	312.38	158.26	154.12	128	148	2011
Dak Mi 4B	29	23.5	105	105.3	107.28	0.688	0.066	0.622	130	42	2012
Dak Mi 4C	82.6	11.5	66.2	67.2	68.86	2.67	0.52	2.15	140	18	2012
Song Bung 4	1448	114	205	222.5	228.11	510.8	233.99	276.81	166	156	2015
Song Bung 4A	2276	46	95.4	97.4	99.95	10.6	1.58	9.02	166.4	49	2012
Song Bung 5	2369	41.5	58.5	60	64	20.27	2.45	17.82	239.24	57	2013
Song Bung 6	2386	39.2	31.8	31.8	45.89	3.29	0	3.29	239.8	29	2012
Za Hung	537	25	445	450	457.27	1.12	0.74	0.38	53.4	30	2009
Khe Dien	72	41	187.4	206.94	211.78	50.98	50.35	0.63	11.3	9	2007
Song Con 2	81	48	319	340	345.68	29.19	25.41	3.78	9.7	3	2009
An Diem 2	169.8	24.5	344	348.5	353.34	0.28	0.19	0.09	9	15.6	2010

the first validation period was 1996–2010, and the second was 2011–2020. The observed streamflow data at the Thanh My and Nong Son stations were used for model calibration and validation.

In this study, reservoirs were established with their parameters. Two main parameters with the highest sensitivity used to calibrate the reservoirs are the hydraulic conductivity of the reservoir bottom (RES_K; mm/h) and the number of days to reach target storage from current reservoir storage (NDTARGR; days) (Kim & Parajuli, 2014; Qiu et al., 2019). In addition, some reservoirs are located downstream of the hydrological station (Figure 1a). Therefore, to increase the reliability of the setup model for reservoir operation and to combine it with available data, the reservoir outflow was further calibrated. The calibration time belongs to the second validation period at hydrological stations. Specifically, the reservoir's released streamflow was calibrated in four large reservoirs (A Vuong, Song Bung 4, Dak Mi 4, Song Tranh 2) from 2017 to 2020 using monthly time steps.

The SWAT-CUP tool (SWAT Calibration and Uncertainty Procedures) with Sequential Uncertainty Fitting algorithm (SUFI-2) was used to evaluate the sensitivity of the parameters of the SWAT model (Abbaspour, 2013; Sao et al., 2020). Furthermore, five commonly used model efficiency criteria were used to evaluate model performance, including the correlation coefficient (R), Nash-Sutcliffe coefficient (NSE), percent bias (PBIAS), root-mean-square error (RMSE), and the ratio of the root-mean-square error to the standard deviation of measured data (RSR) (Moriasi et al., 2015).

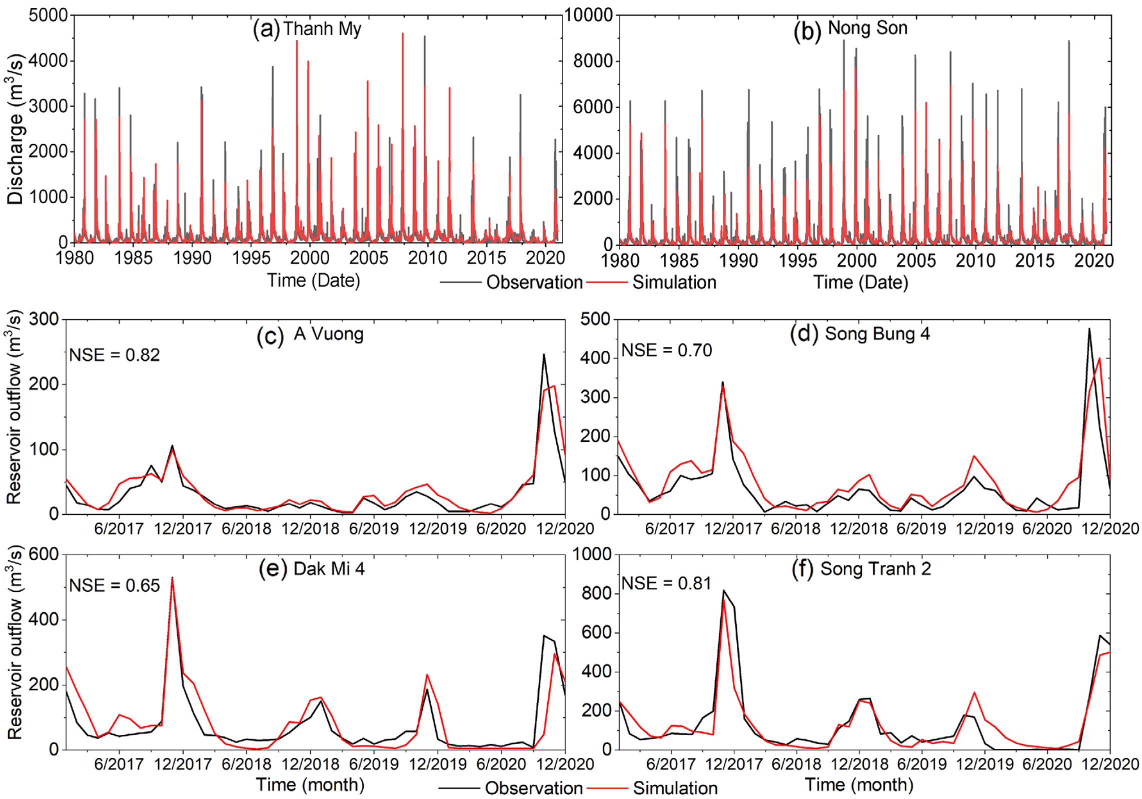

FIGURE 3 Calibrated and validated hydrographs of the streamflow at (a) the Thanh My station and (b) the Nong Son station; calibrated (1980–1995), first validated (1996–2010), second validated (2011–2020). Calibration of the outflow of the reservoirs from 2017 to 2020 at (c) A Vuong, (d) Song Bung 4, (e) Dak Mi 4, and (f) Song Tranh 2.

TABLE 3 Statistical indices in the calibration and validation of the streamflow at Thanh My and Nong Son.

Statistical indices	Thanh my station			Nong son station		
	Calibrated (1980–1995)	First validated (1996–2010)	Second validated (2011–2020)	Calibrated (1980–1995)	First validated (1996–2010)	Second validated (2011–2020)
R	0.82	0.88	0.83	0.90	0.90	0.91
NSE	0.66	0.72	0.67	0.81	0.81	0.80
RSR	0.58	0.53	0.58	0.44	0.44	0.45
RMSE (m^3/s)	119.61	142.12	105.30	214.28	305.29	246.79
PBIAS	3.76	−12.38	−32.89	2.28	1.83	−6.29

4 | RESULTS

4.1 | Calibration and validation of SWAT model

The simulated and observed streamflow plots for the calibration and validation performances are presented in Figure 3a,b, respectively. The five efficiency criteria presented in Table 3 reveal the quality of the model, which agrees with the observed data. The R, NSE, RSR, RMSE, and PBIAS coefficients at the Thanh My and Nong Son stations in the first validation period were 0.88, 0.72, 0.53, 142.12 m^3/s, and −12.38, and 0.90, 0.81, 0.44, 305.29 m^3/s, and 1.83, respectively.

The model results are consistent with the observations in the first and second validation periods. The differences between the observed and simulated results can be explained by the omission of irrigation demands on agricultural activities. However, this has not been evaluated in the present study.

The calibration of the monthly reservoir outflow agrees with the observed data (Figure 3c,d,e,f). The NSE values of the A Vuong, Song Bung 4, Dak Mi 4, and Song Tranh 2 reservoirs were 0.82, 0.70, 0.65, and 0.81, respectively. The validation results indicate that the present model is suitable for further examination of the variation in streamflow under the effect of reservoirs.

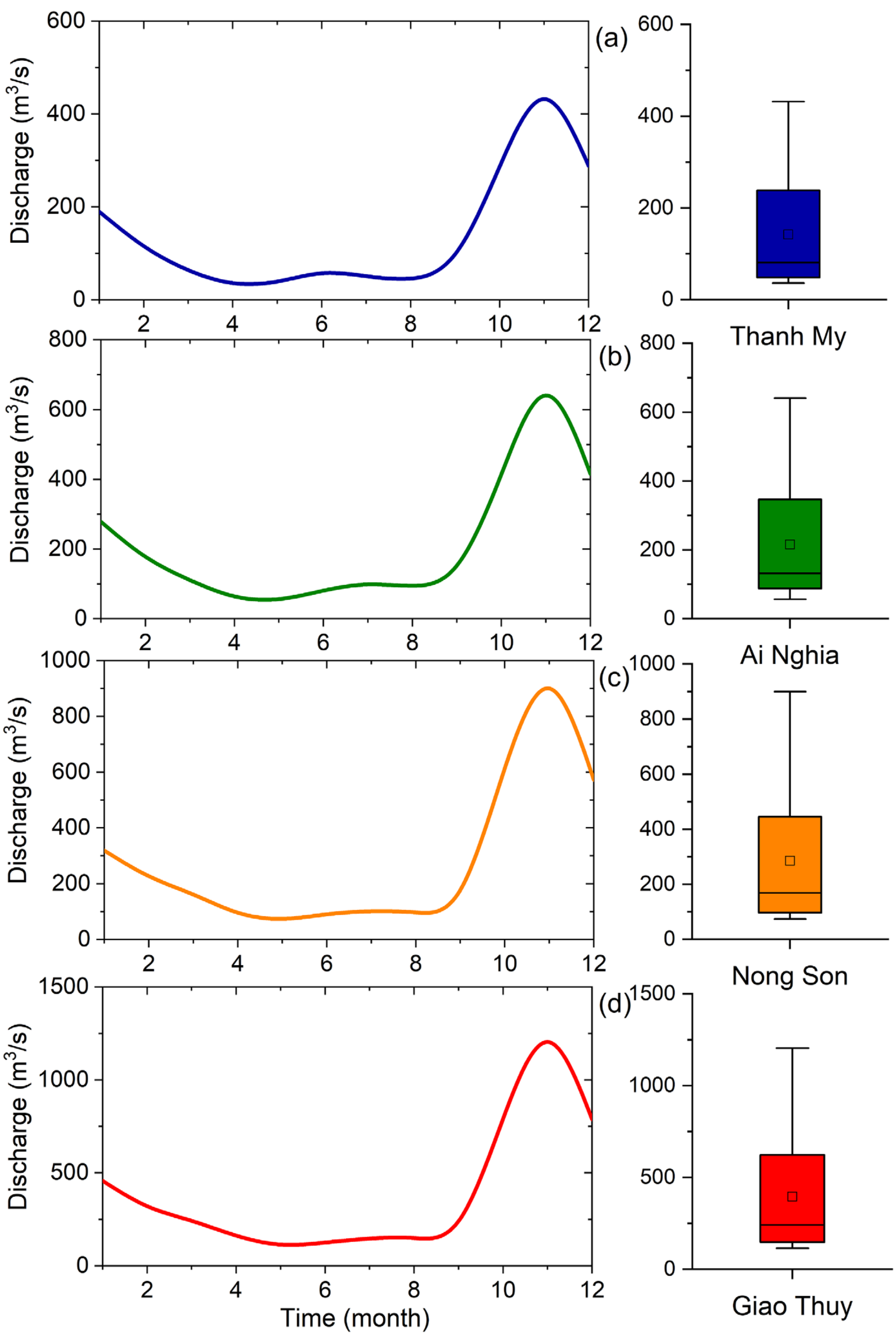

FIGURE 4 Mean monthly streamflow at the four stations simulated with the SWAT model in the period 1980–2020 at (a)–(b) Thanh My and Ai Nghia are in the Vu Gia River, and (c)–(d) Nong Son and Giao Thuy are in the Thu Bon River. Box plots showing the 25th, 50th (median), and 75th percentiles of the daily streamflow time series. The whiskers are defined as the first quartile minus 1:5 × inter-quartile range (IQR), and the third quartile plus 1:5 × IQR.

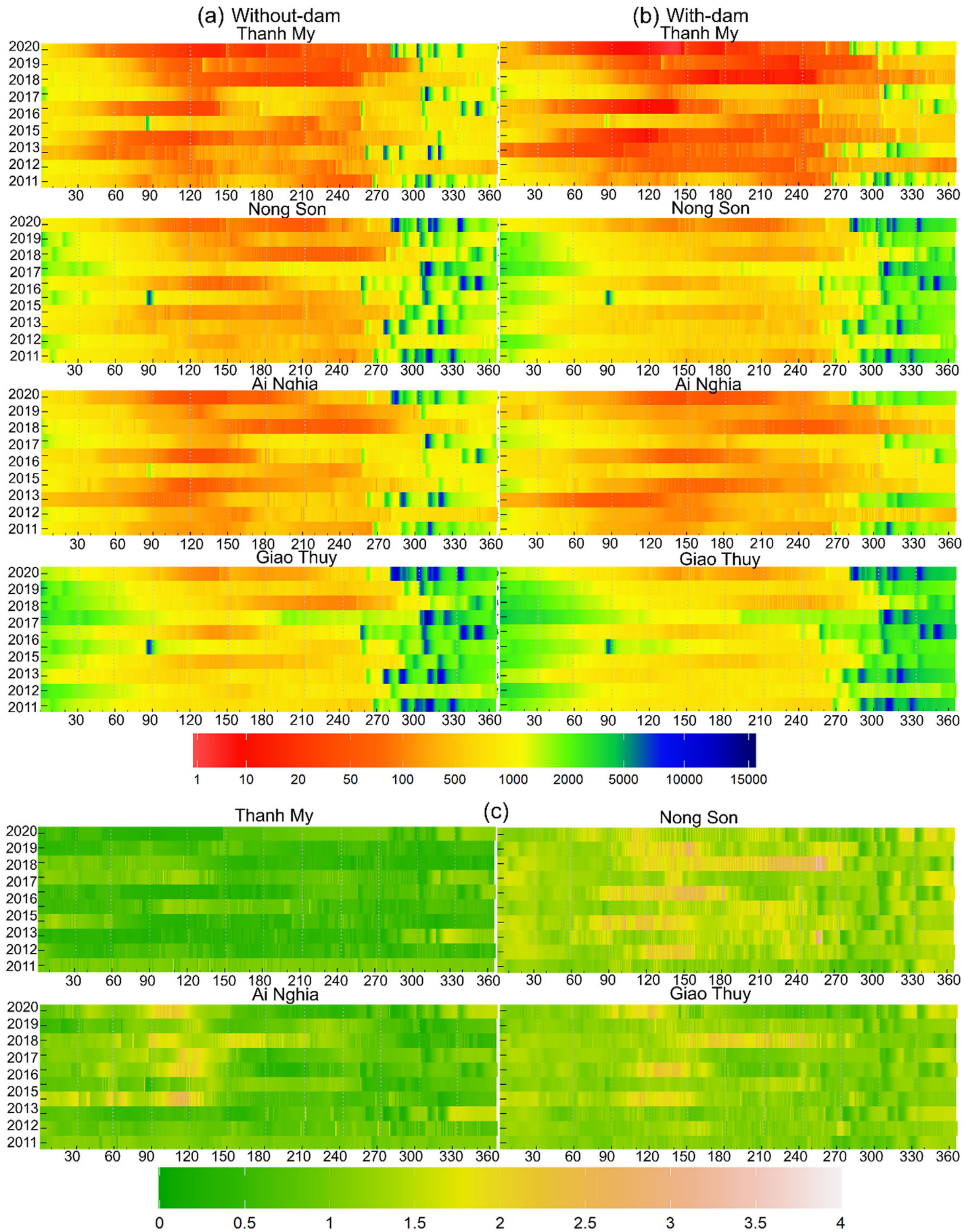

FIGURE 5 Daily streamflow at four stations. (a) Scenario without-dam, (b) scenario with-dam, and (c) the ratio of difference in streamflow between scenarios with-dam and without-dam. The *x*-axis shows the Julian date, and the *y*-axis shows the year.

4.2 | Results of the spatial and temporal evaluation of naturalized discharge

Natural flow simulation results from 1980 to 2020 (scenarios without-dam) show that the Thu Bon sub-basins have more abundant surface water resources than the Vu Gia sub-basins (Figure 4). Therefore, streamflows in the dry and rainy seasons at the Thu Bon River stations are more significant than those in the Vu Gia River. The average annual streamflows at Thanh My, Ai Nghia (in Vu Gia), Nong Son, and Giao Thuy (in Thu Bon) are 142 m^3/s, 215.5 m^3/s, 285.7 m^3/s, and 395.3 m^3/s, respectively. The respective median streamflows are 78 m^3/s, 124.2 m^3/s, 163.1 m^3/s, and 220.2 m^3/s (Figure 4a,b,c,d).

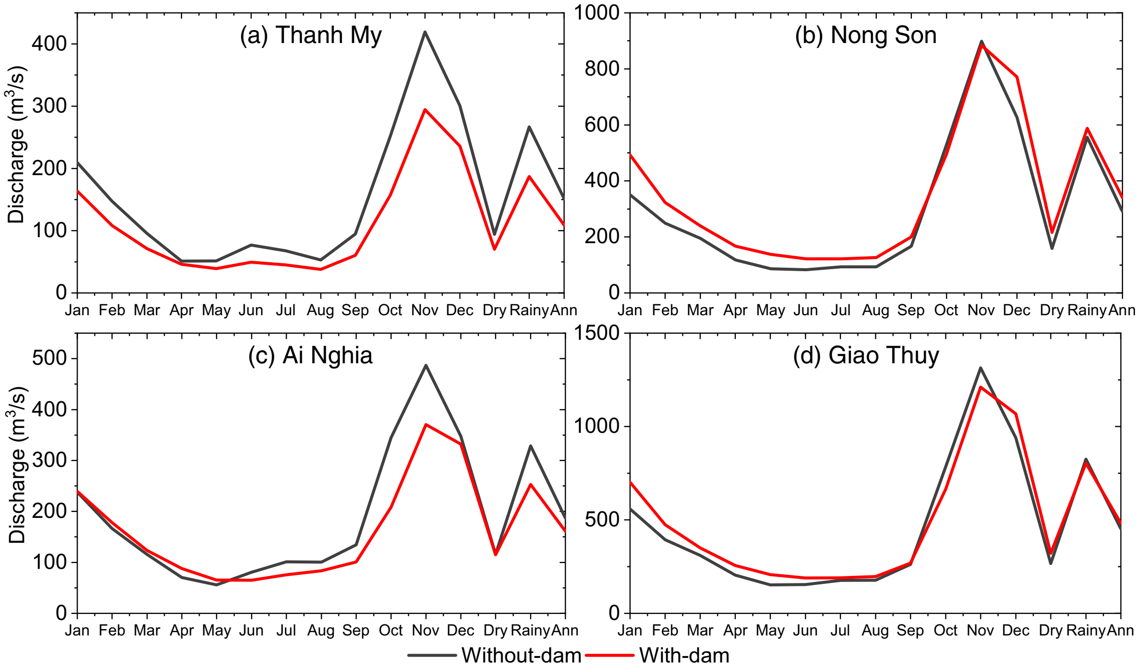

FIGURE 6 Average monthly streamflow at four stations in the 2011–2020 period, (a) Thanh My, (b) Nong Son, (c) Ai Nghia, and (d) Giao Thuy stations. The black line is the scenario without-dam, and the red line is the scenario with-dam.

4.3 | Effects of cascading reservoirs operation on daily streamflow

Figure 5 shows a visual comparison of the simulated daily streamflow for the scenarios without-dam and with-dam from 2011 to 2020. The streamflow time series presented a strong daily variation in the without-dam scenario, with low dry and high peak flows during the rainy season (Figure 5a). In the dry season of the with dam scenario, the streamflow decreased at Thanh My and Ai Nghia stations, especially at Thanh My (Figure 5b). The low level (red) of the streamflow is prominent throughout the period. In contrast, the streamflow increased at the Nong Son and Giao Thuy stations. During the rainy season, streamflow decreased at the four stations. The ratios of difference streamflow between scenarios with-dam and without-dam at Thanh My, Nong Son, Ai Nghia, and Giao Thuy were 0.2–1.65, 0.53–3.39, 0.2–2.69, and 0.46–2.39, respectively (Figure 5c).

4.4 | Effects of cascading reservoirs operation on the water balance

According to Firoz et al. (2018), reservoir operations inverted the seasonality of the naturalized streamflow regime. Strong seasonal variation and streamflow increased during the dry season and decreased during the rainy season. In contrast to Firoz et al. (2018), we found that the streamflow in the scenario with-dam was slightly changed compared to the scenario without-dam (Figures 6b,d, and 7, Table 4). In December, the reservoirs were released to reduce storage capacity, and the streamflow was more extensive than in the scenario without-dam (Figure 6b,d). The water diversion led to a decrease in streamflow (Figures 6a,c, and 7, Table 4). Therefore, Thu Bon's water resources became more abundant, whereas Vu Gia's reduced.

For the Thanh My station, located upstream of the Vu Gia, the average monthly streamflow decreased by approximately 42.5 m^3/s, from 151.6 m^3/s to 109.1 m^3/s. Because of water diversion by the Dak Mi 4 plant, the dry season streamflow decreased by 25.5%. In the rainy season, the streamflow decreased by 79.6 m^3/s, from 266.7 m^3/s to 187.1 m^3/s (Figures 6a and 7, Table 4). However, because of receiving water from Vu Gia, the dry, rainy, and annual streamflow increased at Nong Son by 57.8 m^3/s, 31.9 m^3/s, and 49.2 m^3/s, respectively (Figures 6b and 7, Table 4).

The impacts of the operation of the reservoir, the water transfer of the Dak Mi 4 plant, and the Quang Hue channel are most obvious downstream. During the early dry season, reservoirs in the Dak Mi, Bung, A Vuong, and Con sub-basins increased the flow discharges at Ai Nghia. However, the volume of storage of the reservoir decreased at the end of the dry season (June–August), whereas the Dak Mi 4 plant maintained the generation capacity. Therefore, the streamflow decreased compared to the scenario without-dam (Figures 6c and 7). In the dry season, the streamflow decreased by 1.1% at Ai Nghia and increased by 20.6% at Giao Thuy (Table 4); the streamflow in the rainy season decreased by 75.5 m^3/s, and 21.6 m^3/s, respectively.

In the VGTB basin, the main task of the reservoirs is to produce power. The reservoir operation to produce power has altered downstream flows. The influence depends on the location, volume, capacity of the turbine, etc. of each reservoir. The reservoirs were operated based on a management season (flood season and dry season). During the dry season, the guide curve will determine how much water each

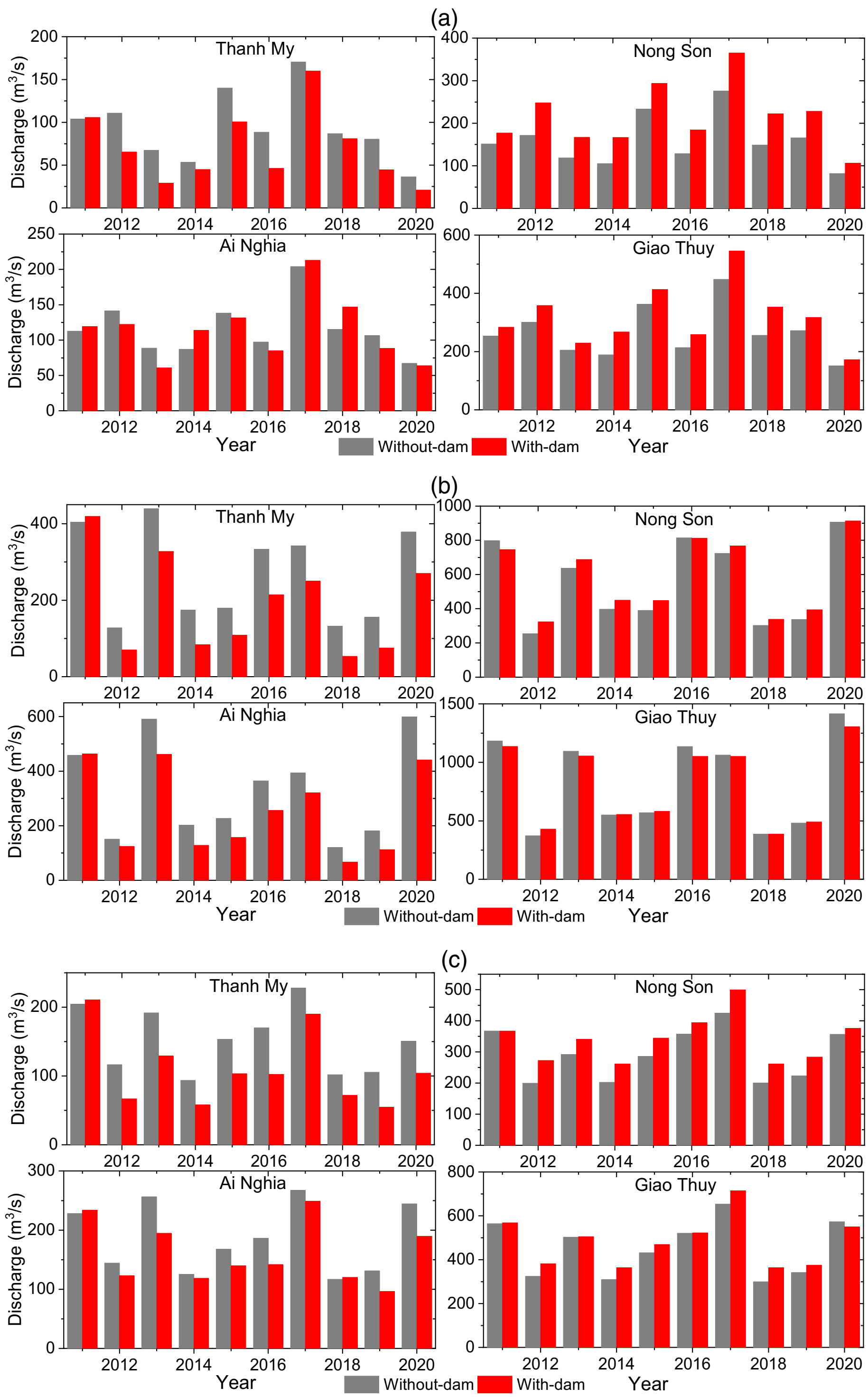

FIGURE 7 Comparison streamflow for the years 2011 to 2020. (a) Dry season (January to August), (b) rainy season (September to December), and (c) annual streamflow. Grey colour is the scenario without-dam, and the red colour is the scenario with-dam.

reservoir can release. With each reservoir, the monthly power production target is also controlled. Therefore, the water will be released to ensure that the energy production is maximized. The release rates are made considering cascading reservoirs and environmental flow. During the flood season, if the inflow is greater than the maximum hydropower discharge capacity and the water level is above the flood control zone, water is first transferred to its full capacity through the turbine to produce hydropower, and the excess water will be released through spill discharge.

4.5 | Assessment of reservoirs operation on streamflow downstream

In this study, we considered the impact and distinguished the effects of four large reservoirs (A Vuong, Song Bung 4, Dak Mi 4, and Song Tranh 2) on downstream streamflow when they operated independently. The level of impact depends on the location, storage capacity, and distance to hydrological stations. Unlike Nauditt et al. (2017), we can conclude that the operation of the Dak Mi 4 plant significantly

TABLE 4 Changes in streamflow at four stations in the period (2011–2020), with the without-dam scenario (gray shading is large and important changes).

Changes		Vu Gia sub-basins		Thu Bon sub-basins	
		Thanh My	Ai Nghia	Nong Son	Giao Thuy
Changes in flow (m^3/s)	Dry seasons	−24.0	−1.2	57.8	54.9
	Rainy seasons	−79.6	−75.5	31.9	−21.6
	Annual	−42.5	−26.0	49.2	29.8
Changes in flow (%)	Dry seasons	−25.5	−1.1	36.4	20.6
	Rainy seasons	−29.9	−23	5.8	−2.6
	Annual	−28.1	−13.9	16.9	6.5

TABLE 5 Impact of each reservoir on seasonal and annual streamflow at the Ai Nghia and Giao Thuy stations (gray shading is large and important changes).

Reservoir	Ai Nghia			Giao Thuy		
	Dry season (%)	Rainy season (%)	Annual (%)	Dry season (%)	Rainy season (%)	Annual (%)
A Vuong	1	−1.4	−0.4	0.3	−0.4	−0.1
Song Bung 4	2	−4.2	−1.5	0.6	−1.4	−0.6
Dak Mi 4	**−14.5**	**−17.4**	**−16.2**	**8.1**	**5**	**6.3**
Song Tranh 2	-	-	-	8.1	−5.9	−0.6

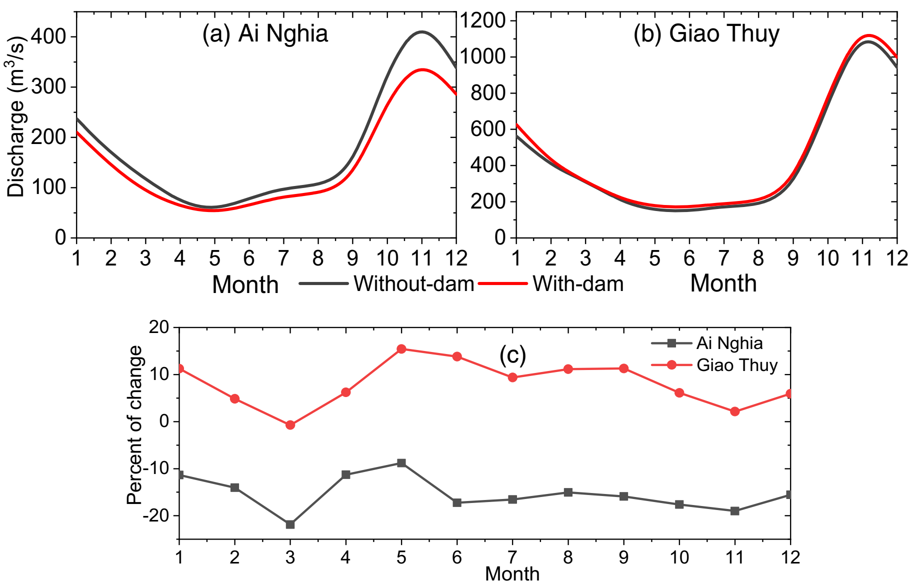

FIGURE 8 (a), (b) Effects of Dak Mi 4 reservoir on average monthly streamflow. (c) Percentage changes of monthly streamflow compared with the scenario without-dam at Ai Nghia and Giao Thuy stations.

affects downstream basins (Table 5, Figure 8a,b). We also show that the operation at the Vu Gia River affects the downstream reaches of the VGTB basin.

The Dak Mi 4 reservoir reduced the seasonal and annual streamflow at the Vu Gia River and increased the flows on the Thu Bon River. Annual, dry season and rainy season flows at Ai Nghia decreased by 16.2%, 14.5%, and 17.4%, respectively (Table 5). In contrast, streamflow increased at Giao Thuy by 6.3%, 8.1%, and 5%, respectively. A negative value for the percentage changes in the monthly streamflow compared with the no-dam scenario was observed at Ai Nghia, whereas a positive value was observed at Giao Thuy (Figure 8c). At Ai Nghia, Dak Mi 4 releases less in March to store water for the driest month (April). Therefore, the streamflow decreased by 21.9% compared to the scenario without-dam.

The remaining reservoirs (i.e., Song Tranh 2, Song Bung 4, and A Vuong) had a negligible influence on streamflow (Table 5). In the rainy season, the reservoirs helped reduce the risk in the downstream floodplain due to the low release of water. Flood reduction efficiency is related to the active storage of reservoirs. The Song Tranh 2 reservoir has the most extensive functional capacity for storage and is the most effective reservoir in terms of flood peak cut and flooding risk reduction. The streamflow during the rainy season decreased by 5.9%

TABLE 6 Seasonal and annual flow characteristics of main sub-basins on Vu Gia and Thu Bon rivers (gray shading is large and important changes).

Sub-basins	Sub-basin	Period (1980–2010)			Period (2011–2020) (without-dam)			Period (2011–2020) (with-dam)		
		Dry season (January–August) (m^3/s)	Rainy season (September–December) (m^3/s)	Annual (m^3/s)	Dry season (January–August) (m^3/s)	Rainy season (September–December) (m^3/s)	Annual (m^3/s)	Dry season (January–August) (m^3/s)	Rainy season (September–December) (m^3/s)	Annual (m^3/s)
Vu Gia	Con River	12.5	55.4	26.8	14.9	64.1	31.3	18.1	61.8	32.7
	A Vuong River	15.1	74.9	35.0	19.7	76.7	38.7	22.3	70.0	38.2
	Bung River	36.1	166.6	79.6	49.4	163.8	87.5	53.7	154.4	87.3
	Giang River	15.7	69.1	33.5	21.9	66.0	36.6	21.9	66.0	36.6
	Dak Mi River	**44.8**	**203.5**	**97.7**	**63.8**	**193.6**	**107.1**	**40.2**	**113.0**	**64.5**
	Ai Nghia	**121.6**	**431.0**	**224.7**	**116.1**	**328.5**	**186.9**	**114.9**	**253.0**	**160.9**
Thu Bon	Khe Dien River	3.8	16.9	8.1	4.0	16.4	8.1	4.5	15.7	8.2
	Que Lam River	4.4	20.1	9.7	4.6	18.8	9.4	4.6	18.8	9.4
	Truong River	**13.1**	**68.2**	**31.5**	**16.1**	**62.7**	**31.7**	**49.9**	**130.1**	**76.6**
	Tranh River	80.9	336.6	166.1	89.8	335.2	171.6	114.4	298.6	175.8
	Khang River	23.6	102.9	50.0	27.5	104.2	53.1	27.5	104.2	53.1
	Giao Thuy	**198.4**	**734.2**	**377.0**	**265.9**	**825.0**	**452.2**	**320.7**	**803.4**	**481.6**

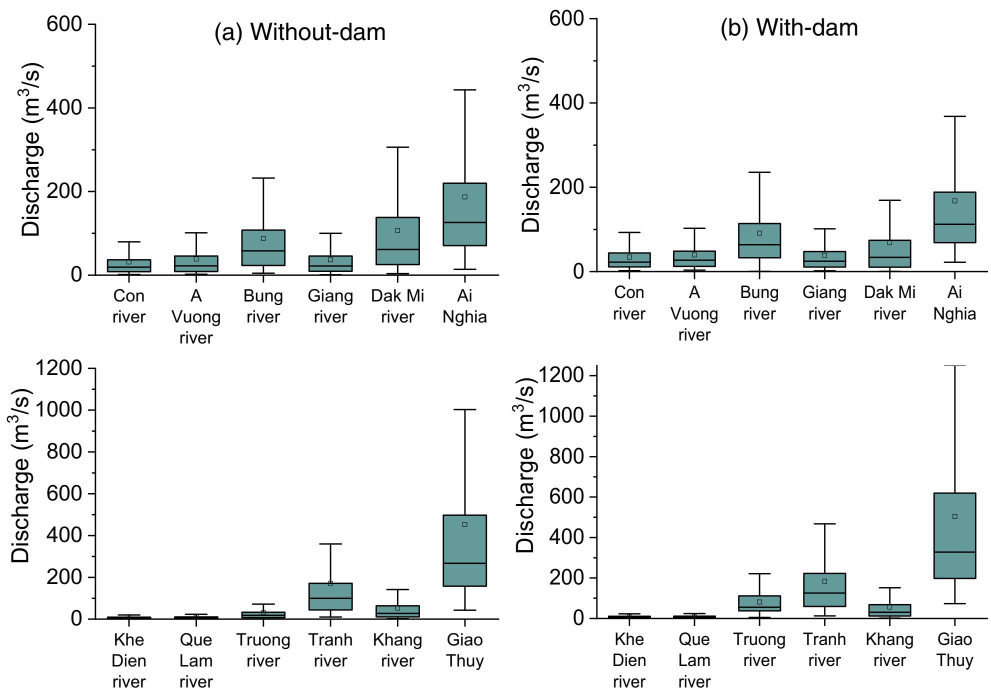

FIGURE 9 Box plots indicate the 25th, 50th (median), and 75th percentiles of the daily streamflow of main sub-basins in Vu Gia and Thu Bon sub-basins in the 2011–2020 period. (a) Scenario without-dam, and (b) scenario with-dam.

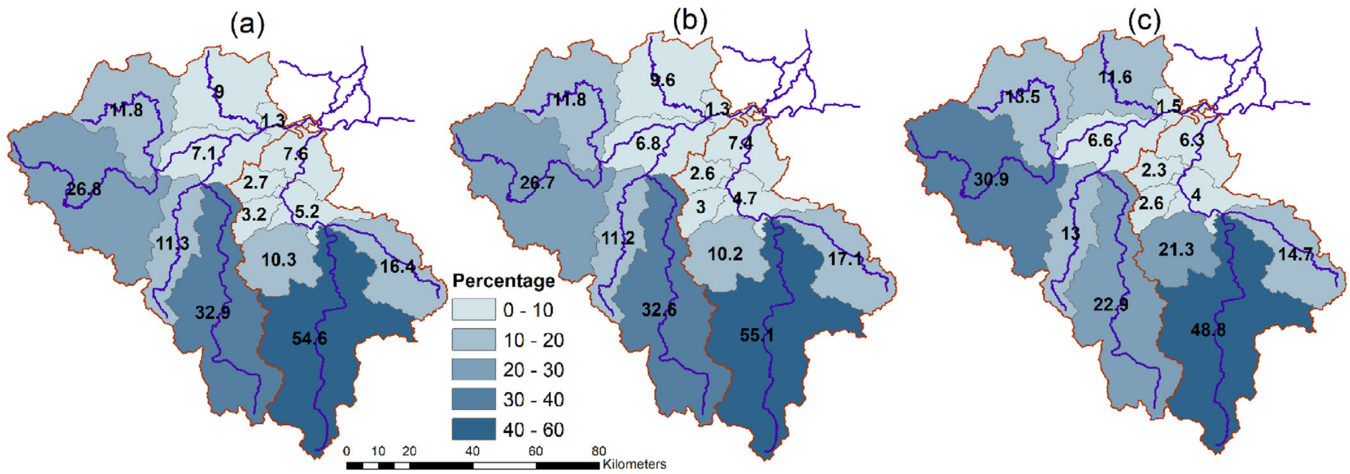

FIGURE 10 Percentage contribution of the streamflow of sub-basins in the Vu Gia and Thu Bon sub-basins. (a) 1980–2010 period, (b) 2011–2020 period without-dam, and (c) 2011–2020 period with-dam. The results only consider the water transfer of the Dak Mi 4 plant in the scenario with-dam and do not consider the Quang Hue channel in all scenarios. The percentage contribution considers the upper Quang Hue channel in the Vu Gia and Thu Bon rivers.

compared to the scenario without-dam (Table 5). Therefore, the Song Tranh 2 hydropower operation only affects the Thu Bon sub-basins.

4.6 | Contribution of streamflow of sub-basins on VGTB basin

The hydrological responses and contributions of each group of cascading dams differed according to sub-basin locations and periods. The Dak Mi River sub-basin contributed the most significant streamflow to the Vu Gia sub-basins from 1980 to 2010 (annual flow is 97.7 m^3/s) (Table 6). The Tranh River sub-basin contributes the most in the Thu Bon sub-basins, with a yearly flow of 166.1 m^3/s. Therefore, hydropower plants have been constructed in these sub-basins (Figure 1a).

Sub-basins without reservoirs (Giang, Que Lam, and Khang Rivers) remained the same in both scenarios (Table 6, Figure 9a,b). In basins with reservoirs (Con River, A Vuong River, Bung River, Khe Dien River, and Tranh River), the streamflow increased in the dry season and decreased in the rainy season (Table 6). The Dak Mi 4 plant transfers water from the Dak Mi River to the Truong River. Therefore, the dry, rainy, and annual streamflows decreased considerably in the Dak Mi River sub-basin and increased in the Truong River sub-basin (Table 6).

The Dak Mi River and Tranh River sub-basins contributed the largest streamflow for the Vu Gia and Thu Bon sub-basins from 1980 to 2010 by 32.9% and 54.6%, respectively (Figure 10a). However, in the period 2011–2020 with dams, the contribution rate of the Dak Mi River was only 22.9%, lower than the Bung River (30.9%) (Figure 10c). However, the Truong River Basin increased the contribution of the Thu Bon sub-basins from 10.3% to 21.3%. The results show that the Dak Mi River and Truong River basins were significantly altered in both scenarios, with the remaining sub-basins slightly increasing in the Vu Gia sub-basins and decreasing in the Thu Bon sub-basins (Figure 10b,c).

5 | DISCUSSION

5.1 | Effects of the Quang Hue channel on downstream streamflow

Flow alteration in the VGTB basin is caused by reservoir operation and water transfer from the Quang Hue channel (Figures 5, 6, 7, and 8, Tables 4 and 5). Surveys and measurements from 2001 show that approximately 43% of Vu Gia's flow is diverted to the Thu Bon River by the Quang Hue channel. In this study, the water diverted to the Thu Bon River is governed and reduced by the cascading hydropower dams. The operation of 11 reservoirs partially compensates for water in the Vu Gia sub-basins that the Dak Mi 4 plant has transferred (Figure 11, Table 7). The annual flow decreased from 141 m^3/s to 121.3 m^3/s in the scenario without-dam compared to the scenario with-dam.

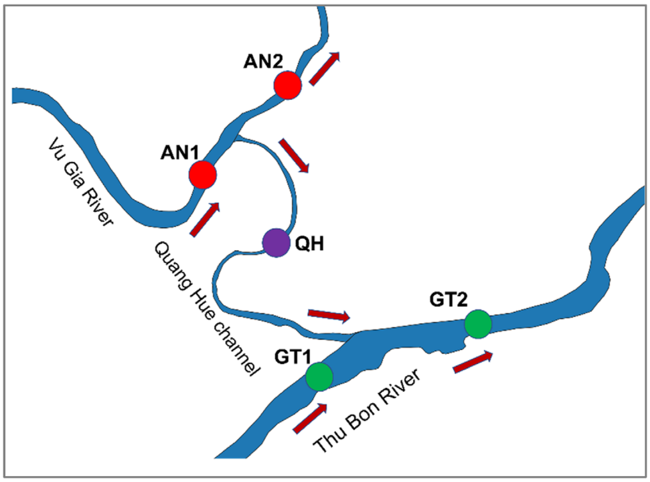

FIGURE 11 Five streamflow extraction locations on Vu Gia River, Thu Bon River, and Quang Hue channel (AN1, AN2, GT1, GT2, QH).

5.2 | Temporal variability in the relationships between rainfall and streamflow at sub-basins

Among the essential components of the basin's water budget, precipitation and runoff are closely related and interrelated through the water balance equation (Rose & Stern, 1965; Shawul et al., 2013). The duration and intensity of runoff depend fundamentally on precipitation and basin-wide infrastructure (Ahn & Merwade, 2014; Ribbe et al., 2017). Most hydropower plants return water to the original river, except Dak Mi 4, which diverts water from the Vu Gia River to the Thu Bon River through the Truong River to increase the efficiency of generated electricity. Therefore, the correlation curve of cumulative rainfall and streamflow decreased in the Dak Mi River and increased in the Truong River between 2011 and 2020 (Figure 12). In the other eight sub-basins, where there is no dam, rainfall is highly correlated with streamflow. However, there is a weak correlation in sub-basins with dams, indicating the obvious effect of dams on streamflow.

The rainfall in the post-2010 period in the Dak Mi River and Truong River sub-basins increased compared to that in the pre-2010 period by 5.8% and 3.6%, respectively (Table 8). However, the average streamflow in the Dak Mi River decreased by 34%, from 97.7 m^3/s to 64.5 m^3/s. Further, in the Truong River, the average streamflow increased from 31.5 m^3/s to 76.6 m^3/s (143.4%). Reducing the Vu Gia streamflow leads to an increasing saltwater intrusion hazard/risk and strongly impairs local socio-economic factors, especially agricultural production and drinking water supply (Nga et al., 2020; Viet, 2014).

TABLE 7 Dry season, rainy season, and annual average streamflow in scenarios without-dam and with-dam.

						QH	
Scenarios		AN1 (m^3/s)	AN2 (m^3/s)	GT1 (m^3/s)	GT2 (m^3/s)	Streamflow (m^3/s)	Percentage of Thu Bon River (%)
Without -dam	Dry season	203.3	115.9	177.8	265.2	87.4	33
	Rainy season	576.8	328.8	577.6	825.6	248.0	30
	Annual	328.0	187.0	311.3	452.3	141.0	31.2
With-dam	Dry season	200.9	114.5	233.5	319.9	86.4	27
	Rainy season	444.3	253.2	613.4	804.4	191.0	23.8
	Annual	282.1	160.8	360.4	481.7	121.3	25.2

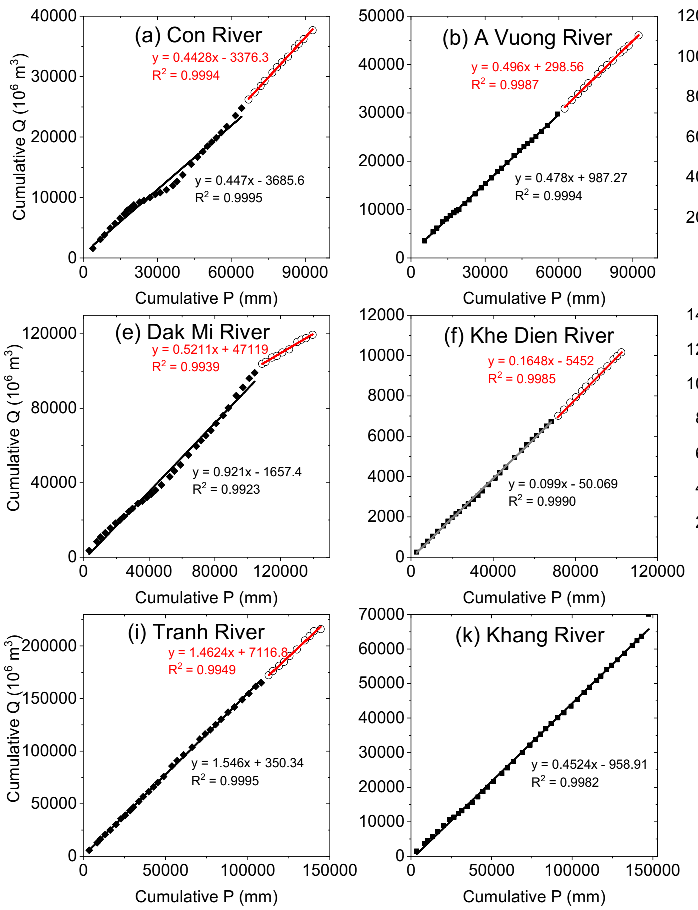

FIGURE 12 Correlation curves showing the relationship of cumulative rainfall and streamflow in sub-basins. (a) Con River, (b) A Vuong River, (c) Bung River, (d) Giang River, (e) Dak Mi River, (f) Khe Dien River, (g) Que Lam River, (h) Truong River, (i) Tranh River, and (k) Khang River.

TABLE 8 Changes in rainfall and average streamflow in the Dak Mi River, Truong River.

River	Period	Rainfall (mm)	ΔP	Flow (m^3/s)	ΔQ
Dak Mi	Pre-2010	3347		97.7	
	Post-2010	3540	193 (5.8%)	64.5	−33.23 (−34%)
Truong	Pre-2010	3493		31.5	
	Post-2010	3620	127 (3.6%)	76.6	45.15 (143.4%)

5.3 | Managing the risk of saltwater intrusion and water shortage downstream to allow sustainable development of the VGTB River basin

Where it was possible to quantify the sub-basin contributions on the downstream reaches at different stations, we correlated the contribution of each dam group in the different sub-basins. In addition, we found that reservoirs with ample active storage (A Vuong, Song Bung 4, Dak Mi 4, Song Tranh 2) have contributed to the effects of the reduction of the wet season, which could help the government mitigate floods. Finally, we discuss the implications for agriculture, drinking water supply, and the mitigation of saltwater intrusion.

From 2011 to 2020, the Vuong sub-basin contributed the largest streamflow (30.9%) to the Vu Gia River (Figure 10c, Table 6). During the dry season, the streamflow and water level downstream depend mainly on the operation of the hydropower plants in this sub-basin. The outflow from the A Vuong and Song Bung 4 hydropower plants flow into the Song Bung 5 and 6 reservoirs. Both reservoirs are regulated daily (can store flow in 1 day and generate electricity only during peak hours; in the evening and early morning) (Figure 1a, Table 2). Therefore, although the flow from the electricity generation of Song Bung 5 and 6 is substantial, it is generated in a short time, leading to a small downstream flow the rest of the time. A low water level downstream affects pumping stations and plants for agriculture and drinking water supply. Moreover, the outlet of the VGTB basin has a semi-diurnal tidal regime, up and down twice a day, with a tidal amplitude of about 0.6 m. Therefore, downstream flow is frequently affected by saline water intrusion during the dry season. Saltwater intrusion-induced water shortages during drought periods are the main constraints that hinder domestic water supply and agricultural production.

These problems require appropriate solutions, not only in the short term but also in the long term. Hydrology simulation and consultation with local experts can offer a variety of measures to cope with water shortages for agriculture, drinking water supply, and saltwater intrusion. The most important measures are redistributing upstream streamflow and ensuring minimal river streamflow from cascading hydropower dams in sub-basins. Specifically, coordination between reservoirs to maintain continuous downstream flow, reduced water transfer in the Quang Hue channel, and improved water use works.

6 | CONCLUSIONS

In this study, we used the SWAT semi-distributed hydrological model to clarify the impact of hydraulic infrastructures on the streamflow of the VGTB River basin from 1979 to 2020. The model quantified the effects of hydraulic infrastructures by comparing the basin's natural and anthropogenic streamflow, distinguished the effects of four major reservoir operations on downstream flow, and quantified the flow contribution of the sub-basins, which were not adequately understood before.

The modelling results show that the Dak Mi 4 reservoir has the most significant influence on the streamflow of the Vu Gia and Thu Bon sub-basins. The overall impact of all reservoirs and water diversions on downstream flow decreased by 1.1% in the Vu Gia sub-basins and increased by 20.6% in the Thu Bon sub-basins in the dry season (Table 4). However, the streamflow in the rainy season decreased in the two basins by 23% and 2.6% (Table 4), respectively, compared to the scenario without-dam.

Owing to water transfers from the Dak Mi 4 plant, the dry season, rainy season, and annual streamflows decreased significantly in the Dak Mi River sub-basin and increased in the Truong River sub-basin. In this study, the water diverted to the Thu Bon River is governed and decreased by cascading hydropower dams. The annual streamflow of the Quang Hue channel decreased from 141 m^3/s to 121.3 m^3/s in the scenario without-dam compared to the scenario with-dam (Figure 11, Table 7). The operation of the 11 reservoirs partially compensates for water in the Vu Gia sub-basins transferred by the Dak Mi 4 plant.

The Dak Mi River and Tranh River sub-basins contributed the largest streamflow for the Vu Gia and Thu Bon sub-basins in the 1980–2010 period by 32.9% and 54.6%, respectively (Figure 10a). However, in the with-dam period (2011–2020), the contribution rate of the Dak Mi River was only 22.9%. Nevertheless, the Truong River Basin increased the contribution of the Thu Bon sub-basins from 10.3% to 21.3% (Figure 10b,c).

These primary findings presented a good approach for understanding comprehensive cascading reservoir and inter-basin water diversion, which could be used as a reference for other basins worldwide. Our findings provide a comprehensive approach to quantify the impact of cascading dams and diversion structures and distinguish their impacts from those of the effect of climate change. This study helps regional decision-makers and stakeholders plan for future water resource management issues and contributes to the current literature that uses combined hydrological models, water diversion, and reservoir operation to investigate the implications of the reservoir in hydrological simulations worldwide.

Flow alteration combined with bathymetry changes increases saltwater intrusion hazard/risk and strongly impairs local socio-economic factors, agricultural production, and drinking water supply. In future research, we will establish the risk index/threshold for which this phenomenon occurs in the VGTB basin. It will provide us with a tool to determine the risk/hazard of saltwater intrusion to support water management for irrigation and drinking water supply.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available upon reasonable request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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REFERENCES

Abbaspour, K. C. (2013). Swat-cup 2012. SWAT calibration and uncertainty program—A user manual.

Ahn, K.-H., & Merwade, V. (2014). Quantifying the relative impact of climate and human activities on streamflow. *Journal of Hydrology*, *515*, 257–266.

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: Model development 1. *Journal of the American Water Resources Association*, *34*(1), 73–89.

Binh, D. V., Kantoush, S., & Sumi, T. (2020). Changes to long-term discharge and sediment loads in the Vietnamese Mekong Delta caused by upstream dams. *Geomorphology*, *353*, 107011.

Binh, D. V., Kantoush, S. A., Saber, M., Mai, N. P., Maskey, S., Phong, D. T., & Sumi, T. (2020). Long-term alterations of flow regimes of the Mekong River and adaptation strategies for the Vietnamese Mekong Delta. *Journal of Hydrology: Regional Studies*, *32*, 100742.

Carvalho-Santos, C., Monteiro, A. T., Azevedo, J. C., Honrado, J. P., & Nunes, J. P. (2017). Climate change impacts on water resources and reservoir management: Uncertainty and adaptation for a mountain catchment in northeast Portugal. *Water Resources Management*, *31*(11), 3355–3370.

Chhuon, K., Herrera, E., & Nadaoka, K. (2016). Application of integrated hydrologic and river basin management modeling for the optimal development of a multi-purpose reservoir project. *Water Resources Management*, *30*(9), 3143–3157.

Di Baldassarre, G., Wanders, N., AghaKouchak, A., Kuil, L., Rangecroft, S., Veldkamp, T. I. E., Garcia, M., van Oel, P. R., Breinl, K., & Van Loon, A. F. (2018). Water shortages worsened by reservoir effects. *Nature Sustainability*, *1*(11), 617–622.

Firoz, A. B. M., Nauditt, A., Fink, M., & Ribbe, L. (2018). Quantifying human impacts on hydrological drought using a combined modelling approach in a tropical river basin in central Vietnam. *Hydrology and Earth System Sciences*, *22*(1), 547–565.

Government of Vietnam. (2019). Decision 1867/QĐ-TTg: Procedures for operating reservoirs system in Vu Gia Thu Bon river basin (in Vietnamese).

ICEM. (2008). *Strategic environmental assessment of the Quang Nam Province hydropower plan for the Vu Gia-Thu Bon River basin, prepared for the ADB, MONRE* (p. 205). MOITT & EVN.

Johnson, S. A., Stedinger, J. R., & Staschus, K. (1991). Heuristic operating policies for reservoir system simulation. *Water Resources Research*, *27*(5), 673–685.

Keitzer, S. C., Ludsin, S. A., Sowa, S. P., Annis, G., Arnold, J. G., Daggupati, P., Froehlich, A. M., Herbert, M. E., Johnson, M.-V. V., & Sasson, A. M. (2016). Thinking outside of the lake: Can controls on nutrient inputs into Lake Erie benefit stream conservation in its watershed? *Journal of Great Lakes Research*, *42*(6), 1322–1331.

Kim, H., & Parajuli, P. B. (2014). Impacts of reservoir outflow estimation methods in SWAT model calibration. *Transactions of the ASABE*, *57*(4), 1029–1042. https://doi.org/10.13031/trans.57.10156

Loi, N. K., Liem, N. D., Tu, L. H., Hong, N. T., Truong, C. D., Tram, V. N. Q., Nhat, T. T., Anh, T. N., & Jeong, J. (2019). Automated procedure of real-time flood forecasting in Vu Gia–Thu Bon river basin, Vietnam by integrating SWAT and HEC-RAS models. *Journal of Water and Climate Change*, *10*(3), 535–545.

MCRHMC. (2022). *Mid-Central Regional Hydro-Meteorological Center, Vietnam*. Mid-Central Regional Hydro-Meteorological Center.

Mittal, N., Bhave, A. G., Mishra, A., & Singh, R. (2016). Impact of human intervention and climate change on natural flow regime. *Water Resources Management*, *30*(2), 685–699.

MOIT. (2015). *Decision for hydropower plant operation: Technical document* (p. 2015a). Ministry of Investment and Trade, Socialist Republic of Vietnam.

Moriasi, D. N., Gitau, M. W., Pai, N., & Daggupati, P. (2015). Hydrologic and water quality models: Performance measures and evaluation criteria. *Transactions of the ASABE*, *58*(6), 1763–1785.

Nauditt, A., Firoz, A. B. M., Trinh, V. Q., Fink, M., Stolpe, H., & Ribbe, L. (2017). Hydrological drought risk assessment in an anthropogenically impacted tropical catchment, Central Vietnam. In *Land use and climate change interactions in central Vietnam* (pp. 223–239). Springer.

NDPAC. (n.d.). Natural Disaster Prevention and Control of Quang Nam Province. http://pctt.quangnam.vn/

Nga, T. T., Cong, V. H., & Hung, L. (2020). Assessing the impacts of climate change and reservoir operation on saltwater intrusion in the Vu Gia-Thu Bon River basin. *In APAC 2019: Proceedings of the 10th International Conference on Asian and Pacific Coasts, 2019*, Hanoi, Vietnam (pp. 1207-1212). Springer Singapore. https://doi.org/10.1007/978-981-15-0291-0_165

Ngo, L. A., Masih, I., Jiang, Y., & Douven, W. (2018). Impact of reservoir operation and climate change on the hydrological regime of the Sesan and Srepok Rivers in the lower Mekong Basin. *Climatic Change*, *149*(1), 107–119.

Nguyen, B. Q., Kantoush, S., Binh, D. V., Saber, M., Vo, D. N., & Sumi, T. (2023). Understanding the anthropogenic development impacts on long-term flow regimes in a tropical river basin, Central Vietnam. *Hydrological Sciences Journal*, 1–14. https://doi.org/10.1080/02626667.2022.2153298

Nguyen, B. Q., Tran, T.-N.-D., Grodzka-Łukaszewska, M., Sinicyn, G., & Lakshmi, V. (2022). Assessment of urbanization-induced land-use change and its impact on temperature, evaporation, and humidity in Central Vietnam. *Water*, *14*(21), 3367.

Nguyen, H. T., Duong, T. Q., Nguyen, L. D., Vo, T. Q. N., Tran, N. T., Dang, P. D. N., Nguyen, L. D., Dang, C. K., & Nguyen, L. K. (2020). Development of a spatial decision support system for real-time flood early warning in the Vu Gia-Thu Bon River basin, Quang Nam Province, Vietnam. *Sensors*, *20*(6), 1667.

Nguyen, L. H., & Fukushi, K. (2019). Addressing climate change in the water sector: The study of run-of-river hydropower potential in Vu Gia-Thu Bon river basin of Vietnam. *IOP Conference Series: Earth and Environmental Science*, *266*(1), 12014.

Nguyen, T. H. (2020). *Optimal operation of multi-reservoir system for flood control. Application to the Vu Gia Thu Bon catchment, Vietnam*. Université Côte d'Azur.

Oki, T., & Kanae, S. (2006). Global hydrological cycles and world water resources. *Science*, *313*(5790), 1068–1072.

Qiu, J., Yang, Q., Zhang, X., Huang, M., Adam, J. C., & Malek, K. (2019). Implications of water management representations for watershed hydrologic modeling in the Yakima River basin. *Hydrology and Earth System Sciences*, *23*(1), 35–49. https://doi.org/10.5194/hess-23-35-2019

RETA. (2011). *Investment, Managing water in Asia's river basins: Charting progress and facilitating – The Vu Gia-Thu Bon Basin*. Department of Natural Resources and Environment.

Ribbe, L., Trinh, V. Q., Firoz, A. B. M., Nguyen, A. T., Nguyen, U., & Nauditt, A. (2017). Integrated River basin Management in the Vu Gia Thu Bon Basin. In *Land use and climate change interactions in Central Vietnam* (pp. 153–170). Springer.

Rose, C. W., & Stern, W. R. (1965). The drainage component of the water balance equation. *Soil Research*, *3*(2), 95–100.

Sao, D., Kato, T., Tu, L. H., Thouk, P., Fitriyah, A., & Oeurng, C. (2020). Evaluation of different objective functions used in the SUFI-2 calibration process of SWAT-CUP on water balance analysis: A case study of the Pursat river basin, Cambodia. *Water*, *12*(10), 2901.

Shawul, A. A., Alamirew, T., & Dinka, M. O. (2013). Calibration and validation of SWAT model and estimation of water balance components of Shaya mountainous watershed, Southeastern Ethiopia. *Hydrology and Earth System Sciences Discussions*, *10*(11), 13955–13978.

Shrestha, B., Maskey, S., Babel, M. S., van Griensven, A., & Uhlenbrook, S. (2018). Sediment related impacts of climate change and reservoir development in the lower Mekong River basin: A case study of the Nam Ou Basin, Lao PDR. *Climatic Change*, *149*(1), 13–27.

Sorooshian, S., Hsu, K., Coppola, E., Tomassetti, B., Verdecchia, M., & Visconti, G. (2008). *Hydrological modelling and the water cycle: Coupling the atmospheric and hydrological models* (Vol. 63). Springer Science & Business Media.

Souvignet, M., Laux, P., Freer, J., Cloke, H., Thinh, D. Q., Thuc, T., Cullmann, J., Nauditt, A., Flügel, W., & Kunstmann, H. (2014). Recent climatic trends and linkages to river discharge in Central Vietnam. *Hydrological Processes*, *28*(4), 1587–1601.

Tran, T.-N.-D., Nguyen, B. Q., Zhang, R., Aryal, A., Grodzka-Łukaszewska, M., Sinicyn, G., & Lakshmi, V. (2023). Quantification of Gridded Precipitation Products for the Streamflow Simulation on the Mekong River Basin Using Rainfall Assessment Framework: A Case Study for the Srepok River Subbasin, Central Highland Vietnam. *Remote Sensing*, *15*(4), 1030. https://doi.org/10.3390/rs15041030

Tran, T.-N.-D., Nguyen, B. Q., Vo, N. D., Le, M.-H., Nguyen, Q.-D., Lakshmi, V., & Bolten, J. D. (2023). Quantification of global Digital Elevation Model (DEM) – A case study of the newly released NASADEM for a river basin in Central Vietnam. *Journal of Hydrology: Regional Studies*, *45*, 101282. https://doi.org/10.1016/j.ejrh.2022.101282

Vale, M., & Holman, I. P. (2009). Understanding the hydrological functioning of a shallow lake system within a coastal karstic aquifer in Wales, UK. *Journal of Hydrology*, *376*(1–2), 285–294.

Viet, T. Q. (2014). *Estimating the impact of climate change induced saltwater intrusion on agriculture in estuaries-the case of Vu Gia Thu Bon*. Ruhr-Universität Bochum.

Vu, M. T., Vo, N. D., Gourbesville, P., Raghavan, S. V., & Liong, S.-Y. (2017). Hydro-meteorological drought assessment under climate change impact over the Vu Gia–Thu Bon river basin, Vietnam. *Hydrological Sciences Journal*, *62*(10), 1654–1668.

Wang, D., & Hejazi, M. (2011). Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resources Research*, *47*(10), 1–16.

Wang, G., & Xia, J. (2010). Improvement of SWAT2000 modelling to assess the impact of dams and sluices on streamflow in the Huai River basin of China. *Hydrological Processes: An International Journal*, *24*(11), 1455–1471.

Wang, H., Chen, L., & Yu, X. (2016). Distinguishing human and climate influences on streamflow changes in Luan River basin in China. *Catena*, *136*, 182–188.

Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L., & Tockner, K. (2015). A global boom in hydropower dam construction. *Aquatic Sciences*, *77*(1), 161–170.

Zhang, Y., Zhai, X., & Zhao, T. (2018). Annual shifts of flow regime alteration: New insights from the Chaishitan reservoir in China. *Scientific Reports*, *8*(1), 1–11.

Zhou, T., Nijssen, B., Gao, H., & Lettenmaier, D. P. (2016). The contribution of reservoirs to global land surface water storage variations. *Journal of Hydrometeorology*, *17*(1), 309–325.

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