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Understanding the anthropogenic development impacts on long-term flow regimes in a tropical river basin, Central Vietnam

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ABSTRACT
The Vu Gia Thu Bon (VGTB) basin constitutes the primary water supply in Central Vietnam. While climate change disturbs stream discharges and affects flood extremes, upstream dam development may intensify or mitigate such impacts. Therefore, this study provides a quantitative evaluation of long-term alterations in the flow regimes of the VGTB rivers from 1977 to 2020 resulting from the impacts of upstream anthropogenic developments. The datasets are divided into two periods, pre-2000 (1977–2000) and post-2000 (2001–2020), using different indices and analytical methods. The analyses show that since 2011, reservoir operations have reduced the maximum and high-flow discharges downstream in excess of climate change and land-use effects. However, due to the impact of water transfer by the Dak Mi 4 hydropower dam from the Vu Gia River to the Thu Bon River through a diversion channel, the minimum and low-flow discharges decreased in the pre-dam period and increased in the post-dam period.

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1 Introduction

Typhoons are a severe natural hazard that affects river basins worldwide. Stronger typhoons usually produce heavy rainfalls, enormous wind speeds, higher waves, and storm surges (Larson *et al.* 2014). The consequences of typhoons include damage to infrastructure, agricultural production and riverbanks; coastal erosion; and the loss of human life. The Vu Gia Thu Bon (VGTB) basin (Fig. 1(a)) is located in the central coastal region of Vietnam, which is prone to a tropical monsoon climate (RETA 2011, Ribbe *et al.* 2017). According to the Japan Meteorological Agency (JMA), the area is frequently affected by typhoons and tropical depressions. In Vietnam, the majority of typhoons (70%) occur in the central parts of the country (Fig. 1(b)), according to the Vietnam General Department of Meteorology and Hydrology. Typhoons, tropical depressions, and cold air have caused heavy rain, leading to severe flooding. Wang *et al.* (2014)'s key findings indicate that increased rainfall in Central Vietnam since the beginning of the 20th century is associated with increased typhoons. Indeed, it has been revealed that there is a strong correlation between the increasing trend of stronger typhoons and the extension of the typhoon season over the last decade. Consistently, the maximum rainfall has been found to increase, along with the higher frequency of typhoons on the south coast of Vietnam (Tan and Thanh 2013). In 2020, four typhoons (i.e. Noul, Linfa, Molave, and Vam Co) affected the VGTB river basin, three of which had magnitudes higher than the long-term average (Fig. 1(d)). Due to the impacts of typhoons, the flood peak at the Ai Nghia and Giao Thuy hydrological stations recorded in the downstream basin reached 12.84 m and 8.97 m, respectively, higher than those in 1999 (Fig. 1(a)). According to the report of the Commanding Committee for Disaster Prevention and Search and Rescue in Quang Nam Province, as a consequence of typhoons in 2020, 28 people died, 19 people were reported missing, and 200 people were injured, and the typhoons resulted in total economic losses of approximately $460 million. The increase in the frequency (Fig. 1(d)) and intensity of typhoons may be a result of climate change.

The VGTB basin ranks fourth in terms of hydropower potential in Vietnam (ICEM 2008); many hydropower plants have been built and are operating in the region. Although hydropower is essential for the country, it has significant adverse effects on river systems, such as flow regime alterations, sediment reduction, flooding, drought, water shortages, agricultural production decreases, and saline intrusion intensification (Dinh 2016, Laux *et al.* 2017, Ribbe *et al.* 2017, Firoz *et al.* 2018). The Vu Gia River is the primary source of water for Da Nang city and regional agricultural activities. A large volume of water was diverted from the Vu Gia River to the Thu Bon River (Fig. 1(a)) when the Dak Mi 4 hydropower plant began operation in 2011. This water diversion led to deficits in the water supply for agriculture and drinking water and increases in salinity intrusion in Da Nang city. Consequently, a polemic controversy between Da Nang city and Quang Nam Province (Fig. 1(a)) regarding the impact of hydropower development has begun. Da Nang city blames Quang Nam Province for a large-scale hydropower cascading system that negatively affects downstream water resources in the

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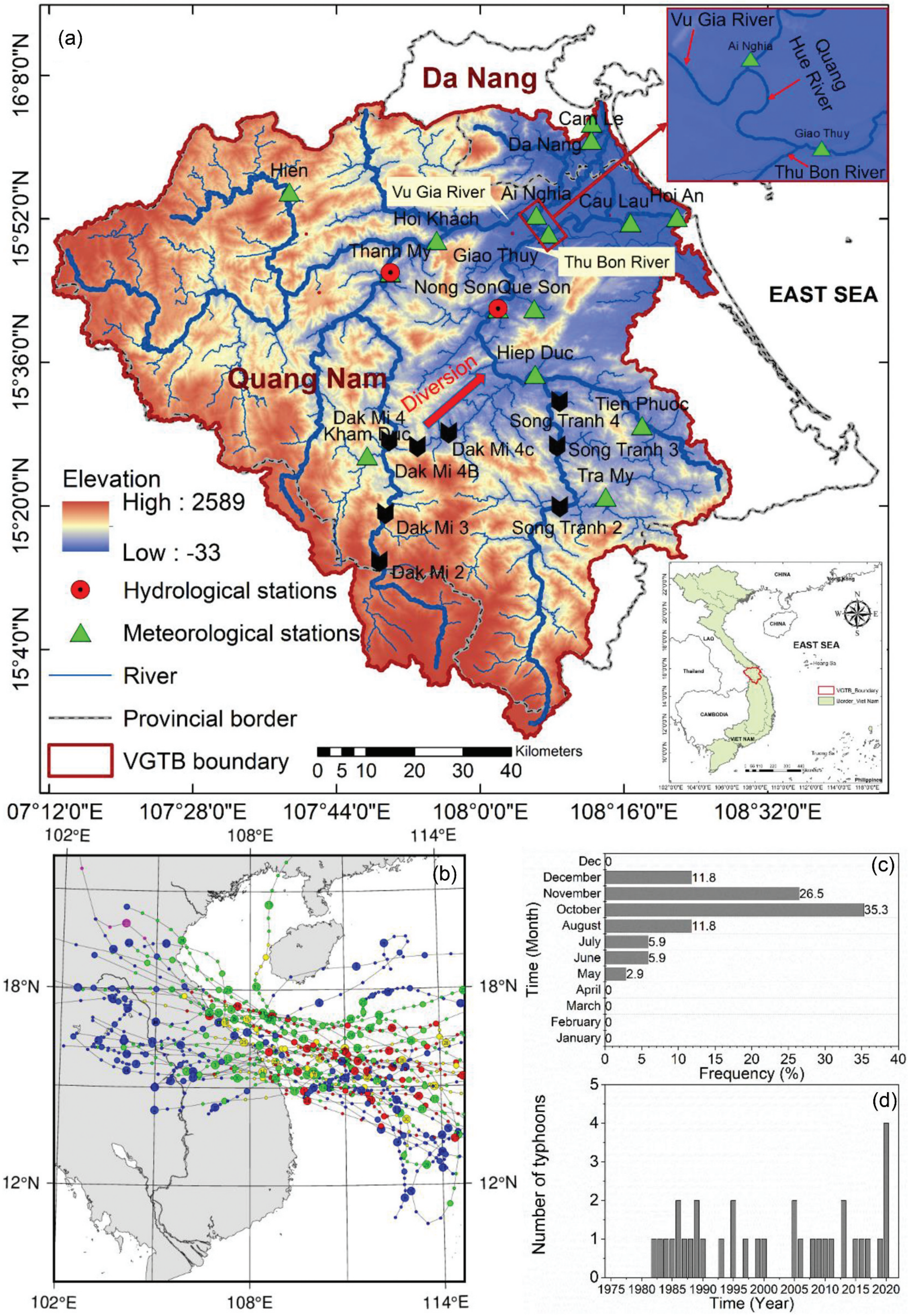

Figure 1. (a) Map of the VGTB River basin, (b) trajectories of typhoons affecting the basin, (c) frequency of typhoons by month, and (d) number of typhoons by year (Source: National Institute of Informatics, Japan. http://agora.ex.nii.ac.jp/) (Japan Meteorological Agency 2013).

dry season (Nauditt *et al.* 2017). Therefore, quantification of the cascading effects of hydropower dams developed in Quang Nam Province and in the entire VGTB basin on the flow regimes in Da Nang city is urgently needed to ease this conflict.

A complex series of impounding reservoirs in the VGTB basin have been built (18 reservoirs) or planned (42 reservoirs) to make the best use of elevation differences and maximize the power generated through water diversion without compensating for reductions in the water level and environmental flow.

The distribution of these dams is heavily concentrated on the Vu Gia River, with 12 small and large reservoirs, of which two diversion channels divert water to the Thu Bon River. Firoz *et al.* (2018) highlighted the impacts of eight upstream dams (six in the Vu Gia and two in the Thu Bon) over a short operational period in 2013 on drought risk and streamflow. That study concluded that the Vu Gia River has a high risk of hydrological drought, which impacts the water supplied for irrigation and drinking water in Danang city, especially in the dry season. In the rainy season, these eight dams reduced the monthly average discharge by 30% (Firoz *et al.* 2018). In contrast, the monthly average flow discharge increased in the Thu Bon River from 24 m^3/s to 62 m^3/s in the dry period (Firoz *et al.* 2018). Additionally, previous studies analysed the impacts of a limited number of dams following operation periods of two years or more. However, the cumulative effects of these 18 dams, plus additional dams built over an extended period ending in 2020, on flow regime alterations due to a changing climate remain unknown and constitute the root of this research.

Nauditt *et al.* (2017) examined the individual impact of a hydropower reservoir with a diversion channel from the drier Vu Gia River to the wetter Thu Bon River from 1980 to 2013. These diversion processes reduced the mean monthly discharge in Vu Gia by 13–125 m^3/s. An additional individual assessment of the Song Tranh 2 reservoir in the Thu Bon River was performed to evaluate the changes in the released flow based on daily measurement data from 1996 to 2018 (Ha and Coynelb 2019). The study revealed that the average flow after the Song Tranh 2 reservoir opened decreased by 103 m^3/s, from 864 m^3/s to 761 m^3/s. Phuong *et al.* (2020) used the classical/modified Mann-Kendall and innovative-Sen methods to evaluate the trend of hydrometeorological factors in the VGTB basin over 36 years, from 1979 to 2014. The authors used a continuous data series from 1979 to 2014 to assess the general trend, which did not accurately reflect the flow characteristics within a reservoir. The authors used only the classical/modified Mann-Kendall and innovative-Sen methods, which do not reflect all the flow regime behaviours of the basin. These studies are limited in that they do not consider the effects of all reservoirs and long-term flow alterations at all stations. The study period is relatively short, and flow indicators have not thoroughly evaluated the flow regime alterations. Therefore, in the present study, we attempt to assess flow regime alterations based on a more extended period (1977–2020) and consider all dams and flow transfer impacts.

Understanding the long-term changes in the flow regime in the VGTB basin is of vital importance for sustainable management and water resource distribution in the coming decades. However, the previous studies are limited in terms of data range (up to 2014) and thus do not assess the cascading effects of all dams (many of which were built more recently) on the flow regime alterations in the VGTB basin. Accordingly, this study aims to quantify changes in the long-term flow regimes in the VGTB basin due to climate change, reservoir cascading, and construction of water diversion structures. The contributions of this paper are (1) a comprehensive evaluation of the long-term flow regime alterations considering a comprehensive range of hydrological alteration indicators and (2) an understanding of the impacts of reservoir operations, climate change/variability, and land-use change on the flow regimes. The results of our research provide evidence-based data regarding historical changes in the hydrology of the VGTB basin, providing stakeholders with helpful information for river basin management and solutions for informing future preparedness and sustainable development.

2 Materials and methodology

2.1 Study area

The VGTB river basin (Fig. 1(a)) is the major basin in the Central Coast region, Vietnam, with an area of 10 350 km^2. The basin has a tropical monsoon climate and two distinct seasons: dry summer (January–August) and heavy rain (September–December). The average annual rainfall varies significantly, from 2000 mm in the central and downstream regions to more than 4000 mm in the southern mountainous areas. There are seasonal differences, with 65% to 80% of the annual rainfall concentrated from September to December (RETA 2011). In the eight months of the dry season, rain accounts for only 20% to 35% of the annual rainfall (Nauditt *et al.* 2017). The driest period usually falls between February and April, with approximately 3% to 5% of the total annual rainfall.

The discharge of the basin is divided into three different seasons: low flow (January–April), transition flow (May–August), and high flow (September–December). Due to the difference in the rainfall distribution, the runoff in the VGTB basin varies significantly between seasons. The flow in the rainy period accounts for approximately 62.5% to 69.2% of the total annual flow. Every year, the basin is frequently hit by four to eight floods. The flood peaks usually occur in October and November due to different weather patterns, such as typhoons, tropical depressions, cold air, and northeast monsoons (Fig. 1(c)) (T. T. Vu *et al.* 2011). The frequency of cyclones ranges from one to two per year (Fig. 1(d)).

Figure 1(a) shows 18 existing dams and diversion facilities and the river gauging stations considered in this study. There are six reservoirs on the Thu Bon River, with a total storage volume of 1575 million m^3 (Fig. 2(a)). There are 12 reservoirs in the Vu Gia basin, with a total storage volume of 1335 million m^3 (Fig. 2(b)). Eight hydropower plants affect the flow at the Thanh My and Nong Son stations: Dak Mi 2, Dak Mi 3, Dak Mi 4, Dak Mi 4B, and Dak Mi 4C in the Vu Gia basin and Song Tranh 2, Song Tranh 3, and Song Tranh 4 in the Thu Bon basin (Fig. 1(a)). The Dak Mi 4 plant in the Vu Gia basin was constructed in 2007 and began operation in 2011. A tunnel was built in the Dak Mi 4 hydropower plant to divert water and sediment from the Vu Gia River to the Thu Bon River (Fig. 1(a)). This diversion led to a significant alteration of the basin's flow regime which is attributed to hydrological, drought and saline intrusion during the dry season in Da Nang city (Firoz *et al.* 2018).

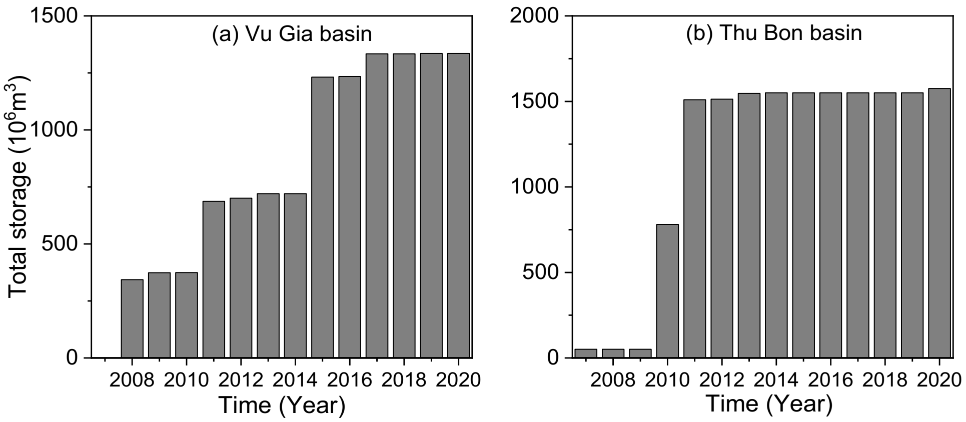

Figure 2. Total storage of hydropower dams in the (a) Vu Gia basin and (b) Thu Bon basin (ICEM 2008, MOIT 2015).

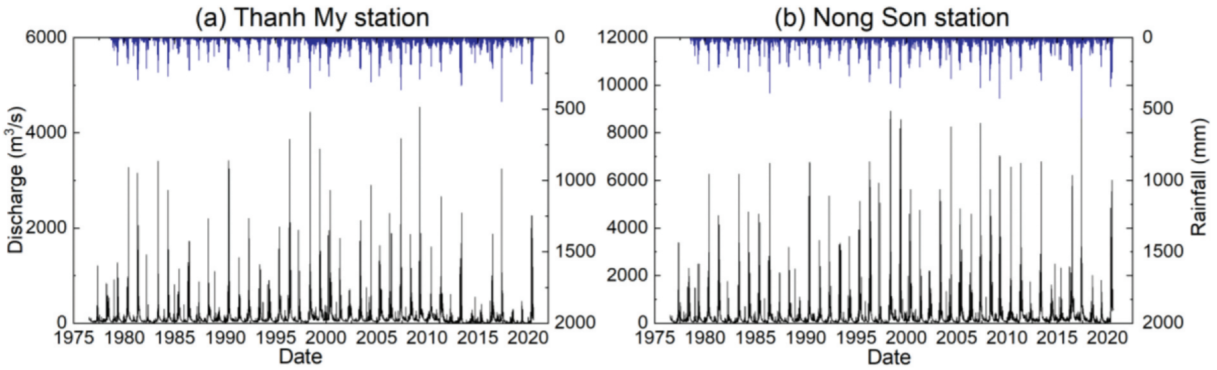

Figure 3. Daily discharge and rainfall at the (a) Thanh My station and (b) Nong Son station. The black line is the discharge, and the blue (shaded) line is the rainfall.

2.2 Data collection

In this study, rainfall data from 15 raingauges were collected from the Mid-Central Regional Hydro-Meteorological Center (Fig. 1(a)). Because of the sparse distribution of raingauges (15 gauges) in the basin, we interpolated the rainfall data from those stations to make a spatial map using the kriging method in ArcGIS 10.4 following the method of Duong and Gourbesville (2014). The discharge and water level data at the Thanh My and Nong Son stations (the only two stations monitoring discharges in the basin) were collected from 1977 to 2020, and the dataset was treated for gaps and missing data (Fig. 3). Data on the operation of the hydropower plants were obtained from the Natural Disaster Prevention and Control Department of Quang Nam Province (NDPAC). Hydraulic infrastructure data were also obtained, from Decision 1865/QD-TTg: Procedures for Operating Reservoir Systems in the VGTB River Basin (Government of Vietnam 2019). Land use in 2001, 2005, 2010, and 2020 was collected from the project “Land Use and Climate Change Interaction in Central Vietnam (LUCCi)” (www.lucci-vietnam.info) to assess the effect of land-use changes on runoff.

2.3 Methodologies

The flow regime is analysed based on the following methods: statistical trend tests (Mann-Kendall, Sen’s slope), indicators of hydrologic alteration (IHA), the index of hydrological regime alteration (FQ), and flow regime metrics. The flood characteristic indices are analysed as a peak over threshold (POT) using the generalized Pareto distribution (GPD). We want to investigate the cumulative impacts of all dams after construction from 2001 to 2020 and prior to construction from 1977 to 2000 to be considered as climate change impacts. Therefore, the research is divided into two periods: pre-2000 (1977–2000) and post-2000 (2001–2020).

2.3.1 Statistical trend tests

The nonparametric Mann-Kendall test and the slope method of Sen are used to evaluate the long-term discharge and rainfall changes. The nonparametric Mann-Kendall test is commonly employed to detect monotonic trends (increasing or decreasing) in data collected over time. The Mann-Kendall test is used to determine the tendency of long-term data (Kendall 1938, Mann 1945), and the rate of change is estimated using the slope method of Sen (Sen 1968).

2.3.2 Indicators of hydrologic alteration (IHA)

IHA is a software program developed by scientists at the Nature Conservancy (Richter *et al.* 1996, 1998, 2003). IHA provides valuable information for those trying to understand the hydrological impacts of human activities and develop environmental flow recommendations for water managers. IHA analysis can help statistically describe how patterns have changed for a particular river or lake due to abrupt impacts

Table 1. Flow regime metrics used in the impact assessment of long-term alterations in the VGTB basin.

Group	Regime characteristic	Hydrologic metric	Units
Magnitude	Average flow	Mean daily discharge of a year	m^3/s
		Mean daily discharge in each month during the low-flow period	m^3/s
		Mean daily discharge in each month during the transition-flow period	m^3/s
		Mean daily discharge in each month during the high-flow period	m^3/s
		Discharges in the 40th and 60th percentiles of the FDC: Q40 and Q60	m^3/s
	High flow	Annual one-day maximum discharge	m^3/s
		Extreme high-flow discharge Q10 (10th percentile of the FDC)	m^3/s
	Low flow	Annual one-day minimum discharge	m^3/s
		Extreme low-flow discharge Q90 (90th percentile of the FDC)	m^3/s
Timing	High flow	Julian date of the one-day maximum discharge	day
	Low flow	Julian date of the one-day minimum discharge	day
Duration and frequency	High flow	Index of hydrological regime alteration in high flow: FQ-high flow	%
	Low flow	Index of hydrological regime alteration in low flow: FQ-low flow	%

such as dam construction or land and water use changes (Opperman 2006). This method includes 32 hydrological indicators, which are categorized into three large groups: (1) magnitude, (2) timing, and (3) duration and frequency (Table 1).

2.3.3 Index of hydrological regime alteration (FQ)

The FQ, adopted from Alcayaga *et al.*, evaluates changes in the frequency and duration of high flow and low flow.

$$FQ(\%) = \frac{NQ_{post}}{NQ_{pre}} \times 100 - 100 \tag{1}$$

where FQ $(\%)$ indicates the frequency of change, and NQ_{pre} and NQ_{post} are the number of days when the flow is higher than the high flow or lower than the low flow in the pre-2000 and post-2000 periods, respectively.

2.3.4 Impact assessment of the flow regime metrics

Reservoir operation depends mainly on operational objectives and hydrometeorological conditions and can lead to changes in flow regimes (Zhang *et al.* 2018). To see changes over the long term, flow metrics (magnitude, variability and frequency, duration, timing, and rate of change) are used (Zhang *et al.* 2018, Van Binh *et al.* 2020). Twenty-three indicators in flow mode metrics over different years are used to evaluate the effects of reservoirs, including relative and absolute values (Table 1). The equation for calculating these values is adopted from Zhang *et al.* (2018) and Van Binh *et al.* (2020).

$$AD^i = V^i_{post} - \bar{V}^i_{pre} \tag{2}$$

$$RD^i = \frac{AD^i}{\bar{V}^i_{pre}} \times 100\% \tag{3}$$

$$\bar{V}^i_{pre} = \frac{\sum_1^N V^i_{pre}}{N} \tag{4}$$

where AD and RD are the absolute and relative deviations of the i^{th} metric, respectively; V^i_{post} and V^i_{pre} are the values of the i^{th} metric in the post-2000 and pre-2000 periods, respectively; $\bar{V}^i_{pre}$ is the mean value of the ith metric in the pre-2000 period; and N is the number of years in the pre-2000 period. If the deviation is greater than 0, the flow regime metrics are positively impacted. If it is less than 0, then the flow regime metrics are negatively impacted. When it is equal to 0, the flow regime metrics have no impacts. The relative difference is divided into five grades based on the percentiles adopted by Zhang *et al.* (2018): slight (−15% ≤ RD < −5% or 5% < RD ≤ 15%), moderate (30% ≤ RD < −15% or 15% < RD ≤ 30%), high (−45% ≤ RD < −30% or 30% < RD ≤ 45%), extreme (RD < −45% or 45% < RD), and no impact (−5% ≤ RD ≤ 5%).

2.3.5 Peak over threshold (POT) method

The POT method is used to analyse the flood frequency for the Vu Gia and Thu Bon basins. The POTs are the flood peaks that are more significant than a given threshold in each year. POT modelling provides additional flexibility and a more comprehensive description of peak floods (Lang *et al.* 1999).

The POT method depends on two factors: independent criteria and threshold selection. Therefore, how the threshold is selected is important. The first step is the consideration of the independence conditions, and the second step is the threshold selection. The distribution of the POT series can be determined by the GPD proposed by Pickands (1975).

3 Results

3.1 Alterations of the flow regime in the dry season

For the flow magnitude, the low-flow discharge of the Vu Gia (one-day minimum, Q90, May–August) was mainly positively impacted at slight to extreme grades from 2001 to 2011 and negatively affected at severe rates from 2012 to 2020 (Fig. 4(a)). The low-flow discharge of the Thu Bon was positively and negatively impacted to a significant degree before becoming positively impacted from 2012, except for 2020, in which it was negatively impacted (Fig. 4(b)). The annual impact variation in the dry season increased slightly in the Vu Gia but increased considerably in the Thu Bon in the post-2000 period (Fig. 5, Table 2). The increased rates of minimum and low-flow discharges were 1–21% for Thanh My and 20–57% for Nong Son.

For the flow variability and frequency, the impacts of the flow metrics were negative to positive in the Vu Gia starting in 2011 (Fig. 4(a)). The most impacted areas in the Thu Bon showed extremely negative grades (Fig. 4(b)). The duration of the low-flow season in the post-2000 period

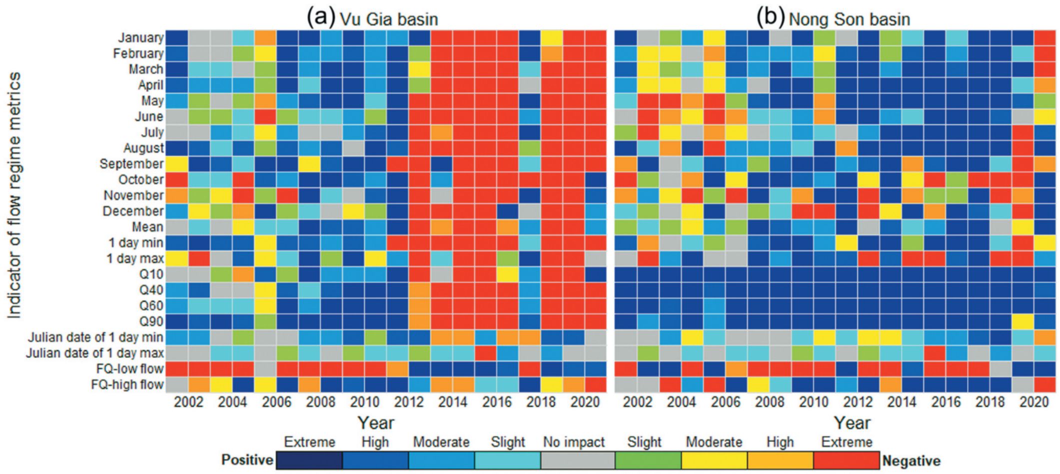

Figure 4. Heatmap quantifying the alteration of the flow regime metrics in the Vu Gia and Thu Bon basins. Blue indicates a positive impact, and red indicates a negative impact.

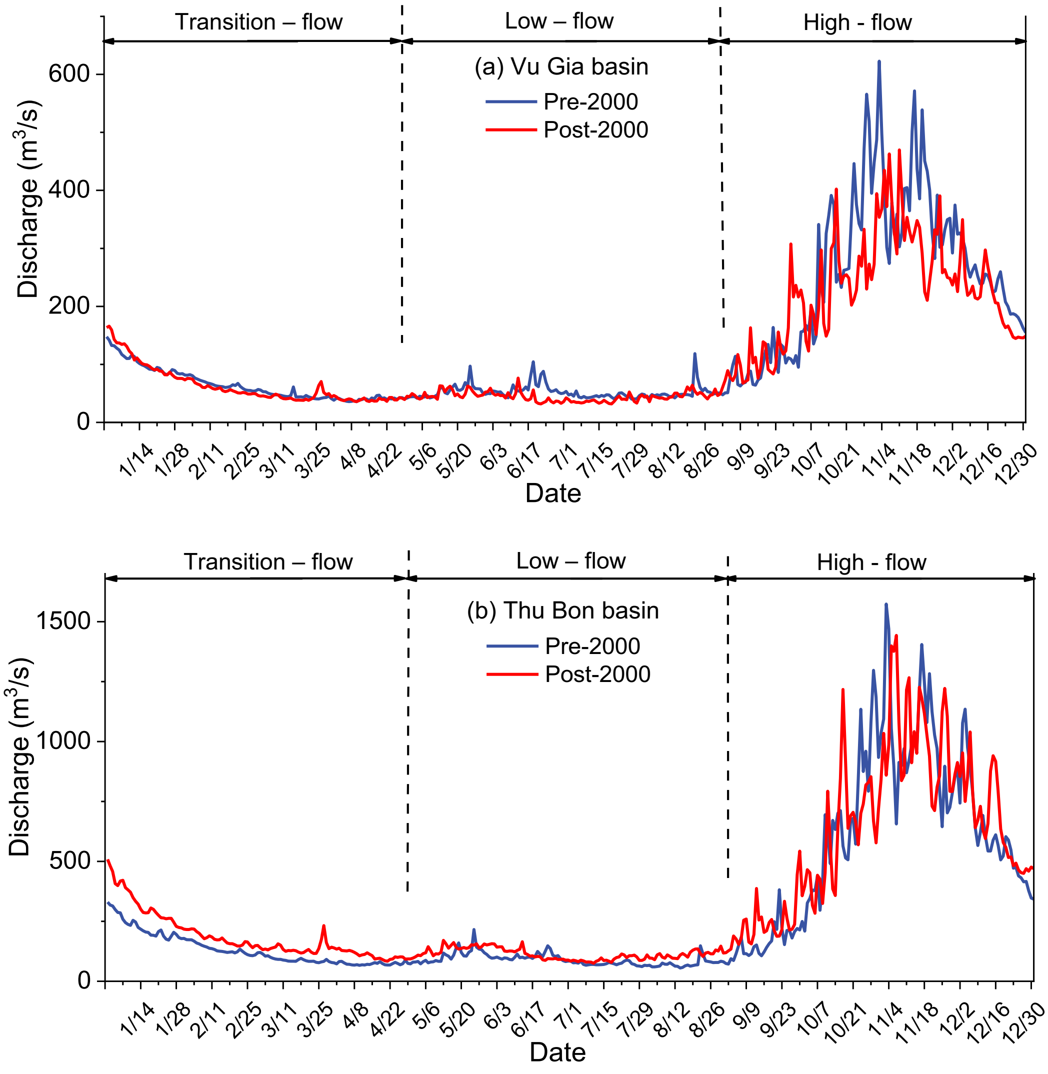

Figure 5. Differences in the discharge hydrographs between the two periods in the transition-flow, low-flow, and high-flow seasons in (a) the Vu Gia basin and (b) the Thu Bon basin. The blue line is the discharge in the pre-2000 period, and the red line is the discharge in the post-2000 period.

Table 2. Results of the IHA analysis to determine discharge alterations at the Thanh My and Nong Son stations.

		Thanh My station			Nong Son station		
Indicator	Units	Pre-2000	Post-2000	Deviation magnitude (%)	Pre-2000	Post-2000	Deviation magnitude (%)
January	m^3/s	92	100	8 (9)	194	234	40 (20)
February	m^3/s	59	59	1 (1)	116	148	32 (27)
March	m^3/s	43	47	4 (9)	76	119	43 (57)
April	m^3/s	34	38	5 (13)	59	91	32 (53)
May	m^3/s	40	41	2 (4)	80	130	50 (62)
June	m^3/s	38	41	3 (7)	76	97	21 (27)
July	m^3/s	39	40	1 (2)	61	72	11 (19)
August	m^3/s	39	42	3 (7)	56	96	40 (72)
September	m^3/s	54	62	7 (14)	88	139	50 (57)
October	m^3/s	126	181	55 (44)	297	322	25 (8)
November	m^3/s	222	224	2 (1)	606	570	−37 (−6)
December	m^3/s	179	200	22 (12)	427	482	55 (13)
Annual	m^3/s	80	90	10 (12)	178	208	30 (17)
One-day minimum	m^3/s	22	23	1 (4)	30	40	10 (34)
Three-day minimum	m^3/s	24	24	1 (3)	31	43	12 (40)
Seven-day minimum	m^3/s	25	26	1 (4)	33	47	14 (41)
30-day minimum	m^3/s	30	33	4 (12)	40	62	22 (55)
90-day minimum	m^3/s	36	43	8 (21)	62	86	24 (40)
One-day maximum	m^3/s	1995	1875	−120 (−6)	4635	5625	990 (21)
Three-day maximum	m^3/s	1180	1219	39 (3)	3408	4527	1119 (33)
Seven-day maximum	m^3/s	816	843	27 (3)	2144	2904	760 (35)
30-day maximum	m^3/s	497	438	−59 (−12)	1247	1286	39 (3)
90-day maximum	m^3/s	278	293	15 (5)	748	801	53 (7)
Date of minimum	Day	172	191	19 (11)	225	219	−6 (−3)
Date of maximum	Day	301	311	10 (3)	304	315	11 (4)
Low pulse count	Number	13.0	6.5	−7 (−50)	10.0	8.5	−2 (−15)
Low pulse duration	Day	4	5	1 (27)	5	2	−3(−56)
High pulse count	Number	7.5	7.5	0 (0)	7.5	10.0	3 (33)
High pulse duration	Day	3	2	−1 (−33)	3	3	0 (0)
Rise rate	Number	6.8	6.6	0 (−3)	15.4	20.0	5 (30)
Fall rate	Number	−4.2	−4.2	0 (−2)	−8.0	−16.1	−8 (102)

increased by 25% in the Vu Gia and decreased by 60% in the Thu Bon (Table 2).

For the flow timing, the Julian date of the minimum discharge was delayed from 172 to 191 days (19 days) in the post-2000 period in the Vu Gia. The appearance of the minimum release in the Thu Bon occurred six days earlier, from 225 to 219 days (Table 2).

There was a distinguishable deviation in the annual impact variations in the basins in the dry season. The low-flow discharge began changing in approximately 2011; the change became obvious in 2012. The red colour (extreme negative) extended from 2012 to 2020 for the Vu Gia. In contrast, the blue colour (extreme positive) was common from 2012 to 2019 for the Thu Bon. These changes were consistent with the operating years of the Dak Mi 4 dam in the Vu Gia basin and the Song Tranh 2 dam in the Thu Bon basin. In contrast, the regulation of Dak Mi 4 decreased the mean daily inflow annually in the Vu Gia. As a result, the regulation of the dam increased the expected flow variability and low-flow frequency.

3.2 Alterations of the flow regime in the rainy season

The results from the POT method (Fig. 6 (a) and (b)) served as a guideline for analysing the flood frequency and identifying peak floods. The thresholds from the POT method for the Vu Gia and Thu Bon basins were 850 and 2400 m^3/s, respectively. This method allowed us to characterize the statistical distribution of shorter record lengths post- and pre-dam. In the Vu Gia, based on the Mann-Kendall test, the discharge increased statistically from 1977 to 2000 and decreased statistically from 2001 to 2020. In the Thu Bon, the trends in the two periods increased. In contrast to Firoz *et al.* (2018), we found that the longer period had a statistically significant frequency. Figure 7 illustrates the results of the flood frequency distribution for the Vu Gia and Thu Bon basins based on the GPD. The frequency of flood flows in the post-2000 period was smaller than that in the pre-2000 period in the Vu Gia (Fig. 7(a)). Water received from the Vu Gia combined with reservoir operations led to a higher flood frequency in the Thu Bon (Fig. 7(b)).

Due to anthropogenic intervention in the post-2000 period, the maximum discharges in the Vu Gia decreased by 6%, and those from the Thu Bon increased by 21% (Table 2). The magnitude of the high-flow discharges (one-day maximum, Q10, September–December) in the Vu Gia were positively impacted from 2001 to 2011 before becoming negatively impacted with small to severe rates from 2012 to 2020 (Fig. 4(a)). For the Bon, high-flow discharges were positively and negatively impacted and clearly negatively impacted in 2019 (Fig. 4(b)). The high-flow discharge in both basins increased during the four months of the rainy season, except for November in the Thu Bon. The largest increases in the Vu Gia and Nong Son were 44% and 57%, respectively.

The high-flow frequency (FQ-high flow) in the Vu Gia changed from a positive to a negative impact grade starting in 2011, whereas it was mostly a positive grade in the Thu Bon (Fig. 4 (a) and (b)). The duration of the high-flow discharge decreased in the Vu Gia by 33% and did not change in the Thu Bon.

For the flow timing, the patterns of discharge hydrographs in the Vu Gia and Thu Bon were also altered (Fig. 5 (a) and ((b)): the peak discharge occurred 10 and 11 days later in the

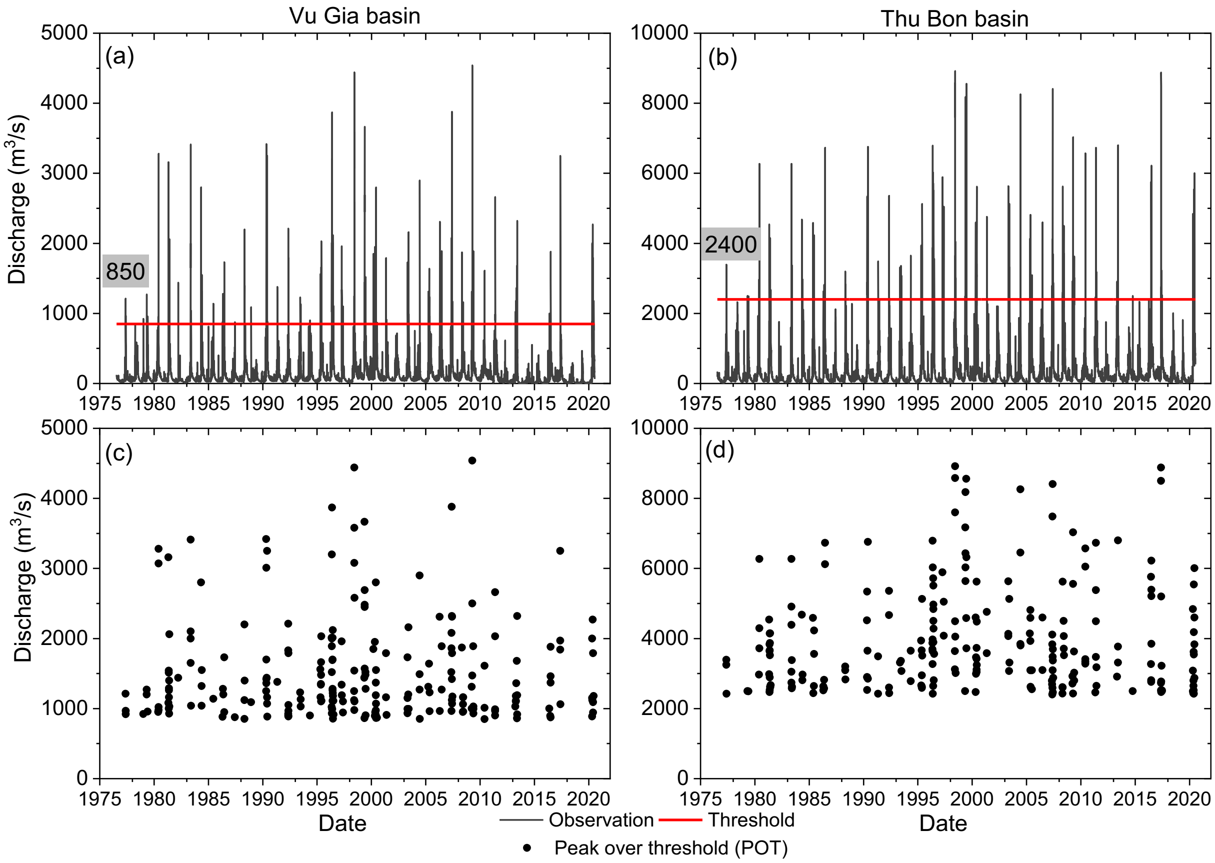

Figure 6. Threshold and POT samples selected in (a, c) the Vu Gia basin and (b, d) the Thu Bon basin. The black line is the observed discharge from 1977 to 2020, the red (horizontal) line is the threshold of the POT, and the point is the peak over the threshold.

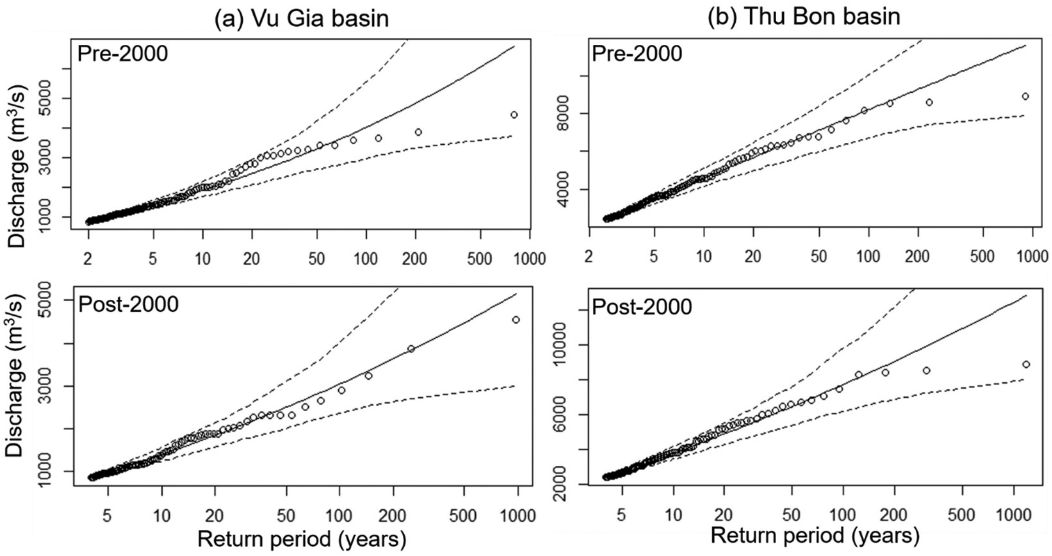

Figure 7. GPD of the POT in the pre-2000 and post-2000 periods for the (a) Vu Gia basin and (b) Thu Bon basin.

post-2000 period than in the pre-2000 period, respectively (Table 2).

3.3 Alterations of the average flow

The results of the Sen slope test show that the mean annual discharge in the Vu Gia (p = .012) and Thu Bon (p = .027) basins significantly increased in the pre-2000 period by 0.14 m^3/s/year and 0.25 m^3/s/year, respectively. However, during the post-2000 period, the annual discharge slightly decreased in the Vu Gia (by 0.21 m^3/s/year) and slightly increased in the Thu Bon (by 0.1 m^3/s/year) (Fig. 8).

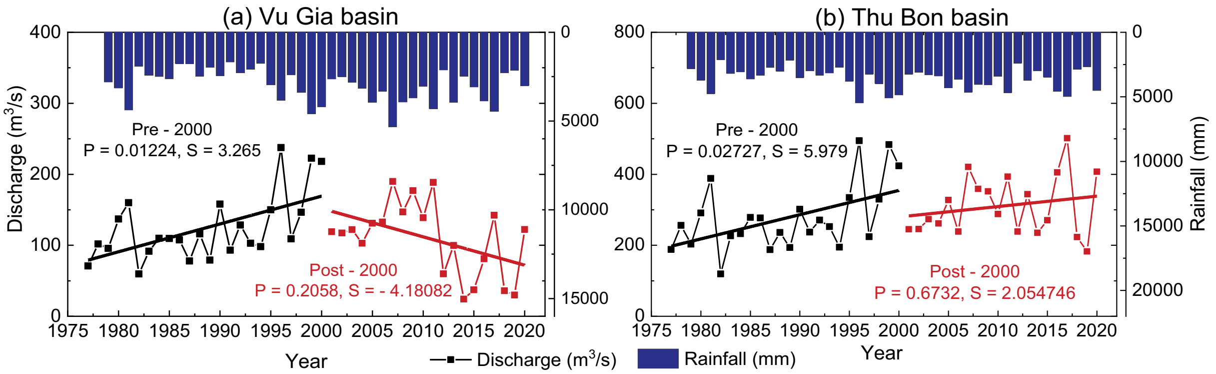

Figure 8. Long-term annual discharge and rainfall in the (a) Vu Gia basin and (b) Thu Bon basin. The black and red (shaded) lines are the discharge, and the blue bars are the rainfall.

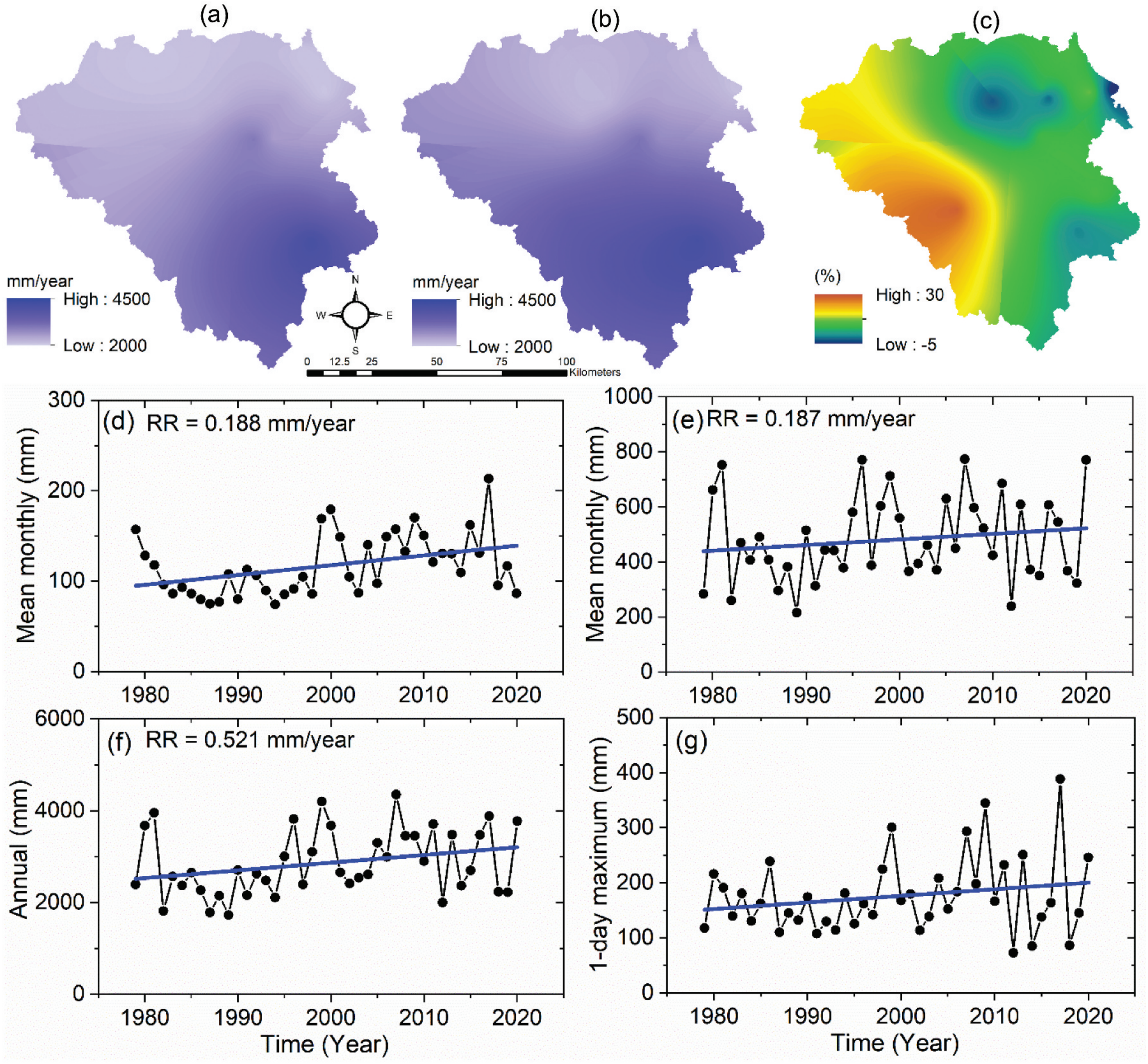

Figure 9. Temporal and spatial variations in the rainfall in the VGTB basin. (a) Mean annual rainfall in the pre-2000 period, (b) mean annual rainfall in the post-2000 period, and (c) mean annual rainfall changes in the post-2000 period relative to the pre-2000 period. (d–g) Long-term monthly means of the dry season, rainy season, annual rainfall, and one-day maximum values from 1979 to 2020.

The flow alteration in the dry and rainy seasons led to changes in the average flow in both basins. For the magnitude of the flow metrics, the average flow discharge in the Vu Gia (mean, Q40, Q60) was positively impacted from 2001 to 2011 and negatively impacted with extreme grades from 2012 to 2020 (Fig. 4(a)). The average flow discharge in the Thu Bon was mostly positively impacted (Fig. 4(b)). In the post-2000 period, the average annual flows in the Vu Gia and Thu Bon increased by 12% (from 80 to 90 m^3/s) and 17% (from 178 to 208 m^3/s), respectively (Table 2).

Table 3. Changes in the dry season, rainy season, and annual rainfall values in the pre-2000 and post-2000 periods.

		Pre-2000	Post-2000	
Time		Rainfall (mm)	Rainfall (mm)	Change (%)
Dry season	Mean	831	1054	+ 26.84
	One-day maximum	132	90	− 31.85
Rainy season	Mean	1881	1974	+ 4.94
	One-day maximum	301	389	+ 29.35
Annual		2712	3028	+ 11.65

3.4 Temporal and spatial variability in the relationships between rainfall and discharge

The impact of climate variability and the generated upstream inflow and operation of dam reservoirs are causing changes in time and space. Therefore, we wanted to investigate the climate change/variability drivers of flow alterations. Figure 9(a) and (b) show spatiotemporal variations in the rainfall in the VGTB basin. The most considerable changes in rainfall in the pre-2000 and post-2000 periods occurred mainly in the mountainous areas; smaller changes in rainfall occurred in the plains (Fig. 9(c)). The Mann-Kendall test of the rainfall showed no statistically significant trends in the dry season, rainy season, annual rainfall, and one-day maximum values in the VGTB basin. However, a slight increase was estimated from 1979 to 2020 (Fig. 9(d–g)). A comparison of the rainfall in the post-2000 period with that in the pre-2000 period shows that the rainfall increased slightly in the rainy season and annually and rose sharply in the dry season, by 4.94%, 11.65%, and 26.84%, respectively (Table 3).

In this paper, we mainly compare the pre-2000 and post-2000 periods. Therefore, we discussed these two periods first; then, we elaborated by further discussing post-2010 (2011–2020) to provide more evidence of dam impacts. Figure 10(b) shows that the correlations between the cumulative runoff and cumulative rainfall in the Thu Bon were linear in the three periods. However, in the Vu Gia, the curves were linear from 1979 to 2010 and changed suddenly starting in 2011 (Fig. 10(a)). This result shows that water transfer via the Dak Mi 4 plant reduced the flow on the Vu Gia River. Water stress on the Vu Gia resulted from the diversion of water at Dak Mi 4 to the Thu Bon.

The total rainfall in the dry season in the Vu Gia basin during the post-2010 period was 1090 mm, 47.4% higher than that in the pre-2000 period and 5.7% lower than that in the post-2000 period (Fig. 11(a)). The dry flow was 36.1% and 46.8% lower than those in the pre-2000 and post-2000 periods, respectively. The mean annual flow in the post-2010 period was 82 m^3/s, 33.9% and 40.4% lower than those in the pre-2000 and post-2000 periods, respectively (Fig. 11(a)). In the Thu Bon basin, the total rainfall values in the dry seasons of the pre-2000, post-2000, and post-2010 periods were approximately 1021, 1204, and 1193 mm, respectively. Once it began to receive flow from the Vu Gia River, the flow of the Thu Bon in the post-2010 period was higher than those in the pre-2000 and post-2000 periods by 59.5% and 42.7%, respectively (Fig. 11(b)). Currently, Da Nang city often lacks water for domestic and agricultural production in the dry season. In addition, saltwater intrusion is more severe. Da Nang city and Quang Nam Province often place stress on water sources from the VGTB basin. Da Nang city requires Quang Nam to compensate for the water transferred by the Dak Mi 4.

3.5 The impact of hydropower and diversion on the alteration flow regime

3.5.1 The impact of hydropower and diversion on flood control

The most critical flood control issues for the downstream part of the VGTB basin are the reduction in the peak flood and the duration of the high-water level (Nguyen 2020).

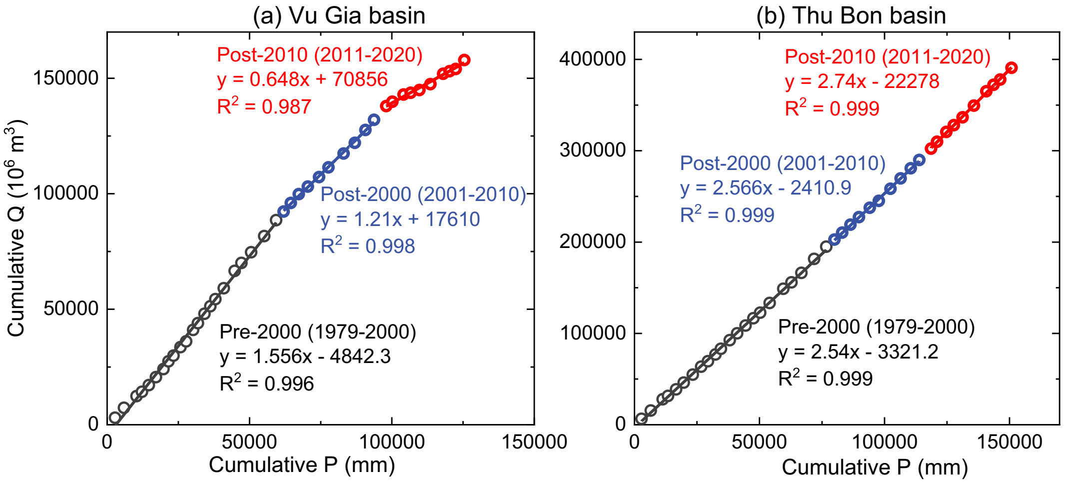

Figure 10. Curves of the cumulative rainfall and discharge in the pre-2000 (1979–2000), post-2000 (2001–2010), and post-2010 (2011–2020) periods for the (a) Vu Gia basin and (b) Thu Bon basin.

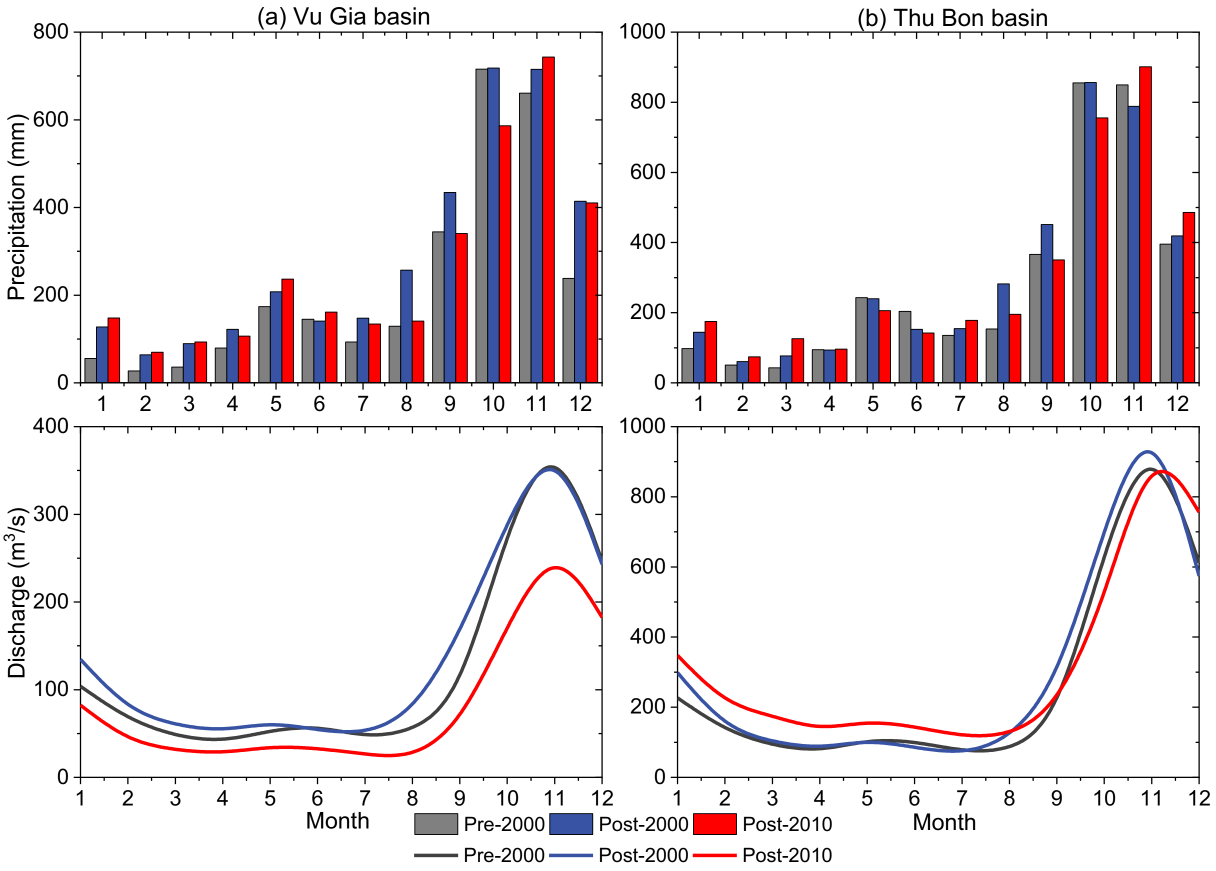

Figure 11. Monthly average rainfall and discharge of the Vu Gia and Thu Bon basins. The black line plots the pre-2000 (1979–2000) period, the blue line plots the post-2000 (2001–2010) period, and the red line plots the post-2010 (2011–2020) period.

The flood storage capacity influences the decrease in the peak flood downstream. It is important to forecast the flow to the reservoir to maintain a suitable storage capacity. Currently, there are few raingauges in the basin, which makes it challenging to accurately forecast the flow to the reservoirs. The large flood of 2017 is a typical example; the inaccurate flow forecast of the Dak Mi 4 reservoir did not lead to a cut-off flood peak, which resulted in flooding downstream (Fig. 12). The Song Tranh 2 reservoir had better forecasts and operation.

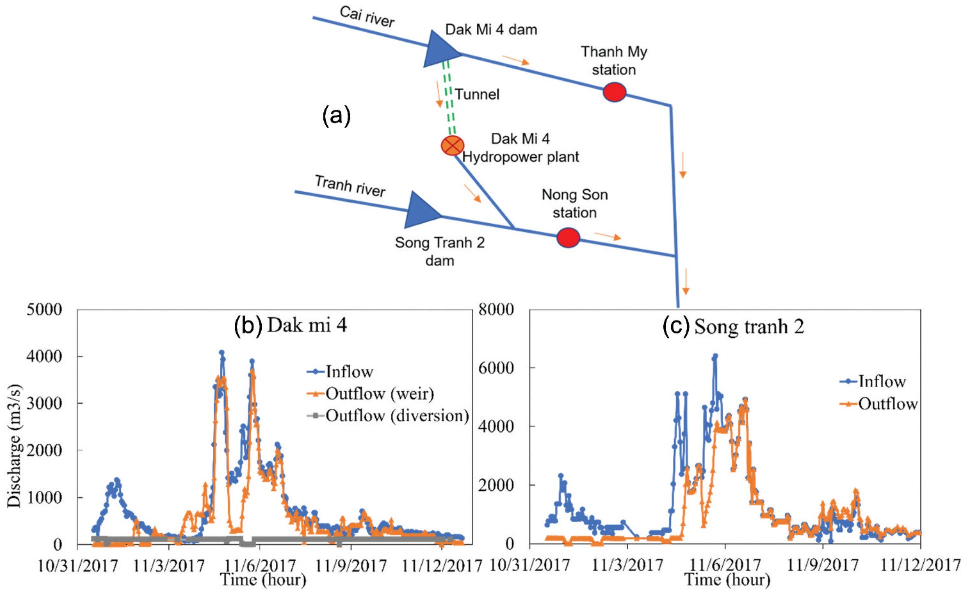

Figure 12. (a) River network and reservoirs upstream of the VGTB basin. (b) Inflow, outflow and diversion of the Dak Mi 4 reservoir. (c) Inflow and outflow of the Song Tranh 2 reservoir in the 2017 flood.

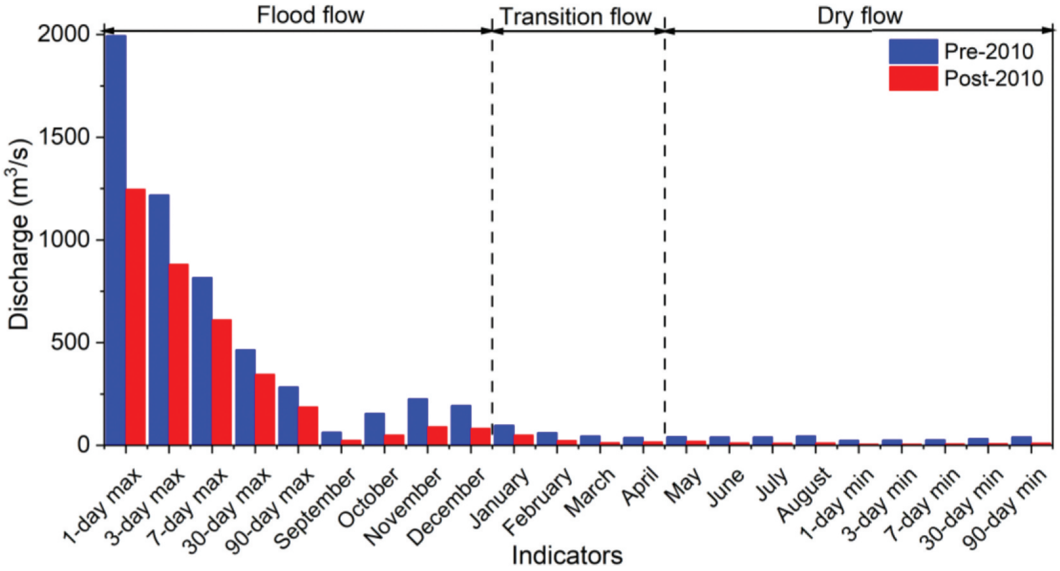

Figure 13. Changes in the extreme and monthly discharges before the Dak Mi 4 reservoir opened (pre-2010) and after the Dak Mi 4 reservoir opened (post-2010) at the Thanh My station from the IHA results.

3.5.2 *The impact of water diversion structures*

According to the research results of Firoz *et al.* (2018), the intensity and frequency of droughts in the entire VGTB basin mainly depend on upstream hydropower operation and water transfer from the Vu Gia basin to the Thu Bon basin by the Dak Mi 4 plant. The average annual amount of water transferred by the Dak Mi 4 plant is approximately 1.08×10^9 m^3 (average 34.17 m^3/s, 26.7% of the Vu Gia River's flow). Moreover, with high energy demand in the dry season, some of the water needed for the minimum release of the Vu Gia River was used for power generation and discharge to the Thu Bon River. Part of the sediment along the flow is transferred to the Thu Bon basin, which leads to an imbalance of the natural state in the Vu Gia basin. This imbalance affects the sediment and morphology downstream.

IHA was used to analyse the periods before and after the building of the Dak Mi 4 reservoir at Thanh My: pre-2010 (1977–2010) and post-2010 (2011–2020). The flow regime alterations were considerably reduced during the dry and rainy seasons (Fig. 13). The minimum and low-flow release decreased by 53.5–76.3%. The maximum discharges significantly decreased during the post-2010 period by 37.5%. Similarly, the high-flow clearance decreased by 57.3–67.4%. As a result, the date of the minimum discharge increased from 180 to 193 days.

4 Discussion

The results of the analysis show that the flow regime changes in the dry and rainy seasons in the two basins (Figs 4–8, Table 2). The annual discharge in the Vu Gia basin decreased from 2001 to 2020 (especially from 2011 to 2020), although the corresponding rainfall increased (Figs 9–11). Therefore, we argue that these alterations in discharge are mainly due to reservoir operations and water transfer. However, another factor is land use/cover (LULC), which also has a significant impact on watershed hydrology. Therefore, we investigated whether the impacts of land-use changes act as drivers of flow alterations.

4.1 *Drivers of flow alterations from land-use change*

To understand the hydrological regime of the basin, it is necessary to assess the relationship between the watershed hydrological processes and LULC change (Meiyappan and Jain 2012). LULC changes may significantly affect the watershed hydrological regime and surface runoff of the basin (Jia *et al.* 2007). To clarify the effects of LULC change on the runoff in the VGTB basin, LULC maps from 2001, 2005, 2010, and 2020 were used to analyse the river section upstream of the Thanh My and Nong Son stations. The analysis shows that the land cover in the upstream area is dominated by forests, followed by mixed agricultural land, built-up areas,

Table 4. Statistics of LULC change in the VGTB basin from 2001 to 2020, from upstream to Thanh My station in the Vu Gia basin and Nong Son station in the Thu Bon basin.

		Year 2001		Change in 2005 compared to 2001		Change in 2010 compared to 2001		Change in 2020 compared to 2001	
No.	Land-use types	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)
1	Forest	2710.98	51.89	−31.70	−1.17	100.69	3.71	59.16	2.18
2	Mixed agricultural land	2404.10	46.02	30.89	1.28	−112.92	−4.70	−78.44	−3.26
3	Built-up area	33.99	0.65	0.48	1.42	8.32	24.47	15.37	45.22
4	Water	74.91	1.43	0.32	0.43	3.91	5.22	3.91	5.22

and water (Table 4). The forest area increased by 2.18% from 2001 to 2020. The other LULCs changed minimally over time. This result is similar to the research of Nauditt *et al.* (2017). Therefore, LULC changes cannot explain the changes in flow in the VGTB basin, and thus the flow regime alterations are likely related to the operation of the reservoirs.

4.2 Challenges of water resource management in the downstream VGTB basin

The impacts of reservoir operation are particularly pronounced for the Vu Gia basin. Therefore, the Vu Gia basin is the most vulnerable. The Vu Gia basin mainly supplies water for Da Nang city and sizeable agricultural irrigation systems in Quang Nam Province (Fig. 1(a)). The flow and water level downstream during the dry season depend on the operation of the reservoirs. The flow from the reservoirs also maintains water levels to supply water for domestic use and agricultural production and to reduce salinity. The changes in flow impact the cropping pattern downstream, which is highly dependent on the water during the dry season. The reduction in flow during the rainy season is expected to reduce sediment and nutrient transport and possibly affect aquatic habitats (Pitlick and Wilcock 2001). The change in water quality due to sediment imbalance and the loss of habitats have potentially created long-term impacts for communities in the VGTB River basin.

Hydroelectric reservoirs upstream have retained significant amounts of coarse sand, gravel, and suspended sediment instead of transporting them downstream. This sediment reduction may aggravate erosion downstream from the dam. In addition, sand mining in the middle and downstream areas has removed large deposits of sediments from the riverbed. Finally, the changes in deposition have led to bed incision, which then decreases the water level. Bed incision has affected drinking water and agricultural production and increased saltwater intrusion. These issues have been detected in the Mekong and Red rivers (Kondolf *et al.* 2014, D. V. Vu *et al.* 2014, Nhan and Cao 2019, Van Binh *et al.* 2021). We anticipate that similar consequences are highly likely to occur in the VGTB basin. In recent years, saltwater intrusion hazard/risk has increased in Vu Gia River and strongly impairs socio-economic factors in Danang city, especially agricultural production and drinking water supply (Viet 2014, Nga *et al.* 2020).

5 Conclusions and outlook

We evaluated the long-term discharge changes in the VGTB river basin over 44 years (1977 to 2020) through a detailed analysis of runoff and related factors such as rainfall, land use, reservoir operation, and water diversion. We found that reservoir operation and water transfer by the Dak Mi 4 plant are the main reasons for flow alterations in the Vu Gia and Thu Bon rivers.

Based on the indicators analysed, the flow regime in the post-2000 period changed compared to that in the pre-2000 period. The Vu Gia basin changed more than the Thu Bon basin. Since 2011, reservoir operations have reduced the maximum and high-flow discharges downstream, exceeding the climate change effect. However, in the dry season, due to the impact of water transfer, the minimum, low-flow release increased in the Thu Bon basin and decreased in the Vu Gia basin. Reducing the flow downstream of the Vu Gia River during the dry season leads to a decrease in the water level, affecting the operations of pumping stations supplying domestic and agricultural water in Da Nang city and parts of Quang Nam Province. In addition, due to the decreased flow downstream, the salinity condition in Da Nang has become more severe in recent years. Salinity penetrates farther inland and at higher levels, seriously affecting the water supply.

Reservoirs have helped to regulate flow and reduce flooding in downstream areas. However, there are still some floods with low regulatory efficiency. The cause is indicated by the few raingauging stations upstream. Therefore, maximizing the positive efficiency of reservoirs and improving the flow forecasting of reservoirs by constructing more rainfall gauging stations is necessary.

We also note that in the entire VGTB basin, there are only two stations that measure upstream streamflow. The downstream tributaries include many hydropower plants. This leads to difficulty in fully investigating the streamflow and impact of reservoirs. Therefore, in our future work we will study the entire basin using a hydrological model.

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