Changes in the sediment load in the Red River system (Vietnam) from 1958- 2021 because of dam-reservoirs

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Abstract

The sediment regime of the Red River system has changed since dams and reservoirs were implemented, with implications for river processes downstream. We analyzed data for the daily discharge (Q) and suspended particulate matter (SPM) concentrations collected from 1958–2021 at the Son Tay hydrological gauging station, the outlet of the Red River system and entry to the delta. The results showed that the annual sediment load transported by the Red River system decreased significantly, by about 90.4%, over the 64-year study period. From 1958 to 1971, when there were no dams or reservoirs in place, the annual water discharges and sediment loads in the river system were about 115,592×10^6 m^3/yr and 115×10^6 ton/yr, respectively. From 1971 to 2016, a series of dam-reservoir systems were gradually implemented (Thac Ba (1971), Hoa Binh (1988), Tuyen Quang (2008), Son La (2010), Ban Chat (2013), Huoi Quang (2015), and Lai Chau (2016)). By 2016, the annual sediment load and water discharges in the Red River system had decreased significantly, and were 9×10^6 ton/yr and 88,709×10^6 m^3/yr, respectively. The data show that the discharge and sediment loads increased slightly from 2016–2021, perhaps reflecting the combined effects of human activities, such as land-use change, deforestation, and population increases. Climate may also have played a role in these increases, with changes in air temperature and increases in rainfall triggering severe soil erosion and large discharges of sediment into the Red River system.

1. Introduction

Human activities strongly influence riverine sediment fluxes at both the global and regional scale. From the construction to implementation phases, dam-reservoir systems cause considerable change in riverine sediment loads, leading to river bed degradation or aggradation downstream. Studies have estimated that 30% of the global sediment flux is trapped in large dam-reservoir systems (Le et al., 2007; Lu et al., 2015; Walling and Fang, 2003; Warrick et al., 2015). Worldwide, more than 58,000 large dam-reservoirs (height > 15 m) and approximately 2.8 million dams (with reservoir areas > 103 m^2) have been constructed to control floods and provide water supplies (Wang et al., 2021). Around 28% of the large dams are in Asia (Wei et al., 2021). During the construction and operation stages, dam-reservoir systems can have multiple environmental impacts, and can disturb ecosystems and the physical environment (Lu et al., 2015; Brandt, 2000). For example, dam-reservoir systems trap all the bedload and a percentage of the suspended sediment load, thereby reducing the supply of sediment to the river downstream. Depending on the relative change in the sediment supply and transport capacity, there may be a sediment surplus or sediment deficit downstream. Researchers have shown that the reach downstream of dam-reservoir systems is commonly characterized by sediment-starvation, or “hungry” water, leaving the bed and banks susceptible to erosion to compensate for the upstream sediment load (Schmidt and Wilcock, 2008; Kondolf et al., 2014). It is therefore important to investigate how the sediment loads and water discharges of rivers with dam-reservoir systems have been affected by the construction and operation of these structures.

In recent decades, to meet the water demand of the rapidly increasing population and intensive agriculture activities in China and Vietnam, a large number of dam-reservoirs have been constructed along the Red River system (Wei et al., 2021). The Red River (Song Hong in Vietnamese), in the northern part of Vietnam, is the second largest river in Vietnam after the Mekong River, and plays an important role in the economic, cultural, and social life of the Vietnamese people. The Red River drains a basin area of 169×10^3 km^2 (Dang et al., 2010) and had an annual average discharge of 3,740 m^3/s for the period from 1902–1990 at Son Tay (Vinh et al., 2014). Several researchers have studied how the dam-reservoir systems have influenced the annual water discharge and sediment transport regime in the Red River system (Le et al., 2007; Dang et al., 2010; Vinh et al., 2014; Lu et al., 2015; Le et al., 2018; Wei et al., 2021), and have mainly reported that the annual sediment loads transported by the Red River system fell into two periods, i.e., before and after the impoundment of the Hoa Binh and Thac Ba dam-reservoirs. For example, Le et al. (2007) reported that the total sediment load decreased by about 70% since the impoundment of the Hoa Binh and Thac Ba reservoirs in the 1980s. Other researchers (Lu et al., 2015; Le et al., 2018; Wei et al., 2021; Ve et al., 2021) reported that the sediment delivery decreased from about 50×10^6 to 12×10^6 t/yr when the Tuyen Quang (2008) and Son La (2010) dam-reservoirs came into operation. No researchers however, have so far reported how the newest large dam-reservoir systems, namely Ban Chat (2013), Huoi Quang (2015), and Lai Chau (2016), have influenced the sediment loads and water discharges in the Red River system. Further, as far as we know, there have been no attempts to quantify the overall impact of all the large dam-reservoir systems on the monthly and annual sediment fluxes at the delta scale.

A series of reservoirs and dams have been constructed and brought into operation along the Red River system since the 1970s. It is however difficult to obtain comprehensive information about all the dam-reservoirs along the Red River system as most of the data are not accessible to the public. In this study, therefore, we limited our investigation to the large-capacity dam-reservoir systems (> 0.1 km^3) along the part of the Red River system that is in Vietnam. There are seven dam-reservoirs with maximum storage capacities greater than 0.1 km^3, namely Thac Ba (1971), Hoa Binh (1988), Tuyen Quang (2008), Son La (2010), Ban Chat (2013), Huoi Quang (2015), and Lai Chau (2016) (Fig. 1), all of which have intercepted varying amounts of sediment. At present, there is a lack of understanding about how the sediment loads and water discharges have been influenced by these structures.

The aim of this study was to analyze a dataset of daily water discharges and suspended particulate matter (SPM) concentrations, collected between 1958 and 2021 at a permanent observation station (the Son Tay hydrological gauging station) near Hanoi, which is at the upstream limit of the dynamic tide and the entry point to the Red River Delta. We analyzed these long-term data to gain an understanding of how water discharges and sediment loads have changed in response to the construction and operation of the large-capacity hydropower dam-reservoir systems that have been implemented in the Red River system in Vietnam since 1958, with a view to offering advice about riverine planning and management.

2. Methods

2.1 Geography and general characteristics

The Red River rises in the mountains in Yunnan Province, China, at a mean elevation of 2,000 m. The Red River flows southeastward through China (48.8%), Laos (0.9%), and seven provinces in Vietnam (50.3%) before flowing into the Gulf of Tonkin (Nguyen et al., 2016) (Fig. 1). It is named the Song Hong in Vietnam because of its reddish-brown color that is caused by its huge load of iron-dioxide-rich sediments (Vinh et al., 2014). The basin has an average elevation of 1,090 m, and 70% of the basin has an elevation greater than 500 m a.s.l. More than 90% of the system flows through hilly upland areas (Le et al., 2018) (Fig. 1) before finally forming a fertile delta plain that is densely populated (Dang et al., 2010). Son Tay, at the outlet of the continental basin and the entrance of the Red River Delta, is downstream from the confluence of three main tributaries, namely the Lo River on the left bank, the Red River upstream of the main river, and the Da River on the right bank (Wei et al., 2021) (Fig. 1). The Da River (named Lixian Jiang in China) has its source in Yunnan Province close to that of the upper Red River, at an elevation of more than 2,000 m. The Lo River (named Panlong Jiang in China) also originates in China, and has its source at an elevation of about 1,100 m.

The climate in the Red River Delta is mainly governed by the sub-tropical East Asia monsoon system, and is characterized by alternating summer (dry season, end of November to April) and winter monsoons (rainy season, May to October, with an extension to November) (Piton et al., 2021; Vinh et al., 2009). The average annual rainfall in the Red River system in Vietnam is 1,600 mm, of which 85–95% occurs during the rainy season (Dang et al., 2010; Wei et al., 2021). Precipitation is the main source of runoff, which leads to wide seasonal variations in river flows. Accordingly, 90% of the annual sediment discharge is discharged to the sea during the rainy season (Vinh et al., 2009). The annual average temperature, humidity, and evaporation are around 24°C, 80%, and 900 mm, respectively (Duc and Umeyama, 2011).

2.2 Hydrology and reservoir impoundment

The hydrological regime of the Red River system is characterized by a unimodal tropical regime. The mean monthly maximum/minimum discharge ratio was 7.9 (1,085–8,600 m^3/s), and the mean annual water discharge was about 3,500 m^3/s, at the Son Tay station over the period from 1960 to 2008 (Dang et al., 2010; Lu et al., 2015). The discharge measured at the Son Tay station is equal to the sum of the discharge of the three major tributaries, the Da, Red (main stream), and Lo Rivers (Fig. 1) (Le et al., 2007). The data from this gauging station, therefore, are suitable for investigating the variations in the water discharges and sediment loads in the Red River system.

Seven large dam-reservoirs have been constructed in the upper reaches of the Red River system in Vietnam since the early 1970s. The Thac Ba dam-reservoir on the Red River, with a maximum storage capacity of 2.49 km^3, is the fourth largest reservoir and has been in operation since October 1971. Tuyen Quang on the Lo River has been in operation since December 2008. Hoa Binh on the Da River, the biggest dam in Vietnam, has been in use since December 1988. Further dam-reservoirs were constructed after 1988, to mitigate the siltation in the Hoa Binh dam-reservoir and to meet the need for economic growth, namely the Son La (in operation since December 2010) (Wei et al., 2021), Ban Chat (2013), Huoi Quang (2015), and Lai Chau (2016) dam-reservoirs (Table 1).

Table 1
Summary information about the large dam-reservoirs already impounded in the Red River system in Vietnam.

Dam	Construction began	Impoundment	Upstream watershed (km^2)	Capacity (km^3)
Thac Ba	8/1964	10/1971	6,170	2.49
Hoa Binh	11/1979	12/1988	57,285	9.45
Tuyen Quang	12/2002	12/2008	1,360	2.245
Son La	12/2005	12/2010	43,760	9.26
Ban Chat	1/2006	2/2013	2,017	2.137
Huoi Quang	1/2006	12/2015	2,930	0.184
Lai Chau	1/2011	12/2016	26,000	1.215

2.3 Sediment load estimates

Data for the daily water discharge, Q, and SPM from 1 January 1958 to 31 December 2021 observed at the Son Tay hydrological gauging station were obtained from the Vietnam Ministry of Natural Resources and Environment (MONRE). The suspended sediment concentrations were determined using a standard depth-integrated sampling procedure, in line with the Vietnamese national standard criteria. The SPM concentrations of samples collected once a day at the reference site were manually determined by filtering through pre-cleaned, pre-weighed Nuclepore filters with a pore size of 0.45 mm and a diameter of 47 mm in the laboratory. The sampling procedures have been described in more detail by Dang et al. (2010), Vinh et al. (2014), and Lu et al. (2015).

Using the daily data for the continuous suspended sediment concentration and the water discharge from the gauging station (Son Tay, Fig. 1) for the period from 1958 to 2021, the suspended sediment loads (SL, metric t/month and t/year) were computed as the product of the monthly and annual water discharges and the corresponding monthly and annual SPM data, following the method of Lu et al., 2015:

SL = 0.0864 × Q × C, (1)

where Q denotes the water discharge (m^3/s), C denotes SPM (g/m^3) and is derived from the daily observations, and 0.0864 is the conversion factor for metric tons/day.

2.4 Mann–Kendall test

The rank-based Mann–Kendall test is widely used to determine temporal trends in hydrological and meteorological data (Lai et al., 2021; Das et al., 2021; Ali et al., 2019). Here, the non-parametric test was applied to analyze the monotonic trends in the time series, based on the annual means for the suspended sediment concentrations, water discharge, and sediment loads for the period from 1958 to 2021 at the 95% confidence level. We investigated the existence of a trend in a time series with a null hypothesis (H_0) of no trend. The linear slope of the trend was determined using the method suggested by Sen (1968) (Gumus et al., 2022). Mann–Kendall test statistics (S) for time series can be calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i)$$

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$$sign\left(x_j - x_i\right) = \begin{cases} +1\, when \left(x_j - x_i\right) > 0 \\ 0\, when \left(x_j - x_i\right) = 0 \\ -1\, when \left(x_j - x_i\right) < 0 \end{cases}$$

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where *n* represents the sample size, and x_i and x_j are sequential data in series.

3. Results

3.1 Monthly water discharge between 1958 and 2021

The monthly water discharges showed wide seasonal and inter-annual variations (Fig. 2). Based on the long-term observed daily water discharge data (1958–2021) the flow was generally highest in the rainy season, from May to October and through to the first half of November. We also found that the mean monthly water discharges observed at Son Tay ranged from 816 to 18,810 m^3/s in the rainy season, and from 164 to 2,987 m^3/s in the dry season (Fig. 2a), over the 64-year period. Correspondingly, the monthly water discharge observed at Son Tay ranged from 4 $\times 10^9$ to 50 $\times 10^9$ m^3 in the rainy season, and from 1.6 $\times 10^9$ to 8 $\times 10^9$ m^3 in the dry season (Fig. 2a). The monthly water discharge was highest in August, followed by July and June, and was lowest in February, followed by March and January.

A significant change point was detected around 2009 (Figs. 2b, 2c) that coincided with the installation and implementation of a series of dam-reservoirs from the end of 2008. Before 2009, the monthly water discharge showed clear seasonal and inter-annual variations, and increased in the rainy season and decreased in the dry season (Fig. 2b), and the monthly water discharges for the rainy and dry seasons averaged about 16 × 10^9 and 3 × 10^9 m^3, respectively.

After 2009, the river was mainly degraded through the rainy season, and the average monthly water discharges for the rainy and dry seasons were about 12×10^9 and 4×10^9 m^3, respectively, with a gentle increasing trend in the dry season (Fig. 2b). The inversions in these seasons were perhaps associated with the installation and operation of a series of dam-reservoirs upstream, and may also reflect the effects of human activities and climate change in recent decades.

3.2 Mean monthly sediment concentrations between 1958 and 2021

The mean monthly suspended sediment concentrations varied considerably at monthly, seasonal, and inter-annual scales throughout the 64-year observation period (Fig. 3). The mean monthly sediment concentrations observed at Son Tay were highly variable, and ranged from 38 to 4,500 g/m^3 in the rainy season, and from 22 to 849 g/m^3 in the dry season (Fig. 3a). There were significant change points around the end of 1988 and 2008.

Before 1988, the mean monthly suspended sediment concentrations were mainly increasing, especially in the rainy season (Figs. 3b, 3c). The average values in the rainy and dry seasons were about 990 and 180 g/m^3, respectively. The mean monthly suspended sediment concentrations were highest around the end of the rainy season, from July to October, and were lowest around the end of the dry season, from February to April (Fig. 3c).

The mean monthly suspended sediment concentrations were lower in the rainy and dry seasons after 1988, when the Hoa Binh dam-reservoir was impounded, than before 1988 (Figs. 3b, 3c). The mean monthly suspended sediment concentrations decreased further after 2009, especially in the rainy season, and the concentrations from 2010–2021 were 76% of what they were from 1988–2010 (changed from 450 to 108 g/m^3). This suggests that the impoundment of the Hoa Binh dam-reservoir in 1988 and the series of dam-reservoirs that was implemented since 2008 strongly impacted on the suspended sediment concentrations in the water, through accumulating and trapping sediment that was transported into the reservoirs.

The mean monthly water discharge and the corresponding sediment concentration were moderately correlated throughout the entire study period, $R^2 = 0.4331$ (Fig. 4). This relationship implies that the yearly variations in the suspended sediment concentrations were probably not closely linked to the magnitude of the mean monthly water discharges, particularly after 1988.

As analyzed, the mean monthly suspended sediment concentrations varied significantly throughout the 64-year observation period (1958–2021), but the mean monthly water discharges only decreased slightly. For example, the mean monthly sediment concentration was about 969 g/m^3 for the period from 1958 to 1971, and was about 114 g/m^3 for the period from 2016 to 2021. However, the mean monthly water discharges were about 3,657 and 3,178 m^3/s for 1958–1971 and for 2016–2021, respectively. In other words, the dam-reservoirs upstream in the Red River system had more influence on the suspended sediment concentration than on the water discharge. The sediment loads in most river systems worldwide with upstream dams have generally decreased because of trapping in the dams (Kondolf et al., 2014).

3.3 Monthly sediment load between 1958 and 2021

The majority of the suspended sediment load in the Red River system is generally transported during the rainy season and when the discharge is high. Accordingly, the monthly sediment load fluctuated widely in the rainy season, and was highest in August followed by July (Fig. 5a). In contrast, the monthly sediment load showed least variation from January to March, during the dry season. Over the 64-year observation period, the monthly sediment load observed at Son Tay ranged from 0.1×10^6 to 101×10^6 t in the rainy season, and from 0.05×10^6 to 6.8×10^6 t in the dry season.

Any sediment deposition generally occurred in the rainy season before 1988. Correspondingly, the monthly sediment loads averaged about 21.5×10^6 and 0.5×10^6 ton in the rainy and dry seasons, respectively. However, after the Hoa Binh dam-reservoir entered its operation phase (1988), the dominant process changed from deposition to erosion, as shown in Figs. 5b and 6a. From 1988 to 2010, the monthly sediment loads averaged about 8.3×10^6 and 0.3×10^6 t in the rainy and dry seasons, respectively. The reduction in the monthly sediment loads was severe from 2009 onwards (see Figs. 5b, 5c, and 6a), when the installation and operation of a series of dam-reservoirs commenced. After 2009, the monthly sediment loads averaged about 1.6×10^6 and 0.4×10^6 t for the rainy and dry seasons, respectively. The monthly sediment load decreased dramatically in the rainy season, in line with the operation and installation of new large dam-reservoirs upstream. The data suggest that the operation of a series of dam-reservoirs strongly influenced the monthly sediment flux in the Red River system because of reservoir sedimentation processes.

In general, the monthly sediment loads and the corresponding suspended sediment concentrations and water discharges were strongly correlated, with R^2 values of 0.77 and 0.67, respectively (Figs. 6b, 6c). These values also reflect the river's response to the dam-reservoir effects upstream (Fig. 6a), and had more influence on the suspended sediment concentrations than on the water discharge.

3.4 Annual sediment loads between 1958 and 2021

The long-term mean annual suspended sediment concentrations, sediment loads, and water discharges were affected by the dam-reservoirs upstream, as shown in Fig. 7 and Table 2. The annual sediment load and the mean annual suspended sediment concentration at the Son Tay station were strongly correlated, $R^2 = 0.9371$ (Fig. 7a). The annual discharge was reasonably stable, while the sediment load changed dramatically, over the 64-year period. The annual sediment erosion changed dramatically, by about 90.4%, but the water budget only changed by about 11%, over the study period (Table 3).

The results from the Mann–Kendal test show that the changes in the mean annual suspended sediment concentrations, sediment loads, and water discharges were statistically significant over the entire observation period ($p < 0.05$) (Table 2). The Sen's slope values were all negative, suggesting the three variables were decreasing annually, and that these parameters will continue to decrease in the future. The trends estimated using the Sen's slope showed that the suspended sediment concentration, sediment load, and water discharge were decreasing at rates of about 18.6 g/m^3, 2.1×10^6 t, and 330×10^6 m^3 per year, respectively.

In the period from 1958 to 1971, before the first dam-reservoir (Thac Ba) went into operation, the annual sediment load was about 115×10^6 t/yr, and the mean annual suspended sediment concentration was as high as about 969 g/m^3. The annual sediment load was proportional to both the mean annual suspended sediment concentration and the annual water discharge (Figs. 7a, 7b). In addition, the annual sediment flux and the water discharge were as high as in this period, suggesting that there was deposition in the lower reach of the Red River system.

Similarly, from 1971–1988, the annual sediment load was also high, and increased slightly from 115×10^6 to 121×10^6 t/yr, which was proportional to the suspended sediment concentration in the water (Fig. 7a). However, the annual water discharge declined from $115{,}592 \times 10^6$ to $112{,}423 \times 10^6$ m^3/yr in this period. These contradictory results imply that the Thac Ba dam-reservoir had a low impact on the sediment flux because of its limited enclosed upstream watershed (Table 1). The important event through this period was the construction of the Hoa Binh dam-reservoir, when the mean annual suspended sediment concentrations, and also the sediment load, increased slightly. The deposition process will be discussed in detail in the Discussion.

As shown in Fig. 7, the annual sediment load declined dramatically from after 1988 because of the Hoa Binh dam-reservoir operations, and the annual sediment flux decreased by around 62% (from 121×10^6 to 46×10^6 t/yr). Note that the extremely high annual sediment flux (135×10^6 t/yr) observed in 1990 may have been attributable to an intense remobilization of the riverbed and/or riverbank sediments because of the management of the Hoa Binh dam-reservoir during the first year of operation (Dang et al., 2010).

From the end of 2008, a series of new dam-reservoirs commenced operation, namely Tuyen Quang, Son La, Ban Chat, Huoi Quang, and Lai Chau, and added to the influence of the earlier dam-reservoirs. The Red River system entered a second significant phase of sediment reduction, and the annual sediment loads decreased by around 80.4%, to about 9×10^6 t/yr. The mean annual sediment concentrations followed a similar trend. These sharp declines reflect the low supply of sediment from the Da and Lo Rivers (Fig. 1), where the sediment was trapped by a series of dam-reservoirs. These results also suggest that erosion processes dominated downstream in the lower reach of the Red River.

The annual sediment loads and the corresponding water discharges were moderately correlated over the entire study period ($R^2 = 0.4608$) (Fig. 7b), but the mean annual suspended sediment concentration and the annual water discharge were weakly correlated ($R^2 = 0.2743$) (Fig. 7c). These results again suggest that the dam-reservoirs were important drivers of the suspended sediment concentrations, and caused significant changes in the sediment flux in the lower reach of the Red River system.

Table 2
Mann–Kendall trend tests for the mean annual suspended sediment concentration, annual sediment load, and annual water discharge.

Variable	**Min.**	**Max.**	**Mean**	**Std. deviation**	**p-value (two-tailed)**	**Significant level**	**Sen's slope**
Annual sediment concentration (g/m^3)	90	1,500	645.6	405.1	0.000	0.05	-18.6
Annual sediment load (10^6 ton)	7.6	202.6	72.8	52.0	0.000	0.05	-2.1
Annual water discharge (10^6 m^3)	73,391.9	159,520.0	107,102.8	17,473.9	0.003	0.05	-330.0

4. Discussion

4.1 Water discharge and suspended sediment concentration as drivers of the sediment flux

This analysis shows that the dam-reservoirs exerted a great impact on the sediment load of the Red River system. To understand whether the upstream dam-reservoirs had more influence on the water discharge or the suspended sediment concentration, the time series data for the river discharges and sediment loads were separated into five different periods, namely (i) 1958–1971 (no large dam-reservoirs), (ii) 1971–1988 (Thac Ba), (iii) 1988–2010 (Thac Ba, Hoa Binh, and Tuyen Quang), (iv) 2010–2016 (Thac Ba, Hoa Binh, Tuyen Quang, Son La, Ban Chat, and Huoi Quang), and (v) 2016–2021 (Thac Ba, Hoa Binh, Tuyen Quang, Son La, Ban Chat, Huoi Quang, and Lai Chau). The sediment loads were either more dependent on the water discharges or the suspended sediment concentration in water at the times when the upstream dam-reservoirs commenced their operations (Fig. 8).

Over the 64-year period, the annual sediment load decreased significantly, by 90.4%, or from 115×10^6 to 11×10^6 t/yr, but the water budgets decreased by about 14.5%, from $115{,}592\times10^6$ to $98{,}862\times10^6$ m^3/yr (Table 3). These changes were statistically significant (Table 2).

Table 3
Summary statistics about the water discharges and the sediment loads at the Son Tay gauging station.

Period	Annual water discharge (10^6 m^3)	Mean annual sediment concentration (g/m^3)	Annual sediment load (10^6 ton)	Dam-Reservoir
1958–1971	115,592	969	115	None of dams
1971–1988	112,423	1,032	121	Thac Ba
1988–2010	105,090	425	46	Thac Ba, Hoa Binh, Tuyen Quang
2010–2016	88,709	103	9	Thac Ba, Hoa Binh, Tuyen Quang, Son La, Ban Chat, Huoi Quang
2016–2021	98,862	114	11	Thac Ba, Hoa Binh, Tuyen Quang, Son La, Ban Chat, Huoi Quang, Lai Chau

Period from 1958–1971

There were no hydropower dams operating in this period. We found that the sediment load and the water discharge were strongly correlated (R^2 = 0.9023), and that the sediment load and the suspended sediment concentration were also strongly correlated (R^2 = 0.7915) (Fig. 9). These relationships show that the sediment flux of the Red River system was more dependent on the water discharge than the suspended sediment concentration in water. Note that the annual water discharge and the sediment concentration were very high in this period (Table 3). When no dam-reservoirs were operating, the sediment load in the river system was mainly proportional to the water discharge, followed by suspended sediment concentration. The results also suggest that deposition occurred in the lower reach of the Red River system in this period.

Period from 1971–1988

After the Thac Ba dam-reservoir started to operate in 1971, the correlations between the sediment load and the water discharge and the sediment load and the suspended sediment concentration were similar (Fig. 10). The Thac Ba dam-reservoir had a limited enclosed area (6,170 km^2) upstream, which meant that it had a small influence on the sediment flux (Table 1). In this period, the data from Son Tay show that the water discharge decreased slightly (from $115{,}592\times10^6$ to $112{,}423\times10^6$ m^3/yr) but the sediment flux increased slightly (from 115×10^6 to 121×10^6 ton/yr). Note that the Hoa

Binh hydropower dam-reservoir was constructed in the period from 1979 to 1988, and the sediment load increased because of changes in runoff and land use. According to Lu et al. (2015), the water discharge capacity decreased in this period but transported a higher sediment load from the upstream part of the main channel. When the sediment supply from upstream exceeds the amount that the river system is able to transport, the flow dynamics decrease and the river becomes choked with sediment downstream. Deposition, not erosion, occurred because of the water reduction, which contrasts to ‘hungry water’ effects, as shown in Table 3.

The Thac Ba dam-reservoir caused limited changes in the suspended sediment concentration, and the construction of the Hoa Binh dam-reservoir was the major cause of the increasing sediment load and sediment concentration in this period (Table 3). This finding is consistent with the conclusions of Lu et al. (2015), Le et al. (2018), and Ve et al. (2021).

Period 1988–2010

The Tuyen Quang (watershed area of 1,360 km^2) and Thac Ba (watershed area of 6,170 km^2) dam-reservoirs on a tributary of the Lo River had limited influence on the water and sediment discharges in the Lo River, and had much smaller upstream watershed areas than the Hoa Binh Dam (57,285 km^2). The combined effects of the Thac Ba (from 1971), Hoa Binh (from 1988), and Tuyen Quang (from 2008) hydropower dams were significant.

We found that the annual sediment load decreased dramatically, from 121×10^6 to 46×10^6 t/yr (~ 62%), after the Hoa Binh dam-reservoir went into operation. The annual sediment load estimated for the period from 2010 to 2016 was about 9×10^6 t/yr, which represented a reduction of about 92.6%. Previous researchers reported that around 60–90% of the suspended sediment load in the Da River has been trapped (sedimentation rate) in the Hoa Binh dam-reservoir (Dang et al., 2010; Le et al., 2018; Ve et al., 2021; Wei et al., 2021). Because the dam-reservoir operations trap sediment, the sediment loads in the water moving out from these dams are low. The suspended sediment load is strongly dependent on the suspended concentration in the water, rather than the water discharge (Fig. 11). This leads to ‘hungry water’, where the relatively clear water that is released from a dam-reservoir tries to pick up sediment as the water flows, which leads to the scouring of some areas of riverbed and erosion of riverbanks downstream (Lu et al., 2015). The results imply that the dam-reservoirs not only affected the water discharges, but also caused a dramatic decrease in the suspended sediment concentrations in the water.

Period 2010–2016

During this period, the sediment load and water discharge observed at the Son Tay station decreased because of the operation of the six large dam-reservoirs, Thac Ba, Hoa Binh, Tuyen Quang, Son La, Ban Chat, and Huoi Quang, and the construction of Lai Chau. These dam-reservoirs trapped sediment, meaning that the sediment input into the Hoa Binh dam-reservoir in the lower stream of the Da River decreased dramatically (Fig. 1). In addition, the water discharge decreased from $105{,}090 \times 10^6$ to $88{,}709 \times 10^6$ m^3/yr, by about 15.6%, and the sediment load decreased from 46×10^6 to 9×10^6 t/yr, by about 80.4% (see Table 3). During this period therefore, the river discharge became the most important influence on the sediment flux (Fig. 12). The change in the mass trend is consistent with the findings of Le et al. (2018) and Ve et al. (2021).

It should be emphasized that sediment trapping in dam-reservoirs along the Red River system affects the downstream reaches through sediment starvation, and also reduces the storage capacity of the reservoirs and can interfere with the functioning of the dam and the hydroelectric powerplant (Kondolf et al., 2014).

Period 2016–2021

The results for the period from 2016 to 2021 were similar to those from 2010–2016. After the Lai Chau hydropower dam started its operation, the sediment load of the Red River system became more dependent on the water discharge than on the suspended sediment concentration in water (Fig. 13). This suggests that, when all the seven large dam-reservoirs upstream went into operation, the water discharge decreased significantly, causing a decrease in the sediment load in the downstream area of the Red River system. The impoundments of the seven large dam-reservoirs strongly influenced both the water discharge and the sediment flux in the Red River system.

It is worth noting that further cascade dam-reservoirs are under construction or planned in the short- to medium-term in China, in the upper channel of the Red River system (Wei et al., 2021). Once completed, the sediment trapping efficiency could increase further, thereby exacerbating the decreases in the sediment load in the lower reaches of the system in Vietnam. However, the mean monthly sediment concentrations might increase slightly in the short-term and during the construction phases, as was observed in recent years (Table 3).

4.2 Impacts of human activities on the sediment load and water discharge

Human activities also influence the sediment flux in the river system. Human activities have considerably affected various estuaries worldwide, including the Rhine-Meuse Delta in the Netherlands, the Ebro Delta in Spain, the Mississippi River Delta in the U.S.A., the Nile River Delta in Egypt, the Mekong Delta, and the Yangtze River Delta in China (Wang et al., 2021; Dang et al., 2010, 2018; Kondolf et al., 2014; Le et al., 2022).

In recent decades, the total population of the Red River Delta has rapidly increased in both rural and urban areas because of natural population growth and urbanization processes (Le et al., 2015, 2022). With population densities varying from 80 to more than 1,000 inhabitants/km^2 in different parts of the river basin, the pressure from the population in the Red River system is increasing (Nguyen et al., 2016). The sediment yield in the watershed, and consequently the sediment load in the Red River system, will increase as agriculture and deforestation activities increase (Fan et al., 2019; Ve et al., 2021). According to He et al. (2007), SPM at the Manhao station in the Yuanjiang River, upstream of the Red River system in Yunnan Province, China, increased continually from 1,870 g/m^3 in the 1960s, to 2,490 g/m^3 in the 1970s, 3,120 g/m^3 in the 1980s, and then to 3,630 g/m^3 in the 1990s.

The forest cover in the mountainous regions in the reaches upstream of the Red River delta declined rapidly over the period from 1950 to 1990, and most rapidly in 1993, with more than 70% of the previous forest area either felled or replaced (Le et al., 2015; Wang et al., 2016). The increases in SPM observed around 1986, associated with the Hoa Binh dam-reservoir construction, and in the 1990s and 2000s (Fig. 8), may have also reflected land-use change rather than climate change (Ve et al., 2021). Wang et al. (2016) pointed out that because of deforestation, the river streamflow and sediment load both increased in the Red River system, mainly because of human-induced land cover change on the side of the Da River (Fig. 1).

4.3 Climate change and hydrological characteristics

Similar to other river systems in tropical areas, most of the suspended sediment load in the Red River system is transported during the rainy season and at high river discharges because of erosion and weathering (Le et al., 2007, 2022). Because of climate change and global warming, the air temperatures in Southeast Asia are predicted to increase by between 2°C and 5°C by 2050 (Le et al., 2007; Amato and Hein, 2014; Le et al., 2022). Increases in the air temperature and rain events in Southeast Asia may accelerate the erosion and weathering processes, thereby exacerbating the suspended sediment loads and water discharges in the river systems. Concentrated rainfall events associated with climate change in this area may result in severe soil erosion and increased sediment discharges into the Red River system. If the rainfall increases by 10%, the suspended sediment load in the Red River system is predicted to increase by more than 20%, from 9×10^6 to 11×10^6 t/yr, as was observed in the 2016–2021 period (Table 3). This measurement is similar to what was predicted by Le et al. (2007).

Additionally, the mountainous areas that form a large part of the upstream basin of the Red River are tectonically very active and have high erosion rates, and are the main source of the sediment that is deposited in the delta (Le et al., 2007). Influenced by the extreme weather caused by climate change, Wei et al. (2021) estimated that the mean annual soil erosion in the Red River basin from 2000 to 2010 was about 64×10^6 t/yr, with areas of high erosion identified in the middle part of the Red River and in the downstream area of the Da River, where the precipitation (> 1500 mm/yr) and surface runoff (> 450 mm/yr) are both high. Consequently, natural characteristics and human activities are likely to influence the sediment flux in the Red River system, and may help explain why the water discharge and sediment load have increased slightly in recent years (Table 3).

5. Conclusions

In this study, the monthly and annual water discharges and sediment loads of the Red River system in Vietnam were calculated from the latest daily data observed at the Son Tay hydrological gauging station, at the outlet of the Red River system and entry to the delta. These estimates consider all the large dam-reservoirs that were built from 1958 to 2021 in the Red River system in Vietnam. The annual suspended sediment load transported by the Red River system has decreased significantly because of the construction and operation of the seven large dam-reservoirs since the 1970s. The results indicate that the annual sediment load has decreased by about 90.4% (from 115×10^6 to 11×10^6 t/yr) over the 64-year observation period, with the decrease mainly attributable to a series of dam-reservoirs operating upstream.

Before the first dam-reservoir, Thac Ba, started to operate, the sediment flux strongly depended on the water flow, follow by the suspended sediment concentration. However, after the Thac Ba (1971), Hoa Binh (1988), and Tuyen Quang (2008) dam-reservoirs started their impoundments, the sediment load became more dependent on the sediment concentration than the water discharge. This suggests that the operations of the dam-reservoirs impacted greatly on the suspended sediment concentration, and also impacted the water discharge but to a lesser degree. However, when all the seven large dam-reservoirs were in operation (from 2016 onwards), the water discharge had more influence on the sediment flux in the river system than the suspended sediment concentration in the water. The operations of the seven large dam-reservoirs upstream have impacted significantly on both the water discharges and sediment loads of the downstream reaches of the Red River system.

As well as the dam-reservoir constructions upstream, human activities, land use change (such as increases in the areas of rice and agricultural land), deforestation, increases in population, and climate change have also impacted on the water discharges, suspended sediment concentrations, and sediment loads in the Red River basin in recent years. These factors will continue to influence both the water discharges and sediment loads in the Red River system in the future. In light of the magnitude of the estimated sediment reduction on the river system, this work underlines the need for an integrated river basin planning and management that involves all these possible drivers in order to ensure a sustainable development of the Red River Delta.

Declarations

CRediT authorship contribution statement

N.H.Q conceived and designed the research, conducted the analysis and prepared figures. P.K.N, P.M.C, and N.T.L data curation. N.H.Q led the writing of the manuscript with revision from N.T.P, M.B and Y.N.

Data availability

The field observation data including suspended sediment concentration and water discharge data are available upon request by contact with the corresponding author (ri.nguyenri@gmail.com).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics Approval

The paper is original unpublished work, and it is not under consideration for publication anywhere else. The final paper has been approved by all co-authors. No data, text, or theories by others are presented, all relevant literature is cited.

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Figures

Figure 1

The geographical location of the Red River system in Vietnam, showing the seven large hydropower dam-reservoirs (blue triangles: TQ-Tuyen Quang, TB-Thac Ba, HB-Hoa Binh, SL-Son La, HQ-Huoi Quang, BC-Ban Chat, and LC-Lai Chau) and the Son Tay hydrological gauging station (red triangle). The Red River basin is delineated by the dashed line.

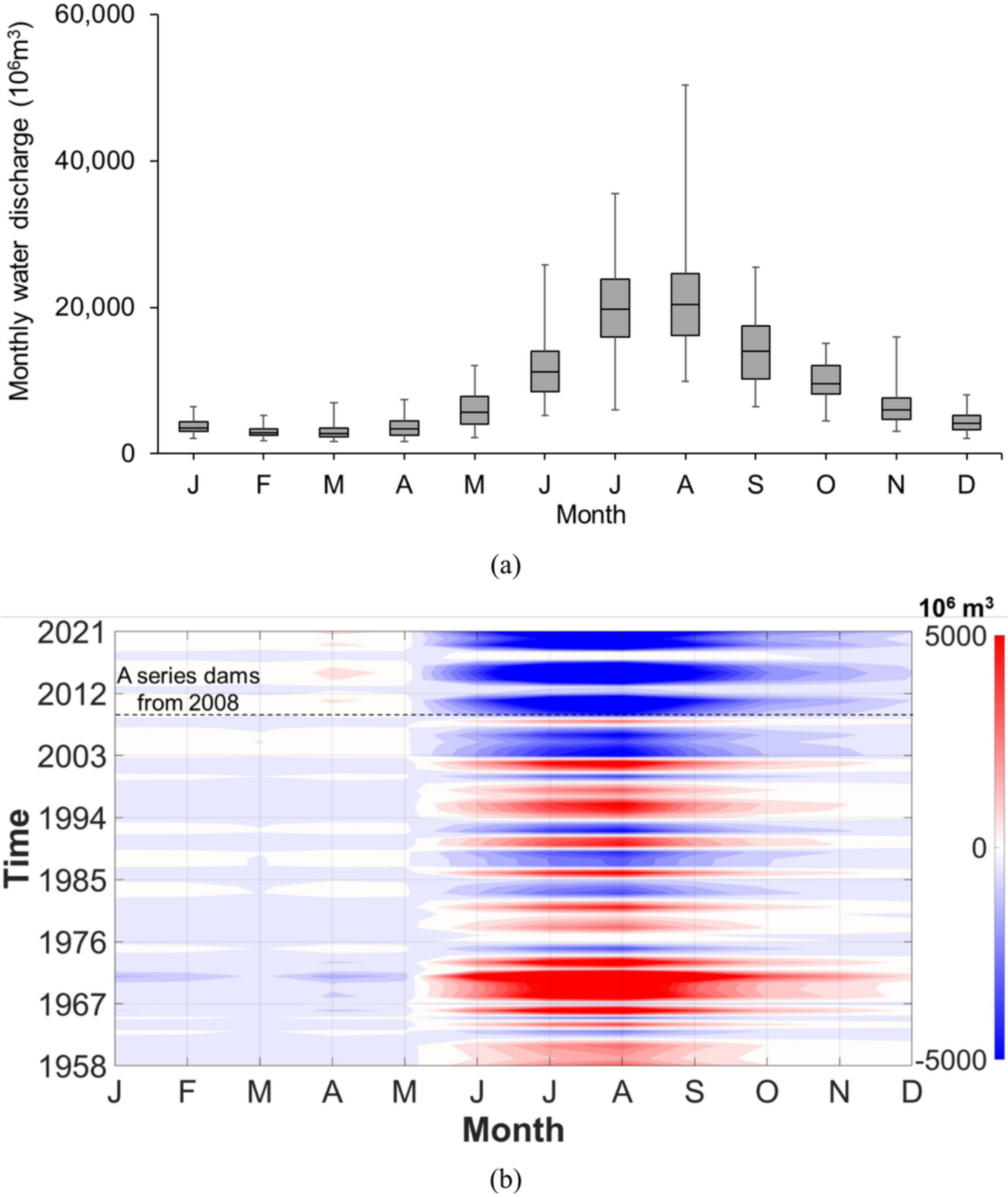
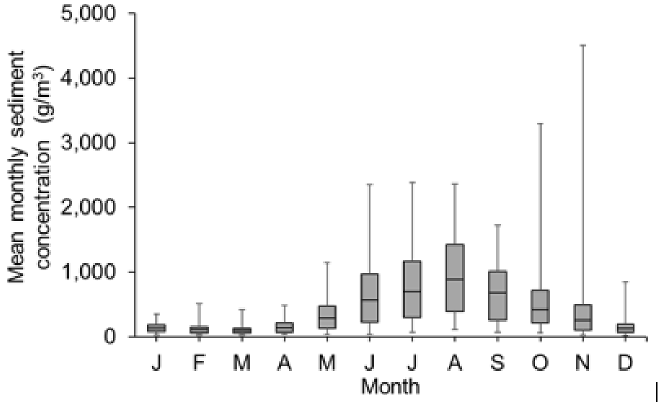
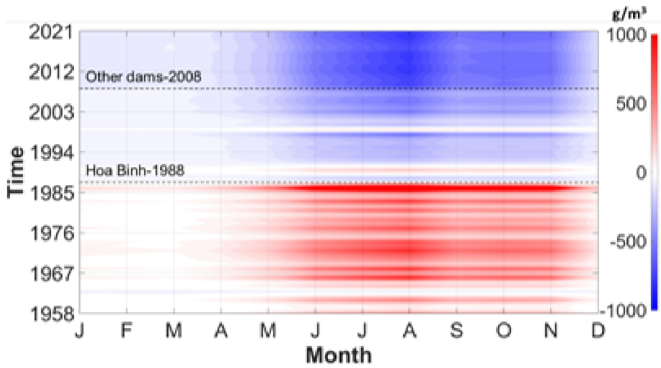


Figure 2

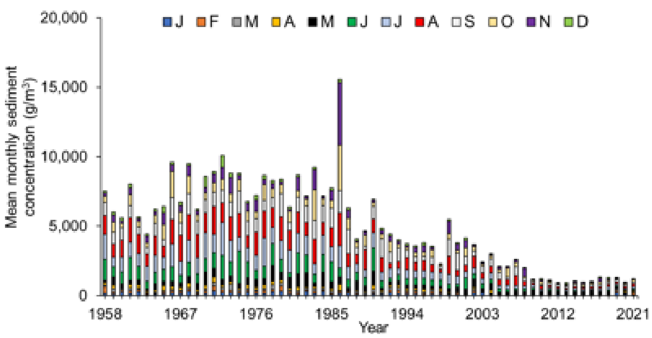
Monthly water discharges in the Red River system from 1958 to 2021, and min to max ranges. (b) Monthly variations in the water discharges relative to the mean value. (c) Variations in the monthly water discharge in the Red River system for the 64-year observation period.



(a)



(b)



(c)

Figure 3

Mean monthly suspended sediment concentrations in the Red River system from 1958 to 2021, showing min to max ranges. (b) Monthly variation in the sediment concentrations relative to the mean. (c) Variations in the mean monthly sediment concentrations in the Red River system over the entire 64-year observation period.

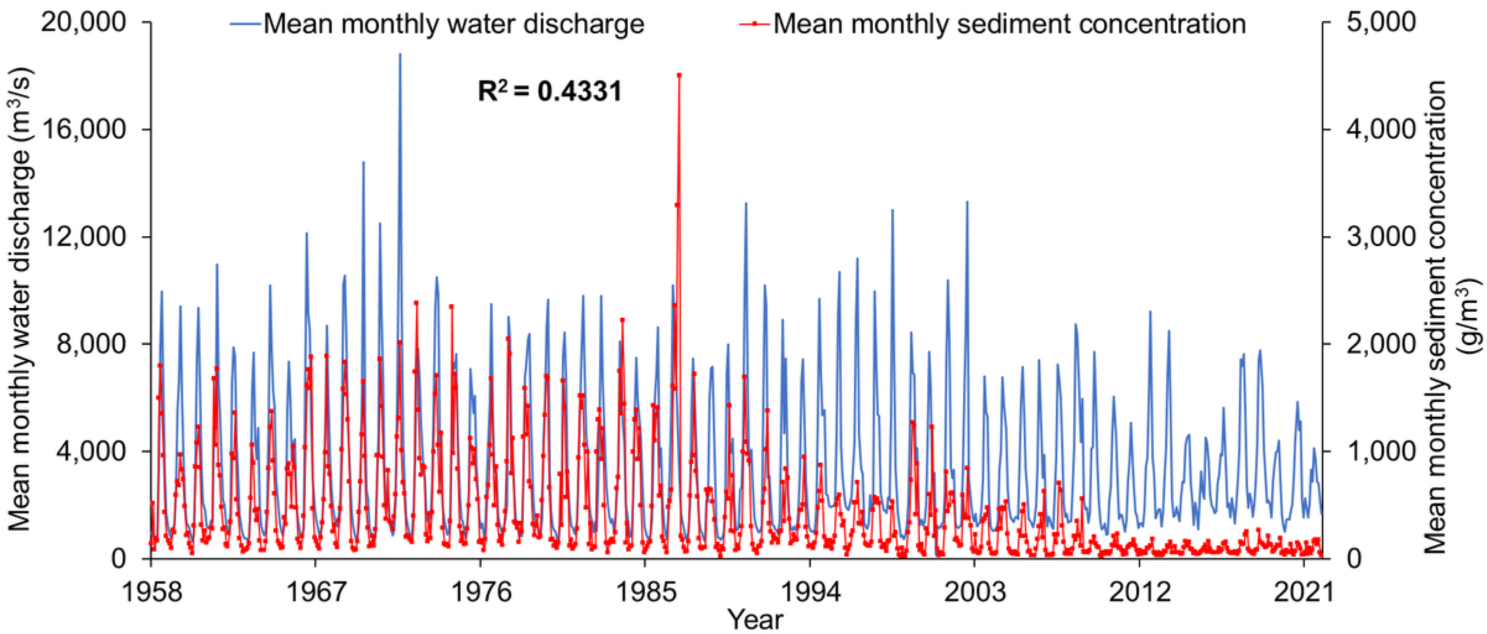


Figure 4

Variations in the mean monthly water discharge and the mean monthly suspended sediment concentration for 1958–2021.

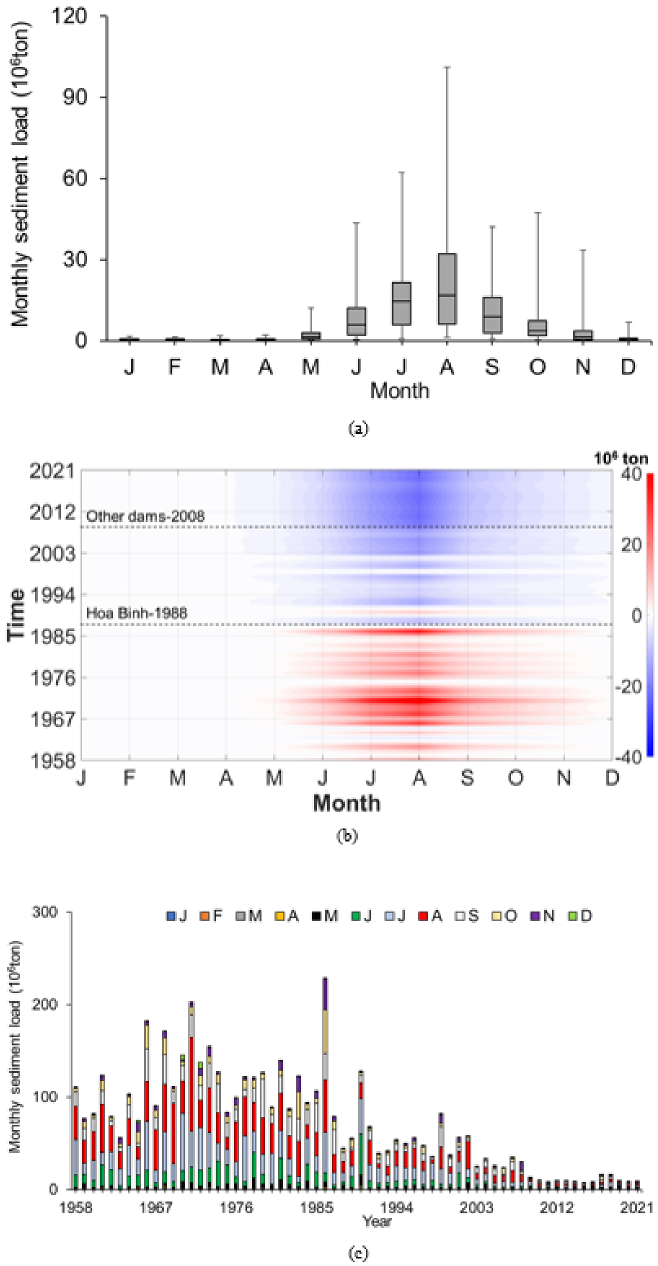


Figure 5

Monthly sediment loads in the Red River system from 1958 to 2021, and their min to max ranges. (b) Monthly erosion/deposition in the sediment loads because of the dam-reservoirs from 1971. (c) Variations in the monthly sediment loads in the Red River system over the entire 64-year observation period.

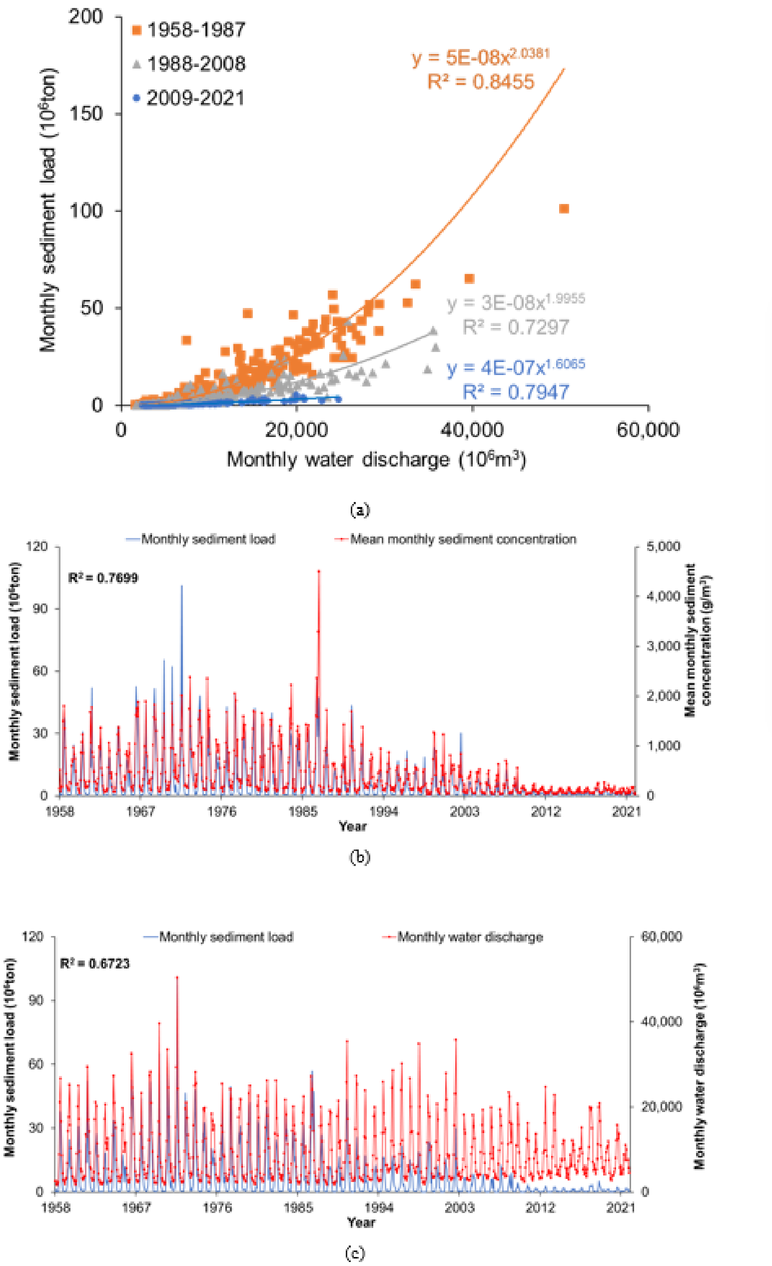


Figure 6

(a) Rating curves between the monthly sediment loads and the corresponding water discharges, divided into three time periods. (b) Correlations between the mean monthly sediment loads and the mean monthly sediment concentrations, and (c) between the mean monthly sediment loads and the mean monthly water discharges for the 1958–2021 period

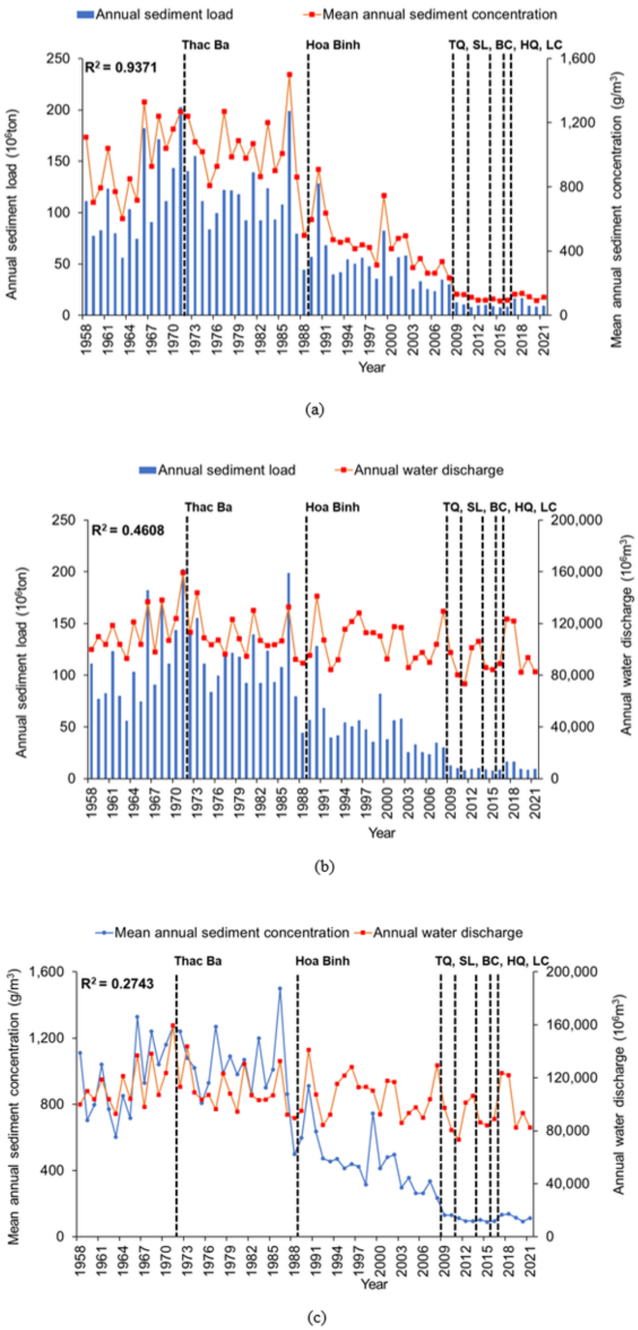


Figure 7

(a) Annual sediment loads and mean annual sediment concentrations in the Red River system from 1958 to 2021. (b) Annual sediment loads and annual water discharges. (c) Mean annual sediment concentrations and annual water discharges. The influence of the dam-reservoirs from 1971. TQ, SL, BC, HQ, and LC represent the Tuyen Quang, Son La, Ban Chat, Huoi Quang, and Lai Chau dam-reservoirs, respectively.

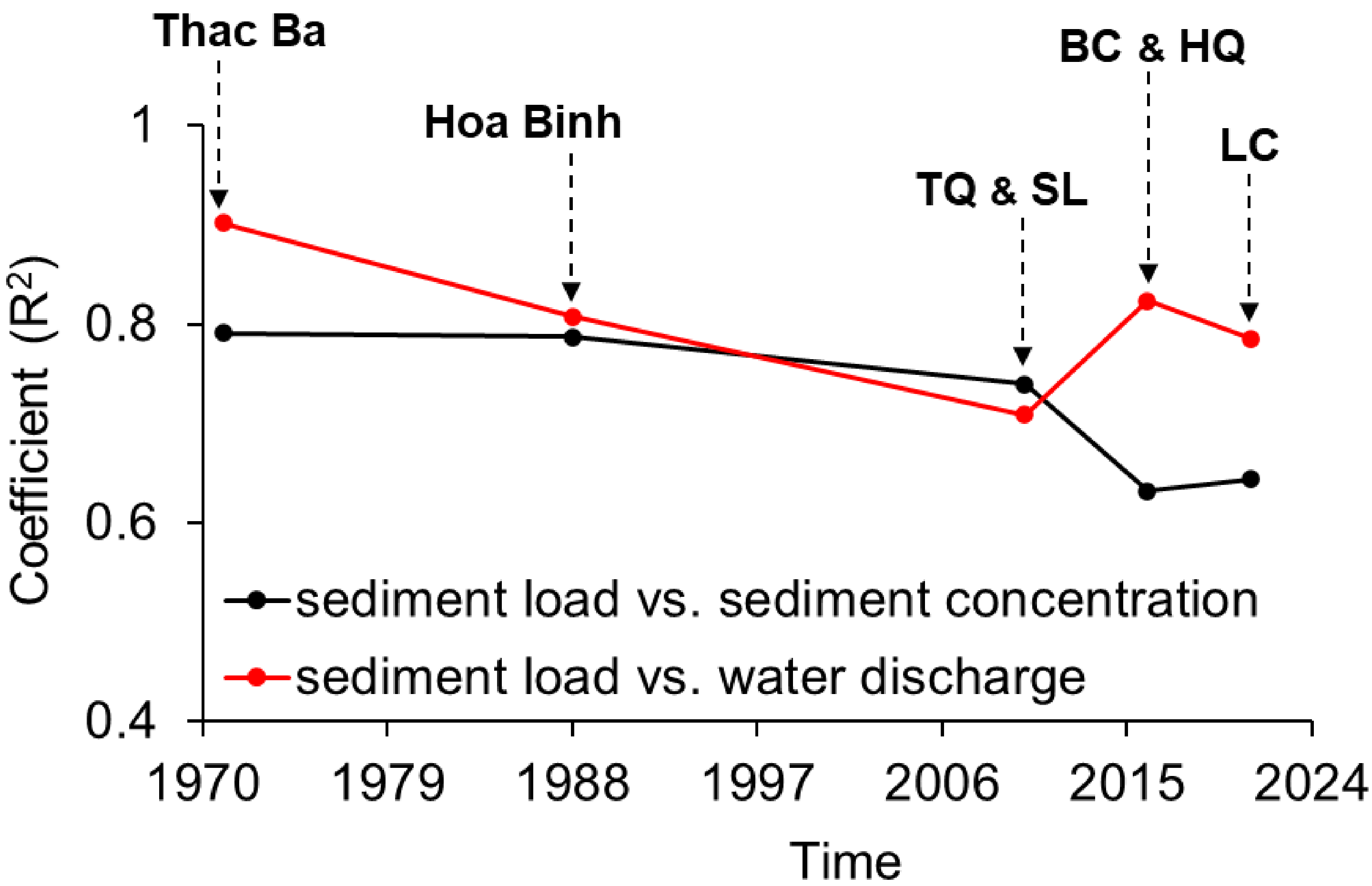


Figure 8

Correlations between the monthly sediment loads and the mean monthly sediment concentrations (black line) and the water discharges (red line) at times when the dam-reservoirs were impounded.

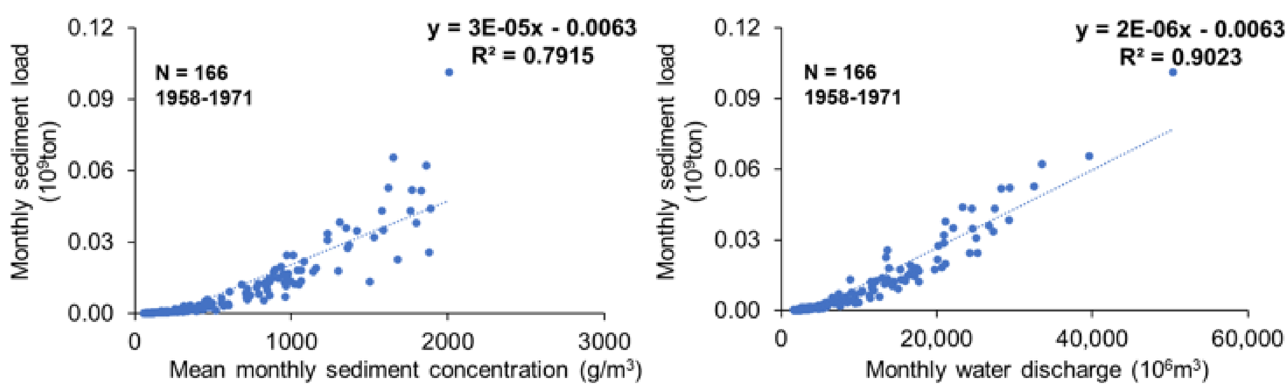


Figure 9

Correlations between the monthly suspended sediment load and the mean monthly sediment concentration in water (left), and the mean monthly water discharge (right), from 1958–1971

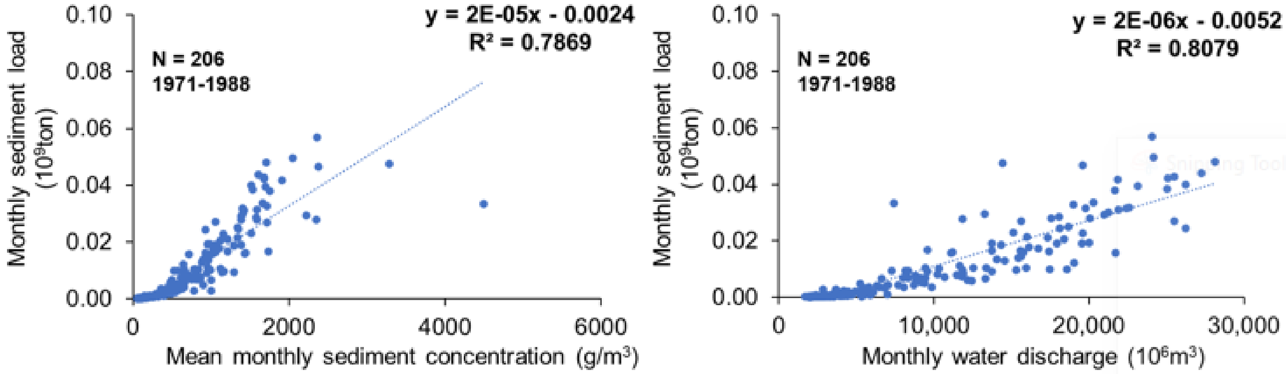


Figure 10

Correlations from 1971 to 1988

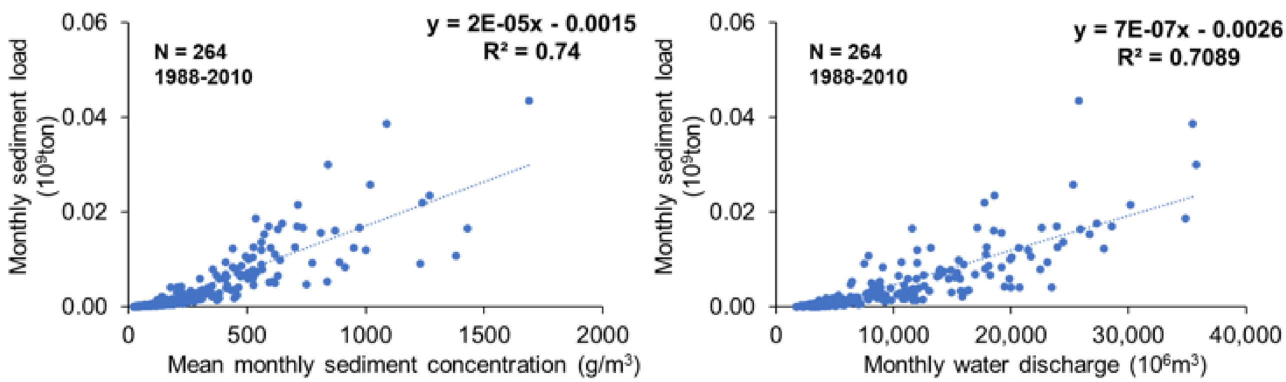


Figure 11

Correlations for the period from 1988 to 2010 between the monthly sediment load and (a) the mean monthly sediment concentration and (b) the monthly water discharge

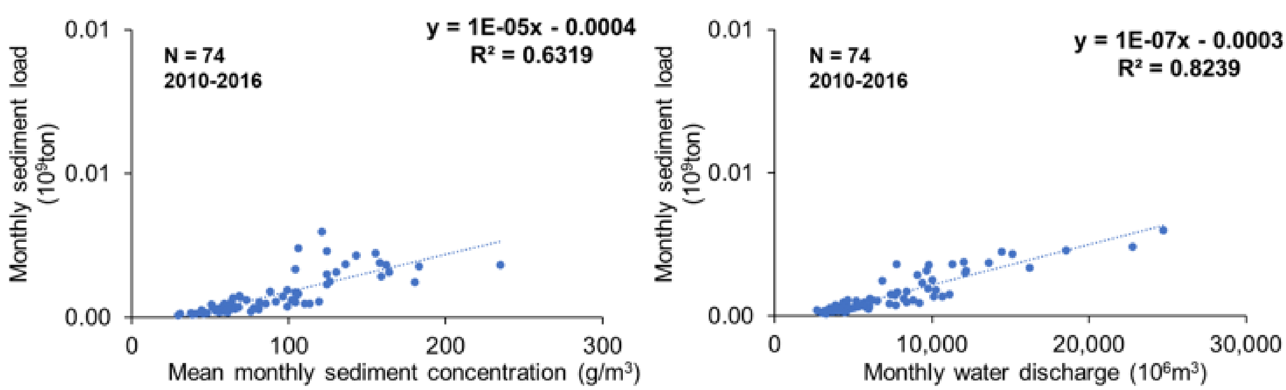


Figure 12

Correlations for the period from 2010 to 2016 between the monthly sediment load and the (a) mean monthly sediment concentration and the (b) monthly water discharge

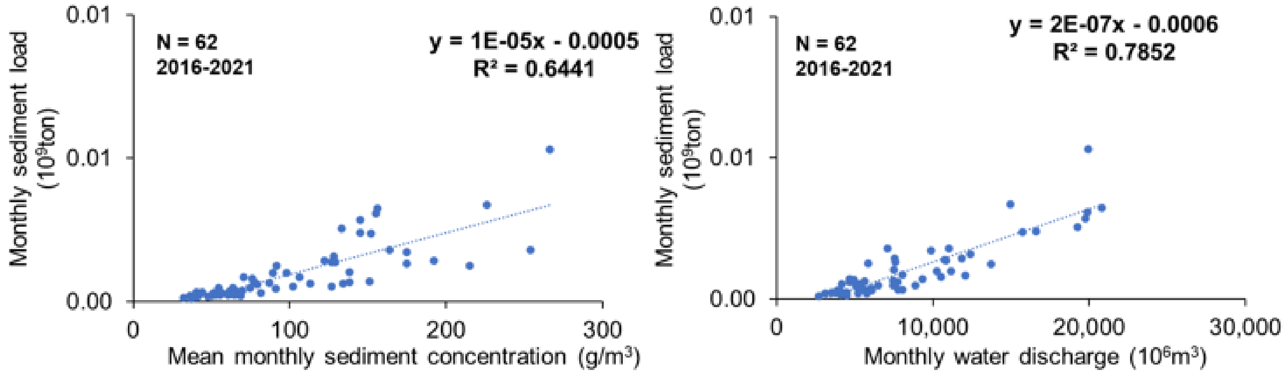


Figure 13

Correlations for the period from 2016 to 2021 between the monthly sediment load and the (a) mean monthly sediment concentration and the (b) monthly water discharge