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Changes to long-term discharge and sediment loads in the Vietnamese Mekong Delta caused by upstream dams

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ABSTRACT

The discharge and sediment loads of the Mekong River (MR) have been significantly altered because of natural processes and anthropogenic activities. We examined the impacts of dams in the MR basin on changes to the long-term discharge and sediment loads from upstream of dams in China (e.g., Jiuzhou) to the Vietnamese Mekong Delta (VMD) at daily, monthly, and annual scales over a 55-yr period (1961–2015) using various statistical methods. Results revealed sediment trapping in the Lancang cascade dams. To clarify the consequences of the reduced MR sediment load on morphological changes in the VMD, bathymetric data measured in 2014 and 2017 were examined along 100 km of the Tien river. The results show significantly reduced suspended sediment loads at all stations in the lower MR, but the sediment loads at Jiuzhou was increased. Thus, the reduced sediment load is caused not by a reduced sediment supply from the upper MR basin but by sediment trapping in the Lancang cascade dams. The sediment was reduced by 74.1% in the VMD; 166.7 ± 33.3 Mt/yr occurred in the predam period and 43.1 Mt/yr occurred in 2012–2015, with 40.2% caused by six mainstream dams in the Lancang cascade. Therefore, the Tien river in the VMD was severely incised, with an incision rate of −0.5 m/yr in 2014–2017. Upstream development has caused large-scale morphological changes in the VMD. Sand mining was responsible for a maximum of 14.8% of the annual riverbed incision in the VMD, while the remainder was caused by upstream hydropower dams.

1. Introduction

Globally, hydropower dams are being increasingly built and planned to meet increasing energy demands. Currently, there are 47,425 large dams in the world (Gupta et al., 2012), and approximately half are in China (Wu et al., 2018). Apart from supplying renewable energy, dams, especially mega-dams (reservoir capacity >10^9 m^3), can alter the flow regimes and trap entire sediment loads transported from upper basins. Therefore, dams have been identified as one of the main factors driving a decreasing trend in the world's sediment flux (Lu et al., 2015). Globally, as much as 53% of the world's sediment flux is trapped by reservoirs (Tena and Batalla, 2013). The sediment load in the Nile River has been reduced from approximately 100 Mt/yr to nearly zero because of the construction of the Aswan High Dam (Milliman and Syvitski, 1992). The closure of the Three Gorges dam in 2003 led to a 95% reduction in the sediment load of the Yangtze River, which decreased from 164 Mt/yr to 9 Mt/yr (Tena and Batalla, 2013).

Since the 1990s, large dams (>15 m high) have been increasingly built and planned (>130 dams were built, under construction, or planned by 2015) in the Mekong River Basin (MRB). Six mainstream dams (Manwan, Dachaoshan, Xiaowan, Jinghong, Gongguoqiao, and Nuozhadu) known as the Lancang cascade (Table 1) and numerous smaller dams have been constructed in the MRB (Fig. 1). These dams, together with gravel and sand mining in the lower Mekong River's (MR) mainstem, have caused significant alteration of the flow regimes and reduction of the sediment load of the lower MR (Lu and Siew, 2006; Kummu and Varis, 2007; Bravard et al., 2013; Räsänen et al., 2017), which is likely to cause adverse impacts on river morphological degradation, coastal erosion, river ecosystems, river navigation, and agricultural production (Bravard et al., 2013; Liu et al., 2013). The discharges at the Chiang Saen station (Fig. 1) increased by 121–187% in March–May and decreased by 32–46% in July–August 2014 because of the effects of the mainstream dams (Räsänen et al., 2017). The completion of the Manwan dam in 1993 reduced the sediment load by >60% at the Gajiu station (Fu et al., 2008), which is 2 km downstream of the dam

Abbreviations: MR, Mekong River; MRB, Mekong River Basin; Q, discharge; SSCs, suspended sediment concentrations; SSLs, suspended sediment loads; VMD, Vietnamese Mekong Delta; MRC, Mekong River Commission; VNCHF, Vietnam National Center for Hydrometeorological Forecasting; ADCP, acoustic Doppler current profiler; GPS, global positioning system.

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Table 1
Characteristics of the dams and reservoirs of the mainstream and tributaries in the MRB. MAR: mean annual runoff; MAS: mean annual sediment; CAP: reservoir total capacity; CAP/MAS: reservoir lifetime; CAP/MAR: retention time.
(Sources: [a]Fan et al. (2015); [b]Kummu et al. (2010)).

Reservoir	[a]Reservoir filling year	[a]Catchment area km^2	[b]MAR km^3	MAS km^3	[a]CAP km^3	CAP/MAS	CAP/MAR
Mainstream dams							
Nuozhadu	Nov. 2011	144,700	55.2	0.0379	22.37	589.9	0.405
Xiaowan	Dec. 2008	113,300	38.5	0.0297	15.13	509.5	0.393
Jinghong	Apr. 2008	149,100	58.0	0.0391	1.23	31.5	0.021
Manwan	Mar. 1993	114,500	38.8	0.03	1.06	35.3	0.027
Dachaoshan	Nov. 2001	121,000	42.3	0.0317	0.88	27.7	0.021
Gongguoqiao	Sep. 2011	97,300	31.1	0.0255	0.51	20.0	0.016
Grouped dams in tributaries							
Nam Phuong	NA	3420	5.4	0.1499	0.08	523.2	0.015
Nam Ma	NA	1128	1.0	0.1483	0.00	0.0	0.000
Huai Bang Lieng	NA	657	1.7	0.072	0.07	953.2	0.040
Nam Beng	NA	2193	0.9	0.2764	0.19	695.3	0.214
Nam Kam	NA	3506	4.7	0.0672	0.00	0.0	0.000
Nam Chi	NA	49,067	29.5	0.4839	0.004	8.1	0.000

NA: not available.

site, and by >50% of the sediment load at Chiang Saen (Lu and Siew, 2006). The six mainstream dams have been predicted to trap as much as 83% of the sediment generated from the upper MRB, which is equivalent to 40% of the total sediment budget of the MR (Kondolf et al., 2014). According to Kummu and Varis (2007), this number could reach 94%. Kondolf et al. (2014) predicted that only 4% of the MR's sediment would reach the Mekong Delta annually if all 133 planned dams are constructed in the future. Sediment reduction is likely to cause riverbed incision and riverbank erosion in downstream reaches. Using remote sensing in the Vientiane-Nong Khai area, Kummu et al. (2008) estimated MR's bank erosion as 0.8 and 1.0 m/yr (for the main channel) and 2.4 and 4.8 m/yr (for the islands) during the periods of 1961–1992 and 1992–2005, respectively.

As the third largest delta in the world (Anthony et al., 2015), the Vietnamese Mekong Delta (VMD) is one of the world's most important deltas in terms of food security. The agricultural production of the VMD depends largely on the variation in natural flow regimes and fine sediment flux from the MR. However, the sediment load of the VMD was significantly reduced from 160 Mt/yr in the predam period (Meade, 1996; Kondolf et al., 2014) to 40 Mt/yr in 2012–2013 (Nowacki et al.,

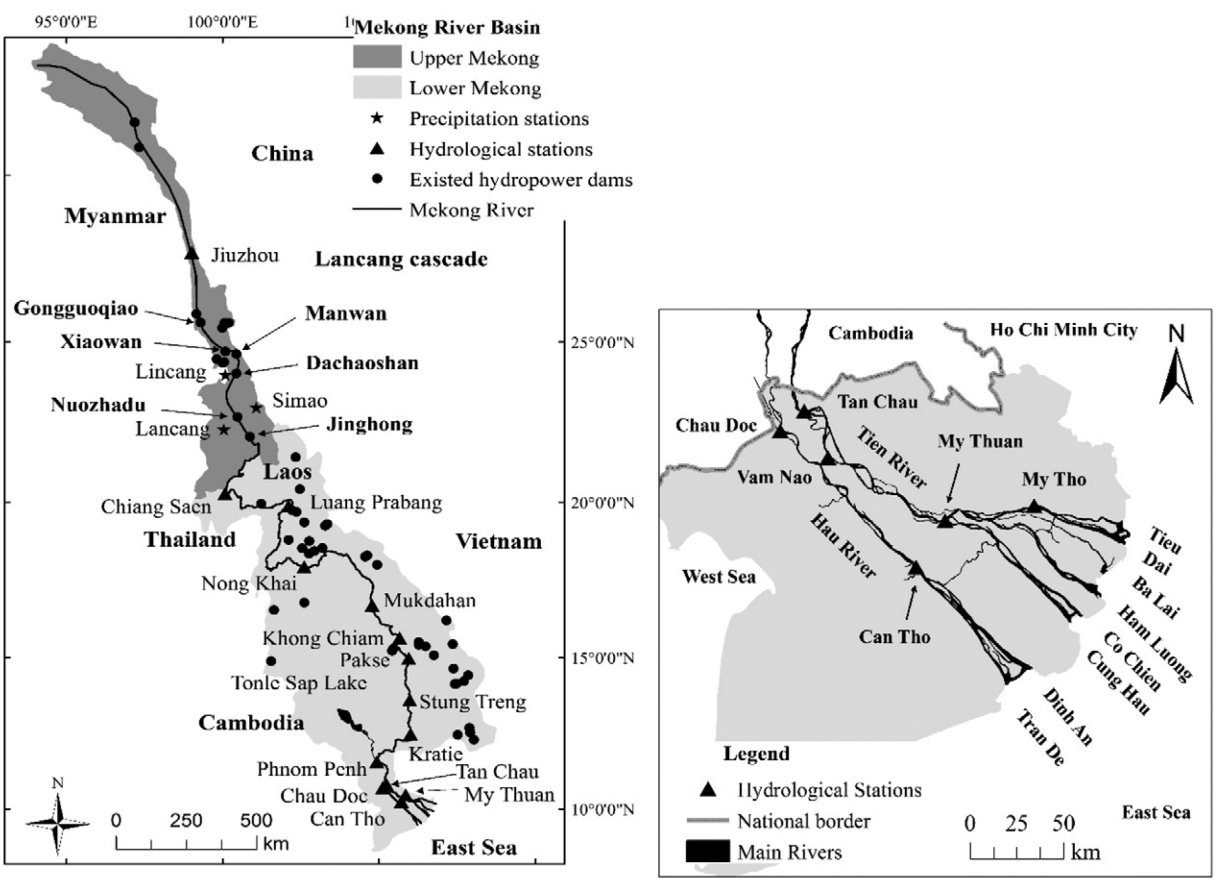

Fig. 1. Left panel: dam locations in the mainstream and tributaries and available hydrological stations and rain gauges in the MRB. Right panel: map of the Vietnamese Mekong Delta.

2015), which was mainly driven by upstream dams and sand mining (Bravard et al., 2013; Ha et al., 2018). Such a sediment load reduction could cause riverbed incision, riverbank erosion in alluvial rivers and channels, and coastline retreat (Li et al., 2017), which may in turn create difficulties in obtaining intake water for irrigation and may increase salinity intrusion in the VMD (Binh et al., 2018a). For instance, the riverbed of the Hau river in the VMD measured in 2008 was incised by 1–5 m more than that measured in 1998, with an average incision of 1.4 m (Allison et al., 2017a). On 22 April 2017, a 130-m-long and 30-m-wide riverbank of the Vam Nao diversion channel (approximately 35 km seaward of the Tan Chau station, Fig. 1) collapsed, which was hypothesized to be partly caused by the reduced sediment supply from the MR and sand mining. Approximately 50–66% of the current VMD's coastline is experiencing erosion (Anthony et al., 2015; Li et al., 2017), as manifested by a shift from an accretionary phase of 10.6 m/yr during the period of 1973–1979 to an erosional phase of −2.1 m/yr during the period of 2010–2015 (Li et al., 2017).

Owing to the importance of the suspended sediment load in the natural functioning of a river system (Lu et al., 2014), multiple studies have attempted to quantify dam impacts on the sediment load reduction in the lower MR by analyzing long-term sediment data (Lu and Siew, 2006; Kummu and Varis, 2007; Xue et al., 2011; Liu et al., 2013) and by employing numerical simulations (Kummu et al., 2010; Kondolf et al., 2014; Darby et al., 2016; Schmitt et al., 2019); therefore, the scientific understanding of dam impacts is gradually growing.

Because of the limited availability of data, prior studies on long-term sediment data analysis ended in 2003. These studies were thus able to capture the impacts of Manwan, but neither longer post-Manwan trends nor impacts of more recent post-Manwan dams on the Lancang and tributary dams in the lower MRB were elucidated. As a result, previous studies have found that dams in the Lancang cascade had little impact on the sediment load of the lower MR through 2002 (Liu et al., 2013) and have had impacts on limited areas upstream of the Chiang Saen station (Wang et al., 2011). Tables 2 and 3 compare the spatial and temporal coverage of the sediment datasets used in our study and previous studies to highlight the originality of our research, indicating that we used updated time series (up to 2015) with a wider spatial coverage compared to prior research. One of the important contributions of our study is that we provided data-based evidence of sediment trapping in the Lancang cascade dams by comparing long-term sediment loads between the Jiuzhou station (data from Fu et al., 2008), which is upstream of the Lancang cascade (Fig. 1), and stations in the lower MR.

We found that the cumulative impacts of existing dams in the mainstream and tributaries on the sediment load of the entire lower MR, down to the VMD, up to 2015 remained largely unknown because of two main limitations of previous studies (i.e., Lu and Siew, 2006; Kummu and Varis, 2007; Kummu et al., 2010; Xue et al., 2011; Liu et al., 2013; Lu et al., 2014; Li et al., 2017; Ha et al., 2018): (i) they did not use recently measured sediment data (after 2003) at the basin scale, and (ii) they did not study the entire MR from the sediment source (upstream of the Lancang cascade) to the sediment sink (the VMD). Therefore, the more recent impacts of dams on the sediment load of the entire lower MR and the VMD remain uncertain.

The quantification of sediment load changes along the MR caused by human activities, such as river damming and sand mining, provides important information for further understanding riverine morphological changes, coastal erosion, aquatic ecology, fisheries, and agriculture in its delta (Lu et al., 2014; Anthony et al., 2015). Brunier et al. (2014) quantified the morphological changes of the Tien and Hau rivers (two main rivers) in the VMD by comparing bathymetric data measured in 1998 and 2008 provided by the Mekong River Commission (MRC). They found that the riverbeds of the Tien and Hau rivers were severely incised, and they claimed that such riverbed incision was mainly attributable to sand mining because of a lack of reliable sediment data along the MR. Apart from Brunier et al. (2014), no study has examined large-scale morphological changes in the VMD using recently measured bathymetric data. Thus, the recent morphological changes of the VMD and the effects of reduction of the sediment supply from the MR caused by river damming on such changes remain unknown.

Given the limitations of past studies in terms of the spatial and temporal changes to the sediment load along the entire lower MR caused by river damming and gaps in our understanding of the effect of the reduced sediment supply from the MR on modern morphological changes in the VMD (Tables 2 and 3), we examined the impacts of hydropower dam development in the MRB on long-term discharge and sediment load changes in the entire MR, from Jiuzhou to the VMD, over a 55-yr period (1961–2015). By comparing river bathymetric data measured in 2014 (provided by the Southern Institute of Water Resources Research, Vietnam) and 2017 (from our field survey in August–September 2017), we quantified recent large-scale morphological changes of the Tien river and Vam Nao channel from Tan Chau to My Thuan (Fig. 1). We discussed how these changes might be linked to sand mining and damming based on an analysis of long-term sediment observations. To this end, we reexamined published annual sediment data from previous

Table 2
Study areas, employed sediment data, methodologies, key findings and shortcomings of previous papers regarding dam impacts on the sediment load of the MR, from which the originality of the present paper is highlighted. TSL: Tonle Sap Lake.

Groups	References	Stations/study area	Range of data	Key findings	Shortcomings (study gaps)
Sediment load changes	Lu and Siew (2006)	From Chiang Saen to the VMD	1962–2000	The Manwan dam reduced the sediment at Chiang Saen by 50%, although only slight impacts on the middle MRB and the VMD were observed	- Sediment data upstream of the Lancang cascade were not considered - No linkage with morphological changes
	Xue et al. (2011)	From Chiang Saen to Pakse	1962–2003	- No significant changes in precipitation and runoff over a 50-yr period - There was a trend of decreased SSC in the lower MR after the Manwan dam construction	- Sediment data upstream of the Lancang cascade and in the VMD were not considered - Lack of detailed analysis of changes in the Mekong's sediment load - No linkage with morphological changes
	Liu et al. (2013)	From Gajiu to Khong Chiam	1960–2003	The sediment load markedly decreased at Gajiu, although such a change was not evident downstream of Yunjinghong after the impoundment of the Manwan dam	- Sediment data upstream of the Lancang cascade and in the VMD were not considered - No linkage with morphological changes
	Lu et al. (2014)	Confluence of the Chaktomuk in Phnom Penh, Cambodia	2008–2011	- The sediment load of the MR during the period of 2008–2010 (50–91 Mt/yr) was much lower than the predam sediment load of 150–160 Mt/yr - The sediment contribution to the VMD from the TSL is substantial during the low-flow season	- Considered a short period of time - Analyzed sediment data in a small area that did not include the entire lower MR - No linkage with dam impacts - No linkage with morphological changes
Morphology	Brunier et al. (2014)	Morphological changes in the Tien and Hau rivers	1998 and 2008	The riverbed was incised, mainly caused by aggregate extraction	The role of existing dams in bed losses remains unclear because of the absence of the Mekong's sediment load

Table 3
Long-term data for discharge, sediment and precipitation used in the present paper. The originality of the present paper is highlighted by comparing the spatial and temporal data used in the present paper and previous papers. We employed longer (time) and wider (space) datasets compared to those of prior studies.

Country	Station	The present paper		Range of sediment data used in prior papers			
		Discharge	Sediment	Lu and Siew (2006)	Xue et al. (2011)	Liu et al. (2013)	Lu et al. (2014)
China	Jiuzhou	–	1965–2003	–	–	–	–
China	Gajiu	–	–	–	–	1965–2003	–
China	Yunjinghong	–	–	–	–	1965–2003	–
Thailand	Chiang Saen	1960–2013	1961–2013	1962–2000	1962–1975	1960–2002	–
Laos	Luang Prabang	1962–2013	1961–2013	1962–2000	1962–2002	1960–2002	–
Thailand	Nong Khai	1969–2013	1961–2013	1971–2000	1972–2003	1960–2002	–
Thailand	Nakhon Phanom	–	–	–	1972–1975	–	–
Thailand	Mukdahan	1961–2013	1961–2013	1962–2000	1962–2003	1960–2002	2009–2011
Thailand	Khong Chiam	1966–2013	1962–2013	1962–2000	1966–1986	1961–2002	–
Laos	Pakse	1961–2013	1961–2013	1962–2000	1962–2002	1960–2001	–
Cambodia	Chruy Changvar	–	–	–	–	–	2008–2011
Cambodia	Phnom Penh	–	–	–	–	–	2008–2011
Vietnam	Tan Chau	1980–2015	1980–2015	1987–1999	–	–	2009–2011
Vietnam	Chau Doc	1980–2015	1980–2015	–	–	–	2008–2011
Vietnam	My Thuan	1999–2015	2009–2015	1987–1999	–	–	–
Vietnam	Can Tho	2000–2015	2009–2015	1987–1999	–	–	–

studies at stations upstream of the VMD, including a station upstream of the Lancang cascade dams (e.g., Lu and Siew, 2006; Fu et al., 2008; Wang et al., 2011; Koehnken, 2014; Lu et al., 2014), in conjunction with long-term daily sediment data covering the period of 1980–2015 in the VMD (provided by the Vietnam National Center for Hydrometeorological Forecasting (VNCHF)). Understanding the associated historical impacts is important for informing the ongoing debate over hydropower dams in the MRB and the possible impacts on the sediment load and morphological changes downstream.

2. Materials and methods

2.1. Study area

The transboundary MR originates in the Tibetan Plateau and flows through China, Myanmar, Lao PDR, Thailand, and Cambodia before emptying into the East Sea of Vietnam through extensive alluvial floodplains in Cambodia and Vietnam (Fig. 1). The MRB is ranked as the tenth largest river in the world in terms of its annual sediment load of 160 Mt/yr (Meade, 1996). The MRB has two parts: the upper MRB within China constitutes 24% of the total area (189,000 km^2), and the lower MRB within Thailand, Lao PDR, Cambodia and Vietnam constitutes 76% (606,000 km^2) of the total area (Lu and Siew, 2006). The upper MRB (called Lancang in China) is a crucial source of water derived from snowmelt, with >70% of the flow contribution occurring during the low-flow season (i.e., April–May) at Vientiane and over 40% of the flow in April (the lowest month) occurring at Kratie (Adamson et al., 2009; Kuenzer et al., 2013).

The MR enters the VMD through two distributaries, the Tien and Hau rivers (Vietnamese names of the Mekong and Bassac rivers, respectively). The Tien and Hau rivers discharge to the East Sea of Vietnam through eight branches. The Tien river conveys 80% of the flow, which is monitored at the Tan Chau station, while the remaining 20% is transported by the Hau river, which is monitored at the Chau Doc station (Fig. 1). However, a portion of the flow from the Tien river is shared to the Hau river via the Vam Nao channel, and from that point forward, the flow between the two rivers becomes nearly equal. The VMD was formed through an abundant supply of 160 Mt/yr of suspended sediment discharged from the MR during the predam period (Kondolf et al., 2014). The plentiful sediment supply from the MR may aid the VMD in sustaining adverse effects of sea level rise, land subsidence (Manh et al., 2014), riverbank erosion and riverbed incision (Kondolf et al., 2014), and coastline retreat (Anthony et al., 2015).

Sixty-four large hydropower dams were built in the MRB through 2015 (Fig. 1), with a total storage capacity of over 80.2 km^3 (accounting for 96.8% and 20.1% of the mean annual discharges at Chiang Saen and Kratie, respectively), and >50% of the capacity (41.2 km^3) was from the six mainstream mega-dams in the upper MRB in China (Table 1). These mega-dams can trap nearly all the input sediment (Binh et al., 2018b). Nuozhadu and Xiaowan are the two largest dams, with a total storage capacity of 38.4 km^3, which is >10 times greater than that of all other dams (Table 1). Therefore, the six mainstream mega-dams are expected to cause the greatest reductions in the sediment load in the lower MR. Additionally, the construction of 11 mainstream hydropower dams is planned in the lower MR, and Xayaburi is under construction in Lao PDR and will be completed in 2019.

2.2. Flow discharge and sediment data

In this paper, the available dataset comprises the daily discharges and suspended sediment concentrations (SSCs) at four stations in the VMD and the annual discharges and suspended sediment loads (SSLs) at seven stations along the MR upstream of the VMD, including one station upstream of the Lancang cascade in China (Table 3). We also include the daily precipitation at seven stations in the MRB, namely, Licang, Simao, Lancang, Jinghong (in China), Chiang Saen, Nong Khai (in Thailand), and Pakse (in Laos) for the period of 1950–2016. Years with available data for each parameter are listed in Table 3, and the stations analyzed in Table 3 are shown in Fig. 1. At Tan Chau and Chau Doc, daily discharge data were continuously available spanning the period of 1980–2015, and daily SSCs were measured (but not continuously) during the period of 1993–2015 (Fig. S1). However, daily SSCs are sparsely available at Tan Chau during the period of 1980–1992, and no records were found for Chau Doc. The tide strongly influences the sediment dynamics at Tan Chau and Chau Doc in the VMD during the low-flow season (January–June) because of low discharges from the MR, while tidal effects during the high-flow season (July–December) are negligible because of high discharges from the MR.

The main sources of these data were the MRC and the VNCHF. Data were also collected from published reports and journal papers (e.g., Lu and Siew, 2006; Fu et al., 2008; Wang et al., 2011; Koehnken, 2014; Lu et al., 2014). All stations use depth-integrated methods to measure the SSCs at several vertical profiles in a cross section (six profiles at Tan Chau and Chau Doc, for example). Additionally, all data were cross-checked before use in this study. For instance, the sediment loads derived from the Water Quality Monitoring Network dataset of the MRC were converted to the hydrological dataset using linear regression (Wang et al., 2011). Sources of the sediment data, measurement methods, and data processing at all analyzed stations, station-by-station, are provided in detail in the supplementary material.

2.3. Sand mining data

We collected the annually licensed sand mining volume in 2008–2017 in the upper part of the Tien and Hau rivers (from Tan Chau/Chau Doc to My Thuan/Can Tho) from local authorities in 2017. Specific mining locations and the volume at each location were unfortunately not provided. The mean annually licensed sand mining volume was 1.7 Mm^3/yr over the period of 2008–2017 and 1.6 Mm^3/yr over the period of 2014–2017, ranging from 1.3 to 1.9 Mm^3/yr.

We also obtained sand mining data in the VMD from Bravard et al. (2013), who conducted field surveys in May 2012. There were ten main mining spots in the entire VMD according to their field surveys. They reported a total mined volume of 7.75 Mm^3/yr at these ten spots. Among these ten spots, four were in the Tan Chau-My Thuan sector in the Tien river, with a mined volume of approximately 3.9 Mm^3/yr.

2.4. Bathymetric field measurements

We hypothesize that the reduced sediment supply from the MR is more likely to result in morphological changes (i.e., riverbed incision and riverbank erosion) in the VMD. To clarify, a boat-based bathymetric survey was conducted in August–September 2017 along approximately 570 km of the Tien and Hau rivers (in the Co Chien, Cung Hau, Dinh An, and Tran De branches) and the Vam Nao diversion channel (Fig. 1). A pole-mounted Trimble GPS-equipped Teledyne RD Instruments Workhorse Rio Grande 600 kHz acoustic Doppler current profiler (ADCP) was used to measure the river depths of 200 cross sections. The ADCP was mounted 0.3 m below the water surface. The distance between two adjacent cross sections was 1–5 km. A handheld Garmin GPS was used to cross-check the reliability of the Trimble GPS. In the field survey, hydrological conditions were carefully observed to ensure the measurement quality and boat safety.

Additionally, hourly water levels at 11 hydrological stations along the Tien and Hau rivers (namely, Tan Chau, Vam Nao, Cao Lanh, My Thuan, Tra Vinh, Ben Trai, Chau Doc, Long Xuyen, Can Tho, Dai Ngai, and My Thanh) were collected during the period of the field survey to derive the river bed elevations from the river depths measured by the ADCP. These stations are operated by the Southern Regional Hydrometeorological Center, Ho Chi Minh City, belonging to the VNCHF. Long-term hourly water levels have been monitored using automatic water level recorders, Steven A-71 of Steven Water Monitoring Systems, Inc., USA (e.g., at Tan Chau, Chau Doc, and Can Tho) and ValDai of Valdai Experimental Laboratory, Russia (e.g., at Vam Nao and My Thuan). The recorded water levels were cross-checked twice daily (i.e., at 7:00 and 19:00 local time) using a country-wide levelling systems. Before releasing the data, the water levels were validated using the HYDTID software developed by the VNCHF to detect and treat noise spikes. The final water levels use the Vietnam national datum at Ha Tien in the Gulf of Thailand.

To demonstrate temporal and spatial morphological changes, river bathymetric data from 1998 and 2014 were collected from Thuyloi University and the Southern Institute of Water Resources Research, Vietnam. The 2014 bathymetric survey was conducted at 491 cross sections for a target region along about 100 km in the upper part of the Tien river from Tan Chau to My Thuan using the ADCP. The distance between two adjacent cross sections ranged from 200 m to 1000 m. The 1998 bathymetric data measured by a bi-frequency echosounder (Brunier et al., 2014) were available along all main branches of the Tien and Hau rivers and the Vam Nao channel and were originally distributed by the MRC. The distance between two adjacent cross sections was 300–500 m. All bathymetric datasets from 1998, 2014, and 2017 were converted to WGS 1984 Universal Transverse Mercator, zone 48 North projection. The datasets were in X, Y, Z coordinates, in which the elevation (Z) values were expressed in meters using the Vietnam national datum at Ha Tien in the Gulf of Thailand.

2.5. Data processing

2.5.1. Suspended sediment concentration and load estimates

The daily SSCs at Tan Chau during the period of 1980–1992 were significantly higher than those in 1993–2015 (Fig. S1). Therefore, the SSC-Q rating curves (Q is discharge) at Tan Chau and Chau Doc were established separately for these two periods to estimate the missing SSCs. During the period of 1980–1992, the missing daily SSCs at Tan Chau were first estimated using the SSC-Q rating curve by compiling all available data from this period. Then, missing daily SSCs at Chau Doc during the period of 1980–1992 were determined as the products of the corresponding daily SSCs at Tan Chau and a factor of 13.3%, which was the mean percentage of SSLs at Chau Doc compared to those at Tan Chau in 1993–2015. This estimation method yielded a mean annual sediment load in the VMD of 166.7 ± 33.3 Mt/yr for the period of 1980–1992 (sum of Tan Chau and Chau Doc), which is comparable to the 160 Mt/yr widely reported in the literature (Meade, 1996; Kondolf et al., 2014). The mean annual discharges at Tan Chau and Chau Doc during the period of 1980–2015 were 9940 m^3/s and 2490 m^3/s, respectively. These hydrographs were divided into the rising stage from April to September and the falling stage from October to March of the following year. The SSC-Q relations in the VMD have clockwise hysteresis (Fig. S2). Thus, the missing SSCs during the period of 1993–2015 at Tan Chau and Chau Doc were estimated based on the SSC-Q rating curves, which were established separately for these rising and falling stages. The estimated SSLs at Tan Chau and Chau Doc based on the SSC-Q rating curves may exert biases because of tidal modulation during the low-flow season; however, the bias is negligible because >90% of the sediment loads at these two stations are transported during the high-flow season (Fig. S3) when the tidal influence on the sediment dynamics is small. The SSC-Q rating curves were generated and fitted using a power relationship:

$$SSC = a \times Q^b \tag{1}$$

Then, the daily SSLs were computed as a product of the daily SSCs and corresponding daily discharges:

$$SSL = \frac{86,400 \times SSC \times Q}{10^6} \tag{2}$$

where a and b are two dimensionless coefficients; 86,400 is the total number of seconds in a day; and 10^6 is a conversion factor. The units of Q, SSC, and SSL are m^3/s, g/m^3, and t/day, respectively. The daily SSLs were then used to examine the monthly and annual SSLs. The SSL of the VMD was the summation of the Tan Chau and Chau Doc station SSLs.

2.5.2. Acquisition of bathymetric maps and bathymetric comparison

The ADCP raw data were checked, and noise spike points caused by boat movement were filtered by high- and low-pass filters. The cross-sectional river depths were then processed using the Teledyne RD Instruments WinRiver II software. In the meantime, the water surface elevations at each cross section at the time of the measurement were interpolated in a matrix of time and distance using hourly water levels at adjacent hydrological stations. Finally, the riverbed elevations were obtained by subtracting the water surface elevations to the corresponding river depths. The results were expressed in X, Y, Z coordinates.

In assessing the morphological changes between 2014 and 2017, the bathymetric point data needed to be interpolated and converted into raster mode. The comparison was obtained for a 100-km-long target region of the Tien river from Tan Chau to My Thuan, including the Vam Nao channel (Fig. 1), using *ArcGIS®10*. We used 491 cross sections measured in 2014 and 38 cross sections measured in 2017 for the assessment of morphological changes. Because the spatial resolution of the bathymetric data in 2014 was finer than that in 2017, we first determined the best interpolation method available in the *Geostatistical*

Table 4
Statistical tests evaluating changes in the long-term monthly and annual SSLs in the VMD (sum of Tan Chau and Chau Doc) over 36 yr (1980–2015). Monthly and annual SSLs decreased statistically ($\alpha < 0.01$) beginning in 1992 after the completion of the Manwan dam.

Month	n	Mann-Kendall trend test			Sen's slope estimator	Pettitt test to find the changing point		
		S	Z	Trend	(Mt)	K_T	t	Shift
January	36	−326	−4.427	–	−0.1118	299	1992	–
February	36	−290	−3.936	–	−0.0375	299	1992	–
March	36	−214	−2.901	–	−0.0146	299	1992	–
April	36	−232	−3.146	–	−0.0066	299	1992	–
May	36	−250	−3.392	–	−0.0198	279	1992	–
June	36	−234	−3.174	–	−0.0982	219	1992	–
July	36	−274	−3.719	–	−0.3503	235	1992	–
August	36	−316	−4.291	–	−0.6484	261	1992	–
September	36	−394	−5.353	–	−0.9692	302	1992	–
October	36	−338	−4.590	–	−0.9517	297	1992	–
November	36	−372	−5.053	–	−0.7578	295	1992	–
December	36	−406	−5.517	–	−0.3605	295	1992	–
Annual	36	−388	−5.271	–	−4.4596	297	1992	–

Analyst module in *ArcGIS®10*, including deterministic and geostatistical methods with different parameters for the 2014 bathymetric data. The best interpolation method was selected based on the minimum error between the measured and predicted values. Then, the selected method was applied to interpolate the 2017 bathymetric data. Universal Kriging using the exponential method with the kernel function was the best method among 111 methods we tested. The two interpolated riverbed elevation maps in 2014 and 2017 had the same number of pixels and the same spatial resolution of 40 m. The morphological changes, as well as volume gains and losses (in m^3), were obtained by subtracting the riverbed elevation map of 2017 to that of 2014 using the *GCD®6* (Geomorphic Change Detection) add-in in the *ArcGIS®10* software. To facilitate comparison with the morphological changes in 1998 and 2008 derived by Brunier et al. (2014), differences between the 2014 and 2017 riverbed elevation maps within the range from −0.6 m to +0.6 m were excluded from comparison to eliminate depth measurement errors by the instrument.

2.6. Data analysis

Statistical tests (Mann-Kendall, Pettitt, and Sen Slope) at the 1% significance level ($\alpha = 0.01$) were used to analyze the trends and changes in the long-term flow and sediment discharges in the MR. The Mann-Kendall test (Kendall, 1938; Mann, 1945) was employed to detect changes in the trends of long-term flow and sediment data. When a trend change was detected, the Pettitt test (Pettitt, 1979) was used to find the change year (turning year) in the time series. Finally, Sen's slope method (Sen, 1968) was used to estimate the slope (or rate of change) of the time series. Sen's slope method is unaffected by non-normal distributions, missing data, and outliers (Zhang and Lu, 2009). These three methods have been widely employed by many researchers in past hydrometeorological studies.

3. Results

3.1. Daily and monthly analyses of the discharge, suspended sediment concentration, and suspended sediment load in the VMD

The Mann-Kendall test revealed that the daily SSC and SSL at Tan Chau decreased significantly over the period of 1980–2015, although the daily discharge was unchanged. The mean daily SSL decreased at a rate of 10,780 t/yr ($\alpha < 0.01$). Similarly, the sediment loads of all months decreased at the 1% significance level (Table 4), whereas the monthly discharge changed gently. The largest sediment reductions occurred in September and October, with a reduction rate of nearly 1 Mt/yr, and April was the month that experienced the smallest reduction rate of 6600 t/yr. The change point occurred in 1992, as detected by the Pettitt test ($\alpha < 0.01$). Fig. 2 shows that the daily SSC and SSL have significantly decreased since 1993, when the Manwan dam was completed in the MR mainstream, whereas the trendlines during the period of 1980–1992 remained nearly unchanged. These stable trendlines during the predam period (1980–1992) were consistent with the relatively stable sediment load at Gajiu (2 km downstream of the Manwan dam) and Yunjinghong (400 km downstream of the Manwan dam) during the period of 1965–1984 (Liu et al., 2013).

Fig. 2 shows that the discharges remained constant; thus, the decreasing SSLs resulted from decreasing SSCs. The reduction in the SSC

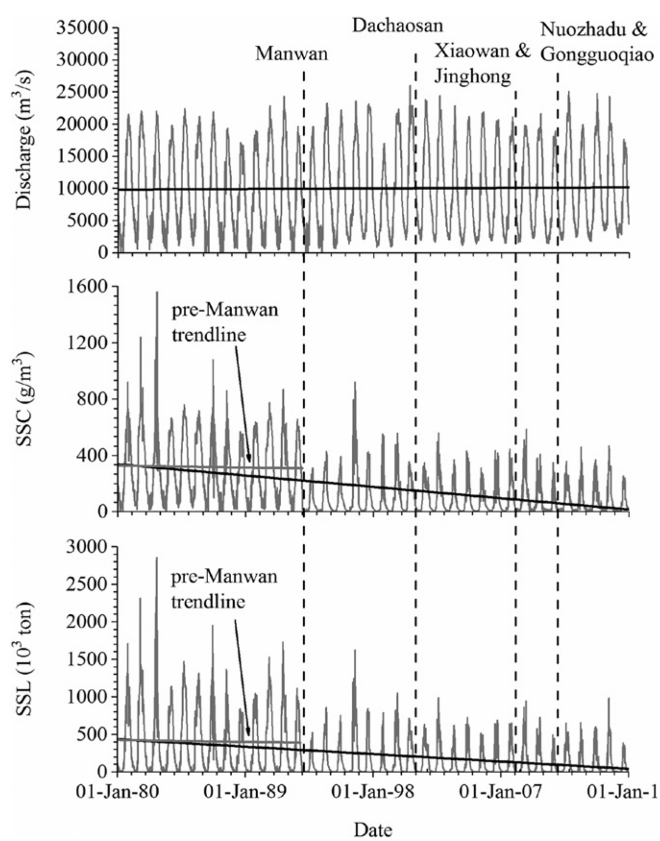

Fig. 2. Long-term daily discharge, SSC, and SSL at Tan Chau.

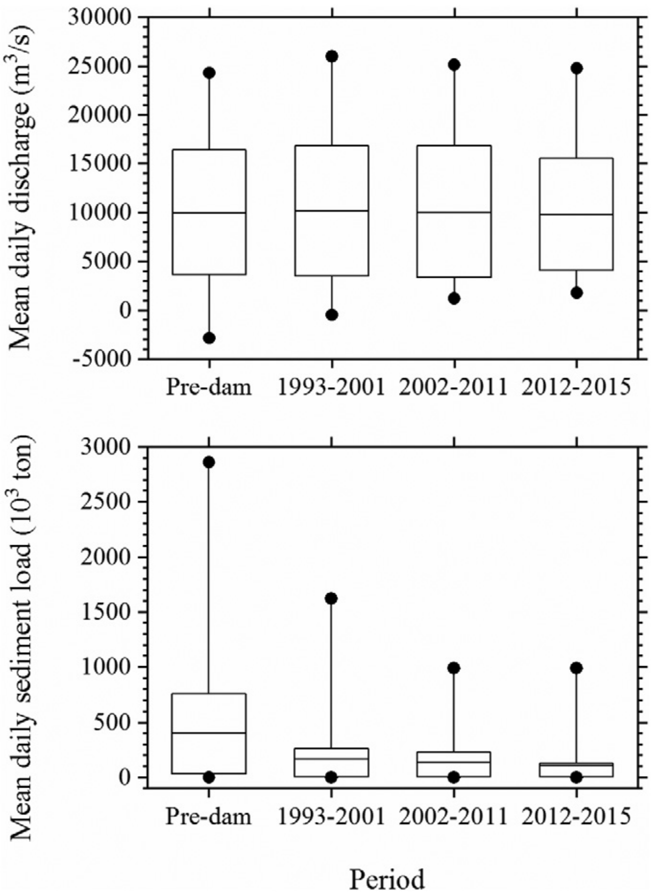

Fig. 3. Box-whisker plots of the mean daily discharges and sediment loads at Tan Chau during the predam and postdam periods, including the mean, 25th percentile, 75th percentile, and minimum and maximum values.

as a response to dam building was nearly instantaneous. Therefore, it is likely that the buffering effect of the trapped sediment in the channel downstream of the dam sites (this sediment deposits during the predam period because of sediment abundance and becomes erosive during the postdam period because of "hungry water" flow) on the VMD is limited.

The SSL time series was divided into four periods according to the completion years of the mainstream dams in the MR as follows: the predam period (pre-1992), when only some small tributary dams existed, and therefore, the sediment regime was relatively pristine, and three postdam periods (1993–2001, 2002–2011, and 2012–2015). Because of dam impacts, the mean daily SSL decreased significantly from 401,960 t/day during the predam period to 165,300 t/day in 1993–2001 (−58.9%), 129,780 t/day in 2002–2011 (−67.7%), and 104,290 t/day in 2012–2015 (−74.1%) (Fig. 3). A decreasing trend was also found for the maximum daily SSL between the predam and postdam periods.

Compared to the predam conditions, the postdam monthly discharge generally increased during the low-flow season (January–May) and decreased during the high-flow season (June–December), whereas the postdam monthly sediment loads decreased significantly in all months (Table 5). The SSL in most months in 2012–2015 was reduced by >60% (except in August) and by up to 90% in low-flow months (December–February) relative to that during the predam period. The completion of more dams in the MRB caused further reductions in the monthly sediment loads in the VMD. A majority (>70%) of the monthly sediment load reductions during the low-flow season from the predam period in the VMD occurred in 1993–2001, after the completion of Manwan, which is in line with the model results of Schmitt et al. (2019). However, the completion of more dams during the periods of 2002–2011 and 2012–2015 further reduced the sediment loads in the high-flow season. For instance, the July sediment load decreased from 15.9 Mt during the predam period to 7.8 Mt in 1993–2001 (−51.0%), 5.9 Mt in 2002–2011 (−63.1%) and 4.8 Mt in 2012–2015 (−69.5%).

Table 5
Changes in the mean monthly discharge and SSL during the predam and postdam periods in the VMD over 36 yr (1980–2015). More dams being completed in the MRB caused more reductions in the monthly sediment loads in the VMD.

Index	Month	Period						
		Predam	1993–2001		2002–2011		2012–2015	
		Magnitude	Magnitude	Change (%)	Magnitude	Change (%)	Magnitude	Change (%)
Discharge (km^3)	Jan	21.26	20.26	−4.69	20	−5.91	21.66	+1.89
	Feb	11.92	11.05	−7.28	11.47	−3.75	12.8	+7.41
	Mar	7.6	7.93	+4.37	7.91	+4.04	10.7	+40.74
	Apr	6.12	6.9	+12.81	6.83	+11.67	9.91	+61.97
	May	8.38	9.84	+17.44	10.37	+23.74	11.97	+42.83
	Jun	20.64	22.08	+6.99	21.07	+2.08	19.74	−4.36
	Jul	39.6	43.65	+10.24	37.86	−4.37	38.1	−3.79
	Aug	57.4	63.1	+9.93	60.26	+4.99	60.22	+4.92
	Sep	65.23	68.46	+4.95	65.49	+0.4	61.78	−5.29
	Oct	63.87	66.68	+4.39	67.35	+5.45	61.69	−3.42
	Nov	51.5	49.18	−4.5	49.31	−4.24	42.19	−18.07
	Dec	34.71	35.18	+1.37	33.5	−3.48	28.53	−17.8
Sediment load (Mt)	Jan	4.2	0.42	−89.97	0.38	−91	0.44	−89.54
	Feb	1.54	0.12	−92.26	0.13	−91.35	0.13	−91.25
	Mar	0.68	0.05	−92.88	0.06	−90.55	0.09	−86.44
	Apr	0.4	0.05	−86.85	0.05	−87.92	0.1	−75.59
	May	0.85	0.19	−78.23	0.15	−82.58	0.12	−86.43
	Jun	5.5	1.94	−64.69	1.14	−79.24	0.94	−82.97
	Jul	15.85	7.76	−51.01	5.85	−63.12	4.83	−69.52
	Aug	30.98	18.14	−41.43	14.74	−52.4	14.47	−53.28
	Sep	37.8	20.7	−45.24	14.03	−62.89	13.34	−64.71
	Oct	33.77	10.63	−68.51	11.33	−66.47	5.94	−82.41
	Nov	23.86	5.94	−75.11	4.5	−81.13	2.03	−91.49
	Dec	10.99	2.47	−77.56	1.36	−87.67	0.7	−93.65

Change (%) = (postpre) / pre ∗ 100. "+": increase and "−": decrease.

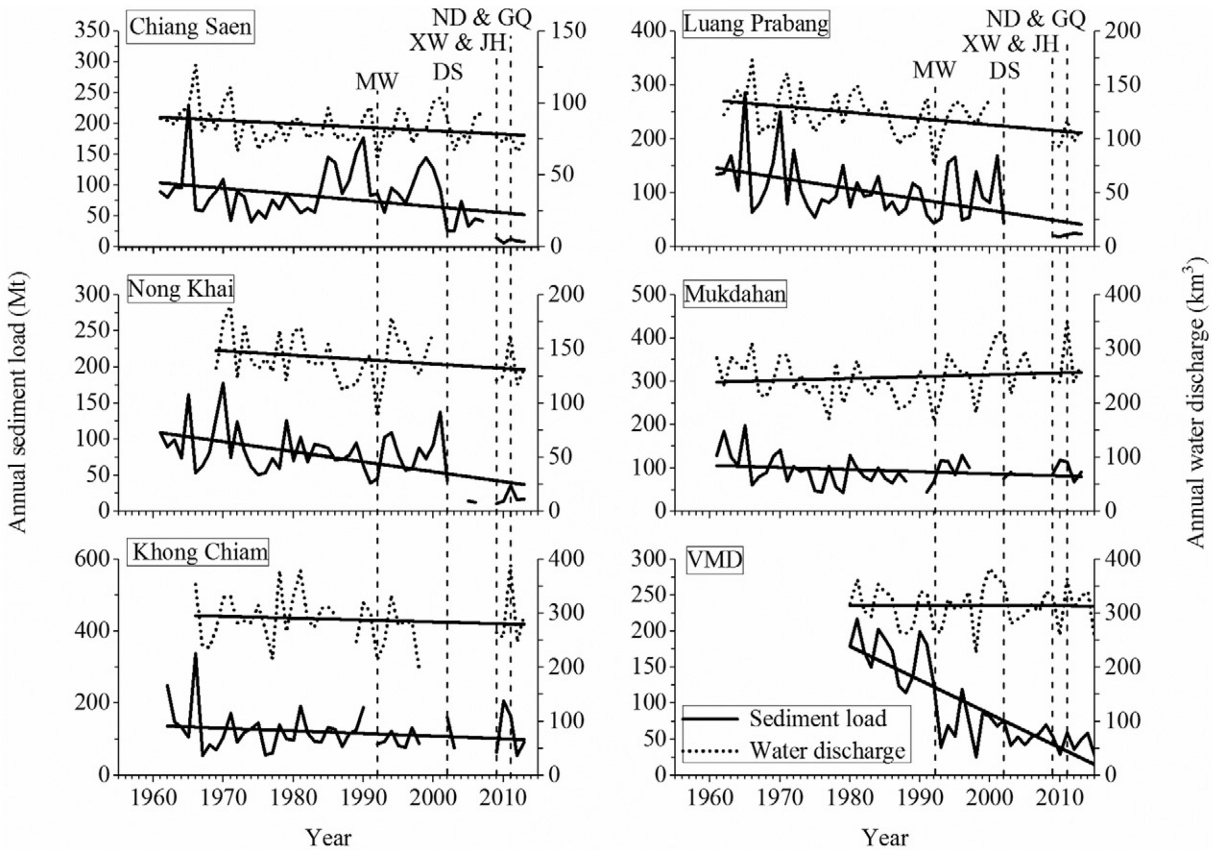

Fig. 4. Long-term annual discharges and sediment loads at six stations along the lower MR. MW: Manwan; DS: Dachaoshan; XW: Xiaowan; JH: Jinghong; ND: Nuozhadu; GQ: Gongguoqiao.

3.2. Annual discharge and suspended sediment load of the VMD during the predam and postdam periods

The long-term annual suspended sediment load at Chiang Saen, Luang Prabang, Nong Khai, Mukdahan, Khong Chiam, and the VMD decreased significantly, especially in 1992, 2002, and 2009 after the completion of the Manwan, Dachaoshan, and Xiaowan and Jinghong dams, respectively (Fig. 4). For instance, at Chiang Saen, the sediment load decreased by >70% after the completion of the Dachaoshan dam, from 94 Mt in 2001 to 26.9 Mt in 2002. Notably, comparing the slopes of the trend lines shows that the sediment load decreased faster than the discharge (Fig. 4). The trend line slopes at Mukdahan and Khong Chiam were milder than those at other stations because the SSLs in 2009–2013 at these two stations were overestimated because of the limitation of the sampling device (Koehnken, 2014). Additionally, the completion of more dams in the MRB caused greater reductions in the annual sediment load at stations along the lower MR. For instance, at Luang Prabang, the sediment load decreased by 77.6% during the period of 2012–2015 when 64 dams were completed, and only a 2.9% reduction occurred during the period of 1993–2001 when 17 dams were completed (Table 6).

Based on 105 suspended sediment data measurements during the period of 1980–1992, we established the SSC-Q rating curve using a power function in the form of Eq. (1). Then, we estimated the annual sediment load (using Eq. (2)) of the VMD during the predam period to be 166.7 Mt/yr. Our estimate is supportive of the reported annual sediment load of the MR of 150–170 Mt/yr (Meade, 1996; Kondolf et al., 2014; Lu et al., 2014). Importantly, our estimate is substantially higher than the estimate of 87.4 Mt/yr by Darby et al. (2016), who used the SSC-Q rating curve with all data spanning the period of 1982–2004 (comprising both predam and postdam sediment data) at Kratie to estimate the predam annual sediment load of the MR. Their value was

Table 6
Changes in the annual discharge and suspended sediment load during the predam and postdam periods at seven stations along the MR.

Station	Period	Discharge		Sediment load	
		Magnitude km^3	Change (%)	Magnitude Mt	Change (%)
Chiang Saen	Predam	85.13		90.39	
	1993–2001	87.26	+2.5	100.24	+10.89
	2002–2011	80.11	−5.89	31.56	−65.09
	2012–2015	70.11	−17.64	9.47	−89.52
Luang Prabang	Predam	125.02		110.35	
	1993–2001	123.86	−0.93	107.19	−2.86
	2002–2011	102.25	−18.21	26.47	−76.02
	2012–2015	103.1	−17.54	24.69	−77.63
Nong Khai	Predam	140.13		85.13	
	1993–2001	149.28	+6.53	88.3	+3.72
	2002–2011	136.22	−2.79	21.81	−74.38
	2012–2015	124.66	−11.04	16.64	−80.46
Mukdahan	Predam	237.5		93.46	
	1993–2001	260.16	+9.54	110.13	−17.83
	2002–2011	270.08	+13.72	98.12	+5.0
	2012–2015	254.13	+7.0	79.9	−14.51
Khong Chiam	Predam	293.37		125.3	
	1993–2001	269.94	−7.99	99.55	−20.55
	2002–2011	303.19	+3.34	134.9	+7.66
	2012–2015	272.44	−7.14	73.01	−41.73
Pakse	Predam	307.88		161.31	
	1993–2001	319.9	+3.91	124.01	−23.12
	2002–2011	322.71	+4.82	92.64	−42.57
	2012–2015	296.2	−3.79	65.92	−59.13
VMD	Predam	389.24		166.7	
	1993–2001	403.8	+3.74	68.41	−58.9
	2002–2011	390.63	+0.36	53.71	−67.72
	2012–2015	378.81	−2.68	43.13	−74.09

Change (%) = (postpre) / pre ∗ 100. "+": increase and "−": decrease.

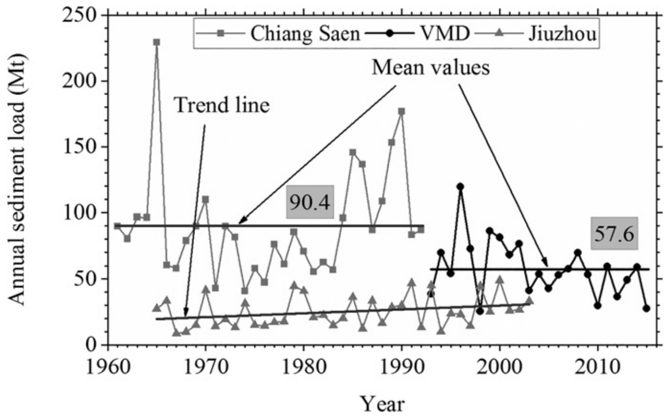

Fig. 5. Annual sediment loads in the upper (Jiuzhou), middle (Chiang Saen), and lower MR (VMD).

therefore likely underestimated because the predam SSCs were significantly higher than the postdam SSCs (Fig. S1).

In the VMD, the annual sediment load decreased sharply, whereas the annual discharge decreased only slightly (Fig. 4). The Mann-Kendall and Pettitt tests showed that the VMD's annual sediment load has statistically decreased ($\alpha < 0.01$) since 1992, at a rate of 4.5 Mt/yr, as determined by Sen's slope test (Table 4). In total, 74.1% of the annual sediment load of the VMD decreased during the period of 2012–2015 as a consequence of all 64 dams in the MRB, and a 58.9% reduction occurred over the period of 1993–2001 (Table 6). During the predam period, the upper MRB contributed 54.3% of the VMD's sediment load (the proportion of the Chiang Saen sediment load (90.4 Mt) relative to the VMD's sediment load (166.7 Mt)), indicating that out of a 74.1% total reduction in the VMD's sediment load, 40.2% was caused by the six mainstream dams in the upper MR, and 32% was a consequence of the Manwan and Dachaoshan dams alone. The annual sediment reductions in the VMD caused by all 64 dams and mainstream dams are shown in Fig. S4. The annual sediment loads of the VMD during the postdam period (1993–2015) were even smaller than those at Chiang Saen during the predam period (Fig. 5). An important finding is that while the annual sediment loads of all stations in the lower MR decreased significantly (Fig. 4), the annual sediment load in the upper MR at the Jiuzhou station upstream of the Lancang cascade increased substantially (Fig. 5). This indicates that the reduction in the sediment load is not caused by a possibly reduced sediment supply from the upper MRB but is because of sediment trapping in dams.

We collected suspended sediment samples along the Tien river during our field survey in August 2017 to determine the grain size distribution. The grain size distribution at Mang Thit and My Thuan, as depicted in Fig. S5, clearly shows that approximately 95% of the suspended sediment was composed of silt and clay. Approximately 90% of the bed material was composed of sand, and the sand was mined from the riverbed. Therefore, sand mining was likely not the main driver of reductions in the suspended sediment load in the VMD during the study period. If sand mining had an influence, the mining activities would have increased the SSCs (through the mud content in the sand bed) in areas surrounding the mined points because of mechanical resuspension. For instance, during our field survey in August 2017, we recorded exceptionally high SSCs just downstream of the mining area, located 83 km from the river mouth of the Tien river. The mean cross-sectional SSC downstream of the mining area (1132 g/m^3) was more than three times greater than that upstream of the mining area (356 g/m^3) (the flow was seaward during the survey time).

3.3. Morphological changes in the VMD

Fig. 6 shows evidence of a critical riverbed incision in the VMD during the period of 1998–2017. The river thalweg in the Tien river from Tan Chau to My Thuan incised significantly, ranging from −0.43 m to −14.87 m deep, with a mean value of −5.2 m during the period of 1998–2014. In other words, the incision rates ranged from −0.03 to −0.93 m/yr, with a mean value of −0.33 m/yr. During the three years between 2014 and 2017, the mean river thalweg incision was −3.73 m, varying between −0.45 and −11.37 m. These incisions were equivalent to −1.24 m/yr (for the mean incision) and between −0.15 m/yr and −3.79 m/yr (for the minimum and maximum incisions, respectively). This finding indicates that the mean river thalweg incision rate during the period of 2014–2017 was approximately fourfold that of 1998–2014. In total, the maximum and mean river thalweg incisions were −20.28 m and −8.92 m, respectively, during the period of 1998–2017. Four typical cross sections along the Tan Chau-My Thuan section (Fig. 6) and another eight cross sections near the estuary (Fig. S6) confirmed a significant riverbed incision in the VMD.

Incision was not limited to the thalweg but extended to the entire cross section (Fig. 7). The incision was highest in the sector from Tan Chau to section A-A (Fig. 7b and e), from section E-E to My Thuan (Fig. 7a and e), and in the Vam Nao channel (Fig. 7a). Moreover, severe riverbed incision was observable in the meandering areas and at the confluence downstream of an island. Fig. 7e shows the net erosion and deposition volume for every one-kilometer-long section of the main branch from Tan Chau to My Thuan, as well as the longitudinal mean depth evolution (the ratio of the net evolution volume to the area). The incision was dominant compared to the deposition. The maximum incision depth reached −2.9 m compared to the limited maximum deposition depth of 1.4 m. Overall, the total net riverbed incision volume for the entire area of the Tien river and Vam Nao channel from Tan Chau to My Thuan between 2014 and 2017 was approximately −157.5 Mm^3, which is equivalent to a mean riverbed incision depth of −1.5 m and a mean annual riverbed incision volume of −52.5 Mm^3/yr with a mean incision depth rate of −0.5 m/yr.

Additionally, we estimated that the riverbed of the Tien river and Vam Nao channel around the Cu Lao Tay island (Fig. 8) was incised by −46.6 Mm^3 during the period of 2014–2017, with a mean incision depth of −1.46 m, which is equivalent to an annual incision volume of −15.6 Mm^3/yr with a mean incision depth rate of −0.49 m/yr. This incision rate was nearly double the mean riverbed incision rate of −0.25 m/yr over the decade of 1998–2008, which had an absolute mean incision of −2.47 m (Brunier et al., 2014).

4. Discussion

4.1. Changes in sediment sources

The largest source that delivered sediment to the MR during the predam period was the upper MRB, contributing 98% of the sediment at Chiang Saen, 82% at Luang Prabang, and 54.3% in the VMD. However, the upper MRB became a minor sediment contributor to the lower MR during the postdam period because a large volume of the sediment was trapped by the mainstream reservoirs; for example, there is a projected 94% trapping efficiency of the eight mainstream dams in the upper MR (Kummu and Varis, 2007). Instead, the Nong Khai-Pakse section (including the 3S river basin) became the largest sediment source for the VMD during the postdam period (over 70%).

Riverbank erosion and riverbed resuspension along the lower MR (especially from Nong Khai to Pakse) caused by “hungry water” were likely additional sources of the postdam sediment that compensated for that diminished by the mainstream dams. This phenomenon is common in other rivers around the world; for instance, during the postdam period of the Mississippi River, sediment resuspended locally from the riverbed during the high-flow season contributed a considerable amount of the sediment downstream (Allison et al., 2017b). Darby et al. (2013) reported mean annual rates of riverbank erosion at Ang Nyay (near Nong Khai) during the period of 1913–2010 and at Pakse

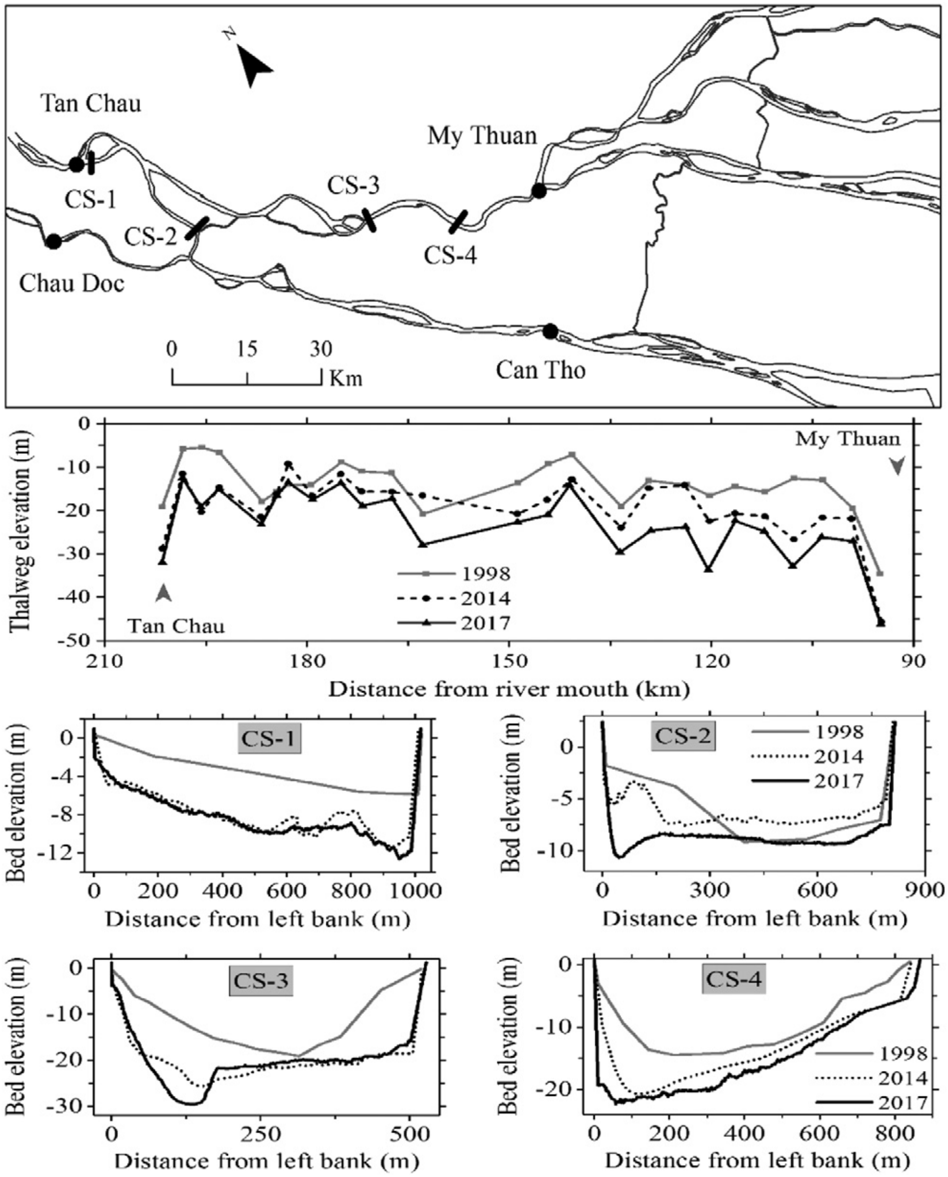

Fig. 6. Longitudinal and cross-sectional riverbed incision along the Tien river between the Tan Chau and My Thuan stations.

during the period of 1923–2010 as 0.68 ± 0.11 m/yr and 0.64 ± 0.16 m/yr, respectively.

4.2. Drivers of flow and suspended sediment changes along the lower MR

There was no clear change in the VMD's daily and monthly discharges during the period of 1993–2001 (Table 5 and Fig. 2), which was attributed to the relatively small reservoir capacity of the existing dams. Therefore, climate conditions, especially tropical cyclones (Darby et al., 2016), controlled the flow regimes during that period. However, decreased high-flow discharges and increased low-flow discharges at stations along the MR during the period of 2012–2015 (Table 5) were mainly driven by hydropower dams in the MRB because of their large reservoir capacity. Although the long-term mean annual precipitation at seven stations (Fig. 1) in the MRB did not significantly change (Fig. S7), which was also reported by (Xue et al., 2011), shifting in the timing and intensity of tropical cyclones was likely an important driver.

However, daily, monthly, and annual SSLs at stations in the lower MR decreased significantly (Tables 4 and 5; Figs. 2–4) after the completion of the Manwan dam in 1992, whereas the long-term sediment load at Jiuzhou, which is the station upstream of the six mainstream dams, increased during the period of 1965–2003 (Fig. 5), providing evidence that the mainstream dams trapped a significant amount of the inflowing sediment from the upper MRB. Owing to the relatively stable long-term precipitation in the MRB, the mainstream dams in the Lancang cascade were the main driver of sediment reductions in the MR upstream of Nong Khai. In addition, a decreasing intensity of tropical cyclones in the MRB during the postdam period before 2005 (Extended Data Fig. 5 in Darby et al., 2016) also played a key role in sediment reduction in the MR.

From Mukdahan to the VMD, decreasing tropical cyclone intensity may have partly driven sediment reductions during the period of 1993–2001. Nevertheless, how tropical cyclones changed after 2005 is unclear (Darby et al. (2016) focused on the period of 1981–2005, and no other studies have focused on this topic). Tropical cyclones, however, appeared to increase in intensity because of climate change (Hoanh et al., 2010), which increased the sediment yield. Therefore, the significant sediment reductions from Mukdahan to the VMD during the period of 2012–2015 (Table 6) were mainly caused by the cumulative impacts of 64 dams in the MRB. Manh et al. (2015) concluded that hydropower dams in the MRB were

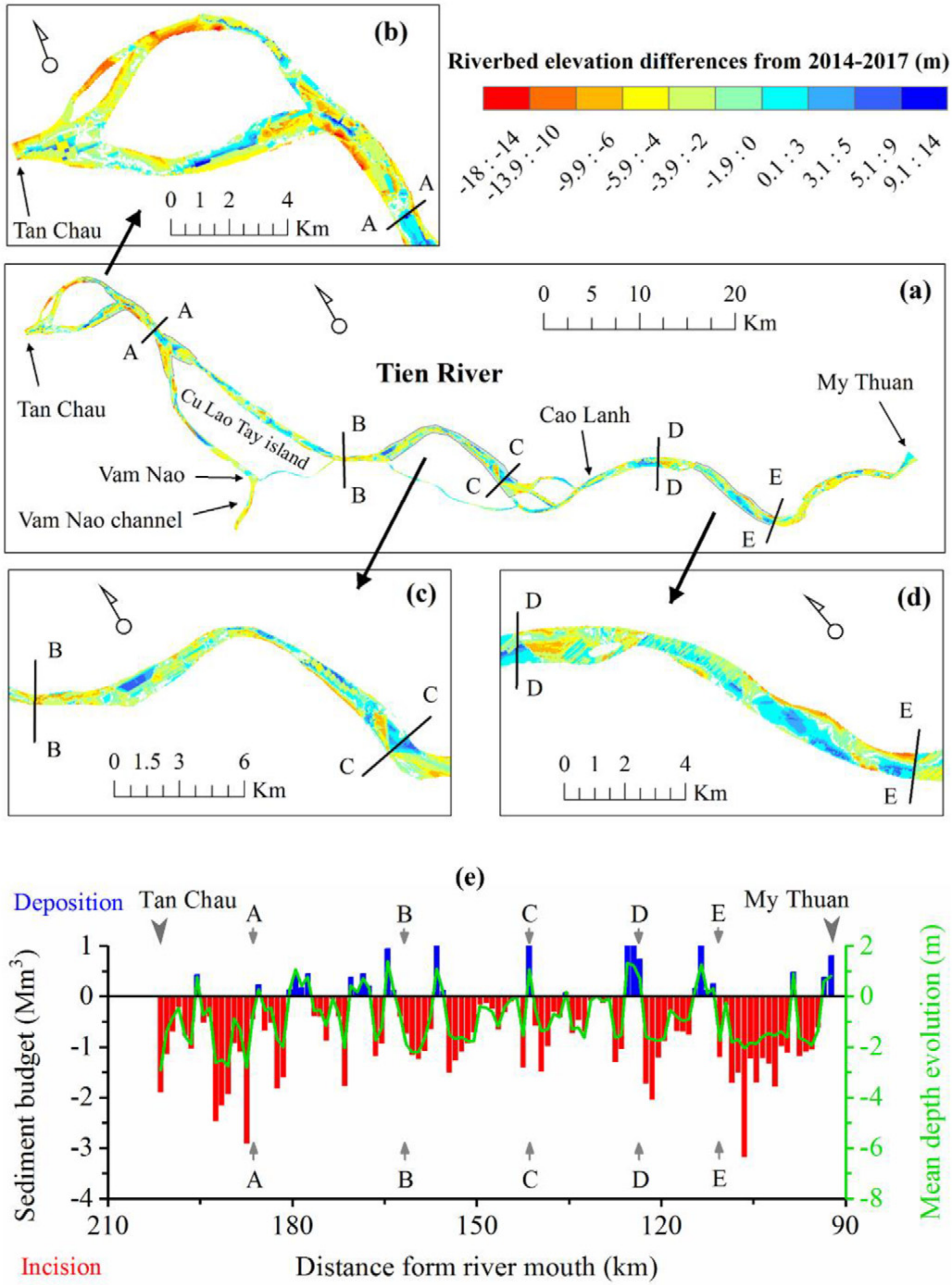

Fig. 7. Morphological changes in the Tien river from Tan Chau to My Thuan and the Vam Nao channel between 2014 and 2017. (a) General morphological changes; (b) from Tan Chau to section A-A; (c) from section B-B to section C-C; (d) from section D-D to section E-E; (e) net evolution volume and mean depth evolution. Riverbed incision is dominant in this sector.

the largest contributors to changes in sediment dynamics in the Mekong Delta compared to climate change and sea level rise influences. Of the 74.1% total sediment reduction in the VMD, 40.2% was induced by six mainstream dams. Our findings are comparable with the results of Kondolf et al. (2014), who estimated that all mainstream dams in the upper MRB would cause a 40% reduction in the sediment load of the lower MR. Hydropower dams were also responsible for a 74% reduction in the annual sediment discharge to the East Sea of Vietnam, from 144 Mt/yr during the predam period (Ta et al., 2002) to 37.7 Mt/yr during the period of 2012–2015, based on our data from the My Thuan and Can Tho stations. Similar to the case for the MR, dam-induced sediment reductions are common around the world, such as in the Red River of Vietnam (Lu et al., 2015), the Yangtze River of China (Tena and Batalla, 2013), the Colorado River of the USA (Tena and Batalla, 2013), the Nile River of Egypt (Milliman and Syvitski, 1992), and the São Francisco River of Brazil (Walling, 2006).

The demand for food security in riparian countries in the MRB has increased because of rapid population growth, socioeconomic development, and urbanization, forcing a rapid conversion from forest cover to cultivated lands. Deforestation for the expansion of cultivated lands increases the total sediment yield. However, our analysis indicates a significant decrease in the sediment load of the entire lower MR, especially during the period of 2012–2015, indicating land-use change in the MRB has not been a key driver. Hoang et al. (2019) found that the impacts of hydropower dams in the MRB have exceeded those caused by irrigation expansion and land-use change.

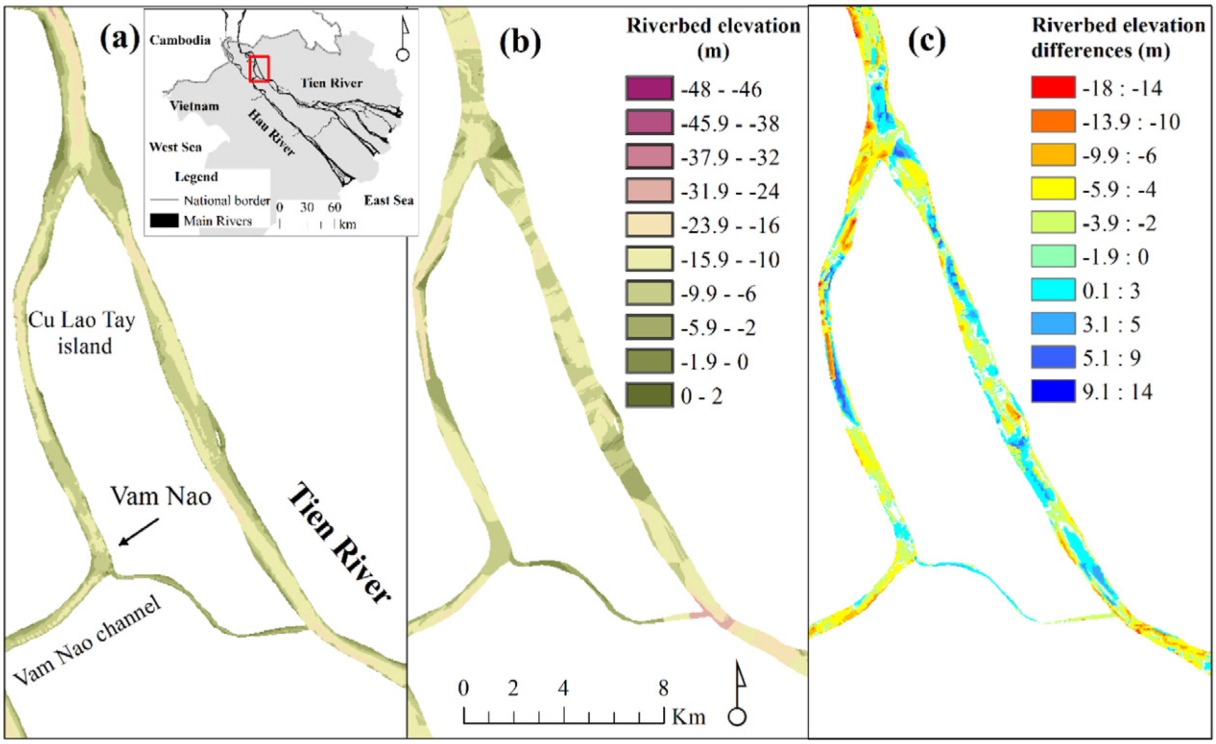

Fig. 8. Morphological changes of the Cu Lao Tay island sector. (a) morphology in 2014; (b) morphology in 2017; (c) morphological evolution between the 2014 and 2017 datasets. Riverbed incision is dominant in this sector.

4.3. Morphological changes in the VMD as a consequence of river damming and sand mining

Comparing the river thalweg and morphology during a short 3-yr period between 2014 and 2017 in the upper part of the Tien river from Tan Chau to My Thuan and the Vam Nao channel revealed severe net riverbed incision (Figs. 6–8), indicating that the recent sediment budget of the VMD has a net deficit. We estimated that the total incision volume during the period of 2014–2017 in our concerned river sector (-157.5 Mm^3) was similar to the total incision volume during the period of 1998–2008 in the entire Tien and Hau rivers (-200 Mm^3) estimated by Brunier et al. (2014). This result implies that the riverbed incision in recent years was more than three times greater than that in the past. Morphological changes are directly linked with bedload transport. By considering that the bedload was equal to 3–15% of the suspended load (Fu et al., 2008; Koehnken, 2014), the annual bedload volume flowing into the VMD during the predam period (pre-1992) was 2.1–20.4 Mm^3/yr (considering an aggregate density of 1.6 t/m^3). With these assumptions, bedload transport during the period of 2014–2017 was 0.6–6.2 Mm^3/yr. While the former values have historically formed the VMD, for instance, with an accretion rate of 16–26 m/yr (Kondolf et al., 2018), the latter values were associated with the large-scale riverbed incision (Fig. 7) in the VMD with an incision rate of -0.5 m/yr. Thus, the VMD has shifted from a net-depositional phase during the predam period to a net-erosional phase during the postdam period. It should be highlighted that such severe riverbed incision during a 3-yr period between 2014 and 2017 was likely not caused by a changing transport capacity, as the annual discharge of the VMD was stable during the period of 1980–2015 (Fig. 4), but it was very consistent with a reduction in the sediment supply (Figs. 2–4). Therefore, human interventions including dams and sand mining may be responsible for the rapid riverbed incision in the VMD during the period of 2014–2017.

Hydropower dams that trap most of the bedload, including sand, are likely the main driver causing large-scale riverbed incision in the VMD. For instance, current and planned dams in the 3S river basin trap 91% and 97% of the sand load, respectively (Schmitt et al., 2018). Riverbed incision around the Cu Lao Tay island sector between 2014 and 2017 (Fig. 8) was nearly double that during the period of 1998–2008. This might be attributed to the full operation of the two largest mega-dams in the Lancang cascade (Xiaowan and Nuozhadu) after 2009. These dams have more capacity to trap most of the incoming sediment from the upstream, therefore causing rapid incision of the riverbed in the VMD in recent years.

Hydropower dams and sand mining are also driving riverbank erosion in the VMD. Fig. S8 shows the typical riverbank erosion, which was obtained during our VMD's field survey in August 2017. Furthermore, land subsidence induced by hydropower dams, sand mining, and groundwater pumping occurred in the VMD (Schmitt et al., 2017; Kondolf et al., 2018). Similarly, the VMD coastline has rapidly retreated (Anthony et al., 2015) because of dam-induced sediment reduction and, to some extent, is likely caused by land-use change and mangrove forest reduction along the VMD's coastline (Allison et al., 2017b).

4.4. Contribution of sand mining to riverbed incision in the VMD

Sand mining is another key driver of riverbed incision. The annual volumes of mined sand during the period of 2008–2017 (Fig. S9) indicates that sand mining might have been strictly regulated since 2011 because of increasing complaints about its impact on recent severe riverbank erosion. Comparing the annual sand mining volume with the annual riverbed incision volume of -52.5 Mm^3/yr during the period of 2014–2017 suggests that sand mining is likely responsible for 2.9% (ranging from 2.6% to 3.6%) and 7.4% of the riverbed incision in the Tan Chau-My Thuan sector in the Tien river and Vam Nao channel (based on our data collected from local authorities and reported data from Bravard et al. (2013), respectively). In a more extreme case, if a sand mining volume of the entire VMD of 7.75 Mm^3/yr was considered (Bravard et al., 2013), sand mining would be responsible for 14.8%. These percentages might be even larger because sand mining operators tend to report lower amounts to reduce their fees (Bravard et al., 2013).

Additionally, aggregate mining in the upper VMD, especially in Cambodia, might have contributed to riverbed incision in the VMD; however, if included, the effect of sand mining would be still much smaller than the effect of upstream development, including river damming.

Fig. 7 shows that riverbed incision in the VMD occurred at the large scale, even in areas without sand mining. Therefore, we argue that although sand mining causes riverbed incision at the local scale, upstream developments, including hydropower dams, are responsible for larger-scale morphological changes. Fig. S6 differentiates the riverbed degradation caused by local sand mining and by large-scale hydropower dams. At cross sections with sand mining (e.g., CS-A), the riverbed geometry is irregular and characterized by deep mined pits, while other cross sections experience riverbed incision with regular shapes and without the appearance associated with sand mining.

5. Conclusions

We investigated the long-term impacts of dams in the MRB on changes to the flow and sediment loads, from upstream of the dams in China to the VMD, over a 55-yr period (1961–2015) at daily, monthly, and annual scales. Our analysis identified the sediment trapping effect of the Lancang cascade dams. We further quantified recent large-scale morphological changes in the VMD and linked those changes to upstream dams and sand mining. The main conclusions are as follows:

(1) The upper MRB was the main contributor to the sediment load of the MR during the predam period (pre-1992). However, the contribution during the postdam period became insignificant because of the completion of six mainstream dams in the Lancang cascade. Instead, the Nong Khai-Pakse section became the largest sediment source.
(2) Although the sediment loads at all stations downstream of the Lancang cascade were significantly reduced, the sediment load at Jiuzhou, which is upstream of the Lancang cascade, increased. This indicates that the reduction in the sediment load is not because of a possibly reduced sediment supply from the upper MRB but is because of sediment trapping in dams.
(3) We estimated the annual sediment load of the MR during the predam period at 166.7 ± 33.3 Mt/yr. Our estimate supports the reported values of 150–170 Mt/yr (Meade, 1996; Kondolf et al., 2014; Lu et al., 2014), although it is substantially higher than the estimate of 87.4 Mt/yr by Darby et al. (2016), who used the sediment data during the period of 1982–2004 (comprising both pre and postdam sediment data) at Kratie to estimate the predam annual sediment load of the MR.
(4) The suspended sediment load of the VMD decreased by 74.1% in 2012–2015 from the predam period, of which 40.2% was caused by the six mainstream dams in the Lancang cascade, and the Manwan and Dachaoshan dams alone were the direct drivers of 32% of the reduction.
(5) The Tien river in the VMD has incised significantly. The incision rate during the period of 2014–2017 was approximately threefold that of 1998–2008. Upstream developments caused large-scale morphological changes in the VMD. Even with the value overestimated, sand mining was responsible for a maximum of 14.8% of the annual riverbed incision in the VMD, while the remainder was caused by upstream development and was mainly caused by hydropower dams.
(6) Morphological changes in the VMD might reduce low-flow water levels, which could increase the salinity intrusion and make water access more difficult. These changes, in turn, would lead to damage to agriculture and aquaculture and thus negatively influence people's livelihoods.

Data availability

All processed data are included in the manuscript and supplementary material. Raw data can be shared upon reasonable request by contacting the first author by email (binhdv0708vl@gmail.com).

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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.

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Appendix A. Supplementary data

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