RIVERBED INCISION IN THE VIETNAMESE MEKONG DELTA DUE TO ALTERED FLOW REGIME AND SEDIMENT LOAD

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ABSTRACT

Sediment load of Mekong River (MR) is of crucial importance for the sustainability and survivability of the Vietnamese Mekong Delta (VMD) in the context of sea level rise induced by climate change. The VMD is sinking due to rapidly morphological degradation caused by altered flow regime and reduced sediment supply from the MR as the result of upstream hydropower dam development. To clarify, we conducted a boat-based bathymetric field survey in August-September 2017 to measure the riverbed elevations along approximately 570 km of the Tien and Hau rivers and the Vam Nao channel in the VMD, which was compared to the river bathymetric data measured in 2014. We estimated that riverbed incision in the Tien river from Tan Chau to My Thuan from 2014 to 2017 (-52.5 Mm^3/yr) was at least three times greater than that in the past 10-20 years. We revealed that rapid riverbed incision in the VMD was consistent with significant decrease in the sediment load, from 166.7 Mt/yr in 1980-1992 (predam) to 44.2 Mt/yr in the 2014-2017 (postdam) when 64 hydropower dams completed in the MR basin. Moreover, reduced flood discharges from the MR due to dam operation, (i.e., resulting in the reduction in the flow power necessary to transport the sediment), sand mining, dyke systems, and channelization are more likely the considerable drivers of riverbed incision in the VMD. Therefore, collaboratively integrated management of the MR among riparian countries is important for the sustainability and survivability of the VMD.

Keywords: Riverbed incision, Vietnamese Mekong Delta, Mekong River, sediment load, dam.

1. INTRODUCTION

Sediment supply from the Mekong River (MR) is of crucial importance for the sustainability and survivability of the Vietnamese Mekong Delta (VMD) in the context of sea level rise due to climate change. The VMD is sinking (Minderhoud et al., 2019) due to rapid morphological degradation caused by altered flow regime and reduced sediment supply from the MR as the result of upstream dam development. Consequently, the VMD is vulnerable to relative sea level rise, accompanying saltwater intrusion.

Dams have been increasingly built and planned in the MR basin since the 1990s under the pressure of the population boom in riparian countries. The completion of the first mega-dam (> 10^9 m^3) in the MR mainstream, Manwan, in 1993 has triggered the construction of the other five mainstream dams, namely Dachaoshan, Xiaowan, Jinghong, Gongguoqiao, and Nuozhadu in the upper MR, known as Lancang cascade and numerous smaller dams in tributaries. Sixty-four large dams (> 15 m high) (Kondolf et al., 2014) have been built in the MR basin by 2015 with a total storage capacity of over 80.2 km^3, of which over 51% (41.2 km^3) was constituted by six Lancang cascade dams in China. Additional eleven mainstream dams have been planned in the lower MR in Thailand, Lao PDR, and Cambodia, of which Xayaburi dam in Lao PDR was operated in October 2019 despite the reservations of the downstream communities regarding its adverse impacts on the environment, fisheries and other aquatic resources (Pokhrel et al., 2018).

Dams trap sediment from the watershed (Kondolf et al., 2014) which is important for the development of the VMD. Moreover, dams also change the flow regimes (Binh et al., 2018) which may affect the flow capacity to transport sediment. Therefore, dams are considered as one of the main drivers of riverbed incision in the VMD (Binh et al., 2020). While dams affect the upstream-downstream connectivity of the sediment and flow budgets, local human activities in the VMD may have great influence on riverbed incision, of which sand mining is a great contributor (Jordan et al., 2019). Additionally, riverbed incision may be exacerbated by delta development such as dyke systems and channelization which increase the erosive flow velocity.

Although some previous studies quantified riverbed incision in the VMD, the causes of the incision were not fully examined. Therefore, this study aims at quantifying riverbed incision in the VMD and linking with dam effects through sediment trapping and flow regime regulations. Moreover, the effects of sand mining, dyke systems, and channelization are also figured out. The results of this study may support water resources management for the sustainability and survivability of the VMD.

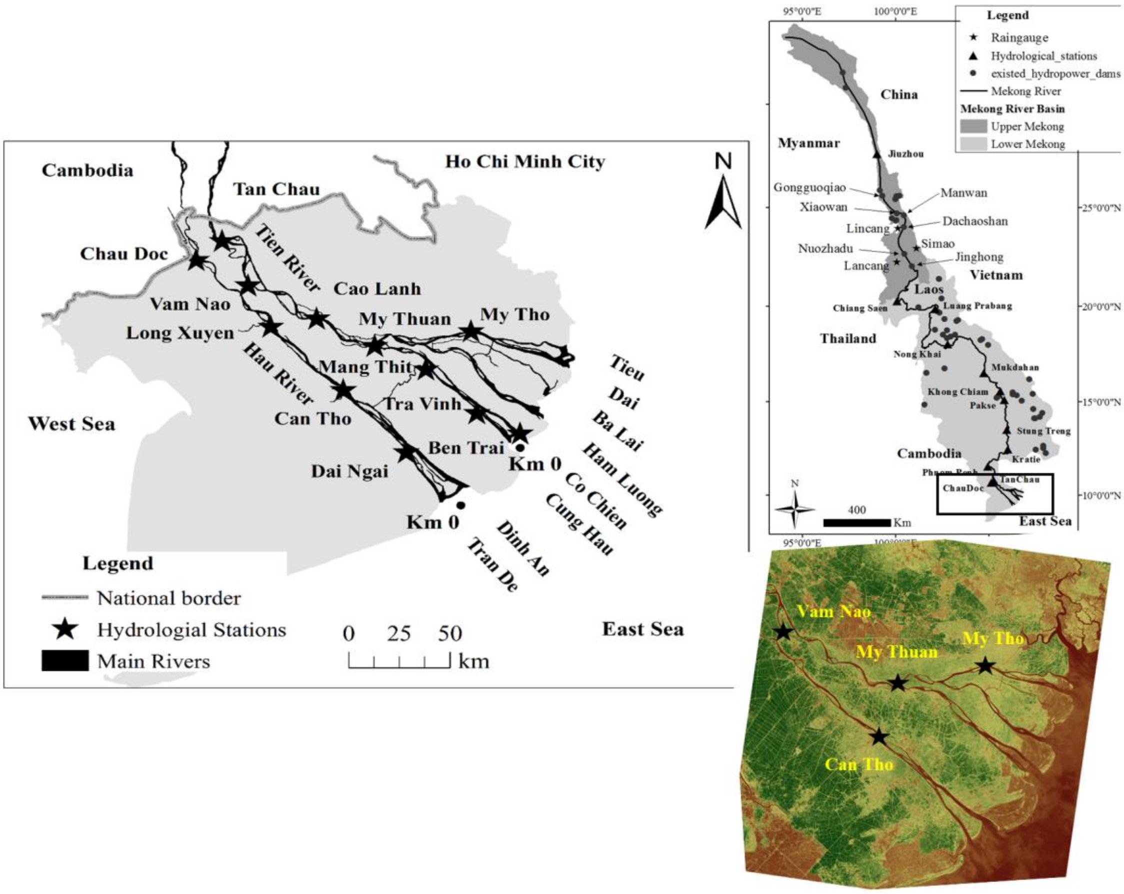

Figure 1. Main rivers and hydrological stations in the VMD.

2. REGIONAL SETTING

The Mekong Delta which is considered as one of the most pristine and productive agro-aquaculture deltas in the world extends from Kratie in Cambodia to the East Sea of Vietnam. The total area is approximately 63,000 km^2, of which approximately 24,000 km^2 belongs to Cambodia and 39,000 km^2 belongs to Vietnam. Located in the lowermost of the MR, the VMD (Figure 1) is home to around 17 million people whose livelihoods depend on agriculture and aquaculture. The VMD has been formed through abundant suspended sediment discharged from the MR of 160 Mt/yr (Kondolf et al., 2014). The VMD stretches from the Vietnam-Cambodia border, several kilometers upstream of the Tan Chau and Chau Doc gauging stations, to the East and West Seas of Vietnam (Figure 1). The Tien and Hau rivers have lengths of approximately 250 and 220 km, respectively (Kantoush et al., 2017). The VMD is a low-lying area, having an average ground elevation from 0.7-1.2 m, sloping seaward (3-4 m near the border to 1-2 in the middle delta and 0.3-0.5 m near the coast).

The VMD is one of the most important deltas in the world in terms of food security, and known as the "rice bowl" of Vietnam. It provides 50% of Vietnam's food and 90% of Vietnam's rice production, making the country become the global second largest rice exporter (Anthony et al., 2015). The agricultural production of the VMD largely depends on the variations of the natural flow regimes and fine sediment flux from the MR. The MR provides approximately 50% of natural fertilizer applied to the VMD annually attached in the suspended sediment (Manh et al., 2014).

3. DATA AND METHODS

The data used in this study are hourly/daily discharge (1980-2018), daily suspended sediment concentration, and river bathymetric data. The discharge and sediment concentration data were provided by the Mekong River Commission and the Vietnam National Center for Hydro-Meteorological Forecasting. The missing sediment concentrations were estimated using the established rating curves between the discharge and sediment concentration (Binh et al., 2020). Then, the Mann-Kendall and Pettitt tests and the slope method of Sen were used to quantify the trends of the time series.

We conducted a bathymetric field survey in the flood season 2017 along the Tien and Hau rivers and the Vam Nao channel, using a Trimble GPS-equipped 600 kHz acoustic Doppler current profiler (ADCP). In addition, hourly water levels at eleven 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 riverbed elevations from river depths measured by the ADCP. Details of data processing can be found in Binh et al. (2020). We also collected the bathymetric data in 2014 from the Southern Institute of Water Resources Research, Vietnam, to investigate riverbed incision. All bathymetric datasets were converted to WGS 1984 Universal Transverse Mercator, zone 48 North projection. To facilitate the comparison between the 2014 and 2017 bathymetric data, original point data (in X, Y, Z coordinates) were interpolated and converted into raster mode, having a spatial resolution of 40 m (Binh et al. 2020). The comparison was performed in ArcGIS®10 using the GCD®6 (Geomorphic Change Detection) add-in.

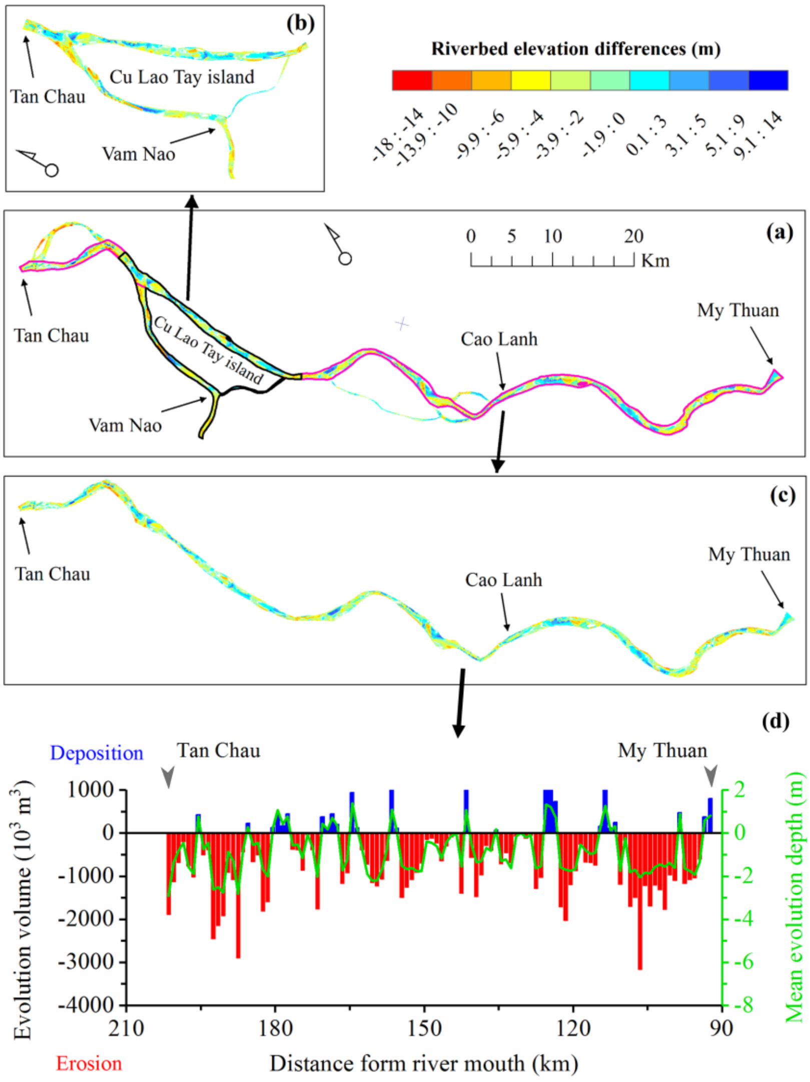

Figure 2. Serious large-scale riverbed incision in the VMD from 2014 to 2017 from Tan Chau to My Thuan.

4. RESULTS

4.1 Accelerating large-scale riverbed incision in the VMD

The VMD has experienced large-scale riverbed incision from 2014 to 2017 (Figure 2). The most severe riverbed incision was in the Vam Nao channel (Figure 2a), around the Cu Lao Tay island (Figure 2b), and 20 km upstream of My Thuan (Figure 2c). Figure 2d shows that deposition has taken place in places but very limited in terms of the extent and magnitude compared to incision. The maximum incision depth (-2.9 m) in the Tien river (Figure 2c) was double the maximum deposition depth (1.4 m). Moreover, the mean incision depth of the Tien river was -1.3 m compared to the mean deposition depth of 0.6 m.

We estimated that the mean incision rate during 2014-2017 from Tan Chau to My Thuan, including the Vam Nao channel (Figure 2) was -0.5 m/yr. In total, the riverbed of this area has incised by -157.5 Mm^3 during 2014-2017, which was in the same order of -200 Mm^3 during 1998-2008 of the entire main rivers of the VMD quantified by Brunier et al. (2014). It indicates that riverbed incision in the VMD in recent years was nearly three times greater than that in the past.

In the Cu Lao Tay area (Figure 2b), the riverbed has incised by a rate of -15.6 Mm^3/yr or -0.49 m/yr from 2014 to 2017, which doubled the rate of -0.25 m/yr from 1998 to 2008 quantified by Brunier et al. (2014). Similarly, the incision volume of the Tien river along about 20 km upstream of My Thuan (Figure 2c) in 2014-2017 was -18.9 Mm^3 or -6.3 Mm^3/yr. It was equivalent to an incision depth of -1.1 m or -0.36 m/yr.

We hypothesize that accelerating riverbed incision in the VMD is mainly caused by reduced sediment supply and reduced flood discharge from the MR due to upstream dams. Moreover, sand mining, dyke systems, and channelization may be important drivers.

4.2 Reduced sediment supply from the MR

The sediment load of the VMD decreased significantly (Figure 3). The Mann-Kendall and Pettitt tests showed that the VMD sediment load has statistically decreased ($\alpha < 0.01$) since 1992, at a rate of 4.5 Mt/yr, as determined by the slope method of Sen. The sediment load of the VMD decreased by 73% from 166.7 Mt/yr in 1980-1992 (predam) to 44.2 Mt/yr in 2014-2017, of which 59% occurred in 1993-2001. Especially, the sediment load dropped to only 30 and 32-35 Mt/yr in the drought year 2010 and 2015-2016, respectively. Similarly, the sediment load at Chiang Saen, Luang Prabang, and Nong Khai decreased by 91%, 72%, and 79% from 1980-1992 to 2012-2013 (Figure 3).

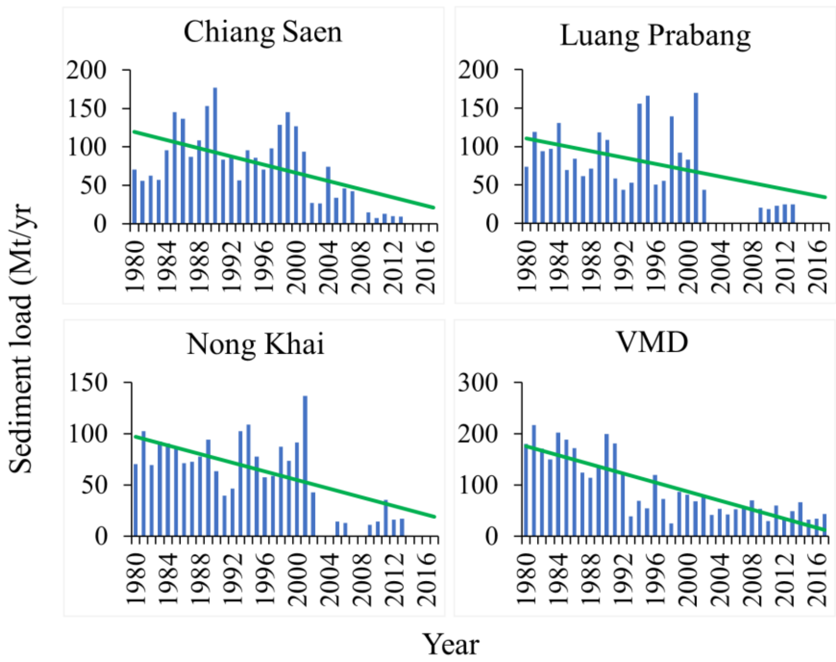

Figure 3. Long-term annual sediment load along the MR.

4.3 Reduced flood discharges

The discharge in the VMD increased in the beginning of the flood season in July and August (Figure 4). For instance, the flood discharge in July and August at Tan Chau increased by 58% and 5%, respectively, from 1980-1992 to 2014-2018. At Chau Doc, the respective numbers were 97% and 11%, respectively. On the other hand, the discharge decreased in the receding phase of the flood season in September and October (Figure 4).

For instance, the discharge in September and October at Tan Chau decreased by -31% and -50%, respectively, from 1980-1992 to 2014-2018. At Chau Doc, the respective numbers were -46% and -68% in September and October, respectively.

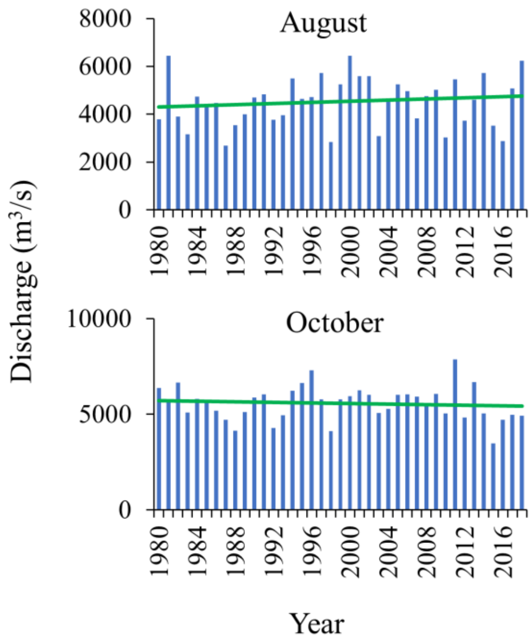

Figure 4. Long-term alterations in the flood season discharge at Chau Doc.

5. DISCUSSION

Riverbed incision in the VMD is accelerating in recent years compared to the past. This is consistent with significant reduction in the sediment load along the MR, especially after the completion of Xiaowan and Nouzhadu which are the two largest dams in the MR basin, completed in 2008 and 2011, respectively. It is well-known that dams trap most of the bedload and substantial volume of suspended load (Binh et al., 2020); therefore, limited sediment supply from the MR due to sediment trapping is the direct cause of riverbed incision in the VMD. Moreover, dams also alter the flow regimes in the VMD. Reduction in the flood discharge in September and October (the months that transport most of the incoming sediment in the VMD) reduces the flow capacity necessary to transport the sediment from the upper MR to the VMD. By trapping sediment and reducing the flood discharge, therefore, dams are the greatest drivers of riverbed incision in the VMD. Moreover, faster incision in recent years compared to the past indicates that more completed dams in the MR basin may cause more severe incision in the VMD; therefore, the future situation in the VMD would be worse if no appropriate management is applied. Therefore, we call for a transboundary cooperation among riparian countries along the MR to sustainably utilize the water and sediment resources of the MR. Sharing data and management schemes among countries are highly encouraged.

Additionally, sand mining is another main driver of riverbed incision in the VMD. Binh et al. (2020) estimated that sand mining in 2012 (data from Bravard et al., 2013) contributed almost 15% of riverbed incision in the VMD. If sand mining of 16 Mm^3/yr in 2015 in the upper part of the Tien and Hau rivers from Tan Chau/ Chau Doc to My Thuan/ Can Tho (Figure 1) was considered (data from Eslami et al., 2019), sand mining would contribute up to 19% of large-scale riverbed incision. At the locations of sand mining only, sand mining in 2015 contributes up to 36% of local riverbed incision. Therefore, policies and actions to control sand mining in the VMD is the must for sustainable development. In fact, Vietnamese government has increased regulation actions to control sand mining, especially from illegal sand miners. However, we believe that the mined sand volume that is overexploited from licensed sand miners may be at some orders greater than that from illegal sand miners. Importantly, detecting and controlling overexploitation from licensed sand miners will be more difficult if authorities do not act drastically.

Besides, dyke systems and channelization may also exacerbate riverbed incision in the VMD. Dyke systems prevent water from overflowing into floodplains, instead, the flow concentrates in rivers. Similarly, channelization increases water flowing in rivers. Consequently, the flow velocity in rivers increases, increasing flow capacity to erode the riverbed, and even the riverbank. Therefore, dykes and channelization accelerate the effects of dams and sand mining on riverbed incision in the VMD.

6. CONCLUSIONS

The VMD has suffered from severe riverbed incision caused by dams, sand mining, dyke systems and channelization, of which dams are the greatest drivers by trapping the sediment and reducing the flood discharge. Riverbed incision in recent years are much faster than that in the past, at least by three times. This accelerated speed of riverbed incision may be the result of the completion of two mega-dams in the upper MR, namely Xiaowan and Nouzahdu. Sand mining can contribute up to 19% of riverbed incision at large scale in the main rivers of the upper VMD and up to 36% at the locations of sand mining. We call for a transboundary cooperation among riparian countries along the MR to sustainably utilize the water and sediment resources of the MR. Sharing data and management schemes among countries are highly encouraged. Furthermore, drastic actions from the authorities on controlling sand mining is the must for sustainability and survivability of the VMD. Finally, construction of dyke systems and channelization should consider their side-effects on riverbed incision and riverbank erosion so that the benefits can be maximized.

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