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Sediment budget as affected by construction of a sequence of dams in the lower Red River, Viet Nam

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ABSTRACT

Dam construction is one of the main factors resulting in riverine sediment changes, which in turn cause river degradation or aggradation downstream. The main objective of this work is to examine the sediment budget affected by a sequence of dams constructed upstream in the lower reach of the Red River. The study is based on the longer-term annual data (1960–2010) with a complementary daily water and sediment data set (2008–2010). The results showed that the stretch of the river changed from sediment surplus (suggesting possible deposition processes) into sediment deficit (possible erosion processes) after the first dam (Thac Ba Dam) was constructed in 1972 and changed back to deposition after the second dam (Hoa Binh Dam) was constructed in 1985. The annual sediment deposition varied between 1.9 Mt/y and 46.7 Mt/y with an annual mean value of 22.9 Mt/y (1985–2010). The sediment deposition at the lower reach of the Red River would accelerate river aggradation which would change river channel capacity in the downstream of the Red River. The depositional processes could be sustained or changed back to erosional processes after more dams (the amount of sediment deposit was much less after the latest two dams Tuyen Quang Dam in 2009 and Sonla Dam in 2010) are constructed, depending on the water and sediment dynamics. This study revealed that the erosional and depositional processes could be shifted for the same stretch of river as affected by a sequence of dams and provides useful insights in river management in order to reduce flood frequency along the lower reach of the Red River.

1. Introduction

Reservoir construction has caused a significant decrease of sediment loads at the global scale. It has been estimated that 30% of the global sediment flux was trapped in large reservoirs (Walling and Fang, 2003). The sediment decrease was more obvious for some of the large Asian rivers (Lu et al., 2011), because of the construction of large reservoirs: e.g., the Yellow River (Yang et al., 2002; Walling and Fang, 2003), the Changjiang/Yangtze River (Wang et al., 2008; Xiong et al., 2009; Xu and Milliman, 2009), and also the Mekong River (Lu and Siew, 2006; Wang et al., 2011). The construction and operation of a reservoir can cause a series of changes in the river channels downstream as a result of the regulation of the river's sediment load and flow regime (Brandt, 2000). Thus dam construction is one of the main factors affecting sediment dynamics, which in turn may cause river degradation or aggradation downstream. Dams greatly influence flow and sediment discharge regimes and can have significant impact on downstream reaches below dams. Dams hold not only water but also large quantities of sediments because of the reduced riverine carrying capacity (Xu and Yan, 2010). By changing flow regime and sediment load, dams can produce adjustments in alluvial channels, the nature of which depends upon the characteristics of the original and altered flow regimes and sediment loads (Brandt, 2000). If flows released from dams have sufficient capacity to move coarse sediment, the water becomes 'hungry water' (Kondolf, 1997), which will erode channels downstream without replacement from upstream affecting the fluvial and deltaic ecological systems (Kondolf and Matthews, 1993). Hungry water is when relatively clear water is released from a reservoir and then tries to pick up sediment as it flows, leading to the scouring of some areas of riverbed and the erosion of riverbanks downstream (Baird and Meach, 2005).

Various studies have documented that low flow regulation may trigger channel changes such as channel degradation, channel aggradation, and channel metamorphosis at different temporal and spatial scales (Hooke, 1997; Grams and Schmidt, 2002; Downs and Gregory, 2004; Gregory, 2006). The types, rates, and extents of channel degradation and aggradation downstream from dams are controlled by many factors, including regulated discharge rates and sediment load, channel geometry, channel material composition, and especially the discharge and sediment input provided by the river's tributaries (Michael and

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Thomas, 2001; Xu and Cheng, 2002; Doyle and Harbor, 2003; Gregory, 2006; Salant et al., 2006). Previous research works have mainly addressed river degradation (Chien, 1985; Galay et al., 1985; Kondolf, 1997), yet case studies on river aggradation remain scarce. Heavy sediment deposition in the lower reaches of the Yellow River caused the riverbed to aggrade at a rate of several centimeters per year (Xu and Cheng, 2002). This aggradation increases the flood risk on the floodplain, making the river channel avulsion prone. The increase in channel aggradation from a large amount of sediment deposition has caused the reduction of channel capacity and consequently increased flood frequency along the river.

The Red River is the second largest river in Vietnam after the Mekong River and plays an important role in the economic, cultural, and sociopolitical life of the Vietnamese people (Le et al., 2007). In recent decades, large water infrastructures have been constructed on its tributaries for energy, irrigation, and flood control. The impacts from the dams on water discharge and sediment transport regime have been addressed. A few studies (Nguyen et al., 1995; Van Maren and Hoekstra, 2004; Le et al., 2007; Dang et al., 2010) have documented the sediment load transported by the Red River before impoundment of Hoa Binh reservoir, ranging from 100 to 170 Mt/y. Le et al. (2007) reported sediment load transport of 40 Mt/y with a 70% decrease of the total load since impoundment of Hoa Binh and Thac Ba reservoirs in the 1980s. Dang et al. (2010) estimated the long-term variability of river sediment transport in the Red River basin, varying between 24 and 200 Mt/y (mean = 90 Mt/y). This sediment load estimate was based on sediment rating curves of two separated periods (1960–1989 and 1990–2008) before and after construction of Hoa Binh reservoir. The study also indicated a reduction of sediment delivery to the delta by half because of construction of the reservoirs.

While the existing studies have focused mainly on the sediment load transport within the Red River system, further study on the sediment budget at the lower reach of the river is of great importance for understanding whether the downstream channel is degraded or aggraded. The main objective of this work is to examine the downstream sediment budget, as affected by the dams constructed in the upper stream of the lower reach of the Red River.

2. Materials and method

2.1. Study area

The Red River has its source in the mountainous Yunnan Province, south of China, at an elevation of 2000 m (Nguyen and Nguyen, 2001). It is named Yuan River in China and flows into Vietnam at Lao Cai Province, where it is named Hong River (Le et al., 2007). The Red River basin has a total catchment area of 169,000 km^2 (Haruyama, 1995; Van den Bergh et al., 2007) – 50.3% of which is situated in Vietnam, 48.8% in China, and 0.9% in Laos – and includes a fertile and densely populated delta plain (14,000 km^2; Van Maren, 2007).

The basin contains two large reservoirs: Thac Ba (first dam) and Hoa Binh (second dam) (Fig. 1). Thac Ba reservoir, impounded in 1972 on the Chay River (a tributary to the Lo River) has a surface area of 235 km^2 and a storage volume of 2.94 km^3 (Vu, 2002). Hoa Binh reservoir, constructed in 1985 on the Da River, is the largest one in Vietnam. It has a surface area of 208 km^2 with an effective storage capacity of 9.5 km^3 (Ngo and Tran, 1998; Vu, 2002). Hoa Binh reservoir has been used for multiple purposes such as flood protection, irrigation, and electricity generation. Recently, two more dams have been built in the lower Red River system: Tuyen Quang reservoir (a surface area of 42 km^2 with an effective storage capacity of 2.2 km^3), completed in 2009 on the Lo River, and Sonla reservoir (a surface area of 440 km^2 with an effective storage capacity of 12.5 km^3), which began filling in May 2010 on the Da River, upstream of Hoa Binh reservoir.

The Red River basin is characterized by a tropical monsoonal climate with a wet season from May to October and a dry season from November to April. The summer season is warm and very humid, with mean temperatures ranging from 27 to 29 °C, whereas the winter season is cool and dry, with mean monthly temperatures ranging from 16 to 21 °C (Li et al., 2006). The average annual rainfall in the whole basin is 1600 mm, 85–95% of which falls during the summer season (Le et al., 2007). Hence, the hydrological regime of the Red River is characterized by a unimodal tropical regime with a mean monthly maximum/minimum discharge ratio of 7.9 (1085–8600 m^3/s), based on the record from 1960 to 2008 at Son Tay (Dang et al., 2010). The mean annual water discharge of the Red River is 3500 m^3/s, corresponding to a specific discharge of 20.5 l/s/km^2 (for the period 1960–2008) (Dang et al., 2010). For the same period, the mean annual water discharges of the Da and the Lo rivers were 1700 and 1050 m^3/s, respectively (Tran et al., 2007).

2.2. Water discharge and sediment data

The daily monitoring of water discharge and sediment during 2008–2010 was performed at five gauging stations: Yen Bai, Vu Quang, Hoa Binh, Son Tay, and Hanoi (Fig. 1).

Daily water samples were collected for the whole 3-year period (2008–2010) at the four sampling stations. A standard depth-integrated sampling procedure was followed to determine the suspended sediment concentration (SSC). The samples for the SSC were filtered in precleaned 0.45-mm pore size, 47-mm-diameter preweighed Nuclepore filters at the laboratory. The filters were dried at 105 °C for 24 h and weighed for quantifying the SSC.

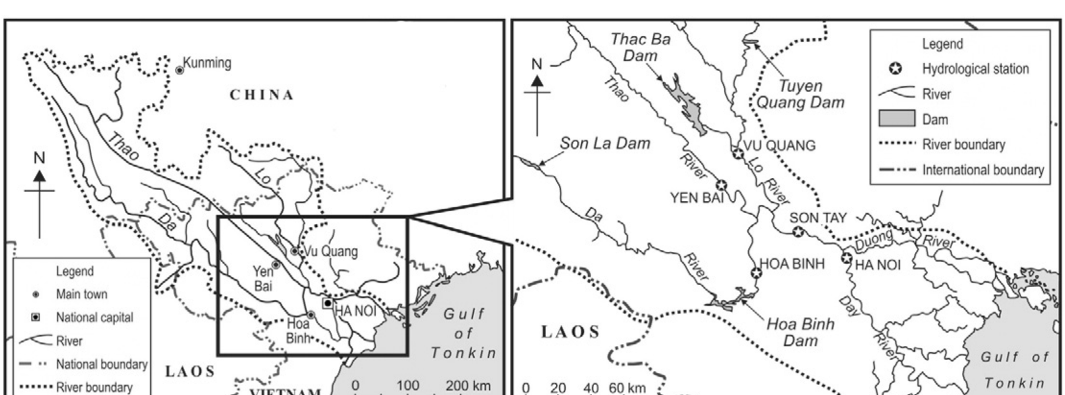

Fig. 1. Map of the Red River system. The three major tributaries (the Lo, the Thao, and the Da) are dominated by bedrock channels, and the main river from the confluence of the three tributaries to the delta is alluvial channel.