Impact of the Hoa Binh dam (Vietnam) on water and sediment budgets in the Red River basin and delta

Vu Duy Vinh [1], Ouillon Sylvain [2,3], Tran Duc Thanh [1], La Van Chu [4]

[1] Institute of Marine Environment and Resources, VAST, 246 Danang Street, Haiphong City, Vietnam

[2] IRD, Université de Toulouse, UPS (OMP), UMR 5566 LEGOS, 14 av. Edouard Belin, 31400 Toulouse, France

[3] University of Science and Technology of Hanoi (USTH), 18 Hoang Quoc Viet, Cau Giay, Hanoi, Vietnam

[4] Vietnam Institute of Meteorology, Hydrology and Environment, 62 Nguyen Chi Thanh, Hanoi, Vietnam

Correspondence to: Sylvain Ouillon (sylvain.ouillon@ird.fr)

Abstract

The Hoa Binh dam, located on a tributary of the Red River in Vietnam, has a capacity of 9.45 x 10^9 m^3 and was commissioned in December 1988. Although being important for flood prevention, electricity production, and irrigation in northern Vietnam, the Hoa Binh dam has also highly influenced the suspended sediment distribution in the lower Red River basin, in the delta and in the coastal zone. Its impact was analysed from 50-year dataset of water discharge and suspended sediment concentration (1960-2010) and the distribution of water and sediment across the nine mouths of the delta was simulated using the MIKE11 numerical model before and after the dam settlement. Although water discharge at the delta inlet decreased by only 9 %, the yearly suspended sediment flux dropped, on average by 61 % at Son Tay near Hanoi (from 119 to 46 x 10^6 t yr^{-1}), and by 59 % in the river mouths (from 85 to 35 x 10^6 t yr^{-1}). Along the coast, reduced sedimentation rates are coincident with the lower sediment delivery observed since the impoundment of the Hoa Binh dam. Water regulation has led to decreased water discharge in the wet season (-14 % in the Red

River at Son Tay) and increased water discharge in the dry season (+12 % at the same station). The ratios of water and suspended sediment flows, as compared to the total flows in the 9 mouths, increased in the northern and southern estuaries and decreased in the central, main Ba Lat mouth. The increasing volume of dredged sediments in the Haiphong harbour is evidence of the silting up of the northern estuary of Cam-Bach Dang. The effect of tidal pumping on enhanced flow occurring in dry season and resulting from changed water regulation is discussed as a possible cause of the enhanced siltation of the estuary after Hoa Binh dam impoundment.

1. Introduction

Asia and Oceania contribute 70 % of the global sediment supply from land to the ocean (Milliman and Syvitski, 1992; Farnsworth and Milliman, 2003). However, recent human activities on large rivers have severely altered sediment discharge, mainly as a consequence of artificial impoundments (Syvitski et al., 2005). Vörösmarty et al. (2003) estimated that around 53 % of sediment flux is now potentially trapped in reservoirs. This reduction of sediment flux dramatically affects deltas (Ouillon, 1998; Syvitski and Saito, 2007). For example, sediment discharge decreased from 480 to approximately 150 x 10^6 t yr^{-1} over a 20 year period in the Yangtze River (Changjiang) (Yang et al., 2006) and from 1,200 to 150 x 10^6 t yr^{-1} over a 40 year period in the Yellow River (Huanghe) (Wang et al., 2006, 2008). Large rivers and their deltas in Southeast Asia have also been impacted by other human activities such as groundwater pumping, irrigation, dredging, and deforestation (Tran et al., 2004; Saito et al., 2007).

The Red River delta (RRD), located in the western coast of the Gulf of Tonkin, is the fourth largest delta in Southeast Asia in terms of delta plain surface, after the Mekong, Irrawaddy, and Chao Phraya deltas. The RRD initiated in the vicinity of Hanoi about 8,000–9,000 years ago. It then prograded with a triangular morphology with an apex near Son Tay, and expanded to reach its current area of 14,300 km^2 (Tanabe et al., 2003, 2005; Hori et al., 2004; Luu et al., 2010) (Fig. 1). The RRD lies entirely below three meters above sea level. Its population was estimated as 16.6 million in 2006, corresponding to an average population density of 1160 inhabitants km^{-2} (Luu et al., 2010).

The Red River (Song Hong) drains a basin area of 160 x 10^3 km^2 (Milliman et al., 1995). Its average discharge over 1902-1990 at Son Tay was 3740 m^3 s^{-1} (To, 2000 quoted by Le et al., 2007). The Red River has two main tributaries, the Lo (or Clear) River and the Da (or Black) River. The last four major floods of the Red River within the return period of 100 years were caused by simultaneous high floods in the Lo, Da and Thao Rivers. The Da River usually played the main role, representing 53-57 % of total discharge (Le et al., 2007). During the biggest flood ever recorded, the water level in Hanoi reached 13.3 m in August 1971 (Luu et al., 2010) and the Ba Lat River mouth shifted 10 km southwards to its current position (van Maren, 2004, 2007).

The construction of the Hoa Binh dam (HBD) on the Da River began on November 6, 1979 and ended on December 30, 1988. HBD has a capacity of 9.45 x 10^9 m^3 of water corresponding to 18 % of the annual discharge of the Da River and has an electric power plant of 1920 MW, delivering about 40 % of the Vietnamese electricity production (Le et al., 2007). In 2012, it was ranked 53rd in the world in terms of electric capacity (International Commission on Large Dams, ICOLD, http://www.icold-cigb.org/). Since its impoundment, HBD has played an important role in flood prevention, electricity production, and irrigation supply in northern Vietnam.

Before HBD impoundment, the Red River suspended sediment flux was estimated to be 100-160 x 10^6 t yr^{-1} at Son Tay (Milliman et al., 1995; Pruszak et al., 2002), corresponding to a specific sediment delivery of 700 to 1100 t km^{-2} yr^{-1}, as compared to a global average of 120 t km^{-2} yr^{-1} (Achite and Ouillon, 2007). At 160 x 10^6 t yr^{-1} the Red River was ranked as the 9th river in terms of sediment flux by Milliman and Meade (1983). The Da River was its main sediment provider until the building of the HBD in the 1980's (Dang et al., 2010). Recent studies have shown that the sediment flux drastically decreased to around 40 x 10^6 t yr^{-1} during the period 1997-2004 following the HBD impoundment (Le et al., 2007). The mean annual sediment trapping efficiency of the Hoa Binh reservoir was estimated to be 88 %, suggesting that the HBD reduces annual sediment delivery to the delta by half (Dang et al., 2010).

The Red River water and sediment discharges are distributed amongst a complex network of connected distributaries with nine river mouths (Fig. 1). Despite the decrease in sediment discharge, Haiphong harbour, located in the Cam estuary, one of the northern distributaries, is silting up (Lefebvre et al., 2012). This silting up has huge economic consequences, rendering urgent the need for an analysis of suspended sediment flux changes in the river basin. In the coastal zone, van Maren (2004) showed that the decrease of suspended sediment downstream of the HBD affects sediment fluxes in the Ba Lat area. After the dam impoundment, alongshore sediment transport rate in shallow water increased from 200,000 m^3 yr^{-1} in 1949 to 300,000 m^3 yr^{-1} in 2000, while in deeper waters (10-30m) in the Ba Lat coastal area, it decreased from a peak of 500,000 m^3 yr^{-1} in 1949 to 300,000 m^3 yr^{-1} in 2000. Although Luu et al. (2010) estimated the water discharge distribution in the Northern, Central and Southern part of the delta after HBD commissioning, the water and suspended sediment distribution of the Red River across its nine mouths has yet to be documented.

This paper aims at complementing the previous studies both in the Red River basin and in its delta before and after the HBD impoundment. Water and sediment fluxes from the three main tributaries were averaged over a long-term series of measurements before and after HBD impoundment (for 20 years before, 1960-1979, and 22 years after, 1989-2010). The variability of water and sediment discharge are examined at different time scales (seasonal, interannual) from measurements and the impact of HBD is assessed. Discharge and sediment concentration have been continuously measured upstream, but no systematic record exists in the Red River delta, where only water level is available at the hydrological stations. This paper provides a first estimate of the water and sediment discharge distribution amongst the nine distributaries, for before and after HBD, from numerical simulations. New data on recent changes in sediment deposition and erosion in estuaries and along the delta coastline are also given and discussed considering the new water regulation.

2. Regional settings

2.1 Geography

The Red River source is located at a mean elevation of 2,000 m in the mountains of the Yunnan province in China (Nguyen and Nguyen, 2001). It is named the Yuan River in China, and flows into Vietnam where it is named the Hong or Thao River because of its reddish-brown color water, due to its huge sediment delivery and to the richness of sediments in iron dioxide. The Red River receives two major tributaries: the Da River and Lo River (Fig. 1). Their drainage basins are 57.2 x 10^3 km^2 for the Thao River (of which 21 % is in Vietnam), 51.3 x 10^3 km^2 (52 % in Vietnam) for the Da, and 34.6 x 10^3 km^2 (64 % in Vietnam) for the Lo. The Da River also originates in the Yunnan province, the elevation of its source being at 2,000 m. The source of the Lo River is located in China at an elevation of 1,100 m, and joins the main branch at Viet Tri city (Nguyen and Nguyen, 2001). The Red River flows 1,200 km before it empties into the Gulf of Tonkin (Bac Bo, in Vietnamese) in the East Sea of Vietnam (South China Sea).

After the confluence of the Da, Thao, and Lo Rivers, the Red River gradient falls to 5.9 x 10^{-5} downstream of the apex of the delta (Gourou, 1936, quoted by van Maren, 2007) and the river diverges into two major distributaries a few kilometers upstream of Hanoi: the Red River to the southwest and the Thai Binh River to the northeast (Fig. 1). In the southwest, the Red River system includes the Tra Ly River, the Red River, the Ninh Co River and the Day River. On the left bank of the Red River, the Duong River is a main distributary (Fig. 2). At Pha Lai in the delta, the Duong-Thai Binh system receives water and sediment from the Cau River (288 km long), the Thuong River (157 km long) and the Luc Nam River (200 km long) and supplies water and sediment to the northeastern parts of the Red River delta. Finally, the Red-Thai Binh river system has, from northeast to southwest, the Cam-Bach Dang mouth (the Bach Dang combines with the Cam to form the Nam Trieu mouth), the Lach Tray mouth, the Van Uc mouth, the Thai Binh mouth, the Tra Ly mouth, the Ba Lat mouth, the Ninh Co (or Lach Giang) mouth, and the Day mouth (Fig. 1, 2). The Ba Lat mouth is the main mouth of the Red River.

2.2 Climate and rainfall

The Red River basin is subject to a sub-tropical climate that is characterized by a summer monsoon from the South and a winter monsoon from the Northeast. The wet season (from May to October) alternates with a dry season and accounts for 85-95 % of the total yearly rainfall. In the period 1997-2004, the mean annual rainfall was 1590 mm in the whole basin (Le et al., 2007). It is slightly higher on the delta, with an average value estimated to be 1667 mm between 1996 and 2006 by Luu et al. (2010), who give the extreme values obtained during 10 years: 1345 mm yr^{-1} with monthly peak of 450 mm $month^{-1}$ in 2006, and 1725 mm yr^{-1} with monthly peak of 360 mm $month^{-1}$ in 1996. The mean annual potential evapotranspiration from 1997 to 2004 was rather homogeneously distributed over the whole basin area, from 880 to 1150 mm yr^{-1} (Le et al., 2007). Episodically, typhoons hit the northern coastline of Vietnam principally from July to November. They move in a northwestern direction and strike obliquely across the coastline (Matthers and Zalasiewicz, 1999).

2.3 Hydrological regimes and sediment transport

The total water and suspended sediment discharge of the Song Hong at Son Tay gauging station before the HBD impoundment were 120 $km^3\ yr^{-1}$ and about 120 x 10^6 t yr^{-1}, respectively, and the average sediment concentration in the river was about 1 g L^{-1}, with a maximum estimated at 12 g L^{-1} during the highest flood ever recorded in 1971. The discharge at the Hanoi station reached a maximum in July–August (about 23,000 $m^3\ s^{-1}$) and a minimum during the dry season (January–May; typically 700 $m^3\ s^{-1}$). Approximately 90 % of the annual sediment discharge was issued during the wet season (Mathers et al., 1996; Mathers and Zalasiewicz, 1999). The Duong-Thai Binh River carries approximately 20 % of the total water discharge (General Department of Land Administration, 1996). The annual discharge of the Cau River is 1.6 $km^3\ yr^{-1}$ or 51.2 $m^3\ s^{-1}$ at the Thac Buoi station, with an average suspended sediment concentration of 250 mg L^{-1}. Its average annual sediment discharge is 0.22 x 10^6 t yr^{-1} (Nguyen, 1984; Nguyen et al., 2003). The annual discharge of the Thuong River is 1.2 $km^3\ yr^{-1}$ (or 40 $m^3\ s^{-1}$) at the Cau Son station, with an average suspended sediment concentration of 122 mg L^{-1}. Its annual sediment discharge is on average 0.12 x 10^6 t yr^{-1} (Nguyen, 1984; Nguyen et al., 2003). The annual discharge of the Luc Nam River is 1.3 $km^3\ yr^{-1}$ (or 42.3 $m^3\ s^{-1}$) at the Chu station, with an average suspended sediment concentration of 330 mg L^{-1}. Its annual sediment discharge averaged 0.2 x 10^6 t yr^{-1} (Nguyen, 1984; Nguyen et al., 2003). These rivers experience a flood season from June to October which brings 70-81 % of their total annual water input and 85-92 % of their total sediment input to the Thai Binh River system.

2.4 Tide and tidal influence in the estuaries

The tide in the Gulf of Tonkin is predominantly diurnal, with one ebb-flood cycle occurring each day, and an amplitude gradually decreasing from 4 m to 2 m from north to south in spring tides (Fang et al., 1999; Nguyen et al., in press) (see Fig. 1). Within the spring-neap 14 day cycle, the tide amplitude at Ba Lat varies from 2.5 m during spring tides to 0.5 m during neap tides.

Salinity intrusion occurs for up to 40 km landwards from the Cam River mouth within the delta, 38 km from the Lach Tray mouth, 28 km from the Thai Binh mouth and 20 km from the Ba Lat mouth (Fig. 1). However, the tidal influence on water level and discharge extends much farther upstream. At Phu Ly (120 km from the coast) on the Day River, daily water levels induced by the tidal propagation vary by 1 m during the dry season and 0.6 m during the wet season (Luu et al., 2010).

Tidal mechanisms are key processes on water distribution in deltas, since they may alter the discharge division amongst distributaries by several percents (from 10 % at the apex to 30 % seaward in the Mahakam delta, Indonesia; Sassi et al., 2011). Tidal mechanisms are also key processes of sediment transport in estuaries (e.g. Allen et al., 1980; Dyer, 1986; Dronkers, 1986; Sassi et al., 2013). In the middle and lower estuaries, deposition is mainly driven by the dynamics of the turbidity maximum zone, whose presence and dynamics are governed by the coupling between river discharge and tidal propagation (e.g. tidal pumping and/or density gradients; Sottolochio et al., 2001). Tidal pumping is caused by the asymmetry of tide, with shorter and more energetic flood periods than ebb periods, and longer high slack water periods than low slack waters, thus favoring deposition near the turbidity maximum (Allen et al., 1980; Uncles et al., 1985; Dyer, 1986; Dronkers, 1986). Fluid mud consolidates slightly during neap tides (Dyer, 1986).

Lefebvre et al. (2012) showed that suspended sediment deposition induced by tidal pumping in the Cam-Bach Dang estuary (Fig. 1) can be up to three times higher during the dry season relative to the wet season. During the dry season, the net sediment flux at the river mouth is positive from the sea to the Cam-Bach Dang estuary, bringing back into the estuary particles brought by previous floods (Lefebvre et al., 2012).

In this study, tidal propagation within the estuaries is included in the numerical model and the tide is taken into account through its boundary conditions in the river mouths.

2.5 Fluvial, tidal and wave influences along the delta coastline

Fluvial-, tide- and wave-dominated processes appear to be important in the development of the RRD, but their relative influence is subject to a remarkable spatial variability (Mathers and Zalasiewicz, 1999; van Maren, 2004, 2007). The northern coastal section of the RRD lies sheltered from strong wave action by the island of Hainan, and the river mouths are mostly funnel-shaped as a consequence of the prevalence of river and tidal forces. In the southern part of the delta, the river mouths are mainly convex in shape as a consequence of the dominant wave forces (Pruszak et al., 2005). The central part of the delta, around Ba Lat mouth, is a mixed tide and wave-dominated coast. The estuaries are mainly composed of silts, and sand is estimated to be, on average, 10 % of the surface sediments in the mouths of the Red River (Tran and Tran, 1995).

2.6 Grainsize within the river basin and the delta

Values of the median diameter D_{50} of surface sediment are, on average, 0.35, 0.16 and 0.175 mm in the Da, Thao and Lo rivers, respectively (Ministry of Agriculture and Rural Development, 2009). Its value is 0.2 mm between the confluence of Da and Thao rivers and the apex and, in the upper two distributaries, 0.18 mm in the Red river and 0.22 mm in the Duong river (Ministry of Agriculture and Rural Development, 2009). Downstream, in the estuaries and coastal zones, D_{50} of the superficial sediments ranges from 5 to 195 μm (Do et al., 2007). In the lower Cam-Bach estuary, surface sediments result from a combination of fine silt and fine sand whose ratio varies greatly over a distance of 5-10 kilometers (Lefebvre et al., 2012).

3. Data and methods

3.1 Data

Data used in this paper are daily water discharge (Q) and suspended sediment concentration (C) over the 50-year period from 1960-2010 (MONRE, 1960-2010). This time period covers the time before (1960–1979) and after (1989–2010) HBD impoundment. The data was collected by the National Hydro-Meteorological Service (NHMS) at the hydrographic stations of the Red River system (Fig. 1): Vu Quang (Lo River), Yen Bai (Thao River), Hoa Binh (Da River), Son Tay (Red River), Ha Noi (Red River) and Thuong Cat (Duong River). Calculations were carried out according to the norm TCN26-2002 of the Vietnamese Hydrometeorology General Department. Measurements were conducted following the standards of the IMHEN (Institute of Meteorology, Hydrology and Environment) belonging to the Ministry of Natural Resources and Environment (MONRE), which apply all over Vietnam, in each gauging station, with the same protocols. NHMS provided daily discharge from water depth, which was measured every minute. Regular calibrations of the water depth-discharge rating curve were conducted (several times a month) at key stations of the Red River, using reels (every 20 meters across the river section, at 5 depths over the water column) and, more recently, ADCPs. Water was sampled along a water column representative of the cross section to determine C after filtration on pre-weighted filters of 0.45 μm porosity: once a day at 7h AM local time during low discharge, twice a day or more during floods. Detailed cross-sections of velocity and C were gauged once a day during high floods. The data were quality-controlled by the Hydrometeorological Data Center (HDC).

Independent validations of discharge estimates (by ADCP) and C estimates (by filtration techniques) were conducted by Dang *et al.* in 2008 (Dang et al, 2010; Dang, 2011) on the Red River at Son Tay. Their study shows (1) that daily C concentrations and Q provided by the MONRE can be considered accurate with 10-15 %, and (2) that the scatter error was probably random rather than systematically-biased (see e.g. Fig. 47 of Dang, 2011). Consequently, and considering the method proposed by Meade and Moody (2010) on the Mississipi River, the annual suspended sediment flux estimates in the Red River may be considered accurate within 5-10 % (Dang et al., 2010). As stated by Whiteman et al (2011), a high frequency of measurement is more important than a decrease in random error in trend detection. As the integration of daily data (which are already values averaged from several measurements over the day during floods) over seasons or years largely smoothed out random variation. In the present paper, considering this uncertainty, the precision given on river discharge and suspended sediment flux is limited to 1 x 10^9 m^3 yr^{-1} and 1 x 10^6 t yr^{-1}, respectively, for the Red River, and to 0.1 x 10^9 m^3 yr^{-1} and 0.1 x 10^6 t yr^{-1} for its tributaries and distributaries.

Other data are also used in the present study:

- Hourly water elevation at the nine river mouths in 1979 and 2006 measured by the NHMS;
- River sections (bed elevation across the river) measured in the Red River system by the NHMS;
- Data on coastal erosion along the RRD from Tran et al. (2001, 2002, and 2008);
- Volumes of dredged sediments in Haiphong harbour provided by the harbour authorities.

3.2 Calculation of water and sediment discharge in upstream rivers

The annual water $Q_{y,i}$ (in m^3 yr^{-1}) and suspended sediment discharge $M_{y,i}$ (in t yr^{-1}) for year i were calculated following norm TCN26-2002, as:

$$Q_{y,i} = \sum_{j=1}^{p} Q_{d,i,j} \times 86400 \qquad (1)$$

$$M_{y,i} = \sum_{j=1}^{p} Q_{d,i,j} \times C_{d,i,j} \times 0{,}0864 \qquad (2)$$

where $Q_{d,i,j}$ (in m^3 s^{-1}) is the average water discharge at day j and year i, $C_{d,i,j}$ (in mg L^{-1}) is the suspended sediment concentration at day j and year i, and p is the number of days per year i.

For a given distributary k amongst the 9 distributaries of the Red River, the ratio of its water discharge to the Gulf of Tonkin (denoted Q ratio) was calculated as:

$$Q\ ratio_k = \frac{Q_k}{\sum_{l=1}^{9} Q_l} \quad (3)$$

In the same way, the ratio of suspended sediment delivery to the Gulf of Tonkin (denoted M ratio) for a given distributary k amongst the 9 distributaries of the Red River was calculated as:

$$M\ ratio_k = \frac{M_k}{\sum_{l=1}^{9} M_l} \quad (4)$$

Q ratio and *M ratio* can be calculated for a given year or from the average of yearly values over a given period.

3.3 Calculation of water and sediment discharge in estuaries

3.3.1 The MIKE11 model

In order to estimate water and sediment discharge from estuaries into the coastal zone before and after HBD impoundment, a data-driven modeling approach was set up using the MIKE11 model (Vu et al., 2011). MIKE11 is a modeling package for the simulation of surface runoff, flow, sediment transport, and water quality in rivers, channels, estuaries, and floodplains (DHI, 2009). MIKE11 is an implicit finite difference model for one dimensional unsteady flow computation and can be applied to looped networks and quasi-two dimensional flow simulation on floodplains. The model has been designed to perform detailed modelling of rivers, including special treatment of floodplains, road overtopping, culverts, gate openings and weirs. MIKE11 is capable of using kinematic, diffusive or fully dynamic, vertically integrated mass and momentum equations. The solution of continuity and momentum equations is based on an implicit finite difference scheme. This scheme is structured so as to be independent of the wave description specified. Boundary types include water level (h), discharge (Q), Q/h relation, wind field, dambreak, and resistance factors. The water level boundary must be applied to either the upstream or downstream boundary conditions in the model, depending on the hydrodynamic regime (characterized by the Froude number). The discharge boundary can be applied to either the upstream or downstream boundary conditions, and can also be applied to the side tributary flow (lateral inflow). The lateral inflow is used to depict runoff. The *Q/h* relation can only be applied to the downstream boundary.

3.3.2 The cohesive sediment transport module

The cohesive sediment transport module of MIKE11 is based on the 1-D advection dispersion equation:

$$\frac{\partial AC}{\partial t}+\frac{\partial QC}{\partial x}-\frac{\partial}{\partial x}\left(AK_H\frac{\partial C}{\partial x}\right)=C_2q+wS_E-wS_D \qquad (5)$$

where C is the suspended sediment concentration (kg m^{-3}), A the cross sectional area (m^2), K_H the horizontal dispersion coefficient (m^2 s^{-1}), C_2 the tributary concentration, q the tributary (lateral) inflow per unit length, S_E is the source term resulting from erosion (kg m^{-3} s^{-1}), S_D is the sink term resulting from deposition (kg m^{-3} s^{-1}) and w the river bed surface per unit length (in m^2, its value being the river width x 1). The deposition rate is given by:

$$S_D=\frac{W_sC}{h_*}\left(1-\frac{\tau_b}{\tau_{c,d}}\right)\ \text{for}\ \tau_b\le\tau_{c,d}\ \text{and}\ S_D=0\ \text{for}\ \tau_b>\tau_{c,d} \qquad (6)$$

where W_s is the settling velocity (m s^{-1}); τ_b is the bed shear stress (N m^{-2}); $\tau_{c,d}$ is the critical bed shear stress for deposition (N m^{-2}); h_* is the average depth through which the particles settle (m), calculated by the model from the water depth and the Rouse number (see DHI, 2009). The rate of erosion is given by:

$$S_E=\frac{M_*}{h}\left(\frac{\tau_b}{\tau_{c,e}}-1\right)\ \text{for}\ \tau_b\ge\tau_{c,e}\ \text{and}\ S_E=0\ \text{for}\ \tau_b<\tau_{c,e} \qquad (7)$$

where M_* is the erodibility of the bed (kg m^{-2} s^{-1}); $\tau_{c,e}$ the critical shear stress for erosion (N m^{-2}), and h is the water depth. In our simulations, sediment was assumed to always be available at the bed for erosion.

The resolution of the cohesive sediment transport module requires outputs from the hydrodynamics module, namely water discharge, water level, cross-sectional area and hydraulic radius, and calibrated specific parameters (critical shear stress for erosion, critical shear stress for deposition, erodibility). This cohesive sediment transport module associated with MIKE11 has been successfully applied to sediment transport studies by, e.g., Neary et al. (2001), Etemad-Shahidi et al. (2010) and Kourgialas and Karatzas (2014).

3.3.3 Application to the Red River delta

In order to set up the model, the Red River system was designed under a network which includes the main rivers (Fig. 2) from data such as river section and bed elevation collected by the NHMS. To implement our model, 783 river sections provided by the MONRE were used: 51 sections of the Da River, 27 sections of the Thao River, 19 of the Lo River, 156 of the Red River, 44 of the Thai Binh River, 34 of the Luoc River, 31 of the Duong River, and 421 of other rivers or channels of the network (Fig. 2).

For calibration and validation purpose, the model was run with actual data, for real situations. In every calculation the model ran for 32 days for the spin up before the true simulation began. For studying the impact of HBD, the model was run for two typical years as defined by the average of daily Q and C data before (1960-1979) and after (1989-2010) HBD impoundment. The hourly boundary conditions in water elevation at the river mouths came from measurements performed at the gauging stations in 1979 and 2006, respectively.

3.3.4 Boundary conditions

Upper boundaries were fixed across sections at Son Tay on the Red River and at Thac Buoi (Cau River), Cau Son (Thuong River) and Chu (Luc Nam River). Daily Q and C were used as inputs at these cross-sections. Hourly water levels were imposed as boundary conditions in the Bach Dang, Cam, Lach Tray, Van Uc, Thai Binh, Tra Ly, Ba Lat, Ninh Co and Day River mouths. While C at these estuarine boundaries was calculated by the model during ebb periods, we chose to fix it during the flood period. A varying C at river mouths during floods would necessitate either available continuous measurements, or a coupling to a coastal sediment transport model, out of the scope of the present study.

The value of C at the ocean boundaries during flood was obtained from the available measurements. Continuous measurements on periods longer than the spring-neap tide cycle were performed in the Cam and Van Uc Rivers in March (dry season) and August (wet season) 2009 at the Cam River mouth and at the Van

Uc River mouth. The averaged C at the Cam mouth during flood tide was 52 mg L^{-1} in the dry season and 61 mg L^{-1} in the wet season, while it was 60 mg L^{-1} in the dry season and 95 mg L^{-1} in the wet season in the Van Uc River. Other series of measurements were performed during one tidal cycle at the Cam, Bach Dang and Dinh Vu River mouths (Dinh Vu is located just downstream of the confluence between Cam and Bach Dang) in the wet season in 2008, and in the dry season in 2009 (field campaigns presented in Rochelle-Newall et al 2011, Lefebvre et al. 2012, Mari et al. 2012). During flood tides, at 1.5m below the surface, the averaged values lay in the range 72-162 mg L^{-1} in the wet season and 28-72 mg L^{-1} in the dry season. C values were always higher at the beginning of flood (just after low tide) than at the end, just before high tide.

As no measurements were available for the other river mouths, we decided to fix in our calculations a constant value of 50 mg L^{-1} at each river mouth over the whole year during flood periods. This value is within the range and the order of magnitude for the Cam, Bach Dang and Van Uc Rivers.

3.3.5 Calibration and validation

The model was calibrated by changing the values of Manning's roughness coefficients (*n*) at different locations in the river reach. During calibration, the simulated and observed water discharge at Ha Noi, Thuong Cat, Nam Dinh, Cua Cam gauging sites were compared for different combinations of *n* until the simulated and observed water levels matched closely. Optimization of the model's parameters (*n* distribution for hydrodynamics; critical shear stress for erosion $\tau_{c,e}$, critical shear stress for deposition $\tau_{c,d}$ and erodibility M_* for suspended sediment transport) was based on the Nash-Sutcliffe efficiency coefficient E (Nash and Sutcliffe, 1970) calculated for each simulation and given by:

$$E = 1 - \frac{\sum(obsQ - calcQ)^2}{\sum(obsQ - meanQ)^2} \quad (8)$$

in which the sum of the absolute squared differences between the predicted and observed values (Q for hydrodynamics, C for sediment transport) is normalized by the variance of the observed values during the period under investigation. E varies from 1.0 (perfect fit) to -∞, a negative value indicating that the mean value of the observed time series would have been a better predictor than the model (Krause et al., 2005).

The values of *n* used during the calibration process were within the range of 0.020–0.035 $m^{-1/3}$ s as recommended by Chow (1959). To avoid model instability, appropriate computational time step and grid size were selected. In the model setup, the computational time step and grid size were assigned as 30 s and 1,000 m, respectively. Initial water level and discharge conditions were provided to avoid a dry bed situation. Initially, the model was run using a uniform roughness coefficient of 0.03 $m^{-1/3}$ s. During the initial runs, the model over-estimated water level at some stations. Local values of Manning's *n* were chosen at different locations along the river to obtain the best fit between measurements and simulations. The resulting calibration was obtained with a decreasing roughness coefficient from 0.035 $m^{-1/3}$ s (upstream) down to 0.02 $m^{-1/3}$ s (downstream), by local best-fit at the gauging stations. No assumption on the type of global decreasing from upstream to downstream (neither linear, exponential nor other) was done, but a linear variation was applied to determine *n* between two adjacent gauging stations.

Only one-class of particles, of 15 μm-diameter, was considered in our simulations. This value is in agreement with bed sediments size in estuaries, dominated by silts (see §2.6 and Lefebvre et al., 2012). Their corresponding settling velocity obtained from Stoke's law is 0.2 mm s^{-1}. The critical shear stress for erosion of sediment ($\tau_{c,e}$) was tested in the range 0.1-1.0 N m^{-2} (Van Rijn, 2005); after calibration, we selected the value of 0.2 N m^{-2} for our simulations. The critical shear stress for deposition of sediment ($\tau_{c,d}$) was tested in the range 0.005-0.25 N m^{-2} (Van Rijn, 2005); after calibration, we chose to apply a value of 0.15 N m^{-2}. The erodibility was set at 10^{-3} kg m^{-2} s^{-1}.

The efficiency coefficient E was then calculated to quantify the model performance with daily average measured water discharge and sediment concentration in August 2006 upstream (Ha Noi, Thuong Cat) and downstream (Nam Dinh, Cua Cam). E values for water discharge in Ha Noi, Thuong Cat, Nam Dinh and Cua Cam were 0.75, 0.72, 0.71 and 0.69, respectively. The values for suspended sediment concentration at the same stations were 0.67, 0.66, 0.65 and 0.65, respectively, thus providing good agreement between measurements and simulations during the main period for sediment transport (i.e. the wet season; Fig. 3).

4. Results

4.1 Water discharge in the main tributaries

The Red River discharge results from its three major tributaries, Da, Thao and Lo Rivers (Fig. 1). Between 1960 and 2010, the Red River discharge at Son Tay varied from year to year, over the range 80 (in 2010)-161 (in 1971) x 10^9 m^3 yr^{-1} (Fig. 4), with an average value of 110 x 10^9 m^3 yr^{-1}. The average annual water discharge was 116 x 10^9 m^3 yr^{-1} and 106 x 10^9 m^3 yr^{-1} for the periods 1960–1979 and 1989–2010, respectively (Table 1, Fig. 4, 5a).

Lo and Thao Rivers supply about 50 % of the total water discharge of the Red River, the remaining 50 % being provided by the Da River (Table 1, Fig. 5a). The monthly water discharge of the Da and Red Rivers is highly correlated (r=0.950) as are the Red and Duong Rivers (r=0.948). As a result, the HBD not only affects the discharge of Red River but also that of the Duong River.

The measured yearly water discharge exhibited small increases at each tributary after HBD commissioning (Table 1, Fig. 5a): 7.3 % for the Lo River, 4.6 % for the Thao River and 1.9 % for the Da River. Conversely, while the yearly Red River discharge decreased by 9 % from 116 to 106 x 10^9 m^3 yr^{-1}, that of the Duong River increased by 14 %, from 29.2 to 33.3 x 10^9 m^3 yr^{-1}. In other words, the portion of discharge diverted by the Duong River increased from 24 % of the Red River before HBD impoundment, to 31 %.

Seasonal variations in Q were high. Rainy season (June to October) water discharge represents 71-79 % of annual total discharge with only 9-18 % during the dry season (December to April; Table 1). The remaining 5-10 % occurs during the period of lowest rainfall (January, February, and March).

Regulation of HBD has led to changes in the annual water distribution of the Da, Red and Duong Rivers. Discharge increased significantly during dry periods post HBD impoundment on the Da River (+48 %, Station 3 -see location in Fig. 1-), Red River (+12 %, Station 4) and Duong River (+109 %, Station 5; Table 1) (Fig. 5b). This shows (1) that the HBD has a marked impact on water regulation at the seasonal scale and (2) that Duong River responds to variations in the Red River, particularly in the dry season in the section above the connection with the Thai-Binh River.

The trends of the inter-annual variability in yearly water discharge are not straightforward. The coefficient of variation, denoted CV and defined as the ratio of standard deviation to the average, is a suitable indicator of variability. While the inter-annual variability did not change for the Red River at Son Tay after HBD impoundment (with a CV of 15 % amongst yearly values) and decreased by only 3 % for the Duong River, it shows higher variations upstream: from 10 to 18 % for the Da River, from 23 to 15 % for the Lo River and from 14 to 53 % for the Thao River. The CV of Q in the Da River was multiplied by 1.75 after HBD impoundment.

4.2 Suspended sediment discharge

The total suspended sediment discharged from the Red River system depends on water discharge as well as on the suspended sediment concentration of the Lo, Thao and Da Rivers. Before HBD impoudment, C of the Thao River was, on average, 1730 mg L^{-1} and was always higher than the mean C of the Da and Lo Rivers (1190 and 306 mg L^{-1}, respectively; Table 2). C of the Red River (at Son Tay) was 1030 mg L^{-1}. The annual total suspended sediment flux increased both in the Lo River (from 9.2 x 10^6 t yr^{-1} for the period 1960-1979 to 12.7 x 10^6 t yr^{-1} for the period 1989-2010) and Thao River (from 43.4 x 10^6 t yr^{-1} to 51.7 x 10^6 t yr^{-1}; Table 1, Fig. 4), whereas sediment discharge and C decreased in the Da and Red Rivers (Fig. 5c).

The HBD impoundment had a strong effect on sediment discharge and C in the Da, Red and Duong Rivers. While annual total suspended sediment discharge of the Da River was 65.0 x 10^6 t yr^{-1} (about half of the total supply to the Red River delta) before HBD impoundment, it dropped to 5.8 x 10^6 t yr^{-1} after (-91 %) (Fig. 5c). This is equivalent to only 8 % of the cumulated contributions from Da, Lo and Thao Rivers (Table 1, Fig. 5c). At the Hoa Binh gauging station, the annual average C decreased from 1190 mg L^{-1} to 106 mg L^{-1}. As a consequence, annual total suspended sediment of the Red River at Son Tay which averaged 119 x 10^6 t yr^{-1} before the HBD was reduced to 46 x 10^6 t yr^{-1} after the impoundment (-61 %; see Table 1, Fig. 4, 5c), corresponding to a decrease in the average C from 1030 mg L^{-1} to around 400 mg L^{-1} (Table 2). At Thuong Cat on the Duong River, the annual total suspended sediment which averaged 28.9 x 10^6 t yr^{-1} before the HBD was also reduced to 21.6 x 10^6 t yr^{-1} after (-17 %; see Table 1, Fig. 4, 5c), and the average C decreased by 25 %, from 989 mg L^{-1} over the period of 1960–1979 to 738 mg L^{-1} over the period 1989–2010 (Table 2). Interestingly, the total suspended sediment delivery in the Duong River slightly increased in dry season after HBD impoundment, from 0.5 x 10^6 t yr^{-1} to 0.7 x 10^6 t yr^{-1} (Table 1).

The seasonal variability of C is high. Total suspended sediment discharge is highest in July and August and lowest in February and April (Table 2). Suspended sediment discharge for five months of the rainy season (from June to October) made up from 87 % to 96 % (Table 1). While the CV amongst the monthly averaged values of C was the highest in the Da River (112 %) before HBD impoundment and dropped to 70 % after, it remained unchanged in the Lo and Thao Rivers, around 90 and 80 %, respectively (Table 2). The change in the Da River sediment regime also involved a decrease of 6-7 % of the seasonal variability of C in the Red and Duong Rivers.

Despite contrasted changes in the inter-annual variability of river discharge, the main rivers of the Red River system show an enhancement of the variability of relative sediment discharge on the inter-annual scale. While their respective CVs were almost equivalent and ranged between 32 % (Red River at Son Tay) and 36 % (Thao River) before HBD impoundment, they had much higher differences after impoundment and varied from 39 % in the Duong River to 77 % in the Lo River. Moreover, the absolute change of the standard deviation decreased significantly in the Da River by 88 %, in the Red River by 31 % and in the Duong River by 13 % due to a large decrease in suspended load (Table 2). At the Son Tay station, sediment flux ranged between 56 x 10^6 t in 1963 and 201 x 10^6 t in 1971 before HBD impoundment and between 10 x 10^6 t in 2010 and 134 x 10^6 t in 1990 for the period after 1989.

4.3 Influences on the distributaries discharge

The water distribution across the 9 river mouths before and after HDB impoundment was estimated from numerical simulations (Table 3). The present calculations show that water distribution was affected by the impoundment of the HBD. The present discharge ratio is shown on Fig. 6. Water discharge ratio of the estuaries in the North of the RRD slightly increased after impoundment: from 15.5 % (before HBD) to 16.5 % for the Cam and Bach Dang estuaries, from 3.5 % to 3.7 % for the Lach Tray River, from 13.6 % to 14.5 % for the Van Uc River, and from 6.0 to 6.4 % in the Thai Binh River. Water discharge ratio also slightly increased in the Day River, at the South of the delta, from 22.1 % to 23 %. Conversely, this ratio decreased in the central delta, especially at Ba Lat mouth from 24.9 % to 22.5 % (Table 3).

The decrease of total water discharge from all the distributaries of 10 x 10^9 m^3 yr^{-1} between 1960-1979 and 1989-2010 (from around 130 to 120 x 10^9 m^3 yr^{-1}, see Table 3) calculated by the model is due to a decrease of the Red River discharge (Table 1). It should be noted that water use for irrigation, drainage, urban and industrial purposes were not considered in the model. Between the two periods, water discharge of the estuaries increased by 17 % during the dry season (from 17.8 to 20.8 x 10^9 m^3, see Table 3), while it decreased by 14 % during the rainy season (from 98.8 to 85.2 x 10^9 m^3, Table 3), due to water regulation by the HBD.

The decrease in suspended sediment concentration of the Red River caused a strong decrease in suspended sediment concentration as well as suspended sediment discharge in the distributaries. Total suspended sediment delivery decreased both in the dry and rainy season after HBD impoundment from 2.6 x 10^6 t to 1.7 x 10^6 t for the dry season, and from 77.3 x 10^6 t to 30.5 x 10^6 t for the rainy season (Table 4). As a result, the total average annual suspended sediment discharge decreased by 59 % after 1989 from 85 to 35 x 10^6 t yr^{-1}. The changes in suspended sediment distribution mirror the changes of discharge distribution i.e. slight increases of *M ratio* were observed in the Northern part of the delta (from 15.5 % to 17.1 % in the Bach Dang and Cam Rivers) and in the Southern part (from 22.1 % to 22.8 % in the Day River), whereas the *M ratio* decreased in the central part of the delta. Although the suspended sediment discharge in absolute value decreased in most distributaries, it slightly increased in the northern estuaries (Cam, Bach Dang, Lach Tray, Van Uc, Thai Binh) in dry season due to an increase in river discharge (Table 4, Fig. 7).

5. Discussion

5.1 Comparison with former studies

The values of water and sediment discharge calculated in this study from a 50-yr dataset of discharge and sediment concentration at five key stations of the Red River can be compared with the previously published values. We found an average annual water discharge of 116 x 10^9 m^3 yr^{-1} or 3680 m^3 s^{-1} for the period 1960–1979 and of 106 x 10^9 m^3 yr^{-1} or 3350 m^3 s^{-1} for 1989–2010 (Table 1, Fig. 4). These values are consistent with the previous estimates of Dang et al. (2010): 3557 m^3 s^{-1} for 1960-1988, and 3426 m^3 s^{-1} for 1989-2006, and those of other reports or papers (To, 2000; Nguyen et al., 2003; Le et al., 2005). This is to be expected as all estimations were based on data provided by the same administration.

The value of 31 % of water diverted by the Duong River and calculated over 22 years is in very good agreement with the former estimate over 11-years (1996-2006) by Luu et al. (2010) who calculated an average diversion of 30 %, with variations from 25 % during the wetter period 1996-2000 to 35 % during the drier 2001-2006 period. Although the HBD does not influence yearly water discharge, its regulation has modified the range of seasonal variation. Water discharge increased by 48 % in the dry season in the Da River), by 12 % in the Red River and by 109 % in the Duong River (Fig. 5b).

No estimates of water distribution amongst the 9 estuaries have been published for the period before HBD impoundment. However, Pruszak et al. (2005) gave estimates of the water discharge percentage for 6 estuaries, which are reported in Table 3. The date is not given but they probably refer to pre-1989, as they consider a global yearly suspended sediment flux of 116 x 10^6 t yr^{-1}. Their percentage for the Van Uc-Thai Binh system (37 %) is very close to our estimate before 1979 for the whole Duong-Thai Binh system (38.6 % for Cam, Bach Dang, Lach Tray, Van Uc and Thai Binh), and for the Tra Ly as well (10 % by Pruszak et al., 2005, versus 8.4 % in our calculation). The estimates for the Ba Lat, Ninh Co and Day estuaries are the same and represent about 25 %, 6% and 22 %, respectively. Our value for Ba Lat is also consistent with that of van Maren & Hoekstra (2004): 21 %. Other calculations were performed by Luu et al. (2007, see Table

3), for a dry year (2006) and a wet year (1996) post-1989, while ours were calculated for an average post-1989 year. The percentages of Luu et al. (2007) for the three main outlets are very close to our estimates; with those for dry years being in better agreement with our estimates than for the wet years.

Concerning the suspended sediment discharge, it should be noted that there were large increases in sediment discharge and concentration in the Thao and Lo rivers. These were partly caused by human activities in the Chinese part of the Red River (Yuanjiang river), as illustrated by the average C at the Manhao station during the 1960s, 1970s, 1980s and 1990s where values of 1870, 2490, 3120, 3630 mg L^{-1}, respectively, were observed (He et al., 2007). Other impacts in China and in Vietnam such as shifts in land use and deforestation may also contribute to these changes.

The average sediment flux in Hanoi before HBD (119 x 10^6 t yr^{-1}) calculated over 1960-1979 is the same as that calculated by Dang et al. (2010). It is also in good agreement with other previous estimates that ranged between 100 and 160 x 10^6 t yr^{-1}, with a very close estimate (116 x 10^6 t yr^{-1}) given by Pruszak et al. (2005). The value calculated for 1989-2010 (46 x 10^6 t yr^{-1}) is also very close to the value calculated by Dang et al. (2010) (49 x 10^6 t yr^{-1}) for the period 1979-2008. The interannual variability of sediment transport in Hanoi was higher over the period 1960-1979 (range in yearly values: 56-201 x 10^6 t yr^{-1}, standard deviation = 38.4 x 10^6 t yr^{-1}) than during 1989-2010 (10-134 x 10^6 t yr^{-1}, standard deviation = 26.3 x 10^6 t yr^{-1}). This latter range is consistent with the range estimate of between 30 and 120 x 10^6 t as quoted by van den Bergh et al. (2007b), although we found a smaller lower limit due to the recent lower sediment discharge (24 x 10^6 t yr^{-1} in average for 2003-2010; see Fig. 4).

After the HBD impoundment, average daily C decreased from 1190 mg L^{-1} to 106 mg L^{-1} at Hoa Binh (Da River) and from 1030 mg L^{-1} to around 400 mg L^{-1} at the Son Tay Station on the Red River. The annual total suspended sediment discharge, which was 65 x 10^6 t yr^{-1} in the Da River and represented about half of the total supply to Red River, decreased to 5.8 x 10^6 t yr^{-1}. This decrease of 91 % is consistent with an estimated sediment efficiency trapping of 88 % in the HBD (Dang et al. 2010).

The highest value at Thuong Cat station as compared to the Son Tay station may be explained by either new sediment inputs between the two stations (from urban, industrial, agricultural origins or from dredging activities such as observed in Hanoi), or by riverbed and bank erosion induced by the local river load capacity (Ouillon and Le Guennec 1996, van Rijn 2005).

The distribution of sediment discharge from the Red River to the RRD coast changed both spatially and quantitatively, decreasing from 85 to 35 million tons per year (about 59 %). If we consider the period 1989-2010, 50 % of the sediment brought by the Lo, Thao and Da Rivers which did not reach the river mouths settled in the delta. Between Hanoi and the sea, 11 x 10^6 t settle per year, representing 31 % of the sediment discharge at Son Tay, the remaining part being delivered to the ocean. This percentage is similar to that of 1960-1979 (29 %), however, the absolute quantity is divided by 3. This estimate should be considered as a first guess since the model does not take into account neither flocculation nor stratification, and only one sediment class. However, it is consistent with the value of 70 % of sediment delivered to the sea as estimated by Häglund and Svensson (2002).

5.2 Enhanced estuarine deposition

Recently, enhanced deposition occurred in the middle estuaries, in particular the Cam-Bach Dang, Ninh Co and Day Rivers resulting in the need for increased dredging in order to improve navigability. In the Ninh Co and Day Rivers, projects have been set up to improve navigability. The recent changes in the volume of sediment dredged from the estuarine harbour of Hai Phong illustrate the enhanced silting up of the Cam-Bach Dang estuary. The dredged volume of sediment in the port of Hai Phong in 1922, 1983, 1992 was 922.6, 1256 and 1700 x 10^3 m^3, respectively. Nowadays, 4-5 x 10^6 t (1600 - 2000 x 10^3 m^3) of sediments are annually dredged from the port in order to guarantee the port activities (Vietnam Administration of Hai Phong, unpublished). These measurements show that, although sediment delivery decreased after HBD impoundment, siltation recently increased in the Haiphong harbour, i.e. in the estuary of the Cam-Bach Dang river. Which process(es) could explain such an apparent paradox?

Flocculation of estuarine suspended particulate matter is strongly dependent on the suspended sediment concentration, especially in low energetic episodes characteristic of slack water periods (i.e., with a

Kolmogorov microscale >1,000 µm) (Verney et al., 2009), and turbulence has been identified as the most important factor controlling aggregation in the wet season in the Bach Dang estuary (Lefebvre et al., 2012). Apart from the sediment load, sediment deposition in the estuary in governed by hydrodynamics (Q and turbulence). As examined by Lefebvre et al (2012), tidal pumping is a key process in sediment dynamics and deposition in the Cam-Bach Dang estuary, especially during the dry season when deposition in the middle and lower estuary is three times higher than during the wet season. Tidal pumping occurs under two conditions: (1) Q must be low enough that marine water flows into the estuary during flood, (2) Q must be high enough so that the tidal cycle shows a strong velocity asymmetry, with a short but highly energetic flood period. Tidal pumping is probably higher in the northeast of the delta (Cam-Bach Dang, Lach Tray and Van Uc estuaries) than in the central and south delta estuaries because the tidal amplitude is much higher there (Uncles et al., 2002) (see amplitudes in § 2.4).

In this context, two possible origins of enhanced siltation caused by the new water regulation can be envisaged: (a) lower discharges in wet period, and (b) higher discharges in dry season. (a): by limiting flow during floods, the HBD regulation decreased sediment transport capacity of the rivers - especially in the higher floods that flushed the river bed - thereby enhancing deposition in the river, with the knock-on effects of obstructing the boat traffic and the outgoing tidal waters out (Tran et al., 2002). (b): the observed slight increase of river discharge during the dry season after the impoundment of the HBD (Red and Duong Rivers, Fig. 5b) likely enhanced the tidal asymmetry and the associated tidal pumping (Allen et al., 1980; Dyer, 1986). Mechanisms (a) and (b) may be superimposed. However, as shown in Lefebvre et al. (2012), deposition in the estuary mainly occurs in dry season. The changes of Q, turbulence and C variability caused by dam regulation and dam retention may have moved the turbidity maximum zone in dry season.

Unfortunately, no data are available on the location of the extreme turbidity maximum before HBD impoundment, and we are not able to assess if the extreme turbidity maximum in the northern branch of the Red River estuary moved after the impoundment of the HBD towards the harbour estuarine area. The combination of a new water regulation and tidal pumping is a possible origin of this increased siltation. This hypothesis is only an assumption, opening up new avenues of research.

5.3 Erosion and/or accretion along the Red River Delta

During the last geological period, the Van Uc, Thai Binh, Tra Ly and Ba Lat mouths had very rapid accretion zones with sediment accumulation rates exceeding sea level rise (1-2 mm yr^{-1}) and tectonic subsidence (2 mm yr^{-1}, Do et al. 2007). Typical mechanisms of delta progradation involve the forming and connecting sand bars in front of the mouths (Do et al., 2012), thus inducing a progressive development of the delta outward into the Gulf of Tonkin. Recently, the shorelines at these river mouths were expanding at a rate of about 15-100 m per year and the rapid accretion in front of the river mouths caused widespread difficulties for navigation, similar to Haiphong bay. Conversely, sediment deficits in the adjacent areas led to shoreline erosion. Coastal erosion causes loss of land, and the expansion of saline intrusions. The coastal zones where rapid erosion prevails are located from south of the Ba Lat mouth to the Hai Hau district (see location in Fig. 1), and in the nearby the mouths (Do et al., 2012), such as north of the Ninh Co mouth. Shoreline regression in Hai Hau can reach 15 m yr^{-1}. Shoreline changes obtained from maps suggest that the Hai Hau erosion started around the beginning of the 20^{th} century with a decrease in erosion rate during the late 60s. According to geodesic measurements from 1963 to 1985, the Hai Hau district was subsiding with a maximum rate of up to 5 mm yr^{-1} (van den Bergh et al. 2007a). Sediments from the Red River (Ba Lat) are largely transported in a southern direction and do not reach the coastline of the Hai Hau district. Shoreline erosion also takes place north of the Van Uc River (Haiphong city) although with lower intensity. The reduction of sediments exported to the coastal zone due to trapping in the HBD has already been identified as the main cause of intensified erosion in RRD coastal line (Tran et al., 2002; Do et al., 2007, 2012).

To distinguish between various erosion levels, the intensity of erosion was noted as "weak" (less than 2.5 m yr^{-1}), "mean" (2.5 to 5 m yr^{-1}), and "strong" erosion (more than 10 m yr^{-1}) by Tran et al. (2002). In the period 1965-1990, the length of eroded coastline was 59 km, with a mean intensity covering 45.5 % of the shoreline and a strong intensity covering 45.5 %. For the period 1991-1995, the length of eroded coastline decreased to 25.5 km due to dike consolidation and because sections in Bang La (northeast of Van Uc River mouth) and Tien Lang (southwest of Van Uc River mouth) switched from erosion to accretion. However, strong intensity covered up to 87.5 % of the shoreline for this period. The Hai Hau coast became the main eroded coastline with an average erosion rate of 8.3 m yr^{-1} in the period 1965-1991 and up to 15.0 m yr^{-1} for 1991-1995 (Tran et al., 2001).

In the coastal area, recent measurements of sedimentation rate at the outer Tra Ly mouth based on the analysis of ^{210}Pb in sediment cores show that the sediment rate in this area is decreasing (Bui et al., 2012). At 10m depth in front of the river mouth (station HP4 in Bui et al, 2012), the average sedimentation rate for the periods 1966-1975, 1975-1988, and 1988-2011, was 1.8, 1.24 and 1.01 cm yr^{-1}, respectively. Further offshore (at about 20m depth, HP6), the average sedimentation rate for the periods 1964-1976, 1976-1984, 1984-2011 was 0.67, 1.0 and 0.56 cm yr^{-1}, respectively. This tendency is coincident with the reduction of sediment input from the Red river to the sea after HBD impoundment.

In order to assess impacts of HBD on the distribution of suspended sediment along the Red River delta, an integrated model (hydrodynamics-waves-sediment transport) was setup with different scenarios, before and after HBD period (Vu et al., 2011). This model did not take into account the influence of polysaccharide polymers (extra-cellular polymeric substances, EPS) in the aggregation which have been shown to be efficient in the Cam-Bach Dang estuary (Mari et al., 2012). The simulations shown that, in the Haiphong Bay area and during the wet season, the averaged C on water depths <5m, 5-10m, 10-15m, 15-20m, 20-25m, 30-35m decreased by 62%, 66%, 65%, 54%, 42%, 36%, respectively, after HDB impoundment. In front of the Ba Lat mouth and during the wet season, averaged C on water depths <5m, 5-10m, 10-15m decreased by 63%, 56%, and 39%, respectively. These results show that the reduction of sediment delivery has a higher impact on shallow water areas, up to 15m in the North and up to 10m in front of the central delta, where morphologic changes are driven by wave action more than by tidal asymmetry (van Maren et al., 2004).

5.4 Boundary conditions

Although the value of 50 mg L^{-1} fixed at the river mouth during flood periods enabled the calculation of estimates of sediment flux, this arbitrary value likely underestimates the sediment flux from offshore to the estuary, and thus estuarine siltation. To improve the accuracy of sediment flux estimates, the measurement of C at river mouths during flood tides is strongly encouraged in future work. The coupling of the river basin model to a coastal hydro-sedimentary model should allow better estimating estuarine deposition rates, and estimating erosion and accretion rates along the delta as well, enabling a closer analysis in regards to the available measurements.

6. Conclusion

Although the estimates of water and sediment discharge can be improved in the future (e.g. measuring C at the river mouths during flood periods; taking into account bedload transport and several classes of suspended particles as well in the model; connecting the river basin model to a 2D or 3D coastal hydro-sedimentary model; etc), this paper is the first to provide the distribution of water and sediments within the 9 distributaries of the Red River, one of the biggest rivers in the world (ranked 9th by Milliman and Meade in 1983, in terms of sediment input to the ocean). The fluxes were estimated before and after the Hoa Binh dam impoundment, and compared.

The estuaries of the Red River delta are presently silting up and this is partly due to the water flow regulation of the HBD which has led to a decrease in sediment transport capacity and an increase of river discharge in the northern delta during the dry season. All of which likely enhance deposition in the Cam-Bach Dang estuary. Moreover, the decrease of suspended sediment discharge of Red River induced a decrease of sedimentation rate along the delta shoreline. Coastal erosion intensifies when sedimentation and accumulation no longer balance sea level rise and tectonic subsidence, and this factor needs to be taken into account when considering dam regulation. The increase of the suspended sediment discharge ratio in the northern (Cam, Bach Dang, Lach Tray, Van Uc, Thai Binh) and southern estuaries (Day) and its decrease at the Ba Lat, Tra Ly and Ninh Co mouths influenced not only erosion and accretion zones along the RRD coasts, they also altered the geological, morphological, biogeochemical and ecological responses in the estuaries, delta, and coastal areas (e.g. Rochelle-Newall et al., 2011; Bui et al., 2012; Navarro et al., 2012).

River dams have been built in Viet Nam for many decades for energy supply, such as the Day dam in 1937 (on the Day River), the Thac Ba dam in 1970 (on the Chay River), and the HBD in 1989. Sediment trapping in the reservoirs was not considered during the first decades. However, recent studies have documented their impacts on sediment fluxes. Even if the Hoa Binh dam has played a considerable role in flood control, irrigation and electricity production in North Vietnam, this study shows that it also significantly affected water discharge and the suspended sediment input from the Red River basin to the delta and coastal areas. Finally, this work underlines the need for an integrated management plan that extends from the river basin to the coastal zone and that involves the close collaboration of hydrologists, coastal oceanographers, and decision makers.

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Table captions

Table 1. Average water and suspended sediment fluxes obtained from measurements at five gauging stations during the dry season (December-April), the rainy season (June-October), and per year, before (1960-1979) and after (1989-2010) Hoa Binh dam impoundment (see locations of stations in Fig. 1)

Table 2. Average monthly and annual suspended sediment concentration (mg L^{-1}), and intra-annual variability (coefficient of variation of mean monthly values) obtained from measurements at five gauging stations before (1960-1979) and after (1989-2010) Hoa Binh dam impoundment

Table 3. Average water discharge in the nine distributaries of the Red River obtained from numerical simulations in the dry season (December-April), in the rainy season (June-October), and per year, before (1960-1979) and after (1989-2010) Hoa Binh dam impoundment; comparison with previous estimates (Pruszak et al., 2005; Luu et al., 2010).

Table 4. Average suspended sediment fluxes in the nine distributaries of the Red River obtained from numerical simulations in the dry season (December-April), the rainy season (June-October), and per year, before (1960-1979) and after (1989-2010) Hoa Binh dam impoundment

River	Station	Parameter	Before Hoa Binh dam (1960-1979)			After Hoa Binh dam (1989-2010)		
			Dry	Rainy	total year	Dry	Rainy	total year
Lo	1	Q (x 10^9 m^3)	4.4	22.1	30.1	5.8	22.9	32.3
		M (x10^6 t)	0.2	8.3	9.2	0.4	11.6	12.7
Thao	2	Q (x 10^9 m^3)	4.2	17.9	25.1	4.5	18.5	26.3
		M (x10^6 t)	2.0	38.7	43.5	1.4	46.4	51.7
Da	3	Q (x 10^9 m^3)	6.6	42.8	54.5	9.8	39.5	55.5
		M (x10^6 t)	0.6	62.4	65.0	0.3	5.2	5.8
Red	4	Q (x 10^9 m^3)	16.3	86.9	116	18.2	75.2	106
		M (x10^6 t)	3.3	108.6	119	1.9	40.3	46
Duong	5	Q (x 10^9 m^3)	2.7	22.3	29.3	5.8	23.6	33.3
		M (x10^6 t)	0.5	26.1	28.9	0.7	19.2	21.6

TABLE 1

River	Period	Monthly averages													Annual average
		1	2	3	4	5	6	7	8	9	10	11	12	CV (%)	
Lo	1960-1979	24.1	25.1	46.7	66.8	328.6	484.7	444.0	399.4	255.3	151.1	69.4	29.5	92	306
	1989-2010	32.9	30.3	40.1	80.7	216.4	378.4	474.8	399.2	255.1	191.0	71.0	36.0	88	421
Thao	1960-1979	404.8	382.2	417.7	549.7	920.7	1804.9	2426.1	2908.8	2001.2	1225.2	868.0	521.6	80	1730
	1989-2010	324.3	270.8	314.2	523.1	1012.7	2339.9	3150.2	2990.7	2611.4	1413.7	1041.0	317.3	77	2060
Da	1960-1979	45.6	45.6	34.9	265.5	439.1	1249.1	1787.9	1792.4	978.8	509.0	319.3	92.5	112	1190
	1989-2010	35.2	31.4	30.1	30.9	41.2	91.4	153.1	141.6	87.5	52.0	36.9	32.1	70	106
Red	1960-1979	183.3	163.6	156.3	211.5	538.9	1014.0	1383.1	1468.4	1068.6	726.2	484.9	224.6	74	1030
	1989-2010	101.2	93.9	91.9	117.0	262.2	427.1	480.1	606.0	577.1	338.3	252.2	96.8	68	397
Duong	1960-1979	125.8	118.9	103.9	196.8	556.7	1028.4	1291.1	1369.8	1025.2	713.3	452.4	180.8	80	989
	1989-2010	123.1	100.8	131.4	146.3	351.0	717.1	857.4	875.6	772.8	531.2	365.3	138.7	73	738

TABLE 2

River mouth	Water delivery	before Hoa Binh dam (1960–1979)			after Hoa Binh dam (1989–2010)			P* 2005	Luu et al. 2010	
		dry season	rainy season	total year	dry season	rainy season	total year		2006 (dry year)	1996 (wet year)
Bach Dang	Q (x 10^9 m^3)	0.8	6.4	8.0	1.4	6.0	8.4			
	Q ratio (%)	4.5	6.5	6.1	6.7	7.0	6.9			
Cam	Q (x 10^9 m^3)	1.2	10.0	12.2	2.0	8.0	11.5			
	Q ratio (%)	6.9	10.0	9.4	9.9	9.4	9.5			
Lach Tray	Q (x 10^9 m^3)	0.5	3.7	4.6	0.7	3.2	4.5			
	Q ratio (%)	2.5	3.7	3.5	3.6	3.8	3.7			
Van Uc	Q (x 10^9 m^3)	2.1	13.9	17.7	2.9	12.5	17.5			
	Q ratio (%)	11.6	14.1	13.6	14.1	14.6	14.5			
Sub-Total NE	Q ratio (%)	**25.5**	**34.2**	**32.6**	**34.3**	**34.8**	**34.7**	**26.0**	**34.6**	**26.1**
Thai Binh	Q (x 10^9 m^3)	0.9	6.2	7.8	1.3	5.5	7.7			
	Q ratio (%)	5.0	6.2	6.0	6.3	6.5	6.4	11.0		
Tra Ly	Q (x 10^9 m^3)	1.7	8.0	10.9	1.6	6.6	9.3			
	Q ratio (%)	9.5	8.1	8.4	7.8	7.7	7.8	10.0		
Ba Lat	Q (x 10^9 m^3)	5.0	23.8	32.5	4.7	19.1	27.0			
	Q ratio (%)	28.2	24.1	24.9	22.7	22.4	22.5	25.0		
Ninh Co	Q (x 10^9 m^3)	1.2	5.8	7.8	1.2	4.8	6.8			
	Q ratio (%)	6.8	5.8	6.0	5.7	5.6	5.6	6.0		
Sub-Total Center	Q (%)	**49.5**	**44.4**	**45.3**	**42.5**	**42.3**	**42.3**	**52.0**	**44.7**	**56.7**
Day	Q (x 10^9 m^3)	4.4	21.2	28.8	4.8	19.5	27.6			
	Q ratio (%)	**25.1**	**21.4**	**22.1**	**23.2**	**22.9**	**23.0**	**22.0**	**20.8**	**17.2**
Total	Q (x 10^9 m^3)	**17.8**	**98.8**	**130.5**	**20.8**	**85.2**	**120.3**			

*: Pruszak et al., 2005

TABLE 3

River mouth	Sediment delivery	before Hoa Binh dam (1960–1979)			after Hoa Binh dam (1989–2010)		
		dry season	rainy season	total year	dry season	rainy season	total year
Bach Dang	M (x10^6 t)	0.1	4.8	5.2	0.1	2.1	2.4
	M ratio (%)	3.5	6.2	6.1	6.6	6.9	6.9
Cam	M (x10^6 t)	0.1	7.4	8.0	0.2	3.1	3.6
	M ratio (%)	5.4	9.6	9.4	10.2	10.2	10.2
Lach Tray	M (x10^6 t)	0.1	2.8	3.0	0.1	1.1	1.3
	M ratio (%)	2.3	3.6	3.5	4.2	3.7	3.7
Van Uc	M (x10^6 t)	0.3	10.7	11.5	0.2	4.4	5.1
	M ratio (%)	10.7	13.8	13.6	14.5	14.4	14.4
Thai Binh	M (x10^6 t)	0.1	4.7	5.1	0.1	2.0	2.2
	M ratio (%)	4.6	6.1	6.0	6.0	6.4	6.4
Tra Ly	M (x10^6 t)	0.3	6.4	7.1	0.1	2.4	2.7
	M ratio (%)	10.0	8.3	8.4	7.8	7.7	7.7
Ba Lat	M (x10^6 t)	0.8	19.0	21.1	0.4	6.8	7.8
	M ratio (%)	29.9	24.6	24.9	22.3	22.3	22.3
Ninh Co	M (x10^6 t)	0.2	4.6	5.1	0.1	1.7	2.0
	M ratio (%)	7.3	5.9	6.0	5.4	5.6	5.6
Day	M (x10^6 t)	0.7	16.9	18.8	0.4	7.0	8.0
	M ratio (%)	26.4	21.8	22.1	22.9	22.8	22.8
Total	M (x10^6 t)	**2.6**	**77.3**	**84.8**	**1.7**	**30.5**	**35.1**

TABLE 4

Figure captions

Fig. 1 Red River system and the Red River coastal area

Fig. 2 Diagram of the network considered in the Red River delta for the MIKE11 model

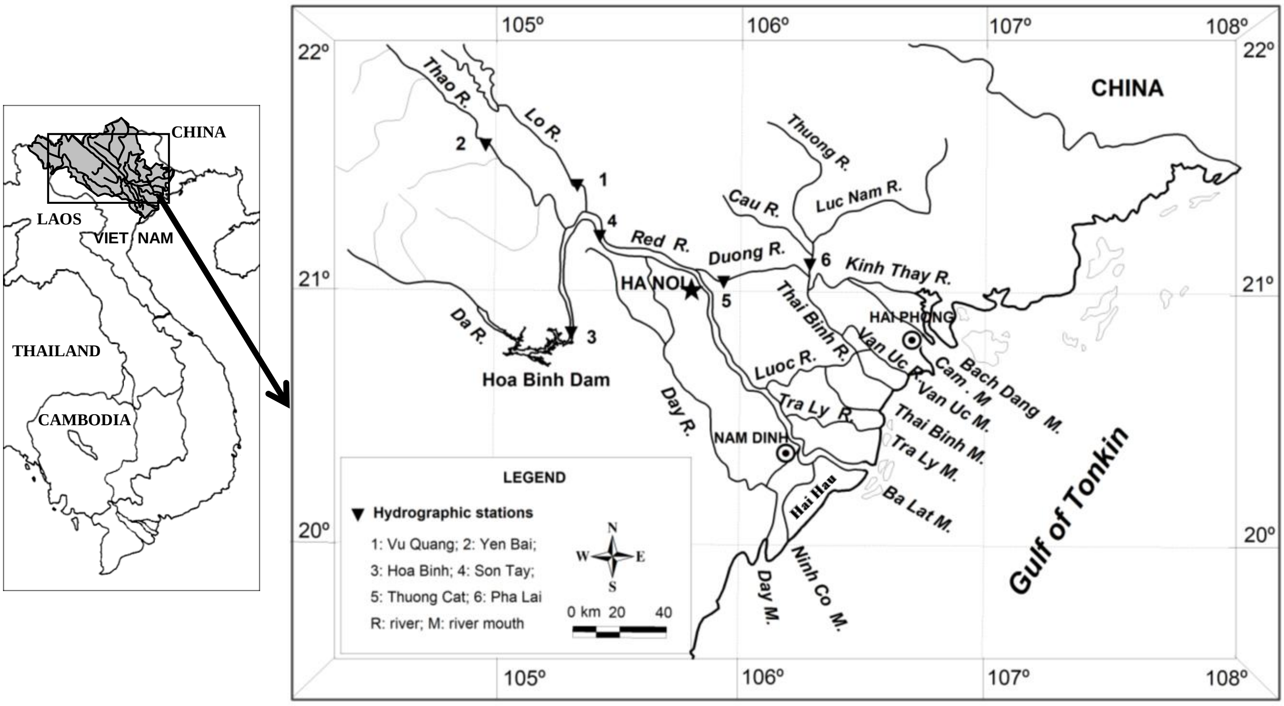
Fig. 3 Comparison of modeled and measured water discharge (Q) and suspended sediment concentration (C) in August 2006 (a - Hanoi; b - Thuong Cat; c- Nam Dinh; d- Cua Cam) after calibration of the model

Fig. 4 Annual water and suspended sediment discharge in the main tributaries of the Red River system (1960-2010), and average values before and after Hoa Binh dam impoundment

Fig. 5 Change in average water and suspended sediment discharge in the main tributaries of the Red River system before and after Hoa Binh dam impoundment: (a) average yearly Q, (b) average Q in dry season, (c) average yearly M.

Fig. 6 Distribution of water discharge amongst the 9 distributaries of the Red River after the Hoa Binh dam impoundment

Fig. 7 Average sediment delivery in dry season, per year, at the river mouths of the 9 distributaries before and after Hoa Binh dam impoundment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LEGEND
Hydrographic stations
1: Vu Quang; 2: Yen Bai;
3: Hoa Binh; 4: Son Tay;
5: Thuong Cat; 6: Pha Lai
R: river; M: river mouth
0 km 20 40
N
W
E
S

FIG. 1

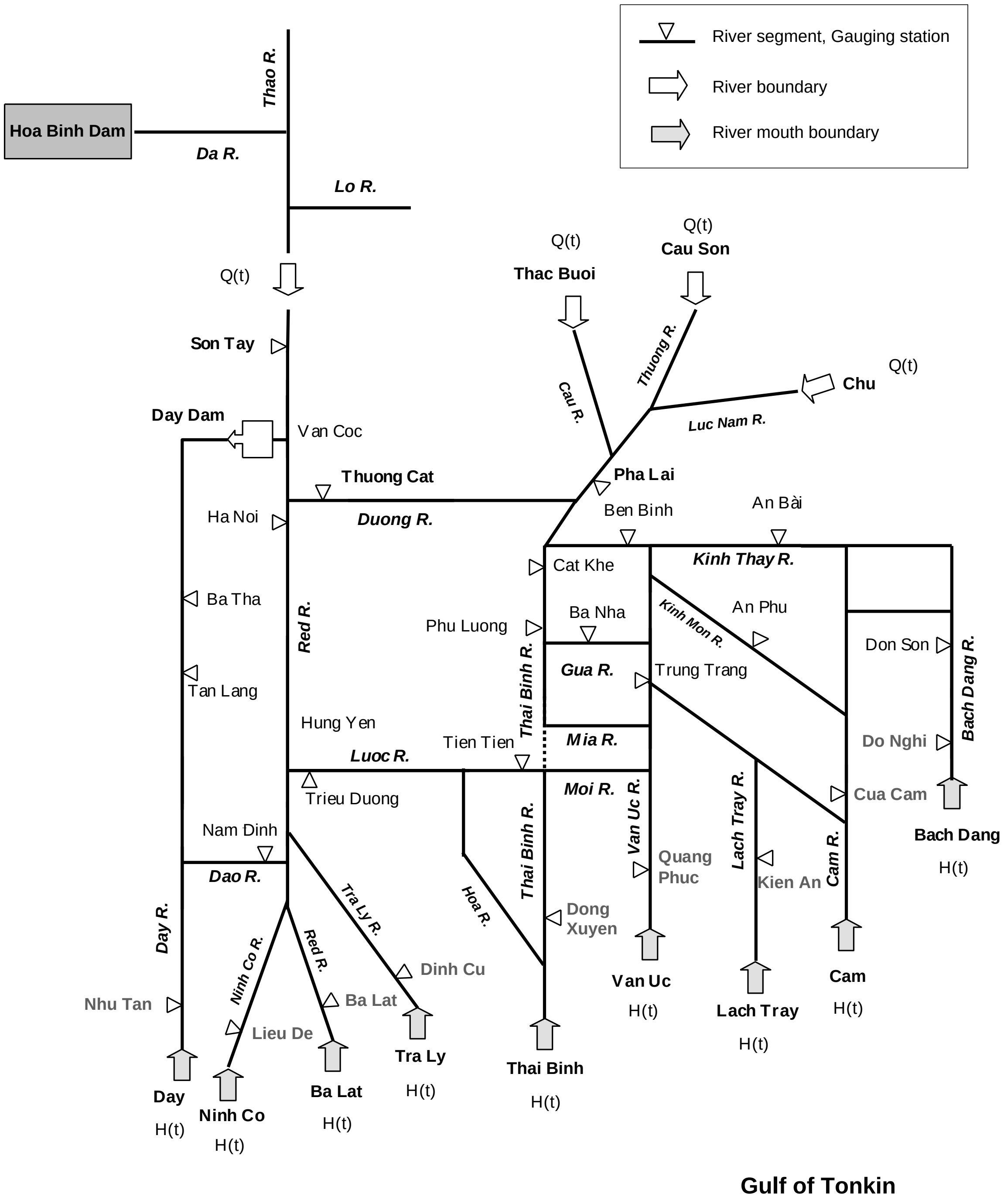
River segment, Gauging station
River boundary
River mouth boundary
Hoa Binh Dam
Thao R.
Da R.
Lo R.
Q(t)
Son Tay
Day Dam
Van Coc
Thuong Cat
Duong R.
Ha Noi
Ba Tha
Red R.
Tan Lang
Hung Yen
Luoc R.
Trieu Duong
Nam Dinh
Dao R.
Day R.
Nhu Tan
Ninh Co R.
Lieu De
Red R.
Ba Lat
Tra Ly R.
Dinh Cu
Day
H(t)
Ninh Co
H(t)
Ba Lat
H(t)
Tra Ly
H(t)
Q(t)
Thac Buoi
Q(t)
Cau Son
Cau R.
Thuong R.
Q(t)
Chu
Luc Nam R.
Pha Lai
Ben Binh
An Bài
Cat Khe
Kinh Thay R.
Ba Nha
Phu Luong
An Phu
Kinh Mon R.
Gua R.
Trung Trang
Thai Binh R.
Mia R.
Tien Tien
Moi R.
Hoa R.
Thai Binh R.
Dong Xuyen
Van Uc R.
Quang Phuc
Lach Tray R.
Kien An
Cam R.
Don Son
Bach Dang R.
Do Nghi
Cua Cam
Bach Dang
H(t)
Thai Binh
H(t)
Van Uc
H(t)
Lach Tray
H(t)
Cam
H(t)
Gulf of Tonkin

FIG. 2

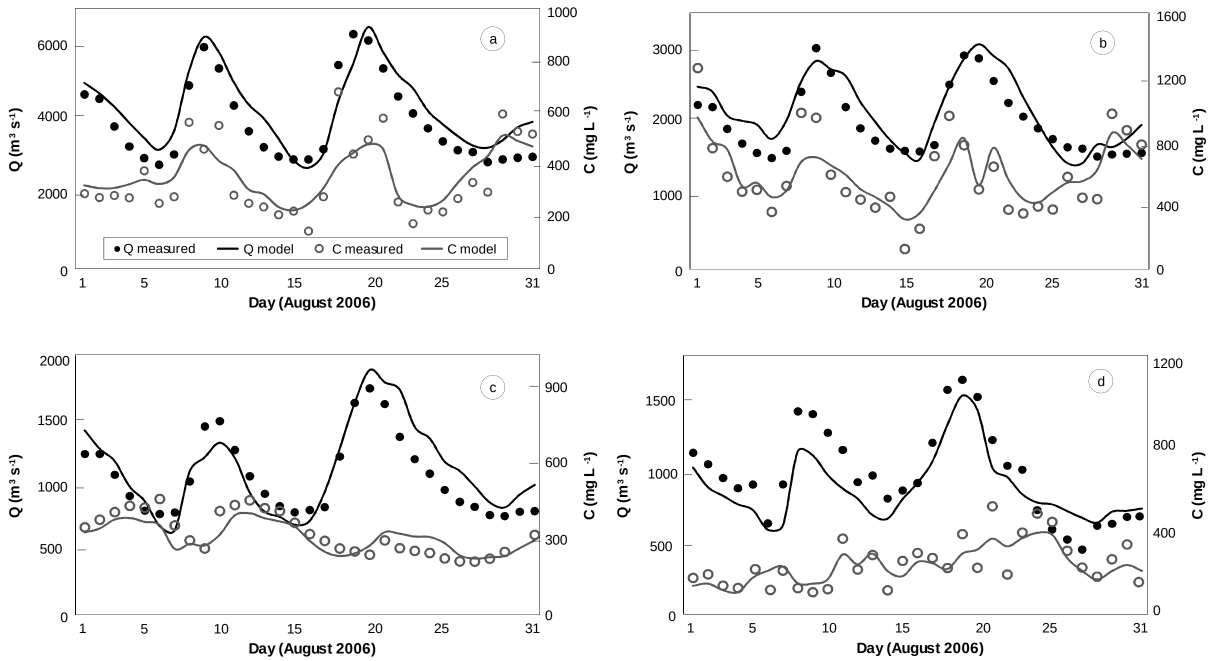
a
b
c
d
Q (m³ s⁻¹)
C (mg L⁻¹)
Day (August 2006)
Q measured
Q model
C measured
C model

FIG. 3

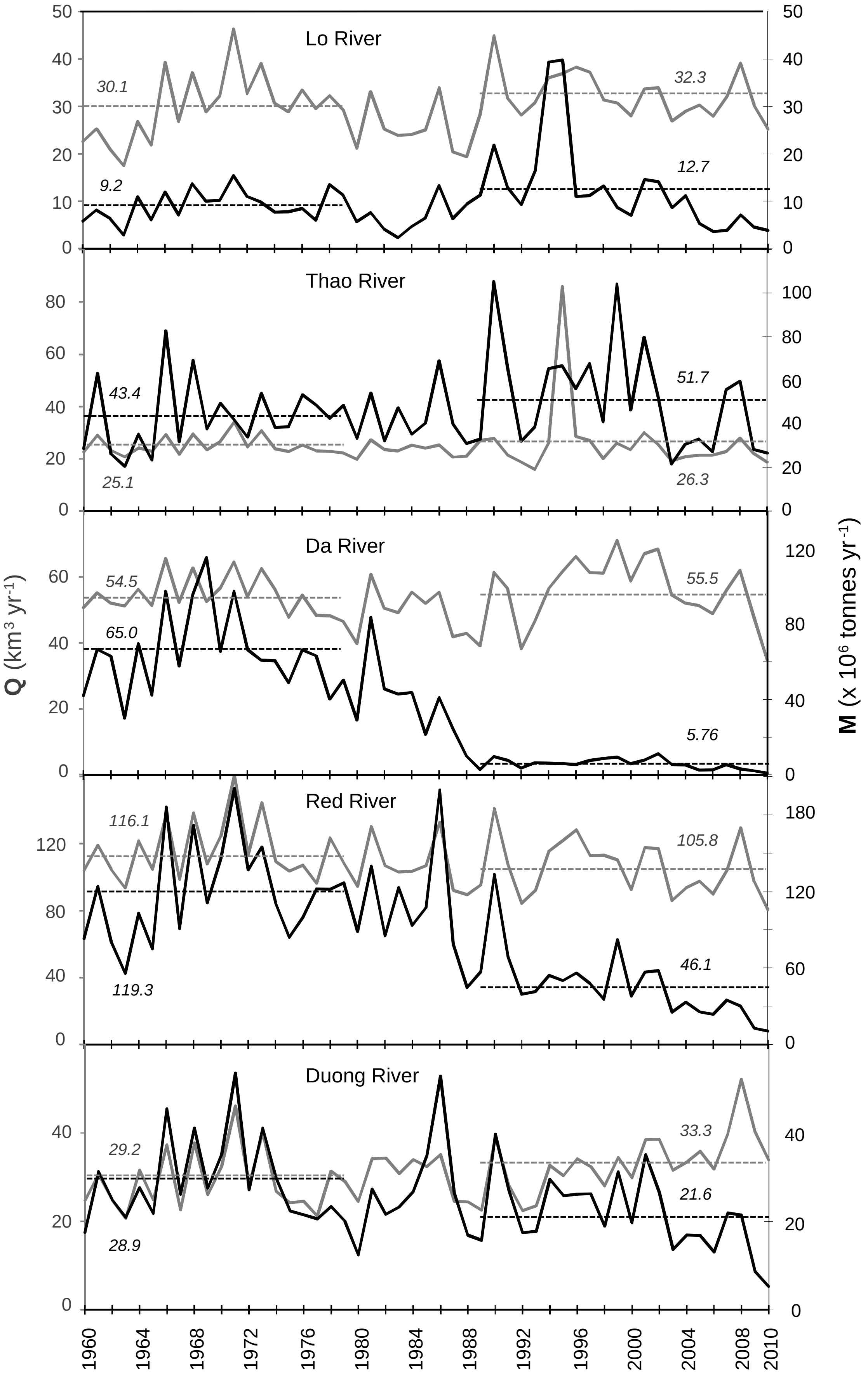
Lo River
30.1
32.3
9.2
12.7
Thao River
43.4
51.7
25.1
26.3
Da River
54.5
55.5
65.0
5.76
Red River
116.1
105.8
119.3
46.1
Duong River
29.2
33.3
28.9
21.6
Q (km³ yr⁻¹)
M (x 10⁶ tonnes yr⁻¹)

FIG. 4

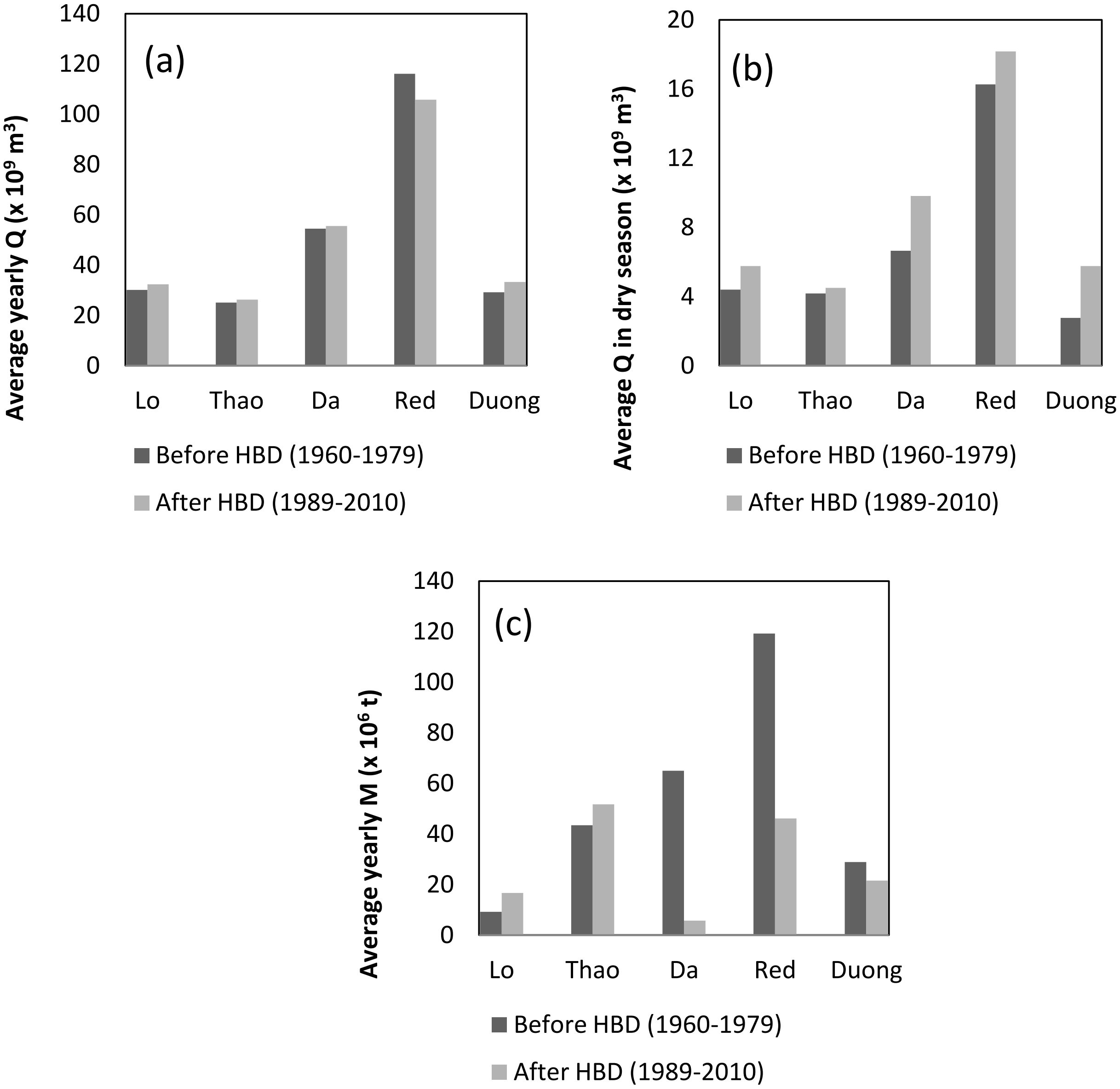
(a)
Average yearly Q (x 10^9 m^3)
140
120
100
80
60
40
20
0
Lo
Thao
Da
Red
Duong
Before HBD (1960-1979)
After HBD (1989-2010)
(b)
Average Q in dry season (x 10^9 m^3)
20
16
12
8
4
0
Lo
Thao
Da
Red
Duong
Before HBD (1960-1979)
After HBD (1989-2010)
(c)
Average yearly M (x 10^6 t)
140
120
100
80
60
40
20
0
Lo
Thao
Da
Red
Duong
Before HBD (1960-1979)
After HBD (1989-2010)

FIG. 5

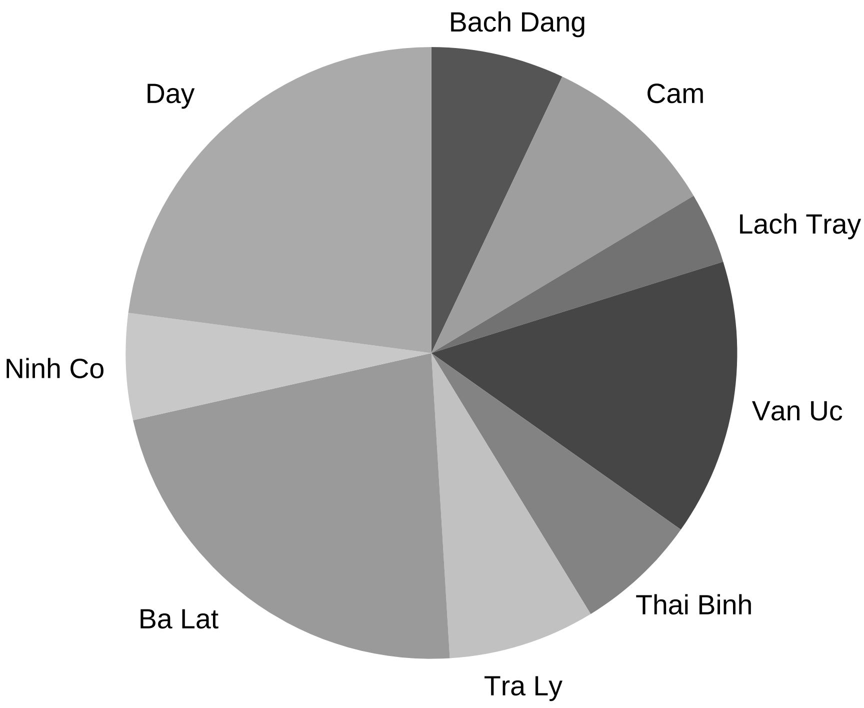
Bach Dang
Cam
Lach Tray
Van Uc
Thai Binh
Tra Ly
Ba Lat
Ninh Co
Day

FIG. 6

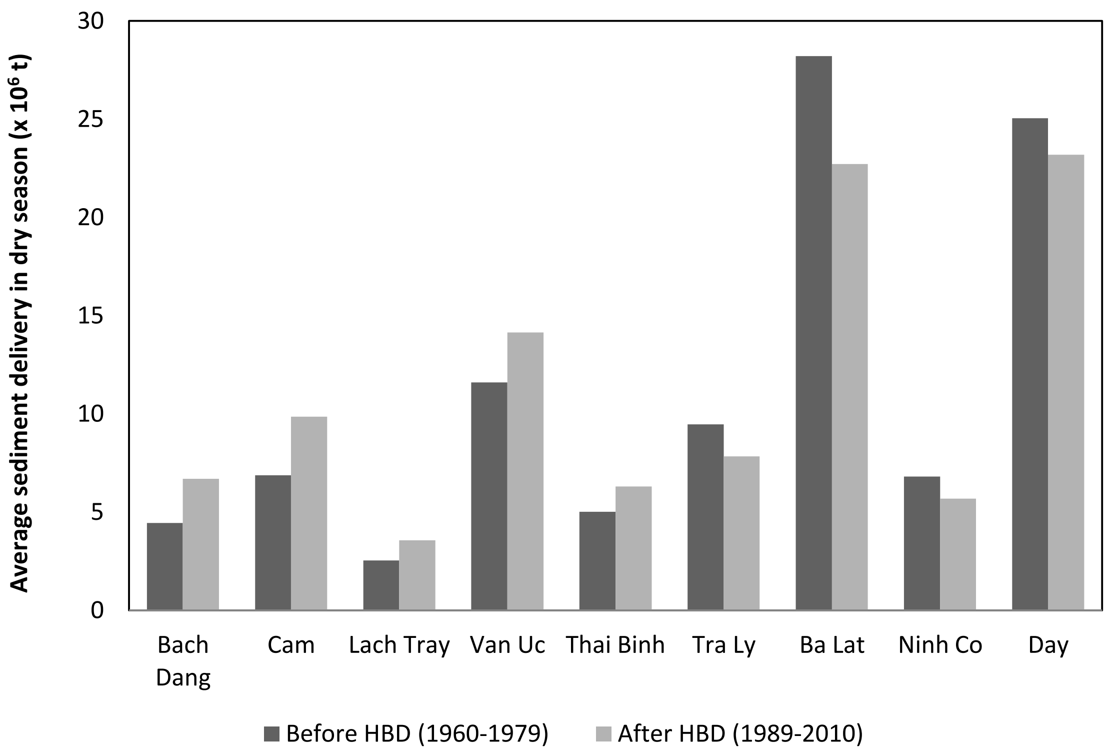
Average sediment delivery in dry season (x 10^6 t)
0
5
10
15
20
25
30
Bach Dang
Cam
Lach Tray
Van Uc
Thai Binh
Tra Ly
Ba Lat
Ninh Co
Day
Before HBD (1960-1979)
After HBD (1989-2010)

FIG. 7