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Discussions

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

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Abstract

The Hoa Binh Dam, located on a tributary of the Red River in Vietnam, has a capacity of 9.45×10^9 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 yr 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 calculated using the MIKE 11 numerical model before and after the dam settlement. Although water discharge at the delta inlet decreased by only 8.8 %, the yearly suspended sediment flux dropped, on average from 119 to 43×10^6 t yr^{-1} at Son Tay near Hanoi, and from 85 to 35×10^6 t yr^{-1} in the river mouths. Water regulation has led to decreased water discharge in the wet season and increased water discharge in the dry season. Suspended sediment discharge proportionally increased in northern and southern estuaries and decreased through the main and central Ba Lat mouth. Tidal pumping, which causes a net sediment flux from the coast to the estuary at low discharge, is high in the northern delta, as a consequence of the high tidal range (up to 4.5 m in spring tide; diurnal tide). The shifts in the dynamic and characteristics of the turbidity maximum zone in the Cam-Bach Dang estuary are probably the cause of the enhanced sediment deposition in the Haiphong harbor. Along the coast, the reduced sedimentation rates are coincident with the lower sediment delivery that has been observed since the impoundment of the Hoa Binh Dam.

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 150×10^6 t yr^{-1} over a 20 yr period in the Yangtze River (Changjiang) (Yang et al., 2006) and from 1200 to 150×10^6 t yr^{-1} over a 40 yr 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 8000–9000 yr 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). 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 160×10^3 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 latter was the main sediment provider to the Red River system, until the building of the Hoa Binh Dam (HBD) in the 1980's (Dang et al., 2010). Before HBD impoundment, the Red River sediment flux was estimated to be $100–160 \times 10^6$ 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 160×10^6 t yr^{-1} the Red River was ranked as the 9th river in terms of sediment flux by Milliman and Meade (1983). Recent studies have shown that the sediment flux drastically decreased to around 40×10^6 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. Despite the decrease in sediment discharge, Haiphong harbor, 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 (10–30 m) 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 completing 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 yr before, 1960–1979, and 22 yr after, 1989–2010). The variability of water and sediment discharge are examined at different time scales (seasonal, interannual) and the impact of HBD is assessed. Discharge and sediment concentration have been continuously measured upstream, but no systematic records exist in the Red River delta, where only water level is available at the hydrological stations. This paper also provides a first estimate of the water and sediment discharge distribution amongst the nine distributaries, for before and after HBD, from numerical simulations and assesses the consequences for the estuaries and coastline morphodynamics.

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2 Regional settings

2.1 Geomorphology

The Red River source is located with a mean elevation of 2000 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 57.2×10^3 km^2 for the Thao River (of which 21 % is in Vietnam), 51.3×10^3 km^2 (52 % in Vietnam) for the Da, and 34.6×10^3 km^2 (64 % in Vietnam) for the Lo. The Da River also originates in the Yunnan province, the elevation of its source being at 2000 m. The source of the Lo River is located in China at an elevation of 1100 m, and joins the main branch at Viet Tri city (Nguyen and Nguyen, 2001). The Red River flows 1200 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 5.9×10^{-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. 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

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mouth, the Tra Ly mouth, the Ba Lat mouth, the Ninh Co (or Lach Giang) mouth, and the Day mouth. 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 yr: 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 sediment discharge of the Song Hong at Son Tay gauging station were 120 $km^3\,yr^{-1}$ and $\sim 120 \times 10^6\,t\,yr^{-1}$, respectively, and the average sediment concentration in the river was $\sim 1\,g\,L^{-1}$, before the HBD impoundment, 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 flowed 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).

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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 0.22×10^6 $t yr^{-1}$ (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 0.12×10^6 $t yr^{-1}$ (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 0.2×10^6 $t yr^{-1}$ (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 Dams

The last four major floods within the return period of 100 yr 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 HBD on the Da River began on 6 November 1979 and ended on 30 December 1988. HBD has a capacity of 9.45×10^9 m^3 of water corresponding to 17.8 % of the annual discharge of the Da River and has an electric power plant of 1920 MW, delivering ~ 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. A second dam, the Son La, located upstream of

HBD, is under construction. The Son La dam has a capacity of 9.26×10^9 m^3 of water, a catchment area of 43.76×10^3 km^2 and will produce 2400 MW of electricity. Construction began in December 2005, it was impounded in May 2010 and it is expected to be commissioned in 2014.

2.5 Tide and tidal influence in the estuaries

The tide in the Gulf of Tonkin is predominantly a diurnal type, 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., 2014). Within the spring-neap 14 days 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. 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 vary by 1 m during the dry season and 0.6 m during the wet season (Luu et al., 2010).

2.6 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 tunnel-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.

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3 Data and methods

3.1 Data

Data used in this paper are daily water discharge (Q) and suspended sediment concentration (SSC) over the 50 yr period from 1960–2010. This time period covers the time before (1960–1979) and after (1989–2010) HBD impoundment (MONRE, 1960–2010). 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. Data on coastal erosion along the RRD from Tran et al. (2001, 2002, 2008) are also used.

3.2 Calculation of water and sediment discharge in upstream rivers

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

$$Q_{y,i} = \sum_{j=1}^{p} Q_{d,i,j} \times 86\,400 \tag{1}$$

$$M_{y,i} = \sum_{j=1}^{p} Q_{d,i,j} \times C_{d,i,j} \times 0.0864 \tag{2}$$

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

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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:

$$Q\ \mathrm{ratio}_k = \frac{Q_k}{\sum_{l=1}^{9} Q_l} \tag{3}$$

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:

$$M\ \mathrm{ratio}_k = \frac{M_k}{\sum_{l=1}^{9} M_l} \tag{4}$$

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 setup 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, 2004). 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,

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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. In order to simulate suspended sediment transport, a module of advection/diffusion of SSC is used in which erosion and deposition are expressed as source/sink terms. This module requires outputs of from the hydrodynamics module, namely water discharge, water level, cross-sectional area and hydraulic radius and calibrated specific parameters.

In order to setup 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. In every calculation the model ran for 32 days for the spin up before the true simulation began.

For calibration and validation purpose, the model was run with actual data, for real situations. For studying the impact of HBD, the model was run for two typical years as defined from the average of daily Q and SSC 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.

3.3.2 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 SSC 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 SSC at these estuarine boundaries was calculated by the model during ebb periods, we chose to fix it at 50 $mg L^{-1}$ during the flood period.

3.3.3 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 was based on the Nash–Sutcliffe efficiency coefficient E (Nash and Sutcliffe, 1970) calculated for each simulation and given by:

$$E = 1 - \frac{\sum(\text{obs}Q - \text{calc}Q)^2}{\sum(\text{obs}Q - \text{mean}Q)^2} \tag{5}$$

in which the sum of the absolute squared differences between the predicted and observed values is normalized by the variance of the observed values during the period under investigation. E varies from 1.0 (perfect fit) to $-\infty$, 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 1000 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

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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 and in the riverbeds) down to 0.02 $m^{-1/3}$ s (downstream and in the main channel).

Stokes' law was used to determine the free settling velocity of the suspended particles in this study. Assuming a low concentration without hindered settling and no flocculation, a settling velocity of 0.2 $mm\,s^{-1}$ was used in our simulations. The critical erosion shear stress 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 deposition shear stress 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 rate of erosion 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 80.5 (in 2010)–160.7 (in 1971) × 10^9 $m^3\,yr^{-1}$ (Fig. 4),

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with an average value of $110.0 \times 10^9\ m^3\ yr^{-1}$. The average annual water discharge was $116.1 \times 10^9\ m^3\ yr^{-1}$ and $105.8 \times 10^9\ m^3\ yr^{-1}$ for the periods 1960–1979 and 1989–2010, respectively (Table 1, Fig. 4).

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). The monthly water discharge of the Da and Red Rivers is highly correlated ($r^2 = 0.902$) as are the Red and Duong Rivers ($r^2 = 0.899$). 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 per tributary after HBD commissioning (Table 1, Fig. 4): 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 8.8 % from 116.1 to $105.8 \times 10^9\ m^3\ yr^{-1}$, that of the Duong River increased by 13.9 %, from 29.2 to $33.3 \times 10^9\ m^3\ yr^{-1}$. In other words, the portion of discharge diverted by the Duong River increased from 24.5 % of the Red River before HBD impoundment, to 31.5 %.

Seasonal variations of Q were high. Rainy season (June to October) water discharge represents 71–79 % of annual total discharge with only 9.4–18 % 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 water distribution of the Da, Red and Duong Rivers. Discharge increased significantly during dry periods post HBD impoundment on the Da River (+47.8 %, Station 3 – see location in Fig. 1), Red River (+11.8 %, Station 4) and Duong River (+109.4 %, Station 5; Table 1). 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 15.2–15.3 % amongst yearly values) and decreased by only 2.8 % for the Duong River, it shown higher variations upstream: from 10.4 to 17.8 % for the Da River, from 23.2 to 14.8 % for the Lo River and from 14.2 to 52.7 % 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, SSC of the Thao River was, on average, 1728 $mg\,L^{-1}$ and was always higher than the mean SSC of the Da and Lo Rivers (1193 and 306 $mg\,L^{-1}$, respectively; Table 2). The SSC of the Red River (at Son Tay) was 1027 $mg\,L^{-1}$. The annual total suspended sediment flux increased both in the Lo River (from $9.2 \times 10^6\,t\,yr^{-1}$ for the period 1960–1979 to $12.7 \times 10^6\,t\,yr^{-1}$ for the period 1989–2010) and Thao River (from $43.4 \times 10^6\,t\,yr^{-1}$ to $51.7 \times 10^6\,t\,yr^{-1}$; Table 1, Fig. 4), whereas sediment discharge and SSC decreased in the Da and Red Rivers.

The HBD impoundment had a strong effect on sediment discharge and SSC in the Da, Red and Duong Rivers. While annual total suspended sediment discharge of Da river was $65.0 \times 10^6\,t\,yr^{-1}$ (about half of the total supply to the Red River delta) before HBD impoundment, it dropped to $5.8 \times 10^6\,t\,yr^{-1}$ after (–91.1 %). This is equivalent to only 7.8 % of the cumulated contributions from Da, Lo and Thao Rivers (Table 1, Fig. 4). At the Hoa Binh gauging station, the annual average SSC decreased from 1193 $mg\,L^{-1}$ to 105.7 $mg\,L^{-1}$. As a consequence, annual total suspended sediment of the Red River at Son Tay which averaged $119.3 \times 10^6\,t\,yr^{-1}$ before the HBD was reduced to $46.1 \times 10^6\,t\,yr^{-1}$ after the impoundment (–61.3 %; see Table 1, Fig. 4), corresponding to a decrease in the average SSC from 1027 to 397 $mg\,L^{-1}$ (Table 2). At Thuong Cat on the Duong River, the annual total suspended sediment which averaged $28.9 \times 10^6\,t\,yr^{-1}$ before the HBD was also reduced to $21.6 \times 10^6\,t\,yr^{-1}$ after (–17.3 %;

see Table 1, Fig. 4), and the average SSC decreased by 25.4 %, 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 0.46×10^6 $t yr^{-1}$ to 0.74×10^6 $t yr^{-1}$ (Table 1).

The seasonal variability of SSC 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 SSC was the highest in the Da River (111.9 %) before HBD impoundment and dropped to 70 % after, it remained quite 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 SSC 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 32.2 % (Red River at Son Tay) and 36.3 % (Thao River) before HBD impoundment, they had much higher differences after impoundment and varied from 38.8 % in the Duong River to 77.4 % 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 56.0×10^6 t in 1963 and 201.0×10^6 t in 1971 before HBD impoundment and between 10.4×10^6 t in 2010 and 133.6×10^6 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). 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. It also increased in the Day River, at the south of the delta, from 22.1 to 23 %. Conversely, this value 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 $10.2 \times 10^9\ m^3\ yr^{-1}$ between 1960–1979 and 1989–2010 (from 130.5 to $120.3 \times 10^9\ m^3\ yr^{-1}$, 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 slightly from 17.8 to $20.8 \times 10^9\ m^3$ during the dry season, while it decreased from 98.8 to $85.2 \times 10^9\ m^3$ during the rainy season (Table 3). This lower variability of water discharge is mainly a consequence of water regulation by the HBD.

The decrease of suspended 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 2.6×10^6 t to 1.7×10^6 t for the dry season, and from 77.3×10^6 t to 30.5×10^6 t for the rainy season (Table 4). As a result, the total average annual suspended sediment discharge decreased by 58.6 % after 1989 from 84.8 to $35.1 \times 10^6\ t\,yr^{-1}$. 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 Cam-Bach Dang estuary in dry season due to an increase in river discharge (Table 4).

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5 Discussion and conclusion

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 $116.1 \times 10^9\ m^3\ yr^{-1}$ or $3678\ m^3\ s^{-1}$ for the period 1960–1979 and of $105.8 \times 10^9\ m^3\ yr^{-1}$ or $3353\ m^3\ s^{-1}$ 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 of the determinations are based on data provided by the same administration.

The value of 31.5 % of water diverted by the Duong River and calculated over 22 yr is in very good agreement with the former estimate over 11 yr (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 47.7 % in the dry season in the Da River (at Hoa Binh station), by 11.8 % in the Red River (at Son Tay) and by 109 % in the Duong River (at Thuong Cat).

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 $116 \times 10^6\ t\ yr^{-1}$. 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 and Thai Binh), and for the Tra Ly as well (10 % by Pruszak et al., 2005, vs. 8.4 % in our calculation). The estimates for the Ba Lat, Ninh Co and Day estuaries are the same and represent ~ 25, ~ 6 and ~ 22 %, respectively. Our value for Ba Lat is also consistent with that of van Maren and 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 yr. 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.

The present calculations show that water distribution was affected by the impoundment of the HBD. While the water ratio of the northern estuaries (Bach Dang, Cam, Lach Tray, Van Uc and Thai Binh) increased from 38.6 to 41.1 % after 1989, it decreased at the Ba Lat mouth from 24.9 to 22.5 %. The total water discharge from the estuaries increased by 17.0 % in the dry season and decreased by 13.7 % in the rainy season after the HBD impoundment, due to water regulation.

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 SSC at the Manhao station during the 1960s, 1970s, 1980s and 1990s where values of 1870, 2490, 3120, 3630 $\mathrm{mg\,L^{-1}}$, 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 ($119 \times 10^6\ \mathrm{t\,yr^{-1}}$) 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 $160 \times 10^6\ \mathrm{t\,yr^{-1}}$, with a very close estimate ($116 \times 10^6\ \mathrm{t\,yr^{-1}}$) given by Pruszak et al. (2005). The value calculated for 1989–2010 ($46 \times 10^6\ \mathrm{t\,yr^{-1}}$) is also very close to the value calculated by Dang et al. (2010) ($49 \times 10^6\ \mathrm{t\,yr^{-1}}$) for the period 1979–2008. The interannual variability of sediment transport in Hanoi was higher over the period 1960–1979 (56–$201 \times 10^6\ \mathrm{t\,yr^{-1}}$) than during 1989–2010 (10–$134 \times 10^6\ \mathrm{t\,yr^{-1}}$). This latter range is consistent with the range estimate of between 30 and 120×10^6 t as quoted by van den Bergh et al. (2007b), although we found a smaller lower limit due to the recent lower sediment discharge ($24.5 \times 10^6\ \mathrm{t\,yr^{-1}}$ for 2003–2010; see Fig. 4).

After the HBD impoundment, average daily SSC decreased from 1193 mg L^{-1} to 105.7 mg L^{-1} at Hoa Binh (Da River) and from 1027 mg L^{-1} to 397.4 mg L^{-1} at the Son Tay Station on the Red River. The annual total suspended sediment discharge, which was 65×10^6 t yr^{-1} in the Da River and represented about half of the total supply to Red River, decreased to 5.8×10^6 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 t (about 58.6 %). If we consider the period 1989–2010, 50 % of the sediment brought by the Lo, Thao and Da rivers is lost in the delta. Between Hanoi and the sea, 11×10^6 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. However, it is consistent with the value of 70 % of sediment delivered to the sea as estimated by Häglund and Svensson (2002).

The increase of the suspended sediment discharge ratio in the northern and southern estuaries and its decrease at the Ba Lat mouth 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).

By limiting flow during floods, the HBD regulation decreased sediment transport capacity of the rivers 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).

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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 middle and lower estuaries, deposition is mainly driven by the dynamics of the turbidity maximum zone (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 sediment deposition induced by tidal pumping in the Cam-Bach Dang estuary 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). Tidal pumping occurs when river discharge is low enough that marine water flows into the estuary during flood and high enough so that the tidal cycle shows a strong velocity asymmetry, with a short but highly energetic flood period. The observed slight increases of river discharge during the dry season after the impoundment of the HBD likely enhanced the tidal asymmetry and the associated tidal pumping (Allen et al., 1980; Dyer, 1986). 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 there much higher (Uncles et al., 2002). Other forcing factors also modify tidal pumping. Flocculation of estuarine suspended particulate matter is strongly dependent on the suspended sediment concentration, especially in low energetic episodes (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). The changes of Q, turbulence and SSC variability caused by dam regulation and to dam retention displaced the turbidity maximum zone and changed its characteristics, such as its seasonal trajectory and the volume of fluid mud. In the Cam-Bach estuary, it is probably a major feature of the recent increase of sediment deposition in the middle and lower estuary.

It is not possible to test this hypothesis using hydro-sedimentary studies due to the lack of data available prior to the HBD impoundment. However, the recent changes in the volume of sediment dredged from the Cam-Bach Dang estuary illustrate the enhanced silting up of the estuarine harbour of Hai Phong. This increase in silting is probably due to the general decrease of river capacity of sediment transport or to the modified dynamics of the turbidity maximum, both of which are directly related to the regulation of water flow by HBD. The dredged volume of sediment in the port of Hai Phong in 1922, 1983, 1992 was 922.6, 1256 and 1700×10^3 m^3, respectively. This is compared to about the $4–5 \times 10^6$ t of sediments annually dredged from the port in order to guarantee the port activities today (Vietnam Administration of Hai Phong, unpublished). During the last geological period, the Van Uc, Thai Binh, Tra Ly and Ba Lat mouths also 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 propagation 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 $m\,yr^{-1}$ 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 20th century with a decrease in erosion rate during the late 1960s. 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 10 m 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 20 m 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 SSC on water depths < 5 m, 5–10, 10–15, 15–20, 20–25, 30–35 m 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 SSC on water depths < 5 m, 5–10 m, 10–15 m 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 15 m in the north and up to 10 m in front of the central delta, where morphologic changes are driven by wave action more than by tidal asymmetry (van Maren et al., 2004).

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. In summary, from its impoundment, Hoa Binh Dam has played a considerable role in flood control, irrigation and electricity production in North Vietnam. However, it also significantly affected water discharge and the suspended sediment input from the Red River basin to the delta and coastal areas. 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 the decrease in sediment transport 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. Finally, this work underlines the need for an integrated management plan that extends from the river basin to the coastal zone

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and that involves the close collaboration of hydrologists, coastal oceanographers, and decision makers.

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References

Achite, M. and Ouillon, S.: Suspended sediment transport in a semiarid watershed, Wadi Abd, Algeria (1973–1995), J. Hydrol., 343, 187–202, 2007.

Allen, G. P., Salomon, J. C., Bassoulet, P., du Penhoat, Y., and de Grandpre, C.: Effects of tides on mixing and suspended sediment transport in macrotidal estuaries, Sediment. Geol., 26, 69–90, 1980.

Bui, V. V., Liu, Z. F., Tran, D. T., Tran, D. L., Chih-Anh, H., Tuo, S., Nguyen, H. C., Dang, H. N., Nguyen, V. Q., and Dinh, V. H.: Sedimentation Rate and Geochronology of Sediments in the Nearshore Zone of the Red River Delta: Evidence from the ^{210}Pb and ^{137}Cs Radiotracer, Mar. Res. Env., Tome XVII, Publishing House for Science and Technology, Hanoi, 59–70, 2012 (in Vietnamese).

Chow, V. T.: Open Channel Hydraulics, McGraw-Hill Book Co., New York, NY, 680 pp., 1959.

Dang, T. H., Coynel, A., Orange, D., Blanc, G., Etcheber, H., and Le, L. A.: Long-term monitoring (1960–2008) of the river-sediment transport in the Red River Watershed (Vietnam): temporal variability and dam-reservoir impact, Sci. Total Environ., 408, 4654–4664, 2010.

DHI: A Modeling System for Rivers and Channels, MIKE11 Reference Manual, Horsholm, Denmark, 2004.

Do, M. D., Mai, T. N., Chu, V. N., Tran, N., Dao, M. T., van Weering, T. C. E., and van den Bergh, G. D.: Sediment distribution and transport at the nearshore zone of the Red River delta, Northern Vietnam, J. Asian Earth Sci., 29, 558–565, 2007.

Do, M. D., Mai, T. N., and Chu, V. N.: An analysis of coastal erosion in the tropical rapid accretion delta of the Red River, Vietnam, J. Asian Earth Sci., 43, 98–109, 2012.

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11, 333–370, 2014

Dronkers, J.: Tide-induced residual transport of fine sediment, in: Physics of Shallow Estuaries and Bays, edited by: van de Kreeke, J., Lecture Notes Coast. Estuar. Studies, Vol. 16, Springer, Berlin, 228–244, 1986.

Dyer, K. R.: Coastal and Estuarine Sediment Dynamics, Wiley, Chichester, 342 pp., 1986.

Fang, G., Kwok, Y. K., Yu, K., and Zhu, Y.: Numerical simulation of principal tidal constituents in the South China Sea, Gulf of Tonkin and Gulf of Thailand, Cont. Shelf Res., 19, 845–869, 1999.

Farnsworth, K. L. and Milliman, J. D.: Effects of climate and anthropogenic change on small mountaneous rivers: Salinas River example, Global Planet. Change, 39, 53–64, 2003.

General Department of Land Administration: Vietnam National Atlas, Hanoi, 163 pp., 1996.

Gourou, P.: Les Paysans du Delta Tonkinois, Mouton & Co, Paris, 1936.

Häglund, M. and Svensson, P.: Coastal erosion at Hai Hau beach in the Red River delta, Vietnam, Msc. thesis, Lund University, Lund, Sweden, 80 pp., 2002.

He, D. M., Ren, J., Fu, K. D., and Li, Y. G.: Sediment change under climate changes and human activities in the Yuanjiang-Red River Basin, Chinese Sci. Bull., 52, 164–171, 2007.

Hori, K., Tanabe, S., Saito, Y., Haruyama, S., Nguyen, V., and Kitamura, A.: Delta initiation and Holocene sea-level change: example from the Song Hong (Red River) delta, Vietnam, Sediment. Geol., 164, 237– 249, 2004.

Krause, P., Boyle, D. P., and Bäse, F.: Comparison of different efficiency criteria for hydrological model assessment, Adv. Geosci., 5, 89–97, doi:10.5194/adgeo-5-89-2005, 2005.

Nguyen, H. K. and Nguyen, V. T.: Geography and Hydrology in Vietnam, Vietnam Nat. Univ. publ., Hanoi, Vietnam, 194 pp., 2001.

Le, T. P. Q., Billen, G., Garnier, J., Théry, S., Fézard, C., and Chau, V. M.: Nutrient (N, P) budgets for the Red River basin (Vietnam and China), Global Biogeochem. Cy., 19, 1–16, 2005.

Le, T. P. Q., Garnier, J., Billen, G., Théry, S., and Chau, V. M.: The changing flow regime and sediment load of the Red River, Viet Nam, J. Hydrol., 334, 199–214, 2007.

Lefebvre, J. P., Ouillon, S., Vu, D. V., Arfi, R., Panche, J. Y., Mari, X., Chu, V. T., and Torréton, J. P.: Seasonal variability of cohesive sediment aggregation in the Bach Dang-Cam Estuary, Haiphong (Vietnam), Geo-Mar. Lett., 32, 103–121, 2012.

Luu, T. N. M., Garnier, J., Billen, G., Orange, D., Némery, J., Le, T. P. Q., Tran, H. T., and Le, L. A.: Hydrological regime and water budget of the Red River Delta (Northern Vietnam), J. Asian Earth Sci., 37, 219–228, 2010.

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11, 333–370, 2014

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D V. Vu et al.

Mari, X., Torréton, J. P., Chu, V. T., Lefebvre, J. P., and Ouillon, S.: Seasonal aggregation dynamics along a salinity gradient in the Bach Dang estuary, North Vietnam, Estuar. Coast. Shelf S., 96, 151–158, 2012.
Mathers, S. J. and Zalasiewicz, J. A.: Holocene sedimentary architecture of the Red River delta, Vietnam, J. Coastal Res., 15, 314–325, 1999.
Mathers, S. J., Davies, J., McDonald, A., Zalasiewicz, J. A., and Marsh, S.: The Red River delta of Vietnam, British Geological Survey Technical Report WC/96/02, Keyworth, UK, 41 pp., 1996.
Milliman, J. D. and Syvitski, J. P. M.: Geomorphotectonic control of sediment discharge to the oceans: the importance of small mountain rivers, J. Geol., 100, 525–544, 1992.
Milliman, J. D., Rutkowski, C., and Meybeck, M.: River Discharge to the Sea: a Global River Index, LOICZ Core Project Office, Texel, the Netherlands, 125 pp., 1995.
Nash, J. E. and Sutcliffe, J. V.: River flow forecasting through conceptual models, Part I – a discussion of principles, J. Hydrol., 10, 282–290, 1970.
Nguyen, N. M., Marchesiello, P., Lyard, F., Ouillon, S., Cambon, G., Allain, D., and Dinh, V. U.: Tidal characteristics of the Gulf of Tonkin, Cont. Shelf Res., in revision, 2014.
Ouillon, S.: Erosion and sediment transport: width and stakes, La Houille Blanche, 53, 52–58, 1998.
Ouillon, S. and Le Guennec, B.: Modelling non-cohesive suspended sediment transport in 2-D vertical free surface flows, J. Hydraul. Res., 34, 219–236, 1996.
Navarro, P., Amouroux, D., Duong, T. N., Rochelle-Newall, E., Ouillon, S., Arfi, R., Chu, V. T., Mari, X., and Torréton, J. P.: Butyltin and mercury compounds fate and tidal transport in waters of the tropical Bach Dang estuary (Haiphong, Vietnam), Mar. Pollut. Bull., 64, 1789–1798, 2012.
Nguyen, V. P.: Streams in Vietnam, Science Publishing House, Hanoi, 209 pp., 1984 (in Vietnamese).
Nguyen, V. P., Vu, V. T., and Tran, T. X.: Water resources in Vietnam, Vietnamese Institute of Meteo-hydrologie, Agricultural Editor, Hanoi, Vietnam, 2003 (in Vietnamese).
Pruszak, Z., Szmytkiewicz, M., Nguyen, M. H., and Pham, V. N.: Coastal processes in the Red River delta area, Vietnam, Coast. Eng. J., 44, 97–126, 2002.
Pruszak, Z., Pham, V. N., Szmytkiewicz, M., Nguyen, M. H., and Ostrowski, R.: Hydrology and morphology of two river mouth regions (temperate Vistula Delta and subtropical Red River Delta), Oceanologia, 47, 365–385, 2005.

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11, 333–370, 2014
Impact of the Hoa Binh Dam
D V. Vu et al.

Rochelle-Newall, E., Chu, V. T., Pringault, O., Amouroux, D., Arfi, R., Bettarel, Y., Bouvier, T., Bouvier, C., Got, P., Nguyen, T. M. H., Mari, X., Navarro, P., Duong, T. N., Cao, T. T. T., Pham, T. T., Ouillon, S., and Torréton, J. P.: Phytoplankton diversity and productivity in a highly turbid, tropical coastal system (Bach Dang Estuary, Vietnam), Mar. Pollut. Bull., 62, 2317–2329, 2011.

Saito, Y., Chaimanee, N., Jarupongsakul, T., and Syvitski, J. P. M.: Shrinking megadeltas in Asia: sea-level rise and sediment reduction impacts from case study of the Chao Phraya delta, Newsletter of the IGBP/IHDP Land Ocean Interaction in the Coastal Zone, 2007/2, 3–9, 2007.

Sottolichio, A., Le Hir, P., and Castaing, P.: Modeling mechanisms for the turbidity maximum stability in the Gironde estuary, France, in: Coastal and Estuarine Fine Sediment Processes, edited by: McAnally, W. H., and Mehta, A. J., Proc. Mar. Sci., Elsevier, Amsterdam, 373–386, 2001.

Syvitski, J. P. M. and Saito, Y.: Morphodynamics of deltas under the influence of humans, Global Planet. Change, 57, 261–282, 2007.

Syvitski, J. P. M., Vörösmarty, C., Kettner, A. J., and Green, P.: Impact of humans on the flux of terrestrial sediment to the global coastal ocean, Science, 308, 376–380, 2005.

Tanabe, S., Hori, K., Saito, Y., Haruyama, S., Vu, V. P., and Kitamura, A.: Song Hong (Red River) delta evolution related to millennium-scale Holocene sea-level changes, Quaternary Sci. Rev., 22, 2345–2361, 2003.

Tanabe, S., Saito, Y., Vu, Q. L., Hanebuth, T. J. J., Kitamura, A., and Ngo, Q. T.: Holocene evolution of the Song Hong (Red River) delta system, Northern Vietnam, Sediment. Geol., 187, 29–61, 2005.

To, T. N.: Flood control planning for the Red River Basin, in: Proceedings of the International European–Asian Workshop: Ecosystem & Flood 2000, Hanoi, Vietnam, 27–29 June, available at: http://www.rrbo.org.vn/defaulte.aspx?tabid=426&ItemID=1153, 2000.

Tran, D. T., Nguyen, D. C., Nguyen, H. C., and Do, D. C.: The study, predict and prevent coast erosion of Quang Ninh to Thanh Hoa, Report of KHCN-5A project, Institute of Marine Environment and Resources, Hai Phong, Vietnam, 2001 (in Vietnamese).

Tran, D. T., Dinh, V. H., Nguyen, V. L., Ta, T. K. O., Tateishi, M., and Saito, Y.: The impact of human activities on Vietnamese rivers and coasts, LOICZ reports and Studies No. 26, LOICZ, Texel, Netherlands, 179–184, 2002.

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Tran, D. T., Saito, Y., Dinh, V. H., Nguyen, V. L., and Ta, T. K. O.: Regimes of human and climate impacts on coastal changes in Vietnam, Reg. Environ. Change, 4, 49–62, 2004.
Tran, D. T., Vu, D. V., Saito, Y., Do, D. C., and Tran, A. T.: An initial estimation on the effects of Hoa Binh hydropower dam on the coastal sedimentary environment in red river delta, J. Mar. Sci. Technol., 3, 1–17, 2008.
Uncles, R. J., Elliott, R. C. A., and Weston, S. A.: Observed fluxes of water, salt and suspended sediment in a partly mixed estuary, Estuar. Coast. Shelf S., 20, 147–167, 1985.
Uncles, R. J., Stephens, J. A., and Smith, R. E.: The dependence of estuarine turbidity on tidal intrusion length, tidal range and residence time, Cont. Shelf Res., 22, 1835–1856, 2002.
van den Bergh, G. D., Boer, W., Schaapveld, M. A. S., Do, M. D., van Weering, T. C. E.: Recent sedimentation and sediment accumulation rates of the Ba Lat, prodelta (Red River, Viet Nam), J. Asian Earth Sci., 29, 545–557, 2007a.
van den Bergh, G. D., van Weering, T. C. E., Boels, J. F., Do, M. D., and Nhuan, M. N.: Acoustical facies analysis at the Ba lat delta Front (Red River Delta, North Vietnam), J. Asian Earth Sci., 29, 535–544, 2007b.
van Maren, D. S.: Morphodynamics of a cyclic prograding delta: the Red River, Vietnam, Ph.D. thesis, Utrecht University, Netherlands Geographical Studies 324, Utrecht, 167 pp., 2004.
van Maren, D. S.: Water and sediment dynamics in the Red River mouth and adjacent coastal zone, J. Asian Earth Sci., 29, 508–522, 2007.
van Maren, D. S. and Hoekstra, P.: Seasonal variation of hydrodynamics and sediment dynamics in a shallow subtropical estuary: the Ba lat River, Vietnam, Estuar. Coast. Shelf S., 60, 529–540, 2004.
van Maren, D. S., Hoekstra, P., and Hoitink, A. J. F.: Tidal flow asymmetry in the diurnal regime: bed-load transport and morphologic changes around the Red River delta, Ocean Dynam., 54, 424–434, 2004.
van Rijn, L. C.: Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas, Aqua Publications, Amsterdam, the Netherlands, 2005.
Verney, R., Lafite, R., and Brun-Cottan, J. C.: Flocculation potential of estuarine particles: the importance of environmental factors and of the spatial and seasonal variability of suspended particulate matter, Estuar. Coast., 32, 678–693, 2009.
Vu, D. V., Nguyen, D. C., and Tran, D. T.: The impact of Hoa Binh Dam on distribution of suspended sediment in coastal areas of red river delta, Proc. 5th Nat. Conf. Mar. Sci. Techn., Hanoi, Vietnam, 20–21 October 2011, 3, 465–474, 2011.

Vörösmarty, C. J., Meybeck, M., Fekete, B., Sharma, K., Green, P., and Syvitski, J. P. M.: Anthropogenic sediment retention: major global impact from registered river impoundments, Global Planet. Change, 39, 169–190, 2003.
Wang, H. J., Yang, Z. S., Saito, Y., Liu, J. P., and Sun, X.: Interannual and seasonal variation of the Huanghe (Yellow River) water discharge over the past 50 yr: connections to impacts from ENSO events and dams, Global Planet. Change, 50, 212–225, 2006.
Wang, H. J., Yang, Z. S., Saito, Y., Liu, J. P., Sun, X., and Wang, Y.: Stepwise decreases of the Huanghe (Yellow River) sediment load (1950–2005): impacts of climate changes and human activities, Global Planet. Change, 57, 331–354, 2007.
Wang, H. J., Yang, Z. S., Wang, Y., Saito, Y., and Liu, J. P.: Reconstruction of sediment flux from the Changjiang (Yangtze River) to the sea since the 1860s, J. Hydrology, 349, 318–332, 2008.
Yang, Z., Wang, H., Saito, Y., Milliman, J. D., Xu, K., Qiao, S., and Shi, G.: Dam impacts on the Changjiang (Yangtze River) sediment discharge to the sea: the past 55 yr and after the Three Gorges Dam, Water Resour. Res., 42, W04407, doi:10.1029/2005WR003970, 2006.

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Table 1. Average water and suspended sediment fluxes measured 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).

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 ($\times 10^9$ m^3)	4.40	22.14	30.08	5.77	22.91	32.34
		M ($\times 10^6$ t)	0.18	8.33	9.22	0.35	11.62	12.68
Thao	2	Q ($\times 10^9$ m^3)	4.18	17.92	25.14	4.50	18.54	26.29
		M ($\times 10^6$ t)	1.95	38.66	43.45	1.40	46.43	51.74
Da	3	Q ($\times 10^9$ m^3)	6.64	42.82	54.49	9.81	39.48	55.54
		M ($\times 10^6$ t)	0.64	62.36	64.98	0.33	5.17	5.76
Red	4	Q ($\times 10^9$ m^3)	16.26	86.91	116.08	18.18	75.18	105.80
		M ($\times 10^6$ t)	3.27	108.55	119.26	1.91	40.32	46.13
Duong	5	Q ($\times 10^9$ m^3)	2.76	22.28	29.25	5.77	23.58	33.33
		M ($\times 10^6$ t)	0.46	26.07	28.93	0.74	19.17	21.57

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

River	Period	Monthly averages													Annual
		1	2	3	4	5	6	7	8	9	10	11	12	CV (%)	average
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	92.2	306.5
	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	88.1	421.4
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	80.2	1728.5
	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	77.5	2058.2
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	111.9	1192.7
	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	70.0	105.7
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	74.0	1027.4
	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	68.3	397.4
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	79.6	989.2
	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	72.8	737.6

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Table 3. Average water discharge in the nine distributaries of the Red River 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).

River mouth	Water delivery	before Hoa Binh Dam (1960–1979)			after Hoa Binh Dam (1989–2010)			P[a] (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 ($\times 10^9$ m^3)	0.79	6.39	7.96	1.39	6.00	8.37			
	Q ratio (%)	4.45	6.47	6.10	6.69	7.04	6.96			
Cam	Q ($\times 10^9$ m^3)	1.22	9.84	12.25	2.05	7.98	11.47			
	Q ratio (%)	6.87	9.96	9.39	9.87	9.36	9.54			
Lach Tray	Q ($\times 10^9$ m^3)	0.45	3.67	4.57	0.74	3.21	4.48			
	Q ratio (%)	2.53	3.72	3.50	3.56	3.77	3.72			
Van Uc	Q ($\times 10^9$ m^3)	2.06	13.89	17.76	2.94	12.46	17.45			
	Q ratio (%)	11.60	14.06	13.61	14.15	14.62	14.51			
Sub-Total NE	Q ratio (%)	25.45	34.21	32.60	34.26	34.79	34.73	26.0	34.6	26.1
Thai Binh	Q ($\times 10^9$ m^3)	0.89	6.16	7.84	1.31	5.54	7.75			
	Q ratio (%)	5.01	6.24	6.01	6.30	6.50	6.44	11.0		
Tra Ly	Q ($\times 10^9$ m^3)	1.68	8.04	10.94	1.63	6.60	9.33			
	Q ratio (%)	9.46	8.14	8.38	7.84	7.74	7.76	10.0		
Ba Lat	Q ($\times 10^9$ m^3)	5.01	23.85	32.5	4.72	19.11	27.03			
	Q ratio (%)	28.21	24.15	24.90	22.71	22.42	22.47	25.0		
Ninh Co	Q ($\times 10^9$ m^3)	1.21	5.76	7.84	1.18	4.79	6.78			
	Q ratio (%)	6.81	5.83	6.01	5.68	5.62	5.64	6.0		
Sub-Total Center	Q (%)	49.49	44.36	45.30	42.54	42.29	42.31	52.0	44.7	56.7
Day	Q ($\times 10^9$ m^3)	4.45	21.16	28.84	4.82	19.53	27.62			
	Q ratio (%)	25.06	21.43	22.10	23.20	22.92	22.96	22.0	20.8	17.2
Total	Q ($\times 10^9$ m^3)	17.76	98.76	130.50	20.78	85.22	120.28			

[a] Pruszak et al. (2005).

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Table 4. Average suspended sediment fluxes in the nine distributaries of the Red River 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 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 (× 10^6 t)	0.09	4.81	5.16	0.11	2.10	2.43
	M ratio (%)	3.45	6.23	6.08	6.63	6.88	6.92
Cam	M (× 10^6 t)	0.14	7.43	7.96	0.17	3.10	3.57
	M ratio (%)	5.36	9.62	9.38	10.24	10.16	10.16
Lach Tray	M (× 10^6 t)	0.06	2.79	2.99	0.07	1.13	1.30
	M ratio (%)	2.30	3.61	3.52	4.22	3.70	3.70
Van Uc	M (× 10^6 t)	0.28	10.65	11.54	0.24	4.40	5.07
	M ratio (%)	10.73	13.78	13.60	14.46	14.42	14.43
Thai Binh	M (× 10^6 t)	0.12	4.72	5.10	0.10	1.95	2.24
	M ratio (%)	4.60	6.11	6.01	6.02	6.39	6.37
Tra Ly	M (× 10^6 t)	0.26	6.40	7.12	0.13	2.35	2.70
	M ratio (%)	9.96	8.28	8.39	7.83	7.70	7.68
Ba Lat	M (× 10^6 t)	0.78	19.00	21.12	0.37	6.81	7.84
	M ratio (%)	29.89	24.59	24.89	22.29	22.31	22.31
Ninh Co	M (× 10^6 t)	0.19	4.59	5.10	0.09	1.71	1.97
	M ratio (%)	7.28	5.94	6.01	5.42	5.60	5.61
Day	M (× 10^6 t)	0.69	16.87	18.76	0.38	6.97	8.02
	M ratio (%)	26.44	21.84	22.11	22.89	22.84	22.82
Total	M (× 10^6 t)	2.61	77.26	84.85	1.66	30.52	35.14

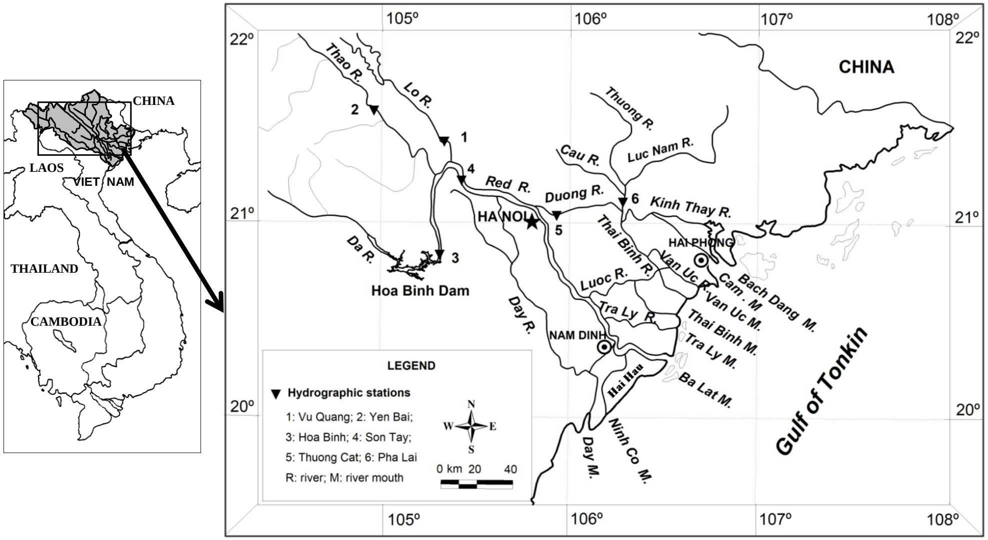

Fig. 1. Red River system and the Red River coastal area.

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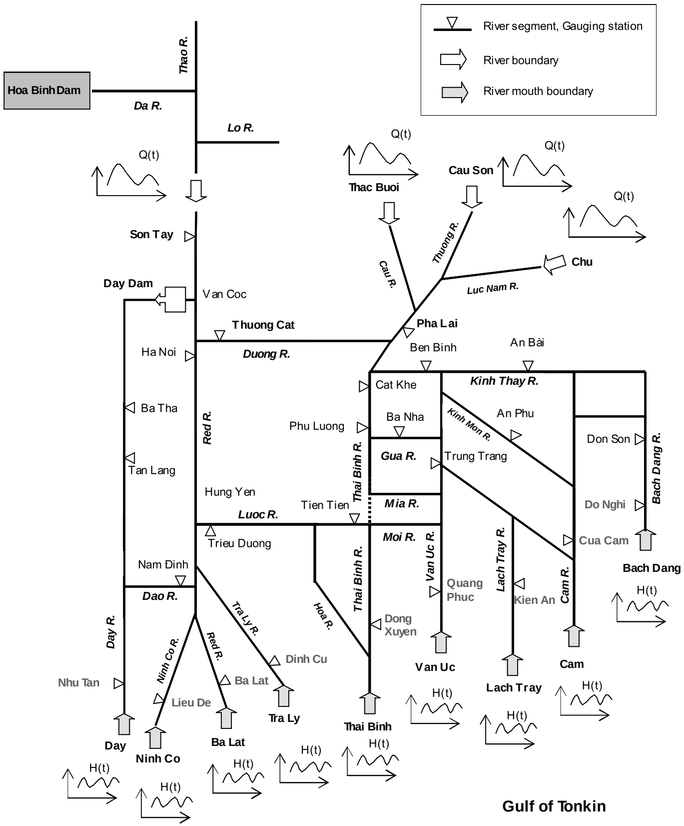

Fig. 2. Diagram of the network considered in the Red River delta for the MIKE 11 model.

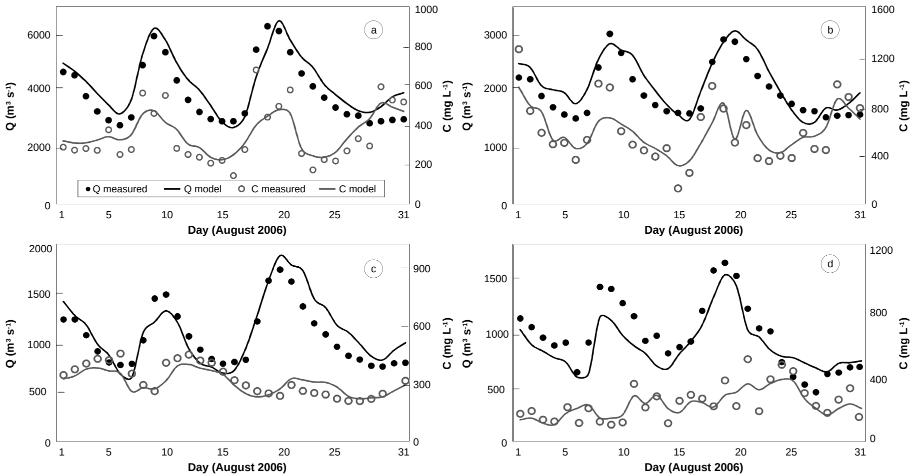

Fig. 3. Comparison of modeled and measured water discharge (*Q*) and suspended sediment concentration (*C*) in August 2006 (**a** – Hanoi; **b** – Thuong Cat; **c** – Nam Dinh; **d** – Cua Cam) after calibration of the model.

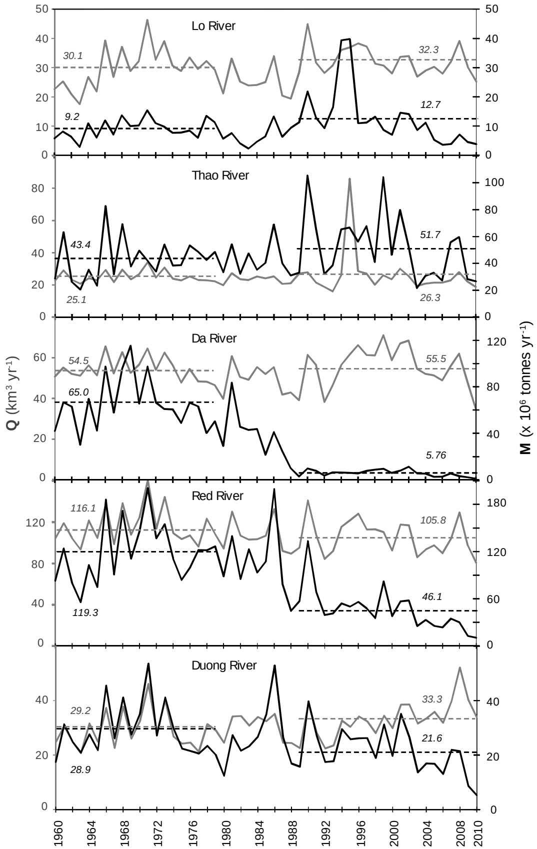

Fig. 4. Annual water and sediment discharge in the main tributaries of the Red River system (1960–2010), and average values before and after Hoa Binh Dam impoundment.