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RIVER HYDROLOGY AND SUSPENDED SEDIMENT FLUX IN THE RED RIVER SYSTEM: IMPLICATION FOR ASSESSING SOIL EROSION AND SEDIMENT TRANSPORT/DEPOSITION PROCESSES

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ABSTRACT

Based on a database of daily water discharge and daily suspended particulate matter concentrations along the Red River and at the outlet of the main tributaries (Da and Lo) during the 2005 - 2010 period, covering contrasting hydrological conditions, the water and sediment fluxes transported by the Red River system were determined. The results showed that only 21 % of the discharge is derived from the upper Red River, 54 % and 25 % being derived from the Da and the Lo Rivers, respectively. In contrast, the distribution of suspended particulate matter (SPM) load is very different of that observed for water discharge: most SPM were eroded from the upstream catchment located in China (78 %). Moreover, annual SPM fluxes (FSPM) showed a strong spatial variability between upstream watershed and the outlet of the river. The mean inter-annual FSPM was 30 Mt/yr (i.e. specific flux of 741 t/km²/yr) at the Lao Cai site, 38 Mt/yr (i.e. 792 t/km²/yr) at the Phu Tho gauging site, 29 Mt/yr (i.e. 193 t/km²/yr) at the Son Tay gauging station. Its values were 4.1 Mt/yr (i.e. 80 t/km²/yr) and 6.6 Mt/yr (i.e. 191 t/km²/yr) for the Da and Lo rivers, respectively. Between the Lao Cai and Phu Tho sites, both erosion and sedimentation processes occurred together, but strongly depended on the hydrological conditions. Between the Phu Tho and Son Tay sites, the important loss of SPM flux suggested a dominant deposition process in the floodplain during high water before the delta. These results proved the complex processes of erosion/sedimentation occurring on the Red River watershed.

Keywords: Red River, erosion, suspended particulate matter concentrations, fluxes, spatial variability, transport, deposition.

1. INTRODUCTION

The fluvial transfer of sediment from the land to the coastal areas and/or the ocean reflects the denudation of the continents and contributes to new depositional environment [1, 2].

Furthermore, quantifying accurately the sediment delivery to the ocean is fundamental to (i) establish global biogeochemical cycles (e.g. for the carbon cycle [1, 3]), (ii) understand many physical processes (e.g. evolution of landscape and coastal landforms [2, 4]) and (iii) evaluate its potential role as a pathway for pollutants from terrestrial to coastal and marine systems [4, 5]. Clarifying the variation of sediment flux through the riverine sediment routing system is necessary to assess the mechanism and source of riverine sediment flux load to the ocean [6]. The understanding of the hydro-sedimentary transfer processes are also essential for improved sustainable management of continental surfaces where human societies are concentrated.

The Red River (China/Vietnam) plays an important role in the economic, cultural and political life of the Vietnamese people. Based on a long-term observation (1960-2008), the mean annual river sediment transport in the Red River was estimated to 90 Mt/yr and the temporal variability (24-200 Mt/yr) was attributed to hydrological conditions and anthropogenic activities (e.g. reduction by half due to the commissioning of a major dam reservoir [2]). However, the previous study of Dang et al. (2010) [2, 7, 8] had not localised sediment sources and identified physical processes because it relied on daily water discharges and SPM concentrations measured at the outlet of the River System and the upstream limit of the dynamic tide, just before the Delta System. This present study is based on recent daily measurements collected at different strategic sites in the Red River System between 2005 and 2010. The objectives of this study are to: (i) quantify the SPM fluxes along the Red River system, (ii) analyse the spatial variability of sediment transport in order to identify the sources of water and SPM flux, and (iii) clarify physical processes of erosion, transport and deposition of sediment by proposing a erosion/transport model for the Red River basin.

2. MATERIALS AND METHODS

2.1 Area descriptions

The Red River system, located in South-East Asia, has a total watershed area of 169 000 km^2, 50.3 % of which in Vietnam, 48.8 % in situated in China and 0.9 % is situated in Laos and includes a fertile and densely populated delta plain (14,000 km^2). The Red River originates from the mountainous area of Yunnan Province in China, flows 1200 km south-eastward and then flows through seven Vietnamese provinces before flowing into the Gulf of Tonkin in the South China Sea (Figure 1). The main tributaries of the Red River are the Da River, on the right bank, and the Lo River, on the left bank (Figure 1).

The Red River basin is characterized by two distinct seasons: the wet season from May to October and the dry season from November to April, due to the South West monsoon in summer and the North East monsoon in winter, respectively. The summer season is warm and very humid, with mean temperatures ranging from 27 °C to 29 °C whereas the winter season is cool and dry with mean monthly temperatures ranging from 16 °C to 21 °C [9]. The average annual rainfall in the Red River System is 1600 mm, with 85 % - 95 % of this falling during the summer season [10].

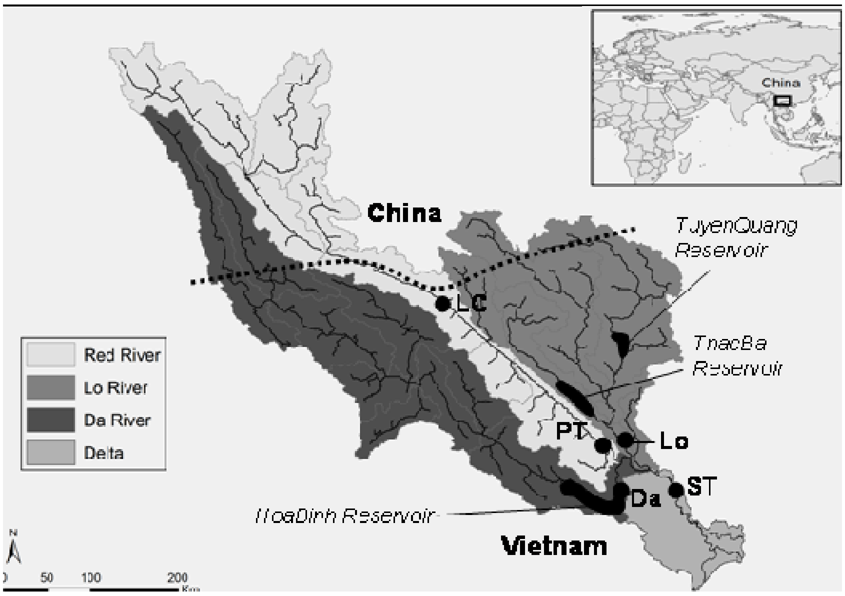

Figure 1. Description of the Red River system and location of study sites.

2.2 Data and methodology

Daily monitoring was performed by the Vietnamese Institute of Metrology, Hydrology and Environment (IMHE) at five strategic permanent observation sites from 2005 to 2010 (Figure 1):

(1) the Lao Cai gauging site (simplified by LC) corresponds to the entry of the Red River in Vietnam and represents river borne material derived from the Upper Red River draining from China;

(2) the Phu Tho gauging site (simplified by PT) is situated at the outlet of the Red River before the confluence with the Da and the Lo Rivers;

(3) the HoaBinh gauging site (simplified by Da) is located at the outlet of the Da River and integrates material derived from the Da system after the HoaBinh Reservoir;

(4) the VuQuang gauging site (simplified by Lo) is located at the outlet of the Lo River;

(5) the Son Tay gauging site (simplified by ST), near Hanoi, is located at the downstream of the confluence with the three main tributaries (Red, Da and Lo Rivers) and at the upstream limit of the dynamic tide; this site is considered to be the outlet of the Red River system and the entry point to the Red River Delta.

Daily SPM concentrations were manually collected one time per day and filtered using pre-weighted filters according to the Vietnamese national standard criteria: during low water levels, daily water samples were collected at 20 - 30 cm from the surface water and 4 m from the right riverbank; during high water discharges, daily samples were collected from depth-integrated vertical profiles. Daily water discharges are estimated from daily measurements of river stage and the stage-discharge rating curve (MONRE, 1997-2004).

2.3. Annual reference SPM flux

Based on the daily database of water discharge and SPM concentrations, the annual SPM fluxes were calculated by summing the daily SPM fluxes which are established by multiplying the daily water discharge with the corresponding SPM concentration:

$$F_{SPMa} = \sum_{i=1}^{n} \mathbf{F_{SPMd}} \text{ with } F_{SPMd} = [SPM]_d \times Q_d$$

where: F_{SPMa} is the annual SPM flux (expressed in t/yr); F_{SPMd} are the daily SPM fluxes (t/day); $[SPM]_d$ and Q_d are the daily SPM concentrations (mg/l) and water discharges (m^3/s), with n = 365 or 366.

3. RESULTS AND DISCUSSIONS

3.1. Variability of the water discharges in the Red River System

Based on daily water discharge measurements during 6 years (2005-2010), two main hydrological features are observed at the five gauging sites which reflect the rivers' response to seasonal rainy distribution and runoff: the dry season, from November to April, is characterized by low water discharges whereas the rainy season, from May to October, is characterized by high water discharges, as classically observed for typical wet river systems with a pronounced monsoon (Figure 2, [11]). As a consequence, daily water discharges in the main channel of the Red River varied between 123 m^3/s to 5500 m^3/s (temporal variation factor = 45) at the Lao Cai site, between 132 m^3/s to 10 100 m^3/s (factor = 76) at the Phu Tho site and between 730 m^3/s to 14 600 m^3/s (factor = 20) at the Son Tay site. In the two major tributaries, daily water discharge ranged from 221 to 10 200 m^3/s (factor = 46) for the Da River and from 92 to 6780 m^3/s (factor = 74) for the Lo River.

The annual water discharges highly varied from one year/site to another (Table 1). The annual water discharges ranged from 363 to 638 m^3/s at Lao Cai, from 568 to 900 m^3/s at Phu Tho and from 2724 to 4095 m^3/s at Son Tay for the Red River System. Concerning both tributaries, annual values ranged from 1551 to 1962 m^3/s and from 576 to 1172 m^3/s for the Da and Lo Rivers, respectively. The annual water discharges measured at the Son Tay site are similar to the sum of the corresponding annual water discharge of the three major tributaries (the Red River at Phu Tho, the Da and Lo Rivers) except for the 2003 year at which the sum of water of three tributaries was higher (>17 %) than that of the Red River at the Son Tay site. The Red River System can be considered as one balanced fluvial system for freshwater fluxes (i.e. water inputs ~ water outputs).

The mean annual water discharges for the 2005-2010 period were 542 m^3/s, 678 m^3/s and 3171 m^3/s for the Red River at Lao Cai, Phu Tho and Son Tay sites and 1717 m^3/s and 809 m^3/s for the Da and Lo Rivers, respectively. The Da River plays a major role of water source for the Red River system, contributing more than half of the total water discharge. The freshwater derived from the Red River at Phu Tho and the Lo River represented, for the study period, 21 and 25 %, respectively. The sub-basin have the following mean specific discharge rate (i.e. water discharge per unit area of the sub-basin): Da River (33 $l/s/km^2$) > Lo River (23 $l/s/km^2$) ~ Red River at Son Tay (21 $l/s/km^2$) > Red River at Phu Tho (14 $l/s/km^2$) ~ Red River at Lao Cai (13.5 $l/s/km^2$). These results showed that the specific discharges of the Red River are comparable to the Mekong River (~19 $l/s/km^2$ [14]) and lower than the Ganges – Brahmaputra System (~35 $l/s/km^2$ [12]), except for the Da River.

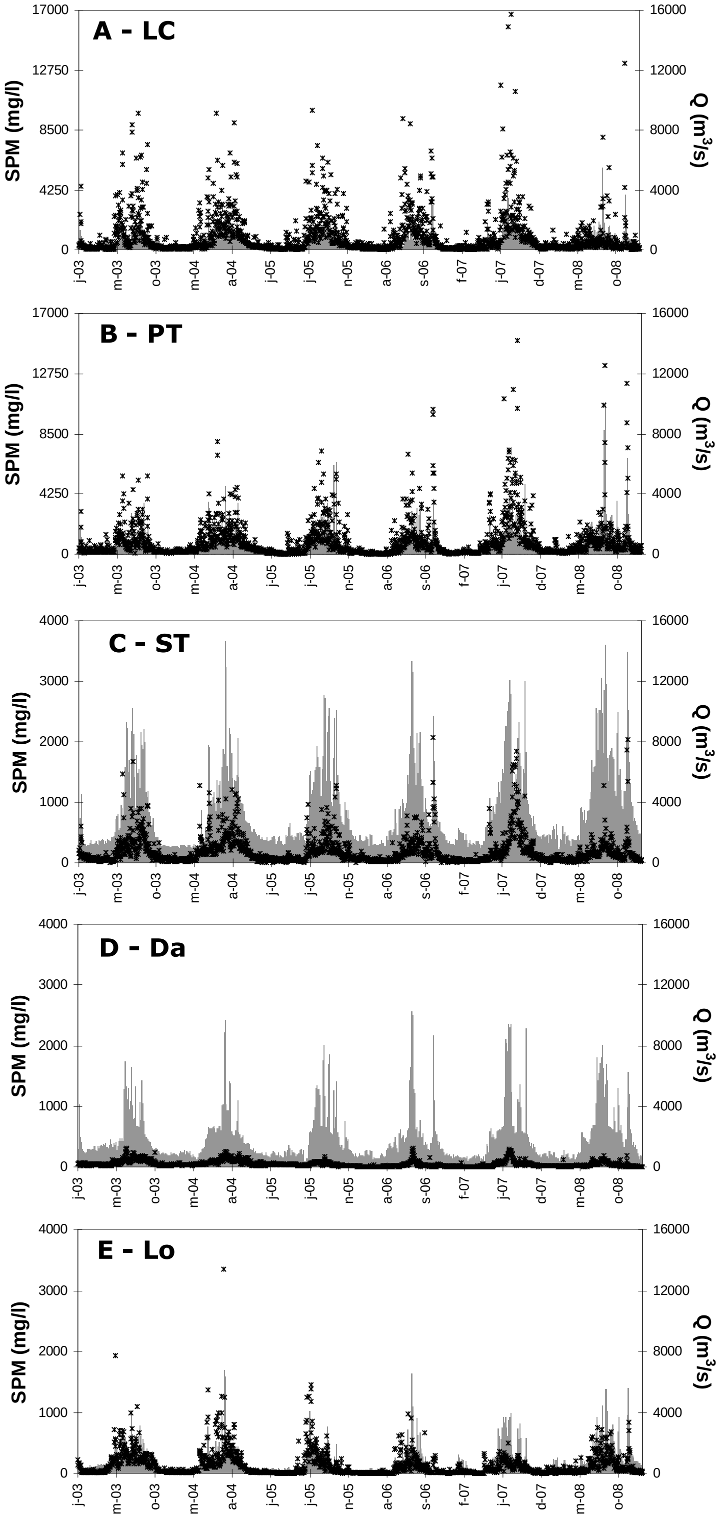

Figure 2. Evolution of daily SPM concentrations (SPM, mg/l) and daily water discharge (Q, m^3/s) for the Red River at the Lao Cai (A), Phu Tho (B), Son Tay (C), and at the outlet of the Da River (D) and Lo River (E) during the 2005-2010 period.

Table 1. Flow and SPM transport regime characteristics for the Red River System at five stations (Q-water discharge in m^3/s; SPM: suspended particulate matter in mg/l; FSPM: annual of SPM flux in 10^6t, Y: specific erosion yields in $t/km^2/yr$; Hyd.: Hydrologycal condition).

Year	Q m^3/s	SPM (mg/l)	F_{SPM} ($*10^6$t)	Y ($t/km^2/yr$)	Hyd.	Q (min-max)	SPM (min-max)
Red River at LaoCai							
2005	608	931	29.6	722	Mean (+10%)	222 - 1 660	18 - 9 667
2006	631	1,070	34.3	837	Mean (+14%)	184 - 2 260	44 - 9 672
2007	420	937	22.7	554	Dry (-24%)	128 - 2 160	25 - 9 870
2008	363	950	22.2	541	Dry (-35%)	123 - 3 100	27 - 9 340
2009	592	1,112	46.9	1,144	Mean (+7%)	130 - 3 820	22 - 16 700
2010	638	536	22.2	541	Wet (+15%)	127 - 5 500	6.9 - 13 200
Red River at PhuTho							
2005	590	697	20.7	431	Dry (-22%)	167 - 3 240	53 - 5 528
2006	652	931	30.9	644	Mean (-13%)	146 - 4 500	159 - 7 980
2007	668	777	33.1	690	Mean (-11%)	140 - 6 080	21 - 7 250
2008	568	734	27.6	575	Dry (-25%)	144 - 3 650	15 - 10 200
2009	693	1,265	56.4	1,175	Mean (+8%)	132 - 4 670	36 - 15 100
2010	900	835	60	1,250	Wet (+20%)	196 - 10 100	90 - 13 300
Red River at SonTay							
2005	2,724	189	25.8	172	Dry (-23%)	1 030 - 10 200	4.1 - 1 673
2006	2,955	232	33.2	221	Dry (-23%)	870 - 14 600	5.3 - 1 270
2007	3,097	163	25.6	171	Mean (13%)	987 - 11 100	2.1 - 1 720
2008	2,850	160	23.6	158	Dry (-20%)	870 - 13 300	6.2 - 2 070
2009	3,303	214	34.8	232	Mean (7%)	830 - 12 100	6.6 - 1 850
2010	4,095	144	30.2	201	Wet (+15%)	730 - 14 400	2.4 - 2 350
Da River							
2005	1,733	74	5.5	107	Mean (+3%)	589 -6 920	16 - 309
2006	1,650	75	5.3	104	Mean (-2%)	283 - 9 650	167 - 264
2007	1,628	38	2.6	51	Mean (-4%)	238 - 8 060	4.1 - 178
2008	1,551	26	2.7	53	Mean (-8%)	317 - 10 200	0.5 - 306
2009	1,777	43	5.4	106	Mean (+5%)	221 - 9 440	0.5 - 296
2010	1,962	31	3.2	63	Wet (+16%)	265 - 8 020	1.3 - 195
Lo River							
2005	878	170	8	235	Dry (-16%)	195 - 4 130	15 - 1 929
2006	764	186	10.6	312	Dry (-27%)	165 - 6 780	13 - 3 350
2007	636	119	5.4	159	Dry (-39%)	102 - 4 110	6.5 - 1 450
2008	576	83	3.5	103	Dry (-45%)	92 - 6 530	2.0 - 979
2009	831	74	3.7	109	Dry (-21%)	99 - 3 970	2.2 - 491
2010	1,172	125	8.6	253	Mean (+12%)	238 - 5 630	6.6 - 842

3.2. Variability of the SPM concentrations in the Red River System

The evolution of SPM concentrations at the five sub-basins of the Red River showed high seasonal and inter-annual variations which are closely linked to the variability of water discharges with the highest values observed during the rainy season (Figure 2). The daily SPM concentrations of the Red River ranged from 6.9 to 16,700 mg/l, from 15 to 15,100 mg/l and from 2.1 to 2,350 mg/l at the Lao Cai, Phu Tho and Son Tay sites, respectively. Concerning both tributaries, the daily values varied between 0.5 and 309 mg/l for the Da River and between 2.0 and 3,350 mg/l for the Lo River. The SPM concentration variability, expressed as the ratio between the maximum and minimum SPM concentrations ranged from 618 (for the Da River) to

2420 (for the Red River at the Lao Cai site); this variability range is one to two orders of magnitude higher than that for the water discharges (see section 3.1).

The mean SPM concentrations of the Red River at Lao Cai, Phu Tho and Son Tay sites in the dry season were 275, 306, and 77 mg/l, respectively. These mean values can increase up to 1,555, 1,430 and 290 mg/l in the rainy season, for the Red River at Lao Cai, Phu Tho and Son Tay sites, respectively. For both tributaries, the mean SPM concentrations were 22 mg/l and 32 mg/l during the dry season and were 72 and 217 mg/l during the rainy season in the Da and Lo Rivers, respectively.

3.3. Variability of the annual SPM fluxes and specific erosion yields: localisation of sediment sources

The main branch Red River annually carried very important SPM loads ranging from 22.2×10^6 t/yr to 46.9×10^6 t/yr at Lao Cai, from 20.7×10^6 t/yr to 60×10^6 t/yr at Phu Tho and from 23.6×10^6 t/yr to 34.8×10^6 t/yr at Son Tay. For the study period, the inter-annual SPM fluxes were estimated at 30×10^6 t/yr, 38×10^6 t/yr and 29×10^6 t/yr at the Lao Cai, Phu Tho and Son Tay sites, respectively (Table 1). The high annual SPM flux estimated at the Lao Cai site (i.e. the entry of the Red River in Vietnam) tend to demonstrate that a significant sediment supply comes from the upstream watershed located in China. The annual SPM fluxes from the Da and Lo Rivers were clearly lower than that of the main branch with inter-annual SPM fluxes accounting for 4.1×10^6 t/yr and 6.6×10^6 t/yr, respectively.

The sum of the inter-annual SPM fluxes transported by the three main branches of the Red River System (Red River at Phu Tho, Da and Lo) into the Red River Delta was calculated. If the water discharge into the Red River Delta is derived from the Da River (superior to 50 %), SPM flux into the Red River Delta is dominated by the Red River (at Phu Tho) with the contribution of 78 % (varied from 61 to 86 %). The Da and Lo River contributed 8 % and 14 % of SPM flux into the Red River Delta, respectively. However, the sum of the mean annual fluxes from three main branches is higher than the mean annual flux at the Son Tay site suggesting significant sedimentation before the entry to the Delta. This sedimentation phenomenon is more developed in section 3.3.

3.4 Erosion / Transport Model for the Red River System

Erosion and transport processes in the middle section of the Red River System

If the inter-annual SPM transport on the 2005 - 2010 period measured at the Lao Cai is lower than that of the Phu Tho site (30 versus 38×10^6 t/yr), SPM flux can show significant difference at the annual scale. For example, the annual SPM flux at Lao Cai was slightly higher than that at Phu Tho in 2005 and 2006, when the annual water discharge at the two sites were comparable (Table 1). In contrast, in the years 2007, 2008, 2009 and 2010, when the annual water discharges at the Phu Tho site were higher than those at Lao Cai, the annual SPM fluxes measured at Phu Tho were superior to those at Lao Cai (Table 1). This phenomenon is more marked in 2008 with a SPM flux at Phu Tho which is 3 times higher than that at Lao Cai.

Based on this observation, we proposed two contrasting processes of erosion/re-mobilisation and sedimentation occurring along the Red River System between the Lao Cai and Phu Tho sites, depending on the hydrological conditions (Figure 3):

- Case 1: when annual water discharges at the Lao Cai and Phu Tho sites are similar, the annual SPM flux have decreased between the Lao Cai and Phu Tho section, reflecting the sedimentation/deposition process between two sites and estimated at ~6×10^{6} t/yr (example 2005-2006, Figure 3A). This sedimentation may be explained by a limitation of the sediment transport may be due to the decrease of the channel slope. This result demonstrates that the slope erosion is the dominant process occurring in the upstream system and a decrease of erosion rate is observed downstream as observed in another humid tropical watershed in Costa Rica [13];

- Case 2: when the annual water discharge at Phu Tho is higher than that at Lao Cai, the annual SPM flux at Phu Tho is also higher, reflecting both erosion/re-mobilisation processes between the Lao Cai and Phu Tho section (example 2007-2008, Figure 3B) and suggests preponderant channel erosion. This increase is consequent to runoff occurring in this section due to the rainfall in the middle part of the Red System.

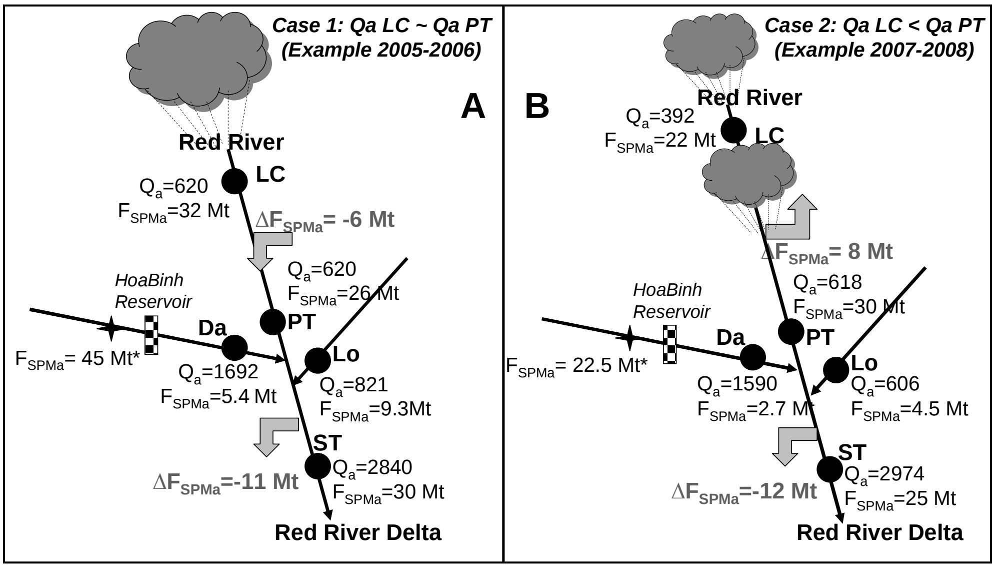

Figure 3. Model of Water discharge (Q in m^3/s) and SPM flux transported by the Red River between Lao Cai and Son Tay, showing (A) the deposition case during 2005-2006 ( ) or (B) the erosion case during 2007-2008 ( ). (*[2]).

Deposition processes in the low reach of the Red River System

Unlike the conservation of water discharge between upstream (i.e. at the outlet of the Red, Da and Lo Rivers) and downstream from the confluence of the three main tributaries (i.e. the Red River at Son Tay site, and see the section 3.1), the SPM flux of the Red Rivers at Son Tay is always lower than the sum of SPM flux of three rivers (generally from 8 to 42 Mt; Table 1), showing an important loss of suspended matter in this river section. This loss of material along the lower courses of the Red River has been already observed in other rivers in the world, like the Negro, Tapajos and Xingu rivers in the Brazilian Amazon [14], the Indus River [15], the Rio Itenez-Guopore River in Bolivia [16], the Yellow River [17] and the Mississippi River [18]. This phenomenon has been attributed to three main processes: diffuse riverbank settling, channelized floodplain sedimentation and/or riverbed deposition [19] .

The inter-annual duration curves (e.g. the mean cumulative water and SPM fluxes as a function of the time) were established for the upstream (Da, Lo and Red River) and the downstream (Son Tay) to clearly identify process involved in SPM transport (Figure 4). We observed that the cumulative water flux at the Son Tay site was similar with the cumulative water flux from the three main tributaries. The cumulative SPM flux measured at the Son Tay site was comparable with the sum of the three tributaries for the November – April period, corresponding to the dry season, while a great difference was found during the May to October period, corresponding to the rainy season. In fact, during the rainy season, the sum of fluxes from the three main tributaries is higher than the flux measured at Son Tay. The difference between these two fluxes highlighted a large sediment loss occurring during this period attributed to sediment deposition on the low reach, just before the delta.

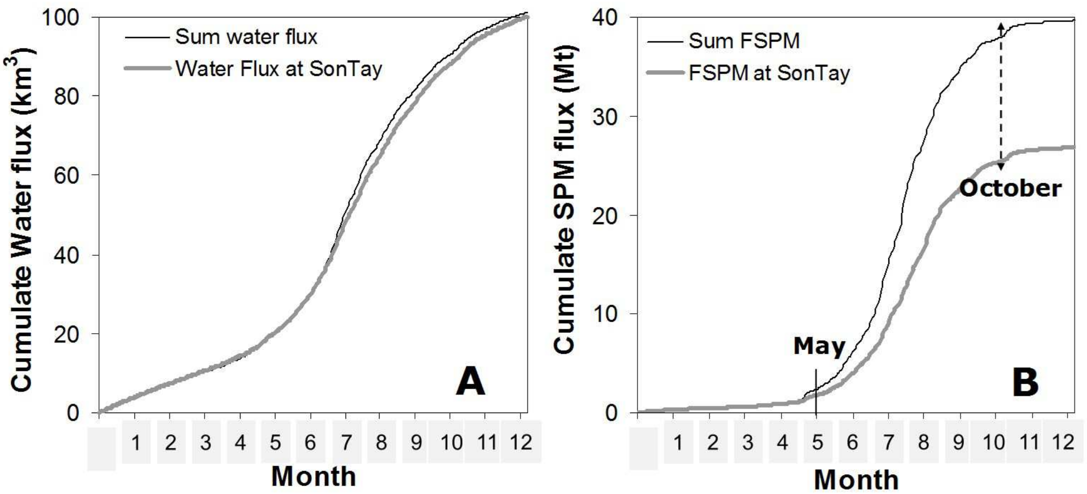

Figure 4. (A) Cumulative Water flux v.s time and (B) Cumulative Suspended particulate matter flux vs. time; Comparison between the water and SPM fluxes measured at the Son Tay site (in grey) and the water and SPM fluxes calculated as the sum of the supplies from the Red River at Phu Tho and the Da and Lo Rivers (“Sum”; in black).

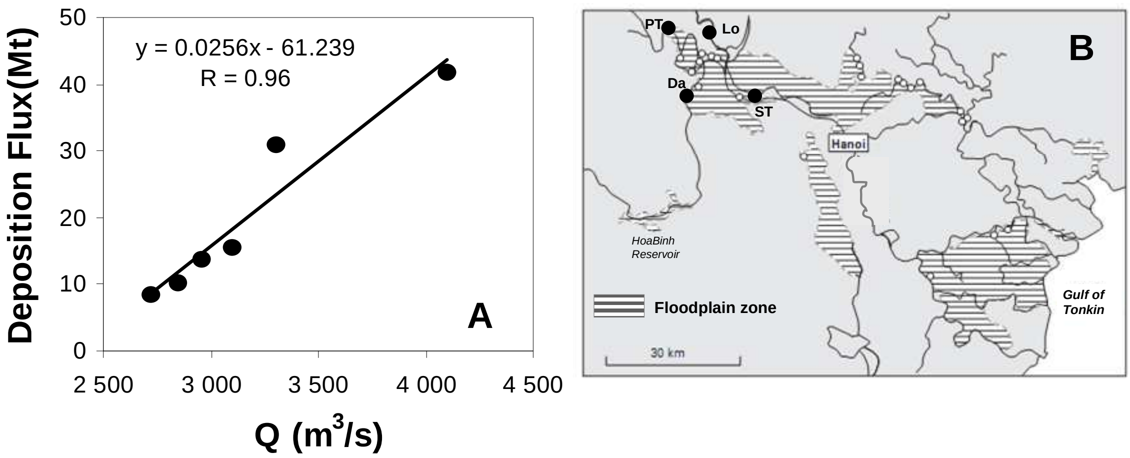

Figure 5. (A): Relationship between the annual deposition SPM flux and the annual water discharge of the Red River at the Son Tay gauging station for the 2005-2010 period; (B): Floodplain map of the Red River Delta (Source: [20]).

Moreover, a very good relationship was observed between the deposited SPM flux and the annual discharge (R = 0.96; Figure 5A), showing that the water discharge plays an important role on alluvial deposition flux along the Red River (between the outlets of main rivers and the Son Tay site) and clearly reflects substantial sedimentation on the floodplains during the rainy season and high water discharges (Figure 5B).

4. CONCLUSIONS AND PERSPECTIVES

Annual water discharge measured at the outlet of the three main tributaries and at the outlet of the System (just before the entry to the Delta) showed that the Red River is one balanced fluvial for freshwater with 50 % water flux delivered from the Da River. The annual SPM fluxes showed a strong spatial variation between the upstream watershed and the outlet of the river. In addition, the source of SPM into the Red River delta was determined: the majority of the SPM comes from the upstream catchment in China. The inter-annual SPM fluxes in the Red River were 30 Mt/yr at the Lao Cai site, 38 Mt/yr at the Phu Tho site and 29 Mt/yr at the Son Tay site.

Finally, SPM flux measured along the Red River and at the outlet of the Da and Lo proved the complex processes of erosion/sedimentation occurring on the basin. Between the Lao Cai and Phu Tho sites, both erosion and sedimentation processes occurred together, but strongly depended on the hydrological condition. Between the Phu Tho and Son Tay sites, the important loss of SPM flux suggested a dominant deposition process in the floodplain during high water before the delta. Further erosion studies (quantification and modelisation) should at a minimum use and analyse SPM load with a long-term observation to better understand SPM transport dynamic.

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