

Water balance and nutrient delivery in a densely populated delta for a future sustainable environment

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Abstract Besides the inputs of material from land-based sources and the in-stream processes leading to transformation, retention and elimination of nutrients during their downstream travel, the nutrient flux transported by river systems depends on a number of factors, including the influence of hydrological fluctuations due to tidal movement. We monitored the daily water discharges and the corresponding nutrient loads within the Day-Nhue River System, and chose the right bank of the Red River Delta, where Hanoi City and its conurbation are located, to further understand the biogeochemical functioning of the delta system. We underline the large impact of the tide on nutrient balance up to more than 150 km from the coastline. The integration of positive and negative fluxes due to the daily tidal cycle allowed calculation of the real nutrients fluxes, which appeared to be underestimated by between 50% to 80% if the calculation is based on daily mean discharge.

Key words Red River Delta; discharge; tidal influence; nutrient export; Vietnam

INTRODUCTION

For a region such as the Red River Delta where river water quality has dramatically deteriorated due to rapid population growth, industrialization and economic development in recent years, a comprehensive model must be built to assess the significance of the complex and inter-related processes and to understand how river water quality and ecological functioning reflect the land-use and human activities in the watershed (Le *et al.*, 2005; Billen & Garnier, 2007; Luu *et al.*, 2012).

Nutrient and contaminant transport via inland waters in populated deltas have been receiving increasing attention as their role in linking land and sea waters, and in wastewater mitigation. Long regarded as a passive conduit between land and ocean, inland water systems are significantly more complex and influential than previously believed. They do not only transport materials from land to sea, but also they store sediments and nutrients internally, and they support the food web of aquatic environment and the water cleaning regulation for the human uses. The aim of this study is to characterize the nutrient fluxes being associated with the hydrological fluctuations due to the tidal influence. Given the lack of observed discharge data in the numerous distributaries of the Red River Delta, the main concern of this study was to determine the hourly impact of the tidal movement on the water river flux by direct discharge calculation through ADCP measurements over a daily cycle. For that, we considered a median scale river, the Day-Nhue River System, approximately 250 km long, emerging from the Red River right side, a few kilometres upstream of Hanoi and flowing towards China Sea. In its mid stream, the Day-Nhue River System receives very heavy sources of pollution from the metropolis area of Hanoi. Then we conclude on the calculation of an effective daily nutrient balance in regards of biogeochemical functioning.

MATERIALS AND METHODS

Delta environment

The Red River Delta is a flat triangular region of 14 300 km², smaller but more intensely exploited and more densely populated than the Mekong River Delta. The principal land use throughout the

delta is rice cultivation. To facilitate rice production, some 1080 km of embankments, 34 400 km of canals, 1310 drains, 217 reservoirs and 1300 pumping stations were constructed. The entire delta region is no more than 10 m above sea level, and much of it is 1 m or less (Le, 1997). On the basis of the 1960–2008 record period, the Red River, about 1200 km long, contributes to flood the delta with a yearly average discharge of 3600 m³/s, but it may increase by more than 60 times at the peak of the rainy season. Some 74% of the river discharge occurs during the rainy season, from June to October. During the 1960–2008 observed period, the Red River discharges 30 000 m³/s at peak flow during the rainy season, compared with only 430 m³/s in the dry season. The average annual sediment concentration of the Red River is approximately 0.8 g/L, varying between 0.2 g/L in the dry season and 1.5 g/L in the wet season (Dang *et al.*, 2010); peaks up to 7 g/L were observed during floods (Dang, 2011).

Meteorological data

The Red River Delta is situated in the sub-tropical monsoon zone. Meteorological data (daily rainfall and daily potential evapotranspiration) were obtained from five national meteorological stations located throughout the delta (MONRE–IMHEN, 1996–2006) and were computed by Luu (2010). The average annual rainfall (from 1986 to 2006) for the entire delta was 1667 mm, 85% of which fell from May to October (rainy season). In general, there has been less rain in recent years, but it has occurred with higher intensity, which results in an imbalance in rainfall distribution throughout the year. For example, yearly rainfall in 1996 was 1725 mm/year, with a monthly peak of 360 mm/month, while those in 2006 were 1345 mm/year and 450 mm/month. The mean annual of the potential evapotranspiration (ETP) was distributed rather homogeneously over the entire delta, varying only from 1006 to 1030 mm/year. The ETP represents 60–70% of the rainfall, providing a low surplus.

Determination of direct river discharge in the Day–Nhue River System

The Day-Nhue River System is one of the main three branches of the nine distributaries of the Red River Delta (Fig. 1). Around 20% of the total Red river delta discharge flows through the Day

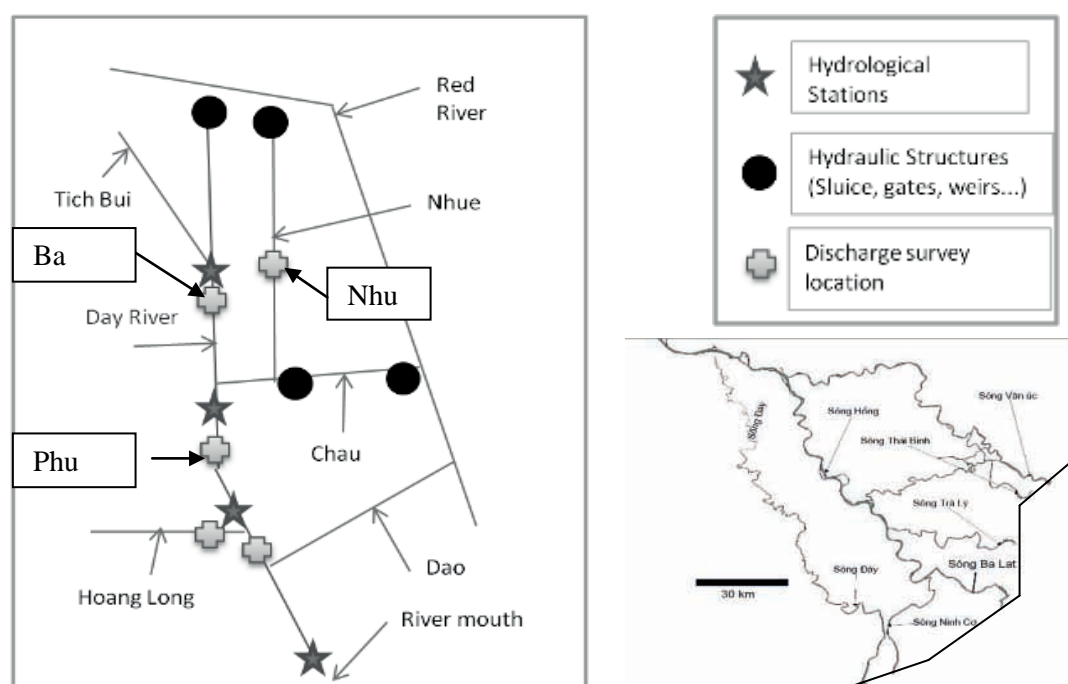


Fig. 1 The Day River system, with the hydrological stations and the discharge survey locations.

River. Four hydrological campaigns were conducted in June, July and August 2007 and in June 2008 at Ba Tha, Phu Ly, Nhue, Que Bridge and Do Bridge stations (Fig. 1). During each of these campaigns, the water flow over an entire cross-section of the river was monitored during a 24 h cycle using an ADCP current meter, after which the data were integrated and used to calculate the instantaneous discharge. In addition, the water levels at these river stations and the sea water levels at Hon Dau station near the coastline were also monitored. When plotted against the corresponding daily mean water levels, these measurements were found to be in reasonable agreement with the discharge vs. water level relationships derived from MIKE11 hydraulic modelling (Luu *et al.*, 2010). These findings validate the approach we used to obtain calibration curves for reconstruction of the discharge from the daily mean water level data available at the National Institute of Meteorology, Hydrology and Environment (IMHEN) (Luu *et al.*, 2010).

Geochemical data

The survey of water quality variables such as pH, temperature, conductivity, dissolved oxygen, nutrients and turbidity were synchronized with the gauging discharge measurements from the three stations chosen on the 4–5 June 2008 (Nhue, upstream of the Nhue River; Ba Tha on the Day River, upstream from the confluence with the Nhue River and the Day River; Phu Ly, downstream from the confluence with the Nhue River) (Fig. 1). The purpose of these surveys was to determine the daily variations of water quality on the Day-Nhue River System. The monitoring was carried out with a Hydrolab 4a multi-parameters probe and an automatic water quality monitoring fixed station was set up at Phu Ly station, equipped with an ISCO 6700 automatic sampler. The automatic sampler attached to the multi-probe sensor can automatically sample and store water samples in standard condition before transfer to laboratories for analysis. The experimental protocols to determine suspended matter (SM) and nutrients (NO_3 , NH_4 , Ptotal) were described in Luu (2010).

RESULTS AND DISCUSSION

Water level and tidal regime

On 4 June 2007, the tide range was high, 2.50 m in Hon Nieu station on the coastline. We decided to gauge on that particular day to get the highest variation of water level and discharge. The water level of the rivers follows the sea water level (Fig. 2). However, we see that the tide signal is distorted compared to the initial signal recorded on the coast in Hon Nieu station. This is due to the distortion of the propagation wave along the way to enter the Day River. Moreover the records of water level until Ba Tha station, which is the furthest station from the sea (at 150 km from the coast line) revealed that there were substantial daily flow variations according to the tide, with flow inversions occurring until at least Ba Tha (Fig. 3). Then the integration of the measurements over the entire tidal daily cycle allowed calculation of the daily residual discharge.

The four hydrological campaigns of hourly hydrological survey recorded during 2007 and 2008 have confirmed that the water level of the Day-Nhue River System is strongly affected by tidal movement over the whole basin, up to >150 km from the coast line. At 100 km distance inland (near Phu Ly town), the daily water level variation can be up to 1 m in dry season and 0.6 m during the flood season. However, the measurements of salinity underlined that salinity intrusion length is weak for the Day River, since the maximum salinity intrusion length is <20 km from the coastline.

Hydrology and tidal regime

The hydrological hourly monitoring proves that the water level within the Day-Nhue River System varies according to the tide (Fig. 4). Because the flood period is shorter than the ebb period, the tidal inflow velocities are higher than tidal outflow velocities, resulting in flood-tide asymmetry. However, this flood-tide asymmetry can be compensated by the river outflow, which is in the same direction of the ebb currents. On average, the propagation times from the coastline to Phu Ly

(100 km from the sea) and to Ba Tha (150 km from the sea) are about 6 h and 11 h in the dry season, and 8 h and 13 h in the flood season, respectively. At Phu Ly, which is the middle point of the Day-Nhue River System, the water current becomes inverse each day. It is less important in the upstream part; however, it was measured until Ba Tha station on the upper river part was studied. At Phu Ly, it was observed that the instantaneous discharges could vary from $+150 \text{ m}^3/\text{s}$ to $-250 \text{ m}^3/\text{s}$. The consequence of this inversion of the river current means the same water mass goes three times across the same river section. A second consequence is that the discharge values describe a daily circle with one daily maximum, and one daily minimum with a short period of stream current at value zero. These two things could imply a significant impact on the sediment transport and water quality behaviour. Then it becomes impossible to calculate the river discharge by a classical calibration equation linking water level (WL in cm) and discharge (Q in m^3/s), since there is no univocal relationship.

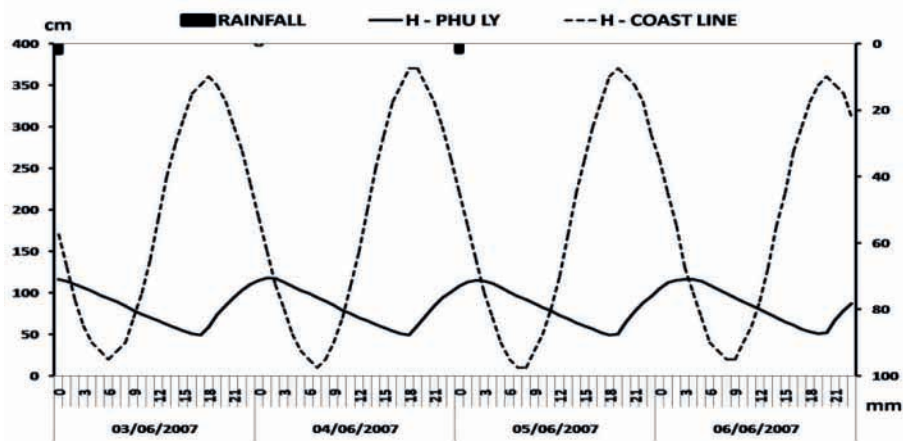


Fig 2 Comparison of the tidal signal at Hon Nieu station on the coastline and the water level recorded at Phu Ly station on the Day River, from 3 to 6 June 2007.

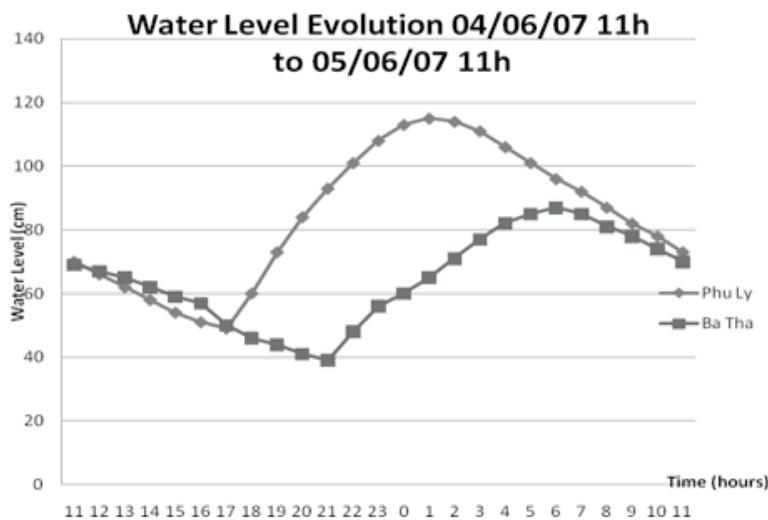
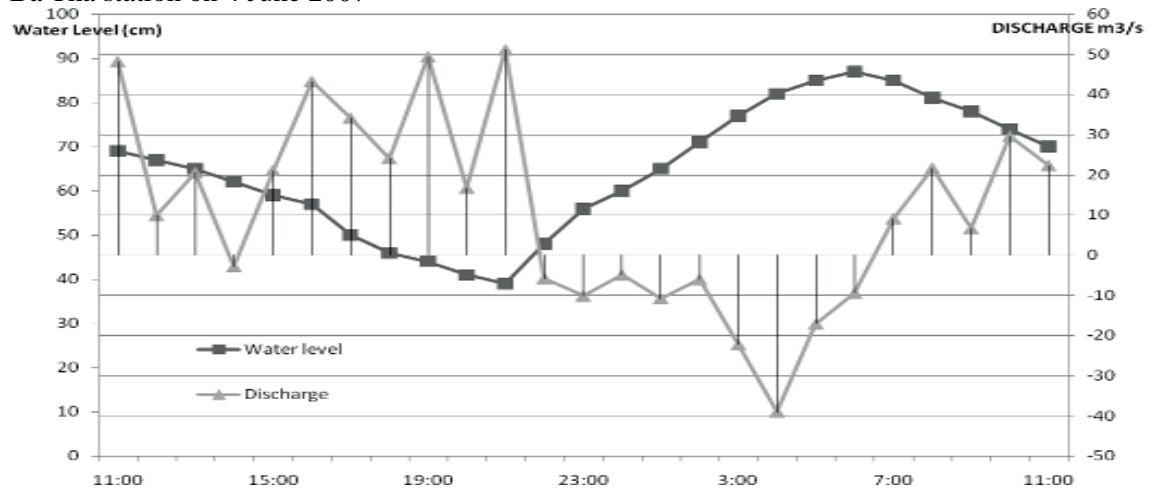


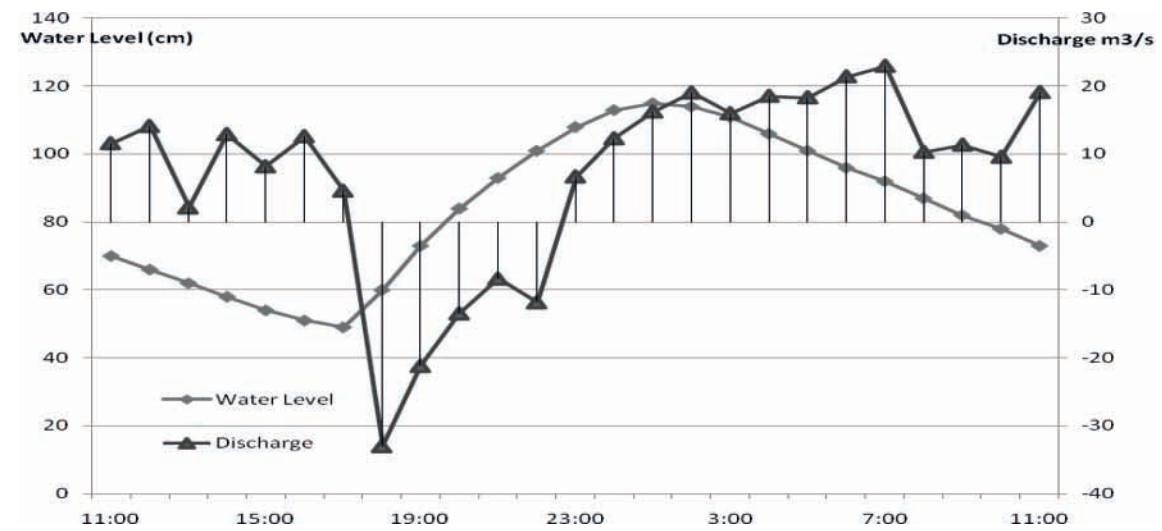
Fig. 3 Influence of the tide on the hourly water level in Ba Tha and Phu Ly stations on the Day River.

For example, at Phu Ly about 60% of the flow goes downstream for 15 h and 40% goes upstream for the rest of the day. The real effective flow is about 25% of the total water volume that goes through a cross-section during 24 h (Fig. 5).

Ba Tha station on 4 June 2007



Nhue station on 4 June 2007



Phu Ly station on 4 June 2007

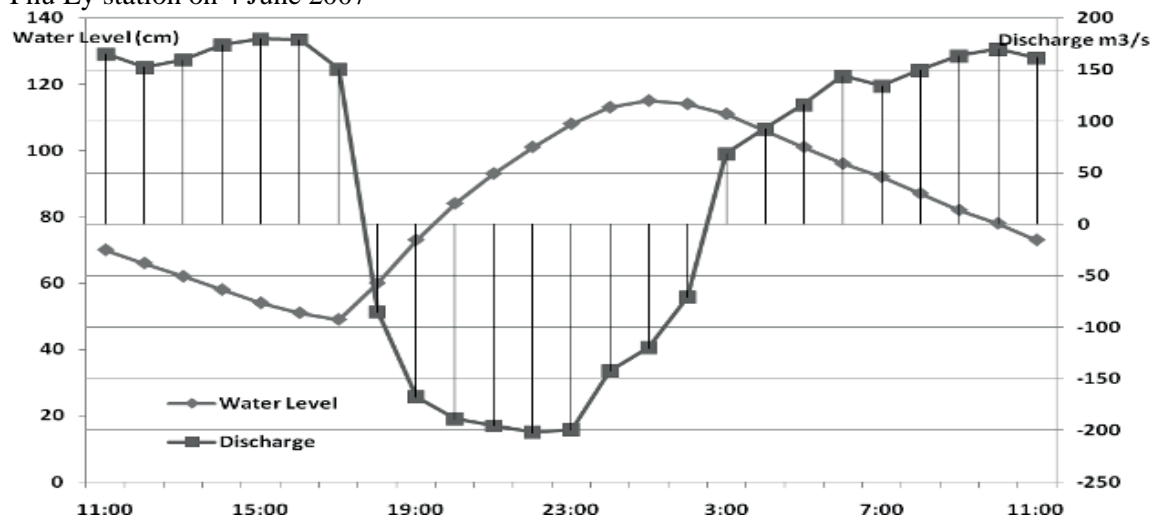


Fig. 4 Continuous river discharge measurements and water level records over a daily period.

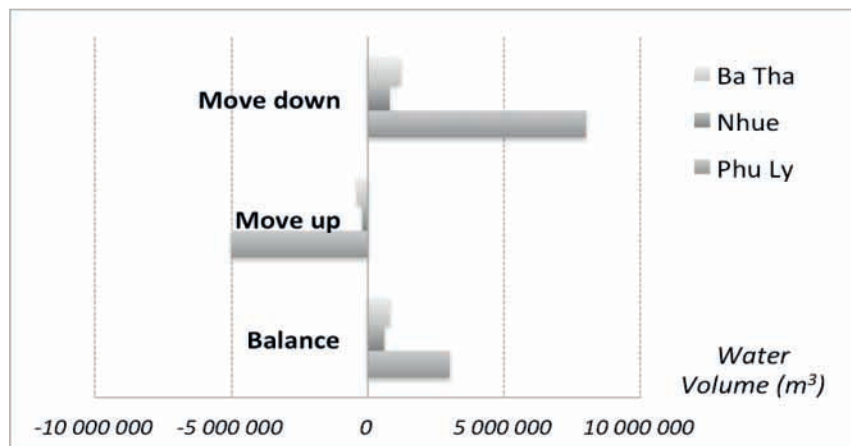


Fig. 5 Daily water volume in direction (positive when the discharge moves downward, negative when the discharge moves upward) in the Day-Nhue River System at three stations (Ba Tha, Nhue and Phu Ly).

Table 1 Concentrations of nutrients (in mg/L), conductivity (Cond in S/cm) and suspended matter (SM in mg/L) in the Day-Nhue River System (upstream and downstream the confluence with the Day and Nhue Rivers) over a daily tidal motion from 4 to 5 June 2008 (PDD: Positive Daily Discharge; NDD: Negative Daily Discharge; PDD+1: Positive Daily Discharge of day + 1).

	Day upstream			Day downstream			Nhue upstream		
	PDD	NDD	PDD+1	PDD	NDD	PDD+1	PDD	NDD	PDD+1
N-NO ₃ mgN/L	0.65	0.70	0.50	0.45	0.45	0.50	0.08	0.07	0.15
N-NH ₄ mgN/L	0.40	0.45	0.45	0.10	0.10	0.10	5.8	5.8	4.2
Ptot mgP/L	0.20	0.15	0.15	0.25	0.20	0.20	0.9	0.8	0.1
Cond (μS/cm)	215	215	250	320	320	320	440	440	360
SM (mg/L)	18	20	18	20	18	20	22	26	21

Water quality and tidal regime

The survey of water quality variables (pH, temperature, conductivity, nutrients and suspended matter) synchronized with the gauging discharge measurements showed that it is really the same water mass, which moves up and down: very few variation of concentration in nitrate, ammonium, phosphorus, conductivity and turbidity were observed (Table 1).

Consequences of tidal regime on the effective nutrient fluxes

Based on the hourly hydrological measurements, we underlined that the same water mass move three times in each section of the river system. It means that the real flux of nutrients transported by river waters is a sum of the flux transported down and up. For example, at Phu Ly station on the 4 June 2007, a water volume of 8 million m³ moves down, then a water volume of 5 million m³ moves up, resulting a balance of 3 million m³ down (Fig. 5). Based on this daily balance, the exportation of nitrate would amount to 1.4 tN-NO₃/day. However, the reality is that 3.6 t of N-NO₃ move down then 2.3 t of N-NO₃ move up, meaning that a total of 5.9 t of nitrate have passed the Phu Ly station in a day. It is nearly four times more than the daily balance of 1.4 t/day previously calculated. The same reasoning can be done for the ammonium and phosphorus.

Our calculation of nutrients fluxes at the three stations, Ba Tha in the upper part of the Day River, Nhue on the upper part of the Nhue River, and Phu Ly downstream of the Day River, indicated that the daily flux of nutrients in the sector influenced by tide cycles are underestimated if the calculation is based on the daily water movement. Indeed, in terms of biogeochemical processes, the fluxes of nutrients should be multiplied by 77% at Phu Ly in the Day River, 36% in

Nhue River and 53% in the upper Day River. Such a behaviour of nutrient fluxes in this sector of the river should locally modify the intensity and spatial pattern of biogeochemical processes. .

CONCLUSION

Due to the use of daily averaged water levels, the tidal influence on daily variations in water level and discharge were not often taken into account. This study based on the hourly discharge measurements revealed that there were substantial flow variations according to the tide, with flow inversions occurring up to the upper part of the Day-Nhue River System, i.e. up to 150 km away from the coastline. The integration of the measurements over the daily tidal cycle allowed calculation of the daily volume of waters going down and the daily volume of waters going up, i.e. with a negative discharge. The sum of these two daily volumes results in a daily residual discharge, currently used for hydrological balance and calculation of biogeochemical fluxes. However, this study showed that the consequence of the tidal move on the calculation of the real daily nutrients fluxes is very significant. Indeed, it appeared that the nutrient fluxes effectively transported by waters could be underestimated between 50% to 80% in comparison with calculation based on daily discharge.

Moreover, the biogeochemical modelling based on the mean daily nutrient fluxes highlighted that the Red River Delta is already at the threshold limit of its capacity to be able to accept the least increase of nitrogen (nitrate or ammonium) and phosphorus, mainly the Day-Nhue River System (Luu *et al.*, 2011, 2012). We assume in this study that the risk on the cleaning capacity of the water-soil compartment of the Red River Delta is more weakened than expected.

The tidal movements add more pressure on the natural delta system and increase the contaminant water risks due to the wastewater fluxes provided by agricultural and urban intensification.

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