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Establishing an empirical equation for the relationship between total suspended solids and total phosphorus concentrations in the downstream Red river water

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Abstract

Recently, the Asian rivers have faced the strong reduction of riverine total suspended solids (TSS) flux due to numerous dam/reservoir impoundment. The Red river system is a typical example of the Southeast Asian rivers that has been strongly impacted by reservoir impoundment in both China and Vietnam, especially in the recent period. It is known that the reduction in total suspended solids may lead to the decrease of some associated elements, including nutrients (N, P, Si) which may affect coastal ecosystems. In this paper, we establish the empirical relationship between total suspended solids and total phosphorus concentrations in water environment of the Red river in its downstream section from Hanoi city to the Ba Lat estuary based on the sampling campaigns conducted in the dry and wet seasons in 2017, 2018 and 2019. The results show a clear relationship with significant coefficient between total suspended solids and total phosphorus in the downstream Red river. It is expressed by a simple equation $y = 0.0226x^{0.3867}$ where x and y stand for total suspended solids and total phosphorus concentrations (mg/l) respectively with the r^2 value of 0.757. This equation enables a reasonable prediction of total phosphorus concentrations of the downstream Red river when the observed data of total suspended solids concentrations are available. Thus, this work opens up the way for further studies on the calculation of the total phosphorus over longer timescales using daily available total suspended solids values.

Keywords: Total suspended solids (TSS), total phosphorus (TP), water quality, Red river, Vietnam.

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INTRODUCTION

Riverine total suspended solids (TSS) are often monitored because they are major carrier of inorganic and organic pollutants, as well as nutrients [1]. It is known that most toxic heavy metals, organic pollutants, pathogens, and nutrients and appreciable amount of bio-degradable organic matters are associated with suspended materials. Measurements of TSS are also relevant to other environmental issues such as soil conservation, land denudation, rock weathering, inputs of elements to the ocean, sedimentation rate in reservoirs, river bed erosion,... [1].

Riverine suspended solids (TSS) in the world are often associated with some elements such as phosphorus (P), nitrogen (N) and carbon (C) [2–4]. For phosphorus, TSS plays an important role in its biogeochemical cycle because they can accept P from overlying water and release P to overlying water. In addition, some previous studies have shown a relationship between TSS concentration and P concentration in water environment [2, 5, 6]. However, recently, a clear decrease in TSS has been observed for many rivers in the world, notably with the construction of a series of reservoirs [7, 8]. It is a well-known fact that change in riverine TSS and P concentrations may result in not only the bio-geochemical processes of the river system, but also that of coastal estuaries and the continental shelf.

The Red river is a typical example of Asian rivers which have suffered from human activities and climate change. Numerous studies demonstrated the reduction of TSS of the Red river due to human activities, notably dam impoundment [7, 8] or riverine water quality including phosphorus concentration [9, 10].

In this study, we aim at i) Assessing the current status of TSS and total phosphorus (TP) concentrations of the downstream Red river after the impoundment of a series of dams in the upstream part; ii) Establishing the empirical equation expressing the relationship between TSS and TP concentrations in the Red river downstream water for the recent period. Sampling campaigns were organized within 2017–2019 to collect the Red river downstream water samples in the longitudinal section from Hanoi city to the Ba Lat estuary and then the empirical equation of the relationship between TSS-TP concentrations was established. Thus, this work provides dataset of the Red river water quality for the recent period and then may open up the way for further studies on the calculation of the TP over longer timescales using daily available TSS values.

METHODOLOGY

Study site

The Red river has a surface basin area of 156,450 km^2, with a length of about 1,160 km. The three main tributaries, namely Da, Lo and Thao, join at Viet Tri city, then flow through the delta and discharge into the Tonkin Gulf through four river mouths (Ba Lat, Lach Giang, Tra Ly and Day). The section from Hanoi city to the Ba Lat mouth is about 164 km long. In the rainy season (May to October), the river has a higher flow than in the dry season (November to next April).

In the upstream Red river system, since 2007, a series of small and medium size reservoirs/dams has been impounded for hydropower in the Chinese part (29 dams on the upstream Thao river; 11 small dams located on the upstream Da river and at least 8 dams located on the upstream Lo river) [11]. In Vietnamese part, there are four large dams/reservoirs along the Red river including the Hoa Binh (in operation since 1989) and Son La (in operation since 2010) reservoirs on the main axe of the Da river, the Thac Ba (in operation since 1975) and the Tuyen Quang (in operation since 2010) reservoirs on the Lo river. Several other reservoirs were in operation in late 2017 such as the Huoi Quang and Lai Chau reservoirs on the Da river [8].

Sampling and laboratory analysis

Forty surface water samples were collected in the period from December 2017 to December 2019 at 7 sites along the Red river from Hanoi city to the Ba Lat estuary (table 1, figure 1) following the Vietnamese Standards for surface water sampling TCVN 6663-6:2018 Part 6: Guidance on sampling of rivers and streams. Water samples are preserved according to the Vietnamese Standards TCVN 6663-3:2016 Part 3: Preservation and handling of water samples.

Table 1. Sampling sites for observation of total suspended solids and total phosphorus concentrations in the downstream Red river

Site name	Site description	Geographic coordinates	Distance to Ba Lat shoreline	Total number of samples/samples in rainy season
SH 1	Chuong Duong bridge, Ha Noi	21°20’20.0”N; 105°51’53”E	164 km	16/8
SH 2	Dai Gia, Phu Xuyen, Ha Noi	20°46’47.3”N; 105°56’49.6”E	123 km	04/2
SH 3	Moc Bac, Duy Tien, Ha Nam	20°42’04.8”N; 106°00’09.1”E	111 km	04/2
SH 4	Dao Ly, Ly Nhan, Ha Nam	20°36’02.7”N; 106°04’30.8”E	96 km	04/2
SH 5	Chan Ly, Ly Nhan, Ha Nam	20°28’46.4”N; 106°11’11.1”E	73 km	04/2
SH 6	Xuan Chau, Xuan Truong, Nam Dinh	20°22’12.2”N; 106°20’37.8”E	35 km	04/2
SH 7	Giao Thien, Giao Thuy, Nam Dinh	20°17’15.0”N; 106°28’08.0”E	17 km	04/2
-	Ba Lat shoreline, Giao Thuy, Nam Dinh (in seawater)	20°14’49.7”N; 106°35’11.9”E	0 km	

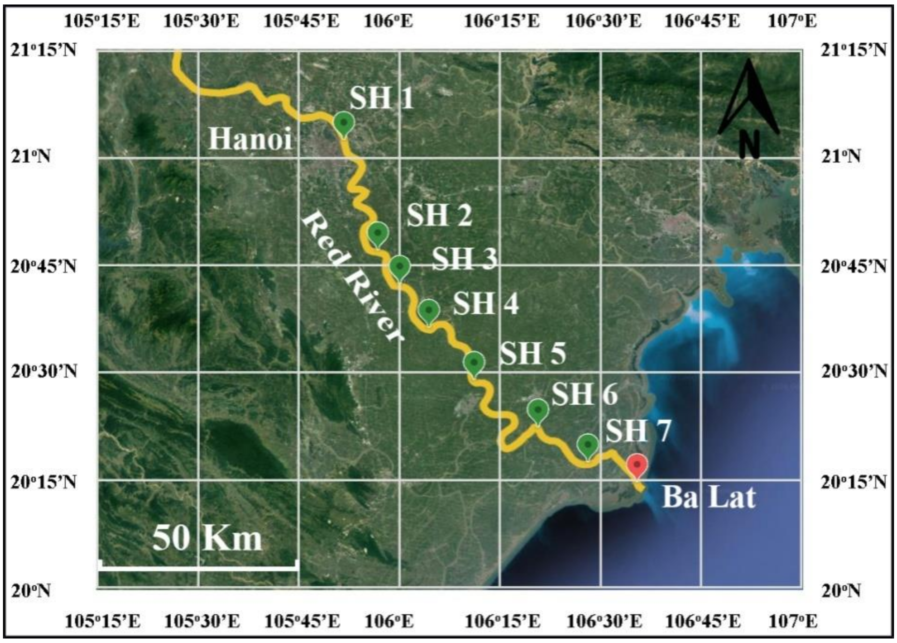

Figure 1. Sampling sites along the Red river system, section from Hanoi city to Ba Lat estuary

Determination of TSS concentrations: Water samples (after well mixing) were filtered immediately by a vacuum filtration through a pre-combusted (120°C in 1 h) glass fiber filter paper (Whatman GF/F, Ø 47 mm). Each filter was then dried for 2 h at 105°C and then weighed. Taking into account the filtered volume, the increase in weight of the filter represented the total TSS per unit volume ($mg.l^{-1}$) [12].

Determination of total phosphorus (TP) concentrations: TP was spectrophotometrically measured on non-filtered water samples by an UV-VIS V-630 (JASCO, Japan) by the method of Eberlein and Katter, 1984 [13].

All analyses were conducted in triplicate and the final result of each variable was the mean of the triplicate measurements. Analytical error was approximately 5%.

RESULTS AND DISCUSSION

TSS and TP concentrations in the downstream Red river

TSS concentrations

TSS concentration in the downstream Red river, the section from Hanoi to the Ba Lat estuary varied widely, from 9.4 mg.l^{-1} to 276.3 mg.l^{-1} with an average value of 62.4 ± 53.5 mg.l^{-1} which exceeded the allowed value of the Vietnamese Standards for surface water quality QCVN 08:2015/BTNMT column A1 (table 2). The difference between the rainy and dry seasons was relatively clear ($p < 0.05$): the average TSS concentration in the rainy season (83.2 ± 62.4 mg.l^{-1}) was 2.1 times higher than that in the dry season (40.5 ± 30.8 mg.l^{-1}). However, no clear difference in TSS concentration along the downstream Red river was observed (figure 2).

Table 2. TSS and TP concentrations of the downstream Red river in 2017–2018

Site name	TSS concentration, mg.l^{-1}	TP concentration, mg.l^{-1}
SH1	56.8 (12.8–186.3)	0.103 (0.05–0.179)
SH2	49.2 (10.8–108.3)	0.094 (0.061–0.162)
SH3	44.9 (9.4–87.7)	0.089 (0.056–0.159)
SH4	48.1 (18–92)	0.103 (0.06–0.161)
SH5	66.1 (39.7–120.3)	0.116 (0.082–0.188)
SH6	60.5 (37.3–93.7)	0.107 (0.083–0.136)
SH7	149.9 (58.8–276.3)	0.15 (0.115–0.169)
Average RR	62.4 (9.4–276.3)	0.106 (0.05–0.188)
QCVN08:2015/BTNMT column A1*	20	-

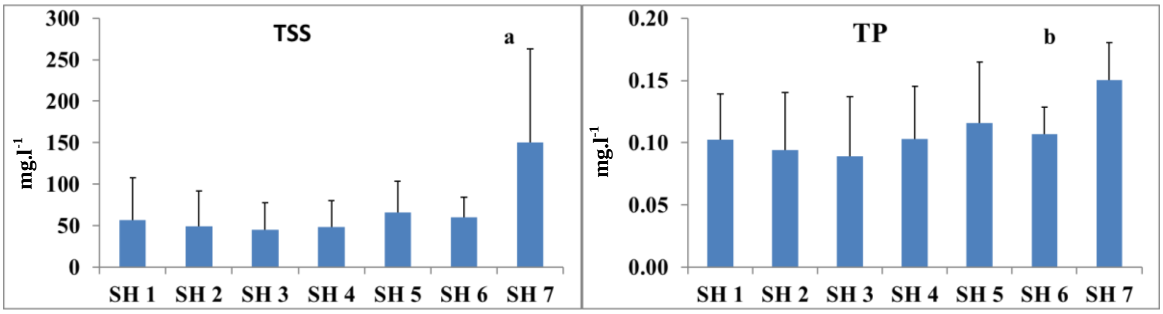

Figure 2. Average values of TSS (a) and TP (b) concentrations at the sites observed in the downstream Red river

The average TSS value in this study was much lower than those observed in the period 1960s (505 ± 112 mg.l^{-1}) at Hanoi site before the Hoa Binh reservoir impoundment and in the period 2002–2003 (611.5 mg.l^{-1}) (table 3) [14] after the Hoa Binh reservoir impoundment. This value was close to the value observed in the period 2010–2015 (77 ± 8 mg.l^{-1}) when a series of large reservoirs went into operation [8]. The results indicate a remarkable decrease in TSS concentration in the downstream Red river due to the operation of a series of reservoirs in both Chinese and Vietnamese Red river upstream areas. Our previous study revealed that the TSS fluxes of the Red river in 2015 (598 ton.km^{-2}.yr^{-1}) were relatively low compared to those of most Asian river systems [15], as a consequence of dam impoundments. However, it was still higher than the mean global annual yield (190 ton.km^{-2}.yr^{-1}) [16].

TP concentration

During 4 sampling campaigns, TP concentrations in downstream the Red river, the section from Hanoi city to the Ba Lat estuary, ranged from 0.050 $mg.l^{-1}$ to 0.188 $mg.l^{-1}$, with an average value of 0.106 ± 0.040 $mg.l^{-1}$ (table 2). The average value of TP concentration in the rainy season reached 0.120 ± 0.040 $mg.l^{-1}$, whereas that in the dry season was 0.091 ± 0.030 $mg.l^{-1}$. No clear difference in TP concentration along the downstream Red river was observed (figure 2).

It is known that in freshwater, phosphorus is often the main factor that limits the production of plant biomass. In addition, the increase of phosphorus concentration is thought to be the major cause of water eutrophication. In the urban rivers, TP concentrations were often very high, e.g the To Lich river (2.89 $mg.l^{-1}$) or the Nhue river (0.39 $mg.l^{-1}$) in Hanoi [14] (table 3). In the comparison with that in the urban rivers, the TP concentrations in the Red river were much lower, probably due to the dilution of its very higher discharges.

The TP concentration in this study was also lower than the value observed in the period of 2012–2013 at Hanoi site (0.04–0.53 $mg.l^{-1}$, with an average value of 0.17 $mg.l^{-1}$) [9] and much lower than the values in the end of the dry (0.21 $mg.l^{-1}$) and the flood seasons (0.56 $mg.l^{-1}$) in the 1980s [17] when limited reservoirs were impounded in the upstream part of the Red river. Thus, we found a clear decrease of TP concentrations of the Red river as reported for TSS concentrations, reflecting the impact of dam impoundments.

Table 3. TSS and TP concentrations of some rivers in the world

River name, country	TSS concentration, $mg.l^{-1}$	TP concentration, $mg.l^{-1}$	Year of observation	References
Corbeira river, Spain	73.1 25–225	0.10 0.005–0.215	2005	[6]
River Taw, at Sticklepath and Pecketsford Bridge, England	3 0–37	- nd*-0.061	2003–2004	[5]
Haihe river, China	-	0.60 (0.3–0.7)	2012	[18]
Huanghe river, China	-	0.04 (0.04–0.06)	2012	[18]
Huaihe river, China	-	0.11 (0.07–0.20) 0.07 (0.03–0.10)	2006 2012	[18]
Minjiang river, China	-	0.05 (0.03–0.07) 0.07 (0.06–0.08	2008 2012	[18]
Sai Gon river at Ho Chi Minh city, Vietnam	from 33.1 ± 25.6 to 98.5 ± 56.7	from 0.1 ± 0.1 to 0.2 ± 0.1	2015–2017	[19]
Day river, Vietnam	-	0.18 (0.01–2.03)	2015	[20]
Nhue river, Vietnam	82.4 (10.2–396.7)	0.39 (0.09–2.99)	2002–2003	[14]
To Lich river, Vietnam	67.4 (36.2–154.0)	2.89 (0.11–9.00)	2002–2003	[14]
Red river at Hanoi, Vietnam	611.5 (26–4040)	0.27 (0.04–1.25)	2002–2003	[14]
Red river at Hanoi, Vietnam	55 (18–153)	0.17 (0.04–0.53)	2012–2013	[14]
Red river, Hanoi to Ba Lat, Vietnam	62.4 (9.4–276.3)	0.106 (0.05–0.188)	2019	This study

Note: nd*: not detected.

Relationship between TSS and TP concentrations of the downstream Red river

Some previous studies presented the close relationship between the TSS concentrations and those of some elements associated (C, N, P,...) in water environment. For example, the relationship of TSS concentrations and their fluxes with particulate organic carbon (POC) was identified in some previous studies of some Asian rivers such as the Yellow river [3], the Changjiang river [4], the Red river [8],... For phosphorus, the relationship between TSS and TP based on the field work was also found in the Great Lakes system (Canada) [2] with the equation as follows:

$$y = 18.83x^{-3.329}$$

Where: x is the annual TSS flux ($kg.ha^{-1}.year^{-1}$); y is the ratio of TP flux to TSS flux ($kg.ton^{-1}$).

The relationship TSS-TP was also reported for the Corbeira river, Spain where the linear regression equations (TP = aTSS + b with R^2 variation between 0.48 and 0.97) were established for different events (baseline, flood,...) [6]. Similar results were found for the stream River Taw (England) where significant positive correlations between TP and TSS were reported [5].

Our previous study on the downstream Red river has also shown a high positive relationship between TSS and TP concentrations [10] but no clear mathematic equation was pointed out. In this study, based on the observation results in the period 2017–2019, the relationship between TSS and TP concentrations in the downstream Red river water, section from Hanoi city to the Ba Lat estuary, was established. This relationship was expressed in the following equation:

$$y = 0.0226x^{0.3867}$$

Where: x: TSS concentration ($mg.l^{-1}$); y: TP concentration ($mg.l^{-1}$) in the Red river water (figure 3).

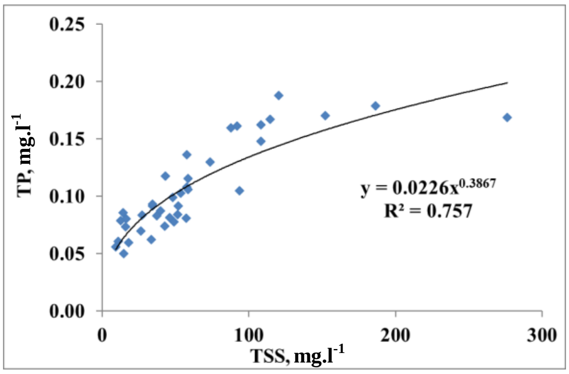

Figure 3. Empirical equation for the relationship between TSS and TP concentrations in the downstream Red river

The exponential equation of TP-TSS shows a strong influence of TSS on TP. This equation allows us to calculate TP concentration in the Red river water when the TSS concentration is available. It is a well-known fact that the determination of riverine TSS concentration is rather simple and often conducted for the Red river. Therefore, the finding of the relationship between TSS and TP concentrations, which facilitates the calculation of TP concentrations in river water, could help to reduce costs in terms of both analyses and laboratory personnel.

On the other hand, it can be seen that due to the close relationship with the TP, the significant reduction of TSS concentration and flux will lead to the clear reduction of TP in the lower part of the Red river. It is known that in Asia, the construction of reservoirs in the upstream rivers has caused dramatic reductions in river discharge, TSS, and nutrient loads into the estuaries and coastal areas [3, 4, 7, 11, 18]. The decreases of TSS and associated substances including P loads have serious consequences, such as increasing coastal erosion, reducing nutrient elements for phytoplankton and aquacultural development, decreasing aquacultural production, loss of shelter and breeding grounds in coastal zones [21]. These problems were observed for some major river systems in Asia, such as the Yellow river, the Changjiang river, the Mekong river [22, 23] and also the Red river where the decrease in TSS fluxes causes intensive coastal erosion, salinization of aqua-cultivated land and changes ecosystems in the coastal zone. In addition, under the impact of the upstream dams, nutrient fluxes (N, P) from the Red river discharging into the coastal zone were reduced by about 32% [7], affecting ecosystems of estuarine and coastal areas. Thus, the TP concentrations should be determined as much as possible to understand the change in ecosystem in the river, estuarine and coastal areas.

Our bias

The above empirical equation was based on a limited number of monitoring samples in the three years 2017–2019 and only for the river section from Hanoi city to the Ba Lat estuary. Thus, it is necessary to increase the observed sample numbers and extend the observation duration time for validating this equation.

CONCLUSIONS

In the downstream Red river, the section from Hanoi city to the Ba Lat estuary in 2017–2019, the TSS concentrations varied in a high range from 9.4–276.3 $mg.l^{-1}$, with an average value of 62.4 ± 53.51 $mg.l^{-1}$. Average value of TSS concentration in the rainy season was found higher than in the dry season whereas no clear difference of TSS concentration along the Red river was detected. The TP concentration ranged from 0.050 $mg.l^{-1}$ to 0.188 $mg.l^{-1}$ with an average value of 0.106 ± 0.04 $mg.l^{-1}$. Similar to TSS longitudinal variation, no clear difference of TP concentration along the Red river was found. Both TSS and TP of the Red river in 2017–2019 were much lower than those observed before 2010s when a series of dams was constructed. The marked decline in TSS, which is related to reduction of TP in the Red river system due to a series of small and medium reservoirs, may affect the ecosystems of the estuaries and coastal zones.

An empirical equation for the relationship between the TSS and the TP concentrations in the downstream Red river water was established, expressing their clear relationship and allowing to calculate TP concentration when TSS measurement results are available. Thus, this work opens up the way for further studies on the calculation of the TP over longer timescales using daily available TSS values.

However, it should be noted that the equation of the TSS-TP relationship was built based on a limited number of monitoring samples, thus it is necessary to increase the observed sample numbers and extend the observation time for validating this equation.

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