Phosphorus Speciation in Wetland Sediments of Zhujiang (Pearl) River Estuary, China

WANG Lili[1, 2], YE Mei[1, 2], LI Qusheng[1, 2], ZOU Hang[1, 2], ZHOU Yongsheng[1, 2]

(1. *Department of Environmental Engineering*, *Jinan University*, *Guangzhou* 510632, *China*; 2. *Key Laboratory of Water/Soil Toxic Pollutants Control and Bioremediation*, *Department of Education of Guangdong Province*, *Guangzhou* 510632, *China*)

Abstract: Phosphorus fractions and adsorption-release characteristics of sediments in the Zhujiang (Pearl) River estuary wetland were investigated. Results showed that the total phosphorus (TP) content in surface sediments ranged from 648.9 mg/kg to 1064.0 mg/kg; inorganic phosphorus (IP) was the major fraction of TP and ranged from 422.5 mg/kg to 643.9 mg/kg. Among the inorganic phosphorus, the main fractions were phosphorus bound to Al and Fe (Fe/Al-P), and calcium-bound phosphorus (Ca-P), accounting for 23%–42% and 21%–67% of IP, respectively. The vertical distribution of TP contents were significantly positive correlated with organic phosphorus (Org-P) and Fe/Al-P contents. The bio-available phosphorus contents in vertical sediments varied from 128.6 mg/kg to 442.9 mg/kg, mainly existed in Fe-Al/P fraction, and increased from the bottom to top sediments. The transport of phosphorus in sediment-water interface was controlled by the soil characteristics. The active Fe and Al content was considered as the main factor that determines adsorption capacity in vegetated marsh wetland. The P buffering capacity of the sediments in vegetated marsh wetland was greater than that in mudflat wetland. The potential risk of eutrophication in the study area is high. Reducing terrestrial phosphorus discharge and preventing the sediment Fe/Al-P release to the interstitial water are the possible solutions to reduce the risk of eutrophication in estuary wetlands, and planting vegetation in estuary wetland can also reduce the release of phosphorus in surface sediment.

Keywords: estuary wetland; phosphorus; fraction; adsorption-desorption

1 Introduction

Sediments act both as a sink and as a source of phosphorus due to continuous transport of chemical species across the sediment-water interface (Adriana and Marcos, 2005). As a major storage of nutrient, sediments play an important role in phosphorus cycling in estuary wetland ecosystem. The phosphorus released from sediments can significantly impact the nutrient budgets of estuarine and fresh water ecosystems (Malecki *et al.*, 2004; Reddy *et al.*, 2007), and is the main factor for eutrophication (Grac and Bolale, 1998). The bioavail-

ability and mobility of phosphorus in sediments are dependent on the original existing chemical forms. The sedimentary phosphorus cycle is characterized by the burial of inorganic phosphorus, degradation of organic phosphorus, and interaction of phosphate with metal oxides in the sediment. Inorganic phosphorus in sediments is found in combination with amorphous and crystalline forms of iron, magnesium, aluminum, and calcium (Malecki *et al.*, 2007). The loosely adsorbed phosphorus (Lsor-P), aluminum-bound phosphorus (Al-P), and iron-bound phosphorus (Fe-P) are easily desorbed from sediments and released to the overlying

water. The Fe-P fraction acts as an important indicator of the phosphorus-release potential of sediment, which has a close relation with the water nutrient status (Ellen and Joselito, 2001; Zhu et al., 2006). Therefore, understanding the phosphorus speciation and its adsorption-desorption characteristics can help to know the process of phosphorus transport at the sediment-water interface and can more efficiently evaluate the risk of eutrophication in the overlying water.

The phosphorus speciation and phosphate adsorption of the sediments from coastal estuaries, oceans, and deep and shallow lakes have been widely studied (Sundareshwar and James, 1999; Wang et al., 2005; Zhou et al., 2005; Wang P et al., 2009). However, those investigations mainly were focused on one or some processes on one kind of sediments, and little was known about the difference of phosphorus speciation and adsorption on different trophic and vegetated marsh wetland sediments. The Zhujiang (Pearl) River estuary (PRE), located in the north of the South China Sea, is the main receiving waters of land-based pollutants. As a result of serious water pollution, the level of nutrients in the estuary significantly increased in the recent decades and led to frequent algae blooms (Huang et al., 2010). Most of previous studies about phosphorus speciation in sediments of PRE mainly were focused on marine areas (Hu et al., 2001; Huang et al., 2003; Yue and Huang, 2005; Yue et al., 2007; Zhang et al., 2009), and little information has been presented about phosphorus speciation in the estuary wetland sediments. These wetlands may intercept large amount of the terrestrial phosphorus discharge.

Therefore, the objectives of this study are to: 1) investigate phosphorus speciation in wetland sediments and determine the potential bioavailability of phosphorus in sediments; 2) analyze the relationship between phosphate adsorption-desorption characteristics and sediment compositions; and 3) evaluate the risk of eutrophication in the estuary wetland.

2 Materials and Methods

2.1 Study area and sample collection

The study area ($22°23'36''$–$22°45''57$N, $113°27'52''$–$113°36'47''$E) is located in the Zhujiang River estuary (PRE), South China. PRE has a subtropical maritime monsoon with a mean annual temperature of $23.3°C$ and an annual precipitation of 1655.7 mm.

Three sampling sites (X-1, X-2, and X-3) from the upstream of the estuary (channels of Xiahengli, Shanghengli and Jiaomen, respectively) and three sampling sites (G-1, L-1, and H-1) from the downstream of the estuary (intertidal zones with mudflat, phragmites, and mangrove regions, respectively) were randomly selected (Fig. 1). Soil cores in the depths of 0–70 cm (X-1 and X-2 sites), 0–40 cm (X-3 site) and 0–10 cm (G-1, L-1, and H-1) were collected with a soil auger (4.8-cm diameter) at each sampling site in spring of 2009; and sectioned into 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, 50–60 cm, and 60–70 cm horizons. All soil samples were taken to the laboratory in sealed plastic bags, were air dried at room temperature, and sieved through a 2-mm nylon sieve to remove coarse debris.
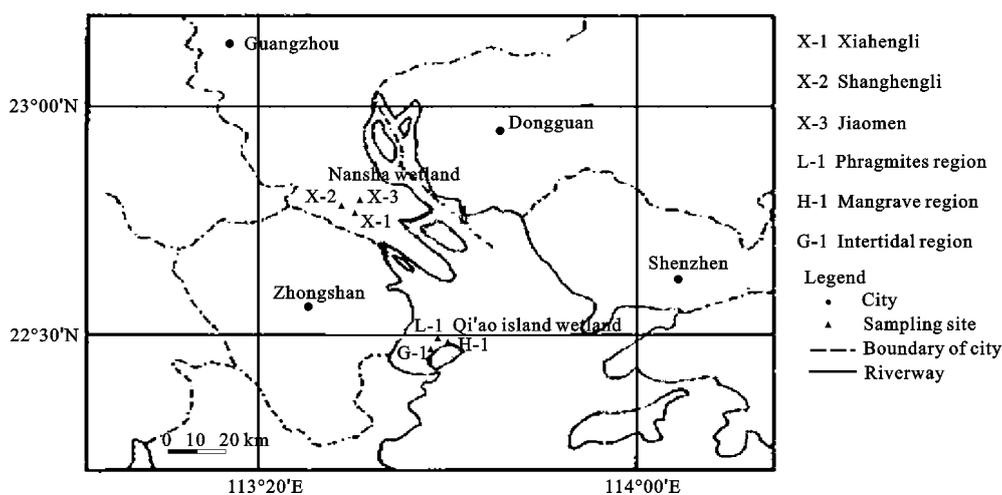
Fig. 1 Location of sampling sites in Zhujiang River estuary wetland

All air-dried soil samples were then ground by using mortar and pestle until all particles passed a 0.149-mm nylon sieve.

2.2 Phosphorus fractionation and soil property measurement

Phosphorus fractions in the sediments were extracted by using the modified standard measurements and testing (SMT) method (Ruttenberg, 1992; Ruban *et al.*, 1999). This operationally defined scheme comprises a sequence of five fractions, including loosely adsorbed phosphorus (Lsor-P, weight 0.500 g of dry sediment, 1 M $MgCl_2$, pH 8, extracted), phosphorus bound to Al and Fe and Mn oxides and hydroxides (Fe/Al-P, collect the last step extract, 1 M NaOH, 3.5 M HCl extracted), phosphorus associated with Ca (Ca-P, wash the last step residue with 1 M NaCl, 1 M HCl extracted); and inorganic phosphorus (IP, weight another 0.500 g of dry sediment, 1 M HCl extracted), organic phosphorus (OP, freez-dried the last step residue, 550℃ calcinate 5 h, 1 M HCl extracted). Moisture content of sediment was determined by oven-dried at 105℃ for 24 h. Organic matter content was determined as loss on ignition (LOI) (Bao, 2000). Total content of Al, Fe and Ca of the prepared soil was determined with $HCl-HNO_3-HF-HClO_4$ extraction. The active iron (Fe-ox), aluminum (Al-ox), and phosphorus (P-ox) were extracted with ammonium oxalate (Danen *et al.*, 1993). All extracted elements were determined with inductively coupled plasma atomic absorption spectrometry (ICP/AES, OPTIMA 2000DV, USA). Quality assurance and quality control were assessed by using duplicates, and one blank and one standard reference materials were applied to each ten samples. The recoveries of spiked samples ranged 92%–105%.

2.3 Phosphorus adsorption-desorption characteristic experiments

Phosphorus adsorption-desorption kinetic experiments and isotherm experiments on the sediments were conducted to investigate the maximum phosphorus adsorption capacity and estimate the rate of adsorption-desorption. Dried sediment samples (0.500 g) were added in a series of 100 mL acid-washed conical flask with 50 mL 0.01 mol/L $CaCl_2$ solution. The conical flask was capped and placed at approximately 25℃ in an orbital shaker. For kinetic experiment, the initial phosphorus concentration was 2 mg/L and in an orbital shaker at 150 rpm for different time intervals, varying within 24 h (0 h, 0.5 h, 1 h, 2 h, 4 h, 8 h, 11 h, and 24 h). For isotherm experiment, five different initial phosphorus concentrations were chosen (0.2 mg/L, 0.5 mg/L, 1.0 mg/L, 1.5 mg/L, and 2.0 mg/L) in an orbital shaker at 150 rpm for 24 h. After the adsorption reached saturation, the sample (initial phosphorus concentration was 2 mg/L) was centrifuged and washed twice with saturated sodium chloride solution to remove the residual monocalcium phosphate (CaH_2PO_4). The $CaCl_2$ solution (50 mL 0.01 mol/L) was then added for phosphorus release experiments (Wang S G *et al.*, 2009). For all the samples, triplicate experiments were carried out and the data were expressed as their average.

2.4 Risk assessment of phosphorus release

The single-factor standard index is widely adopted to estimate the phosphorus pollution in certain areas, specifically to rank the contamination level in comparison between actual level and the standard of certain contaminator (Hakanson *et al.*, 1980; Ma and Wang, 2003). The formula is as follows:

$$S_i = C_i / C_s \qquad (1)$$

where S_i is the pollution index, C_i is the actual phosphorus concentration of the sample i (mg/kg), and C_s is the standard index of phosphorus (mg/kg). According to the environmental quality evaluation criteria for eutrophication (1992) of Ontario, Canada Department of Environment and Energy (DOEE) (Mudroch and Azcue, 1995), if the substance concentration is over 600 mg/kg, then this certain contaminator would cause the minimum level of ecological risk (Yue and Huang, 2005; Yu *et al.*, 2011). It means that 600 mg/kg is the standard index of the single factor. When S_i is higher than 1, the certain contaminator oversteps the standard.

The phosphorus-induced eutrophication risk index (ERI) is developed as the percentage of degree of phosphorus saturation (DPS) divided by phosphorus adsorption index (PAI). DPS normalizes extractable phosphorus by using extractable Al and Fe as a surrogate for phosphorus adsorption capacity (Huang *et al.*, 2004).

$$ERI = (DPS / PAI) \times 100\% \qquad (2)$$

$$PAI = X / \lg C \qquad (3)$$

$$DPS(\%) = 100P\text{-}ox / [0.5(Al\text{-}ox + Fe\text{-}ox)] \qquad (4)$$

where X is the absorbed phosphorus content (mg

P/100g); C is the phosphorus concentration in solution (μmol/L); P-ox, Al-ox, Fe-ox are ammonium oxalate extractable active phosphorus, aluminum, and iron (mmol/kg). Risk assessment is divided into four levels: high risk ($ERI > 25$), higher risk ($20 < ERI < 25$), medium risk ($10 < ERI < 20$), and lower risk ($ERI < 10$).

2.5 Statistical analysis

Statistical analysis was carried out by using SPSS 16.0 for Windows. Results were tested for correlation between the content of the phosphorus in each sediment layer.

3 Results

3.1 Sediment characteristics

Soil properties are listed in Table 1. Al was the domi-

nant metal in the sediments and ranged from 65.9 g/kg to 138.7 g/kg. The Fe contents ranged from 31.6 g/kg to 76.2 g/kg. The percentages of active Fe (Fe-ox) in the total Fe ranged from 7.96% to 22.6%, with an average of 14%, and those of Active Al (Al-ox) ranged from 0.5% to 1.5% of the total Al, with an average of 0.89%.
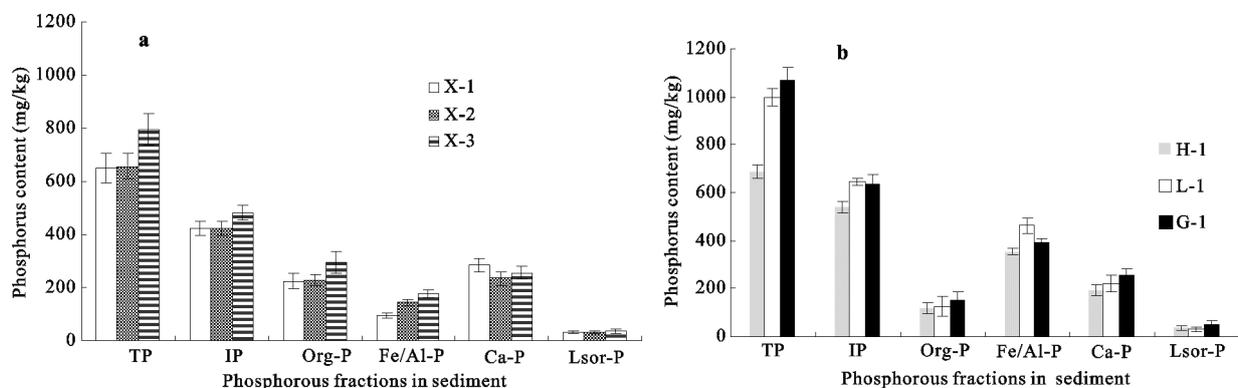
3.2 Phosphorus speciation in surface sediments

Contents of total phosphorus (TP), Org-P, IP, Fe/Al-P, Ca-P, and Lsor-P in the surface sediments are presented in Fig. 2. In the upstream of the estuary, the TP contents varied from 648.9 mg/kg to 794.6 mg/kg and Org-P contents varied from 224.5 mg/kg to 295.7 mg/k, respectively. The IP was the major fraction of TP, and Ca-P was the main fraction of IP. The average contents of Ca-P, Fe/Al-P, and Org-P accounted for 45.7%, 13.0% and 26.5% of the TP, respectively. Lsor-P content

Table 1 Physical and chemical characteristics of soil samples

Sampling site	Depth (cm)	pH	Organic matter (%)	Moisture (%)	Fe (g/kg)	Al (g/kg)	Ca (g/kg)	Fe-ox (g/kg)	Al-ox (g/kg)
X-1	0–10	7.63–7.83	5.58	41.9–42.3	52.9	84.6	12.30	6.872	0.659
	30–40	7.81–8.01	8.91	47.8–48.3	76.2	131.6	13.50	6.483	0.697
	60–70	7.71–7.94	7.14	40.8–41.2	69.9	112.4	19.80	9.101	1.033
X-2	0–10	7.79–7.99	11.40	61.2–62.4	69.6	138.7	10.10	9.289	1.169
	30–40	7.84–8.09	12.70	55.3–56.1	53.1	90.3	7.05	8.314	0.981
	60–70	7.57–7.73	10.20	66.3–68.7	55.4	87.7	12.60	8.287	0.902
X-3	0–10	7.36–7.59	13.30	49.5–50.6	74.0	130.5	5.14	10.210	1.019
	20–30	7.62–7.78	11.10	51.3–53.7	69.3	117.9	4.60	9.073	0.973
	30–40	7.94–8.06	10.50	34.8–36.2	59.2	104.6	6.02	8.172	0.901
G-1	0–10	7.85–8.05	9.46	39.5–48.9	57.9	99.3	6.43	4.606	0.664
L-1	0–10	7.68–7.95	9.82	32.8–38.7	46.4	134.8	4.77	8.248	1.211
H-1	0–10	7.83–8.09	10.50	35.6–51.7	31.6	65.9	3.68	7.135	0.971

Notes: X-1, X-2 and X-3, sampling sites in Nansha wetland, with Xiahengli channel (X-1), Shanghengli channel (X-2) and Jiaomen channel (X-3) named upstream of the estuary; G-1, L-1 and H-1, sampling sites in Qi'ao island wetland, with intertidal region (G-1), phragmites region (L-1) and mangrove region (H-1) named downstream of the estuary

Fig. 2 Contents of various phosphorus fractions in surface sediment in upstream (a) and downstream (b)

was the lowest in the phosphorus fractions, which varied from 32.73 mg/kg to 36.47 mg/kg, and less than 8% in the TP contents.

In the downstream of the estuary, the average content of TP ranged from 687 mg/kg to 1068 mg/kg. The IP was the main fraction of the TP, accounting for 67% of the TP. Fe/Al-P, Ca-P, and Org-P were the next most abundant phosphorus fractions, with an average of 44.8%, 24.8% and 14.7% of the TP, respectively. In all the sediments, Lsor-P content was the lowest, and the average content of Lsor-P was less than 5% of the TP content. Significant differences exist between the upstream and downstream of the estuary for Fe/Al-P and Org-P contents. Org-P contents in the upstream of the estuary were obviously higher than those in the downstream; while the mean content of Fe/Al-P in the downstream of was nearly three times of that in the upstream.

The relationships between phosphorus fractions are shown in Table 2. The results indicated that the highly significant and positive correlation between TP content and IP, Org-P and Fe-Al/P content ($p < 0.01$). As one kind of inorganic phosphorous fractions, Fe/Al-P content also had a close relation with IP content ($p < 0.01$).

3.3 Vertical distribution of phosphorus in sediments

Figure 3 shows the vertical distribution of phosphorus fractions. The TP gradually decreased with the depth, and there was an accumulative peak in the depth of 50

Table 2 Intercorrelations between various phosphorus fractions in sediments

|	TP	IP	Org-P	Ca-P	Fe/Al-P	Lsor-P
TP	1.000	0.899[**]	0.919[**]	0.451	0.807[**]	0.436
IP		1.000	0.238	0.658[*]	0.827[**]	0.394
Org-P			1.000	0.203	0.491	0.321
Ca-P				1.000	0.226	0.152
Fe/Al-P					1.000	0.053
Lsor-P						1.000

Notes: *, $p < 0.05$, significant correlation; **, $p < 0.01$, utmost significant correlation; $n = 21$

cm in X-1 and X-2 sites. The Org-P demonstrated similar vertical distribution pattern to TP because Org-P content was strongly associated with the TP content (Table 2). The IP generally decreased with the depth, but small accumulative peaks appeared in deeper sediments, and the tendency for IP variation with the depth was depending on Ca-P and Fe/Al-P variations in the sites X-1 and X-2, respectively. Being different from sites X-1 and X-2, the highest Org-P content was found in the depth of 10–20 cm in site X-3. The phosphorus fractions of vertical distribution in site X-3 showed Org-P > Ca-P > Fe/Al-P > Lsor-P.

3.4 Adsorption-desorption characteristics of phosphorus in sediments

3.4.1 Phosphorus adsorption characteristics

The results of phosphorus adsorption kinetic experi-
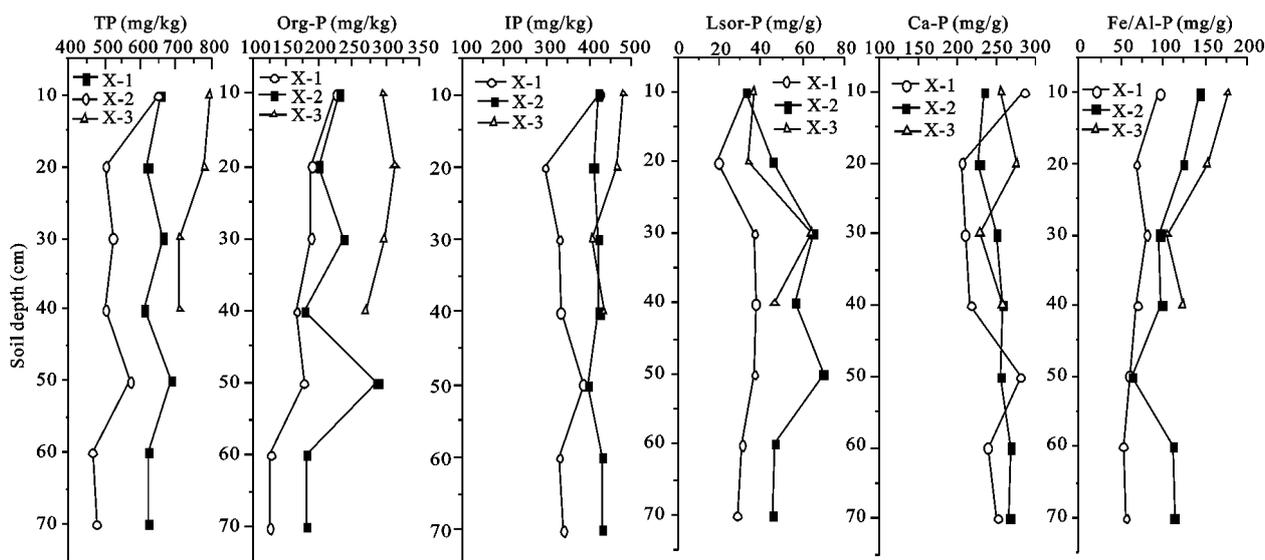
Fig. 3 Vertical distribution of phosphorus content in sediment of upstream of estuary (TP: total phosphorus; Org-P: organic phosphorus; IP: inorganic phosphorus; Lsor-P: loosely adsorbed phosphorus; Fe/Al-P: iron-bound and aluminum-bound phosphorus; Ca-P: calcium-bound phosphorus3.)

ments are shown in Fig. 4. The majority of phosphorus adsorption on sediments was completed in 2–4 h, and the sediments adsorption capacity in the downstream of the estuary was significantly greater than that in the upstream. The adsorption kinetics was similar in both areas, and the average adsorption rate in 0–0.5 h was the highest within 24 h, and ranging from 106.4–241.4 mg/(kg·h) and 214.8–285.6 mg/(kg·h) in the upstream and downstream of the estuary, respectively. These results indicated that a quick adsorption process mainly occurred within 0.5 h. The decrease was possibly due to the less active sites being available to phosphorus.

The relationship between the amount of adsorption phosphorus per unit mass of sediment and its equilibrium concentration are shown in Fig. 5. The results indicated that the adsorption rate increased initially with the increasing equilibrium concentration, and then reached saturation. Adsorption isotherms of the sediments in the study area were similar; and the Langmuir model can properly describe the adsorption properties of the sediments. This was in agreement with the results of Huang et al. (2012). The average phosphate adsorption

capacity was 351.5 mg/kg in the downstream of the estuary, and the maximum adsorption capacity was 555.6 mg/kg in site H-1 in the downstream. The sediment in the downstream of the estuary has significantly higher adsorption capacity than the upstream.

3.4.2 Phosphorus release characteristics

The results of phosphorus release kinetic experiments are presented in Fig. 6. The majority of phosphorus release in both areas was completed in 2 h. The average released phosphorus content was 8.8 mg/kg and 12.7 mg/kg, amounting to 87% and 98% of those released in 24 h for the sediments in the upstream and downstream of the estuary, respectively.

The relationships between adsorption-release capacity and sediments composition are listed in Table 3. The adsorption capacity is significantly negatively correlated with the contents of Ca-P and Lsor-P; and significantly positively correlated with the contents of IP and Fe-Al/P, soil organic matter, active Fe (Fe-ox), Al (Al-ox), and P (P-ox). However, no significant relationship existed between release capacity with phosphorus fractions and sediments composition.
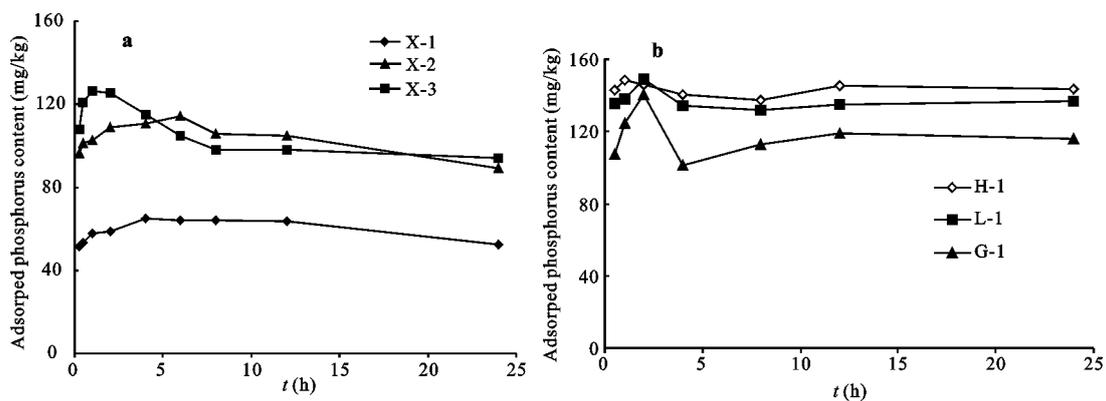

Fig. 4 Phosphorus adsorption kinetic curves on sediments in upstream (a) and downstream (b)
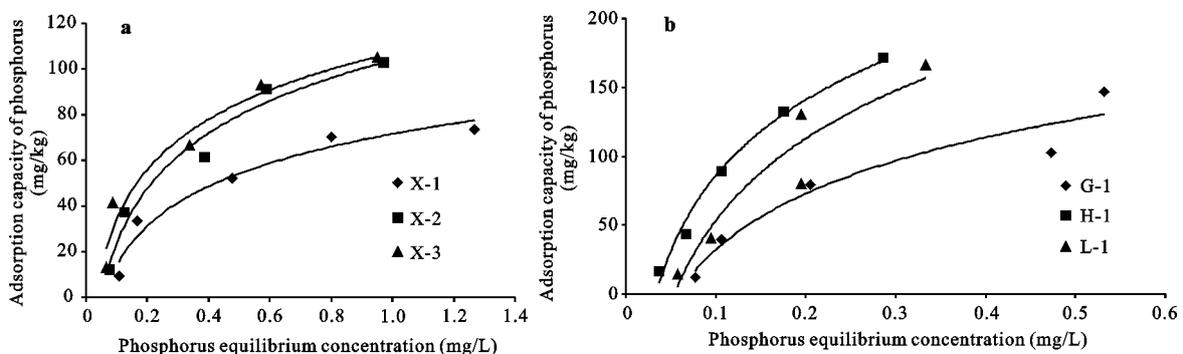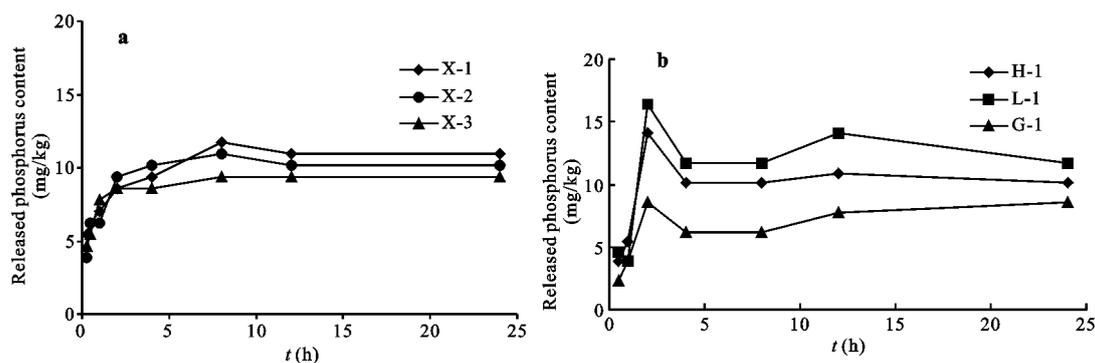

Fig. 5 Adsorption isotherms of phosphorus on sediments in upstream (a) and downstream (b)

Fig. 6 Phosphorus release kinetic curves on sediments in upstream (a) and downstream (b)

Table 3 Pearson correlation coefficients between adsorption-release capacity with sediment composition

	Lsor-P	Fe/Al-P	Ca-P	IP	Org-P	TP	P-ox	SOM	Fe-ox	Al-ox
Adsorption capacity	-0.845^{**}	0.476^{*}	-0.795^{**}	0.514^{*}	-0.286	-0.381	0.472^{*}	0.573^{*}	0.505^{*}	0.565^{*}
Release capacity	0.108	0.306	0.057	0.324	-0.189	0.285	-0.257	-0.321	-0.273	-0.259

Notes: **, $p < 0.01$, *, $p < 0.05$; $n = 21$; SOM, soil organic matter

3.5 Risk assessment in sediments

Pollution indexes in all the sites were higher than 1, ranged from 1.08 (site X-1) to 1.78 (site G-1), implying that the sediments in the study area were polluted by phosphorus. The sediments in the downstream of the estuary wetland were more serious pollution than those in the upstream. The most serious phosphorus pollution occurred in mudflat region. The eutrophication risk index calculated is listed in Table 4. The Results showed that the sediments in both areas had high eutrophication risk.

4 Discussion

4.1 Variation of phosphorus fraction in sediments

The IP was the major phosphorus fraction in the sediments (Table 2). The Fe/Al-P and Ca-P substantially contributed to the supply of IP in these sediments. Generally, Lsor-P, Fe/Al-P, and part of org-P are easily de-sorbed from the sediments and released to the overlying water. These are referred to as the bio-available fraction of phosphorus in the sediment.

The mean Lsor-P content in the sediments was the lowest among the phosphorus fractions, accounting for approximately 10.6% and 6.2% of IP in the upstream and downstream of the estuary, respectively. The fraction of Lsor-P has a close relationship with the sediment environment (Kim et al., 2003), and might release from $CaCO_3$-associated phosphorus or from decaying cells of bacterial biomass in deposited phytodetrital aggregates (Pettersson, 2001). The highest Lsor-P content was 52 mg/kg in the sediment from the intertidal mudflat wetland. By contrast, the sediments from the vegetated area (sites H-1 and L-1) had the lower average content of Lsor-P of 31 mg/kg. This result indicated that macrophytes could effectively decrease the Lsor-P in the sediment and consequently reduce the release of phosphorus from the sediment to the overlying water.

Table 4 Eutrophication risk index in study area

Site	P-ox (mmol/kg)	Fe-ox (mmol/kg)	Al-ox (mmol/kg)	PAI (mg P/100g)/(μmol/L)	DPS (%)	ERI (%)	Risk level
X-1	6.97	122.7	24.4	7.85	9.4	119.7	High
X-2	11.27	165.8	43.2	11.24	10.7	95.2	High
X-3	12.67	182.3	37.7	11.64	11.5	98.8	High
G-1	5.70	82.5	24.6	9.34	10.1	108.1	High
H-1	7.15	127.4	35.9	14.50	8.9	61.4	High
L-1	10.50	147.4	44.8	13.90	10.9	78.3	High

The mean Fe/Al-P content was significantly higher than the other fractions (Fig. 2). The Fe/Al-P includes phosphorus associated with oxides and hydroxides of Al, Fe, and Mn, and this fraction can be released for the growth of phytoplankton when anoxic conditions prevail at the sediment-water interface (Dai *et al.*, 2006; Hou *et al.*, 2009). The higher Fe/Al-P content resulted from the high active Fe/Al oxides content in the sediment. Most the sediments in the estuary wetland originated from the erosion of red soil in the upstream, and the red soil is rich in Fe/Al oxides. Furthermore, the water phosphorus pollution contributed to the high Fe/Al-P content in the sediments (Zhong *et al.*, 2008). The coastal estuary is located in the downstream of the Zhujiang River Delta megacities, so the area received a large amount of phosphorus pollutants. And the changes for nutrient contents, storages in soils and their bioavailabilities to wetland plants along pedogenic chronosequence in the Zhujiang River estuary also demonstrated that a higher soil phosphorus, Al and Fe accumulation potential by plant roots can be expected in fringe marshes to undergo decades of natural pedogenesis with growing impacts from human activities (Xiao *et al.*, 2011). The contents of TP and Fe/Al-P in the sediments of the estuary wetland are nearly three times higher than those in marine sediments of the Zhujiang River estuary (Hu *et al.*, 2001; Yue and Huang, 2005), suggesting that the original phosphorus in the coastal estuary wetland came from land-based contaminated water.

Phosphorus in the sediment was mainly concentrated in the upper sediment (0–20 cm), with significantly higher concentrations compared with those in the deeper sediments (Fig. 3). However, the reason for an accumulative peak of TP and Org-P at the 40–50 cm depth might be the relatively high soil organic matter (SOM) in this increment, because soil organic compounds could act as a stable sink for phosphorus associated with clay particles. It was in agreement with the results of Xiao *et al.* (2012). The vertical distribution of Org-P content in the sediments showed that the current phosphorus pollution in the coastal estuary wetland was more serious than before, causing the Org-P content in the surface sediments to be obviously higher than that at the bottom. The Org-P content accounted for approximately 35% and 15% of TP in the sediments of the upstream and downstream, respectively. These results were attributed to most of the Org-P discharged from the outlet of sewage treatment plants in cities located upstream.

4.2 Adsorption and desorption characteristics on phosphorus transport

The phosphorus adsorption characteristics indicated that phosphorus in sediment-water interface transported quickly. This transport was controlled by the soil characteristics, especially the surface SOM and the adsorption of active Fe (Fe-ox) and Al (Al-ox) to phosphorus in the sediments (Table 3). It was in agreement with the results of Zhang and Huang (2007) and Lu *et al.* (2011). In downstream sediments, a significantly higher phosphorus adsorption capacity was found in vegetated region (Fig. 5), and this situation resulted from the oxidation environment of roots, which caused the higher ratio of active Fe/Al oxides in the vegetated region sediments than in the mudflat region sediments. The difference of adsorption-release capacity in the upstream and downstream might result from the decomposition and accumulation of SOM and the changes of salinity under different environmental conditions, and Bai *et al.* (2007) and Liu *et al.* (2012) also found that the TP contents were closely related to SOM content in the wetland soils, and salinity played an important role in soil nutrient change. However, further study concerning the complex mechanism is still needed.

Although the highest phosphorus-released capacity also appeared in the sediments of the vegetated region in laboratory conditions (Fig. 6), it did not indicate that all phosphorus would be instantly released into the overlying water. On the contrary, phosphorus would be released slowly and absorbed by the roots of vegetation. Therefore, the sediments in the vegetated region presented higher phosphorus buffering capacity and lower release tendency.

4.3 Risk of phosphorus release in sediments

The results of the pollution index (S_i) indicated that high potential eutrophication risk had presented in both study areas (Table 4). Combined with the value of PAI, DPS, and ERI, the sediments in the mangrove region always had a higher PAI and a lower DPS%. Based on this condition, the sediments in the vegetated region had the best ability to trap dissociative phosphorus and reduced the risk of partial release. However, because active Fe/Al oxides are the main factors to retain dissolved phosphorus in solution or mineralized phosphorus from organic

matter (Lau and Lane, 2002), this mechanism of ephemeral retention rather than permanent burying of phosphorus might go against the restoration of eutrophication in the estuary wetland, leading to a potentially high risk.

5   Conclusions

The phosphorus pollution in estuary wetlands is more serious than that in the marine area of the estuary. The Fe/Al-P is the main existing form of bio-available phosphorus in the surface sediments. The transport of phosphorus in sediment-water interface is controlled by the soil characteristics, and the active Fe and Al content is considered as the main factor that determines adsorption capacity in vegetated marsh wetland. The potential risk of eutrophication in the study area is high. Reducing terrestrial phosphorus discharge and preventing the sediment Fe/Al-P release to the interstitial water are the possible solutions to reduce the risk of eutrophication in estuary wetlands, and planting vegetation in the estuary wetland can also reduce the release of phosphorus in surface sediments. However, restricted by the experimental conditions and the fewer samples, the effect of the environmental conditions, especially the changes of hydrodynamic conditions on phosphorus release in the sediments is deficient. In addition, it is necessary to research the biological community structure characteristics of sediments and the impact of vegetation on phosphorous migration and transformation in typical estuary wetland.

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