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Lateral and longitudinal variation in phosphorus fractions in surface sediment and adjacent riparian soil in the Three Gorges Reservoir, China

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Abstract

Hydrological regimes have been significantly altered since the Three Gorges Dam (TGD) raised the water level of the reservoir to the maximum design level of 175 m in October 2010. This change might greatly influence the forms of phosphorus (P) in the sediment and the adjacent riparian soil. The purpose of this study was to reveal the lateral (sediment, water-level-fluctuation zone soil, and upland soil) and longitudinal (from the end of backwater area to the TGD) trends in P factions. Samples from 11 sites located along the main stem and ten sites located along eight tributaries were collected in June 2017. The P fractions were determined using the Standards, Measurements, and Testing (SMT) protocol. The results showed that the order of increase for average pH values was sediment (7.58 ± 0.62), WLFZ soil (7.44 ± 0.29), and adjacent upland soil (7.20 ± 0.68). The total organic carbon in the sediment was also highest with an average of 9.15 ± 2.97 mg·g^{-1}. The average concentrated HCl-extractable P (total P), organic P (OP), inorganic P (IP), HCl-extractable P (HCl-P), and NaOH-extractable P (NaOH-P) were 630.02 ± 212.24, 161.89 ± 90.77, 468.13 ± 194.92, 335.65 ± 159.88, and 51.40 ± 36.20 mg·kg^{-1}, respectively. The concentration of both total P and NaOH-P in the sediment of the main stem exhibited an increasing trend from the backwater area to the TGD. The average concentration of P species in the sediment was higher than those in the upland soil and the water-level-fluctuation zone (WLFZ) soil. For all the sediment and soil samples, the rank order of P species concentrations was HCl-P > OP > NaOH-P. Both IP and HCl-P were highly positively correlated with total P in the upland soil, the WLFZ soil and the sediment. However, only in the sediment, NaOH-P was positively correlated with total P and OP. All P species in the upland soil demonstrated greater spatial heterogeneity than those in the WLFZ soil and the sediment. Redundancy analysis revealed that the main variables explaining the variance in P species concentrations were Al in the upland soil and pH in the sediment.

Keywords Phosphorus fraction · Three Gorges Reservoir · Water-level-fluctuation zone · Sediment · Riparian · Heterogeneity

Introduction

Globally, there are more than 70, 000 large dams, and the number will continue to increase in the next few decades to satisfy the increasing demand for hydroelectricity, flood

mitigation, and reliable water supplies (Lehner et al. 2011; Maavara et al. 2015, 2017). The impoundment of dams can significantly alter the hydrological regime and water temperature, deepen the water depth, slow the water flow rate, and result in changes to the form and bioavailability of phosphorus (P) in sediments and shorelines (Zhang et al. 2016a; Van Cappellen and Maavara 2016). As dams are constructed, the sediment deposition conditions change and impact the adsorption and retention of P in reservoirs (Kunz et al. 2011; Cunha et al. 2014; Lu et al. 2016). Excess P from agricultural, industrial, and municipal sources into freshwater can lead to eutrophication and algal blooms (Xiang and Zhou 2011; Zhang et al. 2016b). The soil and sediment characteristics, and environmental factors, as well as the concentration of P in the overlying water, affect the direction of phosphate transport across the sediment-water interface (Borgnino et al. 2006; Huang et al. 2011).

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However, not all fractions of P are likely to be released from sediments and riparian soils. To determine the bioavailability and mobility of P fractions, several sequential extraction procedures have been developed. The Standards, Measurements, and Testing (SMT) protocol is the most widely used approach to determine P fractions in sediments, soils, and sewage sludge (Zhu et al. 2013). This protocol allows the definition of the following fractions: concentrated HCl-extractable P (total P), inorganic P (IP), organic P (OP), NaOH-extractable P (NaOH-P), HCl-extractable P (HCl-P) (Ruban et al. 2001). Applications of the novel instrumentation and approaches have greatly improved our understanding of sedimentary P forms and rates of burial, such as spectroscopic techniques (^{31}P nuclear magnetic resonance spectroscopy, ^{31}P NMR) (Turner et al. 2014; Zhang et al. 2016a), X-ray spectroscopy and radioactive P isotope tracers (^{32}P and ^{33}P), and diffusive gradients in thin films (DGT) (Defforey and Paytan 2018; Ding et al. 2018).

The first impoundment of the Three Gorges Reservoir (TGR) occurred in June 2003. The water level has varied from 145 m in summer (from June to September) to 175 m in winter (from October to December) since the water level of the reservoir was raised to the maximum design level in October 2010. The river flow pattern and sediment deposition conditions have changed because the water flow velocity has decreased and the submergence depth has increased. The water-level-fluctuation zone (WLFZ), with an area of 302.0 km^2, is the exposed region between the high and low water levels along the bank of a reservoir. The soil properties in the WLFZ have also changed due to periodic wet-dry cycles, and so do sediment properties. Many studies investigated spatial variations in the total and available P (Guo et al. 2011; Wu et al. 2016; Zhuo et al. 2017) and phosphate sorption-release (Zhang et al. 2012; Zhang et al. 2013) only in WLFZ soil or in sediment. However, P fractions in sediment and adjacent riparian soil in the TGR may be affected by complicated topographic characteristics, disturbance of human activity, and special hydrological regulated regime. For the TGR managers, further studies on the P fractions and their influencing factors may contribute to great understanding and better prediction of eutrophication status of TGR.

The main objectives of this study were as follows: (1) to reveal the longitudinal variation (from the end of the backwater area to the Three Gorges Dam) in phosphorus species and (2) to clarify the difference in P fractions and their influencing factors in the surface sediment, the WLFZ soil and the upland soil. The results are beneficial not only for determining the distribution of the P being moved downstream but also for assessing the potential release risk of P in the surface sediment and the WLFZ soil.

Materials and methods

Study area

The Three Gorges Reservoir (TGR) region (28°32′ to 31°44′ N, 105°44′ to 111°39′ E) lies in the central district of the Yangtze River in China. This region has a southeastern subtropical monsoon climate. The mean annual temperature and precipitation are 14.9–18.5 °C and 1000–1300 mm, respectively. The main types of soil are purple soil, paddy soil, yellow soil, and calcareous soil (Bing et al. 2016). The TGR plays a key role in flood control, water supply, power generation and shipping, and national drinking water security. However, the construction of the TGR resulted in the loss of the original vegetation, especially trees and shrubs (Zhang et al. 2013). After the impoundment, nearly 76.25% of suspended sediment and 75.35% of particulate phosphorus were trapped by the TGR (Tang et al. 2018). Consequently, the total P may be accumulated in sediment. The risk of algal blooms outburst may increase.

Sample collection

Field surveys were conducted in June 2017 when the WLFZ was completely exposed. Eleven sample sites were located along the main stem of the Yangtse River (S1, S3, S5, S6, S7, S8, S12, S14, S17, S19, and S21). Ten sample sites were located on eight tributaries (i.e., S2 on the Yulin River; S4 on the Wujiang River; S9, S10, and S11 on the Xiaojiang River; S13 on the Daning River; S15 and S16 on the Shennongxi River; S18 on the Qinggan River; and S20 on the Xiangxi River) (Fig. 1). At each site, three upland soil samples (0–20 cm) were randomly collected by a soil auger at elevations from 180 to 200 m and then mixed to form a composite sample. Six WLFZ soil samples (0–20 cm) were collected in an "S" sampling pattern at elevations from 145 to 175 m and then mixed. At S1, samples were only collected between the elevations of 170 and 175 m due to the high water level during the sampling period. At S2, S3, S4, and S5, samples were collected only between the elevations of 160 and 175 m. To obtain representative samples, three surface sediment samples were collected from each site a Peterson grab sampler and then mixed to provide one sample for analysis. A total of 63 composite samples were collected and immediately put into the plastic bags.

Chemical analysis

The pH of sediments and soils was measured in 0.01 M CaCl$_2$ using a 1:2.5 soil-to-solution ratio. The total organic carbon (TOC) was determined by the potassium dichromate oxidation method according to a Chinese standard method HJ615-2011. For analysis of the total concentration of Fe, Al, Mn, Ca, Mg, and K, samples were digested with a mixture of nitric,
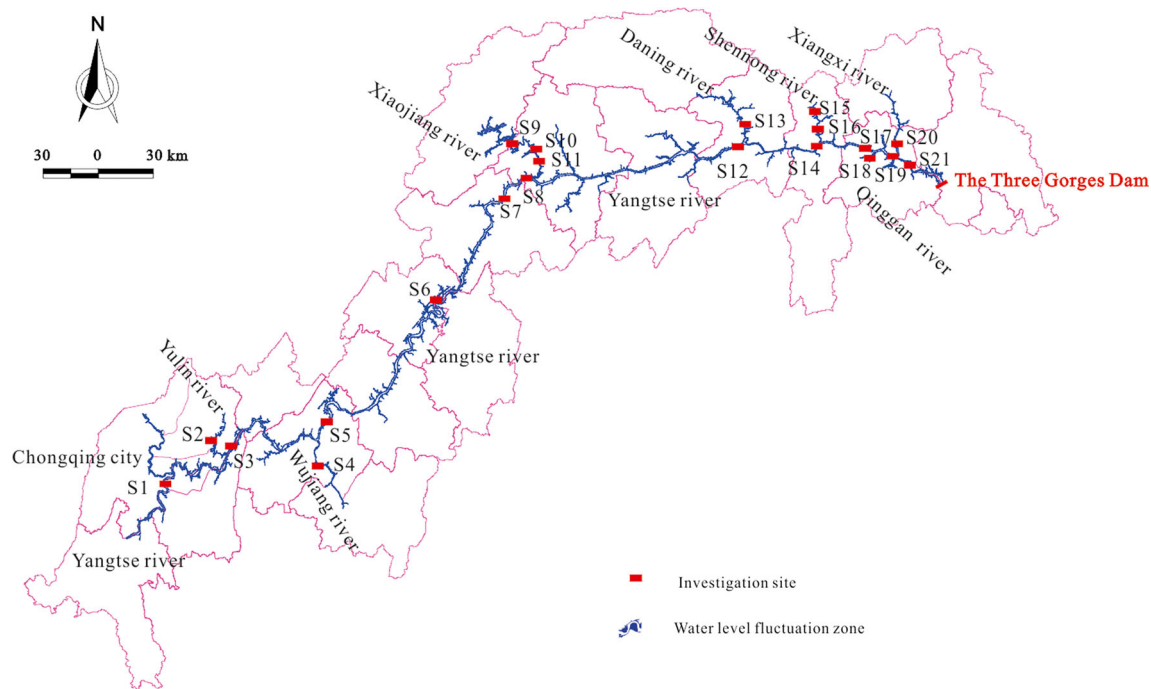
Fig. 1 Investigation sites in the Three Gorges Reservoir

hydrofluoric acid, and hydrochloric acids (9:3:2) (US EPA 1996). The digests were analyzed by inductively coupled plasma mass spectrometry (ICP-MS).

Phosphorus fractionations analysis by SMT

The air-dried samples were sieved with a standard 100-mesh sieve and then the P fractions were measured. The procedure was based on the improved standard, measurement, and test (SMT) procedure, which is an approach for determining phosphorus fractions in sediments. This protocol allows the definition of the following fractions: concentrated HCl-extractable P (total P), inorganic P (IP), organic P (OP), NaOH-extractable P (NaOH-P), HCl-extractable P (HCl-P) (Ruban et al. 2001). The OP content was calculated as the difference between total P and IP (Shan et al. 2016). After each extraction step, the supernatant was filtered through a 0.45 μm Millipore filter. The phosphate concentration in the extract was analyzed using the molybdenum blue method (Fig. 2) (Medeiros et al. 2005; Zhang et al. 2016a).

Statistical analysis

The experimental data were analyzed using SPSS 19.0 for Windows. One-way ANOVA (Student-Newman-Keuls Test, $p < 0.05$) was performed to identify the significant differences in P concentrations in upland soil, WLFZ soil, and sediment (Bing et al. 2016). Pearson's correlation (2-tailed) was used to determine the correlation between P fraction and other properties (Shan et al. 2016). The levels of significance are

reported as non-significant ($p \geq 0.05$), significant (*, $0.05 > p \geq 0.01$), or highly significant (**, $p < 0.01$).

Redundancy analysis (RDA) was also used to reveal the relationships among P species and main influencing factors (Liu et al. 2015). The Monte Carlo permutation test was carried out based on the random permutations. The P fractions and other physicochemical property data were log-transformed to reduce the effects of extreme values, and the other environmental data were also log-transformed ($A = 1.00$, $B = 1.00$) (Leps and Smilauer 2013).

Results

Physicochemical properties of sediments and soils

The pH value varied from 5.09 (S7) to 7.81 (S19), with a mean value of 7.40 ± 0.45. The pH showed a lateral gradient from sediment to upland soil in the main stem and the tributaries. The average pH values in the upland soil, the WLFZ soil, and the sediment in the main stem were lower than those in the tributaries. The order of increase for average pH values was sediment (7.58 ± 0.62), WLFZ soil (7.44 ± 0.29), and adjacent upland soil (7.20 ± 0.68). However, there were no significant differences. The average concentrations of TOC, Fe, Mn, Al, Ca, and Mg in the sediments were higher than those in the WLFZ soil and the upland soil (Table 1). Both human activities and periodic impoundment of the TGR may result in the difference of physicochemical properties among upland soil, the WLFZ soil, and the sediment.

Fig. 2 Classification and measurement of phosphorus species
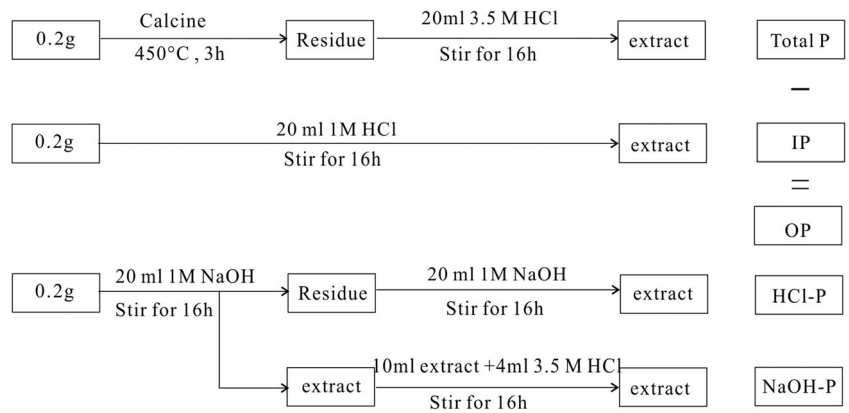
Spatial variation in the total P

The total P concentrations varied greatly from 133.63 mg·kg^{-1} (S18) to 1080.42 mg·kg^{-1} (S21) with an average of 630.02 ± 212.24 mg·kg^{-1} (Fig. 3a). The total P concentrations in the sediment were significantly higher than those in the WLFZ soil and the upland soil from the main stem ($F = 9.093$, $p < 0.01$) and the tributaries ($F = 4.649$, $p < 0.05$) (Fig. 4a). The order of decrease for the total P was sediment (788.44 ± 145.00 mg·kg^{-1}), WLFZ soil (560.11 ± 165.62 mg·kg^{-1}), and adjacent upland soil (541.51 ± 226.89 mg·kg^{-1}). The total P content in the main stem sediment demonstrated an increasing trend from the end of the backwater area (S1) to the Three Gorges Dam (S21), with the highest value at the site nearest to the Three Gorges Dam (S21). In the tributary sediment, the total P concentrations in the Shuangjiang River (S11), the Shennongxi River (S16), and the Tongzhuanghe River (S20) were higher than those in other rivers.

Spatial variation in the OP

The average OP concentrations in the sediment, the WLFZ soil, and the upland soil were 219.34 ± 103.43, 133.85 ± 67.47, and 132.48 ± 71.32 mg·kg^{-1}, respectively (Figs. 3b and 4b). However, the order of decrease for the OP percentage of the total P was upland soil (28.93% ± 17.48%), sediment (27.47% ± 11.88%), and WLFZ soil (25.71% ± 15.55%). The OP concentrations in the sediment were higher than those in the WLFZ soil and the upland soil in the main stem ($F = 6.048$, $p < 0.01$) (Fig. 4b). In the main stem sediment, there was no clear longitudinal trend in OP along the TGR, and the highest value was found at S21. In the tributary sediment, the OP concentrations in the Wujiang River (S4) and the Qinggan River (S18) were higher than those in the other rivers.
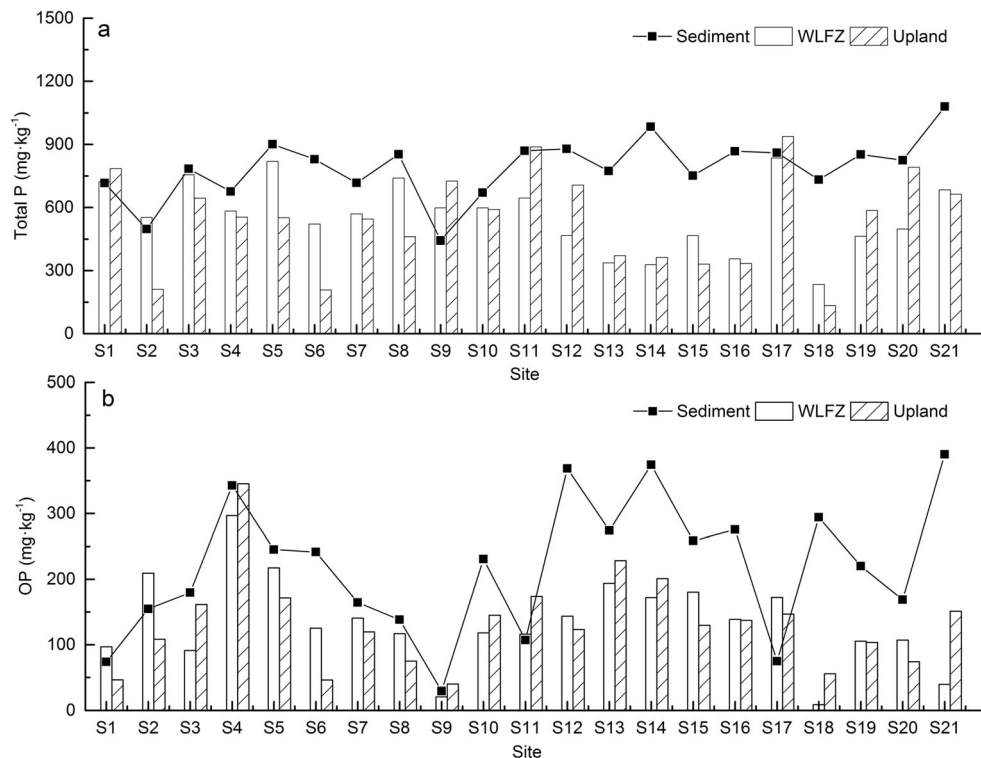
Spatial variation in the HCl-P

The HCl-P concentration ranged from 24.79 to 659.34 mg·kg^{-1}, with an average of 335.65 ± 159.88 mg·kg^{-1} (Fig. 5). The order of decrease for average HCl-P was sediment (374.98 ± 106.83 mg·kg^{-1}), WLFZ soil (321.12 ± 151.90 mg·kg^{-1}), and adjacent upland soil (310.84 ± 205.58 mg·kg^{-1}). However, these values accounted for 51.21% ± 21.69%, 55.05% ± 16.02%, and 47.88% ± 11.54% of the total P, respectively. The HCl-P concentrations in the sediment were higher than those in the WLFZ soil and the upland soil in the main stem and the tributaries, although there were no significant differences (Fig. 4c). In the tributary sediment, the highest HCl-P content was 529.65 mg·kg^{-1}, in the Xiaojiang River (S11).

Table 1 Sediment and soil physicochemical properties

Element	Mean ± SD			CV (%)		
	Sediment	WLFZ soil	Upland soil	Sediment	WLFZ soil	Upland soil
pH	7.58 ± 0.06	7.44 ± 0.29	7.20 ± 0.68	0.70	3.90	9.44
TOC (mg·g^{-1})	9.15 ± 2.97	6.98 ± 3.30	8.00 ± 5.66	32.50	47.27	70.66
Fe (mg·g^{-1})	44.85 ± 8.02	42.33 ± 37.93	37.93 ± 6.27	17.89	18.06	16.55
Al (mg·g^{-1})	28.78 ± 5.27	24.18 ± 5.81	20.97 ± 7.02	18.31	24.06	33.47
Mn (mg·g^{-1})	0.91 ± 0.23	0.75 ± 0.16	0.61 ± 0.18	25.30	21.19	30.11
Ca (mg·g^{-1})	27.64 ± 7.95	22.80 ± 13.56	23.44 ± 32.29	28.78	59.49	137.73
Mg (mg·g^{-1})	10.63 ± 4.62	8.71 ± 4.39	7.73 ± 4.64	43.50	50.39	60.13
K (mg·g^{-1})	24.07 ± 3.30	23.68 ± 5.28	22.50 ± 3.02	16.94	22.33	13.45

SD standard deviation, *CV* coefficient of variation, *TOC* total organic carbon

Fig. 3 Total P and OP content in the sediment, the WLFZ soil, and the upland soil

Spatial variation in the NaOH-P

The NaOH-P was the smallest P fraction in all types of sediment and soil, and its concentration ranged from 4.19 mg·kg^{-1} (S8) to 148.32 mg·kg^{-1} (S19). The mean was 51.40 ± 36.20 mg·kg^{-1}, which accounted for 8.17% ± 5.57% of the total P (Fig. 6). The order of decrease for average NaOH-P was sediment (85.97 ± 32.56 mg·kg^{-1}), WLFZ soil (40.26 ± 21.48 mg·kg^{-1}), and adjacent upland

soil (27.97 ± 24.08 mg·kg^{-1}), which accounted for 10.61% ± 2.89%, 7.23% ± 3.69%, and 6.67% ± 8.05% of the total P, respectively. The NaOH-P concentrations in the sediment were higher than those in the WLFZ soil and the upland soil in the main stem ($F = 19.958$, $p < 0.01$) and the tributaries ($F = 13.305$, $p < 0.01$) (Fig. 4d). In the main stem sediment, the NaOH-P content showed a clear increasing trend from the end of the backwater area to the Three Gorges Dam, with the highest value at S11. In the tributary

Fig. 4 Average concentration of total P, OP, HCl-P, and NaOH-P in the sediment, the WLFZ soil, and the upland soil of the main stem and the tributaries
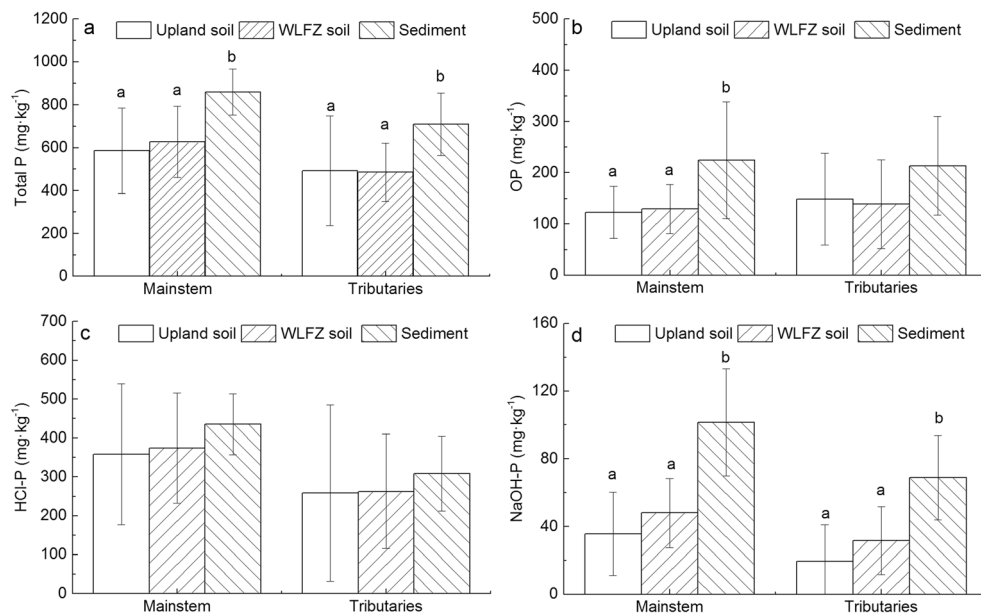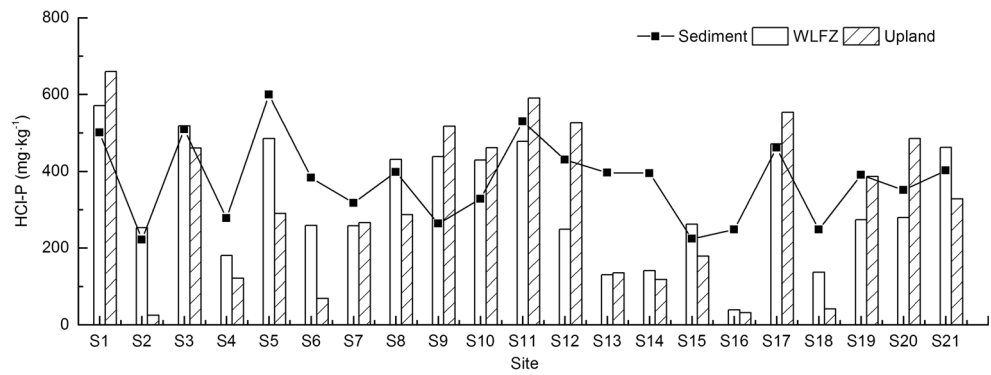
Fig. 5 HCL-P content in the sediment, the WLFZ soil, and the upland soil

sediment, the highest NaOH-P content was found in the Shennong River (S16), with a value of 100.43 mg·kg^{-1}.

Relationships between P fractions

For all the samples, the P fractions were found in the order of HCl-P > OP > NaOH-P. The inter-correlations among various phosphorus fractions were shown in Table 2. Both the IP and HCl-P had significant and positive Pearson correlations with the total P in the upland soil, the WLFZ soil, and the sediment. However, only in the sediments was NaOH-P positively correlated with the total P ($R = 0.809$, $p < 0.01$) and OP ($R = 0.583$, $p < 0.05$). The relationships among different P species were similar in the upland soil and the WLFZ soil.

The correlation structure between P species and influencing factors was summarized as an RDA correlation. The results of the RDA in the upland soil indicated that the contribution of Al ($F = 4.95$, $p < 0.05$) was significant for the variance in the P species. The contributions of the remaining variables were not significant (Fig. 7). The eigenvalues for the first four RDA axes were 0.439, 0.250, 0.008, and 0.002. The contribution of pH in the sediment ($F = 4.14$, $p < 0.05$) was significant for the variance in the P species (Fig. 8). The eigenvalues for the first four RDA axes were 0.526, 0.095, 0.007, and 0.002. However, all variables in the WLFZ soil were not significant (Fig. 9).

Discussion

Lateral and longitudinal variation in the total P in the reservoir

Both Geological factors and dam retention play a major role in affecting the longitudinal variation in phosphorus (P) concentration in the reservoirs. Dams may increase the retention of total suspended solids and result in the accumulation of the total P, especially in areas with a slow water flow rate. After the impoundment, nearly 76.25% of suspended sediment and 75.35% of particulate phosphorus were trapped by the TGR (Tang et al. 2018). Several studies also demonstrated that the reservoirs retained $42 \pm 22\%$ of external phosphorus loading (Kõiv et al. 2010). In the prairie reservoir (Lake Diefenbaker in Canada), the total P retention reached about 90% (Morales-Marín et al. 2017). The Great Plains reservoirs (Kansas, USA) were able to remove 61% of the total P (Cunha et al. 2014). This study presented that both the total P and NaOH-P content in the mainstream sediment demonstrated a clear increasing longitudinal trend (from the end of the backwater area to the Three Gorges Dam) (Figs. 3a and 6). Along the Turawa Reservoir in Poland and the Lancang River in China, the total P also presented an increasing trend from the back water area to the section beside the dam (Trojanowska and Jezierski

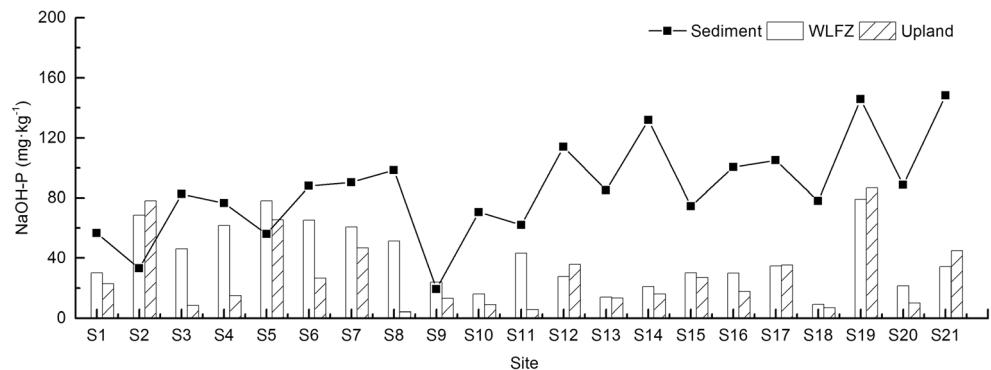**Fig. 6** NaOH-P content in the sediment, the WLFZ soil, and the upland soil

Table 2 Correlation coefficients among phosphorus forms

		TP	OP	IP	HCl-P	NaOH-P
Upland soil ($n = 21$)	TP	1				
	OP	0.005	1			
	IP	0.954**	− 0.295	1		
	HCl-P	0.919**	− 0.264	0.957**	1	
	NaOH-P	− 0.083	0.005	− 0.081	− 0.111	1
WLFZ soil ($n = 21$)	TP	1				
	OP	0.076	1			
	IP	0.922**	− 0.316	1		
	HCl-P	0.880**	− 0.277	0.945**	1	
	NaOH-P	0.413	0.398	0.238	0.155	1
Sediment ($n = 21$)	TP	1				
	OP	0.510**	1			
	IP	0.720**	− 0.230	1		
	HCl-P	0.515*	− 0.145	0.700**	1	
	NaOH-P	0.802**	0.574*	0.444**	0.146	1
Total ($n = 63$)	TP	1				
	OP	0.381**	1			
	IP	0.905**	− 0.048	1		
	HCl-P	0.788**	− 0.107	0.901**	1	
	NaOH-P	0.569**	0.551**	0.360**	0.149	1

* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

2011; Liu et al. 2015). However, along the Silverstream catchment and the Lake Rotorua (a eutrophic lake) in New Zealand, the concentrations of the total P and most P fractions in the sediment showed a general decrease downstream, and which was consistent with greater upstream bank erosion and the

increased precipitation of P (Mcdowell 2003; Peryer-Fursdon et al. 2015). Several studies have shown that stream-bank erosion could be a major source of sediment loading into an aquatic system and potentially a significant source of P (Miller et al. 2014).

Human activities may especially impact the lateral trend of P content in the upland soil and the riparian soil in reservoir areas. In the Susquehanna River in central Pennsylvania, USA, the total P concentration was greater in adjacent bank
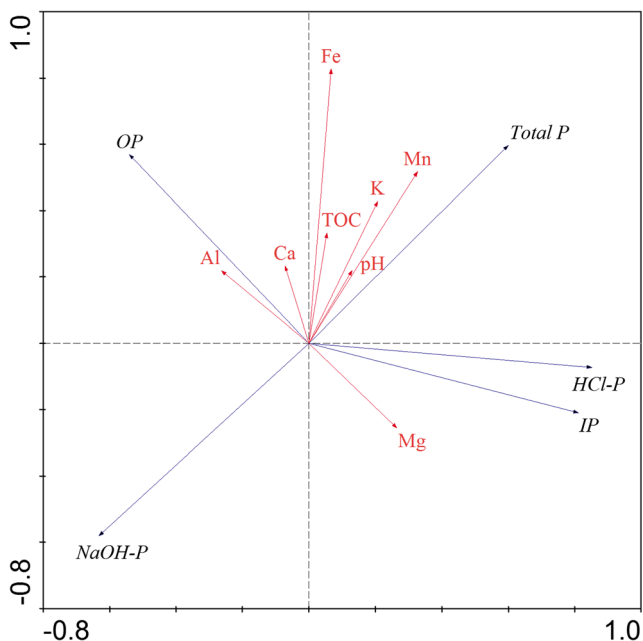

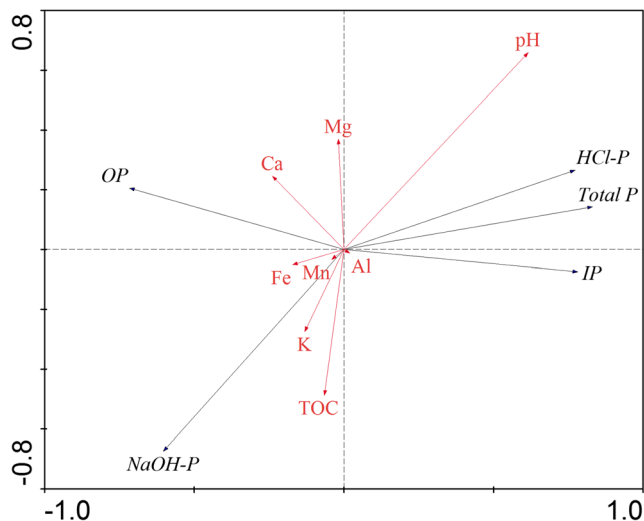**Fig. 7** RDA results for P fractions and other properties in the upland soil

Fig. 8 RDA results for P fractions and other properties in the sediment
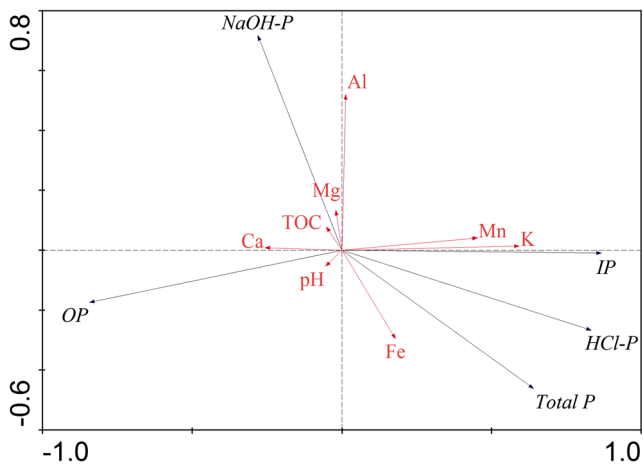
Fig. 9 RDA results for P fractions and other properties in the WLFZ soil

soil (417 mg·kg^{-1}) than in stream bed sediment (281 mg·kg^{-1}) (Mcdowell and Sharpley 2001) because of agricultural intensification. In addition, soil erosion, landslides, soil moisture, and water level variation after dam construction may also affect soil properties and consequently lead a loss of P species in the riparian soil, and an increase in P species in the sediment. This paper demonstrated that the average concentration of P species presented a clear decreasing lateral trend in the order of sediment > WLFZ soil > upland soil (Fig. 4). In contrast, all phosphorus species with higher variation coefficients in the upland soil presented greater spatial heterogeneity than those in the WLFZ soil and the sediment because the upland soil content is more easily affected by anthropogenic activities.

This research showed that the average concentration of the total P in the sediment was 788.44 ± 145.00 mg·kg^{-1}, which is greater than those in the lakes in the mid-lower reaches of the Yangtze River (565~757 mg·kg^{-1}) (Yuan et al. 2010; Wang et al. 2017), indicating greater potential release risk of P in the surface sediment of the TGR. The characteristics of WLFZ soil are very similar to the sediments of a lake or river. Although the mean of total P, OP, NaOH-P in the WLFZ soil were lower than those in the sediment, the risk of P release may increase during submergence period because of human activities during exposed period, such as seasonal farming crops and grazing cattle and sheep.

Release risk of phosphorus fractions in the sediment and adjacent riparian soil

Not all of the P fractions from sediments and adjacent riparian soils can be released into the overlying water. The P release is strongly associated with the concentration of P in sediments and environmental factors such as the concentration of P, pH, dissolved oxygen, and temperature in the overlying water. pH is one of the dominant factors in P release. If the pH decreases sharply, the HCl-P fraction may be greatly released (Huang et al. 2005; Yuan et al. 2009). This study showed that HCl-P

had a weak positive Pearson correlation with pH in the sediment ($R = 0.306$, $p > 0.05$). The mean proportion of HCl-P in the total P in the WLFZ soil (55.1%) was higher than that in the upland soil (51.2%) and the surface sediment (47.9%). The water body pH in the main stem and the tributaries ranged from 7.26 to 8.82 after TGR impoundment (Zhang et al. 2009; Guo et al. 2011). Thus, HCl-P remained stable, with little risk of release in the TGR.

Under alkaline condition, the released P mainly comes from OP and NaOH-P (Xu et al. 2015). Organic phosphorus (OP) compounds are now known to contain many labile species that may play a vital role in aquatic P cycling (Ahlgren et al. 2007; Worsfold et al. 2008). Rydin (2000) claimed that approximately 60% of the OP pool was mobile and that 50% is biogenic and can be degraded and eventually recycled to the overlying water. Both OP and NaOH-P are also affected by the dissolved oxygen (DO). When DO concentration is low, they are easily released to the overlying water (Ahlgren et al. 2007; Zhang et al. 2008). Therefore, these fractions are referred to as the algal-available P (Zhu et al. 2013). This paper showed that NaOH-P concentrations in the sediment were higher than those in the WLFZ soil and the upland soil in the main stem ($F = 19.958$, $p < 0.01$) and the tributaries ($F = 13.305$, $p < 0.01$) (Fig. 4). This lateral distribution of NaOH-P may result from the impoundment of the TGR.

The TGR has significantly altered the river's hydrological regime and water temperature, deepened the water depth, slowed the water flow rate, and resulted in a change in the lateral and longitudinal gradient distribution of P forms in the sediment and adjacent riparian soil. Dams may also increase the retention of suspended sediment and result in the accumulation of P. The release of NaOH-P and decomposition of OP may provide algal-available P and carry a potential risk of P release. Although the concentrations of total P, OP, and NaOH-P in the WLFZ soil were lower than those in the sediment, the soil P release risk during the submerged period may be increased due to human activities (seasonal farming and feeding of cattle and sheep, and so on) during the exposed period.

Conclusion

This research has revealed the difference in the phosphorus fractions in the surface sediment, the WLFZ soil, and the upland soil in the Three Gorges Reservoir. From the end of the backwater area to the Dam, both total P and NaOH-P content presented an obvious increasing trend in the sediment of the mainstream. The average concentration of various P species in the sediment was higher than those in the WLFZ soil and the upland soil. The HCl-P was the main P fraction in most investigated samples, accounting for more than 50.0% of the total P. All P species with the highest coefficients of

variation in the upland soil, compared with the corresponding values in the sediment and the WLFZ soil, presented the greatest spatial heterogeneity.

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