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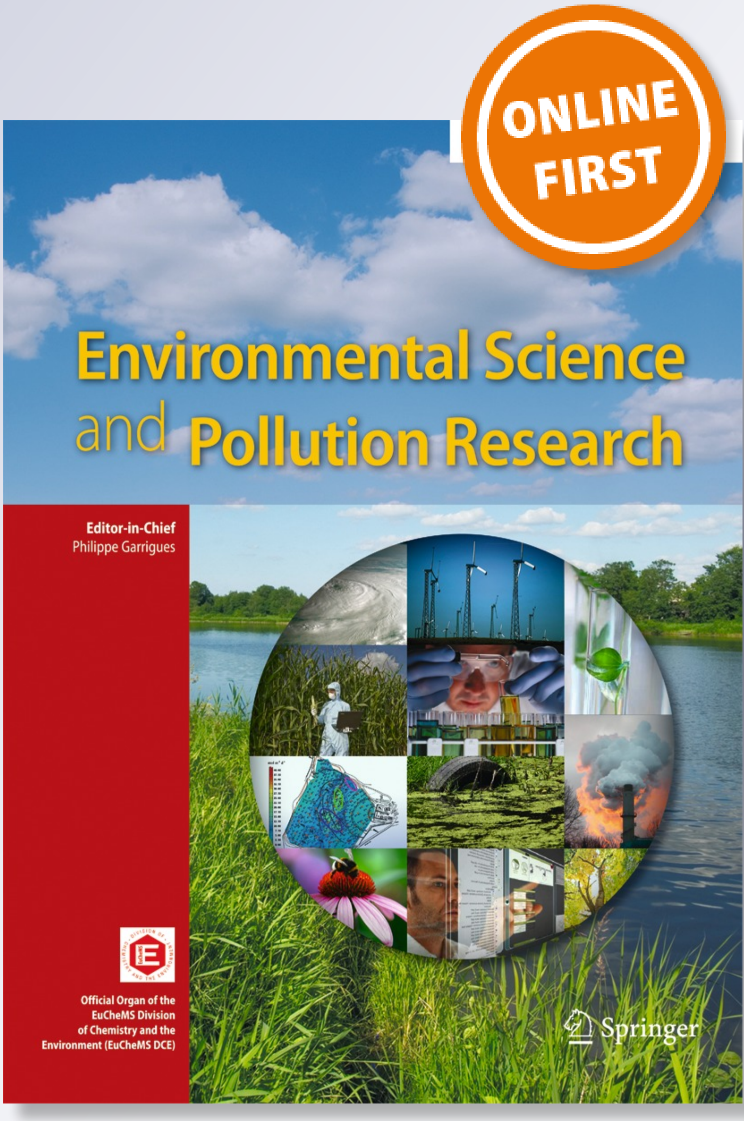


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RESEARCH ARTICLE

# The spatial distribution of phosphorus and their correlations in surface sediments and pore water in Lake Chaohu, China

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## Abstract

The study presents the spatial distribution of different forms of phosphorus in the sediments in Lake Chaohu, a large eutrophic Chinese lake, and their correlation with phosphorus content in pore water. The sediment and pore water samples were taken from 19 sampling sites. A sequential extraction was used to determine the contents of different forms of phosphorus in the sediments. The compositions and spatial distribution of different forms of phosphorus in the sediments and their correlation with orthophosphate and total phosphorus content in the pore water were studied. The following results were obtained: (1) the mean content of total phosphorus was 474.7 ± 20.5 mg/kg, with 390.8 ± 82.4 mg/kg for the eastern lake ($N = 5$), 469.0 ± 53.9 mg/kg for the western lake ($N = 5$), and 524.5 ± 185.3 mg/kg for rivers ($N = 9$); (2) the order of the proportions of the different forms of phosphorus was occluded phosphorus (Oc-P, 52.4%) > debris phosphorus (De-P, 14.2%) > auto-calcium-bound phosphorus (ACa-P, 13.5%) > aluminum-bound phosphorus (Al-P, 9.8%) > organic phosphorus (Or-P, 6.8%) > exchangeable phosphorus (Ex-P, 2.1%) > iron-bound phosphorus (Fe-P, 1.3%); (3) Ex-P, Al-P, and Fe-P had significantly positive correlations with orthophosphate and total phosphorus content in pore water, which showed that these forms of phosphorus were released more easily and had an indirect impact on lake eutrophication.

**Keywords** Phosphorus · Sediment · Pore water · Sequential extraction · Lake Chaohu

## Introduction

Eutrophication in shallow lakes caused by excessive nitrogen or/and phosphorus is a serious water environmental problem around the world (Ryding and Rast 1989; Cooke et al. 1993; Xu et al. 2003). The exogenous nutrient loadings from the ground runoff, industrial wastewater, and domestic sewage mainly contribute to lake eutrophication (Moss et al. 1996, 1997; Van der Molen et al. 1998; Xu et al. 2003). However, for shallow lakes, the endogenous loadings from the frequent resuspension of nutrient-enriched bottom sediments and their continued release of nutrients would play very important role in water eutrophication (Moss et al. 1996, 1997; Van der Molen et al. 1998; Xu et al. 2003). This might be the reason why shallow lakes are more resistant to the curtailment of exogenous nutrient loading compared to deep lakes (Moss et al. 1996, 1997; Edmondson and Lehman 1981; Van der Molen et al. 1998). For most eutrophic lakes, phosphorus is identified as a key limiting nutrient (Cooke et al. 1993; Moss et al. 1996). Pore water is an important medium for the release of nutrients from sediments into lake water (Sundby et al. 1992; Tang et al. 2009). Information concerning the spatial distribution of different forms of phosphorus in the sediments and their correlation with phosphorus content in pore water is of prime theoretical and actual importance when predicting nutrient concentrations in the water column (Van der Molen 1991; Golterman 1995), and in establishing measures of success for lake eutrophication control programs following reductions in external nutrient loading (Levine and Schindler 1989; Rossi and Premazzi 1991).

At present, some analytical methods for different forms of phosphorus in sediments have been proposed. Among the various methods, the sequential extraction techniques, proposed

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first by Chang and Jackson (1957), are the most promising methods for separating and quantifying the various phosphorus reservoirs in sediments (Ruttenberg 1992; Li et al. 1998). Such techniques are regularly used in the study of lakes (e.g., Williams et al. 1976, 1980; Zhu et al. 2004; Guo et al. 2007), rivers (e.g., Lucotte and d'Anglejan 1985; Hu et al. 2001), marine waters (e.g., Morse and Cook 1978; Filipek and Owen 1981; Ruttenberg 1992; Shan et al. 2016), and soils (e.g., Costa et al. 2017; Grigatti et al. 2017). In the present study, sequential extraction techniques were used to separate and quantify the different forms of phosphorus in the sediments from Lake Chaohu, a large eutrophic Chinese lake.

Lake Chaohu with a mean depth of 3.06 m and a mean surface area of 760 km$^2$ is located in southeastern China (30° 25′ 28″–31° 43′ 28″ N, 117° 16′ 54″–117° 51′ 46″ E) (Fig. 1a). It is well known as the fifth largest freshwater lake and one of the most eutrophic lakes in China. Since the late 1970s, the lake has suffered from serious eutrophication due to the discharge of large amounts of exogenous nutrient loadings (Xu 1997; Xu et al. 1999a, b). A lot of comprehensive studies on Lake Chaohu have been performed since the early 1980s (e.g., Tu et al. 1990; Wang and Zhu 1995; Xu et al. 1999a, b; Xu et al. 2001a, b; Jiang et al. 2014; Yang et al. 2016). Many measures, such as controlling the importation of exogenous nutrients, sediment dredging, water diversion, planting aquatic plants, and stocking bighead carp, have been taken. However, the lake is still suffering from serious eutrophication (Jiang et al. 2014; Yang et al. 2016). The release of the endogenous nutrient loading from sediments might be one of the primary causes (Xu et al. 2003).

Some studies on the distribution of phosphorus in the sediments from Lake Chaohu have been performed (e.g., Tang et al. 2009; Ma et al. 2010; Yang et al. 2011). However, these previous studies focused on the phosphorus forms that were relatively simple, which could not reflect the effects of the more different forms of phosphorus on the water. Additionally, in recent years, dredging has been carried out in some parts of the lake. It is necessary to study the characteristics of sedimentary phosphorus forms and their relationship with pore water after dredging. The primary purposes of this study are (1) to explore the contents and spatial distribution of the seven forms of phosphorus in the sediments from Lake Chaohu and (2) to analyze the relationships between the forms of phosphorus in the sediments and the phosphorus content in pore water.

## Materials and methods

### Sampling

Nineteen sampling sites were set up in Lake Chaohu and the main inflow rivers in the basin (Fig. 1). The sites L1–L5 and L6–L10 were located in the western and eastern lake, respectively. The sites R1, R3, R4, R5, R6, R7, R8, and R9 were on the river moths of Nanfeihe River, Paihe River, Hangbuhe River, Baishitianhe River, Zhaohe River, Tongyanghe River, Zhegaohe River, and Shuangqiaohe River, respectively, while the site R10 was on the moth of the outflow river, Yuxing River.

Surface sediment samples were collected in May 2011 using the grab sediment sampler. Samples were stored in HDPE (high-density polyethylene) pots at − 20 °C before being analyzed. After thawing, sediment samples were centrifuged at 11000 r/

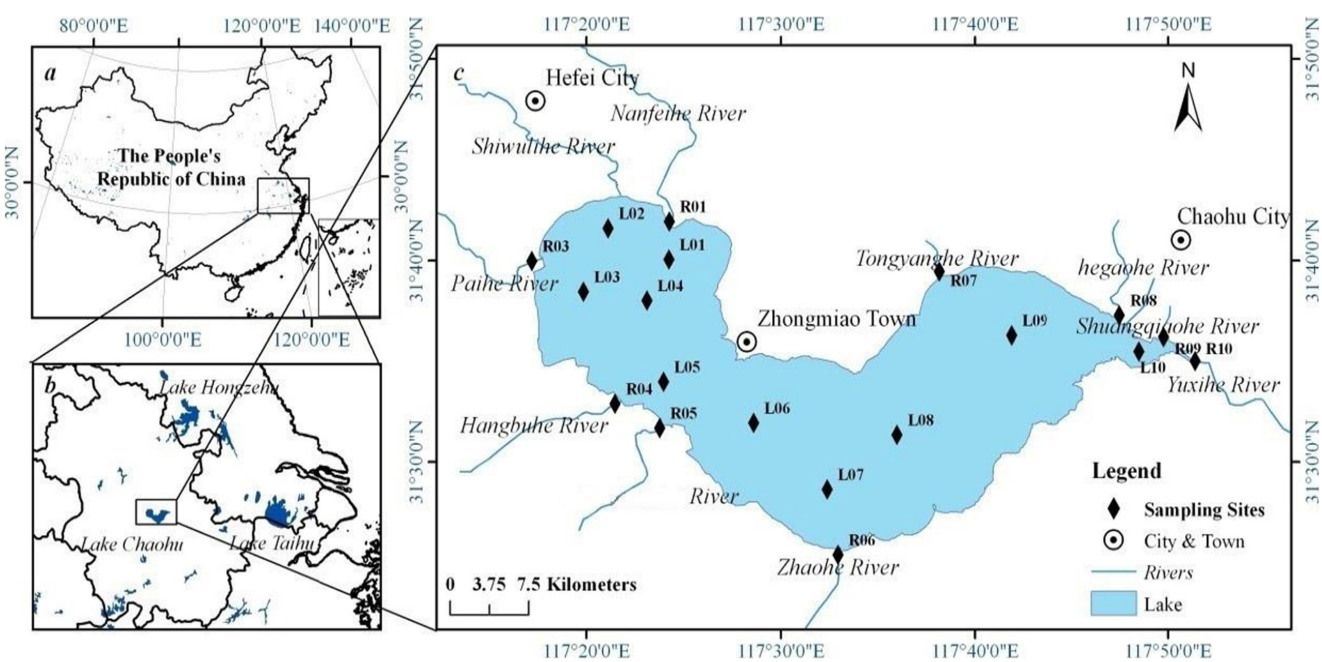


Fig. 1 The distribution of sediment sampling sites on Lake Chaohu

min for 15 min (Sigma 3K-15, Sigma Laborzentrifugen GmbH, Germany). The supernatant fractions were filtered using a 0.45-μm nylon filter to obtain pore water; the remaining samples were freeze-dried by FD-IA-50 freeze-dryer (Beijing Boyikang Laboratory Instrument Co. Ltd., Beijing, China). Freeze-dried samples were ground by RM 200 grinder (Retsch GmbH, Germany) and sieved to pass through a 200-mesh sieve after the removal of plant tissues, shells, etc.

### Extraction and analysis of different forms of phosphorus in the sediments

The sequential extraction and analysis methods for the different forms of phosphorus used in this paper are shown in Fig. S1.

### Analysis of orthophosphate and total phosphorus content in pore water

The analysis of orthophosphate ($PO_4^{3-}$) and total phosphorus (TP) content in pore water was performed according to the national standard method (GB 11893-89). The main steps are as follows: (1) using potassium persulfate (or hydrogen nitrate-perchloric acid) as an oxidizer, phosphorus is converted to orthophosphate; (2) orthophosphate reacts with ammonium molybdate to produce phosphomolybdic heteropoly acid in the presence of potassium antimony tartrate in acid media; (3) phosphomolybdic heteropoly acid is deoxidized by ascorbic acid to produce blue complexes; and (4) the content of total phosphorus is determined by measuring the absorbance of the samples and comparing with the standard curves.

### Statistical analysis

ArcGis (Environmental Systems Research Institute, Inc., America) was used to depict the figures of the spatial distribution of different forms of phosphorus, and IBM SPSS Statistics 18.0 (International Business Machines Corporation, USA) was used for multivariate statistical analysis.

## Results

### Levels of different forms of phosphorus in the sediments

The concentrations of different forms of phosphorus in sediment samples are shown in Table 1. The average concentrations of Ex-P, Al-P, Fe-P, Oc-P, De-P, ACa-P, and Or-P in river sediments ($N = 9$) were 22.4 ± 32.4, 57.6 ± 47.4, 8.1 ± 13.8, 276.9 ± 68.8, 66.4 ± 28.4, 68.0 ± 37.4, and 25.1 ± 5.5 mg/kg, respectively. The average concentrations of Al-P, Fe-P, Oc-P, and Or-P in the western river sediments (70.3 ± 69.4, 16.9 ± 23.5, 244.4 ± 140.0, and 19.61 ± 6.1 mg/kg) ($N = 5$) were higher than in the eastern rivers ($N = 5$), and the average concentrations of Ex-P, De-P, and ACa-P in the eastern river sediments (20.2 ± 32.8, 56.8 ± 44.8, and 64.6 ± 54.9 mg/kg) ($N = 5$) were higher than in the western river sediments ($N = 4$). The average concentrations of Ex-P, Al-P, Fe-P, Oc-P, De-P, ACa-P, and Or-P in lake sediments ($N = 10$) were 4.7 ± 3.7, 41.9 ± 25.2, 5.5 ± 3.7, 220.3 ± 75.1, 64.9 ± 9.5, 58.8 ± 13.3, and 33.9 ± 4.2 mg/kg, respectively. The average concentrations of different forms of phosphorus in the western lake sediments ($N = 5$) were all higher than in the eastern lake sediments ($N = 5$). The concentrations of Oc-P in river and lake sediments were the highest among the seven forms of phosphorus (276.9 ± 68.8 and 220.3 ± 75.1 mg/kg).

### Composition of different forms of phosphorus in the sediments

The composition of the different forms of phosphorus in the sediments from Lake Chaohu is shown in Fig. 2. The proportions of Ex-P were the lowest in the sediments of sampling sites R3 (Paihe River), R4 (Hangbuhe River), and most sampling sites on the lake (L2, L3, L4, L6, L7, L8, and L9). The proportions of Fe-P were the lowest for L1, L5, L10, and most sampling sites on rivers (R5, R6, R7, R8, R9, and R10). Or-P had the lowest proportion at sampling site R1 (Nanfeihe River). Al-P was approximately 2.7–21.6% of the total phosphorus in the sediments. Oc-P had the highest proportions (32.5–72.5%). ACa-P and De-P had approximate proportions (5.3–22.0 and 7.3–22.2%, respectively). Or-P was approximately 2.7–13.3% of the total phosphorus. Inorganic phosphorus was the dominant form of phosphorus in the sediments, and the proportions of Or-P were much lower, which showed that the organic matter in the sediments in Lake Chaohu had almost disappeared, and phosphorus was mainly deposited in the form of an inorganic phase. The concentrations of Al-P and Fe-P in the west were higher than in the east. The concentrations of other forms of phosphorus in the west were approximate the same as the east. The proportion of Ex-P in lake sediments (4.3%) was higher than in the river sediments (1.1%). Al-P, Fe-P, Oc-P, ACa-P, and De-P in lake and river sediments had approximately the same proportions. The proportion of Or-P in lake sediments was 4.8%, lower than in the river sediments (7.9%). Oc-P was approximately 51.2–52.8% of the total phosphorus in lake and river sediments, higher than other forms of phosphorus.

### Spatial distribution of different forms of phosphorus in the sediments

The distribution of seven forms of phosphorus in sediments is shown in Fig. 3, and the spatial distribution of

**Table 1** The concentrations of different forms of phosphorus in sediment samples (mg/kg)

| | | Ex-P | Al-P | Fe-P | Oc-P | De-P | ACa-P | Or-P | Total |
|---|---|---|---|---|---|---|---|---|---|
| Sampling points | R1 | 87.9 | 150.2 | 44.0 | 348.1 | 72.5 | 49.5 | 21.1 | 773.2 |
| | R3 | 2.9 | 36.6 | 3.4 | 287.0 | 28.7 | 21.1 | 16.1 | 395.7 |
| | R4 | 10.0 | 81.6 | 10.9 | 374.5 | 69.2 | 80.8 | 25.5 | 652.5 |
| | R5 | 4.5 | 35.7 | 4.1 | 262.4 | 76.5 | 92.0 | 26.2 | 501.2 |
| | R6 | 2.2 | 9.8 | 0.4 | 202.0 | 64.1 | 60.2 | 17.8 | 356.4 |
| | R7 | 4.6 | 16.0 | 1.0 | 198.4 | 31.7 | 26.1 | 30.3 | 308.0 |
| | R8 | 8.3 | 55.3 | 4.5 | 197.9 | 50.7 | 64.3 | 31.5 | 412.4 |
| | R9 | 69.4 | 109.6 | 3.5 | 347.1 | 123.0 | 145.8 | 27.6 | 825.8 |
| | R10 | 11.9 | 23.9 | 1.4 | 274.6 | 81.5 | 72.2 | 29.5 | 494.9 |
| | L1 | 12.9 | 96.1 | 10.6 | 172.6 | 60.0 | 57.6 | 35.1 | 444.9 |
| | L2 | 7.1 | 59.7 | 11.3 | 156.8 | 69.5 | 63.1 | 32.8 | 400.3 |
| | L3 | 4.1 | 50.2 | 7.8 | 309.1 | 60.0 | 52.5 | 31.4 | 515.1 |
| | L4 | 5.2 | 55.0 | 7.4 | 286.7 | 74.3 | 66.2 | 36.9 | 531.7 |
| | L5 | 6.5 | 48.6 | 6.0 | 224.8 | 68.1 | 62.4 | 36.8 | 453.2 |
| | L6 | 2.1 | 28.0 | 2.5 | 89.3 | 56.5 | 60.4 | 36.5 | 275.2 |
| | L7 | 0.9 | 28.1 | 3.2 | 142.1 | 78.5 | 62.9 | 37.6 | 353.3 |
| | L8 | 1.1 | 24.7 | 2.7 | 287.2 | 64.0 | 43.8 | 36.8 | 460.3 |
| | L9 | 1.3 | 15.6 | 2.7 | 262.6 | 46.3 | 34.8 | 24.3 | 387.7 |
| | L10 | 5.4 | 13.3 | 0.9 | 271.5 | 71.6 | 84.2 | 30.7 | 477.5 |
| Rivers (R1–R10) | Max | 69.4 | 150.2 | 44.0 | 374.5 | 123.0 | 145.8 | 31.5 | 825.8 |
| | Min | 2.2 | 9.8 | 0.4 | 197.9 | 28.7 | 21.1 | 16.1 | 308.0 |
| | AM | 22.4 | 57.6 | 8.1 | 276.9 | 66.4 | 68.0 | 25.1 | 524.5 |
| | SD | 32.4 | 47.4 | 13.8 | 68.8 | 28.4 | 37.4 | 5.5 | 185.3 |
| Lake (L1–L10) | Max | 12.9 | 96.1 | 11.3 | 309.1 | 78.5 | 84.2 | 37.6 | 531.7 |
| | Min | 0.9 | 13.3 | 0.9 | 89.3 | 46.3 | 34.8 | 24.3 | 275.2 |
| | AM | 4.7 | 41.9 | 5.5 | 220.3 | 64.9 | 58.8 | 33.9 | 429.9 |
| | SD | 3.7 | 25.2 | 3.7 | 75.1 | 9.5 | 13.3 | 4.2 | 77.5 |
| Western Lake (L1–L5) | Max | 12.9 | 96.1 | 11.3 | 309.1 | 74.3 | 66.2 | 36.9 | 531.7 |
| | Min | 4.1 | 48.6 | 6.0 | 156.8 | 60.0 | 52.5 | 31.4 | 400.3 |
| | AM | 8.5 | 72.3 | 8.6 | 232.9 | 67.2 | 59.4 | 34.2 | 469.0 |
| | SD | 6.2 | 33.6 | 3.7 | 107.7 | 10.1 | 9.7 | 3.9 | 53.9 |
| Eastern Lake (L6–L10) | Max | 5.4 | 28.1 | 3.2 | 287.2 | 78.5 | 84.2 | 37.6 | 477.5 |
| | Min | 0.9 | 13.3 | 0.9 | 89.3 | 46.3 | 34.8 | 24.3 | 275.2 |
| | AM | 5.3 | 36.8 | 4.1 | 179.3 | 50.5 | 47.0 | 25.0 | 390.8 |
| | SD | 3.2 | 25.2 | 3.3 | 96.2 | 30.1 | 32.0 | 15.1 | 82.4 |
| Western Rivers (R1–R5) | Max | 10.0 | 150.2 | 44.0 | 374.5 | 76.5 | 92.0 | 26.2 | 773.2 |
| | Min | 2.9 | 35.7 | 3.4 | 262.4 | 28.7 | 21.1 | 16.1 | 395.7 |
| | AM | 5.3 | 70.3 | 16.9 | 244.4 | 45.1 | 48.4 | 19.1 | 580.6 |
| | SD | 4.0 | 69.4 | 23.5 | 140.0 | 27.2 | 38.1 | 6.1 | 166.1 |
| Eastern Rivers (R6–R10) | Max | 69.4 | 109.6 | 4.5 | 347.1 | 123.0 | 145.8 | 31.5 | 825.8 |
| | Min | 2.2 | 9.8 | 0.4 | 197.9 | 31.7 | 26.1 | 17.8 | 308.0 |
| | AM | 20.2 | 64.7 | 11.3 | 232.4 | 56.8 | 64.6 | 18.6 | 479.5 |
| | SD | 32.8 | 41.2 | 10.7 | 87.6 | 44.8 | 54.9 | 10.4 | 205.7 |

*Max* maximum, *Min* minimum, *AM* arithmetic mean, *SD* standard deviation

TP in the sediments in Lake Chaohu is shown in Fig. 4. The concentrations of Ex-P in the central lake were relatively lower, and the minimum was 0.9 mg/kg at the sampling site L7. The concentration of Ex-P increased along the east and the west, and the maximum was 87.9 mg/kg at R1 (Nanfeihe River).

The concentrations of Al-P in the eastern lake were relatively lower, and the minimum was 9.8 mg/kg at R6 (Zhaohe

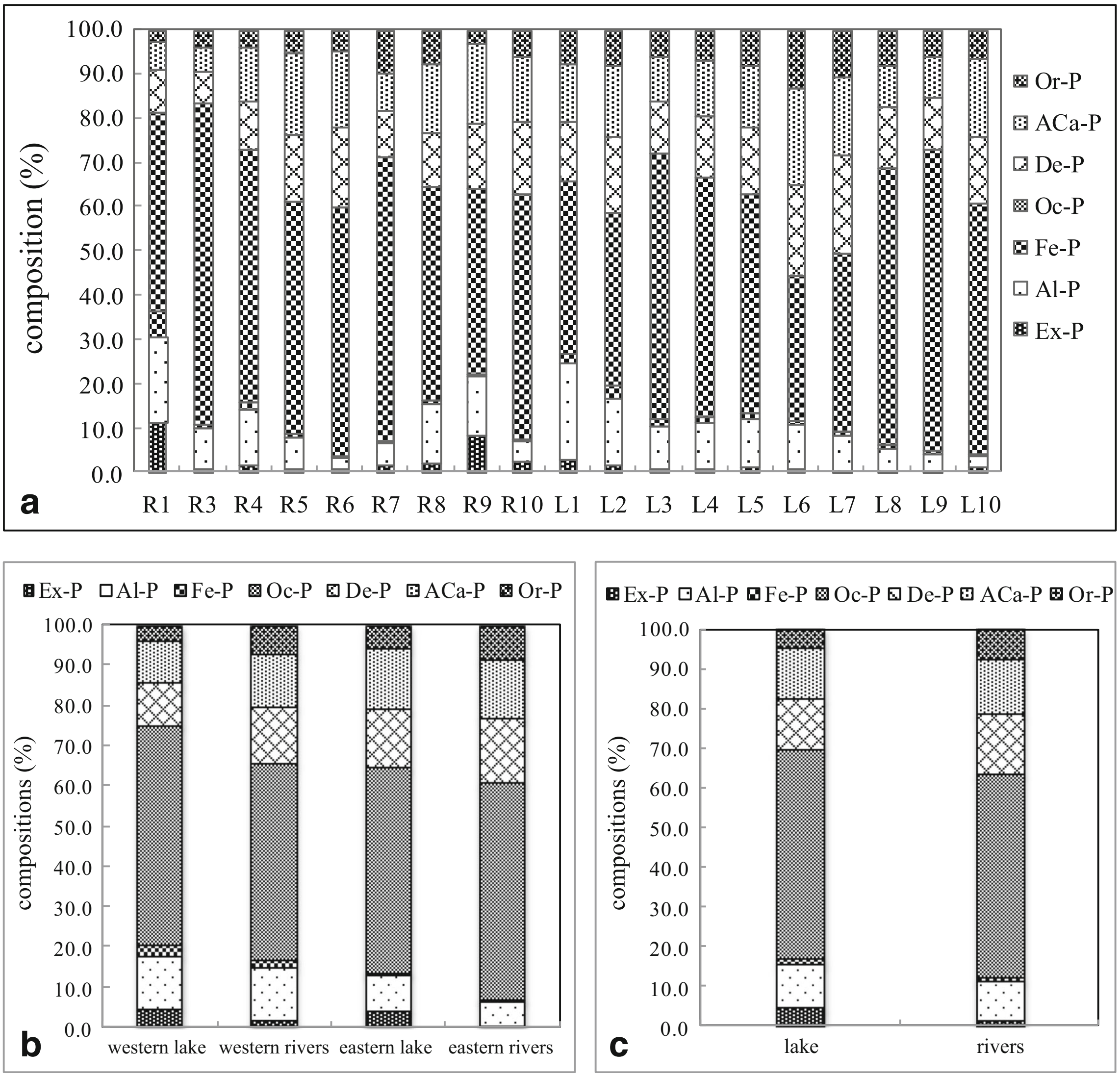


**Fig. 2** The compositions of different forms of phosphorus in the sediments from Lake Chaohu. **a** Different sampling sites. **b** Different regions of the lake and rivers. **c** Lake and rivers

River). The concentrations of Al-P increased along the east and the west, and the maximum was 150.2 mg/kg also at R1. For the same reason as Ex-P, the concentration of Al-P at R1 was the highest.

The concentrations of Fe-P in the central and eastern lake were relatively lower, and the minimum was 0.4 mg/kg at sampling site R6. The concentrations of Fe-P increased along the west, and the maximum was 44.0 mg/kg at R1.

The concentrations of Oc-P in the central lake were relatively lower, and the minimum was 89.3 mg/kg at L6. The concentrations of Oc-P increased along the east and the west, and the maximum was 374.5 mg/kg at R4 (Hangbuhe River).

The concentrations of ACa-P in the northeast of lake and estuary in the west were relatively lower. The minimum was 21.1 mg/kg at the sampling site R3, and the maximum was 145.8 mg/kg at R9 (estuary on the east).

The concentrations of De-P in the northeast of the lake and the estuary on the west were relatively lower. The minimum was 28.7 mg/kg at R3, and the maximum was123.0 mg/kg at R9. The similar influence factors were found for the distribution of both De-P and ACa-P.

The concentrations of Or-P in the estuary in the northwest and south and the water source area in the east were relatively lower, and the minimum was 16.1 mg/kg at R3. The concentrations of Or-P in the central and western lake were relatively higher, and the maximum was 37.6 mg/kg at L7. There were a few little differences in the concentrations of Or-P at all sampling sites.

## Spatial distribution of $PO_4^{3-}$ and TP in the pore water

The spatial distribution of $PO_4^{3-}$ and TP in pore water in Lake Chaohu are shown in Fig. 5. The maximum of the

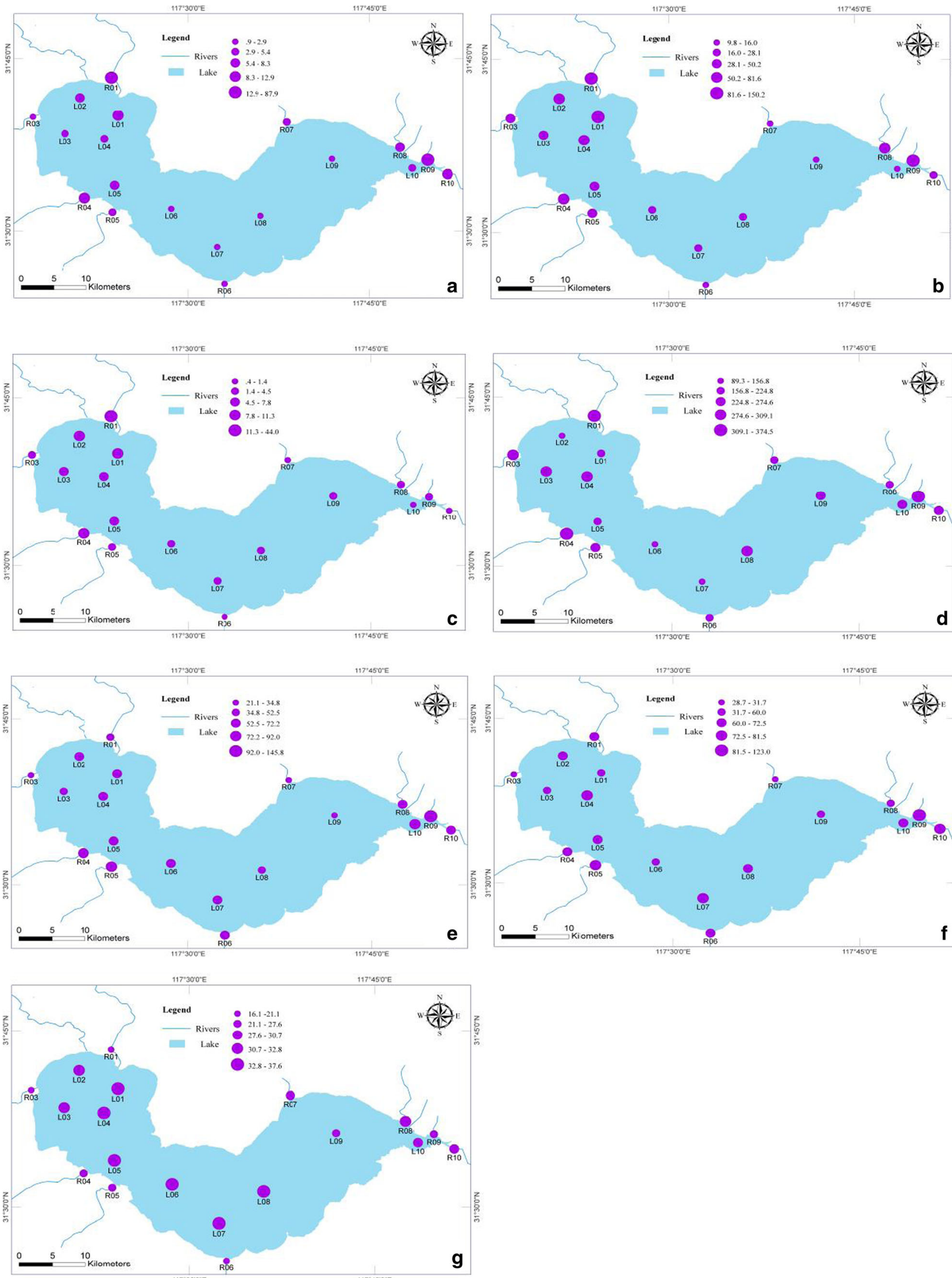


**Fig. 3** The spatial distributions of different forms of phosphorus (mg/kg) in the sediments from Lake Chaohu. **a** Ex-P. **b** Al-P. **c** Fe-P. **d** Oc-P. **e** ACa-P. **f** De-P. **g** Or-P

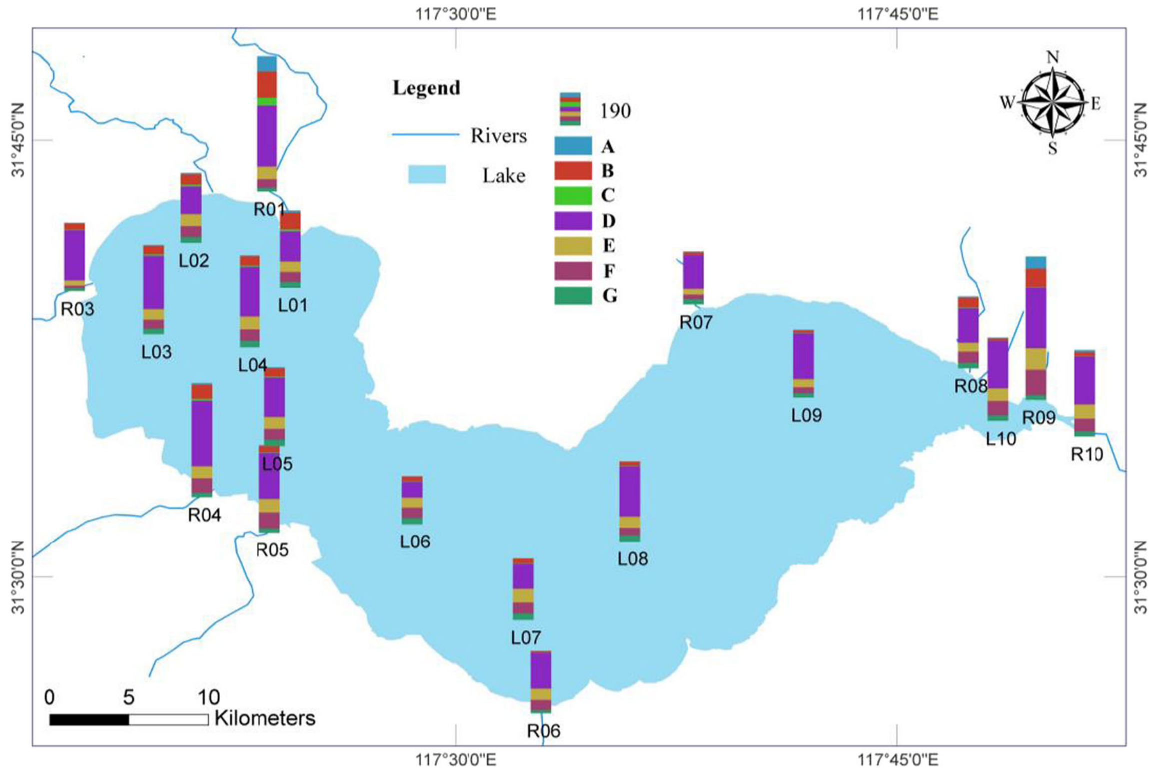


**Fig. 4** The spatial distribution of total phosphorus (TP) (mg/kg) in the sediments from Lake Chaohu (A: Ex-P; B: Al-P; C: Fe-P; D: Oc-P; E: De-P; F: ACa-P; G: Or-P)

concentrations of $PO_4^{3-}$ in pore water was 1.56 mg/L at R1. The concentrations decreased along the southeast and southwest, and the minimum was 0.05 mg/L at L3. The concentration of $PO_4^{3-}$ in pore water in the eastern lake (0.07 ± 0.01 mg/L) was approximately equal to the concentration of $PO_4^{3-}$ in the western lake (0.09 ± 0.03 mg/L). The concentration of $PO_4^{3-}$ in the pore water in the western rivers (0.49 ± 0.72 mg/L) was much higher than in the eastern rivers (0.13 ± 0.06 mg/L). The concentration of $PO_4^{3-}$ in rivers was 0.29 ± 0.48 mg/L, higher than in the lake (0.08 ± 0.02 mg/L). The maximum of the concentrations of TP in pore water was also at R1 (1.79 mg/L), and the minimum was 0.22 mg/L at R7. The concentrations of TP in the eastern and western lake were approximately equal (0.28 ± 0.02 and 0.29 ± 0.05 mg/L, respectively). The concentration of TP in the western rivers was 0.77 ± 0.70 mg/L, higher than in the eastern rivers (0.29 ± 0.06 mg/L). The concentration of TP in the sediments of rivers (0.50 ± 0.50 mg/L) was also higher than in the lake (0.28 ± 0.04 mg/L).

There was a high correlation between $PO_4^{3-}$ and TP in pore water, with a correlation coefficient of 0.978 (significant at the

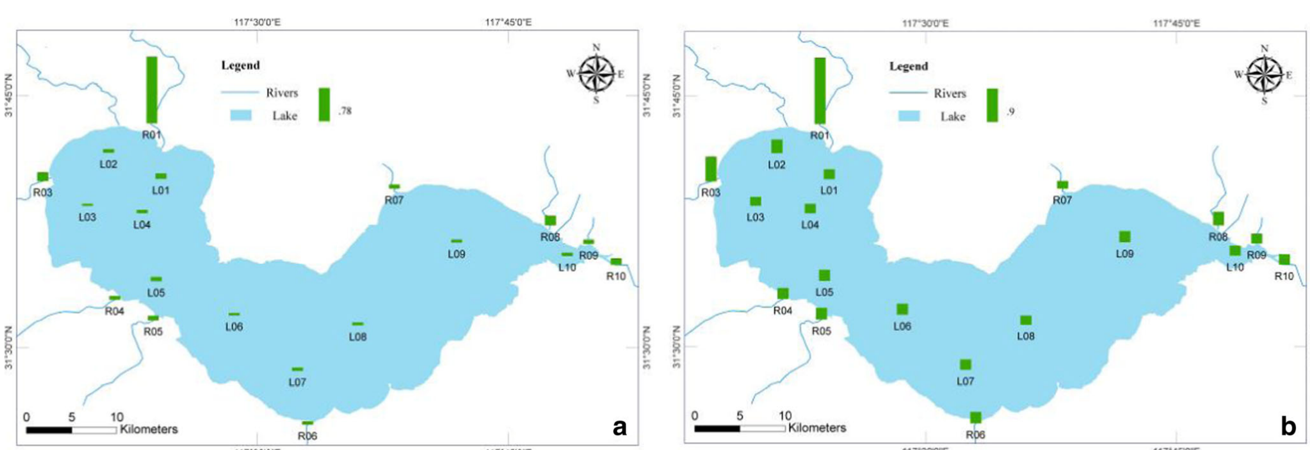


**Fig. 5** The spatial distributions of $PO_4^{3-}$ (**a**) and TP (**b**) in the pore water from Lake Chaohu

**Table 2** The correlation coefficients between different forms of phosphorus and the contents of $PO_4^{3-}$ and TP in the pore water

| Correlation coefficients | Ex-P | Al-P | Fe-P | Oc-P | De-P | ACa-P | Or-P | $PO_4^{3-}$ | TP |
|---|---|---|---|---|---|---|---|---|---|
| Ex-P | 1.000 | | | | | | | | |
| Al-P | 0.834** | 1.000 | | | | | | | |
| Fe-P | 0.727** | 0.804** | 1.000 | | | | | | |
| Oc-P | 0.477* | 0.416 | 0.334 | 1.000 | | | | | |
| De-P | 0.523* | 0.409 | 0.106 | 0.304 | 1.000 | | | | |
| ACa-P | 0.401 | 0.328 | − 0.086 | 0.262 | 0.899** | 1.000 | | | |
| Or-P | − 0.289 | − 0.106 | − 0.212 | − 0.438 | 0.180 | 0.106 | 1.000 | | |
| $PO_4^{3-}$ | 0.768** | 0.667** | 0.923** | 0.321 | 0.046 | − 0.136 | −0.357 | 1.000 | |
| TP | 0.719** | 0.630** | 0.901** | 0.315 | − 0.027 | − 0.198 | − 0.452 | 0.978** | 1.000 |

"*" and "**" indicate that the correlation coefficients were significant at the 0.05 and 0.01 level, respectively

0.01 level), demonstrating that the concentration of TP in pore water had a great influence on the concentration of $PO_4^{3-}$.

### Relationship between different forms of phosphorus in the sediments and $PO_4^{3-}$ and TP in the pore water

The correlation coefficients between seven forms of phosphorus and the concentrations of $PO_4^{3-}$ and TP in pore water are shown in Table 2. Ex-P, Al-P, and Fe-P had significantly positive correlations with $PO_4^{3-}$ in pore water, with correlation coefficients of 0.768, 0.667, and 0.923, respectively. ACa-P and Or-P had negative correlations with $PO_4^{3-}$ in pore water. Ex-P, Al-P, and Fe-P also had significantly positive correlations with TP in pore water, with correlation coefficients of 0.719, 0.630, and 0.901, respectively.

## Discussion

### Levels and composition of different forms of phosphorus in the sediments

The proportions of Ex-P and Fe-P in surface sediment in Lake Chaohu were relatively low, which was related to the environmental background of the lake and rivers. ACa-P comes mainly from minerals and is difficult to dissolve or adsorb in general. Oc-P comes mainly from bound phosphorus or phosphorus in the state of natural rock covered by hydro ferric oxide. The high concentrations of ACa-P and Oc-P manifested the natural source was the main source of the sediment in Lake Chaohu. The concentrations of Or-P in the sediments at different sampling sites varied greatly. The compositions of Or-P were between acid extraction and alkali extraction, and the forms of phosphorus extractable by alkali in the eastern and western lake were much different, which was related to the distribution of pollutant sources around Lake Chaohu and the hydrodynamic conditions.

For shallow lakes, the hydrodynamics is one of the primary factors for the release of phosphorus (Sundby et al. 1992). The hydrodynamics of the lake and the forms of phosphorus in different seasons could be different, which might affect the release of phosphorus from the sediment and lead to the changes in the levels and composition of phosphorus in the sediments.

### Spatial distribution of different forms of phosphorus in the sediments and $PO_4^{3-}$ and TP in the pore water

The northwest and northeast of Lake Chaohu are near Hefei City and Chaohu City, respectively, and water pollution in these areas is more serious. Dongpu Reservoir is built with an upstream dam on Nanfeihe River (R1), which is located on the northwest portion of the lake. As a result, Nanfeihe River has small amount of runoff and a low capacity for self-purification, and a small amount of the pollutants could cause the deterioration of water quality. Nanfeihe River also has a low sewage interception ratio and high overflow frequency (Gu et al. 2004). At present, the water pollution of the Nanfeihe River is severe, and the estuary of the Nanfeihe River (R1) and adjacent lake region (L1) are areas with the highest degree of eutrophication. Ex-P is mainly the phosphorus adsorbed or coprecipitated by activated Fe/Mn oxides, hydroxides, and clay minerals in the sediments. The discharge of domestic and industrial sewage, as well as the decrease of the self-purification capacity of the river, led to the high concentrations of Ex-P in this area. Zhaohe River (R6) is an artificial river with good management, which provides the guarantee for the survival of the benthos and makes the concentration of Al-P lower than in other areas. Since the forms and concentrations of Fe-P could easily change due to the oxygen-enriched and anaerobic environment, the distribution of Fe-P was greatly influenced by the water quality of the Nanfeihe River and the Zhaohe River.

Hangbuhe River is a main river in Shucheng County. For Hangbuhe River, natural disasters were frequent in history: mound area was deficient in water and often affected by drought. Floods usually occurred in the polder during flood season (Tang et al. 2009). The contents of FeO and microorganisms in the river were relatively higher, providing conditions for the accumulation of Oc-P.

The distribution of ACa-P was related to the characteristics of ACa-P binding to mineral surface and was also affected by the Shuangqiaohe River (R9) and the Paihe River (R3). The influence factors of the distribution of De-P were similar to the factors for ACa-P.

The sampling site R1 was set up on the Nanfeihe River, close to urban area. The concentrations of $PO_4^{3-}$ and TP in pore water in the sediment of R1 were having the maximum values among all sampling sites, which were related to the natural environment and water quality of the Nanfeihe River.

### Relationship between different forms of phosphorus in the sediments and $PO_4^{3-}$ and TP in the pore water

Since the sediment-water interface is not under complete anaerobic conditions, a high proportion of dissolved phosphate released into the pore water might be adsorbed or coprecipitated by iron oxides and clay minerals to form authigenic minerals during the process of mineralization and degradation of organic matter in sediments (Yan 1998). This kind of process is the main method for the transformation of phosphorus. Dissolved phosphate in pore water could flow into overlying water and affect the water quality when environmental conditions are changed. Ex-P, Al-P, and Fe-P are all reactive phosphorus and could be released into pore water and flow into overlying water to affect the concentrations of $PO_4^{3-}$ and TP in pore water and the overlying water. As a result, the contents of these forms of phosphorus in the sediment could also have an indirect influence on the degree of water eutrophication.

## Conclusions

1. The concentrations of Oc-P in the lake and the rivers were all the highest among the seven forms of phosphorus (32.5–72.5%). The proportions of Ex-P were lowest in the sediments form Paihe River, Hangbuhe River, and from the most of lake area, and the proportions of Fe-P were lowest for the lake area nearby the river mouths of Nanfeihe River, Hangbuhe River, Baishitianhe River and nearby the Chaohu City, and for Baishitianhe River, Zhaohe River, Tongyanghe River, Zhegaohe River, Shuangqiaohe River, and Yuxing River. Or-P had the lowest proportion in Nanfeihe River. Inorganic phosphorus was the dominant form of phosphorus in the sediments from the lake and the rivers.
2. The concentrations of Al-P and Fe-P in the west were higher than those in the east. The concentrations of other forms of phosphorus in the west were approximately the same as in the east. The proportions of Oc-P in surface sediment in Lake Chaohu were the highest, and the proportions of Or-P were relatively low. The proportion of Ex-P in lake sediments was higher than river sediments. Al-P, Fe-P, Oc-P, ACa-P, and De-P in lake and river sediments had approximate proportions.
3. The northwest and northeast of Lake Chaohu are near Hefei City and Chaohu City, respectively. The regional distribution and water pollution of the rivers around Lake Chaohu had important impacts on the distribution of different forms of phosphorus.
4. Ex-P, Al-P, and Fe-P had significantly positive correlations with $PO_4^{3-}$ and TP in pore water, and ACa-P and Or-P had negative correlations with $PO_4^{3-}$. There was also a high correlation between $PO_4^{3-}$ and TP. The results showed that Ex-P, Al-P, and Fe-P in the sediments were the main sources of $PO_4^{3-}$ in pore water, and the concentration of TP in pore water also had a great influence on the concentration of $PO_4^{3-}$. As a result, the contents of Ex-P, Al-P, and Fe-P in the sediment could have an indirect influence on the degree of water eutrophication.

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