



OPEN Variations of phosphorus in sediments and suspended particulate matter of a typical mesotrophic plateau lake and their contribution to eutrophication

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Internal phosphorus loading (IPL), as an important part of lake phosphorus cycle and the key to solve the eutrophication problem, is still an important cause of regional and seasonal algal blooms for some mesotrophic lakes located in plateau areas. We investigated the composition, distribution of P fractions in sediments and suspended particulate matter (SPM) of Erhai Lake, southwest China, and explored the relationships between environmental variables and spatial-temporal variations of P fractions. The total P (TP) in surface sediments ranged from 817 to 1216 mg/kg, with inert Ca-P (32%) and Res-P (24%) predominating, at a moderate level. The comparison of short-term release fluxes (0.08 mg/(m²·d)) and long-term release fluxes (0.09 mg/(m²·d)) reflected that the northern region was recovering slowly from the previous P pollution. Mobile-P (the sum of loosely adsorbed P, iron bound P, and organic P) accounted for 52.3% of the TP in SPM and showed high spatial-temporal variations, which were closely related to the growth of algae throughout the investigation. The results suggested that sediments could make a sustained contribution to IPL, and that the P in SPM was highly active and significantly contributed to eutrophication in Erhai Lake especially at the time of seasonal alternations. Our data provided important theoretical bases for the relationship between internal phosphorus loading and eutrophication in plateau lakes.

Keywords Internal phosphorus loading, Long-term P release, Suspended particulate matter, Phosphorus fractions

Phosphorus (P) is a limiting nutrient that supports primary production in freshwater ecosystems¹. However, the excessive phosphate discharged by human activities input to the water column and accumulate², resulting in a status change (eutrophication) in aquatic ecosystems, with the deterioration of water quality³ and the food web shifting from one dominated by macrophyte production to a phytoplankton-dominated system⁴. Historically, P loading control has been recognized as the key to controlling eutrophication^{5,6}. The lakes in the Yunnan-Guizhou Plateau are characterized by more tributary water systems entering the lake, less flowing water systems and weak self-purification ability. Erhai Lake, as one of the largest plateau lakes in Yunnan Province, which has a high average elevation, deep water level and long water residence time, with spring all year round, strong sunlight and high algae biomass⁷. Since the 1990s, due to the rapid intensive development of agriculture and the application of chemical fertilizers, a high load of P has been discharged into the lake. Consequently, the ecological environment of Erhai Lake continued to deteriorated⁸, and the process of anthropogenic eutrophication simultaneously accelerated. The local government has taken a series of protective measures such as accelerating the structural adjustment of agricultural industries, reducing the emission of external pollution, implement the total sewage interception project and promoting the construction of shoreline ecological zone⁹. Nowadays, the water quality in Erhai Lake has improved during summer and autumn (predominantly in the south)¹⁰. However, algal blooms caused by lake eutrophication still occur occasionally, although the external pollution has been effectively controlled¹¹. At present, Erhai Lake is still undergoing a transition to the early stage

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of eutrophication¹². Accordingly, our study attempted to (1) investigate the distribution of P in the sediments of Erhai Lake and estimate the P release from the sediments in the northern region where algal blooms occur more frequently. (2) analyze the spatial-temporal variations of P composition in SPM and the relationship between P composition and algal bloom occurrence. (3) understand the contribution of IPL to the eutrophication in Erhai Lake.

Materials and methods

Study site

Erhai Lake (E100°05′–100°17′, N25°36′–25°58′), the seventh largest freshwater lake in China and the second largest freshwater lake in the Yunnan-Guizhou Plateau, covers an area of about 250 square kilometers and has a drainage area of 2565 km². The average water level is 1974 m, the maximum depth is 21.0 m, and the average depth is 10.5 m¹³. Erhai Lake is 42.5 km from north to south and 9 kilometers from east to west. The volume of the lake is about 2.96×10^9 m³ and the average annual inflow is 8.25×10^8 m³. The “North Three Rivers” water system consists of Miju River, Luoshi River and Yongan River, Southern Boluo River system and The western “Cangshan eighteen streams” are the main channels into Erhai lake¹⁴. The Xi'er River is the only outflow. The average annual rainfall is 850 mm, and the rainy season (May to October) accounts for 85% of the precipitation.

Sample collection and handling

In September 2022, surface sediments were collected with a Petersen grab sampler at 19 sampling sites (Fig. 1), including the north (S1–6), the middle (S7–13) and the south (S14–19). The surface sediments were homogenized quickly then transferred into airtight plastic bags. Overlying water samples at each site were stored in clean glass bottles and sent to the laboratory for analysis within 24 h. In September 2023, we collected sediment cores (approximately 9 cm in diameter and 20 cm in length) at S2, S3, S20 in the northern area of Erhai Lake. Three sediment cores were collected at each sampling site. The sediment cores were transported to the laboratory within 4 h after collection and then stored in the dark at 20 °C. P fluxes across the sediment–water interface were measured using the static release method^{15,16}. One sediment core at point S2 were cut at 1 cm interval, and all sediment samples were stored in pre-cleaned polyethylene bags, sealed, then refrigerated until laboratory analysis.

SPM samples were collected at 5 sampling sites (S1, S6, S8, S10, S19) in April, May, July, and September of 2023, which covered periods of rapid propagation, growth, and decay of algae. About 50 L of water was collected from each site and filtered through pre-combusted (450 °C for 4 h) Whatman grade GF/F filter using a vacuum pump. The filtered particles were then freeze-dried and stored in the dark (< 4 °C).

Short-term P flux and long-term P release

S2, S3 and S20 were selected to determine the total phosphorus (TP) and soluble reactive phosphorus (SRP) fluxes. The brief process was to drain the overlying water of the sediment cores, slowly siphon filtered lake water

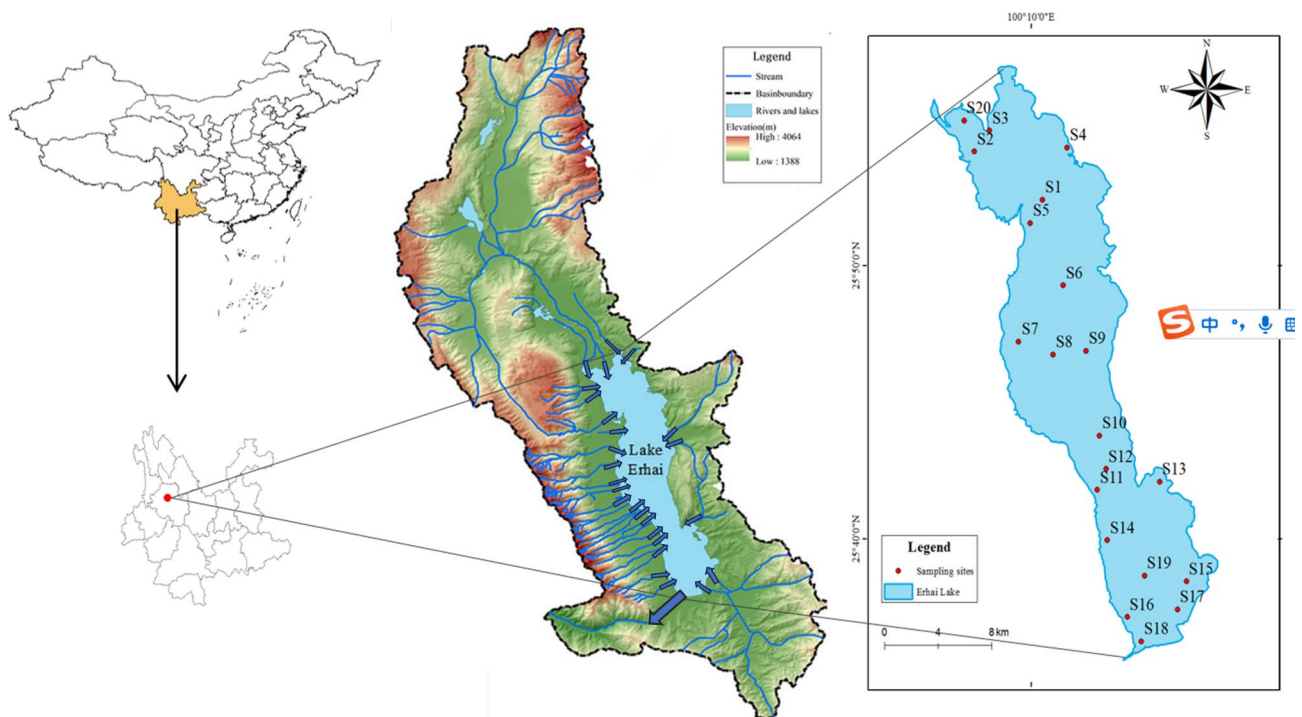


Fig. 1. Location of the study area and sampling sites. Map created in ArcGIS version 10.1, <http://www.esri.com>.

(2 L) to the sediment surface (three replicates at each site), and then these sediment cores were incubated in a dark chamber for 10 days at $20 \pm 5^\circ\text{C}$. 100 ml samples were taken 10 times at the following time interval: 8, 16, 24, 24, 24, 24, 24, 24, 48, 48 and 72 h. After sampling, filtered lake water was supplemented to maintain the water volume. The short-term release rates of TP and SRP were calculated as^{17,18}:

$$F_n = \frac{V(C_n - C_0) + \sum_{j=1}^n V_{j-1}(C_{j-1} - C_i)}{S \times t} \quad (1)$$

where F_n is the nutrient flux on the n^{th} day ($\text{mg}/(\text{m}^2\cdot\text{d})$), C_0 is the initial nutrient concentration (mg/L). V and V_j represent the volume of overlying water and sampling water (L), respectively. C_n and C_{j-1} are the nutrient concentration (mg/L) on the n^{th} and $j-1^{\text{th}}$ sampling day, respectively. C_i is the nutrient concentration of the replenished water (mg/L). S is the cross-sectional area of the column (m^2), and t is the incubation time (d). The final measured flux of TP and SRP is an average of 10 days.

The sediment core at S2 was sliced to measure the variations of vertical P concentration. Assuming that P is deposited in a stable state, the long-term release of P can be calculated as the difference between P accumulation at the sediment surface and P burial at a stabilization depth^{19,20}.

$$P_{\text{release}} = U_0 \times (C_0 - C_s) = S \times (1 - \Phi) \times \rho_d \times (C_0 - C_s) \quad (2)$$

C_0 (mg/g) represent dry sediment P concentration in the surface sediment and C_s (mg/g) represent dry sediment P concentration at the stabilized layer. U_0 ($\text{g}/(\text{m}^2\cdot\text{yr})$) represent mass sedimentation (accumulation) rate, S (cm/yr) is the deposition rate, Φ is the porosity, and ρ_d (g/cm^3) is the dry density of the sediments.

Analytical measurements

Concentrations of TP and SRP in lake water were determined using molybdenum blue methods²¹. The pH (W-pH), dissolved oxygen (W-DO) and temperature (W-T) of the overlying water were measured on site using the HACHHQ40D portable multimeter. According to Lorenzen²², Chlorophyll *a* was extracted with 90% acetone, extracted in 4°C darkness for >2 h, and determined by spectrophotometry (Chinese Environmental Standard HJ 897–2017). The sediment organic matter is measured according to Chinese Environmental Standard NY/T 1121.6–2006²³.

The P fractions in sediments and SPM were determined by sequential extraction method²⁴, which includes loosely adsorbed P (L-P), iron bound P (Fe-P), organic P (Org-P), aluminium bound P (Al-P), calcium bound P (Ca-P) and residual P (Res-P). At each step, the extract was filtered through a $0.45\ \mu\text{m}$ glass fiber membrane prior to analysis. Molybdenum blue method was used to analyze the P concentration of each step, and the average value was obtained by two repeated analyses. TP in sediments was estimated to be the sum of the six P fractions. The TP was also determined by SMT method²⁵. TP extracted by Hupfer method was compared with the TP extracted by SMT method, and the extraction rate was 96–103% (Table S1).

Statistical analyses

Microsoft Office Excel 2021 (Microsoft Corp., Redmond, WA, USA) was used for data processing to represent data as mean and standard deviation. Statistical tests were performed using SPSS 26.0 (SPSS Inc., Armonk, NY, USA). ArcGIS 10.8 (Esri Inc., Redlands, CA, USA) was used to analyze and plot the location and spatial distribution of P fractions. Pearson correlation analysis method was used to determine the relationship between environmental factors and P fractions. All analyses and visualizations of results were implemented using Origin 9.1 (Origin-Lab Inc., Northampton, MA, USA).

Results and discussion

Characteristics of P fractions in surface sediments

Prior to sediment sample collection, the water temperature of Erhai Lake dropped from $23.9\text{--}25.1^\circ\text{C}$ in August to $19.7\text{--}22.8^\circ\text{C}$ in October (Fig. S1). The concentration of chlorophyll *a* fluctuated in August and September ($0.018\text{--}0.025\ \text{mg}/\text{L}$), and then gradually decreased after entering October (the lowest value of $0.007\ \text{mg}/\text{L}$)^{26,27}. The TP in the water body decreased from the highest value of $0.027\ \text{mg}/\text{L}$ in August to the lowest value of $0.020\ \text{mg}/\text{L}$ in October. The distribution of W-TP, W-SRP, W-T and W-Chl *a* had a significant spatial consistency that each variable was highest in the north and gradually decreased from north to south (Fig. S2a–e).

The TP content in surface sediments ranged from 817 to $1216\ \text{mg}/\text{kg}$ (Fig. 2), with an average of $967\ \text{mg}/\text{kg}$, consistent with previous studies on Erhai Lake^{28,29}. Compared with other plateau lakes, such as Dianchi Lake $2050.0\ \text{mg}/\text{kg}$, Caohai Lake $692.9\ \text{mg}/\text{kg}$ and Chenghai Lake $920\ \text{mg}/\text{kg}$ ^{30–32}, Erhai Lake was at a moderate pollution level³³. L-P, Org-P and Fe-P, under certain conditions, such as anaerobic and high pH environment, because of the reduction of phosphate complexes and mineralization of organophosphates, can easily release into the water body and become bioavailable to algae³⁴. The L-P was the lowest ($6.70\text{--}17.10\ \text{mg}/\text{kg}$, a mean value of $12.41\ \text{mg}/\text{kg}$) fraction, accounting for only $0.73\text{--}1.62\%$ of TP in surface sediments (a mean value of 1.28%). Researches have shown that L-P is the most active part of inorganic P, which can be directly absorbed and utilized by submerged plants and plankton at any time, and the proportion of L-P is the lowest in most lake sediments^{28,31,35}. Fe-P is most closely related to the migration and transformation of P in lake environment³⁶. Fe-P ranged from 92 to $262\ \text{mg}/\text{kg}$, with an average of $187\ \text{mg}/\text{kg}$, accounting for 19% of TP. Org-P ranged from 36 to $123\ \text{mg}/\text{kg}$, with an average of $78\ \text{mg}/\text{kg}$, accounting for 8% of TP. The mobile-P (the sum of L-P, Fe-P, and Org-P) accounted for $13\text{--}36\%$ (a mean value of 29%) of TP, with concentrations ranging from 138 to $363\ \text{mg}/\text{kg}$ (a mean value of $278\ \text{mg}/\text{kg}$), which was close to the content in Dianchi Lake sediments, but significantly higher than Taihu Lake ($181\ \text{mg}/\text{kg}$) and Chaohu Lake ($148\ \text{mg}/\text{kg}$)^{17,37}. Al-P, Ca-P are conventionally considered to

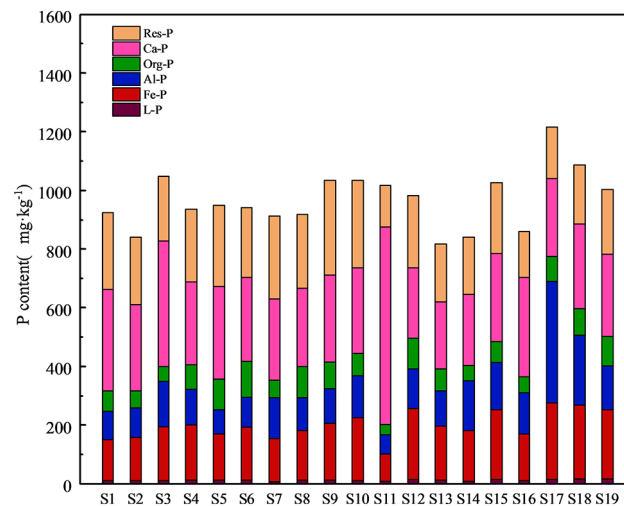


Fig. 2. Variation of different forms of P contents in surface sediments of Erhai Lake.

be relatively stable^{38,39} and participate in the P cycle of lakes under certain conditions^{40,41}. Al-P ranged from 64 to 412 mg/kg (a mean value of 145 mg/kg), accounting for 15% of TP in sediments. However, many studies indicated that Al-P can dissolve under alkaline conditions ($\text{pH} > 9$), especially during the heavy algal bloom seasons^{42,43}. The content of Ca-P ranged from 229 mg/kg to 671 mg/kg (a mean value of 312 mg/kg), accounting for 32% of TP in sediments. Because of the large river drop and low forest coverage rate in Yunnan Plateau lake area, the sediments were mainly the product of weathering in the basin, and soil erosion caused a large amount of Ca-P to enter the lake⁴⁴. Res-P, the most stable part in all P forms content⁴⁵, ranged from 141 mg/kg to 260 mg/kg (a mean value of 231 mg/kg), accounting for 24% of TP in sediments.

L-P, Fe-P and Al-P in the surface sediments were positively correlated with S-TP ($p < 0.05$, $r = 0.52$; $p < 0.01$, $r = 0.58$; $p < 0.01$, $r = 0.66$ respectively, Fig. S3), in other words, the three fractions mainly determined the level of TP content at each site. The contents of Ca-P and Res-P fluctuated little among different sites (Fig. 2) and had no significant correlation with S-TP, although they occupied a high proportion of TP. Both Fe-P and Org-P had significant negative correlation with Ca-P ($p < 0.05$, $r = -0.57$ and $p < 0.05$, $r = -0.54$ respectively, Fig. S3), which indicated that there might be a transformation process from Fe-P, Org-P to Ca-P^{46,47}. The L-P, Fe-P Org-P and Res-P were positively correlated with sediment organic matter ($p < 0.05$, $r = 0.56$; $p < 0.01$, $r = 0.64$; $p < 0.001$, $r = 0.71$; $p < 0.05$, $r = 0.52$ respectively, Fig. S3), while Ca-P was negatively correlated with sediment organic matter ($p < 0.01$, $r = -0.68$), reflecting that the high mobile-P content in sediments was caused by human activities and organic matter accumulation^{48,49} which increased oxygen demand leading to redox related P release⁵⁰. In addition, mineralization of organic material might also be accompanied by the release of P into the water column⁵¹. L-P, Fe-P and Org-P were negatively correlated with water pH and temperature (Fig. S3), suggesting that the increase of pH and temperature could lead to the release of P from sediments and the increase of IPL. There was no significant correlation between W-TP and S-TP at the corresponding point (Fig. S3)³⁷, especially the low P content in the sediments at the northern region (Fig. 2) but the higher TP concentration in the overlying water (Fig. S2a). Over the years, the rapid development of agriculture in the northern catchment has led to large amounts of nitrogen and phosphorus pollutants entering the lake with runoff, laying the foundation for continued eutrophication in the northern region⁵².

The composition and content of P in the sediments of Erhai Lake varied greatly with spatial distribution (Fig. 3). From north to south, TP sediment distribution in Erhai Lake increased in the direction of water flow (Fig. 1). The highest P content was found in the south-central (962.4 mg/kg on average) and the south (1005.4 mg/kg on average) (Fig. 3h). The maximum P content was 1216 mg/kg at the shallower coastal district (the inlet of Boluo River) (Fig. S7) due to the pollution from the Xiaguan urban area⁵³. The TP in southern sediments increased in recent years, while in northern central sediments remained at a relatively stable level⁵⁴. The content of L-P increased from north to south, and was higher in the east than in the west (Fig. 3a) and the maximum (17 mg/kg) was reached at S18, where the water flowed into the Xi'er River. At the middle of the lake, S12 had a high L-P content of 15 mg/kg. Water depth generally controlled redox conditions at the water-sediment interface⁵⁵, which resulted in the distribution of Fe-P was similar as that of L-P (Fig. 3b), and the maximum was 262 mg/kg at the southern near-shore site S17 (Fig. S7). The highest Org-P content was 123 mg/kg, found at S6 in the north-central part of the lake (Fig. 3c), and Res-P reached highest content of 322 mg/kg at S9 (Fig. 3g). Org-P and Res-P can be used to characterize the degree of incomplete mineralization and humification of organic matter load deposition in water environment⁵⁶. Compared with the northern and southern parts, the central region of Erhai Lake was deeper (Fig. S7), and the hydraulic retention time became longer, typically at an average time of three years, leading to the gradual accumulation and deposition of organic debris produced by aquatic vegetation (Fig. S1f), and finally higher levels of Org-P and Res-P were found in sediments of the central region. The distribution of Al-P was relatively average throughout the lake (Fig. 3e), with a higher content only in the south, where S17 reached a maximum value of 412 mg/kg, which was different from the previous research

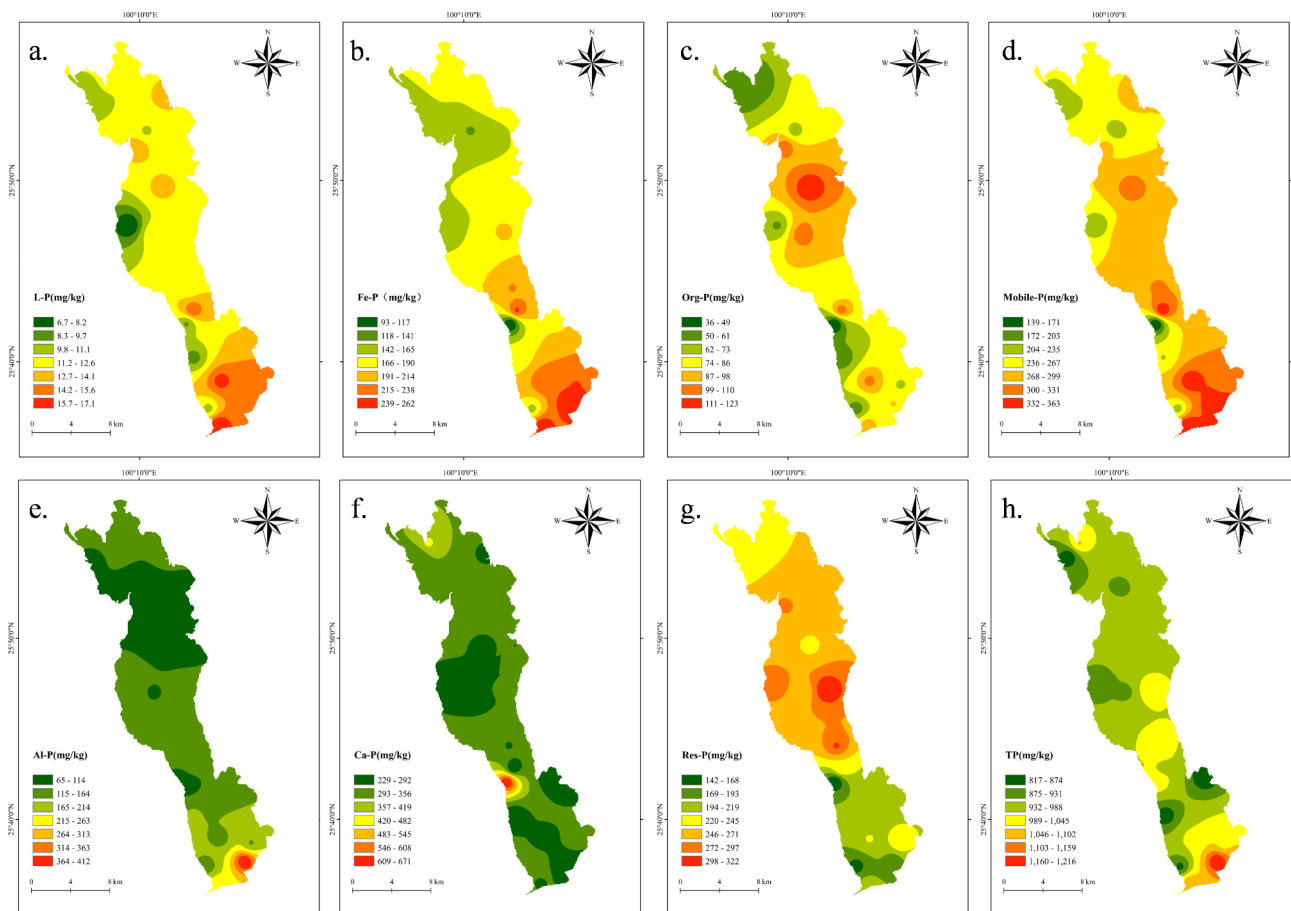


Fig. 3. Contents and spatial distribution of phosphorus in the sediments of Erhai Lake.

conclusions on the enrichment of Al in the deep area of Erhai Lake²⁸. Ca-P combined with authigenic apatite and calcium carbonate in sediments is an important reservoir of phosphate in lake ecosystems. The high Ca-P content in the northern part of Erhai Lake was attributed to the large amount of calcium carbonate particles carried by the rivers in the area (Fig. 3f). However, the southern basin was dominated by red soil, which was carried into the lake to reduce the pH to release Ca-P from sediments.

Short-term phosphorus flux and long-term phosphorus release

In recent years, the concentration of TP in the overlying water of Erhai Lake presented a spatial pattern of high in the west and low in the east, high in the north, low in the south and the middle, and increased significantly in the rainy season⁵⁷ when the water temperature became high in summer and autumn, causing algal blooms⁵⁸ and promoting the release of internal nitrogen⁵⁹ and phosphorus⁶⁰. The three sites (S2, S3 and S20) in the northern region of Erhai Lake during the rainy season were selected for core sediment sampling, and the fluxes of TP and SRP at the sediment-water interface were calculated (Table S3). The average flux of TP is 0.13 mg/(m²·d), significantly lower than Lake Taihu (2.65 mg/(m²·d)) and Lake Erie (1.35 mg/(m²·d)), higher than Lake Caohai (0.075 mg/(m²·d))^{17,61,62}. Compared with the previous studies, the P fluxes in the northern part of Erhai Lake did not change significantly⁶³.

The vertical distributions of P fractions at S2 are shown in Fig. 4. The highest TP content (793 mg/kg) was found in the top 1 cm of sediments. With the increase of depth, the TP in sediments showed a decreasing trend, and basically kept Ca-P > Res-P > Al-P > Fe-P > Org-P > L-P in each layer²⁸. L-P content of 15.75–26.63 mg/kg accounted for 2.2–3.3% of TP and decreased by 41% from the top to the bottom. The Org-P content was 44.80–91.94 mg/kg, and the bottom decreased by 51% compared with the top. The content of BD-P was 70.73–96.03 mg/kg, and the bottom decreased by 26% compared with the top. Al-P content was 73.46–93.74 mg/kg, and the bottom decreased by 9.6% compared with the top. On the contrary, the content of inert component Ca-P and Res-P increased with depth from 289.29 to 326.20 mg/kg and 192.07 to 222.64 mg/kg respectively, and the bottom increased by 11% and 16% compared with the top. The heterogeneity between different layers could prove that mobile-P was an important source of IPL in the long run^{43,64,65}. Al-P content fluctuated with depth, indicating that it was relatively stable and could contribute to IPL in some specific time periods^{66,67}. Ca-P and Res-P basically did not participate in the P cycle and accumulated over time and eventually buried at deeper depths. When the depth came to 7–9 cm, the contents of each P fraction changed greatly, and the relatively inert fractions (Ca-P, Res-P and Al-P) increased significantly. Therefore, it could be considered that the sediments in

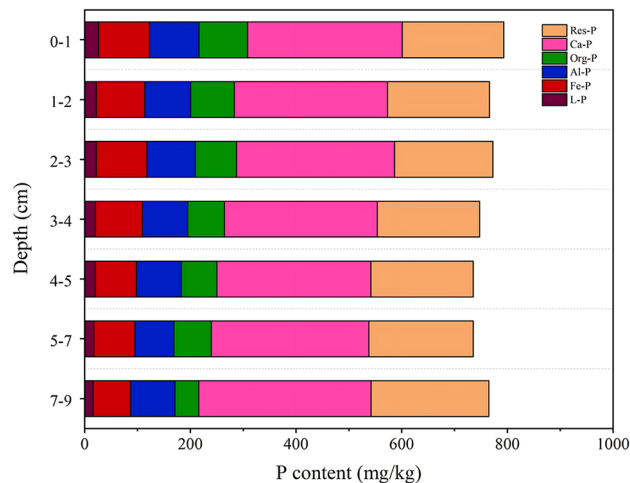


Fig. 4. The vertical distributions of P fractions at S2.

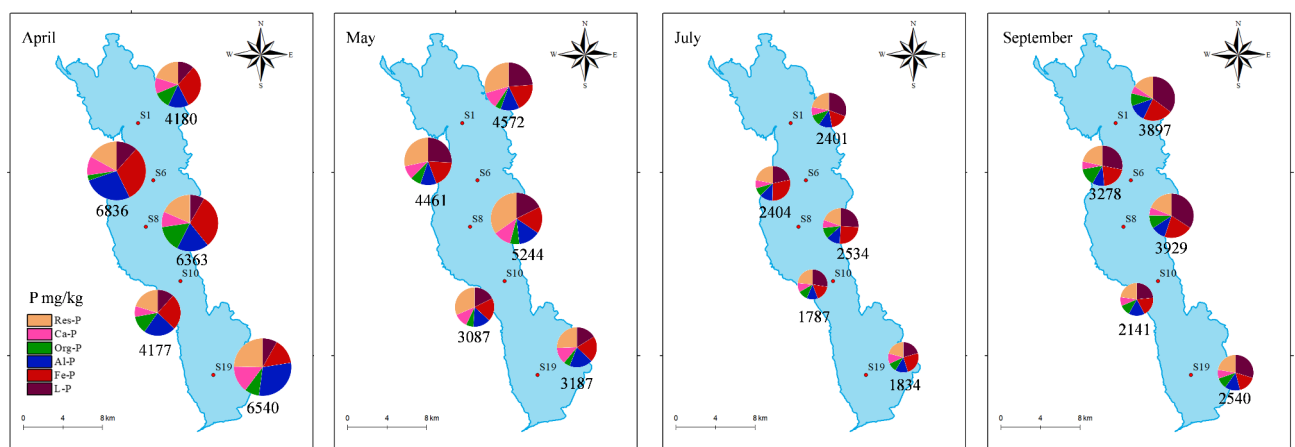


Fig. 5. The contents of different P fractions in SPM at each sampling site in Lake Erhai.

this layer had reached a relatively stable state. By ^{137}Cs and ^{210}Pb dating methods, the sedimentation rate in the northern part of Erhai Lake was approximately 0.24 cm/yr ⁶⁸. Accordingly, the long-term release flux at S2 was estimated to be $33.26 \text{ mg}/(\text{m}^2\cdot\text{yr})$. Notably, the sediment P release flux measured in this study can only partially reflect the contribution to IPL. Sediment resuspension^{69–71}, the activities of benthic organisms⁷², Pumping effect of cyanobacteria⁷³ can enhance the P release, which has a salient impact on the SRP concentration. These physical and biochemical processes might explain that although the sediment P concentration in the northern region was lower than that in the southern region, the SRP concentration in the northern water could keep higher than that in other regions for a long time (Fig. S4b). Even so, this result reflected the fact that although the northern lake has suffered severe eutrophication in the past, it is now in the process of a slow recovery⁷⁴.

Monthly variations of phosphorus in SPM and Contribution to the IPL

In Erhai Lake, the TP content in SPM at all sites ($1787\text{--}6836 \text{ mg/kg}$) was much higher than that in corresponding sediments (Fig. 5). Specifically, mobile-P, which sustained aquatic plants and animals, accounted for an average of 52.3% of TP, but only 28.7% in sediments. The proportion of Al-P (15.4% on average) was close to that of sediments, while the proportions of inert Ca-P (9.3% on average) and Res-P (23.1% on average) were significantly lower than that of the sediments (Fig. 2). The differences of each P fraction between SPM and sediments indicated that most P in SPM was bioavailable, and the affinity of SPM for mobile-P was stronger than that of sediments⁷⁵. During the sampling period, the TP and each P fraction had the similar changes with time in different nutrient regions (Fig. 5). TP in SPM from S1 (Northern area with strong current) remained low in all periods, while TP in SPM from S6 (maximum water depth) and S8 (central circulation zone) had higher values. TP in SPM from S10 (once large aquatic plants grew) and S19 (near the outlet of the Xer River) gradually decreased over time. From April to May, TP in SPM at most sites decreased from an average of 5619 mg/kg to an average of 4110 mg/kg except S1 where algae growth was faster. During this period, the increase of water temperature (Fig. S5) promoted the activity of microorganisms, the decomposition of organic matter and the

release of Org-P⁴⁰. Because of the decrease of DO (Fig. S5), the reduced environment led to the reduction of ferric iron and desorption of Fe-P^{69,76}. In addition, the chemical bonds of Al-P in SPM can break under alkaline conditions, resulting in P release from Al-P and more frequent P exchange between SPM and water body^{74,77–79}. Due to the above possible biochemical reaction processes, there were significant reductions in Fe-P, Org-P and Al-P (Fe-P decreased from 26% of TP in April to 18% in May, Org-P decreased from 10 to 6%, Al-P decreased from 23 to 14%). On the contrary, the percentage of L-P and Res-P increased greatly (L-P increased from 10 to 20%, Res-P increased from 20 to 30%). From May to July, higher temperature since the beginning of summer made the biomass of algae and TP of water reach the peak (Fig. S5). TP continued to decrease to an average of 2192 mg/kg. The proportion of Fe-P (22% of TP) and Org-P (10% of TP) increased while the proportion of Al-P (14% of TP) continued to decrease. The proportion of Ca-P (8% of TP) and Res-P (22% of TP) decreased. The continuous increase in the proportion of L-P (25% of TP) was a further enhancement of the potential of SPM to provide P to the water body. When the time came to September, the algae began a period of decline as the TP in SPM increased to 3157 mg/kg. The proportions of Al-P (12% of TP) and Fe-P (20% of TP) decreased while the proportions of L-P (30% of TP) and Org-P (11% of TP) reached the peak. There was no significant change in the proportions of Ca-P (7% of TP) and Res-P (20% of TP). According to the four sampling results, the TP content in SPM was significantly negatively correlated with the growth of algae (Fig. S6), which was different from previous studies^{80,81}. SPM in lakes was mainly composed of phytoplankton, bacteria, zooplankton, suspended sediments and allochthonous particles⁸². In this study, the growth of algae was accompanied by an increase the proportion of mobile-P, especially L-P in SPM (Fig. 5) and an increase in the content of SPM in the water body (Table S4), which was comprehensively manifested as the increase of SRP in the lake (Fig. S4b). Contrary to the situation in sediments, L-P was negatively correlated with other P fractions (Fig. S6). Fe-P, Al-P, Org-P were transformed to more bioavailable state, L-P, and further converted into SRP in the water. This process was most pronounced between April and May (Fig. 5), when the water temperature changed most dramatically (Fig. S5). Throughout the sampling period, Al-P and Fe-P were the main fractions of the transformation and the P supply to the water body. (From April to May, Al-P and Fe-P led the transformation, then Al-P in July, and finally Fe-P in September.)

In general, the proportions of P fractions in SPM had similar variations in most trophic areas (Fig. 5), which meant that P fractions in SPM reflected the overall nutrient status of water more acutely than in sediments⁸³. In addition, it is worth noting that the P composition in the northern region always changed ahead of other regions (Fig. 5) and can therefore be used as a harbinger of the future development of nutritional status of the entire lake.

Contribution of sediments and SPM to the IPL in Erhai Lake

It is generally believed that during the warm rainy season, the IPL in Erhai Lake can have the most significant influence on the TP in the overlying water, and lead the changes of algal blooms. The vertical distributions of P fractions revealed the P release mechanism and diagenetic transformation process. For most of the time, mobile-P took on the role of the main P contributor from sediments to the lake, and Al-P could be a potential P source when some environmental conditions were met. The long-term release flux (0.09 mg/(m²·d)) was higher than the local short-term release flux (0.08 mg/(m²·d)), which meant P pollution in northern sediments has been gradually alleviated. In the overlying water, PTP occupied a considerable proportion of water TP (Table S4), and the TP in SPM was much higher than that in sediments. More importantly, the proportion of mobile-P (52.3%) meant that P carried by SPM had high reactivity and exchange ability with ambient waters. During the observation time, TP content and composition in SPM varied spatiotemporal dynamically. Since the beginning of summer, the proportion of algae in SPM increased, which was reflected in the decrease of TP in SPM and the increase of SPM concentration in water. At the same time, Org-P, Fe-P and Al-P decreased and while L-P increased even in the period of algal decline, proving that SPM actively participated in the P cycle of the lake and promoted the eutrophication of the lake.

Conclusion

By studying the distribution and spatial-temporal variations of P in lake sediments and SPM, we can reach the following conclusions:

1. Inert Ca-P (32%) and Res-P (24%) were the dominant P fractions in the sediments of Erhai Lake, followed by Fe-P (19%), Al-P (15%), and L-P (1.3%). In contrast, not only the TP in SPM was higher than the sediments, but the mobile-P dominated in TP of SPM (52.3%), which had higher bioavailability potential.
2. Sediments could make a sustained contribution to IPL. The vertical distributions of P fractions indicated that L-P, Org-P, Fe-P in the sediments had major contribution to IPL in the long term. The P content and composition in SPM showed high spatial-temporal variations throughout the growth cycle of algae when substantial proportion of P in SPM transformed into readily bioavailable L-P, leading to an increase in the concentration of SRP in the overlying water.
3. After the external pollution was controlled, the SPM and sediments could still support the eutrophication which was manifested as the regional algal bloom in the rainy season. In addition, follow-up studies can employ other detection techniques to determine the P fractions, especially organic P compounds of algae, water, SPM and sediments, which is of great value for further determining the P cycle process and formulating effective nutrient management guidelines for plateau lakes.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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