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# Seasonal stratification and phosphorus release from sediments at Lake Hongfeng, Southwestern Plateau, China

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**Abstract.** This study investigated the relation between seasonal stratification and sediment phosphorus release in a seasonally stratified lake. Lake quality monitoring was conducted for 10 months from April 2010 to January 2011 in Lake Hongfeng, southwestern China. Destratification generated strong mixing from surface to bottom waters in the early autumn. The lake water was well-mixed vertically within 3 days and became anoxic within next few months. Total phosphorus concentrations of the whole water column increased by 15–20% as a result of high surface sediment concentrations of total phosphorus and reactive phosphorus. In seasonally stratified lakes, high reactive phosphorus content in sediments may form a larger flux of dissolved phosphorus in the sediment–water interface following turnover. Technical measures should be taken to increase dissolved oxygen concentration and control the water circulation in this lake, especially during the cooling period, to weaken the effect of destratification and prevent sediment phosphorus release.

## Introduction

Eutrophication is a serious global environmental problem that threatens water resources, human health, and socially sustainable development [1]. Major consequences of eutrophication include decreased water quality, increased phytoplankton blooms, oxygen depletion, and fish death [2]. Phosphorus (P) is often a growth-limiting element for aquatic organisms and plays a significant role in the eutrophication process of reservoirs [3]. In addition to the industrial and agricultural pollutant input, sediments are also important sources of nutrients to the overlying water during the eutrophication process of lakes [4]. Sediments may continuously release nutrients, causing eutrophication of lakes over the long-run, even after the external sources are removed [5,6].

Previous studies showed that deterioration of water quality mainly occurs in summer in shallow lakes such as Taihu Lake, China [7]. Physical parameters such as temperature and light play an important role on nutrient release [8]. Wind-driven resuspension may exacerbate the deterioration of the water quality [6]. Biological activity can also promote the release of nutrients at the water–sediment interface [5]. In deep water, water depth is the most important factor affecting the distribution of macrozoobenthos. Sediments generally maintain relatively higher organic matter contents, and nutrients are continuously released from sediment pore water to stagnant water [9]; however, the overall water quality in deep lakes usually remains stable through hypolimnetic dilution [10].

Southwestern China has about 38 lakes with moderate depths of 10–50 m and a total surface area of approximately 700 $km^2$ [10]. These lakes may be too deep to be protected by macrophytes in their littoral zones and too shallow to allow mitigation of nutrients recycling through hypolimnetic dilution [11]. Previous observations showed that seasonal thermal stratification exists in these lakes [12]. Vertical water mixing can often be generated by destratification, and strong convection disturbs the water–sediment interface, which releases reducing substances and nutrients to the overlying water. Until now, however, the relation between seasonal water stratification and phosphorus release in these lakes with moderate depths has not been thoroughly investigated due to lack of long-term field observation and lab analysis. We therefore conducted a 10-month field observation to investigate the relation between the evolution of seasonal water stratification and phosphorus release and suggest lake management approaches to protect the water quality of the drinking water source.

**Sampling sites**

Hongfeng Lake (106.24°N, 26.30°E) is the largest artificial freshwater reservoir in Southwest Plateau, China, with an area of 57.2 km$^2$ and an average depth of 10.5 m (Fig.1). Two principal rivers discharge some 530 million m$^3$ of industrial wastewater into the lake each year. Many effluents contain nitrogen, phosphorus, or heavy metals. In addition, Hongfeng Lake serves as the principal water resource for Guiyang City, Guizhou Province as well as an important entertainment and tourist attraction. Lake Hongfeng is located in the subtropical humid monsoon climate zone, where warm and cold airflows alternate strongly. Annual sunshine is 1278 h, the average annual precipitation is 1176 mm, annual average relative humidity is 81%, and the frost-free period is 275 d. The mean annual temperature is about 14.1 C, ranging from extremes of 35.5 to −8.6 C. The annual average wind speed is 2.5 m/s, and the static wind frequency is 19.7%.

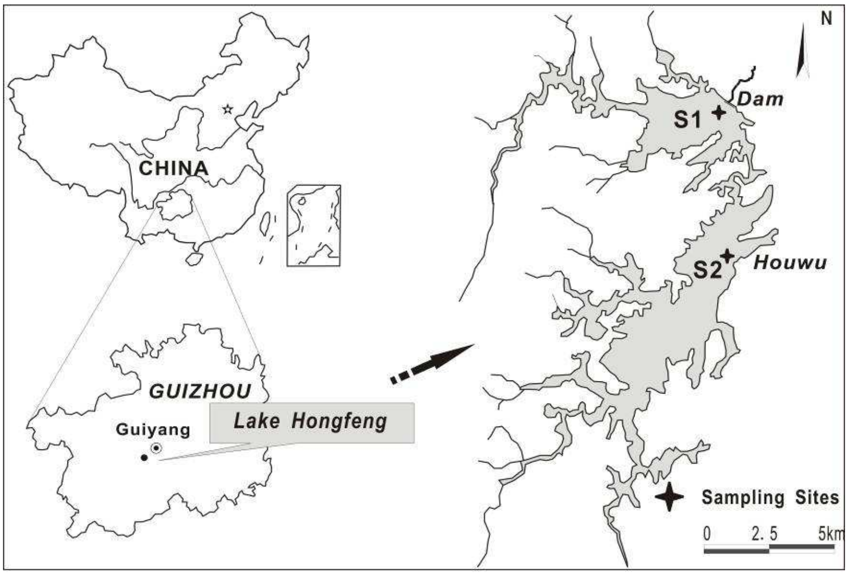


Fig. 1 Location of sampling sites in Lake Hongfeng: S1–Dam Area; S2–Houwu Area.

**Sample collection and analysis**

The 2 sampling sites were S1 (Dam Area, the deepest part) and S2 (Houwu Area, the most polluted part) (Fig. 1). Sediment cores were collected at stations S1 and S2 in September 2010 using an undisturbed lake sediment sampler (Institute of Geochemistry, CAS). The samples were collected with a 5 cm diameter Plexiglas cylinder tube, and the sediment core was sliced into 2 cm sections, which were kept in sealed plastic bags and transferred to laboratory in iceboxes (<4 C) where they were freeze-dried. Samples were then ground and sieved with a standard 100 μm-mesh sieve for chemical analysis. Phosphorus forms in sediments were separated following, in principle, the sequential extraction scheme suggested by Hupfer et al. (1995) for the determination of $NH_4C1$–P (P extracted with 1 M $NH_4C1$ solution, loosely bound P), BD-P (P extracted with 0.11 M bicarbonate/dithionite solution, redox-sensitive P bound to Fe-hydroxides and Mn compounds), NaOH-srP (soluble reactive P extracted with 1 M NaOH solution, P bound to metal oxides, mainly of Al and Fe), NaOH-nrP (calculated as the difference between total P and soluble reactive P extracted with 1 M NaOH solution, organic P), HC1-P (P extracted with 0.5 M HCl solution, calcium-bound P), and rest-P (P extracted with 1 M HCl solution, refractory organic P) [13].

We investigated seasonal stratification at 2 m intervals monthly from April 2010 to January 2011. During each month, water quality parameters of temperature, dissolved oxygen (DO), and pH were monitored in the field by multiparameter water quality observation analyzer YSI (6600V2-2-Dt; YSI Co., USA), which has a temperature range of 5–50 C ± 0.15 SE. DO ranged from 0 to 20 mg/L (<2% error). Water samples from surface to bottom were collected with a Niskin water sampler in September and October 2010, respectively. All samples were transferred to precleaned plastic bottles (250 mL), acidified with nitric acid in the field, and then transferred to the lab and kept at 4 C. Total phosphorus (TP) in the water was determined by the $K_2(SO_4)_2$-oxygenation method in the lab.

## Results and discussion

### *Seasonal water stratification*

Thermal stratification generally exists in deep lakes, such as Pao-Cachinche Reservoir, Lake Erie, and alpine-type lakes [14,15]. This depth is a necessary condition for the formation of thermal stratification. Effects of residence time on thermal stratification are manifested mainly by changes in depth of the thermocline [9]. Tropical lakes have small vertical differences in temperature but are nevertheless able to generate a stable stratification [14]. Man-made lakes with water residence time longer than 200 days usually present a lacustrine zone and can also develop thermal stratification [16]. Residence time of Lake Hongfeng was ~0.26 yr, which allowed seasonal stratification (Fig. 2).

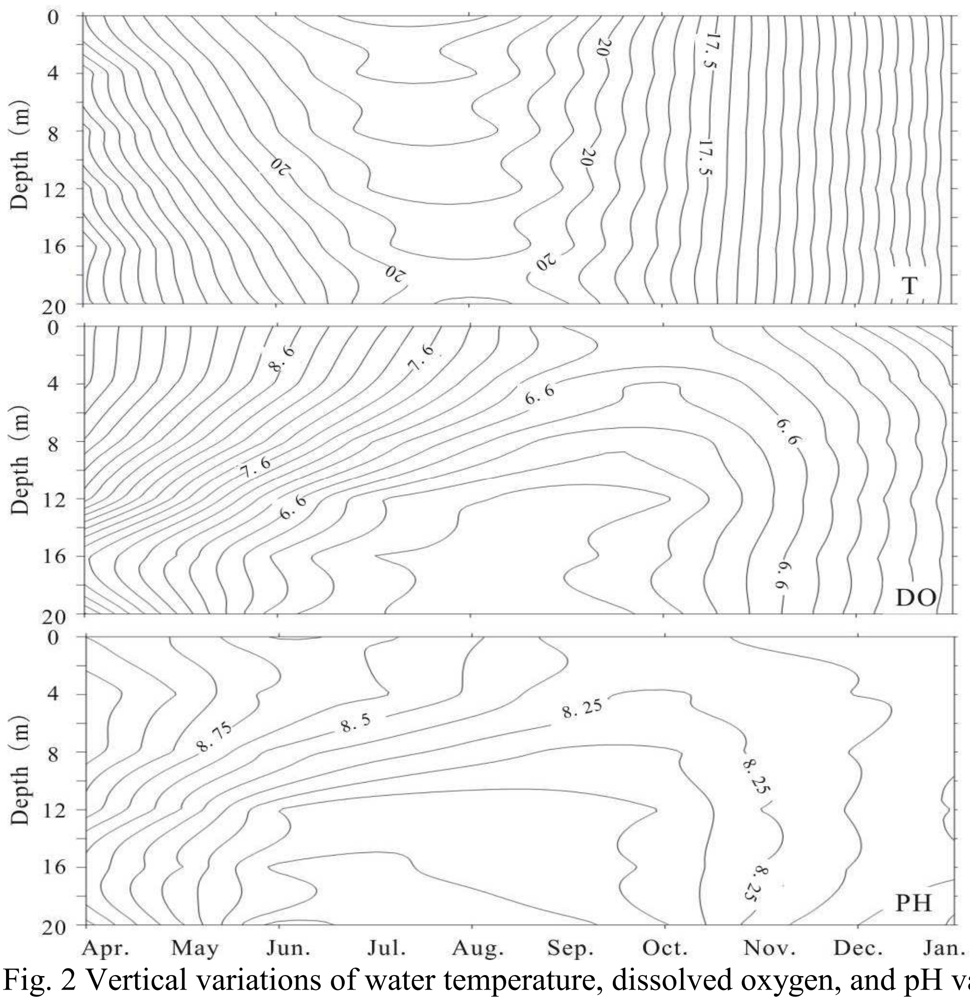


Fig. 2 Vertical variations of water temperature, dissolved oxygen, and pH value in Lake Hongfeng, 2010.

Seasonal water stratification in Lake Hongfeng formed periodically in winter and spring, was most significant in summer, and then suddenly disappeared in early autumn. During our observations, the surface water temperature varied between 12.2 and 28.3 C, average 21.2 C. The bottom water temperatures were 11.2–24.5 C, average 19.5 C. Thermal stratification appeared in early spring and disappeared in early autumn. In the autumn, water was evenly mixed vertically, and temperature, DO, and pH values were reduced over a short term.

Epilimnion waters are characterized by chemically oxidizing conditions due to the continuous dissolution of oxygen across the air–water interface whereas hypolimnion waters may exhibit lower DO concentrations and redox potentials due to the decay of organic matter and oxidation reactions [17]. There were differences in DO between the surface water and the bottom water except in autumn, with seasonal or monthly variations (Fig. 2). Surface water DO ranged from 3.6 to 8.5 mg/L, dropping to the lowest level during the autumn, even lower than 4.0 mg/L, the limit value for fish survival. For the rest of the year, DO remain at normal levels. The pH value of surface water ranged from 7.5 to 8.9, with the minimum observed in autumn. The spatiotemporal distribution patterns of DO and pH in the water column were similar in Lake Hongfeng.

***Phosphorus forms in sediments***

We analyzed 36 samples to determined phosphorus forms in sediments of Lake Hongfeng (Fig. 3). TP contents in sediments of the Dam Area ranged from 691.3 to 2203.8 mg/kg, with surface sediments significantly higher than those in bottom sediments. It was evident that the P level in the sediments was high compared with other eutrophic lakes such as Taihu Lake and Chaohu Lake [1,18], probably because the P load was aggravated by the rapid development of industry, agriculture, and urbanization. TP in surface sediments reached the maximum value near about 5 cm and then reduced as the depth increased; TP below 20 cm stabilized at ~800 mg/kg. The main P forms in sediments were NaOH-srP and rest-P, which accounted for 76.7–89.0% (mean value 84.3%) of the TP in sediments. Rest-P contents ranged from 213.2 to 322.9 mg/kg, with little change in the vertical profile. NaOH-nrP accounted for most of the difference between TP and reactive phosphorus extracted by 1M NaOH solution, which also showed little vertical change. Surface sediments were enriched with reactive phosphorus such as $NH_4Cl$-P, BD-P, and NaOH-srP.

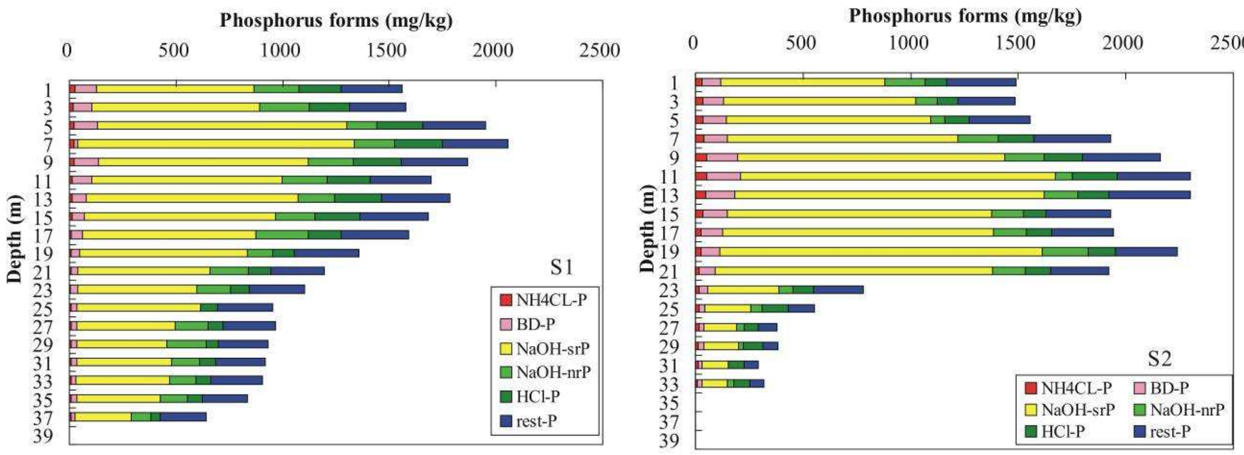


Fig. 3 Phosphorus forms in sediment of Lake Hongfeng: S1-Dam Area; S2-Houwu Area.

Similar to the Dam Area, TP contents in surface sediments of the Houwu Area were significantly higher than those in bottom sediments, ranging from 336.2 to 3794.3 mg/kg. At about 21 cm in depth, TP contents in sediment sharply increased from 743.2 to 2742.2 mg/kg. Mean TP contents were 2660.1 and 465.7 mg/kg in the surface sediments compared to below 21 cm, respectively. NaOH-srP was the main phosphorus form in surface sediments at 51.2–67.2%, with a mean content of 1190.5 mg/kg. Below 21 cm, NaOH-srP comprised 38.3% of TP, with a mean content of 184.8 mg/kg. NaOH-nrP content was about 107.2 mg/kg, and rest-P was 32.9 mg/kg. Vertical variations of sediment P contents showed that total P contents progressively increased from relatively low concentrations of 20–30 cm to higher concentrations at present day, likely reflecting an incremental P input with increasing anthropogenic impacts. TP concentrations in the top 10 cm sediment were generally high, ranging from 1486.3 to 2459.4 mg/kg, which indicated that the lake sediments had a great potential to supply phosphorus to the overlying water [6].

***Phosphorus release***

The strong, alternating warm and cold air flows over Lake Hongfeng can create unexpected convection and material exchange generated by stratified differences in water density that dominate the thermal subdivision of the lake [14]. In autumn, the lower atmospheric temperature increases the density of surface water, and frequent horizontal wind disturbances strengthen vertical water mixing [15,19].

Observations indicate that seasonal water stratification was significant in September (Fig. 4) when the depth of thermocline ranged from 8 to 12 m. Temperature, DO, and pH above the thermocline decreased with increasing water depth. These physical and chemical parameters were essentially the same in the bottom water. TP concentrations in the water near the water–sediment interface were significantly higher than those in the upper water. After the seasonal water stratification disappeared in October, the lake showed strong seasonal anoxia. Vertical mixing of the lake water column, called turnover, can significantly affect pit lake water chemistry [17]. Temperature, DO, and pH values in Lake Hongfeng were the same for surface water and bottom water and significantly lower in autumn than other seasons. When turnover occurred, DO concentration was lower than 4.0 mg/L, and pH was 7.5. Synchronous changes of pH values and DO concentrations may imply that they were both affected by the seasonal water stratifications in Lake Hongfeng. TP concentration of the whole water column increased 15–20% during the destratification.

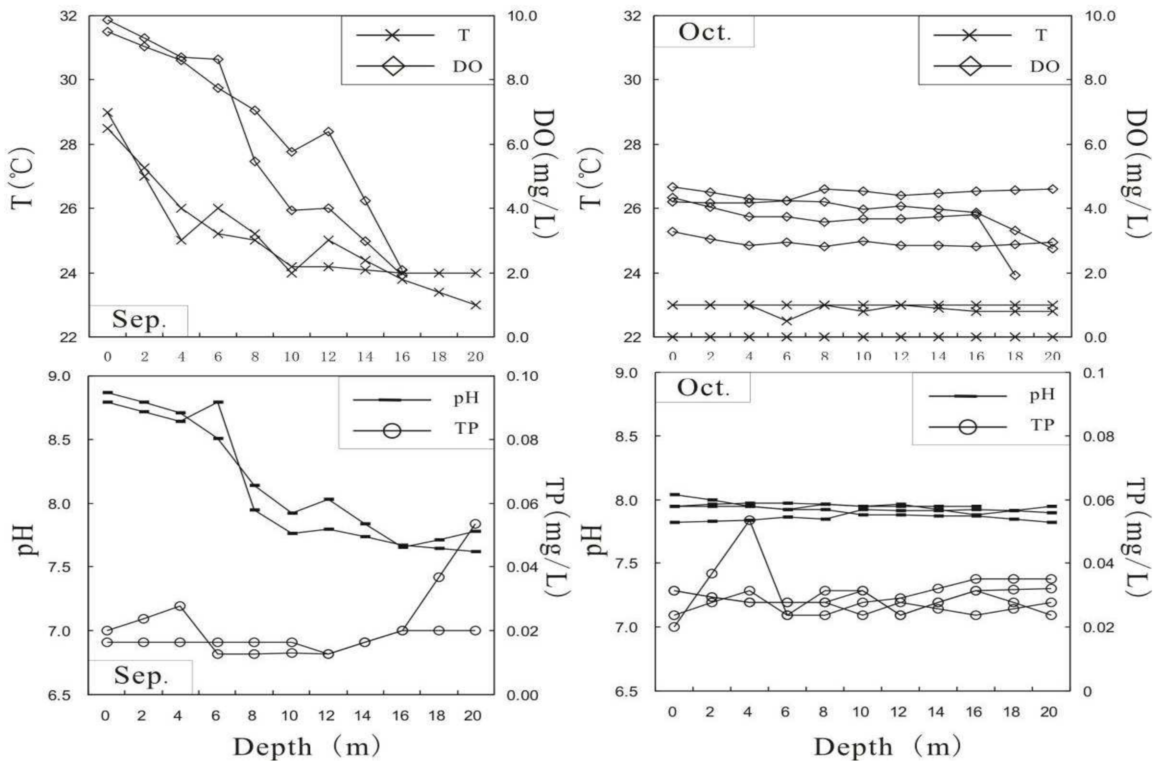


Fig. 4 Variations of water temperature, DO, pH, and TP before (Sep) and after (Oct) seasonal stratification disappeared.

The sinking depths of surface waters in the studied lake reached the water–sediment interface (Fig. 4). Lake mixing generated by the destratification disturbed the bottom sediments and enhanced the release of TP in surface sediments. Concentrations of DO affect the release of internal nutrients [6] controlling the redox potential at the sediment and water interface. DO plays an important role in the transformation of iron- and aluminum-bound P in the sediments. In oxic and aerobic conditions, phosphate can bind with $Fe^{3+}$ to form $Fe_2(PO_4)_3$. At the same time, dissolved phosphate in the overlying water can be adsorbed by $Fe(OH)_3$ in the sediments [5]. In anoxic and anaerobic systems, P can be easily released from the sediments to the overlying water [20]. The released P in the sediment–water interface may be mainly BD-P, HCl-P, and NaOH-srP fractions. Some studies consider that the oxidative environment is more advantageous because rest-P can easily release P by decomposition [19,21]. NaOH-srP and rest-P account for 76.7–89.0% of TP in sediments of Lake Hongfeng. Between them, NaOH-srP is the largest proportion of inorganic phosphorus, about 60%; therefore, high concentrations of reactive phosphorus in sediments with hypoxic conditions may form a larger flux of dissolved phosphorus in the sediment–water interface.

***Lake management***

The process of water quality deterioration generated by unstable stratification usually happens within a few days in seasonal stratified lakes with moderate depth, and timely measures should be taken. DO should be increased by aeration, yet water circulation should be artificially controlled, especially during the cooling period, to weaken the effect of destratification and prevent sediment P release.

Artificial destratification by air-bubble plumes has been reported to reduce evaporation from large dams, suggesting that a continuous source of cold water at the bottom of the lake would make conditions ideal for an artificial destratification system to be effective in reducing surface temperature and evaporation rates, but this is unfeasible from a water management point of view [22]. The possibility of providing kinetic energy by solar means has attracted man's attention since the early development of solar technology [23]. A recently developed technology, solar powered circulation (SPC), overcame some of the limitations of aerators by circulating only epilimnetic water without the need for electric-grid power and was successfully applied to control destratification in three drinking-source water reservoirs [24]. SPC technology (e.g. SolarBee) may be used to solve the sudden deterioration of water quality in seasonal stratified lakes with moderate depth. Although this possibility is unlikely to be cost-effective, it deserves further investigation.

**Conclusions**

Seasonal water stratification that occurs in lakes with moderate depth has been observed in Lake Hongfeng. Vertical mixing of the lake water column was generated in September 2010, and unexpected deterioration of water quality was found to be caused by an increase in nutrients and a decrease in DO during the destratification. Monitoring of water stratification and the appropriate mitigation measures are essential throughout the year to protect the water quality for sustainable use of water resources for human consumption as well as for a healthy environment. Artificial destratification by air-bubble plumes or solar powered circulation may be used to alleviate the sudden deterioration of water quality in seasonal stratified lakes with moderate depth.

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