Journal of Oceanology and Limnology

https://doi.org/10.1007/s00343-026-5476-y

Research Paper

The distribution, occurrence, and influencing factors of phosphorus fractions in saline lake sediments and its basin topsoils: a case study of Qinghai Lake, China*

Hongpan XUE[1, 2, 3], Shun WANG[1, 2, **], Yiyan CHEN[3], Hongyu LI[1, 2], Bo DONG[1, 2], Ronglei DUAN[1, 2], Xiuping DING[1], Xin ZHOU[3], Haicheng WEI[1, 2, **]

[1] *Key Laboratory of Green and High-end Utilization of Salt Lake Resources, Qinghai Institute of Salt Lakes, Chinese Academy of Sciences, Xining 810008, China*

[2] *Qinghai Provincial Key Laboratory of Geology and Environment of Salt Lake, Xining 810008, China*

[3] *School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China*

Received Nov. 24, 2025; accepted in principle Jan. 30, 2026; accepted for publication Mar. 26, 2026

© Chinese Society for Oceanology and Limnology, Science Press and Springer-Verlag GmbH Germany, part of Springer Nature 2026

Abstract Qinghai Lake (QHL) provides an ideal location for investigating the phosphorus (P) cycling in saline lakes. Understanding P cycling in QHL through sediment P fractions, which are well-established indicators for studying P cycling and its environmental impacts, is critical for scientific prevention and control of eutrophication. While prior studies have examined P fractions in QHL sediments, systematic research on their distribution, speciation, and controlling factors in surface sediments and basin topsoil remains lacking. Here, this study provides a comprehensive analysis of P distribution, occurrence, and influencing factors in QHL surface sediments (QHSS) and basin topsoils (QHWT), integrated with a sequential extraction scheme, high-resolution microscopic-microarea analysis, and existing data of QHL. The results demonstrate the rank order of P fractions in the QHSS was HCl-P (calcium-bound P)>Res.-P (residual P)>NaBD-P (iron and manganese (hydroxide) oxy-bound P)>NaOH-P (aluminum-bound P), while the rank order of P fractions in the QHWT was HCl-P>NaOH-P>Res.-P>NaBD-P. HCl-P in QHWT likely originated from apatite released from the weathering of parent rock within alluvial materials, whereas in QHSS it was predominantly associated with apatite introduced into the lake through soil erosion and co-precipitation with carbonate minerals. NaBD-P and NaOH-P were likely derived from clay mineral and some Fe-oxides in the topsoils and sediments. The distribution of P fractions in topsoils and sediments was shaped by natural factors (abundant calcium deposits, low precipitation, high evaporation, alkaline lake water) and human activities (agriculture, grazing, tourism). Based on the spatial distribution characteristics of NaBD-P and NaOH-P in the topsoils and sediments, key areas for ecological prevention and control in the QHL basin were identified, including the southern Hema River Town, the southeastern Daotang River Town, and the northwestern region. Within the lake, the shallow water areas in the west, northwest, and southeast of the lake should be focused. These findings enrich the theoretical framework for P geochemical cycling in lake and provide direct guidance for QHL to accurately identify the prevention and control areas within the basin and lake area, thereby supporting the formulation of targeted management strategies.

Keyword: phosphorus fraction; micro-area analysis; lake sediment; topsoil; Qinghai Lake

1 INTRODUCTION

Eutrophication of lacustrine ecosystems, including saline lakes, has become a global environmental threat for decades, negatively affecting both aquatic ecosystems and public health (Smith and Schindler,

* Supported by the National Natural Science Foundation of China (No. 42172019), the 2024 Annual "Kunlun Talent · High-end Innovation and Entrepreneurship Talent" Program-Directly Recognized Introduction of Outstanding Talents (to Hongpan XUE; No. QHKLYC-GDCXCY-2024-592), and the Youth Interdisciplinarity Team of Fundamental Research, Qinghai Institute of Salt Lakes, Chinese Academy of Sciences (No. IJCTD-2022-1)

** Corresponding authors: wangshun@isl.ac.cn; hcwei@isl.ac.cn

2009). Most of the related environmental protection measures focus on reducing the input of external phosphorus (P), as P is a limiting nutrient in lacustrine ecosystems and a major contributor to lake eutrophication (Worsfold et al., 2016). However, such measures are often insufficient for lake restoration (Schindler, 2012), largely due to internal P load (Tammeorg et al., 2016; Orihel et al., 2017). It can trigger a positive feedback loop of lake eutrophication, increasing primary productivity, worsening trophic status, and delaying recovery even after reducing external P load (Orihel et al., 2017).

Compared to the total phosphorus (TP) concentration, sediment P fractions are more effective in understanding the source, transformation, and bioavailability of P and potential ecological risk (Rydin, 2000; Kaiserli et al., 2002). These fractions are commonly categorized as: loosely absorbed P in pore water, redox-sensitive Fe and Mn (hydr)oxides bound P, P bound to metal oxides of Al and Fe, Ca-bound P (e.g., apatite-P), and organic P (Søndergaard et al., 2001). Existing studies on lake sediments P fractions have mainly explored: (1) the distribution and influencing factors of P fractions in different lake types (Zhu et al., 2013); (2) transformation mechanism between different P sediments fractions (Chen et al., 2021; Wu et al., 2021); (3) the bioavailability and release risk of sediment P (Rydin, 2000; Kaiserli et al., 2002); (4) extraction methods of sediment P fractions (Wang et al., 2013); (5) the response of sediment P availability in historical nutrient changes and mixing regimes (Tu et al., 2019, 2020, 2021). However, most of these existing sediment P fractions studies were conducted on eutrophic freshwater lakes, with studies on arid saline lakes, characterized by extreme geochemical conditions, remaining limited. Saline lakes, as important water resources and ecological barriers in arid and semi-arid regions, playing vital roles in maintaining regional ecological security and supporting sustainable development (Zheng, 2010; Valiente et al., 2022). In recent years, intensified human activities have led to the eutrophication of some saline lakes, such as Lake Ulungu in Xinjiang (Ji et al., 2018), and the Great Salt Lake in the USA (Wurtsbaugh et al., 2012), posing serious threats to the aquatic ecosystems and public health. Therefore, a thorough understanding of the distribution, occurrence patterns and influencing factors of P in salt lakes sediments under extreme conditions is crucial for the precise assessment of salt lake eutrophication risks and the formulation of prevention and control strategies.

Lakes on the Qinghai-Xizang Plateau are mostly brackish and saline (Liu et al., 2021). In recent decades, climate warming and increased precipitation have driven a sharp increase in the number and area of lakes in this region (Zhang et al., 2020), accompanied by changes in lakes species diversity and nutrient structure (Liu et al., 2021). Algal blooms have been observed (Hao et al., 2020; Zhu et al., 2020). However, due to the harsh natural environment and vast spatial extent in this region, studies on P fractions in saline lake sediments are limited and spatially scattered. A systematic understanding of the distribution, occurrence, and drivers of sediment P in these lakes is urgently needed to support effective ecological management on the Qinghai-Xizang Plateau.

Qinghai Lake (QHL), locates in the northeastern Qinghai-Xizang Plateau, is the largest inland closed-basin saline lake in China (Fig.1a), which provides an excellent site for in-depth research on the distribution, occurrence and influencing factors of P in saline lake sediments. It is also crucial in maintaining the local ecological security and is a renowned tourist destination (Fan et al., 2021; Duan et al., 2022). In recent years, the TP in the water of QHL has increased from 0.02 to about 0.06 mg/L during 2012–2018, while the sediment TP increased from 0.61 to 1.51 g/kg during 2012–2020 (Ao et al., 2014; Hao et al., 2020; Cheng et al., 2024, in press). Studies have shown that there is a close relationship between the growth of *Cladophora* and P in QHL, especially P released from sediments in newly inundated areas (Zhu et al., 2020). At present, *Cladophora* blooms have been observed in the western and northwestern parts of the QHL (Fig.1b–c) (Hao et al., 2020; Zhu et al., 2020; Duan et al., 2022; Wu et al., 2024), indicating growing eutrophication risks. Consequently, it is of urgent necessity to carry out research on the distribution, occurrence, and control mechanisms of P in the surface sediments in QHL and its watershed topsoils, which will contribute to the scientific formulation of ecological prevention and control strategies for QHL.

In recent years, several studies have investigated the P fractions in the QHL sediments (Huo et al., 2011; Ao et al., 2014; Li et al., 2025). These studies have performed preliminary analyses of the P fractions in the surface sediments of the lake and their relative contributions to the TP. Simultaneously,

research has also been undertaken on the mineral-mediated P removal mechanism and its environmental significance in the sediments of QHL (Li et al., 2025). However, a systematic research on the distribution, occurrence, and influencing factors of P fractions in the surface sediments of QHL and the topsoil of its basin remains insufficient.

Here, the surface sediments in QHL (QHSS) and its watershed topsoils (QHWT) were examined. The aims of this study were to (1) investigate the composition, occurrence characteristics, and spatial distribution patterns of P fractions in QHSS and QHWT and its influencing factors, and (2) examine the relationships among different P fractions in both archives and preliminarily determine the key areas for ecological prevention and control of QHL. For these purposes, a sequential extraction scheme was employed to identify different P fractions in sediments. The field emission scanning electron microscope (FE-SEM) equipped with an energy-dispersive X-ray spectrometer (EDS) and laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) were used to invesitgate the occurrence characteristics of P elements in sediments and topsoil. Based on the distribution patterns and occurrence characteristics of P in the QHWT and QHSS, along with the existing data of QHL, the factors influencing its distribution and formation were analyzed. The potential relationships among different P fractions in the lake sediments and topsoils were investigated, and the key areas for ecological prevention and control in the lake area and the basin were preliminarily identified. These findings will enhance the theoretical understanding of P geochemical cycling in lakes and provide direct guidance for QHL to accurately identify priority zones for prevention and control in both the basin and the lake area, thereby supporting the formulation of targeted management strategies.

2 STUDY AREA

The QHL (36°32′N–37°15′N, 99°36′E–100°16′E) is located in the southeast of the Qinghai Lake Basin (Fig.1a), covering an area of approximately 4 625.6 km^2, with a maximum water depth of 27 m (Ding et al., 2024; Li et al., 2024). It is surrounded by the Datong Mountains, Riyue Mountains and Qinghainan Mountains (Fig.1b). The QHL is mainly fed by direct rainfall and river runoff, and the Buha River contributes about 50% of the total recharge capacity (Henderson et al., 2010). Its catchment spans an area of 29 660 km^2 (Ding et al., 2024), which is predominantly comprised of late Paleozoic marine limestone, schist, and sandstone, along with Triassic granite, Mesozoic diorite and granodiorite with minor late Cambrian phyllite and gneiss (Fig.2) (LIGCAS et al., 1979). The Quaternary alluvial and lacustrine sediments cover about one-fifth of the catchment, concentrated around lakes and rivers (Jin et al., 2010a). Fault escarpments and lacustrine sediment terraces are widely developed along the southern shore.

The QHL is located at the convergence of the East Asia monsoon region, the arid northwest China, and the Qinghai-Xizang Plateau. It has shaped the local climate which is cold and dry (average annual temperature ranges from 0.3 to 1.1 °C, annual rainfall varies from 291 to 579 mm, 80% of which occurs from June to September) with strong evaporation (annual rates of 1 300–2 000 mm) and winds (Li et al., 2025). Most of the QHL basin is covered by alpine meadow, scrub, steppe, swamp meadow, grazing land, and farmland (Gou et al., 2022). Additionally, it contains various types of soils, including meadow soils, black calcareous soils, chestnut calcareous soils, marshy soils, and sandy soils (Sun et al., 2008).

Lake water of QHL has a salinity of ~11 g/L (pH: 8.92–9.08) and is of Mg-SO_4 sub-type (Jin et al., 2010a; Li et al., 2024). The numerous limestones in the QHL drainage basin, coupled with the arid climatic conditions, result in widespread carbonate precipitation in QHL. Additionally, significant amounts of calcite and aragonite are stored on the lakebed. The QHL is a P-limited and nutrient-deficient lake, with an average TP and total nitrogen (TN) concentration of 0.02 and 0.8 mg/L in surface water (Ao et al., 2014; Hao et al., 2020), respectively. However, significant interannual fluctuations of TP have been observed in recent years, ranging from 0.01 to 0.06 mg/L (Hao et al., 2020). Despite these nutrient variations, the composition and structure of the benthic community in QHL have remained stable for many years (Meng et al., 2016). Tourism to QHL has developed since the 1980s, which makes it one of the most scenic places in China (Ao et al., 2014). However, emerging ecological issues in QHL, such as *Cladophora* blooms (Fig.1b–c), have threatened both the landscape and ecological security (Hao et al., 2020; Zhu et al., 2020; Duan et al., 2022).

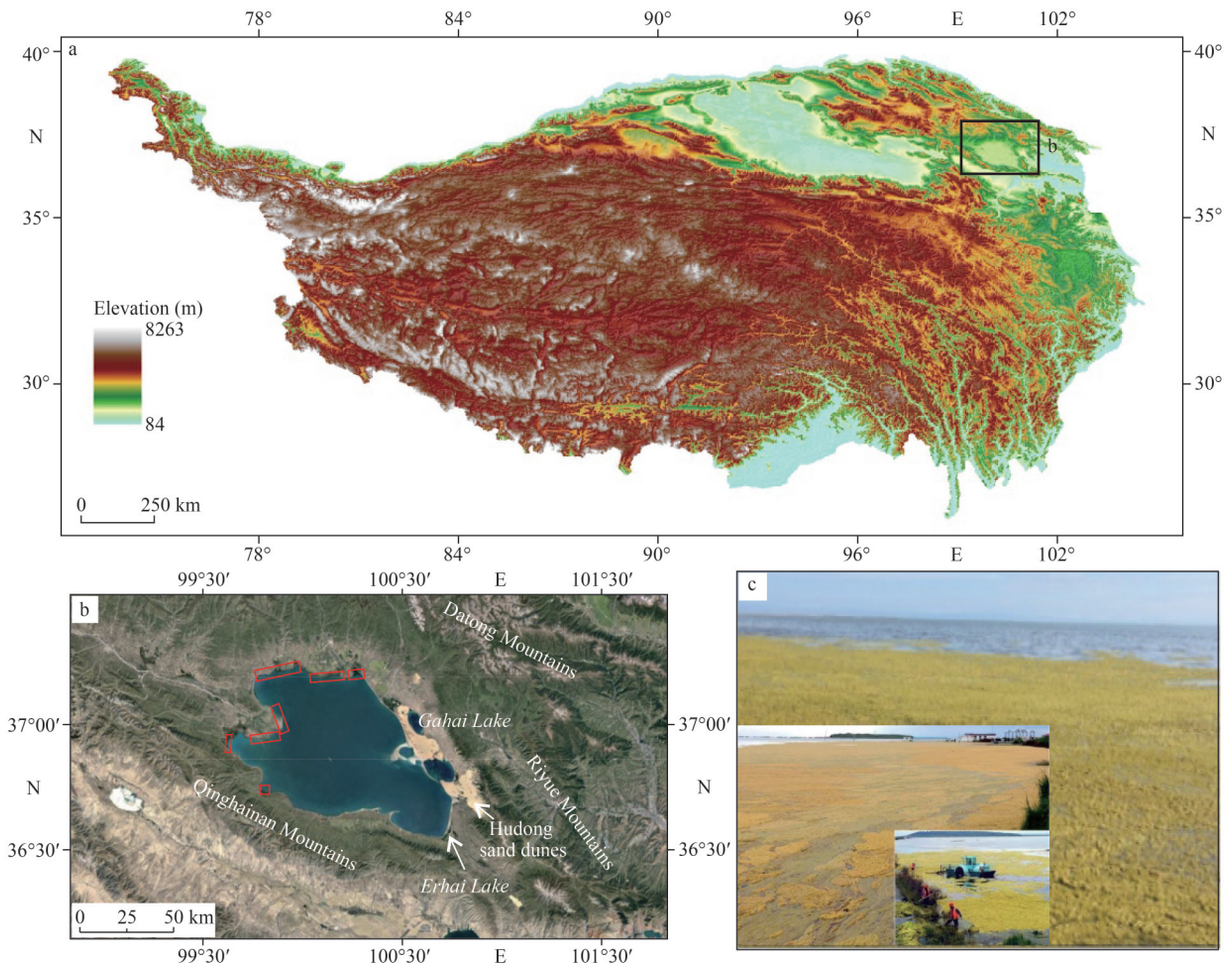


Fig.1 Location of Qinghai Lake and distribution map of *Cladophora* blooms

a. the location of Qinghai Lake (black rectangle); b. regional overview map of Qinghai Lake, red rectangle represents the distribution area of *Cladophora* blooms (Duan et al., 2022); c. photo of *Cladophora* bloom in Qinghai Lake, cited from Duan et al. (2022) and Zhu et al. (2020).

3 MATERIAL AND METHOD

3.1 Sampling

In August 2020 and May 2021, 61 surface-sediment samples were collected by an Ekman grab sampler from the lake bottom, covering the main lake and sublakes (Fig.2). The longitude, latitude, and water depth information for each sample were recorded using GPS and a bathymeter. The sampling sites covered a range of water depth from 4 to 28.3 m. Meanwhile, 51 topsoil samples (0–10-cm depths) were collected from the basin of five main major rivers (Buha River, Shaliu River, Quanji River, Hargai River, and Heima River) in August 2020 (Fig.2). These samples were freeze-dried before sequential P extraction and other analyses.

3.2 Analytical method

3.2.1 P fraction extraction

The bulk samples from surface sediment and topsoil were ground, sieved through a 200-mesh (75 μm) sieve, and then used for P fractions extraction. The extraction procedure used in this study (Fig.3) was principally modified from the methods of Lukkari et al. (2007) and Wang (2014). P is sequentially extracted from dry sediments (0.2 g) using 40 mL of extractant for F1–F3 and 25 mL of extractant for F4. F1 fraction was extracted with 0.11-mol/L $Na_2S_2O_4$ in a 0.11-mol/L $NaHCO_3$ buffer (pH 7.0) which are termed NaBD later, F2 fraction was extracted with 1.0-mol/L sodium hydroxide (NaOH), and F3 fraction was extracted with 0.5-mol/L HCl. Sediment residue from step 3 was freeze-dried, combusted for 2 h at 550 °C, and then extracted with 1.0-mol/L HCl to obtain F4 (Lukkari et al., 2007). Extractant solutions were all prepared using ultra-pure water. Extractions were conducted in the Promethe 50-mL centrifuge tubes and agitated at room temperature using an orbital shaker. The extraction time of each fraction were 16 h, and all

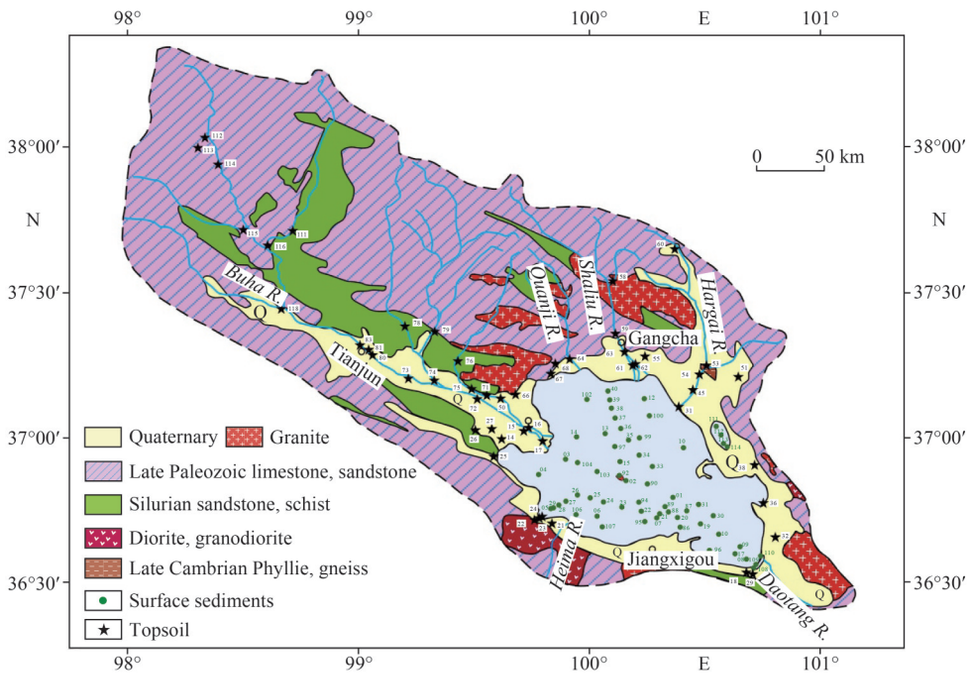


Fig.2 Location of sampling sites

The surface sediment sampling locations from a previous study (Cheng et al., 2024, in press) are denoted by green circles and associated numbers (excluding the 'QHSS-' prefix) and correspond to the x-axis coordinates in Fig.4. The black pentagrams and associated numbers (excluding the 'QHWT-' prefix) are the surface soil sampling locations from this study, corresponding to the *x*-axis coordinates in Fig.5), the main lithological units of the QHL catchment basin (LIGCAS et al., 1979), and major rivers feeding the lake. The Qinghai Lake catchment boundary is shown as black dashed lines. Buha R.: Buha River; Quanji R.: Quanji River; Shaliu R.: Shaliu River; Hargai R.: Hargai River; Hema R.: Hema River; Daotang R.: Daotang River.

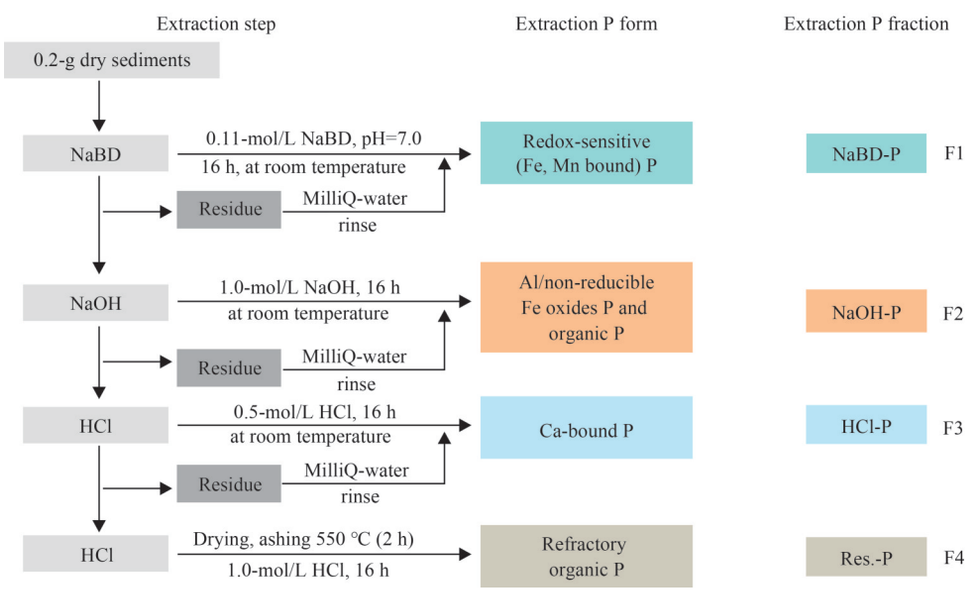


Fig.3 Scheme of sequential P extraction

Modified from Lukkari et al. (2007) and Wang (2014). 0.11-mol/L sodium dithionite ($Na_2S_2O_4$) dissolved in 0.11-mol/L sodium bicarbonate ($NaHCO_3$) buffer (pH 7.0), which is termed NaBD.

rinse steps were 15 min. Following these extraction procedures (Fig.3), the supernatants were collected after centrifugation at 4 000 r/min for 15 min at room temperature. P concentrations in the supernatant of each fraction were measured by inductively coupled plasma mass spectroscopy (ICP-MS, Thermo Fisher Scientific iCAP RQ). TP in sediment was obtained from the sum of F1-F4 fractions.

3.2.2 In-situ micro-area analysis

To assess the occurrences of P, sediment samples that are rich in P with significant differences in P fractions composition were selected. Freeze-dried sediment powder was embedded in a resin substrate and prepared as a polished thin-section (2.5 cm× 2.5 cm). After carbon coating, the thin-section was used for SEM-EDS characterization using a field-emission SEM (TESCAN MIRA3) under an acceleration voltage of 10 kV and a beam current of 15 nA.

Trace elements of samples were determined using a NWR 193-nm wavelength ArF Excimer laser-ablation (LA) system coupled to an iCAP RQ (ICP-MS). The ICP-MS was tuned using NIST 610 standard glass to yield low oxide production rates. 0.7-L/min He carrier gas was fed into the cup, and the aerosol was subsequently mixed with 0.89-L/min Ar make-up gas. The laser fluence was 5.0 J/cm^2, with a repetition rate of 6 Hz, a 30-μm spot size, and an analysis time of 45 s, followed by a 40-s background measurement. Trace element compositions are calibrated against two reference materials (NIST SRM 610 and BCR-2G) using a total normalization method (Liu et al., 2008). The glass standard SRM 612 and BIR-1G are analyzed to evaluate the data quality (Wu et al., 2019a). The raw data were processed using the 3D Trace Element data reduction scheme (DRS (Paton et al., 2011)) of IOLITE software. In IOLITE, user-defined time intervals are established for the baseline correction procedure to calculate session-wide baseline-corrected values for each isotope. Detailed analytical techniques have been described in Chu et al. (2023) and Liu et al. (2008).

4 RESULT

4.1 Sequentially extracted P fraction in the QHWT and QHSS

The results of sequential extraction P fractions from the QHWT and QHSS are shown in Figs.4–5 and Supplementary Tables S1–S2. In the QHWT, TP concentration varied from 623.82 to 1 279.54 μg/g, with an average of 958.55 μg/g (Supplementary Table S1), which is dominated by HCl-P fraction, with concentrations ranging from 272.34 to 1 030.18 μg/g (mean: 626.64 μg/g, ~65.19% of TP) (Fig.4a–b; Supplementary Table S1). The NaOH-P (mean: 145.24 μg/g, 15% of TP) and Res.-P (mean: 123.61 μg/g, 13% of TP) fractions represented secondary reservoirs (Fig.4a–b; Supplementary Table S1), while NaBD-P was a minor component at 7% of TP (Fig.4b; Supplementary Table S1).

TP concentrations in the QHSS were significantly lower than those of the QHWT, ranging from 128.87 to 1 096.92 μg/g, with an average of 565.20 μg/g (Supplementary Table S2). The dominance of HCl-P fraction was also observed in QHSS, with concentration ranging from 107.12 to 843.17 μg/g (mean: 338.00 μg/g, ~60.31% of TP) (Fig.5a–b; Supplementary Table S2). The Res.-P was the second most P fraction, which comprised average ~18% of the TP. The contents of NaBD-P and NaOH-P were similar in size, with an average of 67.98 μg/g (~12% of TP) and 57.72 μg/g (~10% of TP), respectively (Fig.5a–b; Supplementary Table S2). Notably, the sample QHSS-33 has the lowest content of TP and all individual P fractions. Furthermore, sub-lakes of QHL—such as Erhai Lake and Gahai Lake—exhibited significant fluctuations in the concentrations of TP and its constituent fractions (Fig.5a).

4.2 The spatial distribution characteristics of different P fractions in the QHWT and QHSS

The spatial distribution of QHWT P fractions is illustrated in Fig.6. The concentrations of NaBD-P are highest in the Hudong dunes and Daotang River watershed (eastern QHL Basin). Intermediate levels occurred in the Shaliu River and Quanji River watersheds (northern QHL Basin), while the lowest concentrations were observed in the Buha River watershed (Figs.2 & 6a). The overall distribution of NaOH-P in the QHWT is similar to that of NaBD-P, with the highest concentrations found in the Shaliu River and Quanji River watersheds and the Daotang River watershed (Figs.2 & 6c). Conversely, the HCl-P proportions in the QHWT show an increasing trend from lake shores to surrounding regions, and two peaks are observed in the Hudong dunes in the eastern QHL region and Buha River watershed in the western QHL basin (Figs.2 & 6e). Finally, the proportions of Res.-P in the topsoils are markedly elevated in the Daotang River and Hema River watersheds. Appreciable levels were also observed in the central Buha River watershed (Figs.2 & 6g).

In the surface sediment, the concentrations of NaBD-P are notably higher near the western, northwestern, and eastern shore of QHL, and gradually decrease towards lakecenter (Fig.6b). NaOH-P displayed a zonal distribution, with high concentrations concentrated around the Shaliu River estuary, the central region, and near Jiangxigou Town (Fig.6d). The HCl-P is widely distributed with

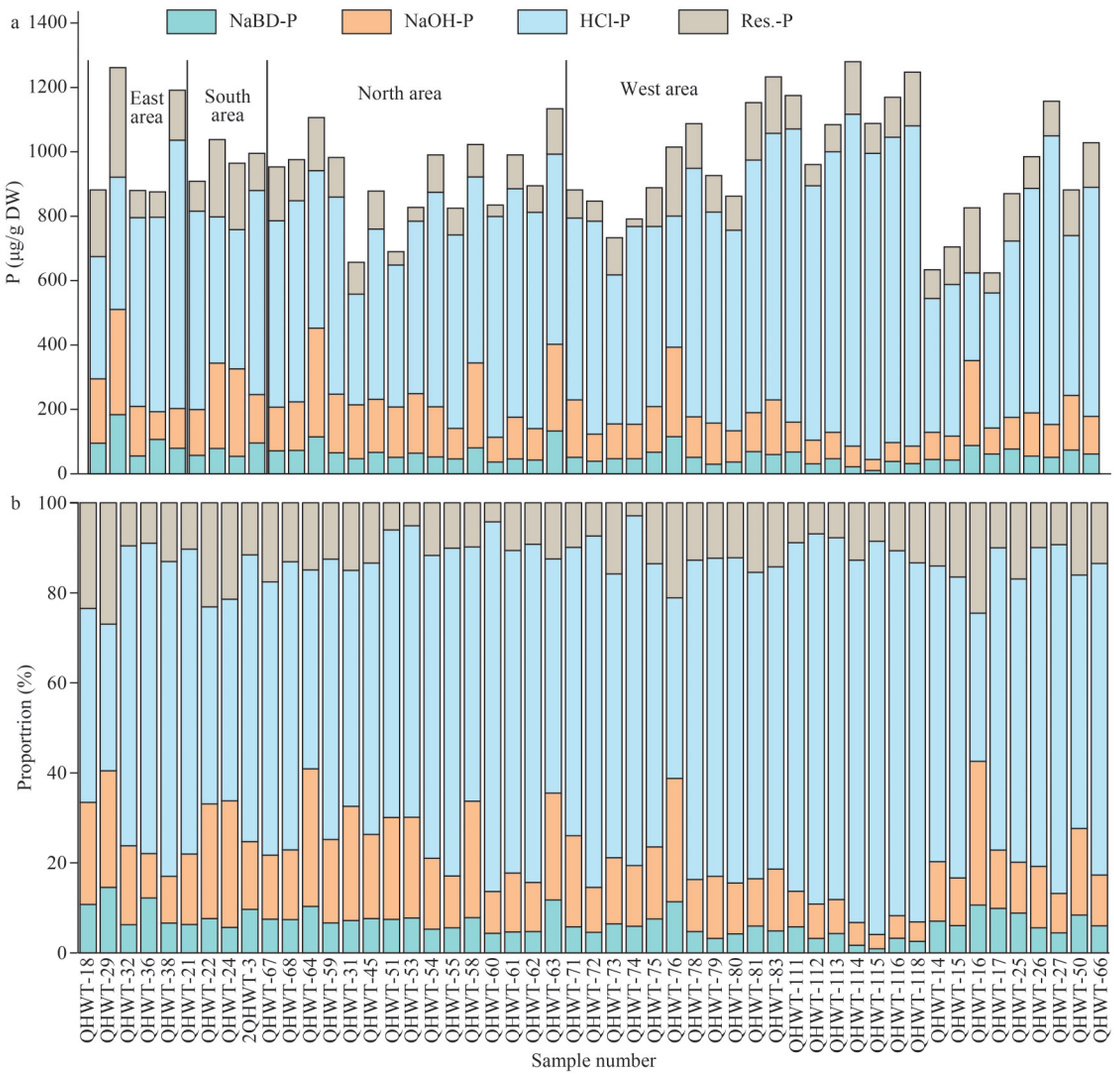


Fig.4 The concentrations of P fractions (a) and their contribution to the QHWT total P (b)

The concentrations refer to the dry weight of sediments (DW).

highest concentrations found in the southern and southeastern regions of the lake area (Fig.6f). Similarly, Res.-P was extensively distributed at high levels across the lake, with peaks found in the central and east areas (Fig.6h).

4.3 Occurrence of sedimentary P in the QHWT and QHSS

The SEM-EDS analysis of the QHWT and QHSS samples identified some micron-sized particles enriched in both P and Ca, which exhibiting a homogeneous distribution (Supplementary Figs.S1 & S2b). These particles were identified as apatite. Additionally, F element was detected in some QHWT apatite particles (Supplementary Fig.S1b), suggesting the presence of fluorapatite. These apatite particles are expected to contribute significantly to the HCl-P fraction. Clay minerals were also commonly observed in the QHWT and QHSS samples (Supplementary Fig.S3a–e). However, the distribution of P within these minerals could not be reliably detected using EDS (Supplementary Fig.S3a–e), as the P content was below the technique's detection limit. Given the high sensitivity of LA-ICP-MS for microanalysis, this technique was employed to quantify the P concentrations within micro-areas of the sediments. The results revealed that element P was highly concentrated in the regions enriched with clay minerals (Supplementary Fig.S3f) and within some Fe-oxides (point 2# in Supplementary Fig.S2 & Table S3). By contrast, P was barely detectable in clastic particles, such as K-feldspar, quartz, plagioclase, ilmenite, biotite, albite, calcite (Supplementary Figs.S2 & S4 & Tables S3–S4). These results directly confirmed that clay minerals and Fe oxides play

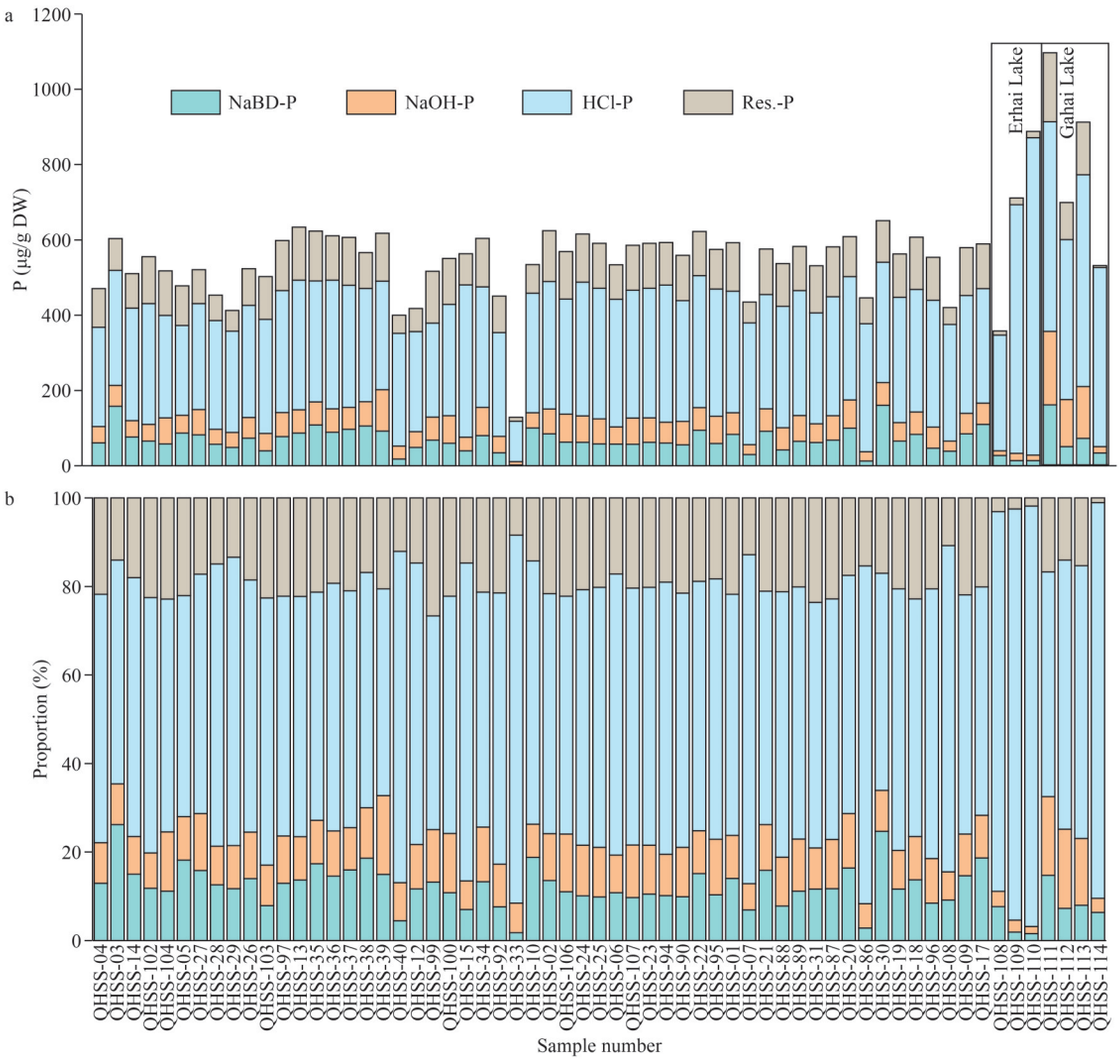


Fig.5 The concentrations of P fractions (a) and their contribution to the QHSS total P (b)

The concentrations refer to the dry weight of sediments (DW).

significant roles in the P retention in the QHWT and QHSS, which are responsible for hosting the NaBD-P and NaOH-P.

5 DISCUSSION

5.1 The factor influencing the distribution and occurrence of different P fractions in the QHWT and QHSS

Previous studies have demonstrated that various natural factors, including parent materials, climate, topography, organisms, and soil types, could significantly influence soil P fractions (Zhang et al., 2005; Mage and Porder, 2013; Xiao et al., 2021). Similarly, the lake sediments P fraction could be controlled by factors such as sediment characteristics, hydrodynamic conditions, and biochemical reactions (Hou et al., 2014; Zhao et al., 2014; Zhang et al., 2017). The intensified human activities, such as fertilizer application and alterations in land use, have also been proven to affect the P composition (Maranguit et al., 2017; Ye et al., 2017). As a result, this chapter explores the effects of natural and human factors on the distribution and occurrence of different P fractions in the QHWT and QHSS.

The HCl-P represents the P bound in apatite and is a stable, non-bioavailable fraction under neutral to alkaline conditions (Kaiserli et al., 2002). In the QHWT and QHSS, P mainly occurs in form of HCl-P (Figs.4 & 5; Supplementary Tables S1–S2), which might be attributed to the apatite observed by SEM (Supplementary Fig.S1 and point 5# in Supplementary Fig.S2d). In the QHL basin, carbonate rocks/ limestone and clastic rocks are widely distributed,

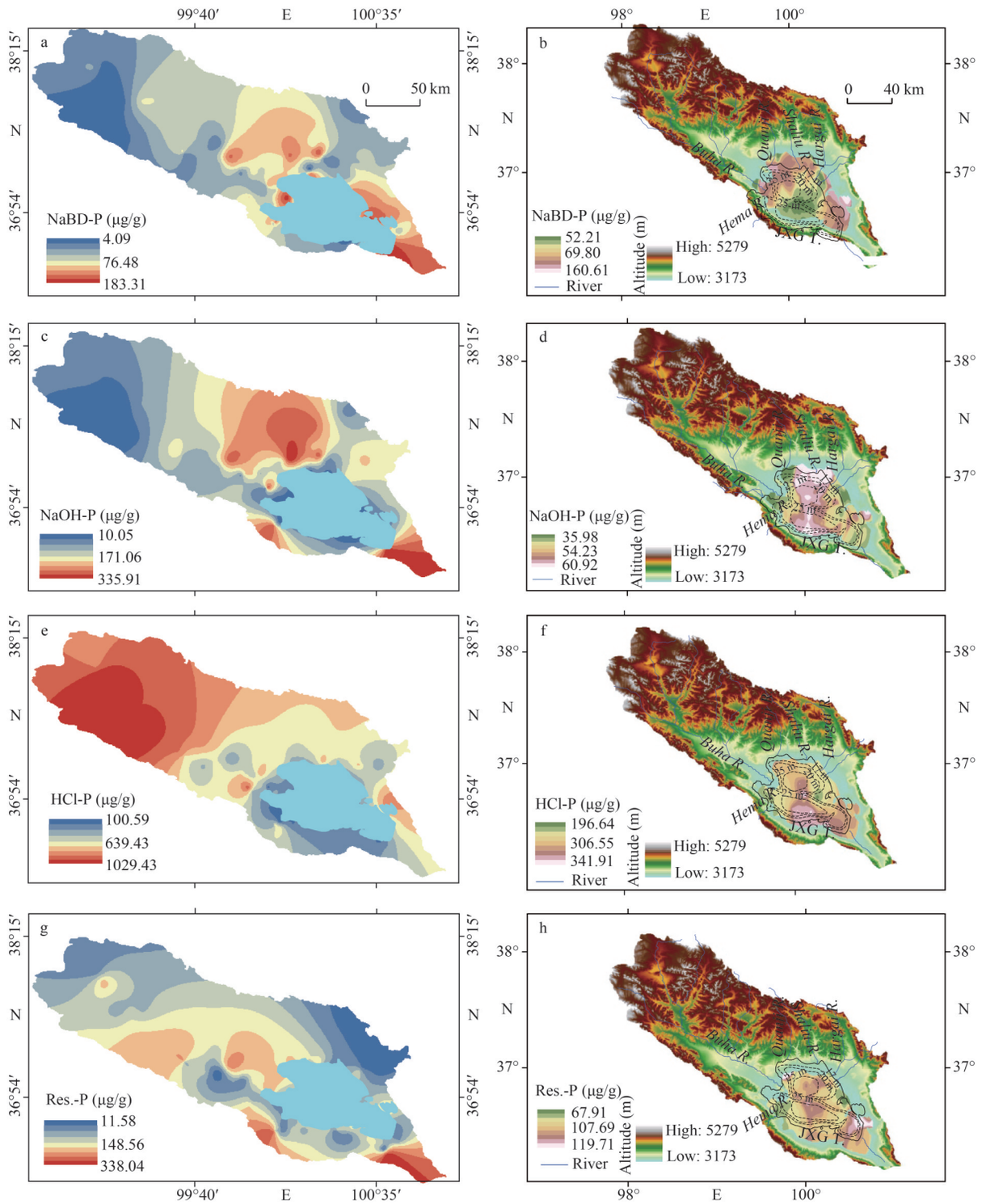


Fig.6 Spatial distribution of concentration of NaBD-P, NaOH-P, HCl-P, and Res.-P in the QHWT (a, c, e, g) and QHSS (b, d, f, h)

The water level isobaths of QHL are shown as black dashed lines. Buha R.: Buha River; Quanji R.: Quanji River; Shaliu R.: Shaliu River; Hargai R.: Hargai River; Hema R.: Hema River; JXG T.: Jiangxigou Town.

which constitute the parent rocks of alluvial material (LIGCAS et al., 1979) (Fig.2). This could release a substantial amount of apatite in weathering process (Mehmood et al., 2018; Xiao et al., 2021). Meanwhile, the cold, dry climate and the alkaline nature of local river water (pH 7.60–8.55; Jin et al.,

2010a) may further inhibit apatite dissolution. Such conditions result in comparatively high concentrations of HCl-P in the QHWT (Fig.4), particularly in the upper reaches of the Buha River (western QHL basin) (Fig.6e). Notably, the HCl-P content in the topsoils of the Hudong Dune within the QHL basin is also relatively high (Fig.6e), which may be attributed to the apatite-rich aeolian deposits in this region (Fig.1b), as dust-borne P often occurs as clastic and biogenic apatite (Zhang et al., 2018; Xue et al., 2025). Therefore, the formation of HCl-P in the QHWT is mainly related to the apatite released by the parent rock of the alluvial material during the weathering process, with its preservation favored by the region's alkaline and cold-arid conditions.

In the QHSS, apatite particles originating from the weathering of surrounding watershed bedrock are transported into the lake via soil erosion and subsequently deposited, becoming the main source of HCl-P in the QHL sediments. Furthermore, carbonate rock minerals such as calcite and aragonite occur widely on the lakebed (Jin et al., 2010a; Li et al., 2024, 2025). Research indicates that carbonate minerals are capable of removing P from sediments through adsorption or coordination with soluble reactive P, which occupies the active sites for crystal growth, thus leading to the formation of stable P-containing compounds (Lin and Singer, 2006). During this process, phosphate ions within water may either combine with calcium ions (Ca^{2+}) or co-precipitate with carbonate minerals (Dittrich and Koschel, 2002; Lin and Singer, 2006; Walsh et al., 2019; He et al., 2025), converting labile P into stable apatite-like minerals (Yin et al., 2011; Li et al., 2025). Owing to the substantial calcium deposits in the QHL basin (Jin et al., 2010a, b), along with limited precipitation and high evaporation conditions, the mechanism of P removal via the co-precipitation of carbonate minerals might become especially significant. These conditions facilitate the formation of carbonate minerals in the water body of QHL, thereby enhancing this geochemical pathway for P sequestration (Jin et al., 2010a; Li et al., 2024). This speculation is also supported by a recent study on the mineral-mediated P removal process in saline lake sediments of the Qinghai-Xizang Plateau (Li et al., 2025). Meanwhile, the pronounced evaporation rate and geochemical stability of the lake could promote the HCl-P accumulation and the alkaline conditions of the lake (pH 8.92–9.08) further suppress the dissolution of HCl-P, explaining its widespread distribution particularly in the southern and eastern regions, including sub-lakes (Gahai Lake and Erhai Lake) (Fig.6f). Notably, the intense aeolian activity in QHL basin is likely to transport a substantial amount of apatite-containing dust particles (Zhang et al., 2022b; Xue et al., 2025), representing an additional allochthonous source for sedimentary HCl-P.

The NaBD-P, i.e., Fe/Mn-P, represents P bound to redox-sensitive Fe and Mn compounds. Under anaerobic conditions, it can be readily released or transformed into other P forms (Rydin, 2000). The NaOH-P corresponds to the P associated with Al and Fe (hydro)oxides, which exhibits potential instability, particularly in high pH environments. Previous studies have already demonstrated the influence of anthropogenic activities and terrestrial input on both NaBD-P and NaOH-P fractions (Ruban et al., 2001; Zhao et al., 2014; Ni and Wang, 2015; Ni et al., 2020; Nie et al., 2022). In the QHWT, NaOH-P is the second abundant P fraction, while NaBD-P exhibits the lowest content (Fig.4a–b; Supplementary Table S1). In the QHSS, both fractions concentrations are relatively low (Fig.5; Supplementary Table S2). These two P fractions might mainly be associated with the adsorption of P by clay minerals and Fe oxides within the QHWT and QHSS, as evidenced by LA-ICP-MS analysis (Supplementary Fig.S3, point 2# in Supplementary Fig.S2 & Table S3). The sediment clay minerals is important carries of P as their large surface area, stable structure, and broad pH adaptability provide them with strong affinity for P species (Fontes and Weed, 1996; Linquist et al., 1997; Kumari and Mohan, 2021; Li et al., 2021; Xiong et al., 2022; Chen and Arai, 2023). Notably, Fe is often an integral component of clays, existing as surface-loaded Fe oxides or within the mineral structure itself (Bergaya and Lagaly, 2013). Existing experimental studies further support that clay minerals and Fe/Al (hydr)oxides are vital adsorbents of P and serve as crucial P sinks in most soils (Edzwald et al., 1976; Gérard, 2016; Xiong et al., 2022). In a short, clay minerals and some Fe oxides are likely conducive to the formation of NaBD-P and NaOH-P in the QHWT and QHSS.

In the QHWT, the abundance of clay minerals is relatively high (Yuan et al., 2019). Previous studies have also indicated that QHSS contains a large amount of silty clay and an assemblage of clay minerals, dominated by illite and chlorite (Jin et al., 2010a; Li et al., 2025), which may be conducive to the formation of NaBD-P and NaOH-P (Lukkari et al., 2007; Zhao et al., 2023). Meanwhile, the

development of tourism, along with that of agriculture and animal husbandry in the QHL basin, may result in an increase in pollutants input. It might influence the content changes and spatial distribution of NaBD-P and NaOH-P. According to the statistics from the relevant local departments, the number of tourists visiting the QHL scenic area exceeded 4 million in 2018. In the same year, the annual pesticide usage in the four counties surrounding the lake amounted to 1.25×10^7 kg, and the numbers of cattle and sheep sold reached 145 500 and 1 957 300, respectively (Hao et al., 2020). Specifically, agricultural practices, including fertilization and pesticide application may directly elevate the content of exchangeable P and readily-lost P in the topsoil (Liu et al., 2017; Han et al., 2019). A portion of this P can combine with clay minerals or iron/aluminum oxides to form NaBD-P and NaOH-P (Zhu et al., 2018). Overgrazing, meanwhile, leads to vegetation degradation, topsoil exposure, and disruption of soil structure, promoting the detachment and transport of mineral-associated NaBD-P and NaOH-P. The substantial amounts of animal manure deposited on the surface undergo mineralization and decomposition, releasing phosphate that can react with local iron and aluminum minerals. Consequently, higher concentrations of NaBD-P and NaOH-P are observed in the lower reaches of the Quanji River and Shaliu River (northern basin) (Fig.6a & c). The domestic sewage generated from towns around QHL (e.g., Gangcha County, Heimahe Town, and Daotanghe Town) and the tourism development on the southern shore of the lake has a relatively high concentration of dissolved phosphate, potentially increasing NaBD-P and NaOH-P levels in the topsoil as well (Fig.6a & c).

Phosphate and P-bearing particles generated by agricultural, grazing, and tourism activities can bind with clay minerals or iron/aluminum oxides in surface soils, forming particulate NaBD-P and NaOH-P. Together with the native mineral-associated NaBD-P and NaOH-P in topsoil, these materials enter lakes via surface runoff and soil erosion and ultimately settle (Noll et al., 2009; Zhang et al., 2010; Copetti et al., 2019), markedly influencing NaBD-P and NaOH-P contents near shorelines and river mouths. Another portion of the P-containing substances is directly introduced into the lake, where they are adsorbed onto the clay minerals surface and active iron and aluminum colloids in the surface sediments or suspended matter, or undergo surface complexation reactions with them (Linquist et al., 1997; Kumari and Mohan, 2021; Chen and Arai, 2023). Consequently, high-value areas of NaBD-P and NaOH-P are formed near the lake and river mouths and even in the sedimentary centers of the lake. This is reflected in the spatial distribution of these fractions within the QHSS (Fig.6). In the northern and western QHL, the contents of NaBD-P and NaOH-P are relatively high, while the south QHL exhibits particularly elevated NaOH-P levels (Fig.6b & d). Additionally, it is worth noting that the distribution of NaBD-P may also be affected by the dissolved oxygen content at the sediment-water interface in the lake area. In nearshore areas, the low water levels could hinder the stratification of the water body, while low vegetation cover allows wind-driven mixing (Stevens et al., 2000). It may facilitate the binding of Fe/Mn compounds with phosphate, thereby causing an increase in NaBD-P concentrations of these shallow zones, particularly in the western, northern, and southeastern coasts of the lake district (Fig.6b).

The Res.-P is defined as the P fraction that remains unextracted after sequential extraction procedures (Condron and Newman, 2011), consisting primarily of biologically unavailable organic P and inorganic P (Rydin, 2000; Lukkari et al., 2007). In the QHWT, Res.-P concentrations are relatively high and comparable to those of NaOH-P (Fig.4a–b; Supplementary Table S1). Elevated Res.-P levels are predominantly found in the topsoils of the Daotang and Heima River basins, with secondary hotspots in western regions (Figs.2 & 6g). This accumulation is likely driven by the progressive transformation of various P forms into more recalcitrant, occluded species as weathering proceeds (Condron and Newman, 2011; Stutter et al., 2015). Furthermore, the grazing activities within the QHL basin, which are capable of generating a substantial quantity of animal manure (abundant in organic P), in conjunction with human activities like agriculture (Li et al., 2009; Yuan et al., 2019), appear to augment the concentration of refractory organic P (e.g., phytates P, predominantly comprising humic acid-associated P and Res.-P, Ni et al., 2020) in topsoils. Several researches have indicated that phytate P is the primary form in which P is stored in indigestible P-containing materials, such as legumes, triticeae, cereals, and the indigestible excrement of animals (Lantzsch et al., 1992; Ravindran et al., 1994; Waldrip et al., 2015). Agricultural intensification and overgrazing have the potential to elevate the phytase content in the soil (Suzumura and Kamatani, 1995; Ni et al.,

2020). As result, this may potentially increase the Res. -P levels in the topsoils of the southern QHL region (Fig.6g).

Similarly, Res.-P constitutes a significant fraction of the QHSS TP (Fig.5). Its spatial distribution is similar to that of HCl-P (Fig.6h). The alkaline conditions and high $CaCO_3$ concentration in QHL water not only promote the formation of low-activity apatite but also support the generation of non-apatite Ca-bound P compounds, such as dicalcium phosphate (Ca_2-P) and octacalcium phosphate (Ca_8-P) (Xiong et al., 2011). These compounds may contribute a significant proportion of Res.-P. Meanwhile, Fe and Al compounds in sediments can immobilize P and may also generate inert inorganic Res. -P fractions (Brucker and Spohn, 2019). Additionally, organic P in QHL sediments is predominantly composed of nonlabile organic P, such as phytate (Huo et al., 2011), which may also serve as a notable component of Res.-P.

To date, several studies have been conducted on the composition, distribution, and influencing factors of phosphorus in the soil of lake basins. Through an in-depth investigation of the P fractions in the soil and sediment within the Yanghe Reservoir area in northern China, it has been discovered that the TP in the soil was mainly HCl-P, whereas the contributions of NaOH-P and NaBD-P were relatively low, which is mainly associated with the geological background of in this region (Zhang et al., 2010). This situation is similar to the composition pattern of P fractions in the QHWT (Fig.4). Nevertheless, in the sediment of the Yanghe Reservoir area and the adjacent river channels, an increase in TP is observed, which can be ascribed to the increase of Fe/Al-P (namely NaOH-P and NaBD-P) and organic P. It may relate to the non-point source pollution induced by human activities (Zhang et al., 2010). Meanwhile, in a study examining the distribution characteristics of inorganic P fractions in the soil of different land-use types in the Dianchi Lake source area (Yunnan-Guizhou Plateau), it was found that HCl-P was the main inorganic P fraction under the greenhouse farmland, greenhouse ditches, and open farmland in flat ground. In the mountainous area, the soil of *Pinus yunnanensis* forest, barren grassland, and P-rich farmland is mainly composed of NaBD-P (Peng et al., 2021). In comparison, the composition and distribution characteristics of soil P in the lake basins of the middle and lower reaches of the Changjiang (Yangtze) River differ from those of the QHWT. A study on the spatial distribution of riparian soil P fractions in watersheds of western Taihu Basin revealed that NaOH-P and NaBD-P are the primary P forms, with a relatively low content of HCl-P. Furthermore, organic matter, clay minerals, and carbonates exert a significant influence on the formation of these P forms (Yu et al., 2018). These findings suggest that different land-use patterns and types of human activities within lake basins can impact the distribution and composition patterns of P in the soil, reflecting pronounced regional heterogeneity.

In the QHSS, the rank order of P fractions is HCl-P>Res.-P>NaBD-P>NaOH-P, with HCl-P accounting for an average of 60.31% of TP (Fig.5). Comparable studies have reported even higher proportions of HCl-P in QHSS, reaching up to 93% of TP (Li et al., 2025). Similar pattern could be observed in freshwater lakes in the Yunnan-Guizhou Plateau area and the Mongolia-Xinjiang region in China, such as Fuxian Lake (He et al., 2025), Dianchi Lake (Wang, 2012), Daihai Lake (Chen, 2021), and Dalinor Lake (Hou et al., 2014), where HCl-P concentrations are elevated relative to NaOH-P and NaBD-P. Nevertheless, the proportion of HCl-P to TP commonly observed in freshwater lake systems is substantially lower than that in the QHSS (Wang, 2012; Hou et al., 2014; Chen, 2021; Sun et al., 2022; He et al., 2025). This disparity may be associated with factors such as the geological background and climatic conditions of the lake, the lake's sedimentary environment, and human activities. In the Yunnan-Guizhou Plateau, lakes generally occur in watersheds with low urbanization and industrialization but are affected by high soil-erosion rates, warm-humid climates, karst geology, and local exploitation of phosphorus-rich minerals (Li et al., 2015). Consequently, the P fractions in the lake sediments of this region predominantly exist in the form of HCl-P, whereas the proportions of NaOH-P and NaBD-P are relatively low. A study on Fuxian Lake, a typical karst freshwater lake, reveals that synergistic interactions between biological and carbonate pump effects can facilitate the carbonate-phosphate co-precipitation, leading to the formation of HCl-P (He et al., 2025). In the lakes of the Mongolian-Xinjiang region, it is presumed that most are mainly influenced by the calcareous soil types in the area, the high rate of soil erosion, and relatively weak human activities. Furthermore, the arid and less-rainy climatic conditions, together with the alkaline lake water, promote the formation and

preservation of HCl-P (Hou et al., 2014; Chen, 2021). In contrast, due to the high levels of urbanization and industrialization within the watersheds, warm and rainy climatic conditions, the distribution of ferruginous and aluminous acidic soils, and weakly acidic to neutral lake water, lake sediments in the eastern plain lake region—especially in the middle and lower Changjiang River basin (e.g., Taihu, Chaohu, Wudong, Dongting, and Poyang lakes)—are characterized by higher proportions of NaOH-P and NaBD-P and relatively low HCl-P (Xiang and Zhou, 2010; Wang, 2012; Ni et al., 2020). The marked contrast in P-fraction composition between these freshwater systems and QHSS underscores that the formation mechanisms of sedimentary phosphorus in saline lakes may differ fundamentally from those in freshwater environments. In subsequent research, the formation mechanism of P fractions composition in other saline lakes should be interpreted with prudence.

5.2 The relationship between different P fractions in the QHSS and QHWT, and its significance for ecological prevention and control of QHL

Soil P originates from both natural weathering and anthropogenic activities, which could enters lake water bodies via groundwater and surface runoff. Some of these P may be permanently buried or released back into water bodies under certain conditions. Other P is utilized by living organisms. Based on this simplified P cycle model, it can be inferred that the distribution and occurrence patterns of P in lakes may be substantially influenced by the topsoils P content, which is often showed as a decrease or increase of TP and similarities in P fraction composition along the topsoil-to-lake sediment continuum (Noll et al., 2009; Zhang et al., 2010; Kerr et al., 2011). Critically, this study observed a decrease in TP along the topsoil-to-lake sediment continuum (Section 4.1), a finding that aligns with the results reported in previous studies (Noll et al., 2009). Similarities in the composition and spatial distribution of P fractions and the characteristics of P occurrence were also observed in the topsoil and lake sediment continuum of QHL (Figs.4–6; Supplementary Figs.S1 & S3). This is evidenced by the parallel dominance of HCl-P in both media (Figs.4–5), its occurrence in similar mineral phases (apatite and clays; Supplementary Figs.S1 & S3), and corresponding spatial patterns of NaBD-P and NaOH-P near the Quanji River and Shaliu river inflows (Figs.6a–d). These observations suggest that the composition and spatial distribution of P in the QHSS may be influenced by those of the basin topsoils, although only a weak statistically significant relationship between their different P fractions was observed (Supplementary Fig.S5). This finding is also supported by previous research on the distribution of P fractions in the sediments of Yanghe Reservoir in northern China and its soil basin (Zhang et al., 2010). This weak statistical relationship suggests an absence of a direct linear relationship between them. This can primarily be ascribed to the intricacy of the P migration process. During the migration from the watershed to the lake, P may experience processes such as adsorption-desorption, precipitation-dissolution, biological utilization, and selective erosion and transport, which obscure the direct linear connection between the P fractions in the topsoils and sediments (Noll et al., 2009; Kerr et al., 2011). After entering the lake, the P fractions in the lake sediments may be influenced by internal lake processes, such as the sedimentary environment, microbial activities, and alterations in hydrodynamic conditions, resulting in changes in their content and mutual conversion among the P fractions (Ekholm and Lehtoranta, 2012; Wu et al., 2019b, 2021; Tu et al., 2021). Given this, similar to the freshwater lake system, effective water environmental protection and pollution control for QHL, it is imperative to first prioritize the identification of P sources within its basin and the high-value areas of active P in the surface soil, and then conduct management of these areas. Particular attention should be given to the southern Heima River Town, the southeastern Daotang River Town, and the northwestern region (Figs.2 & 6), which are substantially influenced by agricultural, livestock, and tourism activities. Secondly, it is essential to identify the high-value areas of active P, such as NaBD-P and NaOH-P, in the sediments of QHL and the high-risk areas of their release, such as the shallow water areas in the west, northwest, and southeast of the lake as well as the central area of the lake (Fig.6). Integrating the lake itself with its basin is beneficial for the systematic management and prevention of ecological issues in QHL.

Previous studies have indicated a strong correlation between *Cladophora* growth and TP levels in QHL (Zhu et al., 2020). This study provides enhanced details supporting this relationship: NaBD-P and NaOH-P exhibit relatively high concentrations in the western and northwestern regions of QHL (Fig.6b &

d), consistent with the distribution pattern of bloom areas of *Cladophora* (Fig.1b–c). The high bioavailability of these fractions likely supplies essential P for *Cladophora* growth, explaining the established correlation with TP. Therefore, in the future, it would be necessary to monitor and manage to the impact of these two P fractions on the ecosystem of QHL.

The abundant HCl-P and the relatively high concentrations of non-bioavailable Res.-P in the QHL sediments constitute the major P sinks in QHL sediments (Li et al., 2025). However, previous studies have indicated that changes in lake physicochemical conditions, such as decreased salinity, reduced pH, or increased water level, can trigger the release of P previously buried in the sediment and facilitate transformations among different P forms (Kaiserli et al., 2002; Orihel et al., 2017; Wu et al., 2021). This process may subsequently provide additional soluble P, supporting the growth of organisms in the overlying water column (Orihel et al., 2017). In recent years, influenced by the warming and humidifying environment on the Qinghai-Xizang Plateau, the QHL has exhibited sustained increases in the water level and surface area (Fan et al., 2021). These hydrological shifts have significantly altered the physicochemical properties of the lake, including reduced salinity (Jin et al., 2010a; Li et al., 2024), decreased water clarity (Zhang et al., 2022a), and the expansion of newly inundated zones (Hao et al., 2020). These environmental changes may exert notable influences on the formation, deposition, and release of lake sediments P fractions. For example, rising water levels could foster an anoxic environment at the sediment-water interface, thereby facilitating the release of NaBD-P in the shallow water area along the shore of QHL (Fig.6b). Meanwhile, the desalination of water bodies caused by rising water levels may be detrimental to the formation of carbonate minerals, thereby weakening their capacity to immobilize P. It could ultimately result in a reduction in HCl-P content in the sediments. These P released from sediments can enter the water column and potentially stimulate algal growth such as *Cladophora*. In extreme cases, this may trigger harmful *Cladophora* blooms, posing a significant ecological threat to the lake. Therefore, future research should prioritize assessing the impacts of the ongoing warming-moistening trajectory of the Qinghai-Xizang Plateau on biogeochemical coupling within QHL's ecosystem. Timely prevention and mitigation strategies should be formulated to safeguard the long-term ecological integrity of QHL under these hydroclimatic shifts.

6 CONCLUSION

This study unveiled the distribution and occurrence of patterns of P in an inland closed basin and its influencing factors. The results demonstrated the rank order of P fractions in the QHSS was HCl-P> Res.-P>NaBD-P>NaOH-P, while the rank order of P fractions in the QHWT was HCl-P>NaOH-P>Res.-P> NaBD-P. The formation of HCl-P in the QHWT may be primarily attributed to apatite released from the parent rock of alluvial materials during the weathering process, whereas its presence in QHSS is likely mainly associated with apatite introduced into the lake via soil erosion and co-precipitation with carbonate minerals. The NaBD-P and NaOH-P are likely originated from clay mineral and some Fe-oxides in the topsoils and sediments. The natural factors within the QHL basin, including substantial calcium carbonate deposits, limited precipitation, intense evaporation, and alkaline lake water, combined with anthropogenic factors such as agricultural cultivation, livestock grazing, and tourism activities, may collectively influence the occurrence and distribution characteristics of P fractions in the surface soil and sediments. In the case of the basin, special attention should be given to the southern Hema River Town, the southeastern Daotang River Town, and the northwestern region. Regarding the lake area, the shallow water areas in the west, northwest, and southeast of the lake should be focused. Simultaneously, attention should also be directed toward the potential impacts of the warming and humidification trends on the Qinghai-Xizang Plateau, particularly their influence on sediment phosphorus burial processes and the overall ecosystem of QHL.

7 DATA AVAILABILITY STATEMENT

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

8 ACKNOWLEDGMENT

Special thanks are due to the editor and three anonymous reviewers for their suggestions, which have greatly improved the manuscript. We thank

Qinghai Lake Scenic Area Protection and Utilization Administration Bureau for their help during the sediment campaign.

References

Ao H Y, Wu C X, Xiong X et al. 2014. Water and sediment quality in Qinghai Lake, China: a revisit after half a century. *Environmental Monitoring and Assessment*, **186**(4): 2121-2133, https://doi.org/10.1007/s10661-013-3522-7.

Bergaya F, Lagaly G. 2013. Handbook of Clay Science. Elsevier, Amsterdam.

Brucker E, Spohn M. 2019. Formation of soil phosphorus fractions along a climate and vegetation gradient in the Coastal Cordillera of Chile. *Catena*, **180**: 203-211, https://doi.org/10.1016/j.catena.2019.04.022.

Chen A, Arai Y. 2023. A review of the reactivity of phosphatase controlled by clays and clay minerals: implications for understanding phosphorus mineralization in soils. *Clays and Clay Minerals*, **71**(2): 119-142, https://doi.org/10.1007/s42860-023-00243-7.

Chen F X, Lu S Y, Deng Y et al. 2021. Different forms of phosphorous transformation and release prediction with environment factor in sediments from Lake Dongting, China. *Desalination and Water Treatment*, **214**: 402-412, https://doi.org/10.5004/dwt.2021.26744.

Chen M. 2021. Characteristics of Phosphorus Fractions Based on Lake Ecoregions Differences. Inner Mongolia University, Hohhot. (in Chinese with English abstract)

Cheng Y Q, Wei H C, Duan R L et al. 2024. Distribution characteristics and indicative significance of grain size and elemental content in surface-sediments of Qinghai Lake, Northeastern Tibetan Plateau. In press.

Chu G B, Chen H Y, Zhang S T et al. 2023. Geochemistry and geochronology of multi-generation garnet: new insights on the genesis and fluid evolution of prograde skarn formation. *Geoscience Frontiers*, **14**(1): 101495, https://doi.org/10.1016/j.gsf.2022.101495.

Condron L M, Newman S. 2011. Revisiting the fundamentals of phosphorus fractionation of sediments and soils. *Journal of Soils and Sediments*, **11**(5): 830-840, https://doi.org/10.1007/s11368-011-0363-2.

Copetti D, Tartari G, Valsecchi L et al. 2019. Phosphorus content in a deep river sediment core as a tracer of long-term (1962-2011) anthropogenic impacts: a lesson from the Milan metropolitan area. *Science of the Total Environment*, **646**: 37-48, https://doi.org/10.1016/j.scitotenv.2018.07.256.

Ding Z Y, Lu R J, Liu X K et al. 2024. Geochemical evidence of provenance diversity in Holocene sandy land of Qinghai Lake Basin in the north-eastern margin of Qinghai-Tibet Plateau and its implications for climate change. *Sedimentology*, **71**(1): 54-80, https://doi.org/10.1111/sed.13128.

Dittrich M, Koschel R. 2002. Interactions between calcite precipitation (natural and artificial) and phosphorus cycle in the hardwater lake. *Hydrobiologia*, **469**(1-3): 49-57, https://doi.org/10.1023/A:1015571410442.

Duan H Y, Yao X J, Zhang D H et al. 2022. Long-term temporal and spatial monitoring of cladophora blooms in qinghai lake based on multi-source remote sensing images. *Remote Sensing*, **14**(4): 853, https://doi.org/10.3390/rs14040853.

Edzwald J K, Toensing D C, Leung M C Y. 1976. Phosphate adsorption reactions with clay minerals. *Environmental Science & Technology*, **10**(5): 485-490, https://doi.org/10.1021/es60116a001.

Ekholm P, Lehtoranta J. 2012. Does control of soil erosion inhibit aquatic eutrophication? *Journal of Environmental Management*, **93**(1): 140-146, https://doi.org/10.1016/j.jenvman.2011.09.010.

Fan C Y, Song C Q, Li W K et al. 2021. What drives the rapid water-level recovery of the largest lake (Qinghai Lake) of China over the past half century? *Journal of Hydrology*, **593**: 125921, https://doi.org/10.1016/j.jhydrol.2020.125921.

Fontes M P F, Weed S B. 1996. Phosphate adsorption by clays from Brazilian Oxisols: relationships with specific surface area and mineralogy. *Geoderma*, **72**(1-2): 37-51, https://doi.org/10.1016/0016-7061(96)00010-9.

Gérard F. 2016. Clay minerals, iron/aluminum oxides, and their contribution to phosphate sorption in soils—a myth revisited. *Geoderma*, **262**: 213-226, https://doi.org/10.1016/j.geoderma.2015.08.036.

Gou H T, Wei H C, Duan R L et al. 2022. Spatial distribution of modern pollen and fungal spores and their ecological indication in Qinghai Lake on northeastern Tibetan Plateau, China. *Ecological Indicators*, **144**: 109474, https://doi.org/10.1016/j.ecolind.2022.109474.

Han Y L, Chen K L, Yu D Y. 2019. Evaluation on the impact of land use change on habitat quality in Qinghai Lake basin. *Ecology and Environmental Sciences*, **28**(10): 2035-2044, https://doi.org/10.16258/j.cnki.1674-5906.2019.10.014.

Hao M Y, Zhu H, Xiong X et al. 2020. Analysis on the distribution and origin of *Cladophora* in the nearshore water of Qinghai Lake. *Acta Hydrobiologica Sinica*, **44**(5): 1152-1158, https://doi.org/10.7541/2020.133. (in Chinese with English abstract)

He H B, Liu Z H, Chen J G et al. 2025. Enhanced biological pump and carbonate pump synergy: the primary pathway for phosphorus clearance in the century-long dynamics of a karst lake. *Global and Planetary Change*, **245**: 104694, https://doi.org/10.1016/j.gloplacha.2025.104694.

Henderson A C G, Holmes J A, Leng M J. 2010. Late Holocene isotope hydrology of Lake Qinghai, NE Tibetan Plateau: effective moisture variability and atmospheric circulation changes. *Quaternary Science Reviews*, **29**(17-18): 2215-2223, https://doi.org/10.1016/j.quascirev.2010.05.019.

Hou D K, He J, Lü C W et al. 2014. Spatial variations and distributions of phosphorus and nitrogen in bottom sediments from a typical north-temperate lake, China. *Environmental Earth Sciences*, **71**(7): 3063-3079, https://

doi.org/10.1007/s12665-013-2683-6.

Huo S L, Zan F Y, Xi B D et al. 2011. Phosphorus fractionation in different trophic sediments of lakes from different regions, China. *Journal of Environmental Monitoring*, **13**(4): 1088-1095, https://doi.org/10.1039/C0EM00696C.

Ji F F, Shen J Z, Ma X F et al. 2018. Changes in water quality and analysis of underlying causes in ulungur lake. *Journal of Hydroecology*, **39**(3): 61-66, https://doi.org/10.15928/j.1674-3075.2018.03.009. (in Chinese with English abstract)

Jin Z D, Wang S M, Zhang F et al. 2010a. Weathering, Sr fluxes, and controls on water chemistry in the Lake Qinghai catchment, NE Tibetan Plateau. *Earth Surface Processes and Landforms*, **35**(9): 1057-1070, https://doi.org/10.1002/esp.1964.

Jin Z D, You C F, Wang Y et al. 2010b. Hydrological and solute budgets of Lake Qinghai, the largest lake on the Tibetan Plateau. *Quaternary International*, **218**(1-2): 151-156, https://doi.org/10.1016/j.quaint.2009.11.024.

Kaiserli A, Voutsa D, Samara C. 2002. Phosphorus fractionation in lake sediments-Lakes Volvi and Koronia, N. Greece. *Chemosphere*, **46**(8): 1147-1155, https://doi.org/10.1016/S0045-6535(01)00242-9.

Kerr J G, Burford M A, Olley J M et al. 2011. Examining the link between terrestrial and aquatic phosphorus speciation in a subtropical catchment: the role of selective erosion and transport of fine sediments during storm events. *Water Research*, **45**(11): 3331-3340, https://doi.org/10.1016/j.watres.2011.03.048.

Kumari N, Mohan C. 2021. Basics of clay minerals and their characteristic properties. *In*: Do Nascimento G M ed. Clay and Clay Minerals. IntechOpen, Rijeka, Croatia, https://doi.org/10.5772/intechopen.97672.

Lantzsch H J, Hillenbrand S, Scheuermann S E et al. 1992. Comparative study of phosphorus utilization from wheat, barley and corn diets by young rats and pigs. *Journal of Animal Physiology and Animal Nutrition*, **67**(1-5): 123-132, https://doi.org/10.1111/j.1439-0396.1992.tb00592.x.

Li D L, Wei H C, Zou Y F et al. 2025. The role of mineral mediation in organic carbon preservation and phosphorus removal in saline lake sediments of the Tibetan Plateau. *Journal of Hydrology*, **661**: 133568, https://doi.org/10.1016/j.jhydrol.2025.133568.

Li R, Wang S R, Xiao S B et al. 2015. Sediments phosphorus forms and loading in the lakes of the mid-lower reaches of the Yangtze River and Yunnan Plateau, China. *China Environmental Science*, **35**(6): 1831-1839, https://doi.org/10.3969/j.issn.1000-6923.2015.06.028. (in Chinese with English abstract)

Li X C, Huang L, Fang H W et al. 2021. Phosphorus adsorption by sediment considering mineral composition and environmental factors. *Environmental Science and Pollution Research*, **28**(14): 17495-17505, https://doi.org/10.1007/s11356-020-12206-9.

Li X Y, Ma Y J, Xu H Y et al. 2009. Impact of land use and land cover change on environmental degradation in Lake Qinghai Watershed, northeast Qinghai-Tibet Plateau. *Land Degradation & Development*, **20**(1): 69-83, https://doi.org/10.1002/ldr.885.

Li Y, Wang Y Y, Kong F C et al. 2024. Lithium isotope systematics in an endorheic saline lacustrine system: insights from Qinghai Lake, China. *Applied Geochemistry*, **175**: 106190, https://doi.org/10.1016/j.apgeochem.2024.106190.

LIGCAS (Lanzhou Institute of Geology of Chinese Academy of Sciences), Institute of Hydrobiology, Chinese Academy of Sciences, Institute of Microbiology, Chinese Academy of Sciences et al. 1979. A Synthetically Investigation Report on Qinghai Lake. Science Press, Beijing. p.1-23. (in Chinese)

Lin Y P, Singer P C. 2006. Inhibition of calcite precipitation by orthophosphate: speciation and thermodynamic considerations. *Geochimica et Cosmochimica Acta*, **70**(10): 2530-2539, https://doi.org/10.1016/j.gca.2006.03.002.

Linquist B A, Singleton P W, Yost R S et al. 1997. Aggregate size effects on the sorption and release of phosphorus in an ultisol. *Soil Science Society of America Journal*, **61**(1): 160-166, https://doi.org/10.2136/sssaj1997.03615995006100010024x.

Liu C, Zhu L P, Wang J B et al. 2021. *In-situ* water quality investigation of the lakes on the Tibetan Plateau. *Science Bulletin*, **66**(17): 1727-1730, https://doi.org/10.1016/j.scib.2021.04.024.

Liu J, Yang J J, Cade-Menun B J et al. 2017. Molecular speciation and transformation of soil legacy phosphorus with and without long-term phosphorus fertilization: insights from bulk and microprobe spectroscopy. *Scientific Reports*, **7**(1): 15354, https://doi.org/10.1038/s41598-017-13498-7.

Liu Y S, Hu Z C, Gao S et al. 2008. *In situ* analysis of major and trace elements of anhydrous minerals by LA-ICP-MS without applying an internal standard. *Chemical Geology*, **257**(1-2): 34-43, https://doi.org/10.1016/j.chemgeo.2008.08.004.

Lukkari K, Hartikainen H, Leivuori M. 2007. Fractionation of sediment phosphorus revisited. I: fractionation steps and their biogeochemical basis. *Limnology and Oceanography*: *Methods*, **5**(12): 433-444, https://doi.org/10.4319/lom.2007.5.433.

Mage S M, Porder S. 2013. Parent material and topography determine soil phosphorus status in the luquillo mountains of puerto rico. *Ecosystems*, **16**(2): 284-294, https://doi.org/10.1007/s10021-012-9612-5.

Maranguit D, Guillaume T, Kuzyakov Y. 2017. Land-use change affects phosphorus fractions in highly weathered tropical soils. *Catena*, **149**: 385-393, http://doi.org/10.1016/j.catena.2016.10.010.

Mehmood A, Akhtar M S, Imran M et al. 2018. Soil apatite loss rate across different parent materials. *Geoderma*, **310**: 218-229, http://doi.org/10.1016/j.geoderma.2017.09.036.

Meng X L, Jiang X M, Xiong X et al. 2016. Mediated spatio-temporal patterns of macroinvertebrate assemblage associated with key environmental factors in the Qinghai Lake area, China. *Limnologica*, **56**: 14-22, http://doi.org/

10.1016/j.limno.2015.11.005.

Ni Z K, Wang S R. 2015. Economic development influences on sediment-bound nitrogen and phosphorus accumulation of lakes in China. *Environmental Science and Pollution Research*, **22**(23): 18561-18573, http://doi.org/10.1007/s11356-015-5171-6.

Ni Z K, Wang S R, Wu Y et al. 2020. Response of phosphorus fractionation in lake sediments to anthropogenic activities in China. *Science of the Total Environment*, **699**: 134242, https://doi.org/10.1016/j.scitotenv.2019.134242.

Nie L J, Zeng L H, Ji J et al. 2022. Centurial changes in sedimentary phosphorus forms and trace elements in response to damming and anthropogenic pollution in a floodplain lake, Central China. *Environmental Science and Pollution Research*, **29**(19): 28446-28457, https://doi.org/10.1007/s11356-021-18476-1.

Noll M R, Szatkowski A E, Magee E A. 2009. Phosphorus fractionation in soil and sediments along a continuum from agricultural fields to nearshore lake sediments: potential ecological impacts. *Journal of Great Lakes Research*, **35**: 56-63, https://doi.org/10.1016/j.jglr.2008.08.004.

Orihel D M, Baulch H M, Casson N J et al. 2017. Internal phosphorus loading in Canadian fresh waters: a critical review and data analysis. *Canadian Journal of Fisheries and Aquatic Sciences*, **74**(12): 2005-2029, https://doi.org/10.1139/cjfas-2016-0500.

Paton C, Hellstrom J, Paul B et al. 2011. Iolite: freeware for the visualisation and processing of mass spectrometric data. *Journal of Analytical Atomic Spectrometry*, **26**(12): 2508-2518, https://doi.org/10.1039/C1JA10172B.

Peng P Y, Wu X N, Li Z G et al. 2021. Characteristics of distribution of inorganic phosphorus fractions in soils of different land use patterns in the source area of Dianchi watershed. *Research of Soil and Water Conservation*, **28**(6): 58-64, https://doi.org/10.13869/j.cnki.rswc.2021.06.005. (in Chinese with English abstract)

Ravindran V, Ravindran G, Sivalogan S. 1994. Total and phytate phosphorus contents of various foods and feedstuffs of plant origin. *Food Chemistry*, **50**(2): 133-136, https://doi.org/10.1016/0308-8146(94)90109-0.

Ruban V, López-Sánchez J F, Pardo P et al. 2001. Harmonized protocol and certified reference material for the determination of extractable contents of phosphorus in freshwater sediments-a synthesis of recent works. *Fresenius' Journal of Analytical Chemistry*, **370**(2-3): 224-228, https://doi.org/10.1007/s002160100753.

Rydin E. 2000. Potentially mobile phosphorus in Lake Erken sediment. *Water Research*, **34**(7): 2037-2042, https://doi.org/10.1016/S0043-1354(99)00375-9.

Schindler D W. 2012. The dilemma of controlling cultural eutrophication of lakes. *Proceedings of the Royal Society B*: *Biological Sciences*, **279**(1746): 4322-4333, https://doi.org/10.1098/rspb.2012.1032.

Smith V H, Schindler D W. 2009. Eutrophication science: where do we go from here? *Trends in Ecology & Evolution*, **24**(4): 201-207, https://doi.org/10.1016/j.tree.2008.11.009.

Søndergaard M, Jensen P J, Jeppesen E. 2001. Retention and internal loading of phosphorus in shallow, eutrophic lakes. *The Scientific World*, **1**: 427-442, https://doi.org/10.1100/tsw.2001.72.

Stevens L, Ito E, Olson D. 2000. Relationship of Mn-carbonates in varved lake-sediments to catchment vegetation in Big Watab Lake, MN, USA. *Journal of Paleolimnology*, **24**(2): 199-211, https://doi.org/10.1023/A:1008169526577.

Stutter M I, Shand C A, George T S et al. 2015. Land use and soil factors affecting accumulation of phosphorus species in temperate soils. *Geoderma*, **257-258**: 29-39, http://doi.org/10.1016/j.geoderma.2015.03.020.

Sun H L, Han C H, Liu Z H et al. 2022. Nutrient limitations on primary productivity and phosphorus removal by biological carbon pumps in dammed karst rivers: implications for eutrophication control. *Journal of Hydrology*, **607**: 127480, https://doi.org/10.1016/j.jhydrol.2022.127480.

Sun Y L, Li X Y, Tang J et al. 2008. Climate change and hydrological response in the watershed of Qinghai Lake. *Resources Science*, **30**(3): 354-362, https://doi.org/10.3321/j.issn:1007-7588.2008.03.006. (in Chinese with English abstract)

Suzumura M, Kamatani A. 1995. Origin and distribution of inositol hexaphosphate in estuarine and coastal sediments. *Limnology and Oceanography*, **40**(7): 1254-1261, https://doi.org/10.4319/LO.1995.40.7.1254.

Tammeorg O, Horppila J, Tammeorg P et al. 2016. Internal phosphorus loading across a cascade of three eutrophic basins: a synthesis of short- and long-term studies. *Science of the Total Environment*, **572**: 943-954, http://doi.org/10.1016/j.scitotenv.2016.07.224.

Tu L Y, Gilli A, Lotter A F et al. 2021. The nexus among long-term changes in lake primary productivity, deep-water anoxia, and internal phosphorus loading, explored through analysis of a 15,000-year varved sediment record. *Global and Planetary Change*, **207**: 103643, https://doi.org/10.1016/j.gloplacha.2021.103643.

Tu L Y, Jarosch K A, Schneider T et al. 2019. Phosphorus fractions in sediments and their relevance for historical lake eutrophication in the Ponte Tresa basin (Lake Lugano, Switzerland) since 1959. *Science of the Total Environment*, **685**: 806-817, https://doi.org/10.1016/j.scitotenv.2019.06.243.

Tu L Y, Zander P, Szidat S et al. 2020. The influences of historic lake trophy and mixing regime changes on long-term phosphorus fraction retention in sediments of deep eutrophic lakes: a case study from Lake Burgäschi, Switzerland. *Biogeosciences*, **17**(10): 2715-2729, https://doi.org/10.5194/bg-17-2715-2020.

Valiente N, Jirsa F, Gómez-Alday J J. 2022. Saline lakes as barriers against pollution: a multidisciplinary overview. *Limnetica*, **41**(2): 281-303, https://doi.org/10.23818/limn.41.17.

Waldrip H M, Pagliari P H, He Z Q et al. 2015. Legacy phosphorus in calcareous soils: effects of long-term poultry litter application. *Soil Science Society of*

America Journal, **79**(6): 1601-1614, https://doi.org/10.2136/sssaj2015.03.0090.

Walsh J R, Corman J R, Munoz S E. 2019. Coupled long-term limnological data and sedimentary records reveal new control on water quality in a eutrophic lake. *Limnology and Oceanography*, **64**(S1): S34-S48, https://doi.org/10.1002/lno.11083.

Wang C Y, Zhang Y, Li H L et al. 2013. Sequential extraction procedures for the determination of phosphorus forms in sediment. *Limnology*, **14**(2): 147-157, https://doi.org/10.1007/s10201-012-0397-1.

Wang S R. 2014. Sediment-Water Interface Process of Lakes: Theories and Methods. Sciense Press, Beijing. (in Chinese)

Wang Z H. 2012. Effects of Fe and Al on Phosphorus Fractions, Transformation in the Sediments of Lakes. Northeast Agricultural University, Harbin, China, https://doi.org/10.7666/d.Y2235166. (in Chinese with English abstract)

Worsfold P, Mckelvie I, Monbet P. 2016. Determination of phosphorus in natural waters: a historical review. *Analytica Chimica Acta*, **918**: 8-20, https://doi.org/10.1016/j.aca.2016.02.047.

Wu S T, Wörner G, Jochum K P et al. 2019a. The preparation and preliminary characterisation of three synthetic andesite reference glass materials (ARM-1, ARM-2, ARM-3) for *in situ* microanalysis. *Geostandards and Geoanalytical Research*, **43**(4): 567-584, http://doi.org/10.1111/ggr.12301.

Wu X C, Ma T, Du Y et al. 2021. Phosphorus cycling in freshwater lake sediments: influence of seasonal water level fluctuations. *Science of the Total Environment*, **792**: 148383, https://doi.org/10.1016/j.scitotenv.2021.148383.

Wu Y, Luo J Y, Zhang Q et al. 2019b. Potentials and challenges of phosphorus recovery as vivianite from wastewater: a review. *Chemosphere*, **226**: 246-258, https://doi.org/10.1016/j.chemosphere.2019.03.138.

Wu Z H, Yuan X G, Xiong X et al. 2024. *Cladophora* as ecological engineer: a new test from the largest lake of Qinghai-Tibet plateau with filamentous algal blooms. *Water Biology and Security*, **3**(1): 100210, https://doi.org/10.1016/j.watbs.2023.100210.

Wurtsbaugh W A, Marcarelli A M, Boyer G L. 2012. Eutrophication and Metal Concentrations in Three Bays of the Great Salt Lake (USA). 2009 Final Report to the Utah Division of Water Quality, Salt Lake City, Utah.

Xiang S L, Zhou W B. 2010. Phosphorus existing forms and distribution characteristic in Lake Poyang sediments. *Journal of Lake Sciences*, **22**(5): 649-654, https://doi.org/10.18307/2010.0504. (in Chinese with English abstract)

Xiao H C, Li J W, Xia Y et al. 2021. Characteristics of phosphorus fractions and their driving factors in forest soils with different parent materials in the mid-subtropics, China. *Chinese Journal of Applied Ecology*, **32**(1): 16-22, https://doi.org/10.13287/j.1001-9332.202101.001. (in Chinese with English abstract)

Xiong J, Liu Z H, Yan Y P et al. 2022. Role of clay minerals in controlling phosphorus availability in a subtropical Alfisol. *Geoderma*, **409**: 115592, https://doi.org/10.1016/j.geoderma.2021.115592.

Xiong S G, Xi B D, Wei D et al. 2011. Distribution of different phosphorus fractions in surface sediment of Wudalianchi. *Environmental Science & Technology*, **34**(9): 95-99, 140, https://doi.org/10.3969/j.issn.1003-6504.2011.09.022. (in Chinese with English abstract)

Xue H P, Zhou X, Chen Y Y et al. 2025. Effects of historical dust-mediated atmospheric phosphorus deposition on phosphorus fractions in sediments and primary productivity of Dalongwan Maar Lake, Northeast China. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, **660**: 112679, https://doi.org/10.1016/j.palaeo.2024.112679.

Ye H M, Yuan X Y, Han L et al. 2017. Comparison of phosphorus fraction distribution and influencing factors of suspended and surface sediments in the Tiaoxi watershed, China. *Water Science and Technology*, **75**(9): 2108-2118, https://doi.org/10.2166/wst.2017.079.

Yin H B, Yun Y, Zhang Y L et al. 2011. Phosphate removal from wastewaters by a naturally occurring, calcium-rich sepiolite. *Journal of Hazardous Materials*, **198**: 362-369, https://doi.org/10.1016/j.jhazmat.2011.10.072.

Yu H H, Yuan X Y, Han L et al. 2018. Spatial distributions of phosphorus fractions in riparian soils and their influence factors analysis in watersheds of western Taihu Basin. *Research of Environmental Sciences*, **31**(3): 537-546, https://doi.org/10.13198j.issn.1001-6929.2017.04.01. (in Chinese with English abstract)

Yuan J, Cao G C, E C Y et al. 2019. Soil mineral, mechanical composition and magnetic characteristics of grazing grassland and farmland in 30 years. *Chinese Journal of Soil Science*, **50**(2): 253-259, https://doi.org/10.19336/j.cnki.trtb.2019.02.01. (in Chinese with English abstract)

Zhang C, Tian H Q, Liu J Y et al. 2005. Pools and distributions of soil phosphorus in China. *Global Biogeochemical Cycles*, **19**(1): GB1020, https://doi.org/10.1029/2004GB002296.

Zhang G Q, Yao T D, Xie H J et al. 2020. Response of Tibetan Plateau lakes to climate change: trends, patterns, and mechanisms. *Earth-Science Reviews*, **208**: 103269, https://doi.org/10.1016/j.earscirev.2020.103269.

Zhang L Y, Wang S R, Chu Z S et al. 2010. Distribution characteristics of phosphorus in sediment of Yanghe Reservoir and in soil of its basin. *China Environmental Science*, **30**(11): 1529-1536. (in Chinese with English abstract)

Zhang Q, Yu Q G, Wang S L et al. 2017. Phosphorus fractions, spatial distribution and release contributions in sediments of Jianhu Lake, Northwestern Yunnan Plateau, China. *Acta Scientiae Circumstantiae*, **37**(10): 3792-3803, https://doi.org/10.13671/j.hjkxxb.2017.0160. (in Chinese with English abstract)

Zhang W Z, Wang S L, Zhang B et al. 2022a. Analysis of the water color transitional change in Qinghai Lake during the past 35 years observed from Landsat and MODIS. *Journal of Hydrology*: *Regional Studies*, **42**: 101154, https://doi.org/10.1016/j.ejrh.2022.101154.

Zhang X, Lin C Y, E C Y et al. 2022b. Atmospheric dry

deposition of nitrogen and phosphorus in Lake Qinghai, Tibet Plateau. *Atmospheric Pollution Research*, **13**(7): 101481, https://doi.org/10.1016/j.apr.2022.101481.

Zhang Z J, Goldstein H L, Reynolds R L et al. 2018. Phosphorus speciation and solubility in aeolian dust deposited in the interior American West. *Environmental Science & Technology*, **52**(5): 2658-2667, https://doi.org/10.1021/acs.est.7b04729.

Zhao L, Fang D M, Song W N et al. 2014. Spatial distribution of phosphorus fractions in surface sediments and its impact on soluble phosphorus in mainstream of Haihe River. *Journal of Jilin University* (*Earth Science Edition*), **44**(2): 603-609, https://doi.org/10.13278/j.cnki.jjuese.201402205. (in Chinese with English abstract)

Zhao T X, Xu S, Hao F. 2023. Differential adsorption of clay minerals: implications for organic matter enrichment. *Earth-Science Reviews*, **246**: 104598, https://doi.org/10.1016/j.earscirev.2023.104598.

Zheng M P. 2010. Salt lake resources and eco-environment in China. *Acta Geologica Sinica*, **84**(11): 1613-1622. (in Chinese with English abstract)

Zhu H, Xiong X, Ao H Y et al. 2020. *Cladophora* reblooming after half a century: effect of climate change-induced increases in the water level of the largest lake in Tibetan Plateau. *Environmental Science and Pollution Research*, **27**(33): 42175-42181, https://doi.org/10.1007/s11356-020-10386-y.

Zhu J, Li M, Whelan M. 2018. Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: a review. *Science of the Total Environment*, **612**: 522-537, http://doi.org/10.1016/j.scitotenv.2017.08.095.

Zhu Y R, Wu F C, He Z Q et al. 2013. Characterization of organic phosphorus in lake sediments by sequential fractionation and enzymatic hydrolysis. *Environmental Science & Technology*, **47**(14): 7679-7687, http://doi.org/10.1021/es305277g.

Electronic supplementary material

Supplementary material (Supplementary Tables S1–S4 and Figs.S1–S5) is available in the online version of this article at https://doi.org/10.1007/s00343-026-5476-y.