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Research papers

Lake pigment characteristics and their applicability in reconstructing phytoplankton communities under irregular hydrological regulation in a floodplain lake system

Zhaoxi Li [a,b], Yang Gao [a,b,*], Shuoyue Wang [a,b], Ke Zhang [c], Qi Lin [c], Junjie Jia [a,b], Yao Lu [a,b]

[a] *Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, PR China*
[b] *University of Chinese Academy of Sciences, Beijing, 100049, PR China*
[c] *State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, PR China*

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ABSTRACT

The strong hydrological characteristics and complex biochemical environment of floodplain lake systems make it difficult to obtain accurate, convincing results from sediment pigments used as paleoenvironmental indicators. Understanding pigment migration and preservation mechanisms under hydrological regulation will help explain past ecological changes in these lake systems. This study investigates phytoplankton community structure, chlorophyll distribution, and associated environmental factors throughout a hydrological cycle in Poyang Lake, China. In conjunction with pigment sediment characteristics, this study also compared pigment deposition and preservation mechanisms among three hydrological lake zones (i.e., sub-lakes, main lake, and water channel). Results show a critical loss in sediment pigment information in the main lake and the water channel resulting from the lake's strong hydrodynamic conditions. Moreover, oxygen and sunlight had a general inhibitory effect on pigment in the overlying water, while unfavourable pH environments could affect pigments in the sediment that devoid of protective cell mechanisms. Results also show that as a biological proxy index, sub-lakes sediment pigments accurately reflect phytoplankton community structure in overlying water. Additionally, due to the relative stability of the sub-lakes environment, it can be considered the preferential lake zone from which to obtain proxy indexes in floodplain environments.

1. Introduction

Geographical units specific to lake systems are highly sensitive to climate and environmental changes. They can reflect regional changes in natural environments and interactions between anthropic and natural factors, while also responding rapidly to nutrient and temperature changes. Accordingly, lake systems have been referred to as "sentinels" of global climate change (Gao et al., 2020; Pacheco et al., 2021). As an important material sink of lake systems, lake sediment faithfully preserves a large amount of information about the ecological evolution of such lake systems, providing a basis from which to comprehensively discern lake ecosystem response processes under a background of climate change (Verleyen et al., 2005; Bourel et al., 2021). Obtaining ecological succession information from lake sediment through a series of modern means can address deficiencies in measured data over long-term scales (Thomas et al., 2021; Belle et al., 2021). Moreover, sedimentary photosynthetic pigment records can be used to reveal phytoplankton community alterations (Deshpande et al., 2014; Klamt et al., 2021), while at the same time sedimentary pigments represent productivity (Szymczak-Zyla et al., 2011), phytoplankton classification, (Freiberg et al., 2011) and water environment conditions (Fietz et al., 2007; Montes et al., 2021; Hofmann et al., 2021).

Using sedimentary pigments to reconstruct past phytoplankton community structure and productivity processes require a comprehensive understanding of pigment stability and degradation mechanisms (Hobbs et al., 2010). There are significant differences between surface sediment pigments and those in overlying water, which largely result from the many factors that cause pigment degradation or loss in water (i.e., sunlight, temperature, and zooplankton predation) (Leavitt 1993; Mathew et al., 2021). Studies have shown that 95 % of endogenous

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[*] Corresponding author at: University of Chinese Academy of Sciences, Beijing, 100049, PR China.
E-mail address: gaoyang@igsnrr.ac.cn (Y. Gao).

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pigment in water degrades within a few days (Louda et al., 2002). Additionally, owing to differences in chemical stability caused by the chemical structure of the pigment itself, the pigment structure that ultimately reaches the surface of deposits may correspondingly alter (Buchaca and Catalan 2008). Furthermore, selective degradation becomes progressively more obvious as burial depth increases.

Reconstructing changes in lake environments and associated ecological succession factors using paleolimnology information contained in sediment pigment has progressed somewhat in certain lake systems within the Qinghai–Tibet Plateau (Lami et al., 2010) and in certain lake systems in the middle and lower reaches of the Yangtze River, such as Chao Lake and Tai Lake (Xue et al., 2007; Song et al., 2019). Hu et al. (2014) extracted sediment pigments from two lakes on the eastern Tibetan Plateau and, by comparing them with other environmental proxies, concluded that nitrogen deposition is a controlling factor leading to increased lake productivity, and suggested that sediment pigments can well document the ecological succession of lakes caused by nitrogen deposition on the plateau. Zhang et al. (2019) used sediment pigments to reconstruct the phytoplankton community succession in Chaohu Lake since the 1960s and found that the construction of the Chaohu Lake dam in 1963, increased N and P inputs and higher mean temperatures combined to cause the decline of the dinoflagellate community (from 90 % to 15 %) and the outbreak of the blue-green algae community (from 5 % to 35 %). Because the hydrological conditions of these lake systems are relatively stable, pigments are more easily preserved. However, for subtropical floodplain lake systems vulnerable to seasonal flooding with correspondingly poor pigment preservation, the effectiveness of paleolimnological information in sediment pigment requires further validation.

The effect of hydrodynamic conditions on lake pigments prior to their stable preservation in lakebed sediment via deposition has largely been underestimated, especially in floodplain lake systems with strong hydrodynamic conditions. Pigments in floodplain lake surface sediment remain in overlying water longer under intense resuspension processes, resulting in the degradation of greater than 90 % of pigments into colorless compounds before being permanently buried, which results in a mismatch between pigments in overlying water and that in lakebed sediment (Freiberg et al., 2011). Most pigment that derives from phytoplankton in lake systems degrade to colorless compounds under intense sunlight conditions and high oxygen content at the lakebed surface (Schüller et al., 2015; Sanchini and Grosjean 2020). Additionally, even though sediment pigments derive from planktonic and benthic phototrophic bacteria, cyanobacteria, and algae, aquatic macrophytes and plant material from surrounding watersheds may also contribute sediment pigments. Even though this plant-based and exogenous pigment may be an important component of the ecological information that interferes with sediment pigment, their overall proportions are generally low (Buchaca et al., 2019). Owing to these reasons, paleoclimatic information stored in floodplain lake sediment affected by multiple factors is very complex.

The aim of this study was to reveal pigment deposition characteristics in the water of a large subtropical floodplain lake system under seasonal hydrological regulation. This study hypothesized that the high spatial heterogeneity associated with the hydrological regulation of Poyang Lake is the key factor that has led to the spatial differentiation in surface sediment pigmentation. To validate this hypothesis, we focused on three specific objectives: (i) to clarify the signaling significance of sediment pigments as biomarkers under complex hydrological conditions; (ii) to analyze the regulation mechanisms of environmental factors on lake pigments; (iii) to explore pigment migration characteristics driven by hydrological factors prior to their stable burial in lakebed sediment.

2. Materials and methods

2.1. Study area and sampling sites

Poyang Lake (115°49 E ~ 116°46′ E, 28°24′ N ~ 29°46′ N), in the middle and lower reaches of the Yangtze River in Jiangxi Province, is the largest freshwater lake system in China, with a total basin area of 1.62×10^5 km^2 (Fig. 1a and b). Poyang Lake is a typical floodplain lake system. It undergoes exceptional variation in annual water levels (i.e., 7.9 m–19.4 m) and exhibits hydrological characteristics that have been described as a “river in dry season and lake in wet season” (Fig. 1c) (Liu et al., 2015). Five tributaries feed the lake (i.e., Gan River, Fu River, Xin River, Rao River, and Xiu River) in its southern region before flowing into the mainstem of the Yangtze River via an inflow channel (Yao et al., 2015). Poyang Lake plays an extremely important role in regulating Yangtze River water levels, protecting its water resources and environment while maintaining the health of local ecosystems (Liu et al., 2017). The region has a typical subtropical monsoon climate, with an average annual rainfall of 1622 mm. The rainy season is from March to September, accounting for greater than 80 % of annual rainfall (Jia et al., 2020). The water environment of Poyang Lake has been deteriorating under the development of the economic zone of the lake (i.e., dam construction and fisheries), wherein certain lake areas have become eutrophic (Jia et al., 2019).

2.2. Sample collection

According to associated factors (e.g., hydrological connectivity and topography), the Poyang Lake basin can be divided into three hydrological zones: the main lake, sub-lakes, and the water channel. Accounting for actual sampling conditions, a total of 34 sampling points were selected that were distributed evenly throughout the lake region, including 14 sediment sampling points and 20 water sampling points (Fig. 1b). Sediment sampling points S1–S4 are within the main lake; sub-lakes sampling points S5–S10 are within the southwestern and northeastern regions of the lake; water channel sampling points S11–S14 are within the northern region of the lake (Fig. 1b). All sediment sampling sites were historically surveyed prior to deployment, and based on the actual conditions of the sample sites and the descriptions of local residents, sampling sites were deployed in areas where no significant human disturbance (e.g., sand mining, river excavation) had historically occurred, thus ensuring that the sediment physicochemical indicators were fully representative of the overlying water column.

Surface water samples (at a 0.5 m depth) were collected in 100 ml polyethylene bottles at 4-month intervals (i.e., one hydrological cycle) from September 2019 to April 2021 and then stored in a refrigerator at 4 °C until analyzed. At the same time, electrical conductivity (COND), redox potential (ORP), and water acidity (pH) were also measured using Ultrameter II pH meters (Myron L company, Carlsbad, CA, USA). Concentrations of chlorophyll (Chl) and dissolved oxygen (DO) were measured in situ using a Hydrolab DS5 multiparameter water quality sonde (OTT Hydromet, the United States of America) and a portable fluorescence dissolved oxygen meter (YSI ProSolo, the United States of America), respectively. Phytoplankton was collected from each water sampling point as described by Hu and Wei (2006). Surface water samples (from 0 to 50 cm) were collected in 1 L polyethylene bottles, fixed using Lugol’s iodine, and allowed to rest at room temperature for 48 h. The siphon principle was used to extract the algae-free supernatant from the upper part of the bottles using a rubber hose. The remaining 60 ml of the sample precipitate was transferred to 100 ml polyethylene bottles, stored in a 40 % formaldehyde solution, and then transported to the Nanjing Institute of Geography and Limnology, the Chinese academy of Sciences (CAS), for analysis of algae biomass, density, and species composition.

The Chinese manufactured XDB0205 gravity column sediment sampler (with an inner diameter of 5.5 mm) was used to collect sediment

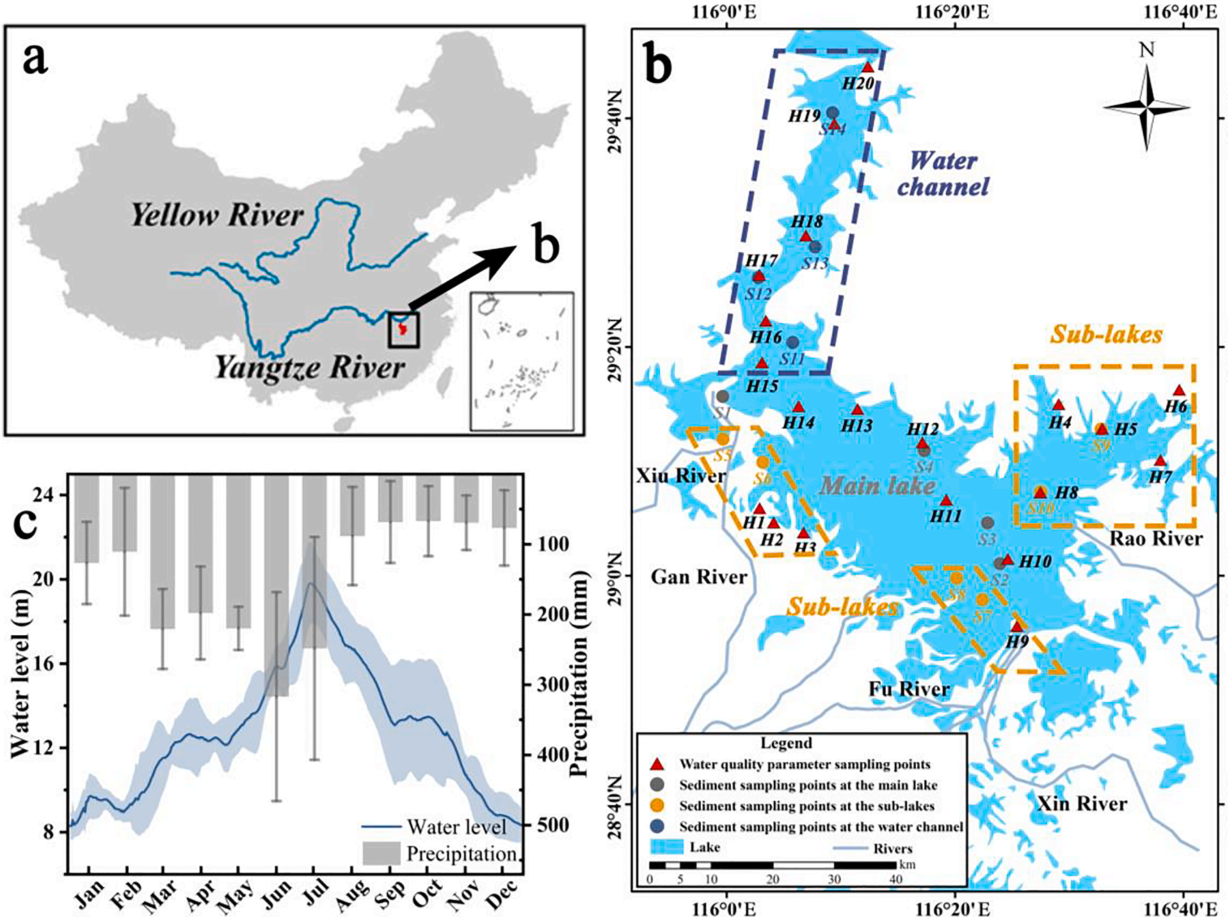

Fig. 1. Map of Poyang Lake sampling points (a and b) and changes in precipitation and water level (c).

samples at a depth of 10 cm in April 2021. Samples were immediately divided at 1 cm intervals and then packed into opaque self-sealing bags. After being frozen (−20 °C), they were transported to the Institute of Geographic Sciences and Natural Resources Research, CAS (IGSNRR, CAS). All samples were weighed before and after being freeze dried (48 h, 0.1 Pa) to calculate moisture content, and then processed for subsequent analysis.

2.3. Laboratory and data analyses

2.3.1. Analysis of physical and chemical water parameters

All collected water samples were immediately stored in a refrigerator at 4 °C until transported to the Institute of Geographic Sciences and Natural Resources Research, CAS, for analysis. Water samples were filtered through 0.45 μm filter membranes (heated to 80 °C for 4 h). Samples were used to test the following indicators: (1) ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), and phosphate phosphorus (PO_4^{3-}-P), which were measured using an AA3 continuous flow analyzer (Germany); (2) total nitrogen (TN) and total phosphorus (TP) concentrations were determined using the TU-1900 dual beam UV–vis spectrophotometer (China); (3) salinity was measured in situ using the WS-600 salinometer (China); (4) species composition classification, population abundance (cells/L) of each species, and biomass ($\mu g \cdot L^{-1}$) were determined following the procedure described by Hu and Wei (2006).

2.3.2. Analysis of sediment pigment

The lyophilized samples were ground into powder under low light conditions. About 1 g of the sediment sample was weighed into a 10 ml glass centrifuge tube (PTFE gasket, wrapped in tinfoil to protect from light), 6 ml of extraction reagent (80 % HPLC acetone: 15 % methanol: 5 % water) was added, sonicated for 1 min in an ice bath and left to stand for 12 h at −20 °C. The sample was centrifuged for 10 min (2500 r/min) and the supernatant was aspirated with a syringe and filtered through a PTFE membrane (0.22 μm, hydrophobic) in a 10 ml brown sample bottle (PTFE gasket). The sample was centrifuged for 10 min (2500 r/min) and the supernatant was aspirated with a syringe and filtered through a PTFE membrane (0.22 μm, hydrophobic) in a 10 ml brown sample bottle (PTFE gasket).

The blow-dried sample was rehydrated with 800 μl of reagent (70 % HPLC acetone: 25 % IPR: 5 % methanol), transferred to a 2 ml brown sample bottle and analyzed on the machine. Analysis of Chl and carotenoid sediment pigments was conducted using an Agilent High-Performance Liquid Chromatography 1260 Series with a quaternary pump, an auto-sampler, a Poroshell 120 EC-C18 column (150 × 3.0 mm; 2.7 μm particle size), and a photodiode array detector. This study applied the extraction and separation pigment procedure modified by Chen et al. (2001). Pigments were calibrated using an authentic standard (Denmark DHI) and expressed as $nmol \cdot g^{-1}$ organic matter (OM). Where OM is determined by the loss on ignition (LOI) method, at an ignition of 550 °C for 2 h, through means of quality differences before and after OM calculations in sediment (Beaudoin 2003).

3. Results

3.1. Distribution of chlorophyll and phytoplankton communities

Poyang Lake has a total of 172 phytoplankton species belonging to eight phyla. Cyanobacteria, Chlorophyta, and Bacillariophyta are the dominant phytoplankton species throughout the lake. Although the community structure varies greatly among the different regions of the lake, no significant difference was observed in total algae density (Fig. 2). In the water channel, the dominant phytoplankton communities are Chlorophyta (28.7 %) and Bacillariophyta (25.2 %), while in the sub-lakes the dominant phytoplankton communities are Cyanobacteria (48.9 %) and Chlorophyta (29.9 %). Comparatively, sub-lakes Bacillariophyta and Cryptophyta density was lowest. The annual average Chl concentration in the Poyang Lake basin is 19.39 μg/L, but its spatial distribution is uneven. Chl concentrations in the main lake and the water channel are lower than the average level of the whole lake (i.e., 17.31 μg/L and 18.44 μg/L, respectively). The average annual sub-lakes Chl concentration can reach as high as 22.66 μg/L, which is much higher than in the other two zones. Consequently, the Chl concentration in the southern region of Poyang Lake (30.98 μg/L), which is mainly comprised of sub-lakes, is significantly higher compared to the northern region (15.70 μg/L) ($p < 0.05$).

3.2. Distribution characteristics of surface sediment pigments

Surface sediment pigment distribution in the Poyang Lake basin is extremely uneven (Fig. 3a), which is associated with irregular hydrological processes. Generally, the total concentration of sub-lakes sediment pigment (with an average of 213.58 nmol/g OM) was much higher compared to the main lake (with an average of 10.62 nmol/g OM). The S8 sampling point had the highest Chl and carotenoid concentrations in the sub-lakes zone, namely, 34.28 nmol/g OM and 56.03 nmol/g OM, respectively. It is interesting to note that we detected no pigments in the S9 sampling point in the sub-lakes zone in the northeastern region of Poyang Lake.

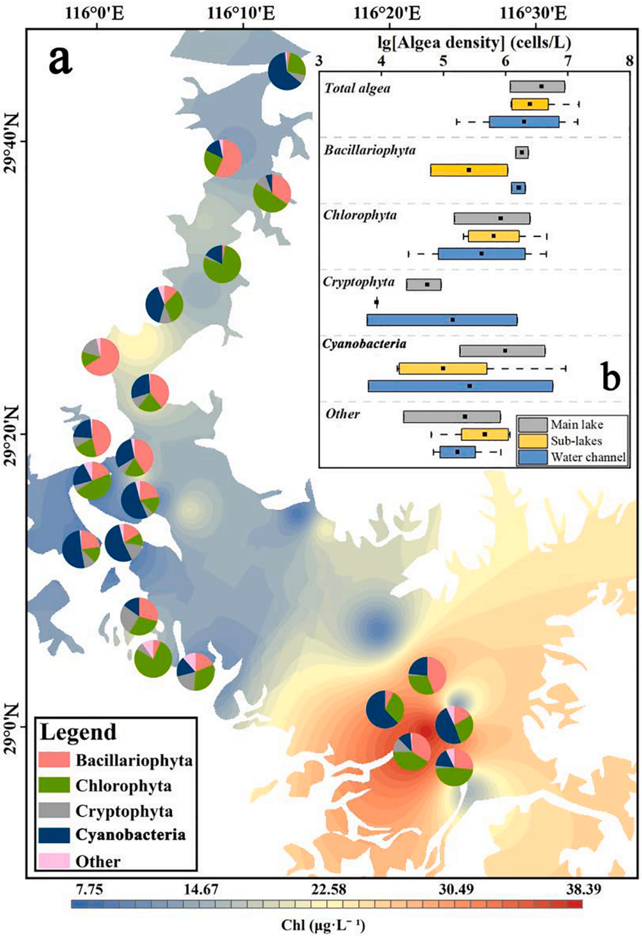

Fig. 2. Spatial distribution characteristics of chlorophyll and phytoplankton communities in water (a) and differences in phytoplankton communities among the three hydrological zones (b). For this study, Euglenophyceae, Chrysophyceae, Xanthophyta, and Dinophyceae were combined into "other" due to their low detection levels.

Among the identified Chl forms, Chl-*a* accounted for 59.77 %–100 % of undegraded Chl, while Chl-*b* was only detected at sampling points S3 (40.23 %), S6 (15.62 %), and S8 (31.39 %). Degraded chlorophyll (i.e., deg-Chl, which includes Phy-*a*1, Phy-*a*2, Phy-*b*1, and Phy-*b*2) accounted for 95.14 %–100 % of total chlorophyll (TChl), which was mainly composed of deg-Chl-*b* (Fig. 3b). Carotenoids, being characteristic phytoplankton pigments, were only detected at certain sampling points, and the composition of carotenoids varied significantly among the different sampling points (Fig. 3c). Carotenoid species were most abundant in sub-lakes surface sediment, while only one carotenoid species was identified in main lake surface sediment (i.e., fucoxanthin [Fucox]). Fucox is the most common carotenoid in Poyang Lake surface sediment, with an average concentration of 0.77 nmol/g OM, which may indicate that diatoms are the dominant phytoplankton species group in Poyang Lake. On the other hand, diatoxanthin (Diato), lutein and zeaxanthin (Lut-Zeax), and β-carotene (β-carot) were only detected in sub-lakes surface sediment, with mean concentrations of 0.42, 16.42, and 7.75 nmol/g OM, respectively.

3.3. Changes in the Poyang lake water environment

This study detected obvious differences in hydrological characteristics among the three Poyang Lake zones, especially between the sub-lakes and water channel zones (Table 1). Hydrologically, the water channel is characterized by its deep depth (13.10 ± 3.76 m), high velocity (0.48 ± 0.06 m/s), and high transparency (0.42 ± 0.09 m). The sub-lakes zone is a unique lake geographical unit type in Poyang Lake during the dry season, which is intermittently connected to the main lake. Thus, it acts relatively independently, with a slow flow rate (0.29 ± 0.08 m/s) and a shallow water depth (0.35 ± 0.06 m). Obvious regional differences were observed in DO, wherein the sub-lakes zone had the lowest average DO (6.93 mg/L) followed by the main lake (8.45 mg/L) and the water channel with the highest overall DO (9.11 mg/L).

The TN concentration of the sub-lakes zone was 1.30 ± 0.06 mg/L, which was significantly lower compared to corresponding values of the main lake and the water channel zones (i.e., 2.05 ± 0.21 and 1.94 ± 0.05 mg/L, respectively) ($p < 0.05$). Similar to TN content, NO_3^--N and NH_4^+-N concentrations were lowest in the sub-lakes zone. For TN content in the main lake and the water channel, NO_3^--N was the main component, accounting for 63.30 %, while its corresponding proportion was only 22.91 % in the sub-lakes zone. Like the high TN concentration at *H*10 in the main lake (i.e., 2.41 mg/L), this sampling point also yielded a high NO_3^--N concentration (1.49 mg/L). However, the changing trend in TP was opposite of that of TN, with significantly lower TP concentrations in the water channel (0.05 ± 0.01 mg/L) compared to corresponding values in the other two zones ($p < 0.05$).

4. Discussion

4.1. Sediment pigment preservation characteristics in a floodplain lake system and their applicability as proxies

Surface sediment pigments derive from primary producers, such as planktonic and benthic phototrophic bacteria, lake algae, and a small amount of plant debris distributed throughout the surrounding catchment (Leavitt and Hodgson 2001; Buchaca et al., 2019). By observing the content and composition of surface sediment pigments, we can indirectly infer the corresponding hydrological conditions of overlying water as well as the nutritional status of a lake system (Mcgowan et al., 2005; Waters et al., 2015). For floodplain lake systems, it has been shown that pigment dynamics in the upper sediment layer are not typically consistent with their dynamic performance in water (Freiberg et al., 2011; Fig. 4), which is consistent with findings from our study.

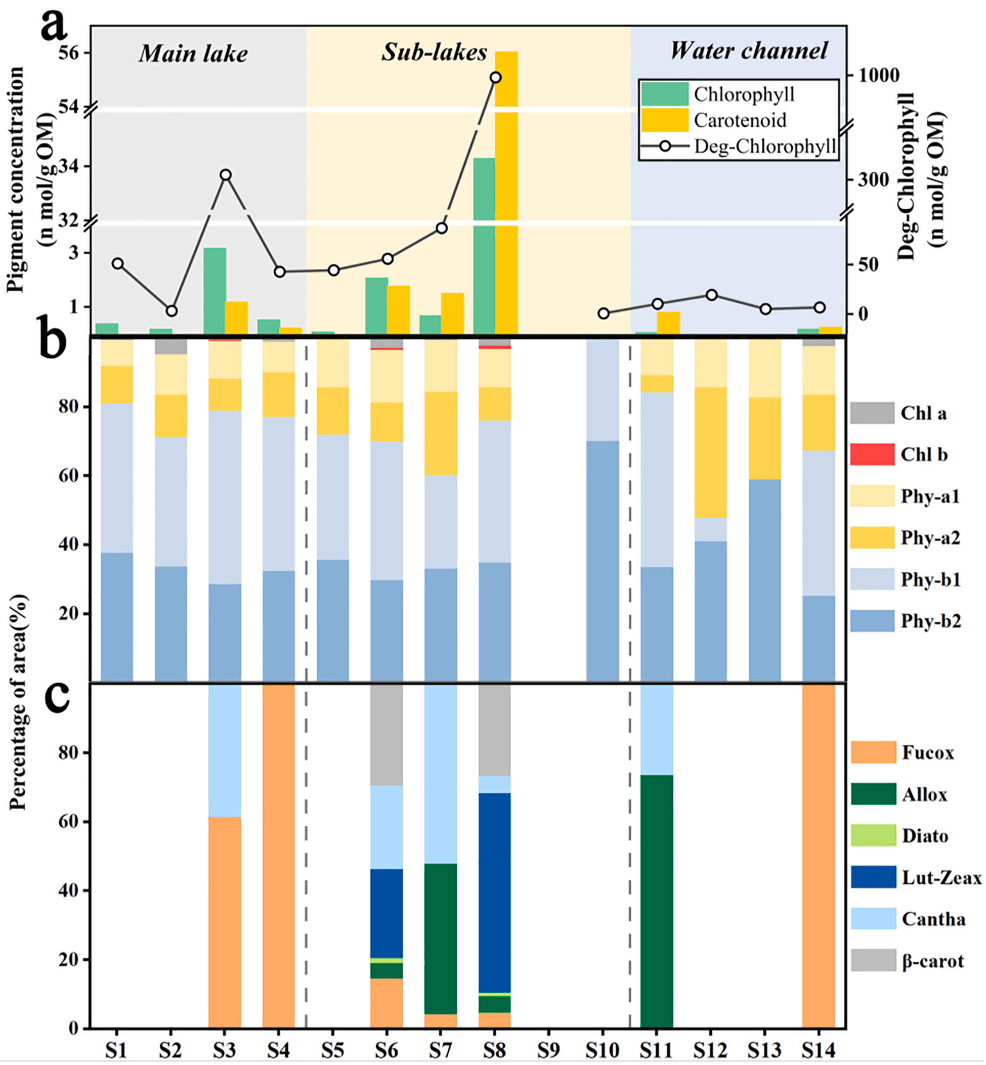

Fig. 3. Sediment pigment characteristics and their composition in the Poyang Lake basin.

Table 1
Physical and chemical characteristics in the different zones of the Poyang Lake basin.

	Main lake			Sub-lakes			Water channel		
	n = 6			n = 8			n = 6		
	Average	SE	(range)	Average	SE	(range)	Average	SE	(range)
Depth (m)	6.2	1.54	(4.20–8.80)	0.35	0.06	(0.25–0.45)	13.10	3.76	(7.00–17.60)
Transparency (m)	0.48	0.12	(0.40–0.70)	0.28	0.14	(0.10–0.50)	0.42	0.09	(0.30–0.50)
Velocity (m/s)*	0.48	0.04	(0.45–0.55)	0.29	0.08	(0.17–0.35)	0.48	0.06	(0.40–0.55)
pH	7.21	0.05	(7.13–7.26)	7.05	0.25	(6.57–7.38)	7.71	0.19	(7.38–7.97)
DO (mg/L)	8.45	0.43	(7.81–9.02)	6.93	1.07	(5.10–8.61)	9.11	0.28	(8.72–9.64)
COND (μs)	134.02	5.91	(126.70–143.40)	103.13	29.96	(70.36–166.00)	423.16	554.90	(141.20–1532.90)
ORP	282	6.48	(271–290)	287.88	14.48	(273–320)	281.00	7.72	(270–293)
TN (mg/L)	2.05	0.21	(1.80–2.41)	1.30	0.23	(1.05–1.78)	1.94	0.05	(1.86–2.03)
TP (mg/L)	0.08	0.02	(0.05–0.10)	0.08	0.02	(0.05–0.13)	0.05	0.01	(0.04–0.06)
NH_4^+-N (mg/L)	0.12	0.02	(0.10–0.16)	0.192	0.06	(0.11–0.31)	0.15	0.04	(0.10–0.19)
NO_3-N (mg/L)	1.28	0.13	(1.09–1.49)	0.32	0.32	(0.05–1.10)	1.24	0.06	(1.13–1.31)
PO_4^{3-}-P (mg/L)	2.11×10^{-3}	4.57×10^{-4}	(1.67×10^{-3}-3×10^{-3})	1.75×10^{-3}	4.33×10^{-4}	(1×10^{-3}-2×10^{-3})	3.45×10^{-3}	1.38×10^{-3}	(1.8×10^{-3}-6.2×10^{-3})

*Poyang lake velocity data was obtained from Wang et al. (2015).

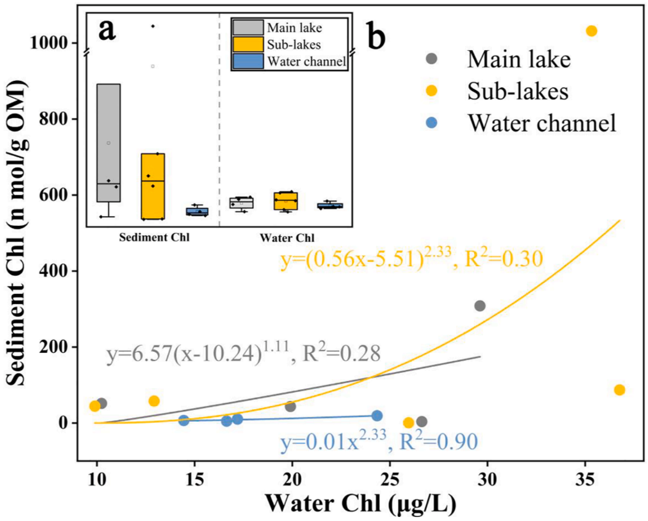

Fig. 4. Fitting characteristics of water-based Chl and sediment-based Chl in the different lake zones.

Moreover, results showed no significant differences in Chl content in water samples in the three Poyang Lake zones, while a difference was found in the Chl content in surface sediment (main lake > sub-lakes > water channel) (Fig. 4a). This suggests that there are no significant differences in the main source of sediment pigment content (i.e., water pigments) in the floodplain lakes. Differences in the distribution of pigments in the sediment are mainly due to degradation during the deposition of pigments into the sediment and by adverse environmental conditions after deposition into the sediment. Sedimentation pigment dynamics were controlled by differences in physical and chemical properties in these three hydrological zones. Moreover, sedimentary pigment that ultimately reached the surface sediment layer did not match that in overlying water (Cahoon and Safi 2002; Song et al., 2019).

Additionally, this study fitted Chl concentrations in water and sediment to explore Chl deposition characteristics (Fig. 4b). It is interesting to note that Chl deposition characteristics in water varied significantly among the different zones, where the sub-lakes yielded the highest deposition ratio followed by the main lake and the water channel with the lowest deposition ratio. For the water channel, surface sediment pigment concentrations were not affected by overlying water pigment concentrations, which were continuously maintained at approximately 10.36 nmol/g OM. Moreover, Chl concentrations in sub-lakes surface sediment were affected by Chl concentrations in overlying water, which rapidly increased with an increase in the Chl concentrations in overlying water, especially when the Chl concentration in water was greater than 25 μg/L. The ratio of Chl to TChl was used to calculate sediment pigment preservation, where the index ranged from 0 (low pigment preservation, indicating that environmental conditions are not conducive to pigment preservation and that pigment degradation is severe) to 1 (high pigment preservation, indicating that environmental conditions are favourable for pigment preservation and that most of the pigments are not degraded) (Buchaca and Catalan 2007; Deshpande et al., 2014; Singh and Krishnan 2019). The sediment pigment preservation index of the Poyang Lake basin was generally low, with an average value of 1.43 %, especially in the water channel, where the preservation index at several sampling points was 0. This means that the degree of Chl degradation in the water channel was high.

Sedimentary pigments are considered important proxies in determining lake productivity, phytoplankton community structure, and aquatic environmental change (Zhen et al., 2016; Chen et al., 2016). Under influencing factors (i.e., sunlight, pH, and hydrological condition), surface sediment pigment diversity in Poyang Lake significantly differed. In particular, surface sediment pigments in the main lake and the water channel lost their significance as water ecology proxies due to their relatively low concentrations and lack of characteristic pigment species. However, surface sediment pigments in the sub-lakes were relatively well preserved, making this the key zone in which to obtain lake proxy indicators.

To further explore the applicability of sub-lakes surface sediment of large floodplain lake systems to serve as proxies from which to determine phytoplankton community structure in lake water, this study classified phytoplankton community structure and corresponding characteristic pigments (Fig. 5). We found that the characteristics of corresponding pigments of the main phytoplankton species (Chlorophyta, Cyanobacteria, Cryptophyta, and Bacillariophyta) in Poyang Lake were well preserved, especially total algae (β-carot and Chl-*a*), Chlorophyta (Chl-*b*, Phy-*b*1, and Phy-*b*2), and the cyano-chloro mixture (Lut-Zeax). It should be noted that since the degradation rate of Chl occurs more rapidly than that of carotenoids (Josefson and Hansen 2003; Mikomagi et al., 2016), especially in shallow lake systems, sunlight can penetrate the overlying water and reach the lakebed. Thus, corresponding degraded pigment should be accounted for when using Chl as an algae reference pigment; otherwise, the status of the actual phytoplankton community may be underestimated.

Dominant surface sediment pigments in Poyang Lake were Chl-*b* (including its associated degradation products) and Lut-Zeax, while their major producers (i.e., Chlorophyta and Cyanobacteria) were also dominant phytoplankton communities in the study area. Generally, adequate sunlight reaches the lakebed of highly transparent lake systems. This forms an autotrophic biofilm on surface sediment which in turn provides new pigments, while Chlorophyta and Cyanobacteria are considered the main producers in this area (Yang et al., 2019; Buchaca and Catalan 2008). This explains why sub-lakes surface sediment pigment is controlled by its characteristic pigment. Previous studies found that pelagic plants were the main sources of Fucox and Diato (Bjørnland et al., 2003; Trice et al., 2004; Alami et al., 2012). Throughout the study area, the proportion of concentrations of these two pigments was<5 %, which was slightly lower than the proportion of Bacillariophyta to total algae (9.62 %). Thus, in Poyang Lake the contribution of pelagic plants to sediment pigments is not significant. Additionally, sediment C/N ratio calculations (with an average of 9.00) further strengthened our conclusion that sediment pigments mainly derived from lake phytoplankton sources (Zhang et al., 2020; Zhao et al., 2020; Li et al., 2021). We found that sub-lakes surface sediment pigments in this floodplain lake system were less affected by exogenous factors while correlating well with its phytoplankton community, which can be used to accurately reflect differences in algal community composition and density.

4.2. *Lake environmental effects on pigments*

Pigment degradation in overlying water is typically rapid and extensive, and the rate of degradation is greatly reduced when pigments reach the sediment layer, especially under anoxic conditions (Villanueva and Hastings 2000). However, pigments are always exposed to overlying water and are affected by chemical oxidation and biological disturbances before being buried deeper in sediment (Buchaca et al., 2019; Gao et al., 2022). Further analysis of the environmental physicochemical parameters that affect pigment preservation revealed differences in the response of different pigments to environmental factors (Fig. 6a). Among pigments, Chl is typically more unstable than carotenoids. However, its degradation products (i.e., pheophorbide) may persistent in sediment records (Rydberg et al., 2020). Moreover, pH affects phytoplankton survival in aquatic environments while also preserving pigments in surface sediment (Li et al., 2021; Chorvatova et al., 2020). Our results emphasize the positive correlation that pH has with aqueous Chl, which is due to the combined effect of carbon dioxide (CO_2) and bicarbonate (HCO_3^-) absorption by phytoplankton in water (Kaijser et al., 2021). As Chl-*a* increases, CO_2 concentrations will decrease and

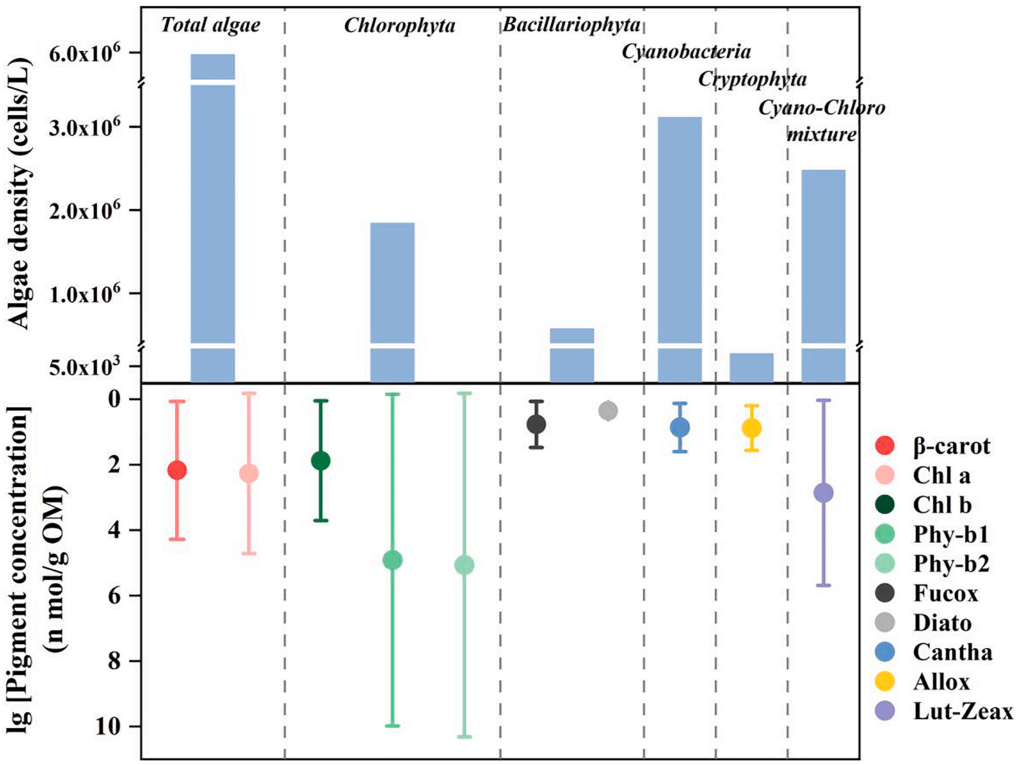

Fig. 5. Algal density and characteristic pigment concentrations in sub-lakes sediment.

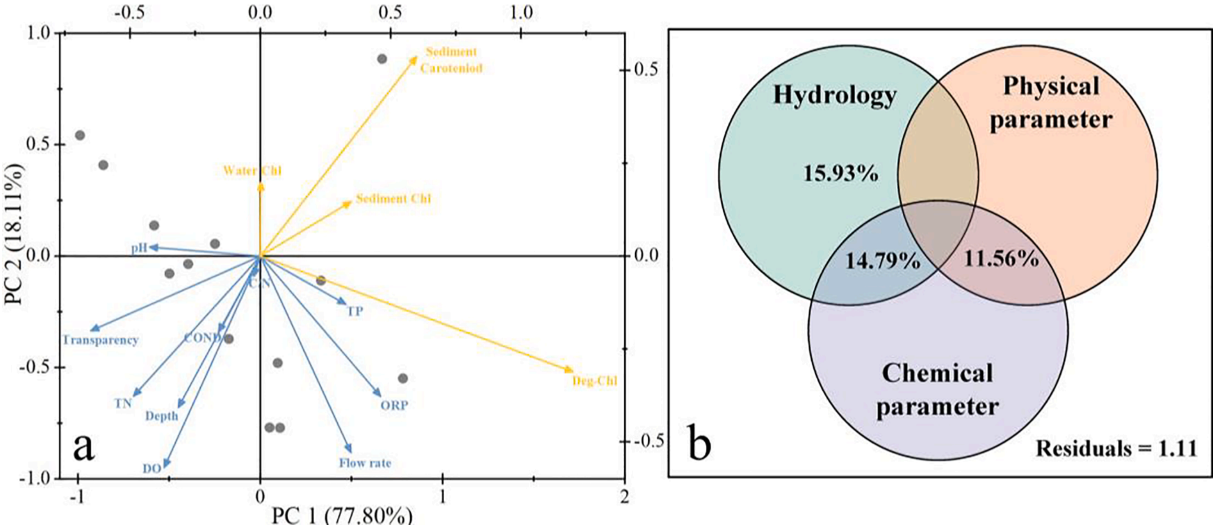

Fig. 6. Redundancy analysis diagram between pigment concentration and environmental variables (a) and Contribution rates of environmental factors to pigment differences in surface sediment analyzed using variance partitioning analysis (VPA) (b). Hydrological parameters (water depth, flow rate), physical parameters (transparency) and chemical parameters (pH, DO, COND, TN, TP, ORP) involved in the statistics have been standardization.

pH will increase, resulting from increased rates of phytoplankton consumption (Balmer and Downing 2011; Crawford et al., 2016). Moreover, given that sediment Chl and deg-Chl lack phytoplankton cell protection mechanisms, they will be directly exposed to a high pH environment, leading to the destruction of their chemical structure, effectuating a negative correlation with pH.

The distribution of pigment of sediment in Poyang Lake was spread well along the axis of PC1, which explained 77.80 % of the variation distribution of pigments, while the distribution of Chl in the water was well distributed along the PC2 axis (18.11 %). DO was the main explanatory variables of PC2, accounting for −0.57, indicating that the oxygen environmental condition of water was the important factor causing the difference of pigment concentration (Fig. 6a). Like other organic matter, pigments will degrade less rapidly under anoxic conditions compared to oxidated conditions (Josefson et al., 2012). Our study found that DO concentrations negatively correlated to pigment concentrations (whether in overlying water or surface sediment), especially carotenoids. Woulds and Cowie (2009) reasoned that anoxic conditions affect pigment abundance by increasing concentrations of refractory pigments that are ultimately buried in sediment. In our study, we found that sediment pigments in Poyang Lake were severely degraded, and most Chl had converted into more stable pheophytin (i.e., deg-Chl).

The sub-lakes, located within the protected area, is largely protected from human activities and nutrient transport, while the main lake and the water channel, in contrast, have increased nutrient input due to human activities such as navigation, sand dredging and domestic sewage. As we investigated, the TN concentration in the sub-lakes was significantly lower than in other areas ($p < 0.05$) (Table 1). Nutrient input has exacerbated lake eutrophication to some extent, as evidenced by the higher algal biomass in the main lake and water channel than in the sub-lakes (Fig. 2b). Algae are a major source of pigment, however the high biomass is not reflected in the sediment pigments. The aquatic conditions (high pH, high DO) in the main lake and water channel resulted in a loss of signal during pigment deposition and after reaching the sediment. This loss is perhaps greater than the pigment recharge from the high algal biomass.

4.3. Hydrological driving mechanisms of pigment migration

Sunlight that reaches the lakebed will decrease as lake depth increases. This lower light intensity reduces photodegradation, thus better preserving lakebed pigments (McGowan 2007). However, this study found that the deposition capacity and the preservation status of sediment pigments at a deep depth (i.e., the water channel) under low sunlight conditions were extremely poor. The water depth and flow velocity, as important hydrological parameters, scored −0.31 and 0.34 on PC1 (sediment pigment) and −0.41 and −0.53 on PC2 (water pigment), respectively (Fig. 6a). Therefore, the strong hydrodynamic condition in this area is the key to this phenomenon. Potential reasons for this are as follows: First, high flow velocities will disturb pigment transportation dynamics in water bodies as they move into adjacent drainage basins, thus reducing the deposition ratio into sediment; second, secondary suspension caused by high flow velocities will enable surface sediment pigments to once again resuspend into the overlying water, which will enhance the degree of secondary degradation (Reuss et al., 2005; Florian et al., 2015). In contrast, sub-lakes water depth was relatively shallow and its flow rate was slow. Although sunlight is strong in overlying water, the extremely short distance before pigments settle ensures their stability. The expediency of pigments in aqueous environments that reach the sediment surface is therefore maximized. Thus, pigment deposition rates in such environments are high. Additionally, low flow rates and low transparency also had a positive effect on sediment pigment preservation (yielding a 1.56 % average preservation index value). To further clarify the controlling factors that cause spatial differences in surface sediment pigments in floodplain lake systems, this study also determined the degree of interpretation of environmental factors (i.e., the hydrological conditions and physical and chemical parameters of sediments) on spatial variation using variance partitioning analysis (VPA) (Fig. 6b). Results showed that the strong hydrological condition of this floodplain lake system accounted for 15.93 % of spatial variability and was considered a key controlling factor of Chl deposition. Previous studies on sediment pigment preservation and distribution have focused on traditional aquatic conditions, with insufficient attention paid to lake dynamics processes (Kuefner et al., 2021; Schüller et al., 2015). This study emphasizes that the effect of intense hydrological conditions on pigment preservation may be underestimations in floodplain lake systems compared to corresponding temperate and high-altitude lake systems.

Fucox is extremely unstable, and its degradation rate is even higher than that of Chl-*a*. Thus, the Fucox signal can easily be lost (Aneeshkumar and Sujatha 2012; Mathew et al., 2021). However, sub-lakes sediment in this study still retained a clear Fucox signal (with an average concentration of 1.15n mol/g OM), indicating that pigment degraded more slowly than expected under the influence of sunlight, oxygen, and other related factors during its descent. Compared to water channel sedimentation characteristics, the hydrodynamic condition of the floodplain lake system was the controlling factor that affected water pigment sedimentation and its preservation rather than other chemical parameters in water. This finding was also confirmed through VPA analysis (Fig. 6b). Moreover, this can also guide the assessment of limnetic paleoenvironmental issues. For floodplain lake systems with strong hydrodynamic conditions, relatively stable sub-lakes zones are best for obtaining historical limnetic information.

The interconnection associated with lake water pigment migration dynamics are as follows: 1) Pigments first settle smoothly onto lakebed sediment; 2) pigments then degrade under the physical and chemical environment of overlying water; 3) pigments are eventually transported to the lower reaches of a watershed as per the specific hydrodynamic condition of the lake (Fig. 7). Understanding proportional differences among these three processes are key to accurately obtaining the paleolimnological information contained in lake sediment. The effect of the factors that promote the degradation of pigments on the components of deposited pigments largely depends on the time it takes for pigments to reach the lakebed, which is directly related to the distance between the pigment source and the sediment (Cuddington and Leavitt 1999; Buchaca and Catalan 2008). This study determined that the degree of sediment pigment preservation information per zone was as follows: water channel < main lake < sub-lakes, which was largely due to differences in water depth.

Although an increase in water depth will reduce sunlight from reaching the lakebed, an increase in settling time will also make pigments degrade more severely in overlying water (e.g., through means of more intensive grazing processes) (Buchaca and Catalan 2007). Additionally, effects of hydrodynamic conditions on pigment deposition have largely been underestimated. This is because flow rates in the main lake and the water channel of Poyang Lake are much higher compared to conventional lake systems due to regional specificity (Li et al., 2014; Qi et al., 2019). Currents drive water pigments, which greatly impact the difficultly in their settling onto lakebed sediment. Moreover, a portion of this pigment will be transported to the downstream basin area, while that in the main lake will be transported to the water channel and that in the water channel will be eventually transported to the Yangtze River. It has been reported that the strong interaction between hydro-geomorphological and sedimentary processes in the Poyang Lake water channel has affected local lakebed morphology (Yuan et al., 2021), while the strong secondary suspension caused by hydraulic scouring has become an important factor affecting sediment pigments. Secondary suspension forces pigments that have already settled onto the lakebed to resuspend and mix with overlying water, thus having to go through the settling process again (Gao et al., 2021; 2022). This means that few pigments ultimately get buried in sediment. Thus, the accuracy of pigment limnological information in the main lake and water channel is lost.

5. Conclusions

This study showed that sediment pigments in the main lake and the water channel of Poyang Lake were severely degraded and thus lost their significance as lake proxy indicators. Combined with phytoplankton community structure in overlying water and the physical and chemical parameters of lake water, we found that phytoplankton growth increased the water column pigment levels, while leading to CO_2 depletion and increased pH. However, high pH suppresses pigments in sediments that have lost their cytoprotective mechanisms. Additionally, hypoxic conditions were conducive to sediment pigment preservation. Although carotenoids were particularly sensitive to oxygen, pheophytin were not and were thus well preserved. Results from this study indicated that secondary suspension and hydrological transport caused by strong hydrodynamic conditions have a higher limiting effect on pigment preservation compared to other parameters and are therefore the main influencing factors prior to the stable burial of pigments in floodplain lakebed sediment. Because the sub-lakes environment is relatively stable, surface sediment pigments can still be used as biomarkers to accurately reflect phytoplankton community structure in overlying water.

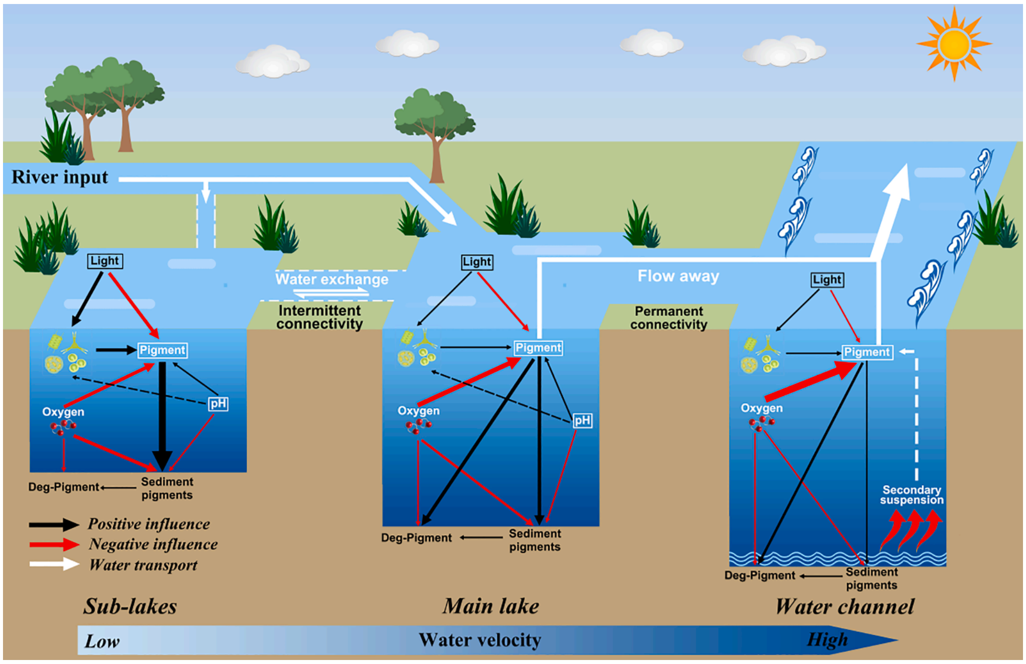

Fig. 7. Schematic diagram of the pigment migration process in a floodplain lake, where nearshore shallow lake systems under weak hydrodynamic conditions (i.e., the sub-lakes), strong hydrodynamic shallow lake systems (i.e., the main lake), and strong hydrodynamic deep lake systems connected to downstream areas (i.e., the water channel) are respectively represented from left to right. Arrow thickness indicates influence strength.

This study was designed to provide additional information to explore material migration characteristics driven by floodplain hydrology and paleoenvironmental assessment accuracy.

CRediT authorship contribution statement

Zhaoxi Li: Writing – original draft, Writing – review & editing. **Yang Gao:** Conceptualization, Writing – review & editing. **Shuoyue Wang:** Writing – original draft, Writing – review & editing. **Ke Zhang:** Data curation. **Qi Lin:** Data curation. **Junjie Jia:** Data curation. **Yao Lu:** Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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