Optical characteristics and factors that influence representative Lakes in the Taihu Lake basin, China

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\textbf{ABSTRACT}

From 2018 to 2019, a survey of a typical lakes system in the Taihu Lake basin, China, was carried out. To provide reference values for the restoration and management of submerged vegetation in the lakes, the optical attenuation coefficient ($K_d$) and euphotic depth ($Z_{eu}$) of the water body were calculated, and the distribution characteristics and factors that influenced the underwater optical field lands with different nutrition levels in the basin were analyzed. The main factor affecting the distribution of photosynthetically active radiation (PAR) in lakes in the Taihu Lake basin is suspended solids (SS), dominated by inorganic suspended matter (ISS). Chlorophyll a (Chl-a), dissolved organic carbon (DOC), and chromophoric dissolved organic matter (CDOM) all affect, although weakly, the optical characteristics of lake wetlands. In CDOM, humic-like components have a more significant impact on $K_d$. The $K_d$ of lakes in the Taihu Lake basin is closely related to permanganate index ($COD_{Mn}$) and especially total phosphorus (TP); The growth of aquatic vegetation is increased in Shanghu, Dianshan-Yuandang, Yangcheng, and Wuli Lakes that have higher $Z_{eu}$ and $Z_{eu}/$Depth values.

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\section{1. Introduction}

Underwater photosynthetically active radiation (PAR) is an important indicator of the turbidity of water bodies and ecological conditions and is also an important factor affecting the photosynthesis and growth of aquatic plants (Karlsson et al. 2009; Brandão et al. 2016; Wang et al. 2020). PAR intuitively reflects the distribution characteristics of the underwater optical field. However, after the light enters the water, it is often affected by various factors such as suspended particulate matter, dissolved organic matter, and planktonic microorganisms, resulting in scattering, absorption, and gradual attenuation. When the underwater PAR attenuation reaches a level at which it cannot satisfy the normal requirements of aquatic plants, it causes the submerged vegetation to retreat and can induce phytoplankton...
outbreaks, often related to negative anthropogenic impacts on the wetland environment (Reinart and Pedusaar 2008; Kuwahara et al. 2015; Bai et al. 2016). At present, the optical attenuation coefficient \( (K_d) \) is commonly used to measure the attenuation characteristics of underwater PAR, and the euphotic depth \( (Z_{eu}) \) is used to represent the depth limit at which aquatic submerged plants can grow. As a metric, \( Z_{eu} \) is a better indicator of the light penetration ability of water bodies more than Secchi depth (SD), and indicates the depth beyond which submerged plants cannot grow normally (Zhou et al. 2018; Li et al. 2019).

The quantitative indicators that affect the attenuation and distribution of underwater PAR include suspended solids (SS), turbidity (Turb), chlorophyll a (Chl-a), dissolved organic carbon (DOC), and chromophoric dissolved organic matter (CDOM). Different factors influence PAR in water bodies in different environments (Zhou et al. 2016; Yu et al. 2020; Zhang et al. 2020). For example, a study on the Chesapeake Bay area in the United States from Testa et al. (2019) found that SS and water salinity could significantly affect the distribution of the underwater light field. Bai et al. (2016) showed that the main factor affecting the distribution of the light field under Erhai Lake was turbidity. The research of Zhang et al. (2020) found that SS and CDOM were the main factors affecting the optical attenuation in Qiandao Lake, and that they variably affected the spectra of different bands. Through investigations of Fuxian Lake, Zhou et al. (2018) found that CDOM had a particularly important impact on lake optical characteristics during the rainy season, followed by SS. In this case, the land input processes directly restricted the distribution of the underwater light field. Walsby’s research in the Baltic Sea (Walsby 1997) and Li’s research in Chenghai Lake (Li et al. 2019) both found that planktonic biomass is an essential factor affecting the optical characteristics of water bodies. The review of the available literature shows that a better understanding of the distribution characteristics and the factors that influence the underwater light field in a specific area will play an important role in the local management and restoration of aquatic vegetation. An untargeted restoration process done without understanding the lake’s optical environment could easily lead to failure and waste (He et al. 2014; Roddewig et al. 2020; Strom et al. 2020).

The Taihu Lake basin is located in a dense network of waterways in the core area of the Changjiang (Yangtze) River Delta in China. This area is also a highly economically developed area in China. The environment of the region has been impacted greatly by human activities. The discharge of production and domestic wastewater has caused serious eutrophication in the water bodies. Studies have shown that in recent decades, the coverage of aquatic vegetation in most lakes in the Taihu Lake basin (including Taihu Lake) has decreased significantly, and the aquatic ecosystem has gradually deteriorated (Liu et al. 2020). Therefore, targeted ecological restoration in the Taihu Lake basin could play an important role in improving people’s quality of life and maintaining sustainable economic development. This research aims to: (1) understand the optical characteristics of water bodies of typical lake wetlands in the Taihu Lake basin; (2) explore the distribution of the underwater light field and factors that influence it; (3) quantify the relationship between optical attenuation characteristics and nutrients; and, (4) determine how improving the light received affects aquatic vegetation coverage in order to provide reference metrics for the restoration and management of submerged plants of the lakes in the basin.

2. Methods

2.1. Overview of the study area

In this study, Changdang, Gehu, Wuli, Shanghu, Yangcheng, Chenghu, Dianshan, and Yuandang Lakes were selected as the research objects (Figure 1). Gehu Lake covers an area
of 164.6 km² with an average depth of 1.2 m, making it the second largest lake in the Taihu Lake basin. Chenghu Lake is located in the lower reaches of Taihu Lake, with a water area of 45.5 km² and an average depth of 1.8 m. Shanghu Lake has an area of 8.2 km² and an average depth of 2.8 m. Wuli Lake is a small lake located deep inland in Meiliang Bay off of Taihu Lake, with an area of only 8.6 km² and an average depth of 2.4 m. Changdang and Yangcheng Lakes have areas of 89.4 km² and 119.8 km², respectively, with an average depth of 1.1 m and 1.8 m, respectively. Aquaculture activities are being carried out in both lakes. Dianshan and Yuandang Lakes are located at the junction of Suzhou and Shanghai. As the two lakes are closely connected, they were analyzed as a whole in this study as "Dianshan-Yuandang Lake". The overall water area is about 72.7 km² and the average depth is 2.1 m.

2.2. Layout of sampling points and sample collection

Samples were collected from the Taihu Lake basin wetland system in April (spring), July (summer), and November (autumn) of 2018, and January of 2019 (winter). The sampling locations are shown in Figure 1. Mixed water samples were collected 50 cm below the surface of the water, stored in a polyethylene bottle and protected from light, then quickly returned to the laboratory for analysis.

2.3. Sample measurement methods

Water depth (Depth), SD, and PAR were measured in situ during sampling. Among them, Depth was measured using a portable depth sounder (SM-5A, Speedtech, USA), and SD
was measured using a 30 cm black and white Secchi disk. PAR was measured using the XR-620CTD digital luxmeter (RBR Ltd., Canada). When measuring, the PAR intensity at the surface was measured first, followed by each deeper layer at a gradient of 0.1 m. Three data points were recorded for each layer, and the average value was used to represent that layer.

Other indicators were analyzed and measured in the laboratory. Total nitrogen (TN), total phosphorus (TP), permanganate index (COD$_{Mn}$), ammonia nitrogen (NH$_3$-N), and Chl-a were determined using the potassium persulfate digestion method, molybdenum antimony spectrophotometric method, acid method, Nessler’s reagent- Spectrophotometric method, and 90% acetone method, respectively. SS was determined using the filtration drying method. Organic suspended solids (OSS) and inorganic suspended solids (ISS) were determined using the loss on ignition method. The measurement methods were all referenced to values found in the literature (Editorial Board of Water and Wastewater Monitoring and Analysis Methods, and State Environmental Protection Administration of China 2002; Chen et al. 2014). The UV2700 spectrophotometer (Shimadzu, Kyoto, Japan) was used for absorbance measurement.

Part of the water sample was first passed through a 0.45 pore size cellulose acetate membrane to determine DOC, and then passed through a 0.22 μm pore size GF/C filter to determine CDOM. The first 20 mL of the filtrate after two filtrations was discarded in case the residual carbon on the filter membrane interfered with the measurement. The filtrate was stored in a polyethylene bottle that was washed using acid, and the sample was measured on the same day. DOC was measured using a total organic carbon analyzer (TOC-V CPN, Shimadzu). The spectrophotometer (UV2700, Shimadzu) was used to scan the absorbance of the filtrate between 200–800 nm at an interval of 1 nm for the CDOM absorption spectrum, and the absorption coefficient of CDOM was calculated on this basis, using methods found in the literature (Wang et al. 2019). The CDOM content was approximately represented by the absorption coefficient at 350 nm ($a(350)$) (Cárdenas et al. 2017). In addition, due to the complex composition and structure of CDOM, this study used the popular parallel factor analysis method to conduct the fluorophore component interpretation for CDOM, using model construction methods as defined in the literature (Chen et al. 2018) in which the separated components represented different CDOM components with different characteristics.

### 2.4. Calculation of optical attenuation coefficient and euphotic depth

Underwater PAR attenuation satisfies (Zhang et al. 2020):

$$K_d = -1/Z \cdot \ln[E(Z)/E(0)]$$

where, $K_d$ denotes the optical attenuation coefficient, $z$ denotes the depth from the water surface to the measurement position, and $E(z)$ and $E(0)$ denote the PAR values at $z$ m and 0 m depth, respectively. A set of no less than three data points at each sample were nonlinearly fitted with an exponential model to obtain the $K_d$ value, and was considered significant when the $R^2 \geq 0.95$.

$Z_{eu}$ was calculated using the following equation (Kirk 2011):

$$Z_{eu} = \ln100/K_d = 4.605/K_d$$

### 2.5. Data processing and analysis

ArcGIS 10.2 (ESRI Inc., Redlands, CA, USA) was used to plot the layout of sampling points. Excel 2016, SPSS 21.0 (IBM Corp., Armonk, NY, USA), and Origin 2019b
(OriginLab Corp., Northampton, MA, USA) were used to calculate the mean and standard deviation, $K_d$ value fitting, ANOVA significance analysis, correlation analysis, and linear regression analysis. In the significance report, $p < 0.01$, $p < 0.05$, and $p > 0.05$ were considered to be extremely significant, significant, and insignificant, respectively.

3. Results

3.1. Nutrient characteristics of typical Lakes in the Taihu lake basin

Table 1 shows the mean value and standard deviation of COD$_{Mn}$, TN, TP, NH$_3$-N, and Chl-a in different seasons in the representative lakes of the Taihu Lake basin. The trophic level index (TLI) can integrate multiple indicators to comprehensively measure the nutritional status of water bodies. This method has been applied with mature classification standards. This study also uses TLI to preliminarily understand the nutritional characteristics of typical lakes in Taihu Lake basin. The calculation of TLI was based on the research of Wang et al. (2019). According to calculations, the TLI of Changdang and Gehu Lakes exceeded 60, indicating that they were moderately eutrophic. Chenghu Lake had a TLI between 55 and 60 on average. The TLIs of Wuli, Yangcheng, and Dianshan-Yuandang Lakes were relatively lower, around 50–55, but were still classified as slightly eutrophic. The TLI of Shanghu Lake was lower than 50, which indicated a mesotrophic lake.

3.2. Optical characteristics of typical Lakes in the Taihu lake basin

The optical characteristics of typical lakes in Taihu Lake basin in each season were shown in Table 2.

The $K_d$ level was the highest in Changdang Lake, with an average of 5.22 ± 0.43 m$^{-1}$ and a range of 3.21–8.71 m$^{-1}$, followed by Gehu Lake and Chenghu Lake, which could reach 6.28 ± 1.51 m$^{-1}$ and 5.97 ± 1.43 m$^{-1}$, respectively, in summer. Wuli Lake, Yangcheng Lake, Dianshan-Yuandang Lake and Shanghu Lake had comparable $K_d$ value levels, with Yangcheng Lake having a slightly higher average of 4.99 ± 1.20 m$^{-1}$ in summer. And were the lowest in Dianshan-Yuandang Lake, with an average of 2.33 ± 0.39 m$^{-1}$ and a range of 0.88–5.23 m$^{-1}$. Seasonally, the $K_d$ value was lowest in the spring, then increased in autumn and winter and was the highest in the summer, with a maximum average of 7.91 ± 0.76 m$^{-1}$, which appeared in the summer at Changdang Lake. The $K_d$ of each lake in winter was relatively lower, with only Gehu Lake having a value higher than that in other lakes ($p < 0.01$). The lowest value occurred in the winter at Dianshan-Yuandang Lake, with a minimum of 1.21 ± 0.31 m$^{-1}$.

Overall, the SD of Yangcheng Lake was significantly higher than that of the other lakes ($p < 0.01$), with an average of 70.33 ± 2.64 cm and the maximum of 127 cm, followed by

| Lake                  | COD$_{Mn}$ (mg/L) | TN (mg/L) | TP (mg/L) | NH$_3$-N (mg/L) | Chl-a (µg/L) |
|-----------------------|-------------------|-----------|-----------|-----------------|--------------|
| Changdang Lake        | 6.43 ± 0.72       | 2.68 ± 1.33 | 0.146 ± 0.047 | 0.26 ± 0.19 | 94.53 ± 49.28 |
| Gehu Lake             | 5.67 ± 1.31       | 3.10 ± 0.70 | 0.172 ± 0.052 | 0.39 ± 0.29 | 70.99 ± 55.41 |
| Chenghu Lake          | 4.48 ± 0.81       | 3.07 ± 0.64 | 0.134 ± 0.054 | 0.34 ± 0.12 | 25.41 ± 26.48 |
| Wuli Lake             | 4.58 ± 0.78       | 1.23 ± 0.51 | 0.066 ± 0.034 | 0.15 ± 0.07 | 41.14 ± 36.06 |
| Yangcheng Lake       | 4.54 ± 1.06       | 1.91 ± 0.60 | 0.083 ± 0.035 | 0.17 ± 0.09 | 37.09 ± 25.06 |
| Dianshan-Yuandang Lake| 4.71 ± 1.20       | 2.57 ± 0.65 | 0.106 ± 0.071 | 0.28 ± 0.19 | 25.29 ± 30.51 |
| Shanghu Lake          | 3.39 ± 0.37       | 0.73 ± 0.19 | 0.031 ± 0.013 | 0.07 ± 0.02 | 23.70 ± 11.84 |

Data are expressed as the mean ± standard deviation of water quality indicators.
Dianshan-Yuandang Lake with the mean of 62.58 ± 5.84 cm. The SD of Wuli Lake and Shanghu Lake were at the same level, they remained at 65.05 ± 5.61 cm and 64.00 ± 5.52 cm respectively during the winter months when the SD was higher. The overall SD of Changdang Lake was the lowest, at 25.97 ± 1.52 cm, with a minimum of only 14 cm. Temporally, SD showed a pattern of highest to lowest values in summer < autumn < spring < winter in most lakes. The winter average of Dianshan-Yuandang Lake was the highest, at 93.86 ± 12.02 cm, and the summer average of Changdang Lake was the lowest, at 16.75 ± 2.05 cm.

### 3.3. SS characteristics of typical Lakes in the Taihu Lake basin

The concentration levels of SS, OSS and ISS in each season of each lake are shown in Table 2.

![Table 2. Optical characteristics and suspended solids characteristics of typical lakes in Taihu Lake basin in each season.](image)

In general, the SS concentration in Changdang and Gehu Lakes was relatively higher in all seasons. In winter and spring, it was significantly higher than that of the other lakes (p < 0.01). The SS level of them in spring and autumn was similar. In summer, the average SS of Changdang Lake was the highest, at 68.77 ± 14.17 mg/L. The SS concentration in Chenghu Lake was similar to that in Gehu Lake and Changdang Lake in summer, but much lower in winter and spring compared with them, and only 14.26 ± 2.62 mg/L in spring. The average SS concentration of Yangcheng Lake in spring was the lowest, with 8.86 ± 6.33 mg/L and a range of 4.25–22.28 mg/L. Wuli Lake, Dianshan-Yuandang Lake and Shanghu Lake all showed values from the greatest to the least in summer > autumn > spring and winter.

The OSS concentration of each lake did not fluctuate greatly either in time or space. On average, that of Changdang Lake in summer was the highest, at 15.51 ± 1.69 mg/L with a range of 13.30–18.10 mg/L. The OSS level of Gehu Lake was slightly lower than that of Changdang Lake, and could reach 14.51 ± 2.63 mg/L in summer. The OSS levels of
Wuli Lake, Yangcheng Lake, Dianshan-Yuandang Lake and Shanghu Lake were similar to each other, and the OSS concentration of Shanghu Lake was the lowest on average in winter at 2.87 ± 0.45 mg/L, with a range of 2.35–3.50 mg/L. The OSS concentration of Chenghu Lake was between the above two categories, with an average of 9.38 ± 2.51 mg/L in summer. In contrast, the ISS concentration fluctuated sharply, with the highest average being 54.86 ± 23.75 mg/L in Chenghu Lake in summer. The ISS concentration of Changdang Lake was lower than Chenghu Lake, with an average of 53.27 ± 12.48 mg/L in summer. Although the average value of Gehu Lake in summer was lower than that of Changdang Lake and Chenghu lake (50.12 ± 16.73 mg/L), the average level of ISS in the whole year was significantly higher than that of other lakes (p < 0.01). Wuli Lake in spring had the lowest average value of 4.74 ± 0.99 mg/L, ranging from 3.38–6.15 mg/L.

Seasonally, with the exception of Yangcheng Lake, the ISS concentration in summer was significantly higher than that of the other seasons (p < 0.01).

3.4. Organic matter characteristics of typical Lakes in the Taihu Lake basin

The DOC of typical lakes in the Taihu Lake basin was stable, and seasonal fluctuations were not obvious (Figure 2a). The range of fluctuation was between 1.67 ± 0.04 – 4.49 ± 0.25 mg/L on average. The two endpoints appeared in Shanghu Lake in spring and Changdang Lake in winter, respectively. The highest DOC was only 5.60 mg/L, which appeared in Gehu Lake in spring. Seasonally, there is great independence in the variation law of DOC in different lake water bodies without a uniform law. In contrast, the absorption coefficient a(350) had obvious seasonal characteristics (Figure 2b). The value of a(350) of each lake in summer was significantly higher than that in other seasons (p < 0.01), with the average value of Dianshan-Yuandang Lake the highest (7.68 ± 0.32 m⁻¹). The lowest value occurred in Shanghu Lake in spring (1.22 m⁻¹).

Through parallel factor analysis, the CDOM of each lakes was separated into three components, C1, C2, and C3. The C1 component represents a terrestrial humic-like component. The C2 component is close to the M peak in the traditional peak group, which is a type of humic-like component with a closer relationship to recent biological activities. The C3 component represents a type of autogenic protein-like component with high
biological sensitivity (Coble 1996; Liu et al. 2019). The distribution of their corresponding fluorescence peaks, $F_1$, $F_2$, and $F_3$, in each season of each lake is shown in Figure 3. The average $F_1$ value of Changdang Lake in summer was the highest, at $0.194 \pm 0.026$ RU. Except for autumn, the $F_1$ values of Changdang and Gehu Lakes in other seasons were significantly higher than those of Wuli, Yangcheng, Chenghu, and Shanghu Lakes ($p < 0.05$). The average $F_2$ of Dianshan-Yuandang Lake in summer was the highest, at $0.23 \pm 0.013$ RU, and that of Shanghu Lake in spring was the lowest, at $0.048 \pm 0.003$ RU. There was not much difference between $F_1$ and $F_2$ in terms of quantity, but the spatial distribution of $F_2$ values were more chaotic and the law was less obvious. The $F_3$ of Yangcheng, Chenghu, Shanghu, and Dianshan-Yuandang Lakes in all seasons were significantly higher than that of other lakes ($p < 0.01$). The highest value was in Yangcheng Lake, which could reach $1.397 \pm 0.168$ RU in summer on average. Seasonally across the whole basin, $F_1$ and $F_2$ both showed the decreasing pattern of summer > autumn > winter > spring. The two components of the whole basin could reach $0.173 \pm 0.030$ RU and $0.196 \pm 0.035$ RU in summer on average. The fluctuation of $F_3$ among different seasons was not obvious, with only $F_3$ in winter insignificantly lower than that in other seasons ($p > 0.05$).

4. Discussion

4.1. Factors influencing the optical characteristics of typical Lakes in the Taihu Lake basin

A large number of studies have shown a significant negative correlation between $K_d$ and SD (Pierson et al. 2008; Kirk 2011; Zhang et al. 2012; Ma et al. 2016; Yu et al. 2019). This conclusion has also been verified in lakes of the Taihu Lake basin, except for the significant weaker correlation between the two parameters of Yangcheng Lake ($r = -0.349$, $p < 0.05$), other lakes all showed an extremely high significant negative correlation ($p < 0.01$).
On the whole, SS was undoubtedly the main factor influencing the optical attenuation characteristics of lakes in the Taihu Lake basin during all seasons (Table 3). Except for Yangcheng Lake, all lakes showed that the effect of ISS was higher than that of OSS. Previous studies have demonstrated that resuspension of lake sediments and rising lake water temperatures are the main causes of elevated ISS levels in lakes, while this process also reduces phytoplankton and benthic biomass (Jin et al. 2022). For some shallow lakes in the Taihu Lake basin, the resuspension of sediments caused by wind and wave disturbance is the main source of SS in the water, especially ISS (Reinart and Pedusaar 2008; Qu et al. 2014). Especially in autumn and winter, when most submerged plants die, the resuspension of sediments becomes easier, and the influence on optical attenuation characteristics is also greater (He et al. 2014). Compared to the surrounding lakes, Taihu Lake in the centre of the basin has a more open water area, where the resuspension of sediment and the deterioration of the water column’s light environment due to wind speed are more pronounced, and there is a close relationship between the release of nutrients from the lake and the resuspension of sediment (Tang et al. 2020).

Compared with SS, the impact of Chl-a on \( K_d \) of all lakes was not notable, only having significant impacts in Shanghu \( (r = 0.928, p < 0.01) \) and Wuli Lakes \( (r = 0.768, p < 0.01) \). However, when analyzed during a single season, the optical attenuation characteristics of some lakes can still be significantly affected by Chl-a in autumn, such as Gehu \( (r = 0.584, p < 0.01) \), Chenghu \( (r = 0.982, p < 0.05) \), and Yangcheng Lakes \( (r = 0.667, p < 0.01) \). This shows that the impact of Chl-a on the lake light field is greatly affected by objective conditions such as season and air temperature (Lv et al. 2012). Similar to the surrounding lakes in the basin, the relationship between the whole Taihu Lake and Chl-a was less pronounced than in SS, with waters more affected by Chl-a tending to have frequent cyanobacterial blooming (Zhang and Chen 2006).

The organic components DOC and CDOM in the lake also impacted the optical attenuation characteristics of the lakes, and the effect of CDOM was stronger than that of DOC. However, due to different lake conditions, the effects were also different. Among them, Shanghu \( (a(350): r = 0.903, p < 0.01) \), Wuli \( (a(350): r = 0.813, p < 0.01) \), Yangcheng \( (a(350): r = 0.865, p < 0.01) \), and Dianshan-Yuandang Lakes \( (a(350): r = 0.767, p < 0.01) \) were affected significantly. At the same time, lakes strongly affected by CDOM had a close positive correlation with fluorescence peaks \( F_1 \) and \( F_2 \) (Table 4). The source and composition characteristics of these components could be obtained by comparison with previous studies. The C1 component is a type of terrestrial humic-like substance, and its fluorophore has a relatively higher degree of substitution and polycondensation. Compared with other components, this component may come from an older stratum (Yamashita et al. 2011). The C2 component is also a type of humic-like compound, which is closely related to recent activities of organisms, including moderate-intensity anthropogenic pollution (Yamashita et al. 2010; Liu et al. 2019). The C3 component is a type of
protein-like substance with a higher degree of degradation. It is usually produced by biological activities and therefore has a higher biological sensitivity. However, it can also be transformed from some non-protein-like substances such as lignin phenols. This component is often related to higher intensities of imported pollutants (Li et al. 2015; Xiao et al. 2018). These results show that the main contribution to the optical attenuation characteristics of these lakes is some imported exogenous humic-like substance, including anthropogenic pollutants. Unlike these typical surrounding lakes in the basin, the CDOM fluorescence fraction of Taihu Lake is dominated by protein-like component, demonstrating that the authigenic sources within the lake are the main source of CDOM in Taihu Lake, and that the main reason for this is the frequent cyanobacterial blooming. Also, due to the longer lake renewal time, the rate of CDOM depletion in Taihu Lake is higher than that of the surrounding lakes (Chen et al. 2018).

In addition, there is a significant positive correlation between the $K_d$ values of Shanghu and Yangcheng Lakes and $F_3$ ($p < 0.05$), which could be related to their aquaculture and algae growth. The artificial salvage and self-decay of a large number of *Vallisneria natans* (Lour.) Hara growing in Shanghu Lake as well as *Elodea canadensis* Michx, *Ceratophyllum demersum* L., and other aquatic plants growing in Yangcheng Lake promote the release of protein-like components, thereby enhancing the contribution of $F_3$ to $K_d$. At the same time, as mentioned above, OSS was strong than ISS in the contribution of SS to $K_d$ in Yangcheng Lake, which could also be related to the metabolic activities of aquatic plants and animals such as crabs.

### 4.2. The relationship between the optical characteristics and the eutrophication level of water bodies of typical Lakes in the Taihu Lake basin

Studies have shown that since the new century, the TN and TP concentrations of Taihu Lake and lakes in this basin have gradually increased. The original large volumes of submerged vegetation in the lake have gradually disappeared, and the existing vegetation is dominated by emergent plants and floating-leaved plants with higher pollution and nutrient tolerance (Li et al. 2008; Penning et al. 2008; Bickel and Schooller 2015). The increase of nutrient levels and the demise of submerged vegetation bred large numbers of phytoplankton, which directly limited the distribution of the underwater light field (Pogozhev and Gerasimova 2011). Therefore, there is an inseparable relationship between the nutrient level of the lake and the optical attenuation. In this study, the $K_d$ values of the lakes in the Taihu Lake basin have a significant linear relationship with TN, TP, and COD$_{Mn}$, and this relationship is more prominent in winter (Figure 4). This and a large number of previous studies have shown that Chl-a, CDOM, and particulate matters produced by phytoplankton themselves and their metabolism will directly affect the optical attenuation characteristics of water bodies (He et al. 2014; Bai et al. 2016). In winter, these components will be minimized in both quantity and influence, and the relationship between

| Lake                  | $F_1$    | $F_2$    | $F_3$    |
|-----------------------|----------|----------|----------|
| Chenghu Lake          | 0.729**  | 0.778**  | 0.012    |
| Wu Li Lake            | 0.862**  | 0.869**  | 0.319    |
| Yangcheng Lake       | 0.810**  | 0.708**  | 0.486*   |
| Dianshan-Yuandang Lake| 0.791**  | 0.737**  | 0.312    |
| Shanghu Lake          | 0.746**  | 0.678**  | 0.562*   |

*Correlation is significant at the 0.05 level (two-tailed).
**Correlation is significant at the 0.01 level (two-tailed).
some elements such as nitrogen and phosphorus and $K_d$ are more easily discovered. In addition, among several indicators, the relationship between TP and $K_d$ was the closest. This conclusion has also been confirmed in previous studies of Taihu Lake, where phosphorus in the lake body is more likely to limit the distribution of the light environment in Taihu Lake compared to other nutrients (Zou et al. 2020). In addition to the $K_d$ value, studies have also shown that there is a close relationship between the transfer and transformation of phosphorous elements and the CDOM in the Taihu Lake basin (Wang et al. 2018; Zhang et al. 2018). This indicates that phosphorous is not only an important factor affecting the distribution of the underwater light field of the lakes in the Taihu Lake basin, but also an important component restricting the biogeochemical processes of the basin.

4.3. The distribution of lake euphotic depth in the Taihu Lake basin and its response to aquatic vegetation

The growth of aquatic vegetation is dependent upon good underwater lighting conditions. $Z_{eu}$ represents the lower limit of the depth at which submerged plants can grow normally.
Therefore, understanding the existing vegetation distribution in the basin and the distribution characteristics of $Z_{eu}$ is of great significance to the restoration of aquatic vegetation in the basin (Lacoul and Freedman 2006; Zhou et al. 2018). This and other studies use the ratio of euphotic depth to water depth ($Z_{eu}$/Depth) to describe the optical environment suitable for the growth of aquatic vegetation (Zhang et al. 2007). As mentioned above, the aquatic vegetation of most lakes in the Taihu Lake basin has shown a declining trend in recent decades (Li et al. 2008), while the outlook for Shanghu, Yangcheng, Wuli, and Dianshan-Yuandang Lakes were relatively optimistic. This is consistent with the spatial distribution of the basin $Z_{eu}$ (Figure 5). Shanghu Lake had the lowest nutrient levels and the best aquatic vegetation coverage. The vegetation was dominated by submerged plants such as *Vallisneria natans* (Lour.) Hara. The aquatic vegetation of Wuli Lake has undergone recovery after previously being damaged. A series of recent ecological management measures have allowed aquatic vegetation to be restored to a certain extent (Yan et al. 2004; Li et al. 2008). Its $Z_{eu}$ also showed a higher level, which was even better than that of Yangcheng Lake with higher vegetation coverage, implying the close relationship between the growth of submerged vegetation and the distribution of the underwater light field. The reason that the $Z_{eu}$ of Yangcheng Lake was lower than that of Wuli Lake might be that the large amount of metabolites discharged by aquatic products raised in Yangcheng Lake during the growth process existed in the form of suspended matter in the lake, which interfered with the propagation of light underwater. On the contrary, the aquatic vegetation coverage of Changdang Lake has been deteriorating (Wu et al. 2015). Although there were still submerged plants growing in the Shanghuang area south of the lake, this had little impact on the whole lake. The $Z_{eu}$/Depth level of Changdang Lake was also at a lower level in the basin.

### 5. Conclusions

Through the analysis of Changdang, Gehu, Shanghu, Wuli, Yangcheng, Chenghu, and Dianshan-Yuandang Lakes in the Taihu Lake basin, the optical characteristics and influencing factors of representative lakes in the Taihu Lake basin were obtained. The main conclusions include:

1. The main factor affecting the distribution of the underwater light field in representative lakes in the Taihu Lake basin was SS, and the effect of ISS in most lakes was higher than that of OSS, followed by Chl-a.

![Figure 5. $Z_{eu}$ (a) and $Z_{eu}$/Depth (b) of typical lakes in different seasons in the Taihu Lake basin.](image-url)
2. DOC and CDOM also had a significant impact in some lakes. In lakes with greater impact of CDOM, most also had a continuous input of pollutants, including humus-like substances.

3. The $K_d$ value of typical lakes in the Taihu Lake basin was closely related to COD$_{Mn}$ and especially TP.

4. In Shanghu, Dianshan-Yuandang, Yangcheng, and Wuli Lakes, when the growth of aquatic vegetation was relatively better, the $Z_{eu}$ and $Z_{eu}/$Depth values were both higher.

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No potential conflict of interest was reported by the authors.

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**Data availability statement**

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

**References**

Bai XH, Cao T, Ni LY, Zhang XL, Tang X. 2016. Seasonal variation of water column optical parameters in Lake Erhai. China. J Hydroecoly. 37:10–16. (in Chinese with English abstract).

Bickel TO, Schooler SS. 2015. Effect of water quality and season on the population dynamics of Cabomba Caroliniana in subtropical Queensland, Australia. Aquat Bot. 123:64–71.

Brandão L, Staehr P, Bezerra-Neto J. 2016. Seasonal changes in optical properties of two contrasting tropical freshwater systems. J Limnol. 75(3).

Cárdenas C, Gerea M, García P, Pérez G, Diéguez M, Rapacioli R, Reissig M, Queimaliños C. 2017. Interplay between climate and hydrogeomorphic features and their effect on the seasonal variation of dissolved organic matter in shallow temperate lakes of the Southern Andes (Patagonia, Argentina). A field study based on optical properties. Ecohydrology. 10(7):e1872.

Chen B, Huang W, Ma S, Feng M, Liu C, Gu X, Chen K. 2018. Characterization of chromophoric dissolved organic matter in the littoral zones of eutrophic lakes Taihu and Hongze during the algal bloom season. Water. 10(7):861–879.

Chen QY, Shen Q, Li JS, Zhang WM, Guan YL. 2014. Improved methods for measuring suspended matter concentration in water based on the analysis of loss on ignition. Ocean Technology. 33:14–23. (in Chinese with English abstract).

Coble PG. 1996. Characterization of marine and terrestrial DOM in seawater using excitation-emission matrix spectroscopy. Mar Chem. 51(4):325–346.

Editorial Board of Water and Wastewater Monitoring and Analysis Methods, and State Environmental Protection Administration of China. 2002. Water and wastewater monitoring and analysis methods. 4th ed. Beijing, China: China Environmental Science Press; p. 610. (in Chinese).
He SW, Li Y, Zhao HG, Pan JZ. 2014. Preliminary study on the optical properties of Lake Gehu. J Lake Sci. 26:707–712. (in Chinese with English abstract).

Jin H, Leeuwen CHA, de Waal DBV, Bakker ES. 2022. Impacts of sediment resuspension on phytoplankton biomass production and trophic transfer: Implications for shallow lake restoration. Sci Total Environ. 808:152156.

Karlsson J, Byström P, Ask J, Ask P, Persson L, Jansson M. 2009. Light limitation of nutrient-poor lake ecosystems. Nature. 460(7254):506–509.

Kirk JTO. 2011. Light and photosynthesis in aquatic ecosystems. 3rd ed. Cambridge, UK: Cambridge University press.

Kuwahara VS, Nozaki S, Nakano J, Toda T, Kikuchi T, Taguchi S. 2015. 18-year variability of ultraviolet radiation penetration in the mid-latitude coastal waters of the western boundary pacific. Estuarine Coastal Shelf Sci. 160:1–9.

Lacoul P, Freedman B. 2006. Environmental influences on aquatic plants in freshwater ecosystems. Environ Rev. 14(2):89–136.

Li J, Liu CQ, Zhu ZZ. 2008. Historical eutrophication in Lake Taihu: evidence from biogenic silica and total phosphorus accumulation in sediments from northern part of Lake Taihu. Environ Geol. 55(7):1493–1500.

Li KD, Zhou YY, Zhou QC, Dong YX, Zhang YL, Chang JJ, Chen L, Lu YF. 2019. Temporal-spatial distribution of euphotic depth and its influencing factors in Lake Chenghai, Yunnan Province, China. J Lake Sci. 31:256–267. (in Chinese with English abstract).

Li PH, Chen L, Zhang W, Huang Q. 2015. Spatiotemporal distribution, sources, and photobleaching imprint of dissolved organic matter in the Yangtze Estuary and its adjacent sea using fluorescence and parallel factor analysis. PLoS One. 10(6):e0130852.

Li YJ, Nian YG, Hu SR, Hu XZ. 2008. Succession of macrophyte communities and its driving factors in Wuli Lake of Taihu Lake. Water Resources Protect. 107:12–16. (in Chinese with English abstract).

Liu C, Du Y, Yin H, Fan C, Chen K, Zhong J, Gu X. 2019. Exchanges of nitrogen and phosphorus across the sediment-water interface influenced by the external suspended particulate matter and the residual matter after dredging. Environ Pollut. 246:207–216.

Liu Q, Li C, Xu J, Niü Y. 2020. Distribution characteristics of aquatic plants in the watershed of Lake Taihu. China Environ Sci. 40:244–251. (in Chinese with English abstract).

Lv XY, Zhang WT, Wu SQ. 2012. Variety of chlorophyll-a and its correlations with environmental factors before and after algal bloom. Yellow River. 34:73–75. (in Chinese with English abstract).

Ma J, Song K, Wen Z, Zhao Y, Shang Y, Fang C, Du J. 2016. Spatial distribution of diffuse attenuation of photosynthetic active radiation and its main regulating factors in inland waters of northeast china. Remote Sensing. 8(11):964.

Penning W, Mjelde M, Dudley B, Hellsten S, Hangaru J, Kolada A, Berg M, Poikane S, Phillips G, Willby N, et al. 2008. Classifying aquatic macrophytes as indicators of eutrophication in European lakes. Aquat Ecol. 42(2):237–251.

Pierson DC, Kratzer S, Strömbeck N, Häkansson B. 2008. Relationship between the attenuation of downwelling irradiance at 490 nm with the attenuation of par (400 nm–700 nm) in the Baltic Sea. Remote Sens Environ. 112(3):668–680.

Pogozhev P, Gerasimova T. 2011. The role of zooplankton in the regulation of phytoplankton biomass growth and water transparency in water bodies polluted by nutrients. Water Resour. 38(3):400–408.

Qu M, Cai Q, Shen H, Li B. 2014. Variation and influencing factors of euphotic depth in Danjiangkou Reservoir in different hydrological periods. Resources and Environment in the Yangtze Basin. 23:53–59. (in Chinese with English abstract).

Reinart A, Pedusaar T. 2008. Reconstruction of the time series of the underwater light climate in a shallow turbid lake. Aquat Ecol. 42(1):5–15.

Roddevig MR, Churnside JH, Shaw JA. 2020. Lidar measurements of the diffuse attenuation coefficient in Yellowstone Lake. Appl Opt. 59(10):3097–3101.

Strom S, Barberi O, Mazur C, Bright K, Fredrickson K. 2020. High light stress reduces dinoflagellate predation on phytoplankton through both direct and indirect responses. Aquat Microb Ecol. 84:43–57.

Tang CY, Li YP, He C, Acharya K. 2020. Dynamic behavior of sediment resuspension and nutrients release in the shallow and wind-exposed Meiliang Bay of Lake Taihu. Sci Total Environ. 708:135131.

Testa JM, Lyubchich V, Zhang Q. 2019. Patterns and trends in Secchi disk depth over three decades in the Chesapeake Bay estuarine complex. Estuaries Coasts. 42(4):927–943.

Walsby A. 1997. Numerical integration of phytoplankton through depth and time in a water column. New Phytol. 136(2):189–209.
Wang JL, Fu ZS, Qiao HX, Liu FX. 2019. Assessment of eutrophication and water quality in the estuarine area of Lake Wuli, Lake Taihu, China. Sci Total Environ. 650(Pt 1):1392–1402.

Wang Q, Pan JZ, Wu XD, Ma SZ, Chen BF. 2018. Feature distribution and source analysis of chromophoric dissolved organic matter of lake wetlands in Taihu Lake basin. Jiangsu Agricultural Sci. 46:279–285. (in Chinese).

Wang W, Yang X, Huang L, Qin J, Zhou Q. 2020. Attenuation of ultraviolet radiation and photosynthetically active radiation in six Yunnan Plateau lakes of China based on seasonal field investigations. J Limnol. 79(2):151–163.

Wang X, Wu Y, Bao H, Gan S, Zhang J. 2019. Sources, transport, and transformation of dissolved organic matter in a large river system: illustrated by the Changjiang River, China. J Geophys Res Biogeosci. 124(12):3881–3901.

Wu XD, Pan JZ, Li WC, He SW, Gao Y. 2015. Status quo of aquatic vegetation and ecological restoration measures in Changdang Lake in summer. In: Song J, Li JT, editors. Lakes and wetlands and green development— the 5th China lakes Forum, Changchun, China. Changchun, China: Jilin People's Press; p. 306–311. (in Chinese).

Xiao K, Liang S, Xiao A, Lei T, Tan J, Wang X, Huang X. 2018. Fluorescence quotient of excitation–emission matrices as a potential indicator of organic matter behavior in membrane bioreactors. Environ Sci: Water Res Technol. 4(2):281–290.

Yamashita Y, Cory RM, Nishioka J, Kuma K, Tanoue E, Jaffe R. 2010. Fluorescence characteristics of dissolved organic matter in the deep waters of the Okhotsk Sea and the northwestern north Pacific Ocean. Deep-Sea Res II. 57(16):1478–1485.

Yamashita Y, Kloeppel BD, Knoepf AG, Zausen GL, Jaffe R. 2011. Effects of watershed history on dissolved organic matter characteristics in headwater streams. Ecosystems. 14(7):1110–1122.

Yan C, Xu Q, Zhao J, Jin X, Ye C, Nian YG. 2004. Study on the key factors and countermeasures of ecoreconstruction in Lake Wuli. Res Environ Sci. 3:44–47. (in Chinese with English abstract).

Yu HY, Li JH, Yang CT, Nan J, Wang XF, Wang H, Shi SQ. 2020. The temporal-spatial dynamics and driving analysis of water optical property in east Taihu Lake during season transition from summer to autumn. Bull Sci Technol. 36:126–135. (in Chinese with English abstract).

Yu R, Qian J, Zhu Y, Zhang H. 2019. Influence of two ecological purification measures on water optical environment in a source water reservoir. China Environ Sci. 39:785–791. (in Chinese with English abstract).

Zhang B, Wang SH, Jiang X, Huang XF, Wang WW. 2018. Identification of WSOM fluorescence spectral components in suspended solids and correlation analysis with nitrogen forms of Lake Wuli, Lake Taihu. J Lake Sci. 30:102–111. (in Chinese with English abstract).

Zhang M, Zhou Y, Zhang Y, Shi K, Jiang C, Zhang Y. 2020. Attenuation of uvr and par in a clear and deep lake: spatial distribution and affecting factors. Limnologica. 84:125798.

Zhang Y, Liu X, Yin Y, Wang M, Qin B. 2012. Predicting the light attenuation coefficient through Secchi depth and beam attenuation coefficient in a large, shallow, freshwater lake. Hydrobiologia. 693(1):29–37.

Zhang Y, Shi K, Zhou Y, Zhang Y, Qin B, Deng J. 2020. Decreasing underwater ultraviolet radiation exposure strongly driven by increasing ultraviolet attenuation in lakes in eastern and southwest China. Sci Total Environ. 720:137694.

Zhang Y, Zhang B, Ma R, Feng S, Le C. 2007. Optically active substances and their contributions to the underwater light climate in Lake Taihu, a large shallow lake in China. J. 170(1):11–19.

Zhang YL, Chen WM. 2006. Variation in the underwater light field under simulated water current conditions in Lake Taihu, China. J Freshwater Ecol. 21(2):191–199.

Zhou Q, Zhang Y, Li K, Huang L, Yang F, Zhou Y, Chang J. 2018. Seasonal and spatial distributions of euphotic zone and long-term variations in water transparency in a clear oligotrophic Lake Fuxian, China. J Environ Sci (China). 72(10):185–197.

Zhou QC, Zhang YL, Zhou YQ, Chen YL, Qin J, Nie JF. 2016. Spectral attenuation of ultraviolet and visible radiation and its relationship with chromophoric dissolved organic matter in autumn/winter in Lake Fuxian, China. J Lake Sci. 28:1316–1327. (in Chinese with English abstract).

Zou W, Zhu G, Cai Y, Vilmi A, Xu H, Zhu M, Gong Z, Zhang Y, Qin B. 2020. Relationships between nutrient, chlorophyll a and Secchi depth in lakes of the Chinese Eastern Plains ecoregion: Implications for eutrophication management. J Environ Manage. 260:109923.