Pol. J. Environ. Stud. Vol. 31, No. 4 (2022), 3221-3233
DOI: *10.15244/pjoes/144658* ONLINE PUBLICATION DATE: 2022-05-05

Original Research

Temporal-Spatial Pattern of Dissolved Organic Carbon and Its Influencing Factors in a Typical Subtropical Lake, Lake Gehu, China

Zijie Long[1], Xiaodong Wu[1]*, Jianying Chao[2], Xuguang Ge[1], Hengting Liu[1], Dandan Liu[1]

[1]College of Urban and Environmental Sciences, Hubei Normal University, Huangshi 435002, China
[2]Nanjing Institute of Environmental Sciences, MEE, Nanjing 210042, China

Received: 14 September 2021
Accepted: 7 December 2021

Abstract

In this study, the spatial and temporal distribution characteristics of dissolved organic carbon (DOC) concentration in Gehu Lake, Taihu Lake Basin, China, and its influencing factors were studied through annual surveys conducted in 2018 and 2019 to aid its management and restoration. The DOC concentration ranged from 1.92 to 5.60 $mg \cdot L^{-1}$, and the average DOC concentration was 3.30±0.78 $mg \cdot L^{-1}$. The DOC concentration was highest in winter, followed by spring, summer and autumn; it was significantly higher in winter and spring than in summer and autumn. The DOC concentration was lower in the northern area and higher in coastal areas. Linear fitting showed that DOC concentration was strongly positively correlated with the absorption coefficient of chromophoric dissolved organic matter, the permanganate index, particulate phosphorus and particulate nitrogen ($p<0.01$) and significantly positively correlated with organic suspended solids ($0.01<p<0.05$). The photosynthesis of phytoplankton and the input of exogenous organic matter were the most important factors affecting the concentration of DOC in Gehu Lake. These results provide information for the governance of Gehu lakes.

Keywords: dissolved organic carbon (DOC), Gehu lake, temporal and spatial distribution, Taihu Lake Basin

Introduction

Dissolved organic carbon (DOC) is one of the most abundant fractions of organic matter in aquatic systems and plays an important role in the dynamics of aquatic environments [1]. 90-95% of organic carbon in lakes is present in the dissolved form [2], it can be used to monitor carbon storage in the water environment [3-5]. DOC in inland water has various terrigenous sources, and its circulation leads to the mixing of biological, physical and photochemical processes [6]. In general, dissolved organic components in water are products of the decomposition of living or dead aquatic organisms, such as large plants and algae [7]. A large amount

*e-mail: wuxd03@163.com

of terrigenous DOC also migrates through surface and subsurface runoff and accumulates in lakes, estuaries and coasts from the soil organic carbon pools of watersheds [8, 9].

Although small in surface area, inland waters, such as streams, lakes and reservoirs, play an important role in the regional and global carbon cycle [4, 10-13]. Raymond et al. estimated that approximately 2.1 Pg of carbon is returned to the atmosphere from freshwater systems each year, 18% of which is derived from lakes and reservoirs and the remaining 82% from rivers and streams [14]. Koehler et al. estimated that approximately 10% of all CO_2 released into the atmosphere by lakes and reservoirs was released through DOC photooxidation [15]. Ye et al. found that DOC in urban lakes with many inflow and outflow rivers and a relatively concentrated industrial distribution shows clear spatial and temporal changes because of the large amount of organic matter associated with surface runoff [16]. Zheng et al. studied the concentration and composition of DOC in rivers under different land use patterns and concluded that several factors may affect the concentration and composition of DOC, even in small watersheds [17]. Joshi et al. found that increases in DOC concentration may affect the water environment. For example, high DOC concentrations can affect the color of natural waters and negatively affect primary production by preventing the spread of solar radiation to deep-water ecosystems [18]. Jepsen et al. studied interannual variation in DOC in runoff with soil–water interaction and found that the distribution of DOC in terrestrial and aquatic ecosystems may be strongly affected by changes in water age [19]. Han et al. found that water temperature and TSS are the primary factors in regulating C concentrations, and their stable isotopic signatures are primarily affected by aquatic photosynthesis and riverine respiration in the upper Han River, China [20].

Lakes reflect environmental changes and play an important role in regulating the microclimate, increasing biodiversity, and maintaining ecological balance [21]. Given the increase in the severity of lake ecological and environmental problems coupled with the growth of global carbon cycle research, there is an urgent need to enhance our understanding of the storage and regulation of organic carbon in inland waters [10, 12, 20, 22]. The study of the spatial and temporal distribution characteristics of DOC in lake water as well as its influencing factors has important implications for water quality assessment, water environment restoration and the carbon cycle [10, 12, 20, 22-24]. In light of rapidly changing climate and land use in many subtropical and temperate watersheds, an improved grasp of DOC dynamics in lakes is essential to understanding whole-ecosystem functioning [4, 25]. Due to the economic and social development in the Yangtze River region, a lot of nutrient elements associated with sewage waste were anthropogenically released into the rivers and lakes in the Yangtze River region. Most of the lakes in the middle and lower reaches of the Yangtze River region have been under mesotrophic or eutrophic conditions [26]. Gehu Lake, which is a typical subtropical shallow lake located in southern Jiangsu Province, China, is the largest lake in the upper reaches of Taihu Lake Basin and provides a natural barrier that helps protect the water ecology of Taihu Lake. As the aims of this study were: (1) to investigate the trophic status of the Gehu lake in the mid-lower reaches of the Yangtze River region; (2) to analyze the mean distribution of DOC; (3) identify the major DOC sources and determine the influencing factors of DOC in Gehu Lake.

Materials and Methods

Overview of the Study Area

Gehu Lake (31°29′~31°42′N, 119°44′~119°53′E) is approximately 20 km away from Taihu Lake and is located in the Wujin District of Changzhou City and Yixing City of Wuxi City, Jiangsu Province. It is the second largest freshwater lake in southern Jiangsu Province after Taihu Lake [27, 28]. The lake is approximately 25 km long from north to south and 6.6 km wide from east to west and has an area of approximately 164 km^2. It is connected to Taihu Lake [21]. Gehu Lake is located in the northern subtropical monsoon climate zone and is characterized by a typical monsoon climate. The average annual precipitation is 1037~1164 mm, and most precipitation is concentrated from June to September. The annual average water surface evaporation is 1058 mm, and the annual frost-free period is 223 to 239 days. With an average depth of only 1.2 m and the bottom of Gehu Lake is relatively flat without obvious fluctuations [29]. The water change cycle is 83 days. Because of the economic development and population growth in the region over the past decade, the discharge rate of industrial and agricultural wastewater and domestic sewage has exceeded the self-cleaning rate of the lake, which has resulted in the gradual deterioration of the water quality of Gehu Lake and its surrounding rivers and lakes. The use of purse seine culture has also increased the severity of eutrophication in Gehu Lake, which has resulted in algal blooms in summer and led to decreases in biodiversity. The highway along the river built in 2008 divides Gehu Lake into two lakes in the north and the south (Fig. 1). Several activities have been conducted in the northern part of the lake, including river diversion, terrain modification, blue-algae fishing and aquatic vegetation restoration [21].

Setting of Sampling Points and Sample Collection

Given the shape and area of Gehu Lake, 6 sampling points (G1-G6) were placed in Zone A, and 14 (G7-G20) were placed in Zone B (Fig. 1). Field surveys of the lakes

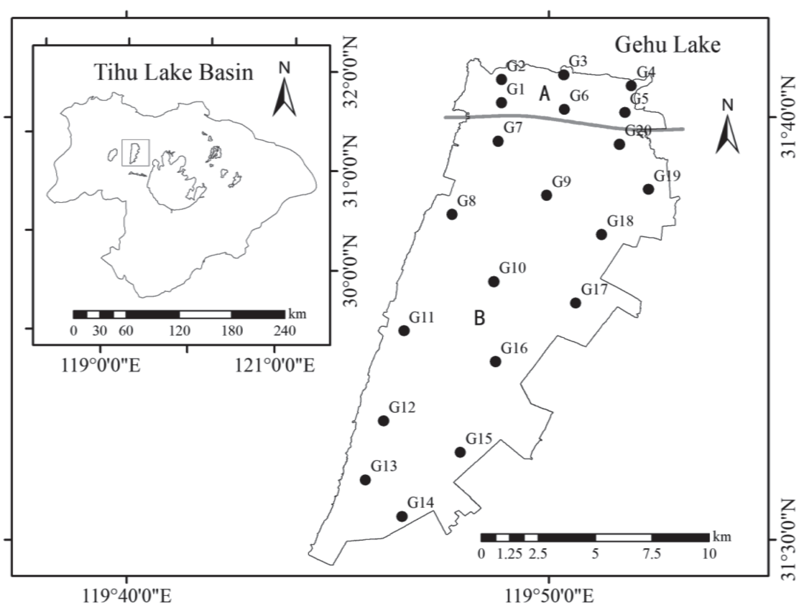

Fig. 1. Map showing the location of Gehu Lake in the Taihu Lake Basin and the location of sampling points (G1-G20) in Gehu Lake. The line through the top of Gehu Lake indicates the location of the highway, which divides the lake into Zone A (A) and Zone B (B).

were conducted in April, August, and November 2018 and February 2019.

Sample Collection, Analysis and Determination

The water depth and secchi depth (SD) were measured in situ when collecting water samples. The depth was measured by an SM-5A convenient depth sounder (American Speedtech), and the SD was measured by a 30-cm black and white Secchi disk. The mixed water samples 0.5 m below the surface were collected with a 1.5-L quartz gravity water sampler, packed into a 2.5-L acid-washed polyethylene bottle and then were analyzed shortly after packing. Some of the water samples were also removed and preserved by filtration. The filtrate was stored at a low temperature (4ºC).

The water samples were filtered through a 0.45-μm GF/C filter membrane that was burned at 550ºC for 6 h. The first 20 mL of the filtrate was discarded to prevent the organic carbon on the filter membrane from interfering with the subsequent determination. The filtrate was stored in 60-mL polyethylene bottles soaked overnight in dilute nitric acid. Thirty mL of the filtrate was used for DOC determination, and the remaining portion was used to determine the absorption and fluorescence spectra of chromophoric dissolved organic matter (CDOM). The samples were determined by the high-temperature catalytic oxidation method with a Shimazu TOC-V_{CPH} Total Organic Carbon Analyzer, and the relative standard deviation of this method was less than 2% [30].

The absorption spectrum of CDOM was measured by a UV-Vis spectrophotometer (UV2700, Shimazu); the optical path of the colorimetric dish was 0.01 m, and the absorbance of the sample was 1 nm at intervals from 200 nm to 800 nm with ultra-pure water as the reference. The formula for calculating the absorption coefficient of each wavelength is

$$a(\lambda) = 2.303 * D(\lambda) / L \quad (1)$$

where $a(\lambda)$ is the absorption coefficient of wavelength λ, m^{-1}; $D(\lambda)$ is the absorbance of wavelength λ; and L is the optical path length, m. In this study, λ is 350 nm, which represents the absorption coefficient of CDOM of Gehu Lake in the 350-nm band [30].

A Fluorolog-3 (Hitachi) spectrophotometer was used to scan three-dimensional fluorescence spectra (excitation-emission matrix fluorescence spectroscopy, EEMs). The light source was a 450-W Xenon lamp. The scanning range of the excitation wavelength was 250-450 nm, and the scanning range of the emission wavelength was 250–580 nm. The diffraction grating slit width of the excitation and emission monochromator was 5 nm, and the interval was 0.2 s. EEMs data correction for instrument differences was performed using fluorescence operation manual correction factors [30]. The humification index (HIX), the recent autochthonous biological activity index (BIX) and fluorescence index (FI) of Gehu Lake were determined by UV-Vis spectroscopy and fluorescence photometry [31]. HIX refers to the ratio of fluorescence intensity of the emission wavelength between 435-480 nm and 300–345 nm at the excitation wavelength of 254 nm, which reflects the humification degree of CDOM. Zhang et al. indicated that when HIX is less than 1.5, CDOM is mainly derived from autologous sources of recent biological activities, and when HIX is between 1.5 and 3, CDOM begins to show the characteristics of humus [32]. BIX is the ratio of fluorescence intensity of the emission wavelength between 380 nm and 430 nm at the excitation wavelength of 310 nm, which reflects the proportion of endogenous substances in CDOM. Generally, when BIX>1, CDOM is mainly derived from endogenous substances newly generated by microbial activities, and when BIX is between 0.6 and 0.7, the production of CDOM by the water body is low. FI refers to the fluorescence intensity ratio of the emission wavelength between 470 nm and 520 nm at the excitation wavelength 370 nm, which reflects the source of humus in CDOM. Generally, when FI<1.4, CDOM is mainly derived from land-based sources, and when FI>1.9, CDOM is mainly derived from the activities of microorganisms and algae [33].

Water samples were filtered through a 0.7-μm Whatman GF/F glass fiber membrane. The membrane was protected from light and stored at –20ºC. Chlorophyll a was determined by the 90% acetone method. The permanganate index (COD_{Mn}) was determined by the acid method. The total suspended solids (TSS), organic suspended solids (OSS) and inorganic suspended solids (ISS) were measured by the filtration-weighing method. Ammonia nitrogen (NH_3-N) was determined by Nessler's reagent colorimetric method. Total phosphorus (TP), total dissolved phosphorus (TDP) and orthophosphate (PO_4^{3}-P) were determined by molybdenum antimony anti-spectrophotometry. Total nitrogen (TN) and total dissolved nitrogen (TDN) were determined by UV spectrophotometry with alkaline potassium persulfate digestion. Granular phosphorus (PP) content was determined by taking the difference of the TP content and TDP content; granular nitrogen (PN) content was determined by taking the difference of the TN content and TDN content [33].

Data Processing

The micro-map of sampling points and spatial distribution interpolation maps were drawn using ArcGIS 10.2. The PARAFAC processing of EEMs data was carried out in MATLAB 2012a using the drEEM_010 package. Means, variances, standard deviations, linear fits and Pearson correlation were analyzed using SPSS 21.0 and Origin 2019b software programs. In the reporting of significance levels, $p<0.01$ indicates highly significant, $0.01<p<0.05$ indicates significant, and $p> 0.05$ indicates not significant.

Results and Discussion

Characteristics of Water Quality Indicators

Fig. 2 shows the results of SD, NH_3-N, PO_4^{3}-P, COD_{Mn}, TN, TP, SS, Nitrogen and phosphorus ratio corresponding to seasonal sampling of Gehu lake. SD was highest in the spring (32.8±13.6 cm), followed by winter (29.8±6.2 cm), autumn (24.1±4.0 cm) and summer (21.2±3.7 cm). The SD was higher in Zone A than Zone B in summer, autumn and winter; however, the SD was higher in Zone B than in Zone A in spring. The average NH_3-N concentration was highest in autumn (0.64±0.27 $mg\cdot L^{-1}$), followed by winter (0.49±0.31 $mg\cdot L^{-1}$), spring (0.26±0.18 $mg\cdot L^{-1}$) and summer (0.18±0.04 $mg\cdot L^{-1}$). The NH_3-N concentration showed significant spatial variation, it was higher in Area A than in Area B. The average PO_4^{3}-P concentration was highest in summer (0.064±0.039 $mg\cdot L^{-1}$), followed by autumn (0.050±0.042 $mg\cdot L^{-1}$), winter (0.030±0.018 $mg\cdot L^{-1}$) and spring (0.017±0.030 $mg\cdot L^{-1}$). The spatial pattern was more pronounced for PO_4^{3}-P concentration than for NH_3-N concentration, the PO_4^{3}-P concentration was higher in Zone A than in Zone B and decreased from north to south. COD_{Mn} of Gehu Lake is in line with the standard of class IV according to The Surface Water Environment Quality Standard (GB 3838-2002). COD_{Mn} was highest in spring, followed by summer, winter and autumn; the average COD_{Mn} was 5.61 $mg\cdot L^{-1}$. COD_{Mn} was higher in Zone B than in Zone A in spring, summer and winter; however, COD_{Mn} was slightly higher in Zone A than in Zone B in spring. The TN and TP averages (3.10 $mg\cdot L^{-1}$ and 0.172 $mg\cdot L^{-1}$, respectively) for Gehu Lake were consistent with a water quality of class V, which is below class IV, and excess ratios of TN and TP were 2.06 and 1.72, respectively. The average concentration of TSS in the lake was highest in summer (61.36±20.91 $mg\cdot L^{-1}$), followed by autumn (40.21±9.18 $mg\cdot L^{-1}$), spring (36.28±13.78 $mg\cdot L^{-1}$) and winter (29.62±5.82 $mg\cdot L^{-1}$). TSS were higher in Zone A than in Zone B in spring but higher in Zone B than in Zone A in the other seasons. TSS in Zone A and B were dominated by ISS, and the proportion of ISS and OSS in each lake area was roughly the same. The TN/TP mass ratio decreased from the lake center to the shore. The TN/TP mass ratio was highest in winter (25±7), followed by autumn (22±3), spring (17±5) and summer (14±2) (Fig. 2). In this study, the TN/TP ratio in spring and summer was lower, whereas the TN/TP ratio in autumn and winter was higher, which is consistent with the changing law of the TN/TP ratio of Taihu Lake [34].

DOM Fluorescence Characteristics

Three-Dimensional Fluorescence Spectral Characteristics

After PARAFAC analysis, three types of components were separated (Fig. 3). The peak domain of component 1 (C1) is relatively broad, with a peak excitation wavelength of 365 nm and emission wavelength of 475 nm, which is close to peak C in the traditional classification of peak groups. Its composition is terrestrial humus, and its conjugated chromophore is easily replaced by an aromatic group; in addition, the degree of condensation is relatively high [35].

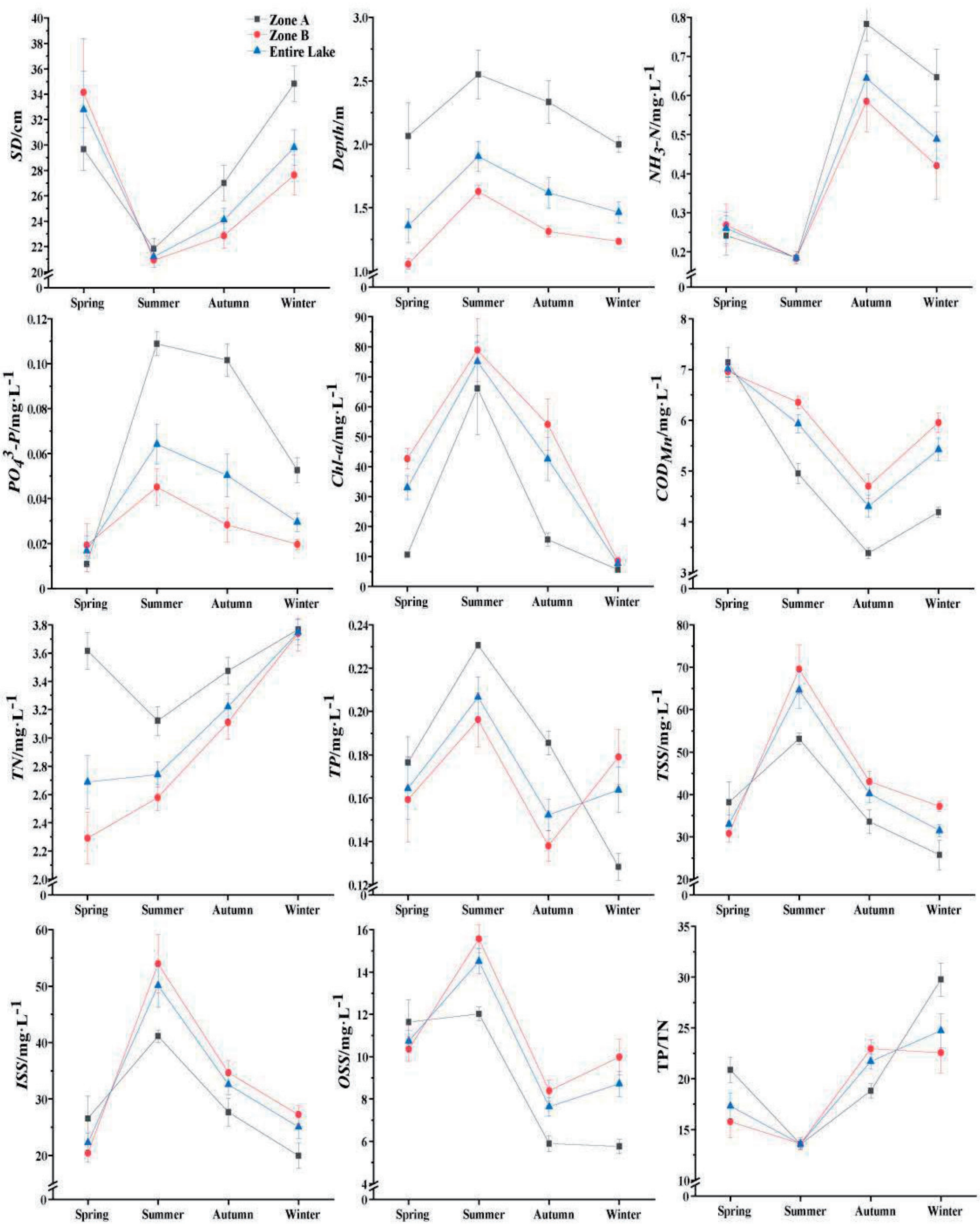

Fig. 2. Seasonal variation in the physical and chemical properties of Gehu Lake.

Component 2 (C2) has the maximum peak value at an excitation wavelength of 325 nm and emission wavelength of 405 nm, which is close to the traditional peak M. It is a humic-like compound that has been widely detected in surface seawater and in Antarctic lakes. This component may be derived from the recent activities of humans and other organisms [36]. Component 3 (C3) has the largest excitation at 280 nm, and the largest emission at 326 nm, which is near the traditional peak B. It is a type of protein-like substance that is sensitive to microbial activities; its degradation degree is higher, which is caused by some nonprotein substances (e.g., lignin phenol, indoles) and promotes the formation of the protein fluorescence chromophore [37]. There is also some research suggesting that the peak domain of this component may be associated with high imported polluting activities; it also reflects the stronger characteristics of the soluble microbial products [38]. Current studies on CDOM sources have suggested that the humic-like components are mainly exogenous inputs, whereas the protein-like components are mainly endogenous outputs [39].

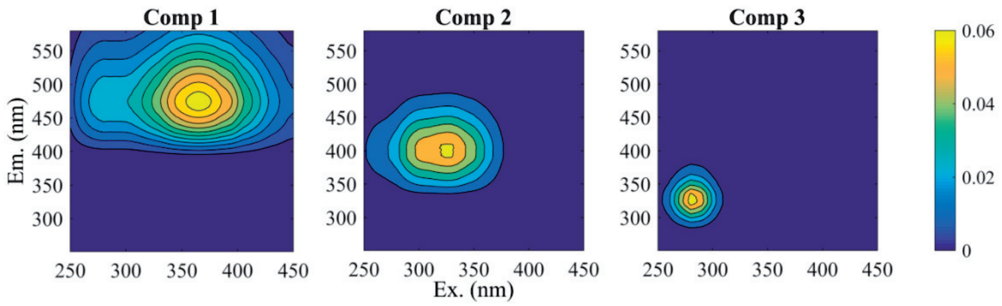

Fig. 3. Fluorescent components separated by PARAFAC.

Characteristics of Fluorescence Indices

HIX, BIX and FI reflect the degree of humification and the self-production capacity of fluorescent-dissolved organic matter (FDOM) in water [40]. The annual average HIX in Gehu Lake ranged from 0.73 to 2.83, and the annual average value was 1.78±0.27. The degree of humification was not high. The overall fluctuation range of HIX was slightly larger than that of the other fluorescence indexes; the highest value was in summer, and the lowest value was in spring (Fig. 4a). The range of seasonal variation was lower for BIX than for HIX. The annual average range was 0.84~1.07, and the average value was 0.95±0.03, indicating low production capacity. The range of FI was the smallest, with an annual average range of 1.03~1.75 and an annual mean of 1.62±0.07, which is not consistent with the classical classification of either a terrestrial origin (<1.4) or an algal origin (>1.9). Nevertheless, this indicates that the endogenous components of CDOM in Gehu Lake are not strongly affected by algal activities.

Seasonal Variation Characteristics of the CDOM Absorption Coefficient a (350) in Gehu Lake

The CDOM absorption coefficient $a(350)$ varied among seasons (Fig. 4b). It was highest in summer (6.98±0.52 m^{-1}), followed by spring (3.28±0.49 m^{-1}), winter (3.25±0.30 m^{-1}) and autumn (2.91±0.36 m^{-1}). The CDOM absorption coefficient $a(350)$ was significantly higher in summer compared with the other seasons, and the maximum value in summer was 7.95 m^{-1}. There were no significant spatial differences among seasons, but it was slightly higher in Zone B than in Zone A. In Zone A, the maximum value of $a(350)$ was 7.14 m^{-1} in summer, and the lowest value was 2.07 m^{-1} in autumn. In Zone B, the highest value was 7.95 m^{-1} in summer, and the lowest value was 3.34 m^{-1} in autumn.

Temporal and Spatial Distribution of DOC in Gehu Lake

The DOC concentration in Gehu Lake showed a seasonal pattern of change in which DOC was highest in winter and then decreased until the autumn when it was at its lowest. Precipitation and thus the flow of rivers increase in spring (Fig. 4c). As a result, the organic matter accumulated in the dry oxidized environment in winter due to the decomposition of soil organic matter and deposition in the surface of soil is brought into the lake by rivers, which increases

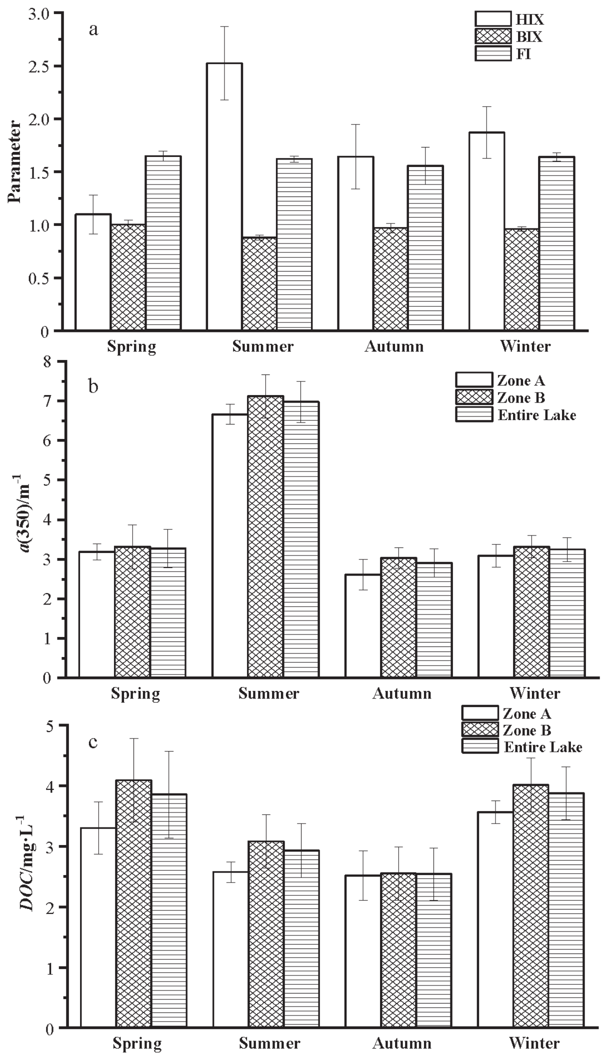

Fig. 4. The distribution of a) humification index (HIX), index of recent autochthonous biological activity (BIX), fluorescence index (FI), b) dissolved organic matter absorption coefficient at 350 nm ($a(350)$) and c) dissolved organic carbon (DOC) values in each lake.

the exogenous input of DOC to Gehu Lake. With the arrival of the rainy summer season, the river flow continues to increase, and the exogenous resources of lake DOC increase as the concentration decreases. This is presumably because the DOC released by algal blooms is rapidly decomposed and utilized by bacteria under high temperatures in summer because of its high bioavailability [16], which reduces the concentration of DOC in the water body; furthermore, there is more rainfall in summer, which dilutes the DOC concentration in lake water. Chen et al. used Landsat-8 and Sentinel-2 satellite images to estimate the temporal and spatial variation in DOC in Saginau Bay of Lake Huron, USA, and also found that the concentration of organic carbon was relatively high in spring and low in summer [41]. The water temperature and water level of Gehu Lake are at their lower in autumn and winter, and the level of organic pollution is high. This is consistent with Li, Xiaojun's research showing that the total organic carbon to total nitrogen ratio in Taihu lake (China) is higher in winter (30.5) than in summer (16.37) [42].

The DOC concentration ranged from 1.92 to 5.60 $mg \cdot L^{-1}$, and the average was 3.30±0.78 $mg \cdot L^{-1}$, which was lower compared with Taihu Lake (range of 2.86-11.83 $mg \cdot L^{-1}$) [43] and Poyang Lake (ranged from 1.79 to 7.22 $mg \cdot L^{-1}$ and average of 3.85±1.41 $mg \cdot L^{-1}$) [44]. The DOC concentration of Gehu Lake gradually increased from north to south (Fig. 5), which is consistent with the spatial pattern of algae density in Gehu Lake [45], indicating that the DOC in Gehu Lake is closely tied to the distribution of algae. Organic matter from domestic sewage, the feces and urine of poultry and animals and bait from purse seine culture around Gehu Lake likely increase the DOC content in the coastal parts of the lake. In spring (Fig. 5a), there was a high degree of variation, with high DOC concentrations in the western portion of the southern region (specifically, near the mouth of the Huangli River and Beigan River), and DOC concentrations gradually decreased in the southeastern region. This stems from the fact that the dissolved organic matter (DOM) in the bottom sediment is continuously released as the river flows downstream. During this process, the DOC content in the river gradually increases and finally flows into the lake, which increases the DOC content near the lake inlet. DOM can be photoproduced by the photolysis of resuspended estuarine or marine sediments [46]. There are no large-scale development and construction projects around the lake entrance, and the DOC in the lake bottom silt and surrounding soil has not been disturbed, which is also the reason for the high DOC concentration in the lake entrance area. In summer (Fig. 5b), the area with high DOC concentrations was near Fengyi and Gaodu in the southernmost part of the lake, and the DOC concentrations gradually decreased northward. In autumn (Fig. 5c), the highest value was recorded near Port Yincun and Zhaiqiao in the southeastern portion of the southern area. This area historically was a large-scale aquaculture area and thus a source of artificial bait. Although this aquaculture area is no longer in operation, there are still many organic substances remaining at the bottom; furthermore, the low average water depth in this area (1.1 m) contributes to the high DOC concentration. In winter (Fig. 5d), the highest value was recorded near Port Dahong in the northeastern part of the lake and near the mouth of the Beigan River in the western portion of the southern area and gradually decreased in the southeastern part of the lake. The higher exogenous input in ports and estuaries explains the high DOC concentrations in these areas.

Analysis of the Influencing Factors of DOC in Gehu Lake

Relationship between DOC and TSS

There are many river estuaries around Gehu Lake, and material and energy exchange with the outside world occurs frequently. The TSS in Gehu Lake are

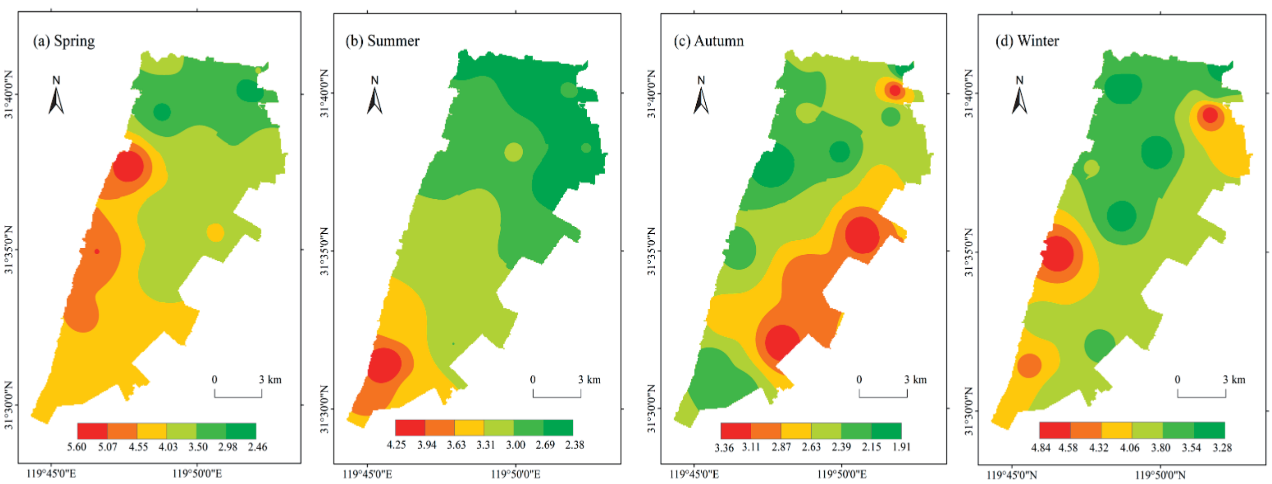

Fig. 5. Spatial distribution of the DOC concentration in spring, summer, autumn and winter in Gehu Lake.

Table 1. Correlations between DOC and other water quality indicators.

	DOC	TP	PP	TN	PN	COD	Chl-a	SS	OSS	ISS	TDN	TDP	TNTP	TDNTDP
DOC	1													
TP	0.015	1												
PP	0.287**	0.686**	1											
TN	-0.077	0.194	0.066	1										
PN	0.302**	0.526**	0.890**	-0.123	1									
COD	0.606**	.245*	0.696**	-0.332**	0.827**	1								
Chl-a	-0.042	0.099	0.407**	-0.178	0.627**	0.595**	1							
SS	0.188	0.428**	0.636**	0.252*	0.446**	0.245*	-0.026	1						
OSS	0.221*	0.571**	0.837**	-0.074	0.797**	0.625**	0.366**	0.804**	1					
ISS	0.178	.398**	0.594**	0.286*	0.390**	0.191	-0.074	0.997**	0.758**	1				
TDN	-0.194	-0.057	-0.321**	0.907**	-0.530**	-0.634**	-0.418**	0.026	-0.401**	0.079	1			
TDP	-0.278*	0.648**	-0.11	0.194	-0.212	-0.393**	-0.291**	-0.082	-0.095	-0.078	0.256*	1		
TNTP	-0.001	-0.653**	-0.529**	0.542**	-0.520**	-0.433**	-0.267*	-0.234*	-0.555**	-0.187	0.684**	-0.339**	1	
TDNTDP	0.087	-.510**	-0.016	0.349**	-0.027	-0.009	0.048	0.063	-0.123	0.085	0.310**	-0.679**	0.692**	1

*indicates a significant correlation at the level of 0.05 (bilateral),
** indicates a significant correlation at the level of 0.01 (bilateral)

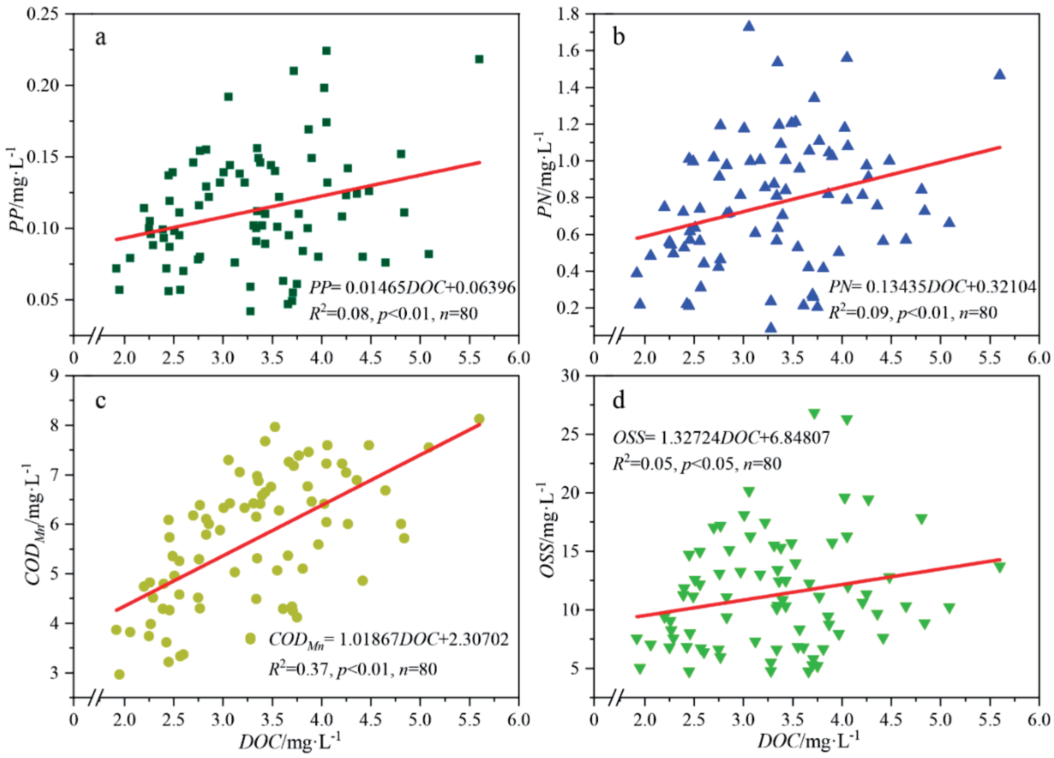

Fig. 6. Mutual correlations between a) dissolved organic carbon (DOC) and Granular phosphorus (PP), b) granular nitrogen (PN), c) permanganate index (COD_{Mn}), and d) organic suspended solids (OSS).

Table 2. Relationship between dissolved organic carbon (DOC) and dissolved organic matter absorption coefficients (a(350)), the fluorescence intensities of components from the PARAFAC model.

	DOC	*a*(350)	C1	C2	C3
DOC	1				
a(350)	0.668**	1			
C1	0.229	0.545*	1		
C2	0.207	0.186	0.516*	1	
C3	0.246	0.209	0.44	0.950**	1

*indicates a significant correlation at the level of 0.05 (bilateral),
** indicates a significant correlation at the level of 0.01 (bilateral)

mainly derived from sediments carried by the river and the sediment resuspension caused by wind disturbance. The proportions of ISS and OSS of Gehu Lake differ greatly (72% and 28%, respectively). The percentage of OSS (28%) was similar to that of Taihu Lake (30%) [47]. DOC was not significantly correlated with ISS ($0.05< p<0.1$, Table 1), but it was significantly positively correlated with OSS ($0.01<p<0.05$, Table 1, Fig. 6d). The degree of eutrophication was high in Gehu Lake. In summer, algae erupted, and water blooms often occurred. Phytoplankton are an important component of OSS and a source of TSS.

Relationship of DOC with Nitrogen and Phosphorus

There was a highly significant positive correlation between DOC and PN and DOC and PP (both $p<0.01$, Table 1, Fig. 6), and the correlation coefficients were 0.302 and 0.287, respectively. PN ranged from 0.087 to 1.727 $mg \cdot L^{-1}$, and the average was 0.764 $mg \cdot L^{-1}$, accounting for 24.7% of TN. PP ranged from 0.042 to 0.224 $mg \cdot L^{-1}$, and the average was 0.112 $mg \cdot L^{-1}$, accounting for 65.4% of TP. PN and PP were highly significantly positively correlated with Chl-a (both $p<0.01$, Table 1), and the correlation coefficients were 0.627 and 0.407, respectively. However, the overall correlation between DOC and TN and DOC and TP were not strong in this study ($p>0.1$ and $0.05< p<0.1$, respectively), indicating an unstable contribution of nitrogen and phosphorus to DOC. It is worth noting that even though DOC lacked a significant linear relationship with TN and TP overall, it showed a good response to TN and TP in each season. These results indicate that the contribution of TN and TP to DOC was influenced substantially by other environmental conditions [33]. TN/TP was highly significantly negatively correlated with OSS and COD_{Mn} (both $p<0.01$, Table 1) and significantly negatively correlated with Chl-a ($0.01<p<0.05$, Table 1). Algae (e.g., blue-green algae) only release less than 10% of photosynthetically fixed carbon when they grow, whereas decaying algae cells can release 10-50% or more of the photosynthetically fixed carbon. The effect of nutrients on phytoplankton organic carbon released by photosynthesis shows a lag [48]. The dead residue of algae is thought to be one of the major sources of PN and PP in Gehu Lake.

Relationship between DOC and COD_{Mn}

COD_{Mn} is the amount of oxidized reducing substances (mainly organic pollutants) in water, and DOC is a comprehensive indicator of organic matter content in water by carbon content (Feng et al. 2018). Previous studies have shown that there is a significant positive correlation between COD_{Mn} and DOC concentration [49, 50]. Linear fitting revealed a significant positive correlation between DOC and COD_{Mn} in Gehu Lake (p<0.01, Table 1). However, there was no significant correlation between DOC and Chl-a (p>0.1, Table 1). Previous studies have shown that the correlation between DOC and chlorophyll is complex [51-54]. There was no significant correlation between DOC and Chl-a in Gehu Lake, it indicates that phytoplankton not playing mainly role in regulating the DOC distribution [53]. The permanganate index of Gehu Lake reached class IV of GB3838-2002 Environmental Quality Standard For Surface Water, and the maximum was 8.12 $mg \cdot L^{-1}$, indicating a high degree of organic pollution. The results showed that the main source of DOC in Gehu Lake was exogenous input; endogenous input was not dominant. The high degree of exogenous input was the reason for the lack of a significant correlation between Chl-a and DOC (p>0.1 Table 1).

Relationship between DOC and CDOM

CDOM is an important component of DOM in water [33]. It affects the distribution of and variation in the underwater light field and is an important source and sink in the global carbon cycle. Its generation, migration, transformation and fate can affect the cycle process of nutrients, such as N, P, heavy metals and organic pollutants [55, 56]. Jiao et al. concluded from a study of 30 rivers that CDOM could be used as a surrogate for DOC in most major rivers of North America [57]. The correlation analysis between the absorption coefficients of DOC and CDOM and the fluorescence components of FDOM revealed that the absorption coefficient of CDOM a(350) was highly significantly positively correlated with DOC (p<0.01, Table 2), indicating that CDOM makes a great contribution to the carbon storage in Gehu Lake. C1 was significantly positively correlated with C2 (0.01<p<0.05, Table 2), indicating that these two types of humic-like substances are similar in composition; their sources and distributions may also be similar. The fluorescence intensity of C3 made an important contribution in quantity, but there was only a significant linear correlation between C3 and C2 (p<0.01, Table 2). Ren et al [33] studied the dissolved organic matter in Qinshan lake which is urban moderately eutrophic lake in the middle reaches of the Yangtze River, found that DOC was highly significantly positively correlated with a(350) (p<0.01), but there was no significant correlation between DOC and fluorescence components of FDOM, which is consistent with the results of our study.

DOC in lake water can be divided into endogenous and exogenous according to its source. Endogenous refers to the products of phytoplankton photosynthesis, the substances decomposed by bacteria and microorganisms and the release of sediment. Exogenous refers to the discharge of pollutants from the outer basin of the lake and the input of organic matter accumulated in soil with rainwater and river flow. Gehu Lake is a deeply eutrophic lake with many inlets of rivers, frequent material and energy exchange with the outside world, a large amount of organic matter and pollutant input by rivers and rainwater and serious organic pollution. The source of DOC in Gehu Lake was mainly exogenous, which is consistent with the results of Wu et al. [26] showing that terrestrial inputs have critical effects on the lakes in the mid-lower reaches of the Yangtze River in China.

Conclusions

In this study, four seasonal water samples were collected for *in-situ* measurements and experimental analysis, and various physical and chemical indicators of water quality and DOC concentrations in Gehu Lake were obtained. The major conclusions are detailed below.

(1) The CDOM absorption coefficient a(350) in Gehu Lake was highest in summer (6.98±0.52 m^{-1}), followed by spring (3.28±0.49 m^{-1}), winter (3.25±0.30 m^{-1}) and autumn (2.91±0.36 m^{-1}). It was slightly lower in the northern area of Gehu Lake compared with the southern area.

(2) The DOC concentration range of the lake was 1.92~5.60 $mg \cdot L^{-1}$, and the average value was 3.30 $mg \cdot L^{-1}$. It was generally lower in the northern part of the lake and higher in coastal areas. DOC concentration was highest in winter, followed by spring, summer and autumn. It was significantly higher in winter and spring than in summer and autumn.

(3) DOC was highly significantly positively correlated with a(350), PN, PP and COD_{Mn} (p<0.01) and significantly positively correlated with OSS (0.01<p<0.05). Phytoplankton photosynthesis and the input of exogenous organic matter are important factors affecting DOC concentrations.

Acknowledgments

This research was funded by the Science and Technology Research Project of Education Department of Hubei Province (No. Q20182502), Innovation Team Project of HBNU of Heavy Metal Pollution Mechanism and Ecological Restoration for Lake Catchment System

(2019CZ014). We thank Zeyong Liao and Yao Hu for their assistance in sampling.

Conflict of Interest

The authors declare no conflict of interest.

References

1. TADEU C.M.O., BRANDAO L.P.M., BEZERRA.NETO J.F., PUJONI D.G.F., BARBOSA F.A.R. Photodegradation of autochthonous and allochthonous dissolved organic matter in a natural tropical lake. Limnologica, **87**, **2021**.
2. WEN Z., SONG K., SHANG Y., ZHAO Y., FANG C., LYU L. Differences in the distribution and optical properties of DOM between fresh and saline lakes in a semi-arid area of Northern China. Aquatic Sciences, **80** (2), **2018**.
3. DRAKE T.W., VAN OOST K., BARTHEL M., BAUTERS M., HOYT A.M., PODGORSKI D.C., SIX J., BOECKX P., TRUMBORE S.E., NTABOBA L.C., SPENCER ROBERT G.M. Mobilization of aged and biolabile soil carbon by tropical deforestation. Nature Geoscience, **12** (7), 541, **2019**.
4. GRIFFIN C.G., FINLAY J.C., BREZONIK P.L., OLMANSON L., HOZAISKI R.M. Limitations on using CDOM as a proxy for DOC in temperate lakes. Water Research, **144** (1), 719, **2018**.
5. HOUNSHELL A.G., RUDOLPH J.C., VAN DAM B.R., HALL N.S., OSBURN C.L., PAERL H.W. Extreme weather events modulate processing and export of dissolved organic carbon in the Neuse River Estuary, NC. Estuarine Coastal and Shelf Science, **219**, 189, **2019**.
6. BAUER J.E., CAI W.J, RAYMOND P.A., BIANCHI T.S., HOPKINSON C.S., REGNIER P.A.G. The changing carbon cycle of the coastal ocean. Nature, **504** (7478), 61, **2013**.
7. CHEN S., XU K., JI D., WANG W., XU Y., CHEN C., XIE C. Release of dissolved and particulate organic matter by marine macroalgae and its biogeochemical implications. Algal Research-Biomass Biofuels and Bioproducts, **52**, **2020**.
8. BUTMAN D., STACKPOOLE S., STETS E., MCDONALD C.P., CLOW D.W., STRIEGL R.G. Aquatic carbon cycling in the conterminous United States and implications for terrestrial carbon accounting. Proceedings of the National Academy of Sciences of the United States of America, **113** (1), 58, **2016**.
9. GODIN P., MACDONALD R.W., KUZYK Z.Z.A., GONI M.A., STERN G.A. Organic matter compositions of rivers draining into Hudson Bay. Present-day trends and potential as recorders of future climate change. Journal of Geophysical Research-Biogeosciences, **122** (7), 1848, **2017**.
10. KLUMP J.V., EDGINGTON D.N., GRANINA L., REMSEN C.C.III. Estimates of the remineralization and burial of organic carbon in Lake Baikal sediments. Journal of Great Lakes Research, **46** (1), 102, **2020**.
11. MOGUEL R.G., BASS A.M., GARNETT M.H., PILOTE M., KEENAN B., MATVEEV A., DOUGLAS P.M.J. Radiocarbon Data Reveal Contrasting Sources for Carbon Fractions in Thermokarst Lakes and Rivers of Eastern Canada (Nunavik, Quebec). Journal of Geophysical Research-Biogeosciences, **126** (4), **2021**.
12. XIAO M., WU F., YI Y., HAN Z., WANG Z. Optical Properties of Dissolved Organic Matter and Controlling Factors in Dianchi Lake Waters. Water, **11** (10), **2019**.
13. WANG H.J., WANG H.Z., LIANG X.M., PAN B.Z., KOSTEN S. Macrophyte species strongly affects changes in C, N, and P stocks in shallow lakes after a regime shift from macrophyte to phytoplankton dominance. Inland Waters, **6** (3), 449, **2016**.
14. RAYMOND P.A., HARTMANN J., LAUERWALD R., SOBEK S., MCDONALD C., HOOVER M., BUTMAN D., STRIEGL R., MAYORGA E., HUMBORG C., KORTELAINEN P., DUERR H., MEYBECK M., CIAIS P., GUTH P. Global carbon dioxide emissions from inland waters. Nature, **503** (7476), 355, **2013**.
15. KOEHLER B., LANDELIUS T., WEYHENMEYER G.A., MACHIDA N., TRANVIK L.J. Sunlight-induced carbon dioxide emissions from inland waters. Global Biogeochemical Cycles, **28** (7), 696, **2014**.
16. YE L.L., WU X.D., KONG F.X., LIU B., YAN D.Z. Sources of dissolved organic carbon and the bioavailability of dissolved carbohydrates in the tributaries of Lake Taihu. Environmental science, **36** (3), 914, **2015**.
17. ZHENG Y., WALDRON S., FLOWERS H. Fluvial dissolved organic carbon composition varies spatially and seasonally in a small catchment draining a wind farm and felled forestry. Science of the Total Environment, **626** (1), 785, **2018**.
18. JOSHI I., D'SA E.J. Seasonal Variation of Colored Dissolved Organic Matter in Barataria Bay, Louisiana, Using Combined Landsat and Field Data. Remote Sensing, **7** (9), 12478, **2015**.
19. JEPSEN S.M., HARMON T.C., SADRO S., REID B., CHANDRA S. Water residence time (age) and flow path exert synchronous effects on annual characteristics of dissolved organic carbon in terrestrial runoff. Science of the Total Environment, **656** (15), 1223, **2019**.
20. HAN X., CHENG X., LI S., YUAN J., ZHANG Q. Carbon concentrations and their stable isotopic signatures in the upper Han River, China. Environmental Science and Pollution Research, **26** (14), 14116, **2019**.
21. WU X., LI W., PAN J., MA S., CHEN B., HE S. Restoration in northern Lake Gehu, a eutrophic lake in China. Chinese Journal of Oceanology and Limnology, **35** (6),1417, **2017**.
22. CHEN S., ZHONG J., LI C., LIU J., WANG W., XU S., LI S.L. Coupled effects of hydrology and temperature on temporal dynamics of dissolved carbon in the Min River, Tibetan Plateau. Journal of Hydrology, **593**, **2021**.
23. MARCARELLI A.M., COBLE A.A., MEINGAST K.M., KANE E.S., BROOKS C.N., BUFFAM I., GREEN S.A., HUCKINS C.J., TOCZYDLOWSKI D., STOTTLEMYER R. Of Small Streams and Great Lakes. Integrating Tributaries to Understand the Ecology and Biogeochemistry of Lake Superior. Journal of the American Water Resources Association, **55** (2), 442, **2019**.
24. MINOR E.C., OYLER A.R. Dissolved organic matter in large lakes: a key but understudied component of the carbon cycle. Biogeochemistry, **101** (3-4), 166, **2021**.
25. JEPPESEN E., BEKLIOĞLU M., ÖZKAN K., AKYÜREK Z. Salinization increase due to climate change will have substantial negative effects on inland waters and freshwater resources. The Innovation, **1** (2), 100030, **2020**.
26. WU Y., LI Y., LV J., XI B., ZHANG L., YANG T., LI G., LI C., LIU H. Influence of sediment DOM on environmental factors in shallow eutrophic lakes in the middle reaches

of the Yangtze River in China. Environmental Earth Sciences, **76** (4), **2017**.
27. XU X., ZHANG L., XUE Y., GAO Y., WANG L., PENG M., JIANG S., ZHANG Q. Microplastic pollution characteristic in surface water and freshwater fish of Gehu Lake, China. Environmental Science and Pollution Research, **2021**.
28. XU X., ZHANG Y., CHEN Q., LI N., SHI K., ZHANG Y. Regime shifts in shallow lakes observed by remote sensing and the implications for management. Ecological Indicators, **113**, **2020**.
29. XU L., PAN J., JIANG J., ZHAO H., LIU C. A history evaluation modelling and forecastation of water quality in shallow lake. Water and Environment Journal, **27** (4), 514, **2013**.
30. CHEN B.F., HUANG W., MA S.Z., FENG M.H., LIU C., GU X.Z, CHEN K. Characterization of Chromophoric Dissolved Organic Matter in the Littoral Zones of Eutrophic Lakes Taihu and Hongze during the Algal Bloom Season. Water, **10** (7), 1, **2018**.
31. SHAO T., WANG T. Effects of land use on the characteristics and composition of fluvial chromophoric dissolved organic matter (CDOM) in the Yiluo River watershed, China. Ecological Indicators, **114**, **2020**.
32. ZHANG W.H., ZHAO D.L., WANG X.Y., HAO Q.Z., LI X.M., GAO P.C. Absorption and Three Dimensional Fluorescence Spectra of CDOM in the Water of the Taibaishan Nature Reserve. Environmental science, **41** (11), 4958, **2020**.
33. REN W.X., WU X.D.., GE X.G., LIN G.Y., ZHOU M.D., LONG Z.J., YU X.H., TIAN W. Characteristics of dissolved organic matter in lakes with different eutrophic levels in southeastern Hubei Province, China. Journal of Oceanology and Limnology, **39** (4), 1256, **2021**.
34. XU H., PAERL H.W., QIN B., ZHU G., GAO G. Nitrogen and phosphorus inputs control phytoplankton growth in eutrophic Lake Taihu, China. Limnology and Oceanography, **55** (1), 420, **2010**.
35. DERRIEN M., KIM M.S., OCK G., HONG S., CHO J., SHIN K.H., HUR J. Estimation of different source contributions to sediment organic matter in an agricultural-forested watershed using end member mixing analyses based on stable isotope ratios and fluorescence spectroscopy. Science of the Total Environment, **618** (3), 569, **2018**.
36. LIU C., DU Y.H., YIN H.B., FAN C.X., CHEN K., ZHONG J.C., GU X.Z. Exchanges of nitrogen and phosphorus across the sediment-water interface influenced by the external suspended particulate matter and the residual matter after dredging. Environmental Pollution, **246**, 207, **2019**.
37. LI P.H., CHEN L., ZHANG W., HUANG Q.H. 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), 1, **2015**.
38. XIAO K., LIANG S., XIAO A., LEI T., TAN J., WANG X., HUANG X. Fluorescence quotient of excitation-emission matrices as a potential indicator of organic matter behavior in membrane bioreactors. Environmental Science-Water Research & Technology, **4** (2), 281, **2018**.
39. WUNSCH U.J., GEUER J.K., LECHTENFELD O.J., KOCH B.P., MURPHY K.R., STEDMON CA. Quantifying the impact of solid-phase extraction on chromophoric dissolved organic matter composition. Marine Chemistry, **207**, 33, **2018**.
40. YANG L.Y., ZHUANG W.E., CHEN T.A.C., WANG B.J., KUO F.W. Unveiling the transformation and bioavailability of dissolved organic matter in contrasting hydrothermal vents using fluorescence EEM-PARAFAC. Water Research, **111** (15), 195, **2017**.
41. CHEN J., ZHU W., TIAN Y.Q., YU Q. Monitoring dissolved organic carbon by combining Landsat-8 and Sentinel-2 satellites: Case study in Saginaw River estuary, Lake Huron. Science of the Total Environment, **718**, **2020**.
42. LI X., ZHAO Y., HAN R., WANG G. Fractionation and Determinants of Sediment Nitrogen and Phosphorus in the Algae-Dominated Moon Bay of Lake Taihu (China). Journal of Coastal Research, **37** (3), 506, **2021**.
43. WANG S., WANG W., CHEN J., ZHANG B., ZHAO L., JIANG X. Characteristics of Dissolved Organic Matter and Its Role in Lake Eutrophication at the Early Stage of Algal Blooms-A Case Study of Lake Taihu, China. Water, **12** (8), , **2020**.
44. JIAN Z., XU J., HUANG X., YANG W., HU Q. Optical Absorption Characteristics, Spatial Distribution, and Source Analysis of Colored Dissolved Organic Matter in Wetland Water around Poyang Lake. Water, **13** (3), **2021**.
45. SHEN, L.J., ZHOU, W. AND SHEN, W. Spatial-temporal distribution of algal density and its driving factors in Gehu lake. Environmental Protection and Circular Economy, **40** (1), 51, **2020**.
46. LIU Q., SHANK G.C. Solar Radiation-Enhanced Dissolution (Photodissolution) of Particulate Organic Matter in Texas Estuaries. Estuaries and Coasts, **38** (6), 2172, **2015**.
47. WU X.D., WANG L., CHAO J.Y.,LIAO Z.Y., HU Y., REN W.X., ZHOU M.D. Characteristics and its influencing factors of suspended solids distribution in Lake Gehu,Taihu Basin. J. Lake Sci, **32** (6), 1848, **2020**.
48. FENG, W.H., QIAN, J., HAO, Z., WANG, Z.F., XU, H.T. AND ZHANG, D.R. Distribution characteristics of dissolved organic carbon and influencing factors in the northern waters of Fujian. Marine Environmental Science, **37** (2), 88, **2018**.
49. KIM S.W., CHO Y.H., CHAE M.H., GIL G.B., SEOK K.S. Characteristics of Organic Matters in Small Streams into the Daecheong Reservoir. Journal of Environmental Analysis, Health and Toxicology, **23** (3), 155, **2020**.
50. KIM Y.H., MOON K.R., YOON S.H., KIM J.H., LIM M.H., JIN J.S., YANG M.S., JUNG H.Y., BAE S.J., CHUNG J.K. Study on the Characteristics of TOC Emission by Industrial Wastewater Classification in Gwangju. Joural of Korean Society of Water Science and Technology, **29** (2), 21, **2021**.
51. YE L., SHI X., WU X., KONG F. Nitrate limitation and accumulation of dissolved organic carbon during a spring-summer cyanobacterial bloom in Lake Taihu (China). Journal of Limnology, **71** (1), 67, **2012**.
52. KIM J., KIM T.H., PARK S.R., LEE H.J., KIM J.K. Factors controlling the distributions of dissolved organic matter in the East China Sea during summer. Scientific Reports, **10** (1), **2020**.
53. SURATMAN S., ZAN N.H.C., AZIZ A.A., TAHIR N.M. Spatial and Seasonal Variations of Organic Carbon-Based Nutrients in Setiu Wetland, Malaysia. Sains Malaysiana, **46** (6), 859, **2017**.
54. WANG P., JOO J.H., PARK B.S., KIM J.H., KIM J.H., HAN M.S. Relationship between dissolved organic carbon and bacterial community in the coastal waters of Incheon, Korea. Oceanological and Hydrobiological Studies, **46** (1), 50, **2017**.

55. PATIDAR S.K., CHOKSHI K., GEORGE B., BHATTACHARYA S., MISHRA S. Dominance of cyanobacterial and cryptophytic assemblage correlated to CDOM at heavy metal contamination sites of Gujarat, India. Environmental Monitoring and Assessment, **187** (1), **2015**.
56. ZHU L., ZHAO Y., BAI S., ZHOU H., CHEN X., WEI Z. New insights into the variation of dissolved organic matter components in different latitudinal lakes of northeast China. Limnology and Oceanography, **65** (3), 471, **2020**.
57. JIAO K.W., LI F.X., ZHOU Q.X. Spatial distribution and pollution level evaluation of nutrients in the Songhua River Basin. J. Agro-Environ. Sci., **34**, 769. **2015**.