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Can relative abundance of diatoms (RAD) serve as an indicator for the water quality assessment in river-connected lakes? A case study at Dongting Lake

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Abstract

In this study, 15 sampling sites were set up in Dongting Lake, a typical river-connected lake in China, to investigate water quality and diatioms in March, June, September and December from year 2017 to 2022. Seven diatom indices, including relative abundance of diatoms (RAD), percentage motile diatoms (PMD), generic diatom index (GDI), diatom quotient (DU), pollution tolerance index for diatoms (PTI), trophic diatom index (TDI), and Pampean diatom index (IDP), were selected to screen the adaptability of water quality assessment comparing with the Nemero index (NI), which is simple to calculate and has always been the main method for water quality assessment in Dongting Lake. The results from 2017 to 2019 showed that the diatom density in Dongting Lake ranged from 0.7×10^4 to 85.5×10^4 ind./L, with a certain decreasing trend. The spatial and temporal changes of some water quality factors were obvious, just like the temperature of water (WT), ammonia nitrogen (NH_4^+–N), dissolved oxygen (DO) and the comprehensive trophic level index (∑*TLI*) ranged from 45.99 to 50.72, with an average value of 47.85, indicating that the overall condition of Dongting Lake was medium nutrition. Correlation analysis showed that PTI, RAD and PMD could represent the information of DU, GDI, TDI and IDP, and were significantly positively correlated with DO ($p < 0.01$), while significantly negatively correlated with electrical conductivity (Cond), potassium permanganate (COD_{Mn}), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD_{Cr}) and ∑*TLI* ($p < 0.001$). The index verification results from year 2020 to 2022 showed that PTI, RAD and PMD were all significantly positively correlated with NI ($p < 0.001$). Taking into account the data integrity of the index calculation and the difficulty degree, RAD was finally selected as the biological indicator for evaluating the water quality of Dongting Lake. The results of this study provide a new path or alternative method for water quality assessment of the river-connected lakes.

Keywords Diatoms, Indices, Dongting lake, Water quality, Assessment

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Introduction

The rapid population growth and the intensifying human activities in the late twentieth century is harming the water ecology and the environment locally, regionally, and even globally. Problems such as the drying up of rivers, biodiversity loss, and water pollution seriously damage the structural function of watersheds [3, 39]. Since a healthy water ecosystem is indispensable to the sustainable utilization of water resources, ecological security, and the sustainable economic and social development for a watershed and a region, comprehensive methods are urgently needed to assess the status of ecosystems and monitor their change [43]. The fundamental monitoring methods that provide detailed information for correct water management can be classified into physical, chemical, and biological methods [34]. Biological monitoring methods can complement traditional physical and chemical monitoring methods [48], which tend to fall short in the following aspects: (1) they cannot comprehensively reflect the response of the ecosystem to the external pollution, (2) they cannot provide information on the effects of environmental changes on the biological communities in the water environment, and (3) they cannot truly reflect the situation in the vicinity of the monitoring points. This is especially relevant for flowing water bodies, for which accurate assessments can be difficult due to the rapidly changing hydrology.

As primary producers, phytoplankton is at the bottom of the food chain in aquatic ecosystems [56]. They have short life cycles and are sensitive to pollutants, and their composition is highly specific to the water body [69]. The nature and quantity of the phytoplankton communities change with the chemical composition of the water. Hence, phytoplankton is often used as an important indicator in monitoring water quality [30, 63]. Diatoms are photoautotrophic eukaryotic phytoplankton and are important components of natural water bodies. They are widely found in various water bodies such as rivers, streams, and lakes. They have high species diversity and short reproduction cycles, and can be easily collected and preserved [27, 49]. Diatoms are extremely sensitive to the changes in the water environment, such as water temperature, pH value, conductivity, nutrient concentration, and heavy metal levels [6]. For example, *Cyclotella meneghiniana* can indicate the nutritional status of water [15] and is also sensitive to water pH [66]. *Achnanthes nodusa* [46] and *Synedra ulna* [20] can indicate the level of Cu and Zn in the water body, respectively. *Synedra acus*, *Diatoma hiemale*, and *Gomphonema parvulum* can also reflect the pollution status of the water body [51]. Since the 1990s, researchers from the European Union, the United States, Australia, South Africa, China, and Brazil have carried out extensive works on diatoms [9, 17, 22, 26, 31, 41, 42, 59]. They used statistical methods to associated diatoms with environmental factors and established a series of functions and mathematical models to identify diatom communities, which greatly improved the accuracy in using diatoms to monitor the changes in water quality. These methods are now widely used to assess river health.

In 2000, the Water Framework Directive of the European Union recommended using diatoms as a routine biological indicator for water environment monitoring, after which many European countries updated their regulations accordingly [7]. Diatom indices are currently widely used in water environment monitoring. Most diatom indices are established based on the diatom species found in the water body, and they categorize the water bodies into different levels based on the ecological habits and pollution resistance of the detected diatoms. The first diatom index was established subsequently standardized the calculation of the diatom index (Descy et al., 1979). Many researchers have customized the diatom index based on the environmental conditions of their research area and established a number of diatom indices to evaluate the water quality of diverse water bodies, including specific pollution sensitivity index (SPI) [8], diatom model affinity (DMA) [38], saprobic index (SI) [47], relative abundance of diatoms (RAD) [19], percent of sensitive diatoms (PSD) [4], percent motile diatoms (PMD) [5], diatom assemblage index to organic pollution (DAIpo) [58], biological diatom index (BDI) [11], trophic diatom index (TDI) [25], pollution tolerance index (PTI) [28], pampean diatom index (IDP) [18], diatom quotient (DU) [24], generic diatom index (GDI) [59], etc.

Lakes are considered open if they are connected to oceans or seas via rivers and water can flow freely between the lake and the river. Over the past century, due to natural changes, lake reclamation, engineering projects, etc., more than 100 river-connected lakes in the middle and lower reaches of the Yangtze River have silted up, diminished, or experienced artificial segmentation. In this region, only Dongting Lake and Poyang Lake are currently both larger than 500 km^2 in size and still maintain natural connection to the Yangtze River [68]. Dongting Lake has become the largest river-connected lake in the middle reaches of the Yangtze River in China. It is the most important flood plain wetland in China as well as a lake wetland with global significance with respect to protection [62]. The water quality evaluation of Dongting Lake is still largely limited to physical and chemical indices, and there are few reports that evaluate the water quality of Dongting Lake based on phytoplankton biological indices [29, 64]. The evaluation of the lake water quality based on the quantitative relationship between diatoms and their environmental influencing factors, as well as the screening of diatom indices, are yet to be accomplished.

Previous studies have shown that Dongting Lake has a much shorter retention time (14 to 18 days) than average lakes. In particular, the waterways in the east Dongting Lake area have largely the same hydrological characteristics as rivers, and the phytoplankton of Dongting Lake is dominated by diatoms (in both species and biomass) [55, 69]. Previous studies have also shown that the index of biotic integrity (IBI) can suitably assess the water quality of rivers and lakes [56, 57], thus providing the foundation for the biological evaluation of the water quality of Dongting Lake based on diatoms. Using the water quality and diatom data of Dongting Lake from 2017 to 2022, this study aimed to clarify: (1) the spatio-temporal succession characteristics of diatom communities, diatom indices and water quality indicators, (2) the relationship between diatom indices and water quality indicators, and (3) the feasibility of using diatom indices to replace water quality indices in water quality evaluation. This research thus could provide new ideas for evaluating the water quality of river-connected lakes, as well as a strong data foundation and scientific and technological support in protecting the water environment of open lakes.

Materials and methods

Study area

Dongting Lake, located at 28°30'–30°20' N and 111°40'–113°40' E in the middle Yangtze River region, is the first largest freshwater lake downstream of the Three Gorges Dam and an important international wetland for migratory birds, with the lake area of 2625 km^2, the total volume of 174×10^8 m^3, the basin area of 25.72×10^4 km^2. It is also an important ecological zone and list of Ramsar Wetlands of international importance in the world designated by World Wildlife Fund (WWF). Dongting Lake is fed by seven rivers, covering four tributaries (Xiang river, Zi river, Yuan river and Li river) and three outlets of the Yangtze River (Songzi river, Hudu river and Ouchi river), and its outflow returns into the Yangtze River from Chenglingji section, which plays an important role in flood control and storage, biodiversity protection, water supply and climate regulation [63, 69].

A total of 15 sampling sites were set up in Dongting Lake(DL): Shahekou (S1), Nanzui (S2), Potou (S3), Jiangjiazui (S4) and Xiaohezui (S5) represented Western Dongting Lake (WD); Wanzi Lake (S6), Wanjiazui (S7), Hengling Lake (S8), Yugongmiao (S9) and Zhangshugang (S10) represented Southern Dongting Lake (SD); Lujiao (S11), East-Dongting Lake (S12), Big-small west Lake (S13), Yueyanglou (S14) and Dongting Lake outlet (S15) represented Eastern Dongting Lake (ED). The overall situation of the study area in Dongting Lake was shown in Fig. 1.

Sampling and analyses

We carried out sampling seasonally from 2017 to 2022 at 15 sites, obtaining with 356 samples in Dongting Lake, including 120, 120 and 116 samples from West Dongting Lake, South Dongting Lake and East Dongting Lake respectively. Water samples were collected from the surface to bottom (three depth) at each site. YSI-EXO professional plus for water quality was used to measure the temperature of water (WT, ℃), electrical conductivity (Cond, S/m), dissolved oxygen (DO, mg/L) and pH in real time at each sampling site. The water transparency (SD, m) was measured using the Secchi disk method. The samples were maintained cool, kept in the dark, and transported to the laboratory within 24 h for analysis. The biochemical oxygen demand (BOD_5, mg/L) was measured by standard dilution method, potassium permanganate (COD_{Mn}, mg/L) was measured by the acidic potassium permanganate method, chemical oxygen demand (COD_{Cr}, mg/L) was measured by potassium dichromate method, ammonia nitrogen (NH_4^+–N, mg/L) was measured by Nessler's reagent spectrophotometry, total phosphorus (TP, mg/L) was measured by ammonium molybdate spectrophotometry, total nitrogen (TN, mg/L) was measured by the alkaline potassium persulfate digestion-UV spec-trophotometric method and Chlorophyll a (Chl*a*, μg/L) was measured by acetone extraction spectrophotometry, which referenced to [35].

The sampling of phytoplankton in both left and right side of each site was carried out from bottom to top in the water column with Stratified sampler, and the collected organisms were stored in 1.5% (V/V) Lugol's and kept a cylindrical separating funnel with a volume of 1L. After the samples were kept in the laboratory for 48 h, the supernatant was gradually sucked through a siphon until the volume of the water sample was concentrated to the final volume of 30 mL. Non-diatom phytoplankton was analyzed using a 0.1 mL counting chamber at a magnification of 400× (Zeiss Axio Obse microscope). Permanent diatom samples were cleaned using a strong acid solution ($HNO_3 + H_2SO_4$; 2:1), from each sample, about 500 valves were counted for each sample using a Zeiss Axio Obse microscope at 1000× under oil immersion. Phytoplankton was identified to the lowest taxonomic level (genus or species) and its densities were expressed as ind./L. Taxonomic identification was performed according to a previously described method [23] and AlgaeBase (www.alagebase.org). Meanwhile, the experts were invited to verify identification results.

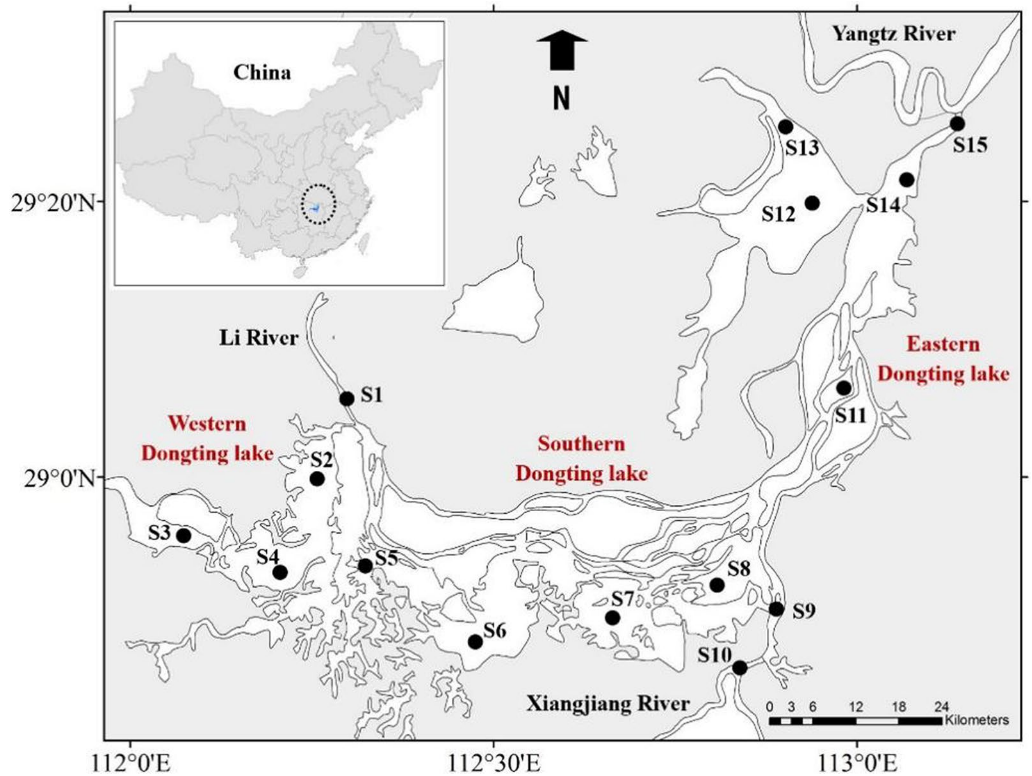

Fig. 1 Sampling sites in Dongting Lake. S1: Shahekou; S2: Nanzui; S3: Potou; S4: Jiangjiazui; S5: Xiaohezui; S6: Wanzi Lake; S7: Wanjiazui; S8: Hengling Lake; S9: Yugongmiao; S10: Zhangshugang; S11: Lujiao; S12: East-Dongting Lake; S13: Big-small West Lake; S14: Yueyanglou; S15: Dongting Lake outlet

Data analysis

As shown in Table 1, seven diatom indices, including relative abundance of diatoms (RAD), percent motile diatoms (PMD), generic diatom index (GDI), diatom quotient (DU), pollution tolerance index for diatoms (PTI), trophic diatom index (TDI), pampean diatom index (IDP), were selected from three aspects: cell abundance, taxonomic composition and pollution tolerance.

The trophic level of the water body was calculated as follows:

$$\sum TLI = \sum_{j} W_j \cdot TLI(j)$$

ΣTLI is the comprehensive trophic level index, $TLI(j)$ is the trophic level index of the j-th parameter, and W_j is the weight of $TLI(j)$. The TLI parameters include Chl$a$, TP, TN, SD, and COD_{Mn}. The grading methods and the calculation of indexes and weights are based on the literature [54].$\sum TLI < 30$ indicates poor trophication, $30 < \sum TLI < 50$ indicates medium trophication, $50 < \sum TLI < 60$ indicates mild eutrophication, $60 < \sum TLI < 70$ indicates moderate eutrophication, and $\sum TLI > 70$ indicates severe eutrophication.

The Nemerow index (NI) is adopted for comprehensive evaluation of water pollution [36], and the calculation formula is as follows:

$$\mathrm{NI} = \sqrt{(F_{max}^2 + F^2)/2};\ F = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{C_i}{S_{ij}};\ F_{max} = max\left[{C_i}/{S_{ij}}\right]$$

Table 1 Candidate indices of diatoms [5, 18, 19, 24, 25, 28, 59]

Category	Metrics	Index calculation and description	Response
Richness	RAD: Relative abundance of diatoms	Number of diatom cells/Total number of phytoplankton cells; Reflecting the nutritional status of water	Decrease
Taxonomic Composition	PMD: Percent motile diatoms	The relative abundance of [Navicula + Nitzschia + Surirella]; Reflecting the degree of sediment deposition	Increase
	GDI: Generic diatom index	Number of [Achnanthes + Cocconeis + Cyclotella] cells/ Number of [Cymbella + Melosira + Nitzschia] cells; Reflecting the degree of water pollution	Decrease
	DU: Diatom quotient	Number of Centrales cells/ Number of Pennales cells; Reflecting the degree of water pollution	Increase
Tolerance and intolerance index	PTI: Pollution tolerance index for diatoms	$PTI = \sum \frac{n_i t_i}{N}$ n_i is the cell number of species *i*, t_i is the tolerance value of species *i* (Table S1), *N* is the total cell number; Reflecting the degree of water pollution	Decrease
	TDI: Trophic diatom index	TDI = (WMS × 25) −25; $WMS = \sum a_j v_j i_j / a_j v_j$ a_j was the abundance of species *j* in the sample. v_j was the indicator value of eutrophication sensitivity of species *j*, which varies between 1–3. i_j is the pollution sensitivity of species *j*, which varies between 1 and 5 (Table S2 for sensitive values); Reflecting eutrophication status of water	Increase
	IDP: Pampean diatom index	$IDP = \sum I_{idp} \times A_j / \sum A_j$ I_{idp} represents the specific value 0–4 of species *j* (Table S3 for details), and *Aj* represents the relative abundance of species *j;* Reflecting the degree of organic pollution and eutrophication of water	Decrease

C_i is the measured concentration of the *i*th pollution factor. S_{ij} is the standard value of the *i*th pollution factor under the *j*th standard. China's GB 3838–2002 Class III water quality standard limit was selected as the standard value, and the classified water quality standard limit is shown in Table 2. NI < 1 indicates little pollution, 1 ≤ NI < 2 indicates light pollution, 2 ≤ NI < 3 indicates medium pollution, 3 ≤ NI < 5 indicates moderate pollution, and NI ≥ 5 indicates severe pollution.

The stepwise multiple-linear regression models were used to explore the relationships between diatom indices and environmental variables. The value of R^2_{adj} was used to identify the most fitting model. Spearman correlation coefficients between environmental parameters and diatom indices were calculated to explore the correlation of the diatom indices with the environmental parameters. A multiple regression model was used to verify the correlation between diatom indices and comprehensive water pollution index. The Spearman correlations, multiple regression model, and variance decomposition were performed in R using the "psych", "relaimpo" packages, respectively, and visualized using the "ggplot2" package.

Table 2 Five classes of surface water bodies of water environmental quality standards (GB3838-2002) in China

Indicators (mg/L)		Classes				
		I	II	III	IV	V
TN	≤	0.2	0.5	1.0	1.5	2.0
TP (River)	≤	0.02	0.1	0.2	0.3	0.4
TP (Lake or reservoirs)	≤	0.01	0.025	0.05	0.1	0.2
NH_4^+–N	≤	0.15	0.5	1.0	1.5	2.0
DO	≥	90% or 7.5	6	5	3	2
COD	≤	15	15	20	30	40
BOD_5	≤	3	3	4	6	10
COD_{Mn}	≤	2	4	6	10	15

Table 3 Environmental variables at Dongting Lake in different periods†

	WT (℃)	pH	Conductivity (S/m)	DO (mg/L)	COD_{Mn} (mg/L)	BOD_5 (mg/L)	COD_{Cr} (mg/L)	NH_4^+–N (mg/L)	TN (mg/L)	TP (mg/L)
March 2017	12.89 (11.60–13.70)	7.62 (7.36–7.85)	26.03 (21.70–39.30)	9.30 (8.53–10.01)	2.13 (1.67–5.25)	2.18 (1.57–5.85)	9.20 (4.17–25.50)	0.28 (0.10–0.44)	1.98 (1.14–2.71)	0.07 (0.05–0.11)
June 2017	24.10 (22.50–25.40)	7.51 (7.25–7.75)	23.08 (19.90–37.70)	6.97 (5.45–7.57)	2.41 (1.73–4.8)	1.86 (1.40–3.70)	9.79 (6.33–20.50)	0.16 (0.06–0.34)	1.88 (1.49–2.41)	0.07 (0.05–0.13)
September 2017	26.67 (25.20–28.40)	7.53 (7.29–7.75)	23.91 (17.40–31.60)	6.77 (5.50–7.30)	2.44 (1.87–5.95)	1.80 (1.27–4.25)	10.08 (5.33–28.50)	0.15 (0.01–0.43)	1.56 (0.89–2.38)	0.09 (0.06–0.11)
December 2017	12.49 (10.20–15.80)	7.54 (7.35–7.74)	26.26 (20.50–35.30)	9.04 (6.70–10.65)	2.17 (1.33–4.55)	1.62 (0.70–4.20)	11.17 (6.50–23.00)	0.29 (0.11–0.50)	1.91 (1.40–2.57)	0.08 (0.04–0.12)
March 2018	12.61 (6.20–18.20)	7.81 (7.50–8.34)	25.01 (10.30–36.00)	9.46 (7.62–10.71)	2.06 (1.39–5.31)	1.28 (0.50–2.40)	8.61 (5.00–21.50)	0.30 (0.12–0.65)	1.76 (0.94–2.71)	0.07 (0.04–0.12)
June 2018	23.32 (18.20–26.50)	7.58 (7.08–8.18)	23.93 (18.70–31.40)	7.13 (6.30–8.30)	2.35 (1.70–5.01)	1.05 (0.20–2.00)	9.63 (4.00–23.00)	0.08 (0.02–0.23)	1.96 (1.26–2.61)	0.07 (0.04–0.09)
September 2018	29.70 (25.00–31.70)	7.51 (6.94–8.17)	24.87 (15.40–33.70)	6.65 (5.30–8.47)	2.31 (1.59–3.22)	1.22 (0.20–2.80)	8.52 (5.00–18.50)	0.10 (0.02–0.22)	1.46 (0.98–2.14)	0.06 (0.05–0.08)
December 2018	15.16 (10.00–17.20)	7.41 (6.45–8.35)	25.45 (18.90–48.20)	8.88 (6.15–10.13)	2.12 (1.13–5.03)	1.42 (0.50–3.05)	7.87 (4.00–24.00)	0.14 (0.03–0.38)	1.66 (1.33–2.18)	0.07 (0.04–0.11)
March 2019	10.27 (8.50–14.00)	7.44 (7.06–8.16)	23.95 (18.70–35.00)	10.85 (8.18–12.88)	2.17 (1.60–4.30)	1.55 (0.60–3.80)	7.87 (4.00–20.00)	0.24 (0.04–0.73)	1.95 (1.13–2.59)	0.06 (0.04–0.10)
June 2019	23.88 (20.00–27.60)	7.64 (7.21–8.00)	21.38 (12.80–35.40)	7.65 (6.60–9.15)	2.37 (1.50–6.60)	1.45 (0.20–4.40)	8.80 (2.00–34.00)	0.08 (0.02–0.19)	1.55 (1.32–2.23)	0.07 (0.05–0.12)
September 2019	28.21 (21.00–31.00)	7.59 (6.75–8.38)	25.03 (16.00–32.50)	6.88 (5.69–8.66)	2.49 (1.60–6.40)	1.44 (0.20–4.00)	10.00 (6.00–37.00)	0.09 (0.02–0.36)	1.65 (1.04–2.14)	0.06 (0.03–0.12)
December 2019	12.73 (8.50–15.20)	7.75 (7.10–8.11)	27.69 (21.10–46.00)	9.07 (7.69–11.59)	2.10 (1.60–4.20)	1.71 (0.60–2.80)	8.33 (4.00–26.00)	0.16 (0.02–0.36)	1.63 (0.77–2.17)	0.07 (0.04–0.09)

† Data are summarized as the mean and the range

Results

Water quality

Some water quality indicators varied strongly between the dry season (March, December) and the rainy season (June, September) and between different sampling areas (Table 3). WT in different seasons was 10.27–29.70 ℃ and was a lot higher (> 12 ℃) in the rainy season than in the dry season. The average pH value (7.41–7.81) was relatively stable across seasons but varied a lot in 2018 among different sampling areas. The average conductivity ranged in 21.38–27.69 S/m across seasons, and it was highly variable among sampling sites, with the difference up to 20 S/m. DO ranged in 6.65–10.85 mg/L across seasons and was much higher (> 2 mg/L) in the dry season than in the rainy season. NH_4-N ranged ranged in 0.08–0.28 mg/L across seasons and was much higher (two to three times) in the dry season than in the rainy season.

There were little seasonal changes in some water quality indicators, for example, throughout the year COD_{Mn} ranged stably within 2.10–2.49 mg/L, BOD_5 ranged stably within 1.05–2.18 mg/L, COD_{Cr} ranged stably within 7.87–11.17 mg/L, TN ranged stably within 1.46–1.98 mg/L, and TP ranged stably within 0.06–0.09 mg/L. Nevertheless, there were substantial variations among sampling sites for COD_{Mn} (> 3 mg/L), BOD_5 (> 2 mg/L), and COD_{Cr} (> 15 mg/L).

Figure 2 shows that from 2017 to 2019, the ΣTLI of the whole Dongting Lake ranged from 45.99 to 50.72, with an average value of 47.85. The lake was overall in a mesotrophic state The eastern area was mildly eutrophic and had notably higher ΣTLI than the rest of the lake. Both the western and the southern areas were mesotrophic, and their ΣTLI exhibited some decline over time. This decline was the most notable for the western lake area, where ΣTLI dropped from 46.43 in 2017 to 40.69 in 2019.

Diatoms and indices

A total of 21 diatom species were identified at Dongting Lake from 2017 to 2019. Among them, the frequency (100%) and abundance of Melosira were the highest, which *Aulacoseira granulata* (Ehrenberg) Simonsen was the dominant population in all seasons, especially in March 2019, followed by Navicula (83.3%), Synedra (75%), Cyclotella (66%), and the frequency of other diatoms was relatively low. Figure 3 shows the temporal variations of the diatoms in the whole lake and in eastern, southern, and western lake areas. Among the three areas, the average diatom density fell in the order of east (20.34×10^4 ind./L) > west (9.36×10^4 ind./L) > south (8.98×10^4 ind./L). The diatom density gradually decreased from 2017 to 2019 for the whole lake as well as for each area, especially in 2018, and the decline was more obvious in the southern and western lake areas.

From 2017 to 2019, the ranges of the diatom indices were: PTI, 0.315–2.87; PMD, 0–0.417; GDI, 0–2.14; DU, 0–14.3; RAD, 0.109–1.00; TDI, 35.3–86.5; IDP, 1.38–2.66 (Fig. 4). Among them, PTI, PMD, RAD, and TDI varied notably across different seasons and sampling sections. From 2017 to 2019, PTI, PMD, and RAD increased initially and decreased subsequently. The decrease was particularly obvious in September 2019, when PTI, PMD, and RAD reached their minimum values of 1.12, 0.06, and 0.419, respectively. Conversely, DU and TDI decreased initially and then increased, and the increase was particularly obvious in September 2019, GDI increased in 2017, and then decreased across 2018 and early 2019, when GDI and TDI attained their maximum

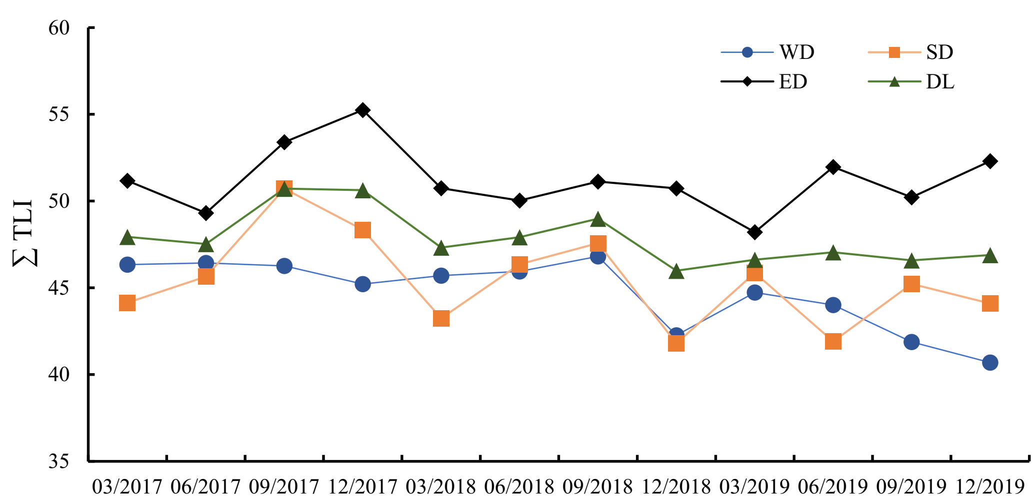

Fig. 2 The trophic level index (ΣTLI) of different lake areas from 2017 to 2019. DL, Dongting Lake; WD, western lake area; SD, southern lake area; ED, eastern lake area

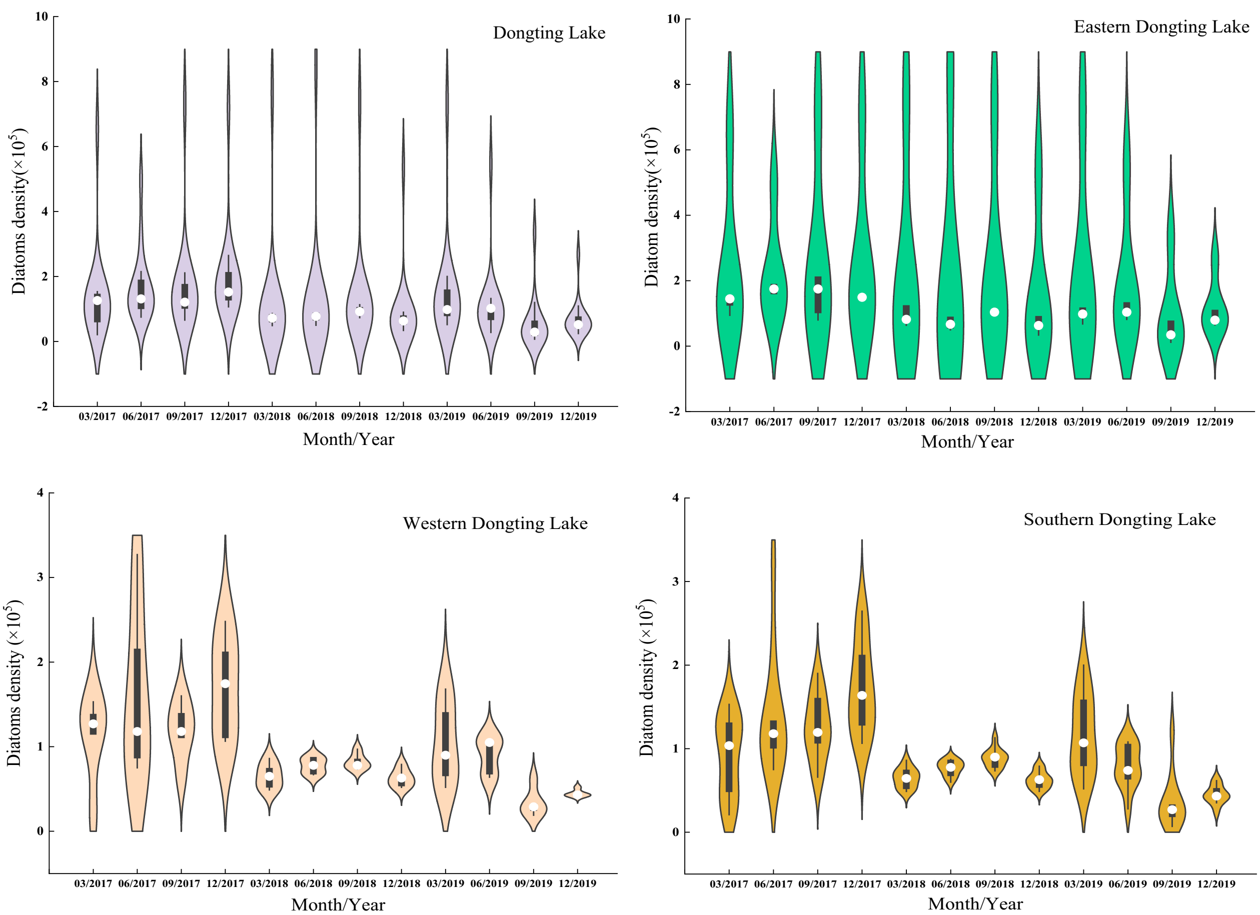

Fig. 3 The diatom density of different lake areas. DL, Dongting Lake; WD, western lake area; SD, southern lake area; ED, eastern lake area

values of 0.627 and 73.2, respectively. IDP was relatively stable and changed little over time.

Among different lake areas, PTI, PMD, and RAD were obviously higher in the western (S1,S2,S3,S4,S5) and southern areas (S6,S7,S8,S9,S10) than in the eastern (S11,S12,S13,S14,S15) area, and S13 had the minimum values of PTI = 0.746, PMD = 0.052, and RAD = 0.288. For all lake areas, GDI, DU, and IDP did not change much, and their maximum values were from the western lake area (GDI = 0.409, DU = 2.02, IDP = 2.18). TDI was obviously higher in the eastern lake area than in the western and southern lake areas, and the maximum value was at S13 (TDI = 71.5).

Screening of diatom indices

Figure 5 presents the correlation analysis between water quality indicators and the diatom indices. WT had significant negative correlation with PMD (R = −0.18, $p < 0.05$) and significantly positive correlation with GDI (R = 0.27, $p < 0.01$). pH and TN had some insignificant correlations with the diatom indices. NH_4^+–N was significantly positively correlated with Σ*TLI* (R = 0.26, $p < 0.01$). Cond, COD_{Mn}, COD_{Cr}, BOD_5, and Σ*TLI* were all significantly negatively correlated with PTI, RAD, and PMD. Significantly positive correlation existed between Cond and DU (R = 0.17, $p < 0.05$) and between COD_{Mn} and TDI (R = 0.20, $p < 0.05$). DO was correlated significantly positively with PTI (R = 0.24, $p < 0.01$) and RAD (R = 0.23, $p < 0.01$) but significantly negatively with GDI (R = −0.19, $p < 0.05$). TP had significantly negative correlations with PTI (R = −0.19, $p < 0.05$) and RAD (R = −0.21, $p < 0.05$).

Among the diatom indices, PTI had significant correlations with RAD (R = 0.99, $p < 0.001$), PMD (R = 0.54, $p < 0.001$), TDI (R = −0.32, $p < 0.001$), and GDI (R = −0.20, $p < 0.05$). PMD had significant correlations with RAD (R = 0.61, $p < 0.001$), IDP (R = 0.43, p < 0.001), and DU (R = −0.31, $p < 0.001$). RAD had significant correlations with TDI (R = −0.30, $p < 0.001$), GDI (R = −0.19, $p < 0.05$), and DU (R = −0.18, p < 0.05). Significant correlations also existed between DU and TDI (R = 0.30, $p < 0.001$) and between TDI and IDP (R = 0.20, $p < 0.05$).

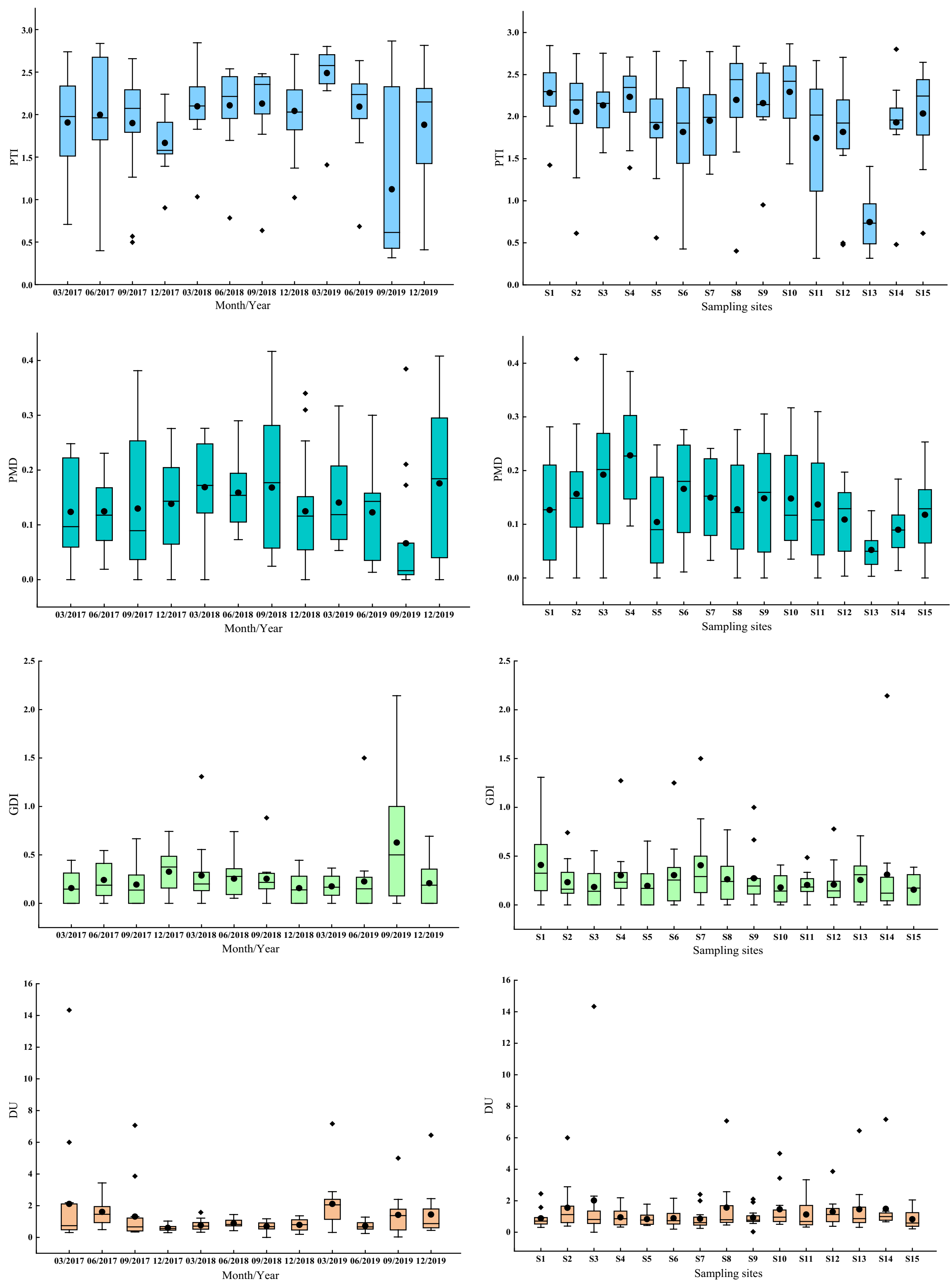

Fig. 4 Spatiotemporal variation of diatom indices

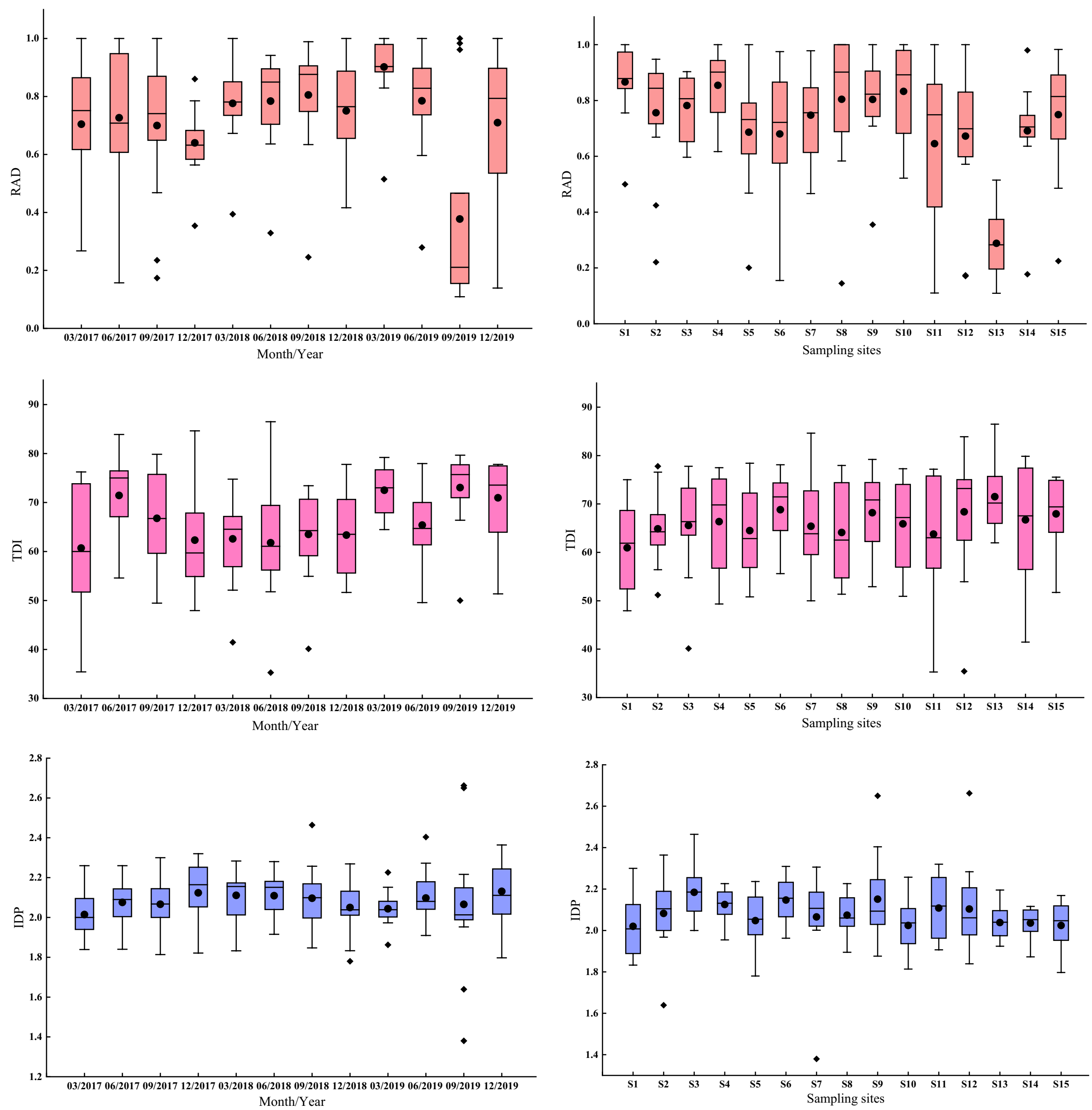

Fig. 4 continued

No significant relationship existed between environmental factors and DU or IDP. Table 4 lists the linear regression models of the diatom indices PTI, RAD, PMD, GDI, TDI, and DU. In general, the main water quality factors influencing diatom indices includes WT, Cond, DO, COD_{Mn}, BOD_5, COD_{Cr}, and TP. However, existing water quality standards lacked specifications about conductivity. Among the models in Table 4, GDI, TDI, and DU were not selected for the next comparison screen because they had WT, COD_{Mn}, and Cond as the only relevant variables with the small correlation coefficients, respectively. In addition, PTI was also problematic because the coefficient for TP was positive in the linear model of PTI, but TP was negatively correlated with PTI (Fig. 5). After comprehensive consideration, the Nemerow index for 2020–2022 was calculated using DO, COD_{Mn}, BOD_5, and COD_{Cr}, to verify the correlation between the diatom indices and the water quality indicators. Figure 6 shows that the Nemerow index ranged in 0.772–1.209 for the whole Dongting

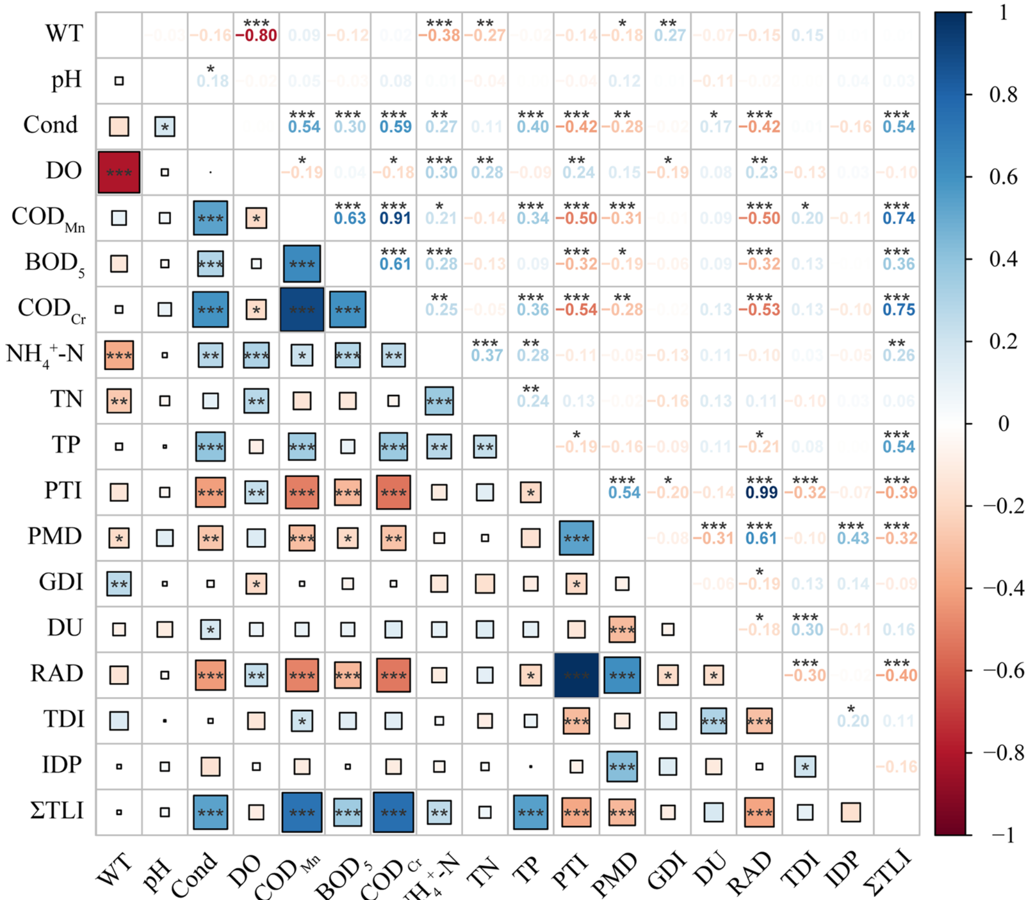

Fig. 5 Correlation analysis of water quality indicators and diatom indices.**P* < 0.05, ***P* < 0.01, ****P* < 0.001

Table 4 Temporal linear regression models of diatom indices†

Metric	Linear regression model	R^2_{adj}	*p*
PTI	$2.340 - 0.016Cond + 0.075DO - 0.130COD_{Mn} - 0.084BOD - 0.021COD_{Cr} + 0.029TP$	0.263	< 0.01
RAD	$0.895 - 0.006Cond + 0.025DO - 0.052COD_{Mn} - 0.028BOD - 0.007COD_{Cr} - 0.089TP$	0.256	< 0.01
PMD	$0.231 - 0.002Cond - 0.014COD_{Mn} - 0.004BOD - 0.001COD_{Cr}$	0.057	< 0.01
GDI	$0.1169 + 0.007WT$	0.032	< 0.05
TDI	$61.544 + 2.055COD_{Mn}$	0.032	< 0.05
DU	$0.606 + 0.024Cond$	0.003	< 0.05

† A stepwise selection procedure based on the independent variables was used

Lake and remained relatively stable between 2020 and 2022. Within the lake, the Nemerow index ranked in the order of eastern area > southern area > western area.

The above correlation analysis of diatom indices showed that PTI, RAD and PMD indices covered most of the information of DU, GDI, TDI and IDP indices. Therefore, PTI, RAD, and PMD were selected for the next correlation screen with the Nemerow index (Fig. 7). Both RAD and PTI were strongly and significantly associated with the Nemerow Index ($R^2 = 0.31$, $p < 0.001$, Fig. 7a, d). The correlation between PMD and Nemerow index was less strong but also significant ($R^2 = 0.07$, $p < 0.001$, Fig. 7b) Extremely significant positive correlation existed between RAD and PTI ($R^2 = 0.99$, $p < 0.001$, Fig. 7f), and RAD also had a significant

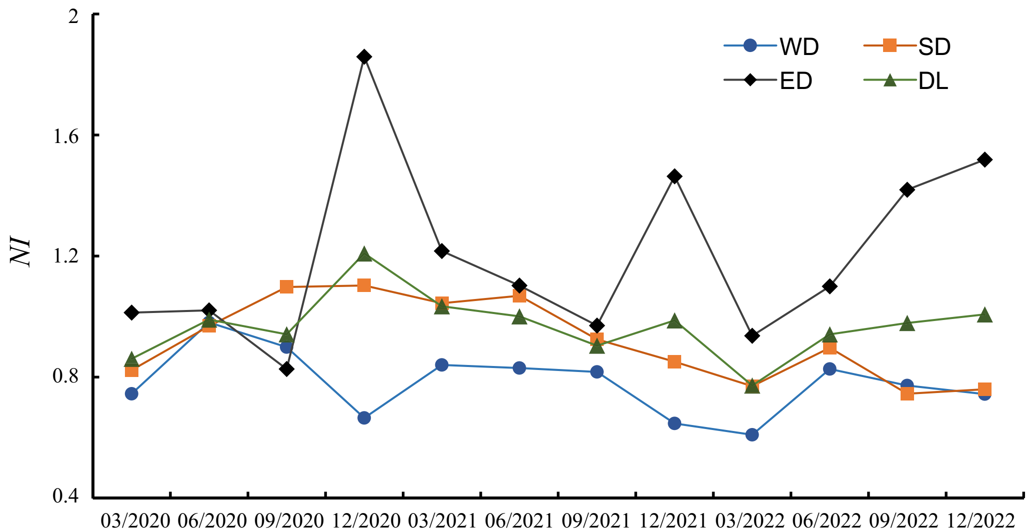

Fig. 6 Nemerow index from 2020 to 2022

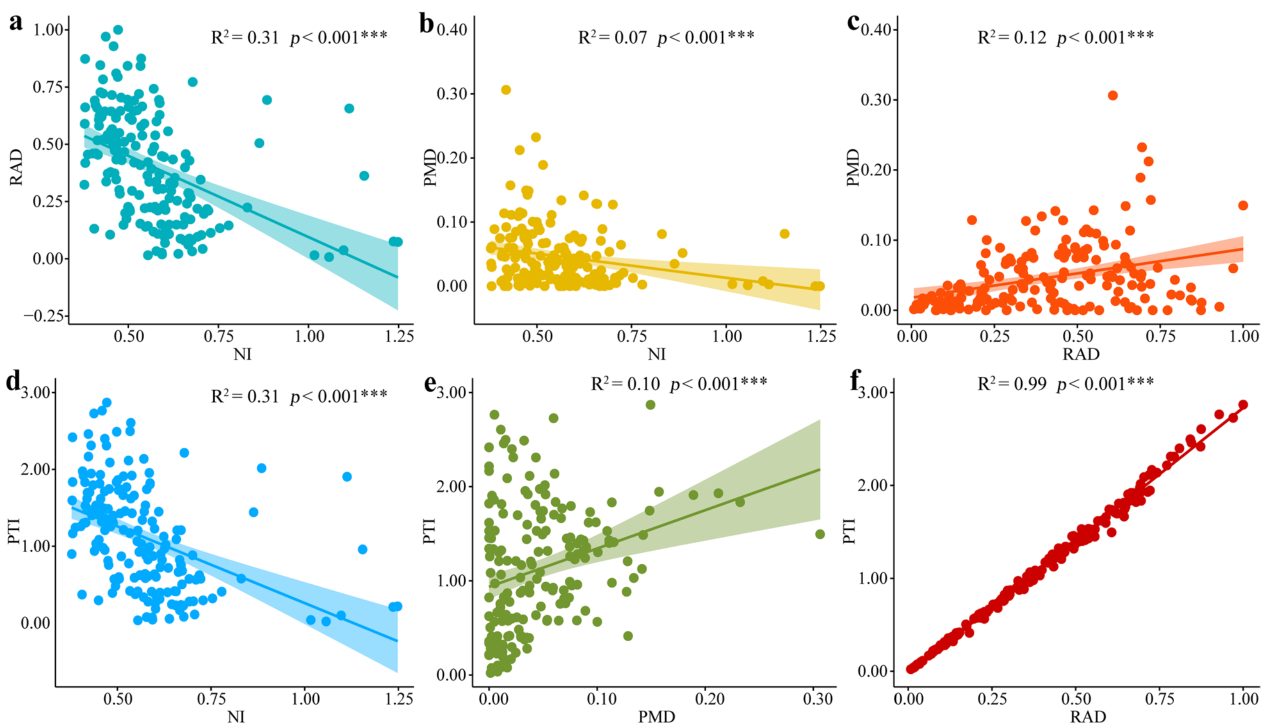

Fig. 7 Correlations among PTI, RAD, PMD, and the Nemerow index (NI)

positive correlation with PMD ($R^2 = 0.12$, $p < 0.001$, Fig. 7c). That is, RAD possessed the main information covered in PMD and could thoroughly represent PTI, and it was highly positively correlated with the Nemerow index. The calculation of RAD was also relatively simple. Thus, RAD was considered as the suitable diatom index for the biological evaluation of the water quality at Dongting Lake.

Discussion

Temporal and spatial variations of diatoms and water chemistry

Three distinct stages could be distinguished for the dominant phytoplankton in Dongting Lake since the early 1990s, i.e., (1) from 1990 to 1999, when diatoms were completely dominant, (2) from 2000 to 2010, when both diatoms and cryptophytes were dominant, and (3) from 2010 to 2022, when both diatoms and chlorophytes were dominant [29, 52, 69]. In this study, although the abundance of diatoms declined to a certain extent from 2017 to 2019, it still accounted for 47.3% of the total phytoplankton abundance and was much more abundant than chlorophytes, which had the second highest abundance (24.2%) (Fig. 1). The diatom abundance in the eastern lake area was obviously higher than that in the western and southern lake areas, mainly due to the shallower water depth, the higher light transmittance, and the slower water velocity, which are more suitable for phytoplankton growth. The section of S13 is in the backwater area and had significantly higher phytoplankton abundance than elsewhere.

The water quality of Dongting Lake used to be Class I to Class III in the 1990s, but is currently mainly Class IV, with regions that are Class V or worse than Class V. The lake as a whole is mildly polluted, and the main pollutant is TP [53, 61]. In addition, the level of TN in the lake is also high, although TN is not considered in the water quality assessment. In this study, the water quality of Dongting Lake were Class IV from 2017 to 2019 due to TP, however, DO, COD_{Mn}, BOD_5, COD_{Cr}, NH_4^+–N all belonged to Class III (Water quality objective of Dongting Lake) (Table 3). The high TP and TN provide ample nutrition and facilitate the growth of phytoplankton. Mesotrophic lakes are often dominated by diatoms, cryptophytes, and dinoflagellates, while eutrophic lakes are often dominated by chlorophytes and cyanobacteria [33, 37]. Dongting Lake has always been dominated by diatoms, but the proportion of chlorophytes has gradually increased in recent years [64, 69], and the lake has reached a tipping point between being mesotrophic and mildly eutrophic [65]. Nevertheless, in this study, Dongting Lake was still mesotrophic overall (Fig. 2), although it was mildly eutrophic in the autumn and winter of 2017. The eastern lake area was constantly mildly eutrophic in recent years, likely due to the relatively high contribution from the region near S13. The periphery of S13 is a typical backwater area of eastern Dongting Lake, where the water is shallow and flows slowly, and the nutrient concentration (nitrogen and phosphorus) is always suitable for phytoplankton growth (particularly chlorophytes and cyanobacteria) [64]. Since 2013, cyanobacteria had become the dominant phytoplankton population a few times in the region around S13. The rising phytoplankton abundance also increased the chlorophyll *a* level, which further promoted the nutrient levels in the water.

Correlation between diatom indices and water quality factors

Dongting Lake is the largest river-connected lake in the middle and lower reaches of the Yangtze River in China. Dongting Lake is fed by seven rivers, and its outflow returns into the Yangtze River from Chenglingji section. The average water residence time is 14 to 18 days at Dongting Lake, and the water volume of the lake changes rapidly. The lake experiences fast water mixing, and the thermal stratification is not obvious [69]. As a result, most areas in the lake, especially the channel areas, are like rivers in their hydrological characteristics. In addition, the entire lake area is dominated by diatoms. Therefore, the diatom indices that are widely used in the biological evaluation of the water quality of rivers were examined in this study, to determine how different diatom indices responded to the water quality indicators at Dongting Lake.

The ΣTLI accounts for the permanganate index and major pollutants such as nitrogen and phosphorus, and it is higher when the water body is more polluted. The indices RAD, GDI, PTI, and IDP all responded inversely to pollution stress and trophic status, and RAD and PTI responded extremely significantly to ΣTLI. In contrast, DU and TDI responded positively to ΣTLI. The results are consistent with the correlation analysis in Fig. 5. It is worth commenting that PMD had a positive response to the degree of sedimentation in the water body. Areas with stronger sediment mixing have lower SD, which inhibits phytoplankton growth [10, 45] and reduces the Chl*a* concentration (a proxy of the phytoplankton abundance), ultimately decreasing the ΣTLI of the water body. This is consistent with the very significantly negative correlation between PMD and ΣTLI found in Fig. 5.

The correlation analysis showed that three indices PTI, RAD, and PMD, which were mainly correlated with WT, Cond, DO, COD_{Mn}, BOD_5, COD_{Cr}, and TP, could fully cover the relevant information in DU, GDI, TDI, and IDP. It is generally believed that higher temperature facilitates the reproduction and growth of chlorophytes and cyanobacteria [2, 40] but not diatoms, which prefer cooler water [1, 50]. Both Navicula and Melosira were dominant in Dongting Lake, but their abundances were correlated positively with PMD and negatively with GDI, respectively. As a result, WT correlated positively with GDI ($p < 0.01$) but negatively with PMD ($p < 0.05$). The observed significantly positive correlation between RAD and DO could be attributed to the fact that phytoplankton absorbs carbon dioxide and releases oxygen during photosynthesis [12]. It has been reported that Navicula and Melosira, which are dominant taxa in Dongting Lake, have significantly positive correlations with DO [64], and the rising Melosira abundance decreases the GDI. Indeed, the present work found that DO was significantly negatively correlated with GDI. Among the water quality indicators, COD_{Mn} and COD_{Cr} represent the amounts of chemical oxidants required to decompose the organic matters in the water, BOD_5 represents the amount of oxygen required by microorganisms to oxidize and decompose the organic matters, and TP represents the concentration of nutrients in the water. Since 2000, and especially in recent years, there was remarkable growth in manufacturing, agriculture, and service industry in the Dongting Lake Economic Belt. The lake experienced rising pollution stress with the direct and indirect discharge of large amounts of domestic sewage, agricultural wastewater, and organic pollutants from the processing of agricultural products, building materials, textiles and clothing, papermaking, chemical industry, etc. [69]. Conductivity is related to the content of dissolved substances in water. The photosynthesis of cyanobacteria is achieved through the transfer of energy and electrons between photosystems. During photosynthesis, the energy and electron transfer takes place as $(PSII) \overset{e}{\rightarrow} PSI \overset{e}{\rightarrow} NADPH$, and the generated carbohydrates are used for growth and metabolism [16]. Therefore, higher conductivity could to some extent promote the growth of cyanobacteria and inhibit the growth of diatoms. The current results showed that both PTI and RAD were significantly negatively correlated with Cond, COD_{Mn}, COD_{Cr}, BOD_5, and TP, whereas DU and TDI were significantly positively correlated with Cond and COD_{Mn}. The findings were consistent with increase in water pollution at Dongting Lake as well as the significantly negative correlations between the dominant phytoplankton (Navicula and Melosira) and Cond, TP, and COD_{Mn} [64].

Biological assessment of water quality based on diatom indices

Phosphorus has different ecological effects on the surface water with different properties. It is specified in China's *Environmental Quality Standards for Surface Water* (GB3838-2002) that the limit of total phosphorus (calculated as P) is 0.2 mg/L for class III rivers and 0.05 mg/L for class III lakes [32]. Excessive total phosphorus has been an entrenched problem at Dongting Lake, for which the local government took measures to address industrial point sources, agricultural non-point sources, and carried out comprehensive river training and management programs. These efforts significantly reduced the black and smelly water bodies in the basin, strengthened the interconnection of water systems, limited the deterioration of water quality, and improved the quality of the ecological environment notably [67]. Nevertheless, the water quality assessment of Dongting lake remained unchanged, although TP met the criteria for water quality assessment in rivers, it exceeds the criteria for lake assessment once it enters the lake. For example, the average annual TP was 0.076 mg/L, 0.065 mg/L, 0.062 mg/L, and 0.065 mg/L respectively for Xiangjiang, Zijiang, Yuanjiang, and Lishui, all of which flow into Dongting Lake, and the annual average TP measured at Songzikou, Taipingkou, and Ouchikou along the Yangtze River was 0.112 mg/L, 0.096 mg/L, and 0.115 mg/L, respectively. Consequently, the TP of Dongting Lake remained high. Local authorities urgently need practical evaluation indicators and methods that can comprehensively reflect the water quality status of Dongting Lake and other large and medium-sized river-connected lakes (e.g., Jingpo Lake [57] in northern China).

As stated previously, physical and chemical indicators have their limitations in reflecting the water quality, and biological indicators can reflect the quality of the water environment more comprehensively and accurately. In this study, the three indices of PTI, RAD, and PMD were selected using the 2017–2019 data and verified using the 2020–2022 data. Figure 7 shows that all three indices were significantly negatively correlated with the Nemerow index. Nemerow index is recommended by GB/T 14848-93 in China, which is simple to calculate and has always been the main method for water quality assessment in Dongting Lake [21, 44, 70]. The correlation between RAD and PTI was close to 1, and they both had stronger correlation with the Nemerow index than PMD and had significant positive correlation with PMD. In terms of calculation, PMD would appear the phenomenon of zero value, and PTI needs to calculate the tolerance value of diatoms to external stress Hence, RAD emerged as the most suitable biological indicator to evaluate the water quality of Dongting Lake. Previous studies have shown that diatoms are dominant in mesotrophic lakes [37], the relative abundance of dominant diatoms are closely related to water quality in Daihai Lake [60], RAD has been selected as an important index for biological assessment of water quality in Dongting Lake during the construction of the aquatic biological integrity index [56], and TN and TP are main driving factors of seasonal succession of diatom community [13]. Of course, the suitability of RAD for water quality assessment in different regions will certainly vary, and we need to assess the accuracy of RAD based on the type and characteristics of the water body.

As a whole, RAD can play an important role in water quality assessment of different lakes in China, which is worthy of attentions by local authorities and need suitability assessment and promotion according to the regional characteristics.

Conclusions

In this study, we investigated water quality and phytoplankton in March, June, September and December from year 2017 to 2022, and selected seven diatom indices, including RAD, PMD, GDI, DU, PTI, TDI and IDP, to screen the adaptability of water quality assessment comparing with NI. The results from 2017 to 2019 showed that the diatom density in Dongting Lake ranged from 0.7×10^4 to 85.5×10^4 ind./L, with a certain decreasing trend. The spatial and temporal changes of major water quality factors were obvious, and the $\sum TLI$ ranged from 45.99 to 50.72, with an average value of 47.85, indicating that the overall condition of Dongting Lake was medium nutrition. Correlation analysis showed that PTI, RAD and PMD could represent the information of DU, GDI, TDI and IDP, and were significantly positively correlated with DO ($p<0.01$), while significantly negatively correlated with Cond, COD_{Mn}, BOD_5, COD_{Cr} and $\sum TLI$ ($p<0.001$). The index verification results from year 2020 to 2022 showed that PTI, RAD and PMD were all significantly positively correlated with NI ($p<0.001$). Taking into account the data integrity of the index calculation (PMD would appear the phenomenon of zero value) and the difficulty degree (PTI index needs to calculate the tolerance value of diatoms to external stress), RAD was finally selected as the biological indicator for evaluating the water quality of Dongting Lake. The water quality of Dongting Lake has been evaluated according to the lake standard for a long time in China, however, the water quality is difficult to meet the standard just because the concentration of TP was always exceeded the Class III water quality standard set by the state (0.05 mg/L).

The results of this study provided an alternative method for the water quality assessment of Dongting Lake, and also put forward a new path for the water quality assessment of the river-connected lakes. In the future, we will screen the diatom indices suitable for water quality assessment in a wider scope, and study the evaluation grade of the diatom indices combined with the existing water quality factor classification and evaluation criteria, in order to provide scientific basis for local administrative departments to carry out accurate and standardized management of river-connected lakes.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-024-00927-4.

Additional file 1.

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Author contributions
Conceptualization, Xing Wang; methodology, Xing Wang; software, Guanghan Yan; validation, Xing Wang and Xueyan Yin; formal analysis, Guanghan Yan; investigation, Guanghan Yan; resources, Xing Wang; data curation, Xing Wang; writing-original draft preparation, Guanghan Yan; writing-review and editing, Xing Wang; visualization, Mingsheng Huang; supervision, Xueyan Yin; project administration, Xing Wang; funding acquisition, Xing Wang. All authors have read and agreed to the published version of the manuscript.

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Data availability
The data will be shared on reasonable request to the corresponding author.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no confict of interests.

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