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Development and Evaluation of the Plankton Biological Integrity Index (P-IBI) in Dry and Wet Seasons for Dianchi Lake

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Abstract: As an important component of lake ecosystems, plankton are often used as indicators to evaluate the health of aquatic ecosystems, such as lakes and reservoirs. The plankton integrity index (P-IBI) is a highly utilized method for evaluating the ecological health of the lakes. This study took Dianchi Lake, located in the Yangtze River Basin, as the research object and analyzed the phytoplankton, zooplankton communities, and environmental factors at 11 sampling points in this lake during the wet season (July) in 2022 and the dry season (February) in 2023. The P-IBI was established to evaluate the health status of this lake ecosystem. The results showed that a total of 83 species of phytoplankton and 31 species of zooplankton were identified in Dianchi Lake, and the number of plankton species in the dry season was significantly higher than that in the wet season. The P-IBI evaluation results for the two hydrological periods were generally "good". Linear regression analysis showed that there was a certain negative correlation between the P-IBI value and the comprehensive trophic level index (TLI), and the evaluation results were generally in line with the actual situation of the water body. Redundancy analysis (RDA) showed that there was a significant correlation between the P-IBI and its constituent parameters and individual water quality environmental factors, such as total nitrogen (TN) and electrical conductivity (EC). In summary, by reducing errors caused by spatial and temporal changes across various hydrological periods, P-IBI represents a more scientifically rigorous technique for lake water ecological health assessments within a certain time range.

Keywords: Dianchi Lake; plankton; biological integrity index; ecosystem health assessment

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1. Introduction

When a basin ecosystem is disturbed by human activities, the resulting increase in the load and carrying capacity can surpass its self-regulation abilities, leading to exacerbated lake eutrophication. Hence, the assessment of river and lake health is the chosen method to monitor changes in the condition of the water environment, to effectively manage and prevent environmental issues. Given the current nature of water ecological security, it is increasingly acknowledged that there is an equally crucial or even superior need for evaluating and safeguarding the health of rivers [1,2]. The presence of aquatic organisms, unlike the hydrological and physicochemical properties of water, is not commonly assessed in the initial evaluation of water body health [3]. Europe and the United States have conducted water ecological assessments earlier and possess extensive research outcomes and expertise [4]. The United States passed the Clean Water Act in 1972 aimed to restore and maintain the chemical, physical, and biological integrity of the nation's water bodies [5]. In 1977, the River Invertebrate Prediction and Classification System (RIVPACS) was developed in the UK [6]. And the European Union Water Framework Directive (WFD) constructed multiparametric biological evaluation models to protect rivers [7]. China was actively promoting the protection of the water environment, from pollution control to the cooperative management of water resources, water ecology, and the water environment [8,9]. Among numerous methods for aquatic ecological health evaluations, the Index of Biotic Integrity (IBI) is a highly utilized method for evaluating the ecological integrity of aquatic environments [10]. First proposed by Karr in 1981 [11], the system integrates a group of biological parameters that are closely related to changes in the surrounding environment. It displays greater sensitivity to disturbances and incorporates various structures and functional features of the biological population to generate a score. The incorporation of diverse biological measures provides an accurate and comprehensive depiction of the water system's state of health, thus positioning this approach as the primary advantage. Consequently, it serves as a crucial tool to appraise the ecological health of water [9,12,13].

Plankton play a vital role in aquatic ecosystems, and when affected by environmental changes, they can cause shifts in community structure and diversity [14,15]. Phytoplankton serve as primary producers and form the foundation of food chains and food webs. The growth of phytoplankton can be regulated by zooplankton, which facilitate the transfer of energy from low to high trophic levels and play a crucial role in ecosystems [16,17]. Analyzing the community characteristics and related parameters of zooplankton and phytoplankton is crucial for clarifying the health status of aquatic ecology and improving environmental stress [18–20]. Currently, there is a scarcity of research on the evaluation of ecological integrity concerning phytoplankton and plants. A researcher developed the plankton integrity index (P-IBI) for Bali River lakes, and the aim was to study the response mechanism of the P-IBI to environmental factors and assess the health status of lakes [21]. Conducting a plankton integrity assessment of Taihu Lake, comparing it with the water quality index (WQI), poor water quality was found. In brief, phytoplankton and plants were used as indicator organisms to establish the P-IBI is an efficient evaluation approach [22].

This study focuses on Dianchi Lake in the Jinsha River system of the Yangtze River Basin, China, providing pertinent scientific guidance and data to facilitate the ecological health evaluation, administration, and restoration of this lake. We developed a plankton integrity index for this lake's wet and dry seasons and evaluated it, and the following scientific questions were raised: (1) whether P-IBI can reflect water quality? (2) What are the key factors affecting the P-IBI? (3) What are the spatial and temporal variation patterns of the P-IBI? (4) Is the P-IBI developed for Dianchi lake feasible?

2. Materials and Methods

2.1. Study Area

Dianchi Lake is located in Kunming, Yunnan Province, which is the sixth largest freshwater lake in China. It belongs to the Jinsha River system of the Yangtze River Basin and is a typical plateau eutrophic lake [23]. The Dianchi Lake water storage area is approximately 309 km^2, the lake volume is 1.56 billion m^3, the average water depth is 5.3 m, and the lake shoreline is approximately 160 km long. It is the main water source of Kunming City [24]. The Dianchi Lake is semi-closed and lacks enough water sources, such as major rivers, while possessing limited self-purification capacity. Additionally, the lake recharge coefficient is considerably lower compared to that of Taihu Lake and Chaohu Lake. On average, the water in the lake is replaced every four years, a water replacement cycle that exceeds that of Taihu Lake and Chaohu Lake [25]. The water level and water temperature of this lake is higher in summer than in winter. Factors, such as the hydrological period conditions of this lake, the surrounding rivers, and the water area, were taken into consideration. During the wet season (July) in 2022 and the dry season

(February) in 2023, a total of 11 points in the center of the lake were selected for water quality monitoring and plankton surveys (Figure 1).

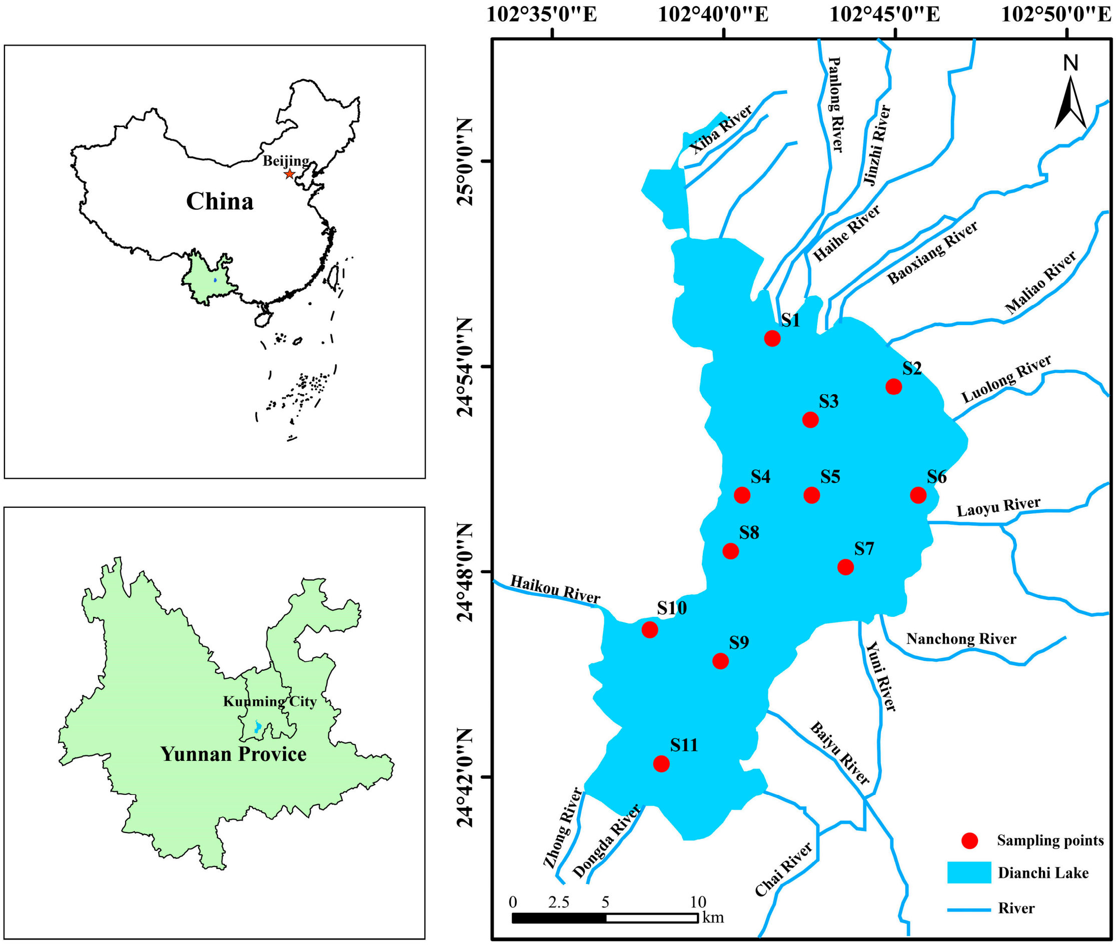

Figure 1. The geographical location of Dianchi Lake in China, surrounding rivers, and sampling sites (red circles).

2.2. Sample Collection and Measurement

2.2.1. Water Sample Collection and Analysis

The water temperature (WT), pH, electrical conductivity (EC), oxidation–reduction potential (ORP), and dissolved oxygen (DO) were determined on-site using a portable multi-parameter water quality tester (YSI Inc., Yellow Springs, OH, USA). The water transparency (SD) was measured using the Secchi disk. Additionally, water samples were collected and preserved with acid and transported back to the laboratory at a low temperature. The total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), ammonia nitrogen (NH_4^+-N), permanganate index (COD_{Mn}), chlorophyll a (Chl.a), and suspended solids (SS) were measured according to the literature [26].

2.2.2. Plankton Collection and Analysis

Phytoplankton samples were obtained by collecting 1 L of water using a 3 L water collector at a depth of 0.5 m and fixed with 1.5% Lugol's iodine solution. After letting the samples settle for 48 h, they were concentrated to 30 mL and then quantified and classified under a microscope [27]. For the phytoplankton identification standards, refer to the literature [28].

Zooplankton samples were obtained by collecting 20~30 L of water at a depth of 0.5 m, filtering it through a 25 μm mesh, and preserving it with a 1.5% formaldehyde solution. After 48 h of laboratory sedimentation, the samples were concentrated, and then, zooplankton were identified and categorized under a microscope [29–31]. For the zooplankton identification standards, refer to the literature [32,33].

2.3. Construction of the P-IBI

2.3.1. Selection of Reference Sites

Based on the literature [34,35], combined with historical environment and data of Dianchi Lake [24,25,36], the reference points and damaged points were determined through the results of an on-site investigation and the analysis of water quality physical and chemical indicators. The sites that were selected as reference points had total phosphorus and ammonia nitrogen levels that met the national Class III water quality standard, as well as a low algal density and TLI. Finally, S1, S2, S3, S8, S9, and S11 with better conditions in the wet season were selected as reference points, S1, S3, S5, S8, and S10 were selected as reference points in the dry season, and the remaining points were used as damage points.

2.3.2. Determination and Screening of Candidate Parameters

Based on examples of P-IBI studies [22,34,35,37,38] and combined with the results of plankton monitoring in this study, the indicators in the plankton integrity system were selected as comprehensively as possible, and the candidate indicators were 35 phytoplankton indicators and 39 zooplankton indicators (Tables S1 and S2). The distribution range of each indicator parameter was analyzed, and indicators for which the distribution range or predictable environmental change range was too narrow, with more than 95% of the sample sites having zero values, and with non-monotonic changes in the disturbance intensity were excluded. Discriminant analysis uses the phase line method for testing, computes the overlap of reference site and damage site boxplots, and selects indicators for which the median lines are not in the range of the 25% to 75% quantiles of each other's boxes. Pearson correlation analysis was performed on the remaining indicators, and the indicators with large correlations, i.e., $|r| \geq 0.75$, and repeated significance were removed.

2.3.3. Data Standardization

We used the ratio standardization method, one of the most accurate and effective [39,40]. For the indicators that decrease with stronger interference, the 95% quantile of all parameter samples was the expected value, and the indicator score was equal to the parameter value divided by the expected value. For the indicators that increase with stronger interference, the 5% quantile of all parameter samples was the expected value, and the indicator score calculation formula was (maximum value − parameter value)/(maximum value − expected value).

2.3.4. Division of the P-IBI Evaluation Criteria

The scores of each survey point under the screening index were obtained through a calculation; the scores ranged from 0 to 1, and greater than 1 was recorded as 1. The P-IBI score of a point was the sum of the scores of all screening indicators. The 95% quantiles of the IBI across all sites served as the standard for the expected value. The IBI range was categorized into five levels using this value, which was the standard for evaluating the health of the lake's water ecology. Therefore, the health status was divided into five levels: excellent, good, moderate, poor, and severe. Sampling sites with IBI scores proximate to this value suggested better ecological health and lower anthropogenic disturbances [41].

2.4. Data Analysis

Origin 2019 software was used to compare the distribution of the 25% to 75% quantile lines of the reference site and the damaged site. Correlation analysis between plankton candidate indicators was performed with SPSS 19.0. Canoco 5 software was used to perform decision curve analysis (DCA) and redundancy analysis (RAD) mapping analysis to the P-IBI evaluation system and water quality factors. ArcMap 10.8 software was used to draw the geographical location and sampling map of Dianchi Lake. The distribution diagram of P-IBI values in Dianchi Lake was drawn using the Kriging interpolation method.

2.5. Definition and Calculation Method of Parameters

The comprehensive trophic level index (TLI) was based on Chl.a, TP, TN, SD, and COD_{Mn} as evaluation factors, and calculated as follows:

$$TLI\left(\sum\right) = \sum W_j \cdot TLI(j) \quad (1)$$

W_j is the weight of the trophic level index of the jth parameter, and TLI(j) is the trophic status sub-index of parameter j [42].

In Equation (1), W_j is calculated as follows:

$$W_j = \frac{r_{ij}^2}{\sum_{j=1}^{m} r_{ij}^2} \quad (2)$$

r_{ij} is the correlation coefficient between the jth parameter and the Chl.a, and m is the number of evaluation parameters [42].

3. Results

3.1. Characteristics of Plankton Community Structure

A total of 83 species of phytoplankton and 31 species of zooplankton were identified in Dianchi Lake (Tables S3 and S4). On a time scale, the mean species of phytoplankton was significantly higher during the dry season (72 species in 7 phyla) than during the wet season (23 species in 5 phyla). Similarly, the dry season showed a higher average number of zooplankton species (22 species in 4 phyla) compared to the wet season (14 species in 3 phyla). Among them, the predominant zooplankton groups were Copepoda and Cladocera. The phytoplankton gradually changed from the pattern of Cyanophyta and Chlorophyta in the wet season to patterns of Bacillariophyta and Chlorophyta in the dry season.

Biomass: Phytoplankton biomass in Dianchi Lake during the dry and wet seasons ranged from 3.39 to 59.22 mg/L, with an average value of 15.64 mg/L (Figure 2a). The highest value appeared at S6 in the dry season, reaching 59.22 mg/L, and the minimum value recorded during the wet season at S10 was 3.39 mg/L. On a time scale, the mean biomass of phytoplankton was higher during the dry season (24.39 mg/L) than during the wet season (6.88 mg/L). The zooplankton biomass during the dry and wet seasons ranged from 0.42 to 15.88 mg/L, with an average value of 5.12 mg/L (Figure 2b). The highest value appeared at S7 during the dry season, reaching 15.88 mg/L, and the lowest value appeared at S1 during the wet season, reaching 0.42 mg/L. On a time scale, the mean biomass of zooplankton was higher during the dry season (7.22 mg/L) than during the wet season (3.02 mg/L).

Density: Phytoplankton density in Dianchi Lake during the dry and wet seasons ranged from 3.58×10^2 to 2.59×10^7 ind/L, with an average of 1.30×10^7 ind/L (Figure 3a). The highest density was observed at S8 during the dry season, with a density of 2.59×10^7 ind/L, and the lowest value appeared at S10 during the wet season, reaching 3.58×10^6 ind/L. On a time scale, the mean density of phytoplankton was higher during the dry season (1.71×10^7 ind/L) than during the wet season (8.80×10^6 ind/L). The zooplankton density in the two water periods ranged from 11.25 to 3.75×10^2 ind/L, with an average value of 1.38×10^2 ind/L (Figure 3b). The highest value appeared at S4 during the wet season, reaching 3.75×10^2 ind/L, and the lowest value appeared at S3 in the dry season, reaching 11.25 ind/L. On a time scale, the mean density of zooplankton was higher during the wet season (1.78×10^2 ind/L) than during the dry season (97.61 ind/L).

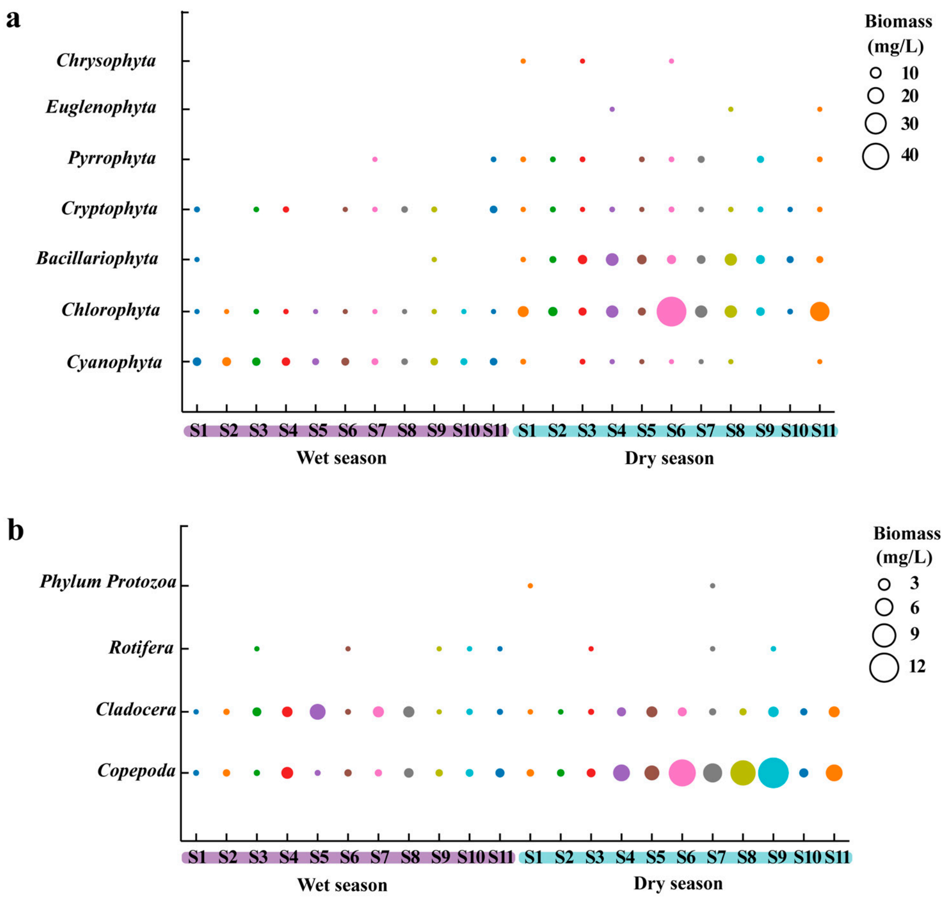

Figure 2. Community structure and biomass of plankton. (**a**) Phytoplankton. (**b**) Zooplankton.

3.2. P-IBI Construction

Reference points for the wet season in Dianchi Lake were S1, S2, S3, S8, S9, and S11. Reference points for the dry season were S1, S3, S5, S8, and S10, and the remaining points were used as damaged points.

By calculating and analyzing the distribution characteristics of each parameter value in the sample points, 21 and 23 parameters were removed in the wet and dry seasons, respectively, due to a distribution range that was too narrow or an excessive number of zero values. After boxplot discriminant analysis (Figures S1 and S2), 42 parameters were eliminated in both the wet and dry seasons. Pearson correlation analysis was performed on the candidate parameters obtained from the discriminant analysis to test the independence of the information reflected by each index. Pearson correlation analysis was performed on the remaining 11 and 9 parameters in the wet season and dry season, respectively (Figure 4a,b). The results showed that the six parameters used for P-IBI evaluation in the wet season included the M8 Margalef richness index, M23 green algae density %, M29 cyanobacterial biomass %, Z6 Shannon diversity index, Z7 Margalef richness index, and Z18 top 3 dominant species density sum. The seven parameters used for P-IBI evaluation in the dry season included the M9 total phytoplankton density, M24 diatom density %, M28 total phytoplankton biomass, M30 Chlorophyta biomass %, Z5 copepod number of species, Z13 total zooplankton, and Z27 Pielou evenness index. Due to differences in the results of discriminant analysis and correlation analysis of candidate parameters in different hydrological periods of Dianchi Lake, the number of parameters that can be used for P-IBI evaluation varies between hydrological periods (Tables 1 and 2). Finally, the scores of each parameter were calculated, and the evaluation standards for the wet season and dry season were formulated (Table 3).

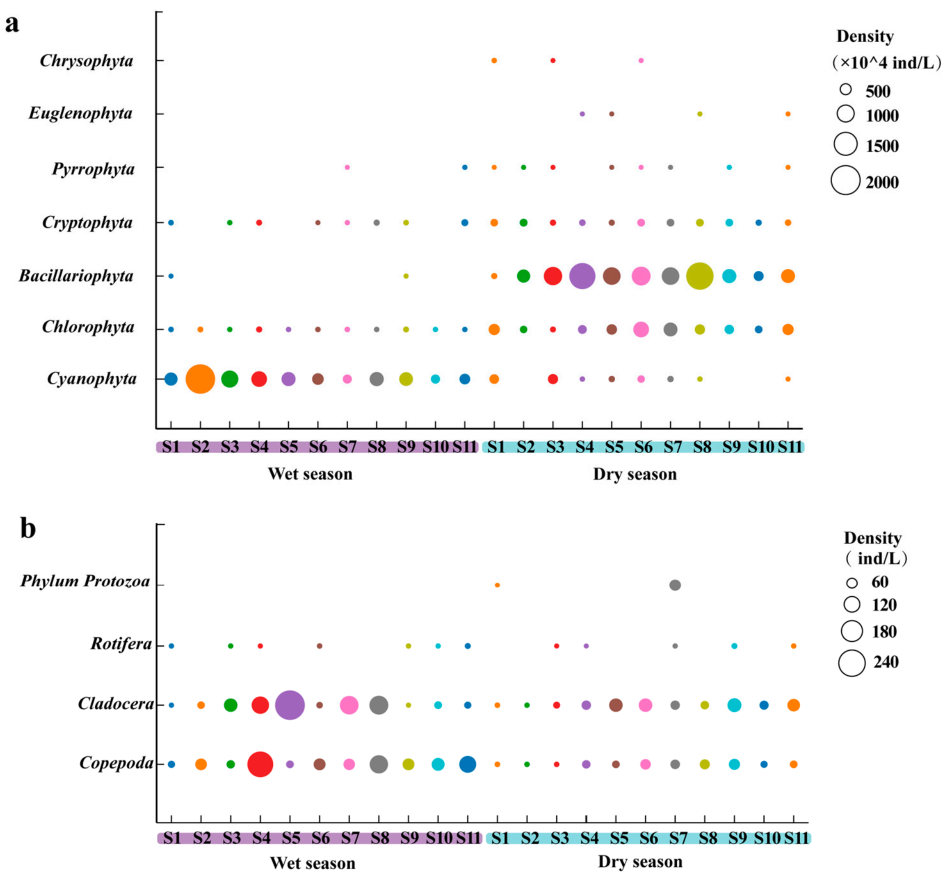

Figure 3. Community structure and density of plankton. (**a**) Phytoplankton. (**b**) Zooplankton.

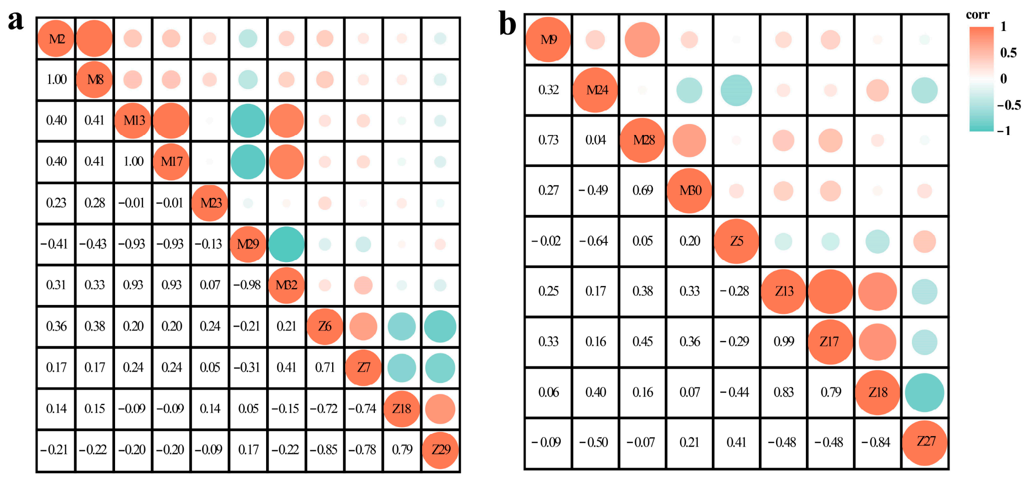

Figure 4. Correlation analysis of candidate parameters in Dianchi Lake. (**a**) Wet season. (**b**) Dry season.

Table 1. Formulas for calculating six metric scores in Dianchi Lake during the wet season.

Parameter	M8 ↓	M23 ↑	M29 ↑	Z6 ↓	Z7 ↓	Z18 ↑
5%	0.16	0.03	0.46	1.11	0.87	49.5
95%	0.59	0.10	0.99	2.07	1.88	328
MAX	0.63	0.11	0.99	2.09	2.03	361
Calculation formula	M8/0.59	(0.11 − M23)/ 0.11 − 0.03	(0.99 − M29)/ 0.99 − 0.46	Z6/2.07	Z7/1.88	(361 − Z18)/ 361 − 49.5

Note: ↓ indicates that the interference enhancement parameter value decreases, and ↑ indicates that the interference enhancement parameter value increases.

Table 2. Formulas for calculating seven metric scores in Dianchi Lake during the dry season.

Parameter	M9 ↑	M24 ↑	M28 ↑	M30 ↑	Z5 ↓	Z13 ↑	Z27 ↓
5%	930.75	0.27	10.18	0.28	2.00	1.33	0.79
95%	2544.90	0.75	46.64	0.82	4.50	14.58	0.95
MAX	2590.80	0.78	59.22	0.82	5.00	15.88	0.95
Calculation formula	(2590.80−M9)/(2590.80−930.75)	(0.78 − M24)/(0.78 − 0.27)	(59.22 − M28)/(59.22 − 10.18)	(0.82 − M30)/(0.82 − 0.28)	Z5/4.50	(15.88 − Z13)/(15.88 − 1.33)	Z27/0.95

Note: ↓ indicates that the interference enhancement parameter value decreases, and ↑ indicates that the interference enhancement parameter value increases.

Table 3. Evaluation criteria for the P-IBI in Dianchi Lake.

Level	Excellent	Good	Moderate	Poor	Severe
wet season	>4.908	3.681–4.908	2.454–3.681	1.227–2.454	<1.227
dry season	>5.823	4.367–5.823	2.912–4.367	1.456–2.912	<1.456

Based on the evaluation criteria of the P-IBI in the wet season, one site was evaluated as "excellent", five sites as "good", four sites as "moderate", and one site as "poor". The average score during the wet season was 3.762, and the overall evaluation was "good". Among them, the locations with good evaluation results were mainly distributed in the southern and northern parts of Dianchi Lake and the waters near the entrance of the Dongda River, whilst the sites with low P-IBI scores were mainly distributed in the central part of Dianchi Lake (Figure 5a).

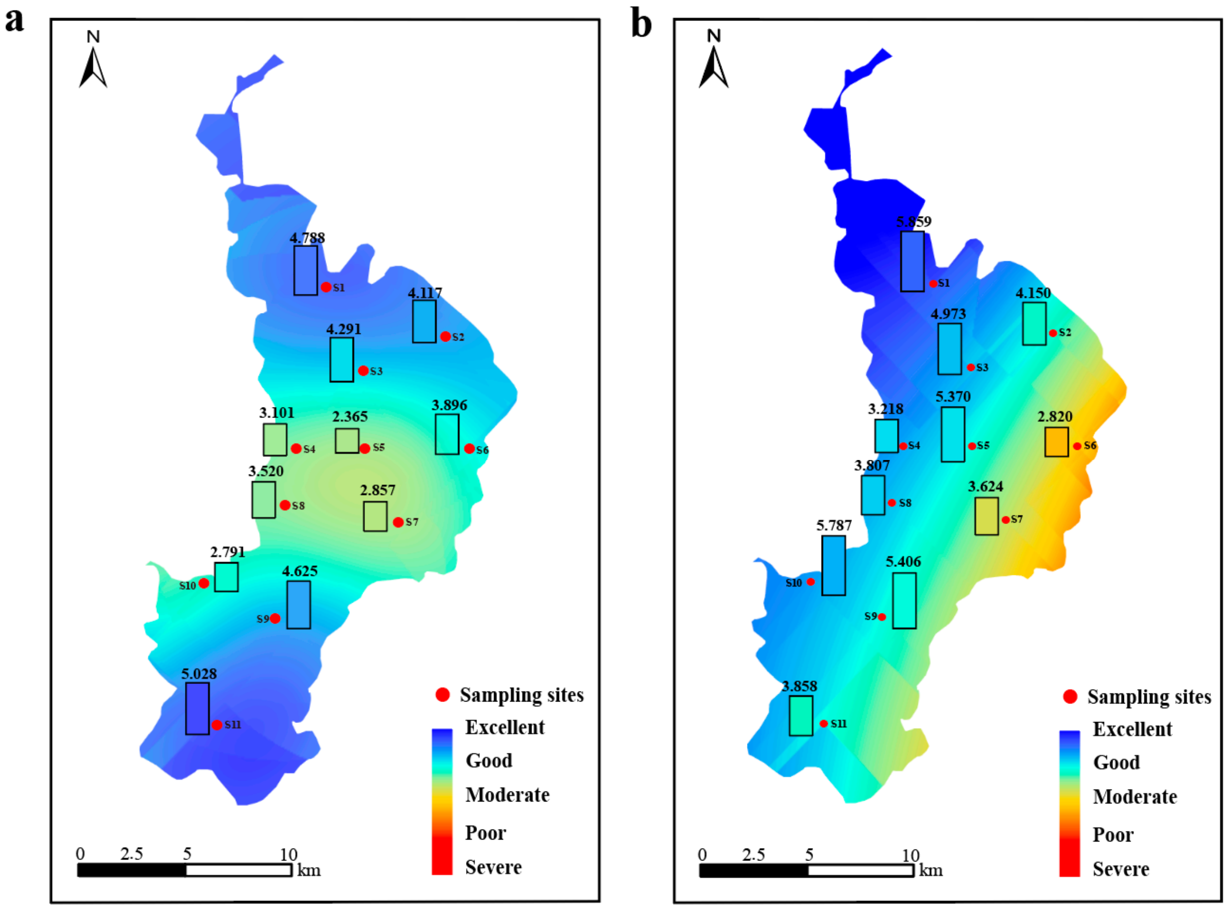

Figure 5. Spatial distribution of P-IBI scores in Lake Dianchi. (**a**) Wet season. (**b**) Dry season.

The health assessment of Dianchi Lake was based on the P-IBI evaluation standard during the low-water period; one site was evaluated as "excellent", four sites as "good", five sites as "moderate", and one site as "poor". The average score during the dry season was 4.443, and the comprehensive evaluation was also in a "good" state. The points with good evaluation results were mainly distributed in the northern and western parts of Dianchi Lake and the waters near the outlet of the Haikou River, whilst the points with poor evaluation results were mainly distributed in the eastern part of Dianchi Lake and the waters near the entrances of the Luolong River and Laoyu River (Figure 5b).

3.3. P-IBI Effectiveness

Dianchi Lake's P-IBI scores ranged from 2.365 to 5.028 in the wet season and from 2.820 to 5.859 in the dry season. The highest score was S1 in the dry season, and the lowest score was S5 in the wet season. The average P-IBI score in the dry season (4.443) was higher than that in the wet season (3.762). On a time scale, since the evaluation system of the two water periods contained different indicators, the P-IBI score in the wet season was significantly lower than that in the dry season. In addition, the average score of the reference points in the two water periods was 4.540, and the average score of the damaged points was 3.665. Compared with the reference point, the scores of damaged points in both the wet and dry seasons were significantly lower ($p < 0.001$ and $p < 0.01$) (Figure 6).

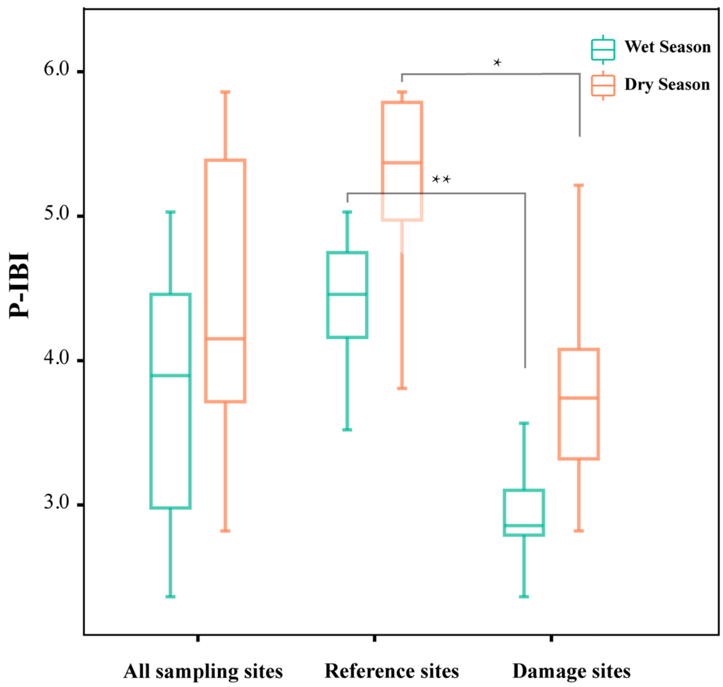

Figure 6. Comparison of P-IBI scores between reference points and damaged points in different hydrological periods. Note: * indicates $p < 0.05$, ** indicates $p < 0.01$.

The linear regression analysis of the P-IBI and TLI showed that the P-IBI and TLI were negatively correlated in both seasons. In the wet season, the value of R^2 was 0.277, with $p < 0.01$ (Figure 7a); in the dry season, the value of R^2 was 0.592, with $p < 0.01$ (Figure 7b).

3.4. Correlation between the P-IBI and Water Quality Factors

Combined with the water quality results (Tables S5 and S6), the RDA results of the P-IBI, its parameters, and water quality factors during the wet season showed that the eigenvalues of the first two axes were 0.501 and 0.230, respectively, and the cumulative contribution of the first two axes was 73.17% (Figure 8a). P-IBI scores were positively correlated with EC ($F = 2.70$, $p = 0.022$) and negatively correlated with TN ($F = 2.20$, $p = 0.048$). The results for the dry period (Figure 8b) showed that the eigenvalues of the first two axes were 0.431 and 0.292, respectively, and the cumulative contribution of the first two axes was 72.23%. The P-IBI score was positively correlated with EC ($F = 2.60$, $p = 0.022$).

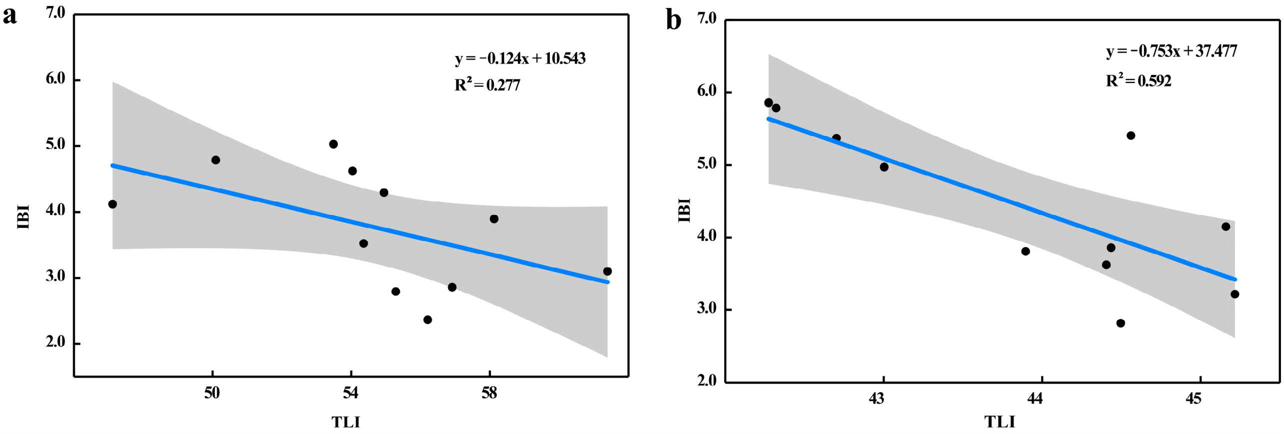

Figure 7. P-IBI scores and TLI linear regression analysis. (**a**) Wet season. (**b**) Dry season.

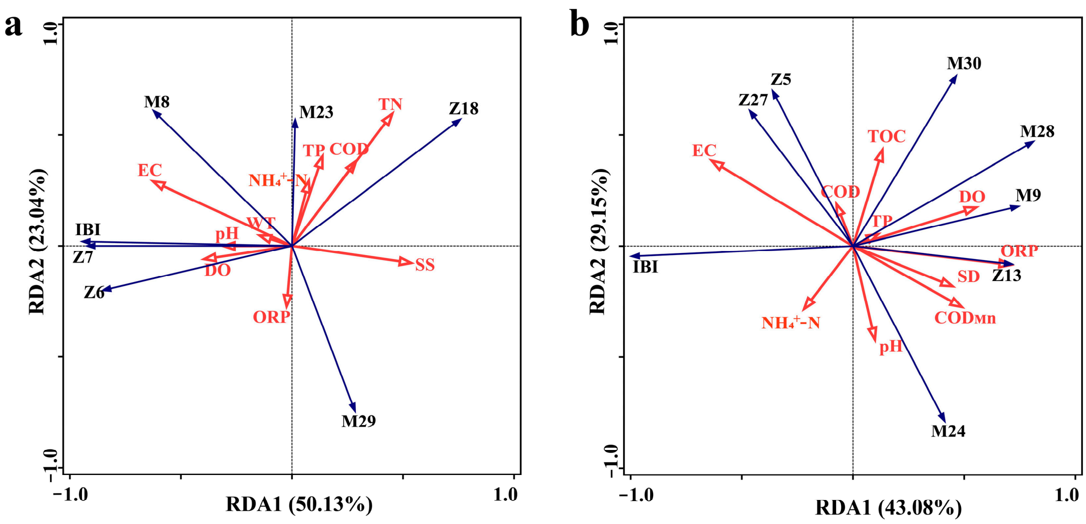

Figure 8. Redundancy analysis of between-environmental parameters, the component metrics, and P-IBI. (**a**) Wet season. (**b**) Dry season.

4. Discussion

4.1. Spatiotemporal Changes in Plankton

The plankton community in Dianchi Lake exhibits evident seasonal variations. Suitable water temperatures are more conducive to plankton growth and reproduction [43,44]. They also increase phytoplankton photosynthesis [45,46]. The water temperature was higher and light was stronger during the wet season in this study. Green algae and cyanobacteria had a competitive advantage, so the concentration of chlorophyll was higher during the wet season. During the dry season, the water temperature decreased, the number of diatoms increased, the number of cyanobacteria decreased, and the chlorophyll was at a low level. The two dominant groups, copepods and cladocerans, did not change significantly during the wet season. The PEG (planktonic ecology group) model suggested that the phytoplankton community is dominated by cryptophytes and diatoms in winter and spring, and by green algae in summer [47]. The findings of this survey were roughly consistent with this model.

4.2. Construction of P-IBI

The IBI is a multi-index evaluation method, and compared with single biological parameters, it had a higher redundant separation ability and a lower coefficient of variation [48]. Thus, it can prevent assessment results from being biased due to the weaknesses of a single parameter. Zhu et al. suggested that the P-IBI should be constructed based on Pielou's index, the cell density of Bacillariophyta, Bacillariophyta taxon %, Chlorophyta taxon %, Cyanophyta cell density, percent Bacillariophyta cell density, Chlorophyta biomass, and the average cell density of taxa to evaluate the ecological status of Lake Gehu in China [38]. Wu et al. considered that the P-IBI should be composed of chlorophyll a, the saprobity index (SI), the cyanobacteria index (Cyl), the Margalef index, species richness (SPR), and the Menhinick diversity index to evaluate the ecological status of underground rivers in Germany [49]. The study used the P-IBI, which included related phytoplanktonic and zooplanktonic parameters. A total of 13 core parameters were applied in the two water periods, and it had a lower coefficient of variation.

The determination of IBI reference points was critical for the evaluation of biological integrity indicators, and it had a direct impact on the accuracy of the final core parameters [34,50]. No standard for reference point selection exists at present. The selection of reference sites is not affected by human activity in principle, but some areas had been damaged by human activity. Therefore, based on the results of the field survey combined with the analysis of physical and chemical indices of water quality, the least degraded sites were selected as reference sites. Wang et al. selected reference points based on the physico-chemical index threshold and habitat index [51], while Zhu et al. selected the water quality index and riparian vegetation cover to determine reference points, and the selection of reference points was of the reference value [41]. In this study, reference points had been established with the consideration of water quality factors, the degree of human disturbance, and the TLI. The final results showed that according to the established P-IBI scoring standards, the reference points of the two hydrological periods had generally higher scores than the damaged points, which also showed that the selected reference points had a certain degree of credibility.

In addition, a significant quantity of research has demonstrated that the construction of biological integrity index is confined to a restricted spatial scale and tailored to different rivers and lakes, which may hinder the widespread application of the IBI in water resource management [38]. The P-IBI constructed in this study was different from that used in other studies. We selected the candidate indicators of phytoplankton and zooplankton and constructed two P-IBIs in the dry season and the wet season, aiming at the temporal and spatial specificity of the biological integrity index, so that the P-IBI could accurately evaluate the biological integrity status of Dianchi Lake.

4.3. Spatiotemporal Changes in P-IBI

The results of the P-IBI assessment at Dianchi Lake exhibited differences in time and location. Upon comparing the distribution of evaluation results during the two hydrological periods, six sites were evaluated as "excellent" or "good" during the wet period, with only five sites during the dry period. The aquatic ecological health status was slightly better in the wet period than in the dry period, which may be caused by varied plankton species and biomass. The evaluation results of Lake Gehu in the Yangtze River Delta showed that the P-IBI in dry and wet periods was consistent [38]. By conducting a seasonal assessment of the P-IBI while researching Fuxian Lake, the findings indicated that the biological integrity of Fuxian Lake was better during the winter and spring, but gradually declined during the summer and autumn [52]. The multimetric P-IBI was developed for Lake Erie through the monthly (May–September) analysis of plankton communities, providing a useful, large-scale method for monitoring water quality changes in offshore lakes [3]. These assessments were similar to the spatiotemporal changes observed in Dianchi Lake. The subtle differences between the seasons was that the water level increases during the high-water period, leading to an increase in water flow that disturbs plankton and ultimately reduces biodiversity. This study's findings demonstrated that the P-IBI value in the central portion of Dianchi Lake is low. This could be attributed to the large number of river inlets on the lake's east bank, as well as the high human population density in the area, and the degree of human interference was particularly significant in the dry season [36].

Furthermore, there existed a negative correlation between P-IBI scores and the TLI at Dianchi Lake. This means that as the TLI increases, P-IBI scores decline. This point had been corroborated in the P-IBI assessment of the Danjiangkou Reservoir. Research has found that as the TLI reaches a certain limit between 35 and 40, P-IBI scores decrease in proportion to the TLI increase [35]. It is possible that the difference between the TLI and P-IBI scores is due to variations in the classification of key parameters. The aforementioned method had also been employed to evaluate lakes situated in the Yangtze River [38] and Poyang Lake [39]. By reducing errors caused by spatial and temporal changes across various hydrological periods, the P-IBI represents a more scientifically rigorous technique for assessing the health of water bodies over extended time frames.

4.4. Factors Affecting P-IBI

Water quality factors can impact the results of P-IBI scores [53]. This study found that EC had a significant positive correlation with P-IBI scores in both the wet and dry seasons. EC is a fundamental water quality parameter that directly reflects the total amount of soluble ions in water [54]. Studies in Taihu Lake [55] and Poyang Lake [56] have found a positive correlation between EC and the plankton community structure, and they were key factors affecting the community structure of plankton. The study in the Songhua River showed that the abundance of the diatom phylum was proportional to the EC [57]. The P-IBI is constructed from plankton parameters, and the above studies can support the results in this paper. Additionally, the observed a negative correlation between P-IBI scores and total nitrogen in the wet water period, which may be due to the fact that an increase in the total nitrogen concentration had a promoting effect on phytoplankton growth under certain conditions [58]. Water temperature emerges as the significant external environmental factor restricting the phytoplankton community in the water column, with a more significant influence than factors, like the nutrient salt concentration [59,60]. Additionally, the water temperature can prevent the outbreak of certain species within the community. Moreover, as a eutrophic body of water, Dianchi Lake had a higher water level and water temperature during the summer high-temperature period, and there were significant changes in phytoplankton-related parameters. The stability of plankton during this period was lower, the density and biomass of plankton were significantly lower than in winter, and the stability of the P-IBI was superior in the dry period than in the wet period. This outcome was further corroborated in the study of Lake Gehu [38].

5. Conclusions

The P-IBI developed for Dianchi Lake was found to be reliable and effectively reflects spatial and temporal variability in water ecosystem health. The water ecological health assessment results were "good". There was spatial and temporal variability in the P-IBI of Dianchi Lake; the aquatic ecological health status was slightly better in the wet period than in the dry period. The RDA results showed a correlation between water quality factors and P-IBI scores and its component parameters, attributing the main factors affecting P-IBI scores to TN and EC. Furthermore, creating a multidimensional IBI that includes both phytoplankton and zooplankton allows for a thorough assessment of different trophic levels in aquatic ecosystems, avoiding bias from temporal and spatial variability and biological singularity. Finally, it is strongly recommended that a suitable index is developed to evaluate different hydrological periods and that quarterly monitoring is carried out over extended time periods.

Supplementary Materials: The following supporting information can be downloaded at: https://figshare.com/s/1d5203f66da5037229b1, Figure S1: Box plot analysis during the wet season; Figure S2: Box plot analysis during the dry season; Table S1: Phytoplankton candidate parameters; Table S2: Zooplankton candidate parameters; Table S3: List of phytoplankton species; Table S4: List of zooplankton species; Table S5: Results of water quality survey in wet season; Table S6: Results of water quality survey in dry season.

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