

Article

Characteristics of Benthic Macroinvertebrate Community Structure in Typical Polders of Dongting Lake and Assessment of Aquatic Ecological Health

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Abstract

As an artificial–natural composite ecosystem, polders face increasingly prominent internal and surrounding water environment problems under sustained strong human activities. To systematically assess the water ecological health status of polders around Dongting Lake, this study took four typical polders around Dongting Lake as research subjects, and two seasonal surveys of benthic macroinvertebrates were carried out in July and December 2024. Through analyses of community structure characteristics and correlations with key environmental factors, the Trophic Level Index (TLI), Water Quality index (WQI), Shannon–Wiener index of benthic macroinvertebrates, and Benthic Macroinvertebrates Index of biotic integrity (B-IBI) were selected to establish an entropy-weighted Bayesian model for comprehensive evaluation of the current ecological health of Dongting Lake polders. In 2024, a total of 47 benthic macroinvertebrate species were found in Dongting Lake polders, including 25 species in the summer and 36 species in the winter. The main groups were Gastropoda, Insecta, and Bivalvia, and the community composition did not show significant seasonal or spatial differences. The benthic macroinvertebrate community structure in the summer was mainly influenced by TN/TP, NO_3^- -N, WD, Tur, and Chl.a, suggesting eutrophication as a critical concern, while in the winter it was mainly regulated by WSW, WT, Tur, and DO, highlighting hydrological conditions as pivotal. The entropy-weighted Bayesian assessment indicated an overall aquatic ecological health status of “moderate” in 2024, with summer conditions superior to those in the winter and notable spatial heterogeneity observed in winter sampling sites within ditches, among which Polder Chengxi exhibited the best condition, while Polder Junshan and Polder Xiangbin Nanhu showed degraded states. Notably, Polder Junshan (JS2 and JS3) displayed clear signs of ecological degradation during the winter, warranting immediate initiation of targeted restoration measures. This study provides a systematic diagnosis and scientifically grounded evaluation of aquatic ecological health in Dongting Lake polders, offering a robust theoretical framework and empirical data for future water environmental protection strategies and ecological restoration practices.

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Keywords: benthic macroinvertebrates; community structure; Bayesian model; ecological health assessment; embankment; Dongting Lake

1. Introduction

The health status of river and lake ecosystems is directly related to regional water security and the sustainable development of human society. Healthy aquatic environments naturally regulate hydrological cycles, mitigate extreme risks like floods and droughts, and purify water to ensure safe supplies. By providing the essential ecological and material foundation for agriculture, industry, and daily life, their degradation inherently undermines long-term economic stability and human well-being. Systematic and multi-dimensional ecological health assessments of river and lake ecosystems are the most effective way to comprehensively understand their health conditions and identify key issues [1]. Benthic Macroinvertebrates due to their ease of collection and high sensitivity to environmental gradients, are selected as indicator organisms to explore the composition of benthic animal communities and to understand the ecological health status of the water and the degree of water pollution [2–5]. In recent decades, extensive research both domestically and internationally has focused on the spatiotemporal dynamics of benthic macroinvertebrate community structures. Internationally, scholars have primarily explored how large-scale environmental drivers—such as watershed land-use modifications, climate change, and shoreline morphological degradation—affect the biodiversity, functional traits, and spatial distribution patterns of lake benthic communities [6,7]. Meanwhile, domestic studies have predominantly focused on typical large shallow lakes in China, deeply investigating the succession and simplification of macrozoobenthic assemblages driven by anthropogenic eutrophication, habitat degradation, and hydrological rhythm alterations [8,9].

Building upon these community analyses, the Benthic Index of Biotic Integrity (B-IBI) has been widely established and applied as a robust tool for evaluating the ecological health of lakes. However, given the complex and multifaceted nature of aquatic ecosystems, relying solely on a single biological indicator or a purely biological index may fail to capture the full spectrum of systemic degradation. Consequently, modern ecological health assessments are progressively transitioning from single-indicator evaluations to multi-dimensional comprehensive frameworks that systematically integrate elements of “water resources, water environment, and water ecology”. Guided by the European Water Framework Directive (WFD), Ochocka and Karpowicz [10] established a novel biological assessment framework that systematically integrates zooplankton community indices with physicochemical properties to evaluate the ecological status and ecosystem health of stratified lakes. Domestically, focusing on China’s unique high-altitude lacustrine environments, Zhang et al. [11] constructed a novel hybrid decision-making framework for lake ecosystem health assessment, successfully integrating ecosystem integrity indicators—including physical habitats, water quantity, water quality, and aquatic life—with socio-economic service functions. The rational allocation of indicator weights and the selection of evaluation algorithms are the core of constructing a multi-dimensional comprehensive evaluation model. Subjective weighting methods have limitations due to over-reliance on expert experience, whereas the entropy weight method, which is based on data dispersion, has been widely applied in water quality assessment and has gradually become a trend in recent aquatic biological assessment research. Yao et al. [12], respectively, applied the entropy weight method to construct a Comprehensive Biotic Index (CBI) for ecological health assessment of East Dongting Lake.

In terms of model selection, the linear weighted combination method is widely used for its computational simplicity, yet it struggles to handle the complex non-linear relationships among various elements of ecosystems. More advanced mathematical models have attracted the attention of many scholars. Li et al. [13] introduced the fuzzy comprehensive evaluation model into water quality assessment, successfully eliminating

errors in the physical threshold boundaries of ecological indicators. Liao et al. [14] introduced the Bayesian model into water quality assessment owing to its advantages in handling data uncertainty, dynamic revision, and low computational cost. Both fuzzy comprehensive evaluation and Bayesian methods can eliminate physical threshold boundary errors; however, the membership degree of the fuzzy comprehensive evaluation method often relies on subjective judgment, while the Bayesian method treats membership degree as conditional probability and objectively estimates probability based on data, thus reducing subjectivity [15–17]. Compared with the traditional evaluation model, the entropy weight–Bayesian model coupling objective weighting algorithm used in this study further makes up for the defects of the subjective prior setting of the single Bayesian model. For the polder area without historical data, a single index evaluation result is proposed to replace the historical data to calculate the prior probability, which has targeted application novelty in the evaluation of water ecosystem in the polder area. At present, the Bayesian model is mainly used in water quality assessment, with relatively few applications in multi-index comprehensive assessment of aquatic ecological health [18,19].

Dongting Lake is the second largest freshwater lake in China. Due to factors such as reclamation, sediment deposition, and the regulation and storage effects of the Three Gorges Project, the water surface area of Dongting Lake has been continuously shrinking over the years, and a large number of typical polders have formed around the lake [20]. Therefore, conducting investigations and research on benthic macroinvertebrates in the polders of Dongting Lake is of certain typicality and representativeness. Polders are mainly distributed in the lowlands along the middle and lower reaches of the Yangtze River and lakeshores in China. They are artificial–natural complex ecosystems formed by local residents through long-term production and living activities such as dike construction, land reclamation, agriculture, and fishery [20,21]. There are two prominent water-related problems in polders: one is the contradiction between water resource utilization and flood–drought disasters and the other is water environment degradation represented by eutrophication [22,23]. Current studies on the water environment of polders mostly focus on water quality. For example, Huang Jiacong et al. [24] explored the migration and transport mechanisms of nitrogen and phosphorus nutrients in polders. At the aquatic biological level, Ji et al. [25] conducted phytoplankton surveys in polders of the Taihu Basin, while studies using benthic macroinvertebrates as indicator species to assess the aquatic ecological health of polder areas remain scarce.

In view of the four typical polders in Dongting Lake area, this study first analyzed the community structure characteristics of macrobenthos in the polders and identified the key driving factors to provide a biological basis for health evaluation. Secondly, a multi-dimensional water ecological health comprehensive evaluation index system integrating the Trophic Level Index (TLI), Water Quality Index (WQI), Shannon–Wiener index of benthic macroinvertebrates, and Benthic Macroinvertebrate Index of Biotic Integrity (B-IBI) was constructed to overcome the information limitations of single index evaluation. Furthermore, aiming at the bottleneck of traditional Bayesian model relying on historical prior data, the prior probability is obtained by replacing historical observation data with single-index evaluation results, and the Bayesian water ecological health evaluation model based on the entropy weight method is established. The flat-top semi-normal distribution likelihood function is introduced to deal with the boundary effect when the index exceeds the optimal or inferior to the worst standard. Finally, through the comparative analysis of the comprehensive evaluation results and the single-index evaluation results, the scientificity and applicability of the method are verified in order to provide a technical paradigm for the ecological health evaluation of the polder water without the previous monitoring data and to provide scientific support for the ecological

zoning control and ecological restoration decision making of the polder water in the Dongting Lake area.

2. Study Area and Methods

2.1. Overview of the Study Area

Four typical embankment areas within the Dongting Lake watershed were selected for this study: Anzao (AZ) and Junshan (JS), adjacent to East Dongting Wetland, and Chengxi (CX) and Xiangbin Nanhu (XB), encircling South Dongting Lake. All are agricultural embankments dominated by double-cropped rice and winter rapeseed cultivation, with Chengxi and Xiangbin Nanhu exhibiting greater aquaculture activity. Polder Anzao is located at the confluence of the lower reaches of the Yuan River and the west bank of East Dongting Lake. Polder Junshan is adjacent to the core reserve of East Dongting Lake and is significantly affected by the water interaction between the inflow from the three outlets of the Yangtze River (Songzi Outlet, Taiping Outlet, and Ouchi Outlet) and the Dongting Lake water system. Polder Chengxi and Polder Xiangbin Nanhu are both located on the alluvial plain at the confluence of the Zi River and Yuan River, representing typical polder ecosystems of South Dongting Lake. These polders feature flat, low-lying alluvial topography, with dense networks of artificial channels and natural streams forming semi-isolated hydrological units separated from main lakes by dikes. Water exchange between internal systems and external basins is strongly regulated by sluices and pumping stations, resulting in predominantly stagnant or slow-flowing conditions with shallow depths (typically 0.5–3.0 m), tightly controlled by seasonal agricultural demand and precipitation. Correspondingly, bottom sediments are primarily composed of fine-grained silt and clay, reflecting weak hydrodynamic forces and long-term detrital accumulation, leading to surface layers that are mud rich and organic matter enriched. The study area has a subtropical monsoon climate, characterized by mild and rainy weather with distinct four seasons. The annual average temperature is 16–17 °C, and the annual average precipitation is 1200–1700 mm. Precipitation is unevenly distributed throughout the year: cumulative rainfall during the flood season (April to September) accounts for more than 70% of the annual total, while precipitation in the dry season (October to March of the following year) is significantly lower.

Surveys of macrobenthic communities and physicochemical water properties were carried out in July (summer) and December (winter) of 2024. During the initial summer baseline survey, three representative sampling sites were established in each polder (12 sites in total). Subsequently, based on an evaluation of the spatial heterogeneity of the preliminary summer data, an adaptive sampling optimization was implemented to better capture the microhabitat characteristics. Consequently, one additional site was introduced per polder during the winter survey, resulting in four sites per polder (sixteen sites in total). The specific geographical locations of all sampling sites are shown in Figure 1, and the on-site environmental photos of each polder are presented in Figure 2.

These sites were strategically selected based on three core criteria: (1) spatial evenness across the polders to minimize statistical bias; (2) habitat representativeness, specifically targeting areas near typical agricultural and domestic activities to reflect anthropogenic stressors [26]; and (3) sampling standardization, utilizing bridges over main channels to ensure stable grab deployment and capture integrated hydrological conditions. In addition, while maintaining extensive and uniform spatial coverage, different morphological characteristics (such as river width, channelization degree, etc.), water use types (domestic sewage, agricultural irrigation, or both), and vegetation coverage were used to select sites in the polder area to truly capture the spatial heterogeneity of microhabitats and benthic communities [27].

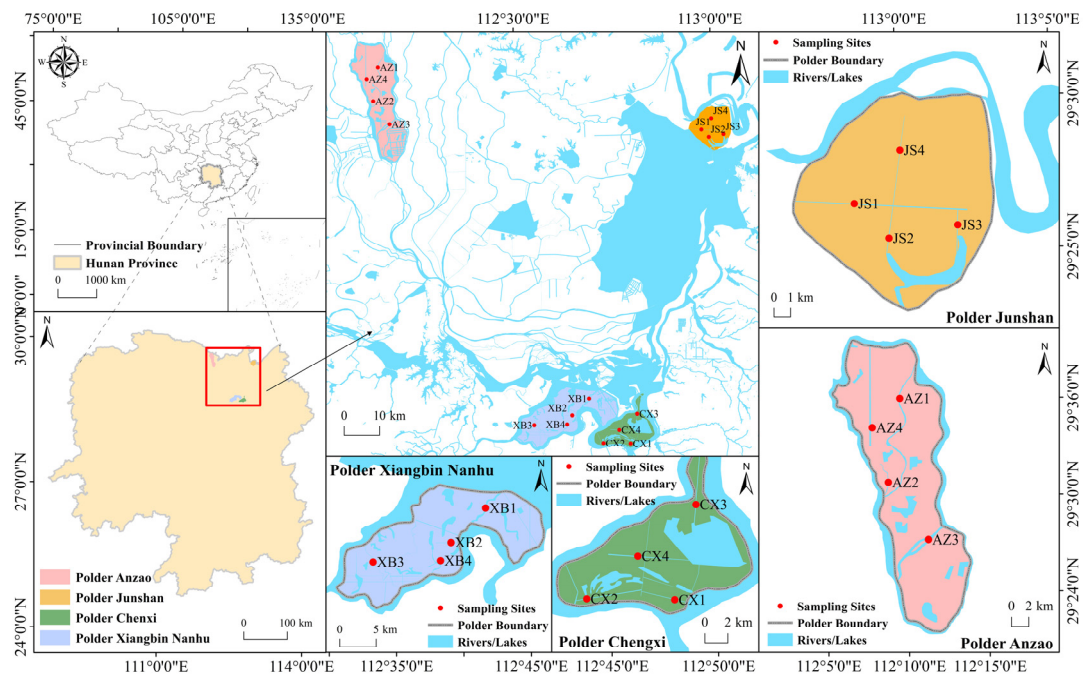


Figure 1. Study area and distribution of sampling locations.



Figure 2. Photographs of field sampling sites in the four regions.

2.2. Sampling and Identification

Benthic macroinvertebrates were quantitatively sampled by collecting three grabs of surface sediment at each sampling point using an ETC-200 Peterson mud grab. The collected sediments were mixed and passed through a 60-mesh three-dimensional rigid frame mesh (pore size 0.25 mm) sieve to remove excess mud and debris and transported to the laboratory for selection. The isolated specimens were preserved in 75% ethanol, and the benthic animals were identified to the lowest possible taxonomic level according to the morphological characteristics of the "Chironomid Larvae of Northern China" [28] and the "Atlas of Common Aquatic Organisms in Chinese Watersheds" [29]. After morphological identification of macrobenthic invertebrates, species richness was assessed by counting the number of genera in a mixed sample consisting of three ETC-200 grabs at each sampling station. The abundance is expressed as the number of individuals per square meter (ind./m²), calculated by dividing the product of the total sampling area and the number of replicates by the total number of individuals for all replicates. The sampling area of each ETC-200 grab is 0.0625 m². Therefore, each station was repeated three times, and the cumulative sampling area was 0.1875 m².

Water environment parameters were measured using portable field instruments and subsequent laboratory analyses. Water temperature (WT), pH, dissolved oxygen (DO), total dissolved solids (TDS), and electrical conductivity (EC) were determined with the

DZB-712 multi-parameter water quality monitor. Turbidity (Tur) was measured using a WGZ-20B turbidimeter. Flow velocity (V), water surface width (WSW), transparency (SD), and water depth (D) were measured with the XZ-3 current meter, measuring tape, Secchi disk, and lead fish, respectively. In the laboratory, ammonium nitrogen ($\text{NH}_4^+\text{-N}$), nitrate nitrogen ($\text{NO}_3^-\text{-N}$), total phosphorus (TP), and total nitrogen (TN) were analyzed using the SAN++ flow injection analyzer. Total organic carbon (TOC) was determined with the Multi N/C3100 TOC Total Organic Carbon analyzer. Orthophosphate ($\text{PO}_4^{3-}\text{-P}$) was measured using the M2e multifunctional microplate reader. Chlorophyll-a (Chl.a) was extracted using the hot ethanol method, and the permanganate index (COD_{Mn}) was determined by the permanganate index method.

3. Data Processing

3.1. Analysis of Relationships Between Communities and Environmental Factors

3.1.1. Screening of Environmental Factors

Non-parametric statistical test was used to analyze the difference of environmental factors. The Mann–Whitney U test was used to evaluate the significant differences between water environmental factors in different seasons. The Kruskal–Wallis H test was used to explore the spatial differences of environmental factors between different polders in the same season and different sampling points in the same polder in the same season [30]. To eliminate multicollinearity and remove redundant environmental variables, a preliminary screening was conducted using Pearson correlation analysis combined with the Variance Inflation Factor (VIF). Variables were retained only if they met two criteria simultaneously: Pearson correlation coefficient $|r| < 0.7$ and $\text{VIF} < 20$. Specifically, for groups of highly correlated variables ($|r| \geq 0.7$), only one representative factor was retained per group based on its ecological significance and VIF value. Subsequently, forward selection and the Monte Carlo permutation test (999 permutations) [18] were applied to the retained variables to identify the key combinations of environmental factors significantly driving the macrobenthic community structure in the polders during the summer and winter ($p < 0.05$).

3.1.2. Correlation Between Community Structure and Environmental Factors

Detrended Correspondence Analysis (DCA) was carried out. The maximum gradient lengths of the two seasons were calculated as 0.48 and 0.4, respectively (both less than 4). Therefore, redundancy analysis (RDA) was selected to analyze the relationship between benthic macroinvertebrate community structure and environmental factors in polders. With the exception of pH, all other environmental factors and benthic macroinvertebrate density indices were subjected to $\log(x + 1)$ transformation before statistical analysis to ensure compliance with the assumptions of normal distribution and homogeneity of variance.

3.2. Indicator Calculation

3.2.1. Shannon–Wiener Diversity Index

$$H = -\sum_{i=1}^S \frac{N_i}{N} \times \ln\left(\frac{N_i}{N}\right) \quad (1)$$

In the formula, S is the total number of species in the community; N is the total number of all identified species; and N_i is the number of the i -th observed species.

3.2.2. Comprehensive Trophic State Index

$$TLI = \sum_{j=1}^m w_j \times TLI(j) \quad (2)$$

Here, $TLI(j)$ is the trophic state index of 5 environmental factors including TN, TP, CODMn, SD, and Chl.a; w_j is the weight of the j -th parameter; and r_{ij} is the correlation coefficient between the j -th index and Chl.a, where $r_{ij}^2(\text{Chl.a}) = 1$, $r_{ij}^2(\text{TN}) = 0.6724$, $r_{ij}^2(\text{TP}) = 0.7056$, $r_{ij}^2(\text{SD}) = 0.6889$, and $r_{ij}^2(\text{CODMn}) = 0.6889$.

3.2.3. Comprehensive Water Quality Index

$$WQI = \frac{\sum_{i=1}^m C_i P_i}{\sum_{i=1}^m P_i} \quad (3)$$

$$P_i = \frac{q_i}{\sum_{j=1}^m q_j} \quad (4)$$

In the formula, C_i is the normalized value of the i -th environmental factor, which was converted to a score of 0–100 using the piecewise linear interpolation method based on the threshold of water quality grade. However, according to the ecological attributes of the index, the direction was distinguished. Among them, NO_3^- -N, NH_4^+ -N, and Tur were negative indicators, DO was a positive indicator, WT was a two-way indicator, and the deviation degree of the optimal range of 15–25 °C was a negative indicator; P_i is the relative weight of the i -th environmental factor; and m is the total number of selected environmental factors for evaluation, including WT, NO_3^- -N, NH_4^+ -N, Tur, and DO. Their relative weights q_i are 2, 3, 2, 1, and 4, respectively. The classification standards of each factor refer to the “Environmental Quality Standards for Surface Water” (GB 3838-2002) [31] and the relevant literature [32–34].

3.2.4. Benthic Index of Biotic Integrity (B-IBI)

(1) Selection of Reference and Impaired Sites.

According to the aquatic ecological survey conditions of polders in Dongting Lake, current standards [35], and previous studies on the development of the benthic macroinvertebrate biotic integrity index [36–39], sampling sites that simultaneously met $\text{DO} \geq 5$ mg/L, NH_4^+ -N ≤ 1 mg/L, and $H \geq 1.0$ were defined as reference sites, and the remaining sites were classified as impaired sites.

(2) Candidate Biological Indices for B-IBI.

A total of biological indices covering five categories—taxon richness, relative abundance, pollution tolerance, feeding functional groups, and biodiversity—were selected as candidate indicators for constructing the Benthic Index of Biotic Integrity for Dongting Lake polders, as shown in Table 1.

(3) Screening of Candidate Parameters.

The selected candidate parameters were sequentially screened through distribution range analysis, discriminatory power analysis, and redundancy analysis to identify the core parameters finally included in the B-IBI calculation [39]. Distribution range analysis: Parameters for which zero-value samples accounted for more than 95% of the total data range were eliminated. Discriminatory ability analysis: The boxplot method (IQ value method) was used to assign scores according to the overlap of the quartile distance between the reference point and the damaged point. The quartile distance without overlap was assigned 3 points; the interquartile range was partially overlapped, and their medians were outside the range of the other's interquartile range, being assigned 2 points; only one median was within the range of the other's interquartile range, being assigned 1 point; and each median is within the range of the other's quartile range, being assigned 0 points. Finally, only the alternative parameters with $\text{IQ} \geq 2$ were retained. Redundancy analysis: Spearman correlation analysis was performed on candidate parameters. For pairs with a correlation coefficient $|r| > 0.75$, the parameter containing relatively greater biological

information and higher ecological importance was retained, along with all parameters that passed the correlation test ($|r| < 0.75$).

Table 1. Alternative parameters for the B-IBI of Dongting Lake embankments.

Index Category	Index Code	Index Name	Response to Disturbance
Taxon Richness	M1	Total Taxon Richness	Decrease
	M2	Mollusca Taxon Richness	Decrease
	M3	Gastropoda + Bivalvia + Insecta Taxon Richness	Decrease
	M4	Gastropoda Taxon Richness	Decrease
	M5	Insecta Taxon Richness	Increase
	M6	Hirudinea Taxon Richness	Increase
	M7	Oligochaeta Taxon Richness	Increase
	M8	Malacostraca Taxon Richness	Increase
	M9	Total Density	Variable
Relative Abundance	M10	Mollusca Percentage	Decrease
	M11	Percentage of the Top 3 Dominant Groups	Decrease
	M12	Percentage of Gastropoda + Bivalvia + Insecta	Decrease
	M13	Insecta Percentage	Increase
	M14	Gastropoda Percentage	Decrease
	M15	Hirudinea Percentage	Variable
	M16	Oligochaeta Percentage	Increase
	M17	Malacostraca Percentage	Increase
Pollution Tolerance	M18	Sensitive Taxon Richness	Decrease
	M19	Tolerant Taxon Richness	Increase
	M20	Sensitive Taxa Percentage	Decrease
	M21	Tolerant Taxa Percentage	Increase
	M22	GBI Index	Variable
	M23	BWMP Score	Decrease
Functional Feeding Groups	M24	Filterer Percentage	Variable
	M25	Predator Percentage	Increase
	M26	Omnivore Percentage	Increase
	M27	Shredder Percentage	Decrease
	M28	Collector Percentage	Increase
	M29	Scraper Percentage	Decrease
Biodiversity	M30	Shannon–Wiener Diversity Index	Decrease
	M31	Pielou Evenness Index	Decrease
	M32	Margalef Richness Index	Decrease
	M33	Simpson Diversity Index	Decrease

3.2.5. B-IBI Calculation

Assume that n core parameters are used. The 95th percentile and 5th percentile of the i -th parameter are taken as the expected value and critical value for that parameter, respectively. A ratio method is used for standardization to obtain S_i . The final B-IBI score is converted to a 100-point system. The calculation formula is as follows:

$$S_i = \begin{cases} \frac{I_i}{E_i} & \text{Reverse parameters} \\ \frac{I_{i(max)} - I_i}{I_{i(max)} - O_i} & \text{Positive parameters} \end{cases} \quad (5)$$

$$IBI = \left(\frac{\sum_{i=1}^n S_i}{n} \right) \times 100 \quad (6)$$

where I_i , E_i , O_i and $I_{i(max)}$ represent the measured value, expected value, critical value, maximum value, and minimum value of the i -th indicator, respectively.

Statistical analyses of benthic macroinvertebrate community structure in this study were performed using Microsoft Excel 2021, and correlation analysis was conducted in SPSS 26.0. Analysis of Similarity (ANOSIM), Non-metric Multidimensional Scaling (NMDS), forward selection, redundancy analysis (RDA), the entropy weight method, and calculations of related indices were all completed in R software (version 4.5.2). The map of the study area was generated using ArcGIS 10.8, and all other figures were plotted jointly with R software (version 4.5.2) and Origin 2022.

3.3. Bayesian Comprehensive Assessment of Aquatic Ecological Health Based on Entropy Weight Method

3.3.1. Weight Determination by Entropy Weight Method

First, the H index, TLI , WQI , and B-IBI were standardized to eliminate the influence of dimensions.

$$\begin{cases} \frac{x_j - \min(x_j)}{\max(x_j) - \min(x_j)} & \text{Positive indicators} \\ \frac{\max(x_j) - x_j}{\max(x_j) - \min(x_j)} & \text{Reverse indicators} \end{cases} \quad (7)$$

The calculation formula of information entropy (E_{ij}) is as follows:

$$E_j = -\frac{1}{\ln m} \sum_{i=1}^m p_j \ln p_j \quad (8)$$

$$p_j = \frac{y_j}{m \sum_{i=1}^m y_{ij}} \quad (9)$$

In the formula, p_{ij} is the proportion of the indicator value of the i -th sample under the j -th indicator to the total values of all samples.

The weight W_j of the j -th indicator is derived from information entropy, and the calculation formula is as follows:

$$W_j = \frac{1 - E_j}{\sum_{j=1}^n (1 - E_j)} \quad (10)$$

The aquatic ecological health status was classified into five grades, namely Excellent, Good, Moderate, Poor, and Very Poor, in sequence. The scoring criteria, classification standards for each indicator, and calculated weights are presented below (Table 2).

Table 2. Indicator weights and evaluation grade division ranges.

Index	Weights	Evaluation Grades				
		Excellent	Good	Moderate	Poor	Very Poor
TLI	0.193	30	30~50	50~60	60~70	>70
WQI	0.249	90~100	70~90	50~70	25~50	0~25
H Index	0.289	2.5~3	2~2.5	2~1	0.5~1	0~0.5
B-IBI	0.268	>81.46	61.09~81.46	40.73~61.09	20.37~40.73	<20.27
CHI	-	4.20~5.00	3.40~4.20	2.62~3.40	1.85~2.62	1~1.85

3.3.2. Bayesian Evaluation Model

The prior probability $P(C_t)$ (0~1) corresponding to the health grade for each evaluation indicator was determined. Specifically, each indicator value was first classified into one of the five grades according to the thresholds in Table 2, and the frequency of each grade across all indicator assessments was counted and normalized. There are only four evaluation indexes in this paper. In order to ensure the robustness and global representativeness of prior estimation, this study aggregates all the index observations of all sampling sections to construct a global prior:

$$P(C_t) = \frac{n_t}{\sum_{t=1}^5 n_t} \quad (11)$$

In the formula, C_t represents the aquatic ecological health result of the t -th grade; n_t is the total number of single-indicator assessments falling into grade. If any grade had zero frequency, a small constant (0.01) was assigned before re-normalization to avoid zero priors.

All four assessment indicators are non-negative, so they are assumed to follow a half-normal distribution. In view of the key defects of traditional normal distribution in environmental assessment, the probability penalty is applied to the index values that exceed the optimal standard or inferior to the worst standard. In this study, the flat-top semi-normal distribution is used as the likelihood function. This method draws on the flat top idea of membership function in fuzzy comprehensive evaluation; that is, the membership degree at the boundary maintains a platform rather than continuous attenuation. In the context of environmental assessment, the index value far exceeding the optimal threshold should not reduce the likelihood probability due to deviation from the mean value; on the contrary, the peak probability should be maintained to reflect the saturation effect of ecological benefits. The calculation formula for the basic likelihood probability is:

$$P(x_i|C_t) = \frac{\sqrt{2}}{\pi\sigma_{it}} \exp\left(-\frac{(x_i - \mu_{it})^2}{2\sigma_{it}^2}\right) \quad (12)$$

$$\mu_{i,t} = \frac{upper_{it} + lower_{it}}{2} \quad (13)$$

$$\sigma_{it} = \frac{|upper_{it} + lower_{it}|}{3.92} \quad (14)$$

In the formula, μ_{it} is the mean value of the i -th evaluation indicator under the t -th health grade; σ_{it} is the standard deviation of the i -th evaluation indicator under the t -th health grade, where $3.92 \approx 1.96 \times 2$, ensuring that the interval [lower, upper] covers approximately 95% of the probability mass under the normal curve. Intermediate level (2~4) and non-boundary values, using the basis of normal likelihood, are unchanged; when the index value exceeds the excellent standard or is inferior to the worst standard (Very Poor) the peak probability density is maintained to avoid the boundary penalty effect of the traditional normal distribution in environmental evaluation.

Combined with the indicator weights determined by the entropy weight method, the posterior probability that the i -th sample belongs to the t -th health grade C_t is calculated as follows:

$$P(C_t|X_i) = \frac{P(C_t) \prod_{j=1}^n [P(x_{ij}|C_t)]^{w_j}}{\sum_{t=1}^n P(C_t) \prod_{j=1}^n [P(x_{ij}|C_t)]^{w_j}} \quad (15)$$

We compare the posterior probabilities of the i -th sample belonging to each health grade, convert the posterior probabilities into the comprehensive aquatic ecological health index (CHI_i), and obtain the evaluation grade S_i according to the grade division intervals of Table 2.

$$CHI_i = \sum_{t=1}^k t \cdot P(C_t | X_i) \quad (16)$$

4. Results and Analysis

4.1. Characteristics of Benthic Macroinvertebrate Community Structure

Two benthic macroinvertebrate surveys were conducted in the summer and winter of 2024. A total of 47 species of benthic macroinvertebrates were collected and identified, belonging to 3 phyla, 6 classes, 15 orders, 21 families, and 39 genera. Among them, 25 species were found in the summer and 36 species in the winter. In the phylum Annelida, there were five species of Hirudinea and two species of Oligochaeta; no species of Polychaeta were collected. In the phylum Arthropoda, there were 10 species of Insecta, including 8 species of the typical representative Chironomidae larvae and 2 other species of aquatic insects. In the phylum Mollusca, there were 9 species of Bivalvia and 17 species of Gastropoda. The total number of species of Gastropoda, Insecta, and Bivalvia accounted for 76.92% of the total species richness, indicating that these three groups constituted the dominant taxa of the benthic macroinvertebrate community at all sampling sites and played a leading role in the community structure. The density survey showed that the average density of benthic macroinvertebrates in the polders of Dongting Lake in 2024 was 193.00 ind./m², with an average density of 113.33 ind./m² in the summer and 79.67 ind./m² in the winter. Gastropoda was absolutely dominant in the density composition (82.9%), followed by Insecta > Bivalvia > Oligochaeta > Hirudinea > Malacostraca > Polychaeta in descending order (Figure 3).

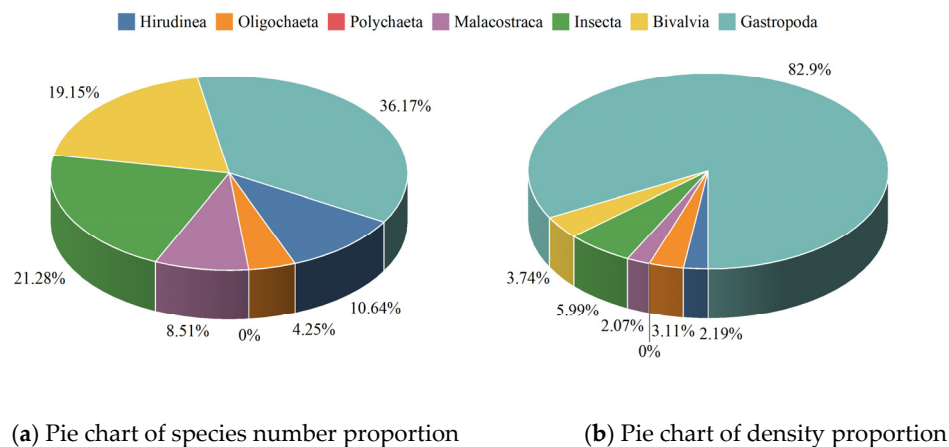


Figure 3. Benthic macroinvertebrate species number and density proportion pie chart in Dongting Lake polders.

The species number of benthic macroinvertebrates in polders near East Dongting Lake was generally higher than that in polders near South Dongting Lake, showing a decreasing trend: Polder Anzao > Polder Junshan > Polder Chengxi > Polder Xiangbin Nanhu. From summer to winter, the species number of benthic macroinvertebrates in Dongting Lake polders showed an overall increasing trend, with the most obvious increase in Polder Anzao. Except for a significant decrease in Gastropoda species, the species number of other taxa all increased. The density of benthic macroinvertebrates showed a decreasing trend, with the sharpest decline in Polder Chengxi. In terms of

density proportion, the percentages of Oligochaeta and Hirudinea increased, while Insecta decreased. Except for Polder Junshan, the proportion of Gastropoda decreased but remained dominant (Figure 4).

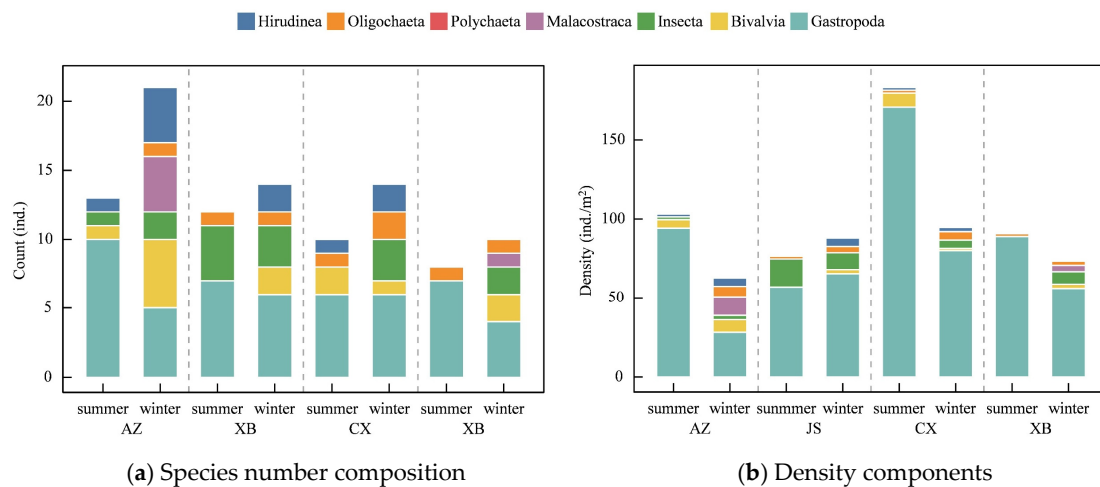


Figure 4. Bar chart of the composition of benthic macroinvertebrate communities in Dongting Lake polders.

ANOSIM analysis was performed separately on the benthic macroinvertebrate community structure in different polders during the two seasons (Figure 5). The results showed that the R value was -0.079 and the p value was 0.697 ($p > 0.05$) in the summer, and the R value was -0.022 and the p value was 0.533 ($p > 0.05$) in the winter, indicating that the benthic macroinvertebrate community structure in each polder exhibited a certain degree of similarity. NMDS analysis of the benthic macroinvertebrate community structure in the polders across the two seasons (Figure 6) showed that the stress value was $0.132 < 0.2$, indicating that the results were reliable. However, no obvious separation was found in the confidence ellipse of the two seasons, indicating that the seasonal difference of community structure was not obvious. Therefore, the benthic macroinvertebrate communities in the polders of Dongting Lake showed a certain degree of similarity in both time and space.

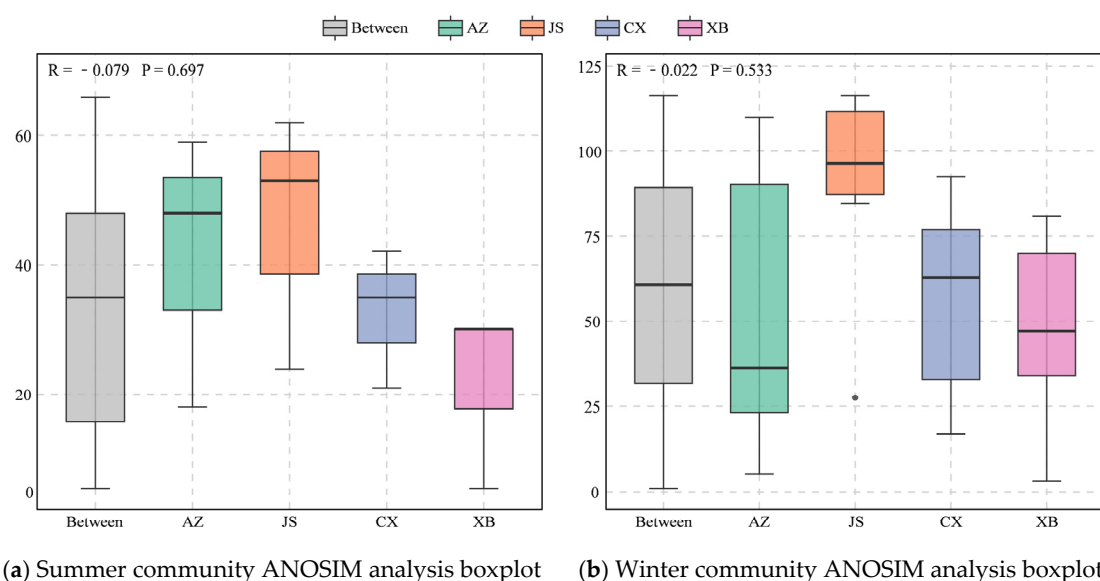


Figure 5. Boxplot of ANOSIM analysis of benthic macroinvertebrate communities in different polders during the summer (a) and winter (b). (Note: “Between” represents the rank of dissimilarities between different polder groups. The black dot indicates an outlier.).

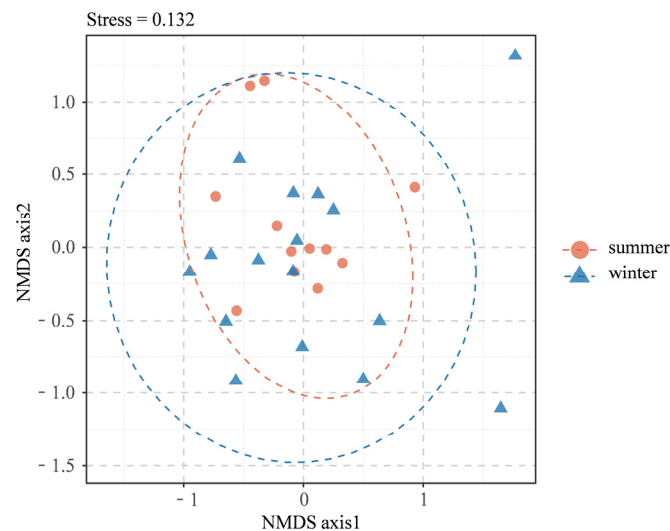


Figure 6. NMDS ordination of benthic macroinvertebrate community structure during summer and winter.

4.2. Relationship Between Community Structure and Environmental Factors.

The U test showed that Chl.a ($p = 0.00067 < 0.001$), $\text{NH}_4^+\text{-N}$ ($p = 0.00003 < 0.001$), TN ($p = 0.00035 < 0.001$), TOC ($p = 0.00083 < 0.001$), DO ($p = 0.00573 < 0.01$), WT ($p = 0.00001 < 0.001$), Tur ($p = 0.00932 < 0.01$), D ($p = 0.00182 < 0.01$), and V ($p = 0.0146 < 0.05$) had significant seasonal differences (Supplementary Materials Figure S1). The H test showed that there were significant differences in DO ($p = 0.0271 < 0.05$), TDS ($p = 0.00329 < 0.01$), Cond ($p = 0.03 < 0.05$), SD ($p = 0.00439 < 0.01$), and pH ($p = 0.00396 < 0.01$) among polders in the summer (Supplementary Materials Figure S2). There were significant spatial differences in Cond ($p = 0.0086 < 0.01$), DO ($p = 0.028 < 0.05$), $\text{NH}_4^+\text{-N}$ ($p = 0.0284 < 0.05$), $\text{PO}_4^{3-}\text{-P}$ ($p = 0.00495 < 0.01$), WT ($p = 0.00673 < 0.01$), TDS ($p = 0.00861 < 0.01$), TN ($p = 0.0086 < 0.01$), and V ($p = 0.0479 < 0.05$) among polders in the winter (Supplementary Materials Figure S3), but no significant environmental factors were found in different sampling points in the summer and winter.

The results of the Pearson correlation analysis are shown in Figure 7. A total of highly correlated environmental factor pairs ($|r| \geq 0.7$) were detected, including four pairs in the summer and two pairs in the winter, as detailed in Table 3.

Table 3. Highly collinear environmental factor groups in Dongting Lake polders.

Season	Highly Collinear Environmental Factor Groups
Summer	$\text{PO}_4^{3-}\text{-P}$, TP, TN
	COD_{Mn} , TOC
	Chl.a, V
	DO, TDS, Cond, pH
Winter	$\text{PO}_4^{3-}\text{-P}$, TP, TN, $\text{NH}_4^+\text{-N}$, DO, TDS, Cond, S, Tur
	COD_{Mn} , Chl.a, SD

The most prominent characteristic of the water environment in the polder area is the high nitrogen and phosphorus concentrations; TN and TP are the most basic and commonly used indicators for assessing the nutritional status of lakes, and their direct

impact on phytoplankton biomass has been widely confirmed. More and more studies on eutrophic lakes have shown that nitrogen and phosphorus often regulate primary productivity together, and only focusing on a single nutrient may mask the complex ecological response of benthic communities to nutrient enrichment. The retention of TN and TP at the same time is an important diagnostic tool for identifying the types of nutrient limitations in water bodies and shows significant changes along the nutrient gradient [40–42]. For organic pollution assessment, TOC can more comprehensively reflect the total organic matter content than COD_{Mn} [43] and is less affected by oxidation efficiency, making it more representative for organic pollution evaluation in agricultural regions. Chl.a is susceptible to hydrodynamic conditions. As a direct indicator of phytoplankton biomass, it provides important implications for the food sources of benthic macroinvertebrates [44,45]. TDS, Cond, and S are highly collinear with each other and act as key limiting factors affecting the survival of benthic macroinvertebrates, with significant impacts on the dominant group Gastropoda in the winter [46]. In the winter, variations in Chl.a and SD are jointly influenced by COD_{Mn} and suspended solids. Finally, among highly collinear environmental factor groups, TN/TP, TOC, Chl.a, and DO were retained in the summer, while DO and COD_{Mn} were retained in the winter.

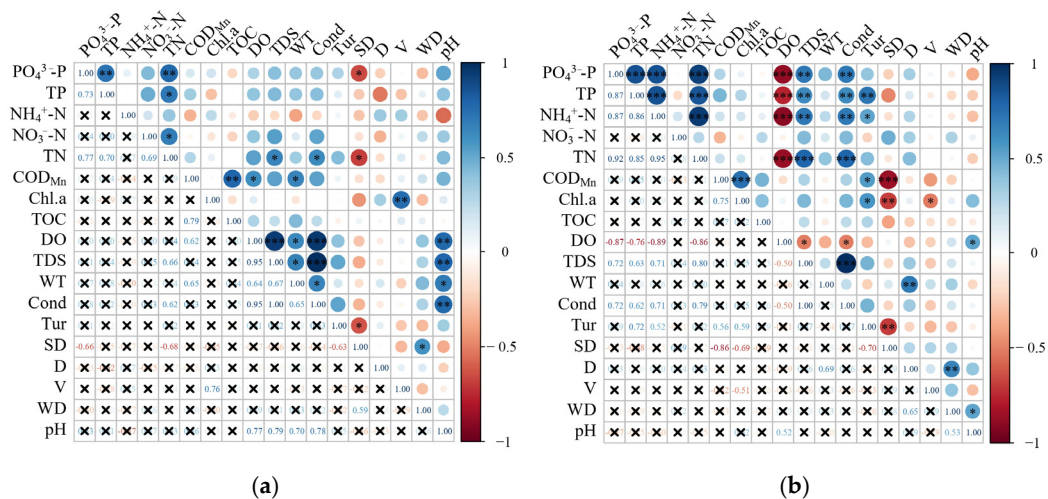


Figure 7. Correlation heatmap of environmental factors in Dongting Lake polders. (Note: ×, not significant ($p \geq 0.05$); *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$). (a) Heatmap of summer environmental factor correlations. (b) Heatmap of winter environmental factor correlations.

After forward selection ($p < 0.05$) and the Monte Carlo permutation test (999 permutations) on the retained environmental factors, TN/TP, NO₃⁻-N, D, Tur, and Chl.a were identified as the key environmental factors shaping the benthic macroinvertebrate community structure in the polders of Dongting Lake in the summer. The explanatory power of the first two axes of the RDA ordination plot was 27.81% and 18.05%, respectively, with a cumulative explanation rate of 61.33% for community variation. WSW, WT, Tur, and DO were determined as the key environmental factors influencing the benthic macroinvertebrate community structure in winter. The explanatory power of the first two RDA axes was 11.99% and 3.87%, respectively, with a cumulative explanation rate of 20.12% (Figure 8).

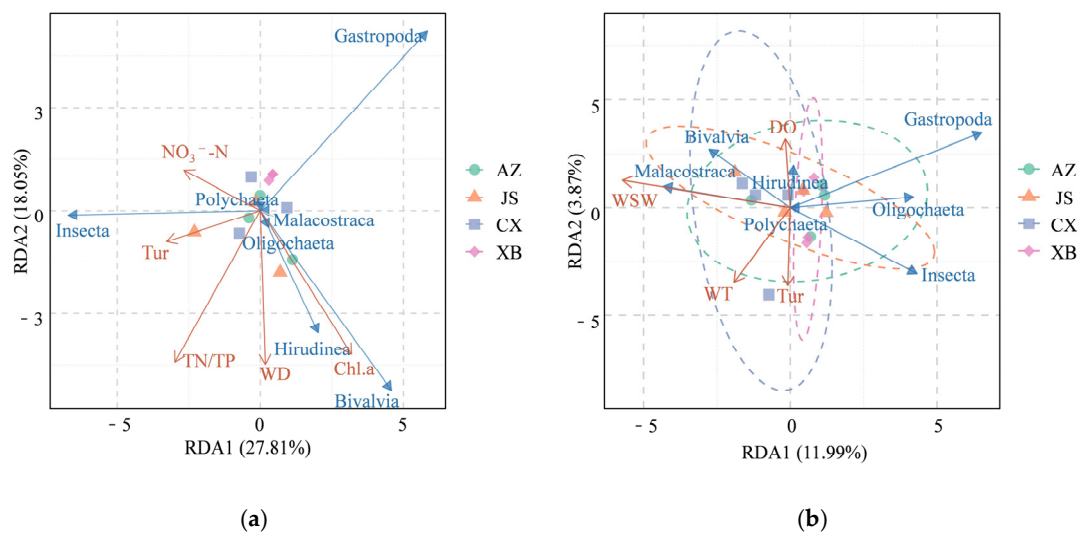


Figure 8. RDA ordination plot of benthic macroinvertebrates in Dongting Lake polders. (a) RDA analysis diagram of summer benthic macroinvertebrates. (b) RDA analysis diagram of winter benthic macroinvertebrates.

4.3. Entropy Weight Bayesian Comprehensive Evaluation Results

4.3.1. H Diversity Index

In 2024, the average Shannon–Wiener diversity index (H) of benthic macroinvertebrates in the polders of Dongting Lake was 1.35 in the summer and 1.33 in the winter, indicating that the embankment area of Dongting Lake was at a moderate pollution level in the two seasons. The community structure was relatively simple and dominated by a few pollution-tolerant groups. The minimum value of the H index appeared in XB2 (0.69) in the summer and CX3 (0.68) in the winter, indicating serious pollution and extreme degradation of the community. The maximum value of was AZ1 (1.85) in the summer and AZ4 (2.05) in the winter, indicating that the diversity was relatively high and the community structure was relatively balanced, but it was still within the range of moderate disturbance. The seasonal difference was not significant ($p > 0.05$). No significant spatial difference in the H index was observed among polders in both seasons ($p > 0.05$) (Figure 9).

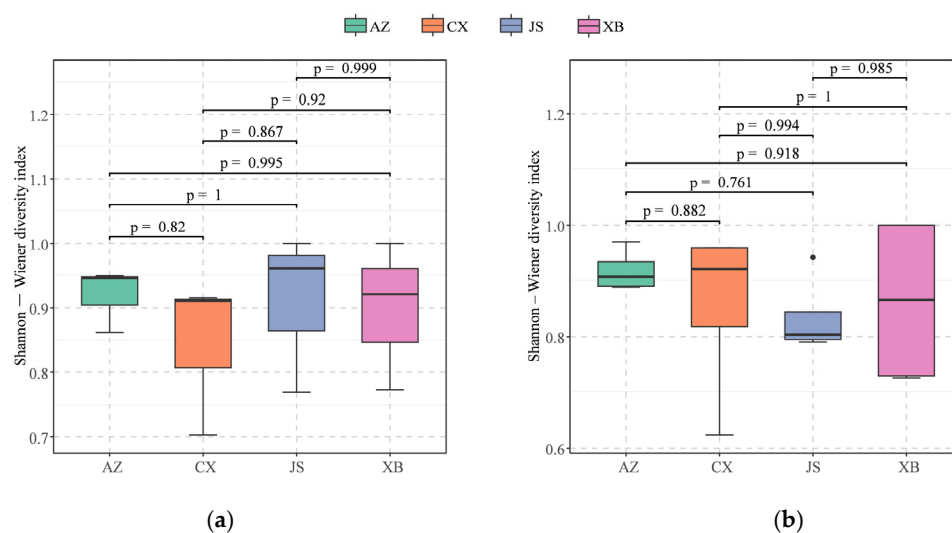


Figure 9. Boxplot of H diversity index of benthic macroinvertebrates in Dongting Lake polders. (a) Summer benthic macroinvertebrates H diversity index boxplot. (b) Winter benthic macroinvertebrates H diversity index boxplot.

4.3.2. TLI

The average Trophic Level Index (TLI) of water in the polders was significantly higher in the winter than in the summer. In the summer, AZ3, AZ2, JS1, and CZ1 were slightly eutrophic, while all other sampling sites were at a mesotrophic level. In the winter, except for JS2 and JS3 which were moderately eutrophic, all other sampling sites were slightly eutrophic, with the highest TLI value at JS3. Among the polders, the eutrophication level of Polder Anzaao increased in the winter but remained slightly eutrophic overall. Polder Junshan showed a relatively high eutrophication level throughout the year. Polder Chengxi exhibited the most stable trophic status, while Polder Xiangbin Nanhu had the largest seasonal fluctuation, with a significant increase in eutrophication in the winter (Supplementary Materials Figure S4).

4.3.3. WQI

The annual average Water Quality Index (WQI) of water in the polders of Dongting Lake in 2024 was 50.05, near the threshold between “Moderate” and “Poor” grades. The average WQI in the summer was 46.39, with all sampling sections graded as “Poor”. The average WQI in the winter was 52.80, and the overall water quality in the winter was better than that in the summer. Only JS2, JS3, JS4, and CX4 remained at the “Poor” grade, while all other sections recovered to “Moderate”. Among the polders, Polder Xiangbin Nanhu had a high upper limit of water quality, whereas Polder Junshan showed serious water quality degradation in the winter (Supplementary Materials Figure S5).

4.3.4. B-IBI

AZ3, JS1, CX1, and XB3, as well as newly added sampling sites AZ4 and XB4 in the winter, were selected as reference sites for the Benthic Index of Biotic Integrity (B-IBI) assessment in the polders of Dongting Lake, with the remaining sites regarded as impaired sites. Indicators with an excessively narrow distribution range (distribution of 0 values exceeding 95%), including M8, M18, M19, M21, M27, and M28, were eliminated, leaving 27 parameters for discriminant ability analysis. Candidate parameters with $IQ \geq 2$ screened by the boxplot method were M2, M3, M4, M9, M11, M23, and M31, totaling seven parameters (Figure 10). Redundancy analysis (Table 4) showed that only M2 was significantly correlated with M3 and M4. Among them, the correlation coefficient between M3 and M23 was close to 0.75, so M4 with relatively fewer outliers was retained. Finally, the core parameters included in the B-IBI calculation were determined as M4, M9, M11, M23, and M31.

Table 4. Alternative parameter correlation coefficient.

Parameter	M2	M3	M4	M9	M11	M23	M31
M2	1.00						
M3	0.84 **	1.00					
M4	0.79 **	0.91 **	1.00				
M9	0.5 **	0.50 **	0.54 **	1.00			
M11	−0.30	−0.38	−0.26	−0.13	1.00		
M23	0.61 **	0.74 **	0.50 **	0.19	−0.39	1.00	
M31	−0.15	−0.14	−0.24	−0.57	−0.21	0.12	1.00

Note: ** indicates $p < 0.01$.

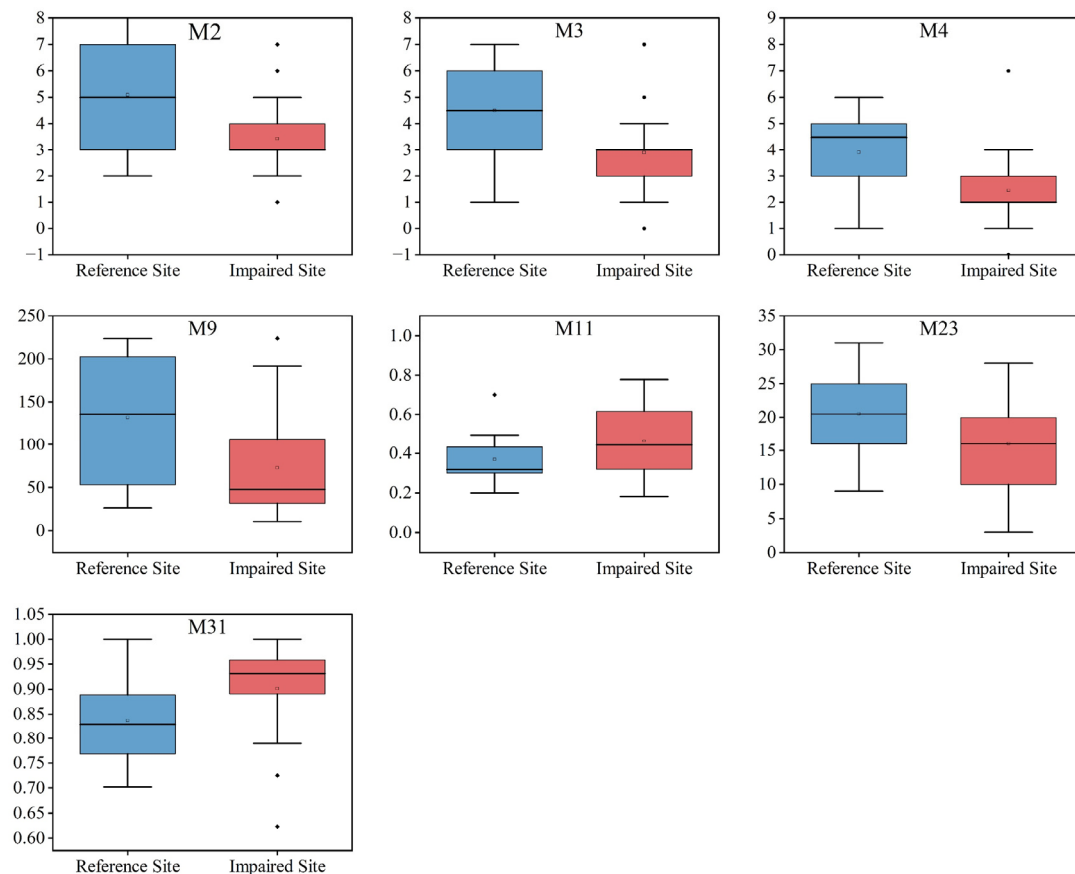


Figure 10. Alternative parameter boxplot ($IQ \geq 2$).

The calculated B-IBI was verified using the IQ value method (Figure 11). An IQ value of 2 indicated a significant distinction between reference sites and impaired sites, demonstrating that the established evaluation system was reasonable and applicable for assessing aquatic ecological health in the polders of Dongting Lake. The annual average comprehensive B-IBI across the polders in the Dongting Lake region was 50.69, and the annual ecological health status was graded as “Moderate”. The average B-IBI was 54.74 in the summer and 47.64 in the winter. Although the summer value was higher than that in the winter, the corresponding health grade remained unchanged. Among all polders, Polder Chengxi exhibited the best health status. Large discrepancies in B-IBI values among sampling sites were observed in Polder Xiangbin Nanhu during the summer and in Polder Junshan during the winter.

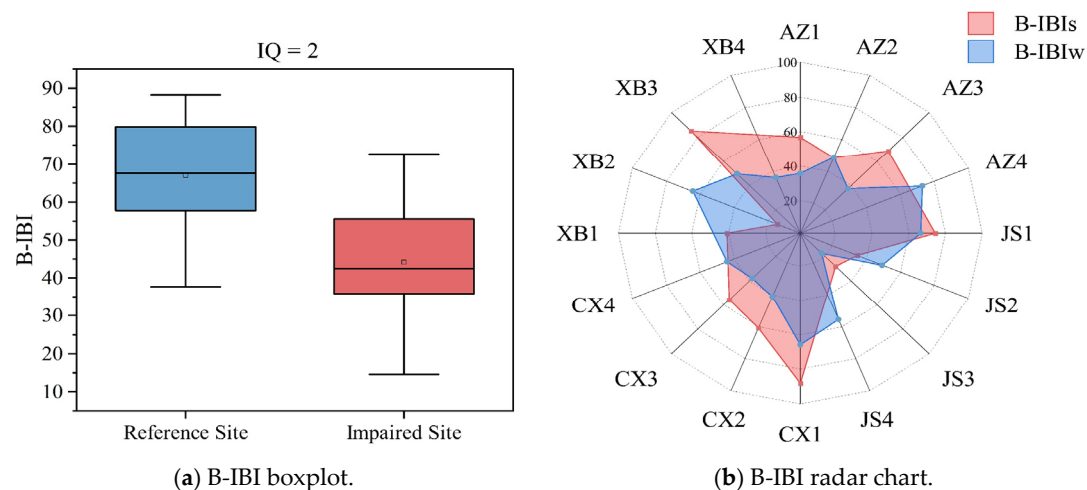


Figure 11. B-IBI results of each sampling point in Dongting Lake embankment.

4.3.5. Comprehensive Evaluation Results

All four evaluation indices passed the Pearson correlation test ($r < 0.8$). The correlations among the indices were reasonable, satisfying the Bayesian independence assumption and providing a fundamental prerequisite for constructing the entropy-weighted Bayesian aquatic ecological health assessment model. The calculation results of the four indicators are shown in Supplementary Materials Figure S6 and Table S1.

The comprehensive evaluation results indicate that the overall ecological health status of typical polders in Dongting Lake in 2024 was moderate, with 85.7% of the sampling sites rated as moderate throughout the year. Seasonal difference analysis showed that all sampling sites were assessed as moderate in the summer, except for site XB2. In the winter, the ecological health status varied distinctly among polders. Polder Chengxi performed better than the others, with site CX1 rated as good. By contrast, some sampling sites in Polder Junshan and Polder Xiangbin Nanhu were rated as poor. The temporal and spatial distribution characteristics and proportion statistics of ecological health grades at each sampling site are presented in Supplementary Materials Figure S7.

5. Discussion

5.1. Characteristics of Benthic Macroinvertebrate Community Structure in Polders of Dongting Lake

A total of 47 benthic macroinvertebrates species were collected and identified in the polders of Dongting Lake in 2024, with Gastropoda, Insecta, and Bivalvia as the dominant groups. The results of this main group composition are consistent with the findings of Wang et al. [25] and Peng et al. [47] in the main body of Dongting Lake, but the total number of species showed a decreasing trend. Compared with Dongting Lake, the polders suffer from poor hydrological connectivity, insufficient water volume, channelized ditches, and increased external pollution input. This is mainly due to the poor hydrological connectivity and obvious channelization of polders. Compared with the natural lake, the habitat space of organisms is compressed, and the input of exogenous pollution is increased, which is not conducive to the survival of sensitive clean water groups [48]. In terms of species composition, compared with Wang et al.'s research [25], the proportion of Oligochaeta decreased, while that of Hirudinea and other groups increased. The main reasons are that the leeches have strong tolerance to the low oxygen and high ammonia nitrogen environment in the polder, and the reduction of water and sediment discharge after the operation of the Three Gorges Project leads to the decrease of sediment cherry blossoms and organic matter in the polder, which is not conducive to the survival of oligochaetes [40, **Error! Reference source not found.**].

We observed a significant seasonal reversal: the total density was significantly higher in the summer, while the species richness peaked in the winter. High temperatures and eutrophication in the summer promoted the rapid reproduction of pollution-resistant dominant species, environmental filtration, and eclosion, showing the phenomenon that the density of certain species was extremely dominant and the overall number of species decreased. Winter low temperatures alleviated interspecific competition, and stable hydrological conditions maintained high habitat heterogeneity, thus supporting the coexistence of more species. The dominant species of benthic macroinvertebrate communities in the two seasons overlapped considerably, and the communities showed certain similarity in spatial and temporal distribution. The polders are located in the lakeside zone of Dongting Lake with similar geographical environments, resulting in insignificant spatial differences. Compared with natural rivers and lakes, polders are

subject to stronger human disturbance than seasonal factors, leading to insignificant seasonal variations [41].

5.2. Relationship Between Benthic Macroinvertebrate Community and Environmental Factors

The key environmental factors shaping the benthic macroinvertebrate community structure in the summer were TN/TP, $\text{NO}_3\text{-N}$, WD, Tur, and Chl.a, with nutrient enrichment indicators playing a dominant role. This pattern indicates that the benthic community structure is shaped by a dual regulatory mechanism involving both eutrophication stress and the availability of food resources. Given the significant influence of nutrient-driven processes, eutrophication control should be prioritized as a key management strategy during the summer season to maintain ecological balance in these wetland systems. Eutrophication is the primary environmental issue in polder waters. Nitrogen, phosphorus, and Chl.a are important indicators of eutrophication and also reflect the dynamics of phytoplankton. In this study, TN/TP and $\text{NO}_3\text{-N}$ were strongly negatively correlated with Gastropoda and positively correlated with Insecta. Lu et al. [42] reported that with the intensification of lake eutrophication in the middle and lower reaches of the Yangtze River, the density of Gastropoda exhibited an initial increase followed by a decline. In contrast, Insecta, particularly pollution-tolerant chironomid larvae, demonstrated strong pollution tolerance and even showed rising population densities. Appropriate nitrogen concentrations promote the growth of primary producers, but excessive levels become inhibitory [43,50–52]. In this paper, it was found that Chl.a was mainly positively correlated with the density of Bivalvia, Hirudinea, and Oligochaeta, which was consistent with the results of Shabani et al. [53] who found that the moderate increase in Chl.a concentration significantly promoted the community density of bivalves and oligochaetes in Sanjiang Plain wetland. High Chl.a concentrations in the summer enhance algal photosynthesis and provide abundant organic detritus and algal food for filter-feeding benthic macroinvertebrates [54]. Variations in light intensity and flow velocity across water depth gradients indirectly affect community composition. Summer Tur is strongly positively correlated with Insecta and strongly negatively correlated with Gastropoda, which was consistent with the results of Zeng et al. [55] in the study of zoobenthos in Yilong Lake. The erosion of summer rainfall runoff brings sediment and organic debris, which provides a food source for the collector chironomid larvae. The increase of turbidity and the lack of light indirectly destroy the anti-predation ability and reproductive behavior of Gastropoda.

In the winter, the key environmental factors were water WSW, WT, Tur, and DO, primarily reflecting physical and pollution-related drivers. This indicates a dominant role of hydrological conditions in structuring the benthic communities, with particular emphasis on the deterioration of hydrological connectivity in polder channels during winter, leading to intermittent flow cessation in certain tributaries. WSW directly reflects hydrological connectivity and physical niche availability, which was positively correlated with Malacostraca and Bivalvia but negatively correlated with Gastropoda. As demonstrated by Pander et al. [56], poor winter connectivity reduces WSW and exposes parts of the riverbed, which shrinks habitat area, limits nutrient transport, and intensifies intra- and interspecific competition. WT and DO are intrinsically linked regulators of survival and metabolism. WT is a critical factor limiting metabolism and reproduction in the winter. Low WT affects community structure by inhibiting the enzyme activity and basal metabolism of sensitive groups [57,58]. In this paper, it was found that DO was positively correlated with most benthic animals except for the negative correlation with Insecta. Verberk et al. [59] found that the tolerance of aquatic insects to hypoxia in colder water was improved. Combined with the analysis of seasonal differences of environmental factors, Chl.a, TN, DO, WT, Tur, and WD were the key factors for the

differences in the community structure of zoobenthos in the Dongting Lake polders, but the seasonal differences in community structure were not obvious.

5.3. Aquatic Ecological Health Assessment of Dongting Lake Polders

Compared with the extreme fluctuations presented by the four single evaluation indicators, the entropy weight–Bayesian comprehensive evaluation results show a buffer and neutralization effect on the local extremum. The overall study area is mostly in the middle health-level section, which is consistent with the results of Yao et al. in the Dongting Lake water ecological health evaluation study. The comprehensive evaluation and single index showed that the water ecological health status in the summer was better than that in the winter. This seasonal difference is mainly controlled by the rhythmic fluctuation of hydrological connectivity and the coupling effect of human disturbance such as agricultural planting and fertilization and aquaculture. In the summer, a large amount of residual pesticides and fertilizers in the four typical agricultural polders flowed into the ditches with abundant rainfall, resulting in nitrogen and phosphorus nutrients becoming the key environmental factors driving the succession of zoobenthos communities. However, the TLI evaluation results showed that the eutrophication degree in the winter was higher than that in the summer, which was mainly due to the concentration effect caused by the sharp decrease in water volume and the blocking of hydrological connectivity in the winter, resulting in a significant increase in the concentration of Chl.a, TN, TP, and other biogenic elements in the water. In terms of spatial patterns, the ecological health conditions of Polder Chengxi and Polder Xiangbin Nanhu adjacent to South Dongting Lake are superior to those of Polder Anza and Polder Junshan near East Dongting Lake. This macro difference mainly depends on the hydrodynamic conditions and pollution load: the water system of South Dongting Lake is relatively rich, and the rate of water renewal and exchange is fast; east Dongting Lake is the main catchment area of the basin, and the endogenous pollution load of historical accumulation is heavy. Specific to the polder scale, land use and human disturbance intensity become the decisive factors. The ecological condition of Polder Chengxi is the best, and its CX1 is the only section that is rated as “good” in the whole region. Polder Anza is far from the main lake area of East Dongting Lake, the input of pollution sources is relatively single, and the health status is stable. The worst situation was found in Polder Junshan and Polder Xiangbin Nanhu, both of which had “poor” sections. The reason is that Polder Junshan, as a large-scale agricultural base and covering scenic spots, has long been subjected to high-load agricultural non-point source and domestic sewage dual input [60,61]; however, the aquaculture industry in Polder Xiangbin Nanhu is developed, and the intensive discharge of aquaculture tail water and frequent human fishing activities have caused serious stress on its water environment and biological community [62].

Compared with the evaluation results of four single indicators, the comprehensive evaluation is more biased towards the mean. For the two “poor” sections of the whole embankment, the TLI of JS3 section was the highest and the WQI was the lowest in the winter, and the typical black and odorous water body characteristics appeared in the sampling and were accompanied by a large number of *Alternanthera philoxeroides*. The internal mechanism is that the degradation of aquatic plant residues in the winter consumes a large amount of dissolved oxygen, releases dissolved organic carbon and nutrients, leads to a significant decrease in the redox potential at the interface between sediment and water, and induces the desorption of iron–manganese-bound phosphorus and the violent release of endogenous phosphorus. The poor physical and chemical environment directly leads to the consistent decline in the B-IBI and WQI at this section. In contrast, the TLI and WQI of the XB2 section in the winter were better, but the performance of H was poor, showing a non-synchronous response of physical and

chemical water quality and ecological health. This is mainly because the sampling point is close to the residential area, and frequent human fishing and other direct disturbances have destroyed the community structure of benthic animals.

In traditional single-index evaluations, assessment results frequently fall close to rigid threshold boundaries, as observed with the TLI at sites AZ1, AZ2, and JS1 in the summer and XB3 in the winter; the WQI at XB3 in the summer; the H index at JS4 in the winter; and the B-IBI at XB1 in the summer. Such borderline cases highlight the limitations of relying on isolated metrics, which merely capture fragmented facets of physicochemical stress or biological responses and are highly susceptible to localized extreme fluctuations. To address this, the half-normal Bayesian model effectively reduced boundary errors from fixed thresholds in traditional methods and accurately identified outliers, further verifying the scientific validity and rationality of the entropy-weighted Bayesian aquatic ecological health assessment model [63]. By objectively quantifying the underlying correlations between water quality parameters and biotic integrity, this integrated approach organically fuses multi-dimensional variables and buffers the interference of local extremes. Consequently, it offers a potential means to mitigate the asynchronous evaluation bias between physicochemical states and ecological responses, providing a more robust, holistic, and objective benchmark for revealing the true health status of aquatic ecosystems.

6. Conclusions and Prospects

A total of 47 benthic macroinvertebrates species were identified in the polders of Dongting Lake in 2024, with Gastropoda, Insecta, and Bivalvia being the main components of the benthic macroinvertebrate community. The species richness in the winter was higher than that in the summer, and the community structure showed a certain degree of similarity in both seasons and spaces. The seasonal distribution of the benthic macroinvertebrate community structure in the polders of Dongting Lake was dominated by different environmental factors: in the summer, it was mainly affected by TN/TP, NO_3^- -N, WD, Tur, and Chl.a; in the winter, it was mainly regulated by WSW, WT, Tur, and DO. It also pointed out the water issues of concern in the embankment areas during different seasons. In the summer, attention should be paid to the problem of eutrophication in the embankment areas, whereas in the winter, it is necessary to strengthen water connectivity to supplement the water supply of some channels. In 2024, the overall aquatic ecological health of the polders in Dongting Lake was rated as “Moderate”. Seasonally, the ecological health in summer was better than that in winter; spatially, the polders near South Dongting Lake were better than those near East Dongting Lake, with Polder Chengxi being the best, while Polder Junshan and Polder Xiangbin Nanhu were relatively poorer. Among them, JS3 showed serious black and odorous water characteristics in the winter. It is recommended that relevant departments promptly develop targeted water ecological restoration plans, with key governance focused on the Polder Junshan.

Research Limitations and Future Perspectives:

- (1) The conclusions of this study are drawn based on data obtained from two seasonal field surveys, which limits the time-series representativeness of the dataset. Furthermore, the sampling design is seasonally unbalanced: four additional sampling sites were set in the winter, causing dataset asymmetry and potentially interfering with the seasonal comparison of relevant indicators. In future research, long-term and continuous dynamic monitoring covering diverse aquatic organisms should be implemented. Meanwhile, balanced seasonal sampling at all reference sites is recommended to provide reliable data support for seasonal comparative analysis.

- (2) This study only preliminarily explored the effects of hydrological connectivity on benthic macroinvertebrate communities, without further quantitative analysis. Follow-up research can construct a targeted hydrological connectivity index system to quantitatively clarify its mechanisms driving the formation and maintenance of benthic macroinvertebrate community structure.
- (3) More hydrological parameters and field-measured data should be integrated into the comprehensive aquatic ecological health evaluation system, to further improve the systematicness and scientificity of the evaluation framework.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18131613/s1>. Figure S1. Environmental factors with significant differences between summer and winter. Figure S2. Environmental factors with significant differences in different polders in summer. Figure S3. Environmental factors with significant differences in different polders in winter. Figure S4. Radial Bar Chart of TLI Index of Dongting Lake polders. Figure S5. Radial Bar Chart of WQI Index of Dongting Lake polders. Figure S6. Calculation results of each index. Figure S7. Evaluation Level Sankey Diagram. Table S1. The calculation results of Bayesian model.

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