Original Research

Development and Use of a Phytoplankton-Index of Biotic Integrity to Assess Yongjiang River Ecosystem Health

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Abstract

In order to assess the aquatic ecosystem health in Yongjiang River, 13 sites from were sampled annually for density of individual phytoplankton species and community composition. Box-plots and Pearson correlation of 21 pre-selected metrics were then analyzed based on annual sampling and statistics data of the phytoplankton community. These metrics represent the characteristics of the phytoplankton community. Five of them were then used independently to evaluate the health of the aquatic ecosystem. It was found that the aquatic ecosystems' health at all sampling sections in Yongjiang River was good. After calculating P-IBI values at each section and then comparing the values with the corresponding evaluation criteria, we found that the health at the upstream sections was better than the downstream sections.

Keywords: phytoplankton, IBI, box-plots, Pearson correlation, ecosystem health assessment, Yongjiang River

Introduction

In the past, physical-chemical indicators, or microbial indicators, or a single bio-indicator were used to assess water environment. Not much attention was paid to the health of an ecosystem. [1]. Nowadays, environmental biology research shows that ecosystem' health is an important indicator and it reflects comprehensively on ecosystem safety. The process of assessment on ecosystem health should also be one of the important links in environmental monitoring, assessment, and environmental health management [2].

As a comprehensive index, the index of biotic integrity (IBI) is a potentially effective ecological health assessment method that is meant to integrate ecological, functional, and structural aspects of aquatic systems [3]. This index reflects the degree of environmental health by combining biological component and structure information [2]. Therefore, this index can be used to quantitatively analyze the relationship between human disturbances and biological characteristics with sensitive responses [4]. The index was applied to fish originally [5]. Later on, benthic animal, algae, plankton, and periphyton were also taken into consideration [6-9]. For example, Kane et al. [10] measured changes in lake ecosystem health with IBI due to the historical (1970) and more recent (1996) data of plankton and trophic status in Lake Erie. The results showed an increase in water quality in Lake Erie between 1970 (eutrophic) and the mid-1990s (mesotrophic). From a German lowland river, the Kielstau catchment, Wu et al. [11] developed a phytoplankton index of biotic integrity (P-IBI) to assess the effects of human disturbance on the ecological status of the lowland river. Similar works were done by Duan et al. [12]

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Table 1. Brief introduction of sampling sections.

Sampling section	Coordinate (Latitude and Longitude)	Brief description
1	29°39′16″N, 121°14′25″E	Shallow water, narrow river course, clear water, visible bottom
2	29°38′23″N, 121°19′50″E	Shallow water, narrow river course, clear water, visible bottom
3	29°43′42″N, 121°24′37″E	Widen river course, muddy water
4	29°45′27″N, 121°25′58″E	Muddy water, many floaters like leaf and living garbage debris
5	29°45′32″N, 121°27′50″E	Muddy water, some floaters like leaf and living garbage debris
6	29°48′20″N, 121°31′00″E	Muddy water, large amount of silt
7	29°52′13″N, 121°34′50″E	Muddy water, small amount of silt
8	29°52′24″N, 121°33′31″E	Muddy water, small amount of silt
9	29°53′32″N, 121°32′52″E	Clearer water, slow flow velocity
10	29°52′29″N, 121°33′44″E	Wide river course, some silt
11	29°53′41″N, 121°35′26″E	Wide river course, some silt
12	29°56′43″N, 121°43′14″E	Wide river course, large amount of silt
13	29°47′26″N, 121°44′56″E	Wide river course, larger amount of silt

in the Liaohe River and Wang et al. [2] in the reservoirs for water sources from Zhejiang, respectively. With their research, they recommend that the techniques used in creating the P-IBI be investigated for determining ecosystem health of other lakes and rivers.

As the main primary producer, phytoplankton plays an important role in the material cycle and energy exchange in the water ecosystem. The species composition and the community structure of the phytoplankton imply the water health directly or indirectly [13, 14].

The Yongjiang River is a river throughout the Ningbo region. The river system provides water resources for drinking, agricultural irrigation, aquaculture, ship transportation and landscape. It has shown that the water has been polluted by organic pollutants according to the regular monitoring data for a long time. In the middle stream, which is across the central part of the city, BOD_5 and COD_{Cr} were higher than the upstream and the downstream sections [15].

In this paper, the aquatic ecological health of the Yongjiang River was assessed by calculating the index of biological integrity composed of phytoplankton (P-IBI).

Materials and Methods

Study Area

The Yongjiang River system is one of the seven major river systems in Zhejiang province, China [16]. There are two larger tributaries in the system, the Fenghua and Yaojiang rivers. The Yaojiang, with total length of 105 km and the basin area of 1,934 km^2, originates from Xiajialing, Siming Mountain. The Fenghua, 98 km long and a valley area of 2,223 km^2, rises in Xiujian Hill, Siming Mountain. Water from the Fenghua and Yaojiang converges in the centre of Ningbo City and flows into the East China Sea. Traditionally, the section of Yongjiang River system that is formed after the convergence of the Fenghua and Yongjiang branches is called the Yongjiang River, with a total length of 26 km and a basin area of 361 km^2. Just before where the Yaojiang connects to the Fenghua, a dam was built in 1959. Since then, the Yaojiang has become a relatively static reservoir. For the most of the year, the Yaojiang is either closed or allows only a small amount of water to flow in. Therefore, the study area in this work included 124 km length (i.e. traditional Fenghua and Yongjian rivers) and 2,584 km^2 basin area.

There were 13 sampling sections in the Yongjian for this study (Fig. 1). The sampling section setting referred to the water quality monitoring points, and according to the distribution characteristics of river trend, the tributaries of the river confluence, villages, and residential areas, and the convenience of the sampling was considered as well. Detailed locations and the other basic information are listed in Table 1.

Sampling

The field sampling was carried out every month from March 2011 to February 2012 along the river sections from the upstream to the downstream. One semi-automatic plastic water sampler with a volume of 2.5 L was used for the quantitative phytoplankton samples. Each sample was 5 L in volume, taken twice at one sample section. To make one sample, 2.5 L water from the surface and the bottom of the river were collected and mixed on the sites. All samples were fixed with formaldehyde (final concentration of 4-5%). Water samples were taken back to the lab and concentrated by setting to 50 ml for phytoplankton identification. Under the microscope (200-400×), the plankton counting chamber was used for the phytoplankton species identification and number counting as the procedure suggested by Zhang and Huang [17].

The phytoplankton species in the samples were identified based on the descriptions in the references [17-20]. For the abundance of phytoplankton counting, 0.1 ml plankton counting chamber was used. Each sample from each section was counted twice (i.e. two subsamples were counted) and the average of the two numbers was used to calculate the final result. The final result is the mean of 12 samples of each section in this study.

Data Processing

During data analysis and construction of P-IBI, considering sampling sections from the upstream to the downstream and the differences of physic-chemical factors at different sections [21]. Sections 1 and 2 were selected as reference sections and the other 11 sections were considered as impaired sections.

According to literature [1, 10, 11, 22] and the practical situation of this study, 21 metrics of phytoplankton community structure indicators were selected as candidates. They reflect the disturbance of stress sensitively (Table 2).

Based on the criteria suggested by Barbour et al. [23], each candidate metric was analyzed by comparing the reference sections to the impaired sections with interquartile box overlapping degree. As a result, higher overlapping degree (> 75 percentile) means that the metric is not sensitive to the change of the environment; lower (< 25 percentile) overlapping degree implies that the metric is sensitive to the environmental changes. All candidate metrics were selected initially due to lower overlapping degree in this study. After the selection of the metrics, the Pearson correlation analysis was performed for testing the independence of each metric.

The ratio scoring method [24] is used as the metrics scoring criteria. Because the ratio scoring method eliminates the effects of subjective factors, the accuracy of it is better than the other scoring methods [25]. After calculation, the distribution range of the scores was from 0 to 1; anything scored more than 1 was recorded as 1. Each selected metric was calculated with the ratio scoring method and the P-IBI equaled to the sum of ratio scoring of each metric. The range of P-IBI values is then divided into four equal parts and the P-IBI value at each section is in one of the four parts. If the P-IBI value of one section is in the part of the maximum range, the health of this section is excellent. If the P-IBI value is in the part of the minimum range, the health is worst. Similarly, good and bad health can also be ascertained respectively by the P-IBI value.

Results

Phytoplankton Composition and Abundance in Yongjiang River

From all samples, 114 species of phytoplankton belonging to six phyla, 41 families and 80 genera, were found. Among them, 65 species were from Chlorophyta, and 33

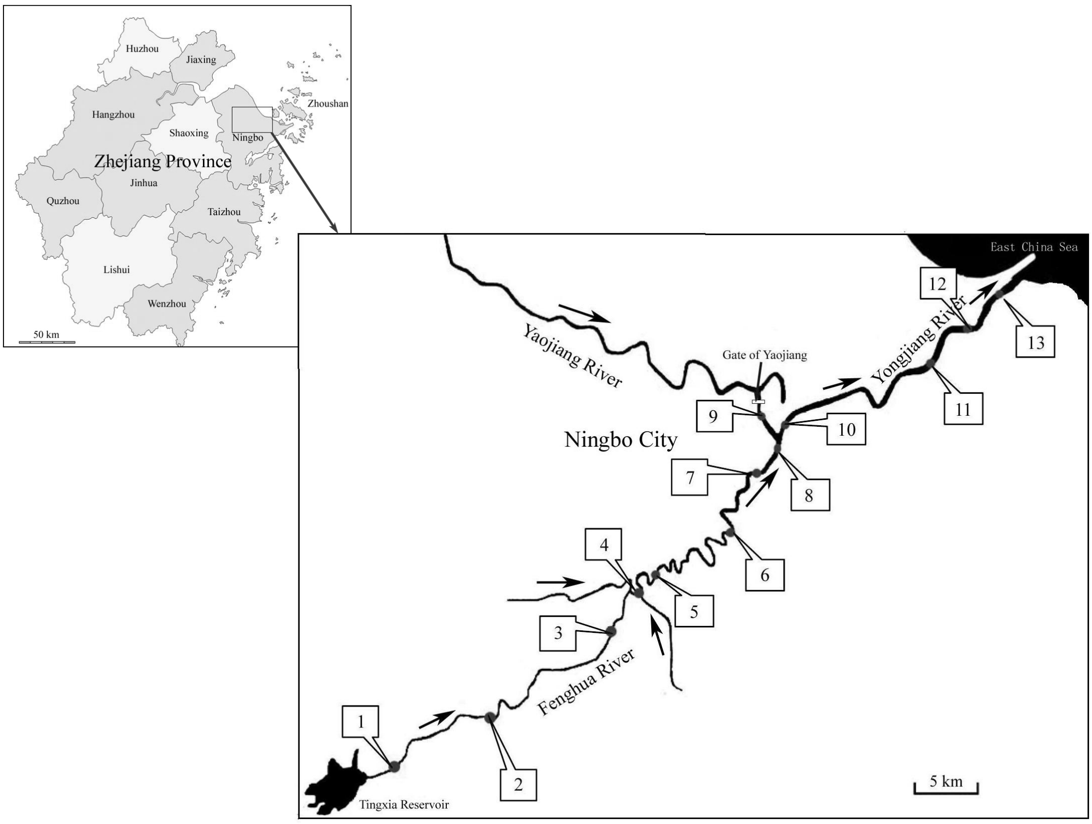

Fig. 1. Sketch map of sampling sites in Yongjiang River.
(Number and dot: numbered sampling section; Black arrow: water flow direction).

Table 2. Candidate metrics for P-IBI in Yongjiang River.

No.	Metrics
M_1	Phytoplankton species number
M_2	Phytoplankton abundance
M_3	Phytoplankton evenness
M_4	Shannon-Wiener index of phytoplankton
M_5	Cyanobacteria species number
M_6	Green algae species number
M_7	Diatom genus number
M_8	Diatom quotient
M_9	Diatom species number
M_{10}	Diatom abundance
M_{11}	Diatom evenness
M_{12}	Shannon-Wiener index of diatom $H = -\Sigma(n_i/N) \ln(n_i/N)$
M_{13}	Generic Diatom Index (IDG); IDG = Abundances of (*Achnanthes*+*Cocconeis*+*Cyclotella*)/ Abundances of (*Cymbella*+*Melosira*+*Nitzschia*)
M_{14}	% total abundance composed of cyanobacteria
M_{15}	% total abundance composed of cyanobacteria and green algae
M_{16}	% total diatom abundance composed of (*Navicula* + *Nitzschia* + *Surirella*)
M_{17}	% total abundance composed of green algae
M_{18}	% total abundance composed of diatom and green algae
M_{19}	% total abundance composed of diatom
M_{20}	% total abundance composed of cyanobacteria, diatom and green algae
M_{21}	Chlorophyll-*a* content

species were from Bacillariophyta. The number of species from Euglenophyta and Cyanophyta were nine and five, respectively.

When considering all samples, the phytoplankton abundances were from 5.2×10^3 to 28.714×10^5 ind./L. The annual variation of phytoplankton abundances at each section is shown in Fig. 2.

Metric Selection

Based on the 50% bit value (i.e. the middle line of box) between the reference and impaired sections, if a metric that was not in the scope of each other range, this metric could be considered effective by box-plot processing of all selected metrics, so that M_2, M_3, M_7, M_8, M_9, M_{12}, M_{13}, M_{14}, M_{16}, and M_{20} met this requirement among 21 metrics (see box-plot in Fig. 3). These 10 metrics were selected as effective metrics in this study.

The Pearson correlation analysis [26] used to find out the independence metrics is shown in Table 3.

From Table 3, it is found that $|r|$ between A_2 and A_{14}, between A_2 and A_{20}, between A_{14} and A_{20} were higher than 0.75. Meanwhile, $|r|$ of A_7 and A_{12}, A_9, and A_{12}, A_{12}, and A_{16} were greater than 0.75 as well. When the $|r| > 0.75$, Pearson's correlation means two metrics are significantly correlated. It implies that their corresponding metrics were not independent. Therefore, A_2, A_7, A_9, A_{16}, and A_{20} were given up and A_3, A_8, A_{12}, A_{13}, and A_{14} were kept for analysis for the next step. Among 10 selected metrics, the corresponding metrics M_3, M_8, M_{12}, M_{13}, and M_{14} were suitable for the index of biological integrity evaluation because they were relatively independent of A_3, A_8, A_{12}, A_{13}, and A_{14}.

Criteria of River Health and Health Status of Yongjiang River

The largest score of P-IBI in this study was 4.9094 after the calculation. According to ratio scoring method [2, 12, 25], the criteria of health assessment for the Yongjiang River was listed in Table 4.

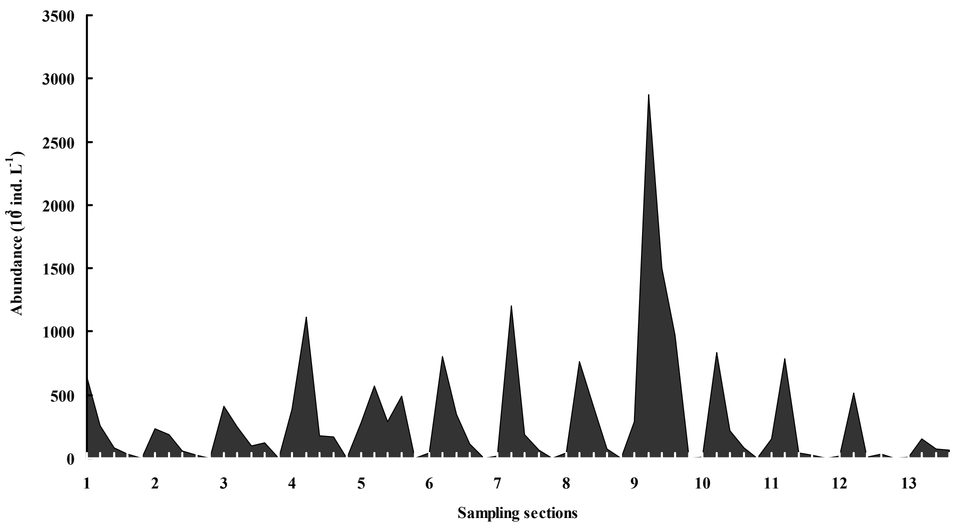

Fig. 2. The annual variation of phytoplankton abundance at different sections in the Yongjiang River.

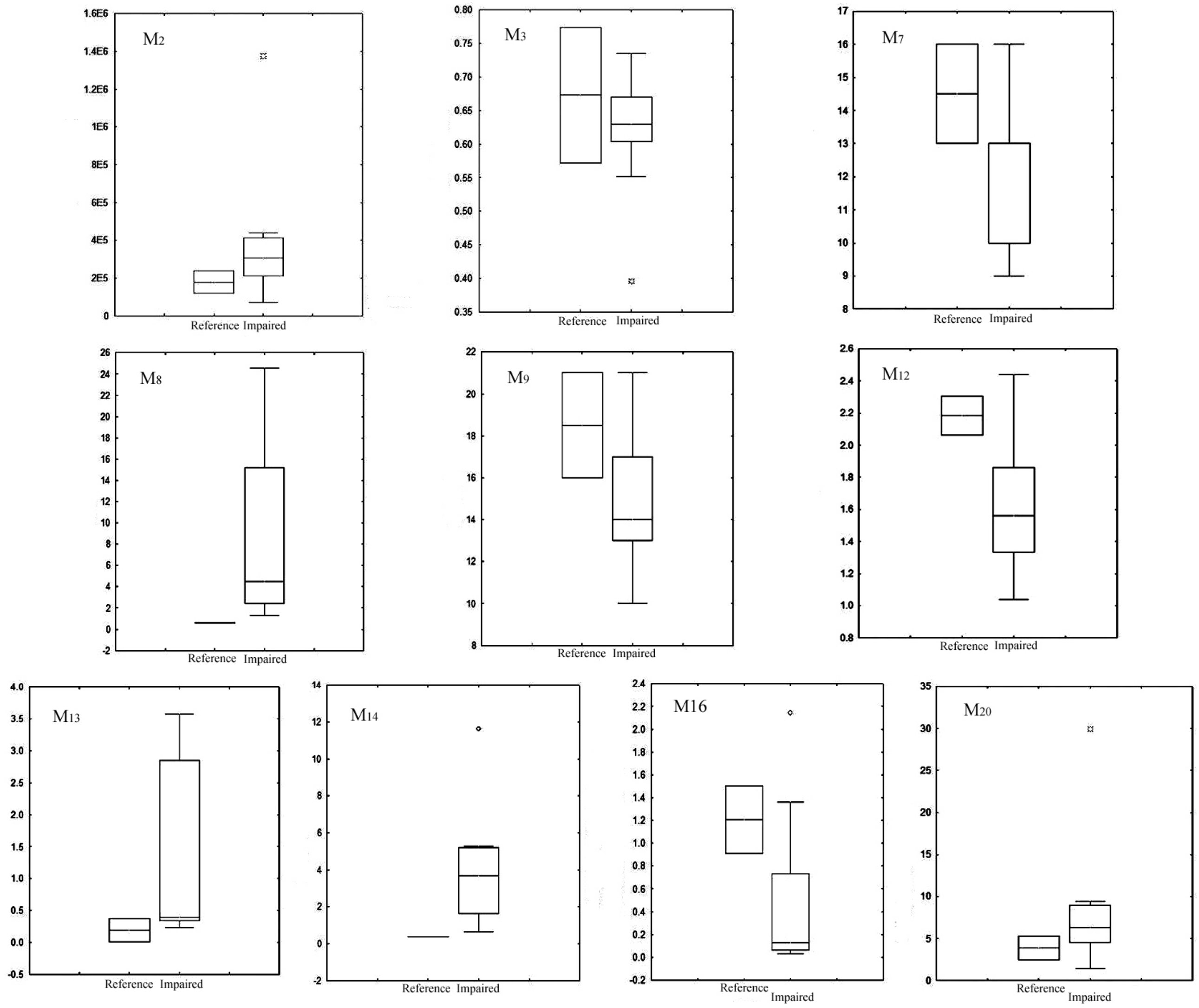

Fig. 3. Box-plots of 10 candidate metrics between reference and impaired sections.
Range bars show the maximum of non-outliers; boxes are interquartile range (25-75 percentile)
M_2 – Phytoplankton abundance, M_3 – Phytoplankton evenness, M_7 – Diatom genus number, M_8 – Diatom quotient, M_9 – Diatom species number, M_{12} – Shannon-Wiener index of diatom, M_{13} – Generic Diatom Index (IDG), M_{14} – % total abundance composed of cyanobacteria, M_{16} – % total diatom abundance composed of (*Navicula* + *Nitzschia* + *Surirella*), and M_{20} – % total abundance composed of cyanobacteria, diatom, and green algae

With the criteria listed in Table 4, the aquatic ecosystem health of the Yongjiang River was evaluated and the results were displayed in Table 5.

Discussions

There are two types of methods for assessment of river health. One type is the prediction model that includes methods such as the river invertebrate prediction and classification system (RIVPACS) and Australian River Assessment (AUSRIVAS) [27]. RIVPACS can predict an existing biomass more accurately in theory. However, if the environmental change was not reflected on the changes for the selected species, the authenticity of the RIPACS evaluation can be affected. Therefore, RIVPACS has its limitations. AUSRIVAS is a modified version of the RIVPACS. The modifications related to the collection and analysis of data is based on the characteristics of the Australian rivers [28]. The other type is multi-index evaluation methods. This type includes the Swedish channel and environmental conditions (RCE) [29], rivers state index (ISC) [30], British river habitat survey (RHS) [31], River health plan (RHP), [32], and IBI [5]. RCE can quickly make an overall evaluation for river health within a short period of time, but the selected index has a wide scope, so it requires a higher level of professional ability to perform the analysis. ISC combines the main status indicators of a river, but selection on the reference river sections is subjective. Both RHS and RHP are better ways to connect the biological indexes and the physical indexes, but some data used for assessment is difficult to obtain. IBI focuses on the biological community structure and biological function in the water bodies. It includes a series of sensitive indexes to environmental changes.

Table 3. Pearson's correlation matrix of the select metrics (r)

	A_2	A_3	A_7	A_8	A_9	A_{12}	A_{13}	A_{14}	A_{16}	A_{20}
A_2	1									
A_3	-0.275	1								
A_7	-0.202	0.483	1							
A_8	0.279	-0.366	-0.556	1						
A_9	-0.082	0.472	0.996	-0.489	1					
A_{12}	-0.038	0.261	0.949	-0.557	0.947	1				
A_{13}	-0.290	0.389	-0.062	-0.423	-0.166	-0.158	1			
A_{14}	-0.900	-0.291	-0.366	0.470	-0.231	-0.239	0.313	1		
A_{16}	-0.103	0.450	0.922	-0.584	0.847	0.888	0.100	-0.329	1	
A_{20}	-0.996	-0.209	-0.175	0.240	-0.061	-0.027	-0.267	0.891	-0.075	1

A_2 – Phytoplankton abundance, A_3 – Phytoplankton evenness, A_7 – Diatom genus number, A_8 – Diatom quotient, A_9 – Diatom species number, A_{12} – Shannon-Wiener index of diatom, A_{13} – Generic Diatom Index (IDG), A_{14} – % total abundance composed of cyanobacteria, A_{16} – % total diatom abundance composed of (*Navicula* + *Nitzschia* + *Surirella*), A_{20} – % total abundance composed of cyanobacteria, diatom, and green algae

Table 4. Criteria of health assessment of P-IBI for Yongjiang River.

P-IBI	0 – 1.2274	1.2275 – 2.4547	2.4548 – 3.6821	3.6822 – 4.9094
Health assessment	Poor	Fair	Good	Excellent

Table 5. P-IBI scores and health assessment for each sampling section in the Yongjiang River.

Section	M_3	M_8	M_{12}	M_{13}	M_{14}	P-IBI	Health assessment
1	0.7621	1.0000	0.8747	1.0000	1.0000	4.6368	Excellent
2	1.0000	0.9986	0.9773	0.9339	0.9996	4.9094	Excellent
3	0.9792	0.9707	1.0000	0.5645	0.9310	4.4454	Excellent
4	0.8393	0.9322	0.9002	0.2129	0.6536	3.5382	Good
5	0.8247	0.9231	0.7883	0.6733	0.8641	4.0735	Excellent
6	0.8500	0.8643	0.7734	0.9281	0.5645	3.9803	Excellent
7	0.8900	0.0000	0.5713	0.9356	0.5689	2.9658	Good
8	0.5276	0.3910	0.6899	0.9423	0.7054	3.2562	Good
9	0.8047	0.4706	0.6616	0.9589	0.0000	2.8958	Good
10	0.8087	0.0575	0.5726	0.9740	0.7678	3.1806	Good
11	0.7354	0.6420	0.5531	0.9287	0.7018	3.5610	Good
12	0.8926	0.8387	0.4395	0.1184	0.8900	3.1792	Good
13	0.9592	0.9047	0.5654	0.0000	0.9782	3.4075	Good

This method was considered to be a simple, sensitive and efficient health assessment method for water ecosystem health [33].

At the same time, some single index methods, such as diversity index, biological pollution index, and algae pollution index are still used to assess aquatic ecological health. Because only the limited information of environmental changes was reflected, these methods are not comprehensive and complete, even though they may be faster.

Since the 1990s, IBI has been widely used to assess aquatic ecosystem health. IBI is the key index system of biological method for health assessment used by the U.S. Environmental Protection Agency. For example, Hill et al. developed a P-IBI assessment system with 10 metrics in the mid-Appalachian basin. They found that there was a difference between watershed upland and lowland regions [34]. In China, the IBI system has been used for assessment of water health as well. The assessment results for Hunhe river health with P-IBI were basically consistent with the results of the physic-chemical index system of the habitat environment [35]. More recently, Shen et al. analyzed the aquatic ecological health of water sources in Zhejiang Province in China using a P-IBI system with 22 metrics. Their results not only reflected the ecological health of water, but also displayed the eutrophication and algal bloom risks in these water bodies [1]. The results of our study match the assessment results of the physic-chemical index system [21].

Similar to the referenced studies, some metrics are eliminated during the primary selection. In different studies, different metrics with different contents were screened out. For example, A_1, A_3, A_5, A_9, and A_{10} corresponding to metrics M_1, M_3, M_5, M_9, and M_{10} were screened out in our study. Due to each metric represent a different biological characteristic, the role of each metric in the whole evaluation system was different. For example, the water bloom algae and poisonous algae mostly resulted from cyanobacteria in eutrophic water. Therefore, the abundance of cyanobacteria deserves attention when evaluating the health in the eutrophic water. A similar phenomenon also appears in the metric reflecting biological diversity. In a clean or good environment, there was higher biodiversity and less abundance. In the deteriorated or contaminated environment, the sensitive species disappeared, pollution-tolerant species bloomed, and species number became fewer; but the abundance can be very high. In these cases, the diversity index should be used to represent environmental quality changes; therefore, the diversity index could explain the degree of environmental stress. Certainly, useable metrics in the IBI system can be different for different studies.

The assessment results of ecosystem health at each section in the Yongjiang River (Table 5) by developing and using P-IBI were similar with the monitoring data from the same sampling [21].

Acknowledgements

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