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Reduction in the phytoplankton index of biotic integrity in riverine ecosystems driven by industrial activities, dam construction and mining: A case study in the Ganjiang River, China

Bing Feng[a], Meng Zhang[a,*], Jianfeng Chen[b], Jun Xu[c], Bangding Xiao[d], Min Zhou[a], Min Zhang[e]

[a] Jiangxi Academy of Environmental Sciences, Nanchang 330039, China
[b] Poyang Lake Eco-economy Research Center, Jiujiang University, Jiujiang 332005, China
[c] Donghu Experimental Station of Lake Ecosystems, State Key Laboratory of Freshwater Ecology and Biotechnology of China, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, China
[d] Key Laboratory of Algal Biology of Chinese Academy of Sciences, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, China
[e] College of Fisheries, Huazhong Agricultural University, Wuhan 430070, China

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ABSTRACT

Industrial activities, dam construction, and mining are three human activities important for societal and economic development. However, the effects of these activities on phytoplankton communities have been less quantitatively assessed than those on other groups, such as macroinvertebrates, fish, and periphytic algae. In the present study, we selected the Ganjiang River basin, a tributary of the Yangtze River as the representative area to develop a feasible phytoplankton index of biotic integrity (Phyto-IBI) to evaluate the effects of industrial activities, dam construction, and mining on the biotic integrity of riverine ecosystems. The results showed that the three activities greatly altered the abundance and composition of phytoplankton, with a reduction in phytoplankton species quantity and diversity and an increase in abundance. The health status of the Ganjiang River was fair, and the health statuses of industrial areas, dam areas, mining areas, and reference points were poor, poor, fair, and good, respectively. The three activities damaged the biotic integrity of the aquatic system. Moreover, compared to industrial activities and mining, dam construction is more harmful to aquatic systems in the Ganjiang River. The locally weighted regression scatter plot smoother (LOWESS) method showed that an ammonium nitrogen (NH_3-N) concentration of 0.65 mg L^{-1} is the environmental protection threshold for planktonic biotic integrity in the Ganjiang River. This study not only quantitatively assesses phytoplankton responses to industrial activities, dam construction, and mining but also provides guidance regarding the ecological monitoring, assessment and protection of riverine ecosystems.

1. Introduction

Biotic integrity is the ability of biological communities to maintain structural balance and to adapt to environmental change (Karr, 1981). Since Karr (1981) assessed river health using an index of biotic integrity, this index system has been extensively expanded and modified (Wu et al., 2012b; Cui et al., 2019; Zhu et al., 2019). The majority of studies used macroinvertebrates (Effert et al., 2019), fish (Cooper et al., 2018; Souza and Vianna, 2020) and periphytic algae (Wu et al., 2012a) to monitor river health for a long time. Indeed, phytoplankton can also indicate the degree of water pollution and eutrophication (Saksena, 1987). In recent years, phytoplankton index of biotic integrity (Phyto-IBI) has been used to evaluate riverine ecosystems (Borics et al., 2007; Lugoli et al., 2012; Pomari et al., 2019). However, few studies have focused on evaluating riverine ecosystems affected by human activities using Phyto-IBI. Therefore, additional studies focusing on phytoplankton to evaluate the biotic integrity of riverine ecosystems are necessary (Wu et al., 2012b; Ruaro and Gubiani, 2013).

The Ganjiang River is the largest river flowing into the largest freshwater lake (Lake Poyang) in China, and also one of the most important tributaries (7th largest) flowing into the Yangtze River. In recent decades, many measures have been implemented for society and economic development in the Ganjiang River basin, such as industrial activities (industrial parks), dam construction, and mining. The rapid development of industry and economy increase the risk of environmental pollution (Mao et al., 2018). In particular, industrial wastewater

* Corresponding author.
E-mail address: tomdeshiye@126.com (M. Zhang).

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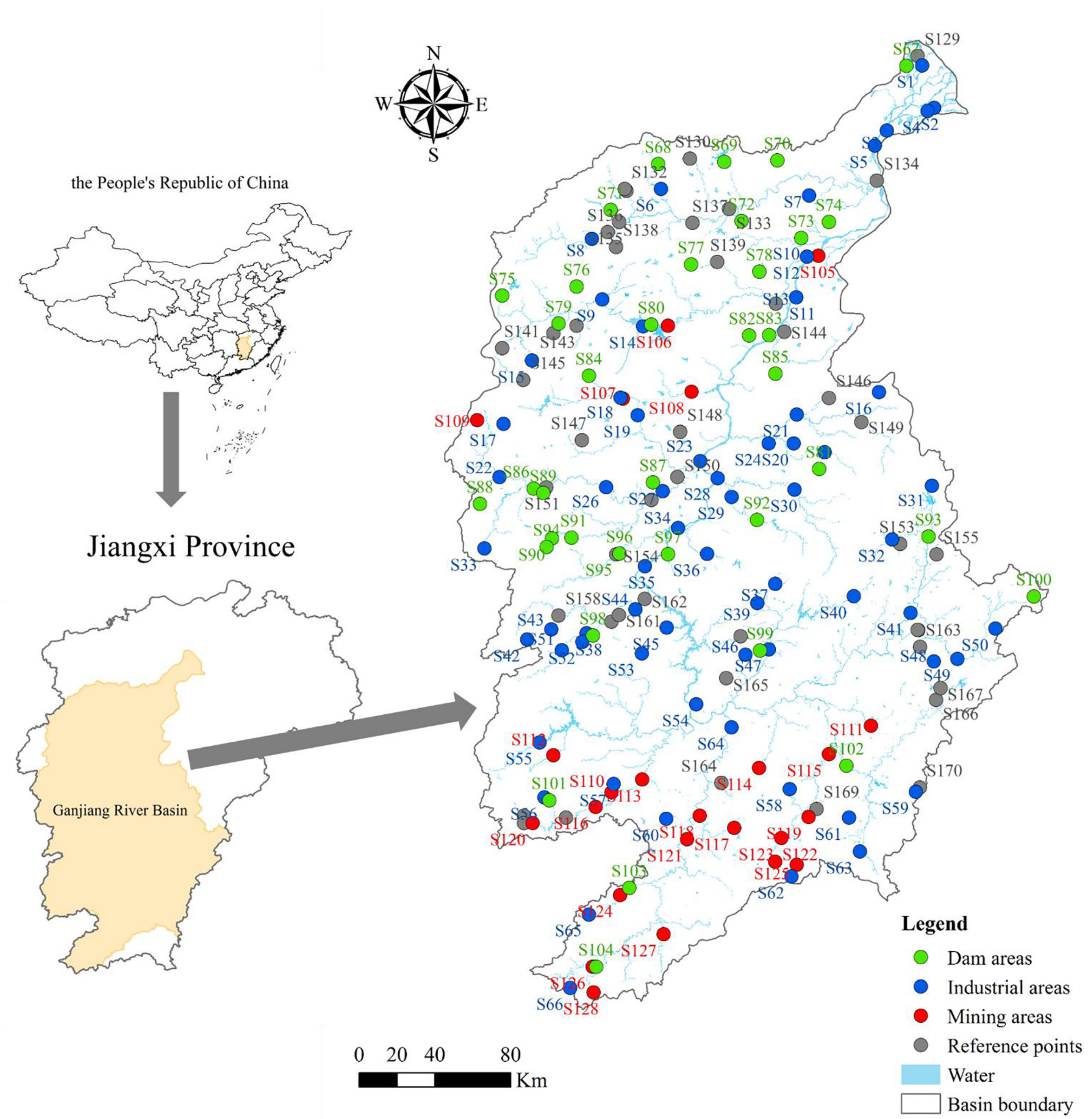

Fig. 1. Sampling locations in the Ganjiang River, China.

can cause the deterioration of water quality (Ludwig et al., 2014). In addition, industries such as pharmaceutical production, paper mills, dyeing, and textile printing can produce persistent pollutants that harmful to wildlife and humans in wastewater (Mao et al., 2018). Large-scale water conservancy projects not only bring tremendous benefits, but also significantly change the ecological environment. Dam construction transforms rivers from a riverine system into a lacustrine system, and changes the longitudinal heterogeneity and water retention times of reservoirs (Moitra and Leff, 2015). These changes may affect material cycles (Scott et al., 2009), river dynamics (Poff et al., 2007), biotic habitats (Poff and Olden, 2017), and river discharge patterns (Azevedo et al., 2010). Due to soil erosion, subsidence, pollution, and water quality deterioration, long-term intensive mining activities have seriously affected the ecological environment (Chen et al., 2017). In recent years, heavy metals pollution in water environment caused by mining and ore processing has become an environmental issue of worldwide concern (Wennrich et al., 2004; Gupta et al., 2005; Moore et al., 2011). Taken together, industrial activities, dam construction and mining all affect the environmental health of aquatic systems. However, the impact on the biotic integrity of aquatic systems remains unclear.

The present work investigated the spatial pattern variations in phytoplankton abundance and composition in the Ganjiang River. The specific aims were: (1) to develop a feasible Phyto-IBI and assess riverine ecosystem health; (2) to compare the Phyto-IBI affected by industrial activities, dam construction, and mining; (3) to reveal the relationships between Phyto-IBI and environmental parameters; (4) to

Table 1
Multiple metrics for calculating the phytoplankton index of biotic integrity (Phyto-IBI) in the Ganjiang River, China.

Category	Candidate metrics	Abbreviation
Community composition	Number of total genera	M1
	Number of Cyanophyta genera	M2
	Number of Chlorophyta genera	M3
	Number of Bacillariophyta genera	M4
	Percentage of Cyanophyta genera	M5
	Percentage of Chlorophyta genera	M6
	Percentage of Bacillariophyta genera	M7
Species richness	Number of total species	M8
	Number of Cyanophyta species	M9
	Number of Chlorophyta species	M10
	Number of Bacillariophyta species	M11
	Percentage of Cyanophyta species	M12
	Percentage of Chlorophyta species	M13
	Percentage of Bacillariophyta species	M14
Species density	Density of total species	M15
	Cyanophyta abundance	M16
	Chlorophyta abundance	M17
	Bacillariophyta abundance	M18
	Percentage of Cyanophyta abundance	M19
	Percentage of Chlorophyta abundance	M20
	Percentage of Bacillariophyta abundance	M21
Species diversity	Shannon-Wiener index	M22
	Margalef index	M23
	Pielou index	M24

obtain the protection thresholds of some environmental parameters.

2. Material and methods

2.1. Study site description

The Ganjiang River, running through Jiangxi Province from south to north, is the largest river flowing into the largest freshwater lake (Lake Poyang) in China, with a drainage basin of approximately 82809 km^2. It is the seventh largest tributary of the Yangtze River, and the main stream is 823 km long. The riverhead and the estuary are located in Shiliaodong (Yangdi town: 116°22′E and 25°57′N) and Wangjiangting (Wucheng town: 116°01′E and 29°11′N), respectively. The Ganjiang River basin has a mid-subtropical humid climate, with an annual average precipitation of approximately 1580.8 mm. The Ganjiang River contains approximately 7.03×10^{10} m^3 of water.

At the spatial scale, 172 sampling sites (S1-S172) were chosen in the Ganjiang River basin in this study according to their location relative to industrial parks, dams, and mining areas (Fig. 1). In industrial areas, dam areas, and mining areas, the sampling sites were within 2 km downstream of the sewage outfall, dam body, and mined mine, respectively. The investigation included 66 sampling sites (S1-S66), 38 sampling sites (S67-S104), and 24 sampling sites (S105-S128) in the areas affected by industrial activities, dam construction, and mining, respectively, and these sampling sites were categorized into the impaired points. In addition, 44 sampling sites (S129-S172) were selected as reference points in uncontaminated area.

2.2. Water sampling and processing

Water samples were collected in December 2012, May 2013, and July 2013. A total water sample of 2 L was collected within 50 cm of the surface using a cylindrical sampler at each sampling site. One liter of the mixed samples was preserved with Lugol's iodine solution (1% V/V) and homogenized thoroughly. After settling for 48 h, the supernatant was removed slowly and the 1 L of water samples was then concentrated to 50 mL for subsequent cell counting and species identification.

2.3. Physicochemical analysis

Dissolved oxygen (DO, mg L^{-1}), pH, water temperature (WT, °C), and electrical conductivity (EC, μs cm^{-1}) were measured in situ by a water quality analyzer (YSI Pro Plus, YSI Incorporated, USA). The stream velocity (V, m s^{-1}) was measured by a flow meter (model 2100, Swoffer Instruments, Tukwila). Turbidity was measured using a turbidity meter (Eutech TB100, USA) based on nephelometric turbidity units (NUT). Total phosphorus (TP, mg L^{-1}), total nitrogen (TN, mg L^{-1}), nitrate (NO_3-N, mg L^{-1}), ammonium nitrogen (NH_3-N, mg L^{-1}), phosphate (PO_4-P, mg L^{-1}), total alkalinity (TA, mg L^{-1}), and chemical oxygen demand (COD_{Mn}, mg L^{-1}) were analyzed according to standard methods (SEPA, 2002). Chlorophyll *a* (Chla, mg L^{-1}) was determined based on the method of Arnon (1949).

2.4. Microscope identification

Algae were analyzed at 400× magnification (10× eyepiece and 40× objective) under an Olympus microscope (CX33, Olympus Optical Co, Tokyo) with a 0.1 mL plankton counting chamber (Sedgewick, Wildco, USA) using the method of Wu et al. (2012b). Algae were identified mainly at the species level, and the abundance was expressed as ind. L^{-1}.

2.5. Phyto-IBI assessment system establishment

In this study, the Phyto-IBI assessment system was established with one hundred and seventy-two collected phytoplankton samples according to the method of Lacouture et al. (2006) and Zhang et al. (2019). These samples were of 4 types: industrial activities (S1-S66), dam construction (S67-S104), mining (S105-S128), and reference points (S129-S172). We compiled a large pool of attributes (a total of 24 metrics), including the community composition, species richness, species density, and species diversity (Li et al., 2013; Yang et al., 2019) (Table 1). These biological metrics were subjected to a distribution range test, discriminant ability test, and redundancy test (Huang et al., 2015; Zhang et al., 2019). Metrics with few algae species and with litter variability were excluded using the distribution range test. The metrics with a high separation ability (less box overlap) between the impaired points and the reference points were screened using the discrimination ability test. Spearman correlation analysis was used to evaluate the redundancy among metrics, and metrics with Spearman correlation coefficient $|r|$ was ≤ 0.75 were selected to avoid redundancy.

The final metrics were rescaled according to the method of Abdelkefi et al. (2013). The metrics that were related positively to disturbance were recalculated using Eq. (1): Metric value = (Maximum − Site value)/(Maximum − 5% quantile). The metrics that were related negatively to disturbance were recalculated using Eq. (2): Metric value = (Site value/95% quantile). The final Phyto-IBI scores were the sum of the calculated values of the selected metrics. The 95% quantile of the Phyto-IBI scores at all sampling sites was regarded as the lower limit of the excellent level. A sampling point where the Phyto-IBI value was greater than the lower limit is considered healthy and is litter disturbed by humans. The Phyto-IBI scores that were less than the lower limit were uniformly divided into 4 categories: good, fair, poor, and extremely poor.

2.6. The calculation of protection thresholds of environmental parameters

The relationship between the Phyto-IBI and environmental parameters was observed using Spearman correlation analysis. The locally weighted regression scatter plot smoother (LOWESS) was applied to obtain the fitted curves between Phyto-IBI and significant correlation parameters (Zhang et al., 2015). The turning points were the points

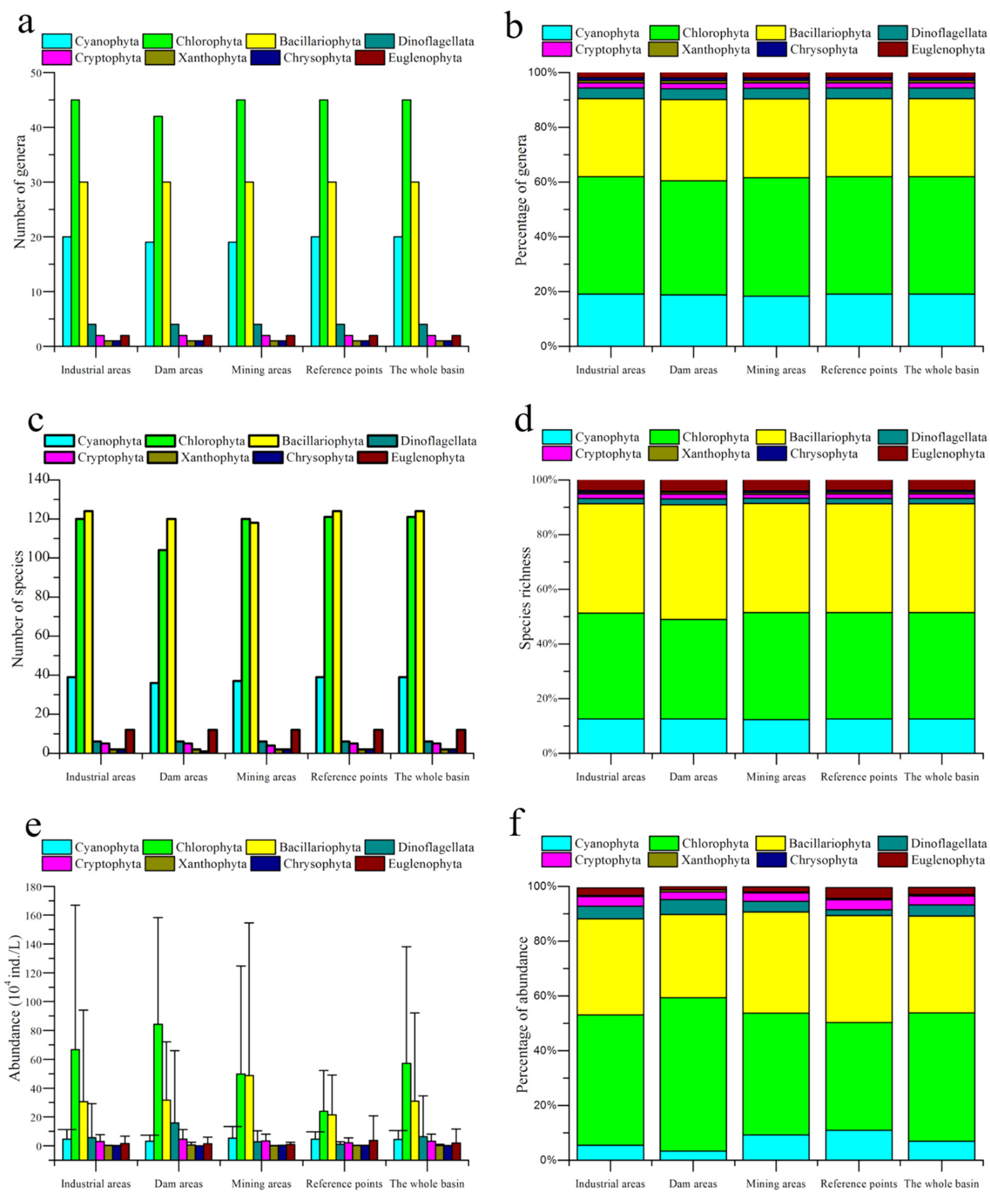

Fig. 2. Phytoplankton genera, species, abundance, and percentages in different areas of the Ganjiang River, China.

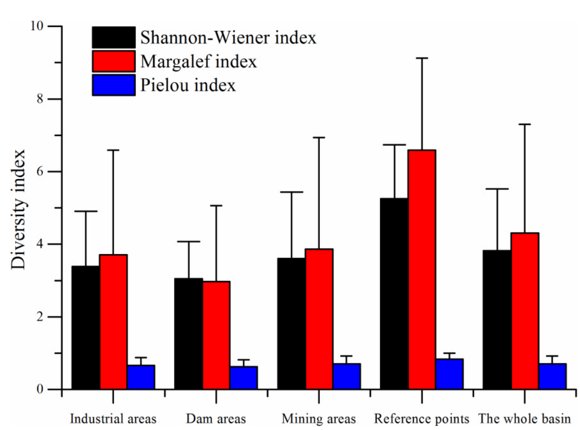

Fig. 3. Phytoplankton diversity in different areas of the Ganjiang River, China.

where the slope of the fitted curves changed from positive to negative. An independent sample *t* test was used on the Phyto-IBI values on both sides of each turning point to ensure the turning points were significant.

Table 2
The classification standards of ecosystem health status in the Ganjiang River.

Level	I	II	III	IV	V
Health status	Healthy > 4.63	Good 3.59–4.63	Fair 2.56–3.59	Poor 1.68–2.56	Extremely poor ≤1.68

The significant turning point of the fitting curve could serve as the protection threshold.

2.7. Statistical analysis

The statistical analysis (discriminant ability test and redundancy test) of establishing Phyto-IBI assessment system were performed by R 3.5.2. The statistical analysis (independent sample *t* test and LOWESS) of calculating protection thresholds of environmental parameters were performed by R 3.5.2. The spatial distribution graphs of sampling sites and planktonic integrity in the Ganjiang River were both generated with ArcGIS 10.3. The graphs of the composition, abundance, diversity, and Phyto-IBI values of phytoplankton in different areas in the Ganjiang

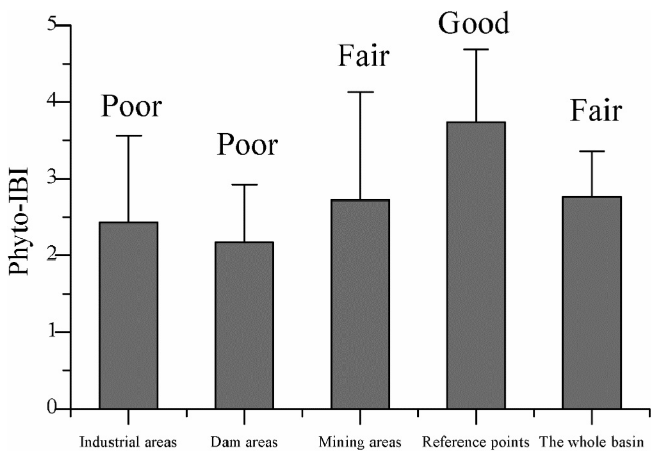

Fig. 4. Phytoplankton index of biotic integrity (Phyto-IBI) scores and health status in different areas of the Ganjiang River, China.

River were generated with Origin 9.1 software (OriginLab, Northampton, USA).

3. Results

3.1. Phytoplankton genus, species and abundance at different areas

Across all sampling sites in the Ganjiang River, 311 species of phytoplankton belonged to 105 genera, including Bacillariophyta of 124 species, Chlorophyta of 121 species, Cyanophyta of 39 species, Euglenophyta of 12 species, Dinoflagellata of 6 species, Cryptophyta of 5 species, Xanthophyta of 2 species, and Chrysophyta of 2 species. The phytoplankton genus, species and density in industrial areas, dam areas, mining areas and at the reference points are shown in Fig. 2. Among the four areas, no obvious differences were observed in the number of genera or the percentage of genera (Fig. 2a and b). The total number of species in the four areas were 310, 286, 301, and 311, respectively. Bacillariophyta and Chlorophyta were dominant in terms of the number of genera and species in the four areas. There were 124 Bacillariophyta dominant species and 120 Chlorophyta dominant species in industrial areas, 120 Bacillariophyta dominant species and 104 Chlorophyta dominant species in dam areas, 118 Bacillariophyta dominant species and 120 Chlorophyta dominant species in mining areas, and 124 Bacillariophyta dominant species and 121 Chlorophyta dominant species at the reference points (Fig. 2c). In the four respective areas, the species richness of Bacillariophyta were 40.00%, 41.96%, 39.87% and 39.87%, and that of Chlorophyta was 38.71%, 36.36%, 39.20% and 38.91% ((Fig. 2d).

The phytoplankton abundances were different in the four areas, i.e., highest in dam areas (141.4×10^4 ind. L^{-1}) and lowest at the reference points (57.2×10^4 ind. L^{-1}) (Fig. 2e and f). The density of the total species across the whole basin was 104.4×10^4 ind. L^{-1}. Chlorophyta and Bacillariophyta were dominant in abundance in the four areas. In the four respective areas, the percentages of Chlorophyta were 47.63%, 56.03%, 44.50% and 39.37%, and those of Bacillariophyta were 35.02%, 30.37%, 36.92% and 39.09%.

3.2. Phytoplankton diversity

Across the whole basin, the Shannon-Wiener index, Margalef index, and Pielou index were 3.8, 4.3 and 0.7, respectively (Fig. 3). In industrial areas, the respective values of the three diversity indexes were 3.38, 3.71 and 0.66. In dam areas, the respective values of the three diversity indexes were 3.05, 2.97 and 0.63. In mining areas, the respective values of the three diversity indexes were 3.60, 3.87 and 0.70. At reference points, the respective values of the diversity indexes were 5.25, 6.59 and 0.84. For all diversity indexes, the highest values appeared at the reference points, and the lowest values appeared in dam areas.

3.3. Phyto-IBI assessment system

Twenty-four candidate metrics representing community composition, species richness, species density, and species diversity were initially selected to establish Phyto-IBI (Table 1). No metric was dropped in the distribution range test. After the boxplot analysis, 14 metrics that exhibited clear differences between the impaired points (industrial areas, dam areas, and mining areas) and the reference points were selected for further testing. Finally, 5 metrics were selected to calculate the Phyto-IBI after the redundancy test, i.e., the percentage of Cyanophyta genera (M5), number of total species (M8), percentage of Cyanophyta abundance (M19), Shannon-Wiener index (M22), and Pielou index (M24). The results of the boxplot method and Spearman correlation analysis for selected metrics are shown in Fig. S1 and Table S1.

3.4. Phyto-IBI calculated in industrial areas, dam areas, mining areas and at the reference points

The Phyto-IBI scores at sampling sites were calculated according to the ratio method. Because the selected five metrics were related negatively to interference, the metric values were calculated by Eq. (2). The 95% quantile of the Phyto-IBI scores at all sampling sites (4.63) was taken as the lower limit of class I (healthy). The Phyto-IBI scores less than 4.63 were divided evenly into 4 grades: good (II), fair (III), poor (IV), and extremely poor (V). The classification standards of ecosystem health status are shown in Table 2. The Phyto-IBI value of the Ganjiang River was 2.76 (fair), and those of the industrial areas, dam areas, mining areas and reference points were 2.43 (poor), 2.17 (poor), 2.72 (fair), and 3.74 (good), respectively (Fig. 4).

In the present study, the spatial distribution of planktonic biotic integrity in the Ganjiang River was analyzed in Fig. 5. Overall, the health statuses were extremely, poor, fair, good and healthy at 22.67% of sampling sites, 24.42% of sites, 24.42% of sites, 23.84% of sites and 4.65% of sites, respectively. Furthermore, 84.38% of the impaired points (industrial areas, dam areas, and mining areas) were lower than the good state, and 65.91% of the reference points were better than the fair state.

3.5. Relationship between Phyto-IBI and environmental parameters

The Phyto-IBI had positive correlation with pH, DO, COD_{Mn}, TN, TP and TA, and was negatively related to EC, turbidity, NH_3-N, NO_3-N, PO_4-P, Chla, WT, and V. Of these environmental parameters, Phyto-IBI had significant correlations with pH, DO, turbidity, NH_3-N, TN, PO_4-P, COD_{Mn}, WT, and V (Table 3). The fitted curves between Phyto-IBI values and the significant correlation parameters were obtained according to the LOWESS method (Fig. 6). No turning point was found in the fitted curves of Phyto-IBI regarding water temperature, DO, turbidity, and velocity. In the fitted curves of Phyto-IBI regarding pH, COD_{Mn}, PO_4-P, NH_3-N, and TN, the turning points were 7.75, 2.20 mg L^{-1}, 0.125 mg L^{-1}, 0.58 mg L^{-1} and 2.14 mg L^{-1}, respectively. The Phyto-IBI scores on both sides of the turning point were observed using the Wilcox test. The results showed that the fitting curves of Phyto-IBI with pH, COD_{Mn}, PO_4-P and TN did not show a significant turning point (pH, $p = 0.152$; COD_{Mn}, $p = 0.333$; PO_4-P, $p = 0.600$; TN, $p = 0.123$), but that of NH_3-N did show a significant turning point ($p = 0.029$).

4. Discussion

Phytoplankton, as the autochthonous primary producers in aquatic ecosystems, form part of the basis of the food web and provide materials and energy for other organisms (Hötzel and Croome, 1999). That

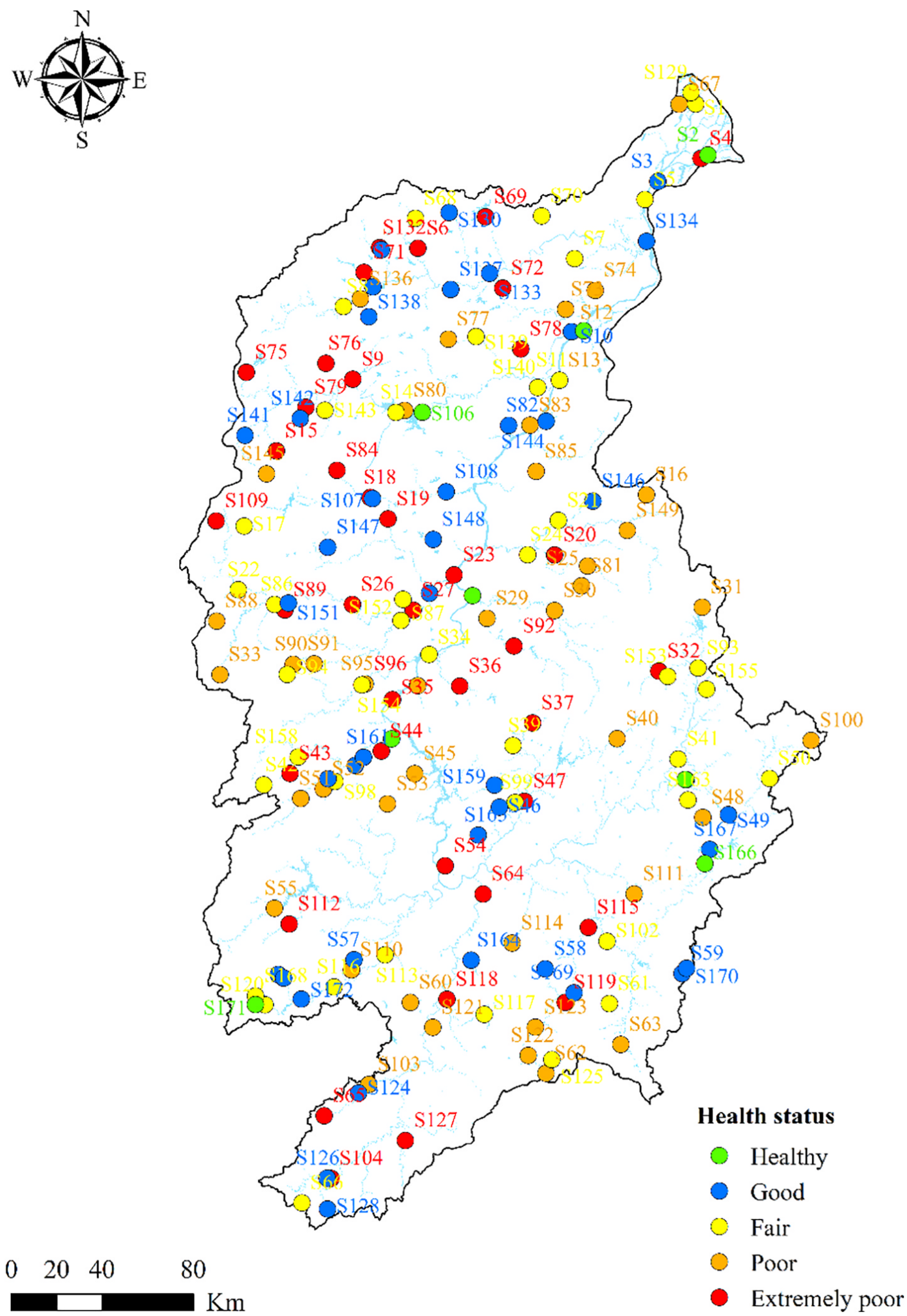

Fig. 5. The spatial distribution of phytoplankton index of biotic integrity (Phyto-IBI) in the Ganjiang River, China.

phytoplankton have shorter life cycles and regeneration times than other indicator organisms of water quality makes the communities very sensitive to anthropogenic influences (Domingues and Galvão, 2007; Cabecinha et al., 2009). Unlike macroinvertebrates and fish, phytoplankton communities are usually present in certain forms before and after disturbance (Wu et al., 2012b). These factors explain why phytoplankton can be used to assess the biotic integrity of aquatic systems.

In this study, we established a Phyto-IBI assessment system to evaluate ecosystem health status of the Ganjiang River using the methods of Lacouture et al. (2006) and Zhang et al. (2019). The results indicated that the Ganjiang River was in a fair status. This conclusion was consistent with the observation of Zhang et al. (2011) and Chen et al. (2011), who used the benthic index of biotic integrity (B-IBI) and fish index of biotic integrity (F-IBI), respectively, to assess the ecological status of the Ganjiang River. The health status of industrial areas, dam areas, and mining areas were poor, poor and fair, respectively, however, that of the reference points was good (Fig. 4). The spatial distribution of Phyto-IBI also showed that the health statuses of most impaired points (industrial areas, dam areas, and mining areas) were lower than the good state and that those of most reference points were better than the fair state (Fig. 5). These results suggested that industrial activities, dam construction and mining disrupt the biotic integrity of the aquatic system of the Ganjiang River. Indeed, the increase in water consumption due to industrialization has caused significant changes in water resources (Kummu et al., 2016), and industrial wastewater can cause deterioration of water quality (Ludwig et al., 2014), especially through increased nutrient input. According to the 2012 environmental statistics annual report of Jiangxi Province, China, the industrial wastewater discharge of the cities in the Ganjiang River basin was approximately 2.92×10^{8} t. This result showed that a large amount of

Table 3
Spearman correlation coefficient of Phyto-IBI and environmental parameters.

	Phyto-IBI
pH	0.179*
DO	0.310***
EC	−0.090
TA	0.009
Turbidity	−0.583***
NH_3-N	−0.167*
NO_3-N	−0.007
TN	0.336***
PO_4-P	−0.224**
TP	0.099
COD_{Mn}	0.207**
Chla	−0.143
WT	−0.651***
V	−0.226**

*** indicates a *P* value less than 0.001, ** indicates a *P* value less than 0.01, and * indicates a *P* value less than 0.05.

pollutants flowed into the Ganjiang River due to industrial activities. In previous studies, nutrients (pollutions) were considered the key factors for phytoplankton growth and composition (Paerl et al., 2011; Song et al., 2017; Feng et al., 2019; Li et al., 2019). Therefore, we speculated that industrial activities affect phytoplankton growth by pollutant emissions, thereby damaging the biotic integrity of the Ganjiang River. In our study, the reduction in phytoplankton species quantity and diversity and the increase in abundance in industrial areas compared to the reference points (Figs. 2 and 3) supported this conclusion. The impoundment and flow regulation of dams are considered to influence riverine ecosystems (McCartney et al., 2000). Due to the strong changes in hydrological regime and habitat after dam construction in the rivers, the phytoplankton composition and abundance are believed to be sensitive indicators of riverine ecosystems health (Zhang et al., 2010; Perbiche-Neves et al., 2011). Dam construction in eutrophic rivers is associated with phytoplankton variations (McCartney et al., 2000), disrupts ecological and longitudinal connectivity (Wu et al., 2012a; Petesse and Petrere, 2012), and has cascading and accumulation effects on riverine ecosystems (Naiman et al., 2000). The high water level and low flow rate caused by dam construction are not be beneficial to pollutant diffusion, which may cause high pollutant concentrations in local areas and create serious environmental issues (Lin, 2011). These could explain why dam construction damages biotic integrity. The reduction in phytoplankton species quantity and diversity and increase in abundance in dam areas compared to the reference points (Figs. 2 and 3) supported this explanation. Similar to industrial activities, mining also deteriorates water quality by discharging pollutants (Chen et al., 2017) and influences planktonic composition and abundance, as observed in this study (Figs. 2 and 3). Indeed, previous studies had shown that mining of ion-absorbed rare earth ores pollutes the water environment in the Ganjiang River (Liu et al., 2015; Shi et al., 2020). Moreover, mining and ore processing can pose a risk of heavy metal pollution (Wennrich et al., 2004; Gupta et al., 2005; Moore et al., 2011), which affects the physiological characteristics of algae (Kondzior and Butarewicz, 2018), and is even toxic to algae (Pinto et al., 2003). Thus, mining can damage biotic integrity. In the present study, the Phyto-IBI values of industrial areas and mining areas were

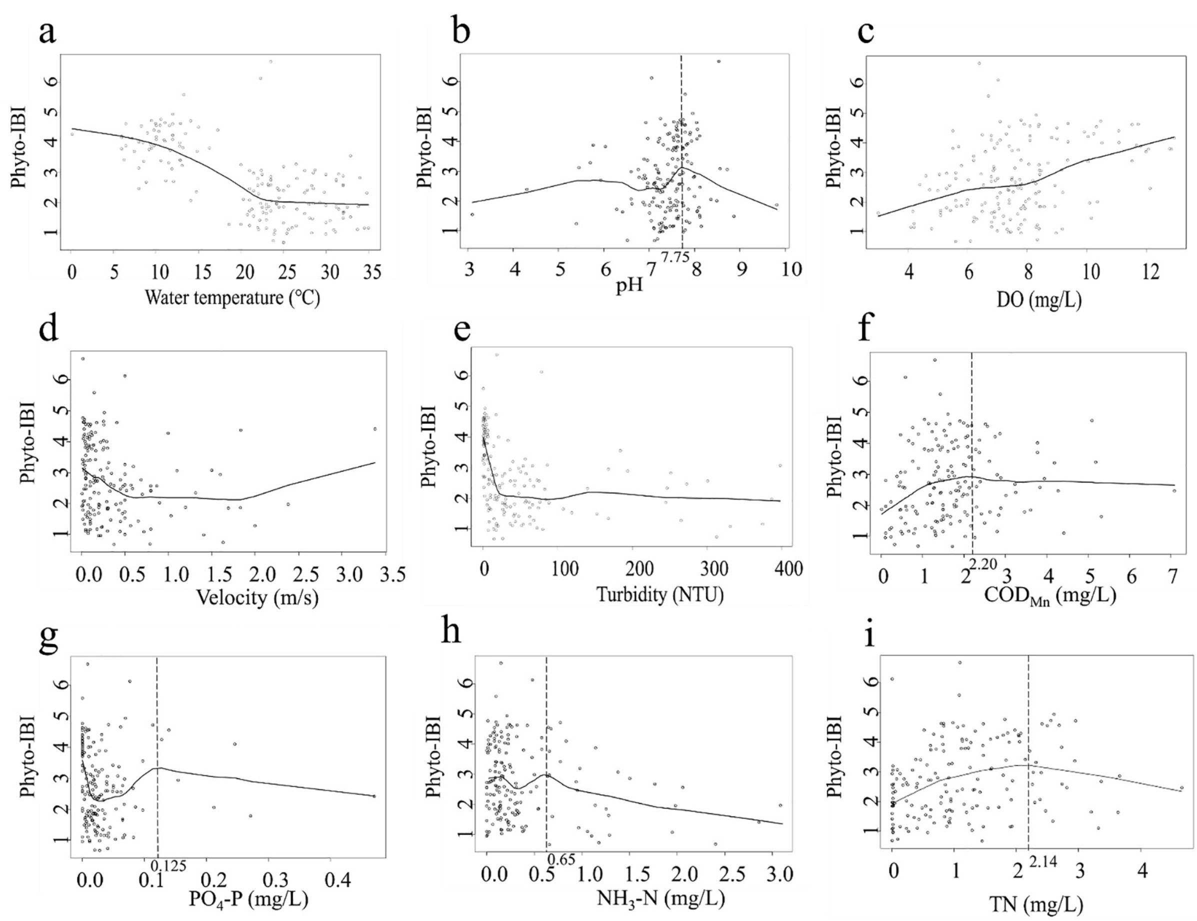

Fig. 6. The fitting curves of Phyto-IBI versus the environmental parameters (a, b, c, d, e, f, g, h, and i represent water temperature, pH, DO, velocity, turbidity, COD_{Mn}, PO_4-P, NH_3-N and TN, respectively).

higher than that of dam areas (Fig. 4). This result indicated that compared to industrial activities and mining, dam construction is more harmful to the aquatic system of the Ganjiang River. Pollutant emissions and dam are considered to be the main influence factors of riverine ecosystems (Zhang et al., 2020). We further speculated that compared to the pollutant emissions caused by industrial activities and mining, dam construction plays a more decisive role in the health status of the Ganjiang River.

Environmental parameters (Table S2), including pH, DO, EC, TA, turbidity, TN, NO_3-N, NH_3-N, TP PO_4-P, COD_{Mn}, Chla, WT, and V, were used for Spearman correlation analysis and LOWESS to obtain the protection thresholds of some environmental parameters (Table 3 and Fig. 6). The results showed that, pH, DO, NH_3-N, TN, PO_4-P, COD_{Mn}, and WT were significantly related to the Phyto-IBI, which was consistent with the conclusion of other authors who found the nutrients significantly affect the phytoplankton community (Lin et al., 2015; Song et al., 2017; Duan et al., 2018; Feng et al., 2019). In the present study, only the turning point of NH_3-N (0.65 mg L^{-1}) can be considered a protection threshold. Zhang et al. (2015) and Zhang et al. (2019) drew similar conclusions and found that the protection threshold of NH_3-N was 0.55 mg L^{-1} in the Xiliao River and 0.46 mg L^{-1} in Lake Balihe. These protection thresholds of NH_3-N are all below the third-grade levels outlined in the environmental quality standards for surface water in China (GB 3838-2002).

5. Conclusions

In this study, Phyto-IBI was developed to evaluate the effects of industrial activities, dam construction and mining on the biotic integrity of the aquatic system of the Ganjiang River. The three activities greatly altered the composition and abundance, with a reduction in phytoplankton species quantity and diversity and an increase in abundance. The overall health status of the Ganjiang River was fair, and the health statuses of the industrial areas, dam areas, mining areas and reference points were poor, poor, fair, and good, respectively. Industrial activities, dam construction and mining damage the biotic integrity of aquatic systems. Moreover, compared to industrial activities and mining areas, dam construction is more harmful to aquatic systems in the Ganjiang River. The LOWESS method suggested that an NH_3-N concentration of 0.65 mg L^{-1} is the environmental protection threshold for planktonic biotic integrity in the Ganjiang River.

CRediT authorship contribution statement

Bing Feng: Writing - original draft, Conceptualization, Methodology. **Meng Zhang:** Supervision, Project administration, Funding acquisition. **Jianfeng Chen:** Investigation. **Jun Xu:** Formal analysis. **Bangding Xiao:** Resources. **Min Zhou:** Data curation. **Min Zhang:** Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.106907.

References

Abdelkefi, A., Vasconcellos, R., Nayfeh, A.H., et al., 2013. An analytical and experimental investigation into limit-cycle oscillations of an aeroelastic system. Nonlinear Dyn. 71, 159–173. https://doi.org/10.1007/s11071-012-0648-z.

Arnon, D.I., 1949. Copper enzymes in isolated chloroplasts polyphenoloxidase in Beta vulgaris. Plant Physiol. 24 (1), 1–15. https://doi.org/10.1104/pp.24.1.1.

Azevedo, I.C., Bordalo, A.A., Duarte, P.M., 2010. Influence of river discharge patterns on the hydrodynamics and potential contaminant dispersion in the Douro estuary (Portugal). Water Res. 44 (10), 3133–3146. https://doi.org/10.1016/j.watres.2010.03.011.

Borics, G., Várbíró, G., Grigorszky, I., et al., 2007. A new evaluation technique of potamoplankton for the assessment of the ecological status of rivers. River Syst. 17 (3–4), 465–486. https://doi.org/10.1127/lr/17/2007/465.

Cabecinha, E., Cortes, R., Cabral, J.A., et al., 2009. Multi-scale approach using phytoplankton as a first step towards the definition of the ecological status of reservoirs. Ecol. Indic. 9 (2), 240–255. https://doi.org/10.1016/j.ecolind.2008.04.006.

Chen, Y., Yuan, L., Xu, C., 2017. Accumulation behavior of toxic elements in the soil and plant from Xinzhuangzi reclaimed mining areas, China. Environ. Earth Sci. 76 (5), 226. https://doi.org/10.1007/s12665-017-6535-7.

Chen, H.W., Zhang, M., Liu, Z.G., et al., 2011. Assessment on freshwater ecosystem integrity and health in Gangjiang river basin through the fish IBI method. Resour. Environ. Yangtze Basin 20 (09), 1098.

Cooper, M., Lamberti, G., Moerke, A., et al., 2018. An expanded fish-based index of biotic integrity for Great Lakes coastal wetlands. Environ. Monit. Assess. 190, 580. https://doi.org/10.1007/s10661-018-6950-6.

Cui, W.Y., Guo, S.Y., Meng, X.Z., et al., 2019. Application of adapted Benthic Index of Biotic Integrity (B-IBI) for river ecosystem health assessment in Zhanghe River Watershed, China. Pol. J. Ecol. 66 (4), 407–415. https://doi.org/10.3161/15052249PJE2018.66.4.008.

Domingues, R.B., Galvão, H., 2007. Phytoplankton and environmental variability in a dam regulated temperate estuary. Hydrobiologia 586, 117–134. https://doi.org/10.1007/s10750-006-0567-4.

Duan, Z., Tan, X., Parajuli, K., et al., 2018. Colony formation in two *Microcystis* morphotypes: effects of temperature and nutrient availability. Harmful Algae 72, 14–24. https://doi.org/10.1016/j.hal.2017.12.006.

Effert, E., Fischer, R., Wahl, D., 2019. Effects of riparian forest buffers and agricultural land use on macroinvertebrate and fish community structure. Hydrobiologia 841, 45–64. https://doi.org/10.1007/s10750-019-04006-1.

Feng, B., Wang, C., Wu, X., et al., 2019. Spatiotemporal dynamics of cell abundance, colony size and intracellular toxin concentrations of pelagic and benthic *Microcystis* in Lake Caohai, China. J. Environ. Sci. 31, 184–196. https://doi.org/10.1016/j.jes.2019.05.010.

Gupta, A.K., Gupta, S.K., Patil, R.S., 2005. Statistical analyses of coastal water quality for a port and harbour region in India. Environ. Monit. Assess. 102, 179–200. https://doi.org/10.1007/s10661-005-6021-7.

Hötzel, G., Croome, R., 1999. A phytoplankton methods manual for Australian freshwaters. Land Water Resour. Res. Dev. Corporation 66.

Huang, Q., Gao, J., Cai, Y., et al., 2015. Development and application of benthic macroinvertebrate-based multimetric indices for the assessment of streams and rivers in the Taihu Basin, China. Ecol. Indic. 48, 649–659. https://doi.org/10.1016/j.ecolind.2014.09.014.

Karr, J.R., 1981. Assessment of biotic integrity using fish communities. Fisheries 6 (6), 21–27. https://doi.org/10.1577/15488446(1981)<0021:AOBIUF>2.0.CO;2.

Kondzior, P., Butarewicz, A., 2018. Effect of heavy metals (Cu and Zn) on the content of photosynthetic pigments in the cells of algae chlorella vulgaris. J. Eco. Eng. 19 (3), 18–28. https://doi.org/10.12911/22998993/85375.

Kummu, M., Guillaume, J.H.A., de Moel, H., et al., 2016. The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. Sci. Rep. 6, 38495. https://doi.org/10.1038/srep38495.

Lacouture, R.V., Johnson, J.M., Buchanan, C., et al., 2006. Phytoplankton index of biotic integrity for Chesapeake Bay and its tidal tributaries. Estuaries Coasts 29, 598–616. https://doi.org/10.1007/BF02784285.

Li, J., Dong, S., Liu, S., et al., 2013. Effects of cascading hydropower dams on the composition, biomass and biological integrity of phytoplankton assemblages in the middle Lancang-Mekong River. Ecol. Eng. 60, 316–324. https://doi.org/10.1016/j.ecoleng.2013.07.029.

Li, X., Yu, H., Wang, H., et al., 2019. Phytoplankton community structure in relation to environmental factors and ecological assessment of water quality in the upper reaches of the Genhe River in the Greater Hinggan Mountains. Environ. Sci. Pollut. Res. 26, 17512–17519. https://doi.org/10.1007/s11356-019-05200-3.

Lin, Q., 2011. Influence of Dams on River ecosystem and its countermeasures. J. Water Resour. Prot. 3 (1), 60–66. https://doi.org/10.4236/jwarp.2011.31007.

Lin, L., Appiah-Sefah, G., Li, M., 2015. Using a laser particle analyzer to demonstrate relationships between wind strength and *Microcystis* colony size distribution in Lake Taihu, China. J. Freshw. Ecol. 30 (3), 425–433. https://doi.org/10.1080/02705060.2014.976666.

Liu, S., Huang, Y., Zhu, X., et al., 2015. Environmental effects of ion-absorbed type rare earth extraction on the water and soil in mining area and its peripheral areas.

Environ. Sci. Technol. 38 (06), 25–32.
Ludwig, F., van Slobbe, E., Cofino, W., 2014. Climate change adaptation and Integrated Water Resource Management in the water sector. J. Hydrol. 518, 235–242. https://doi.org/10.1016/j.jhydrol.2013.08.010.
Lugoli, F., Garmendia, M., Lehtinen, S., et al., 2012. Application of a new multi-metric phytoplankton index to the assessment of ecological status in marine and transitional waters. Ecol. Indic. 23, 338–355. https://doi.org/10.1016/j.ecolind.2012.03.030.
Mao, Y., Yang, S., Xue, C., et al., 2018. Rapid degradation of malachite green by CoFe(2)O(4)-SiC foam under microwave radiation. R. Soc. Open Sci. 5 (6), 180085. https://doi.org/10.1098/rsos.180085.
McCartney M, Sullivan C and Acreman M. Ecosystem Impacts of Large Dams. In: Background Paper No. 2 Prepared for IUCN/UNEP/WCD. Cent. for Ecol. Hydrol. Wallingford, UK, 2000.
Moitra, M., Leff, L.G., 2015. Bacterial community composition and function along a river to reservoir transition. Hydrobiologia 747, 201–215. https://doi.org/10.1007/s10750-014-2140-x.
Moore, F., Esmaeili, K., Keshavarzi, B., 2011. Assessment of heavy metals contamination in stream water and sediments affected by the Sungun Porphyry Copper Deposit, East Azerbaijan Province, Northwest Iran. Water Qual. Expos. Health 3, 37–49. https://doi.org/10.1007/s12403-011-0042-y.
Naiman, R.J., Bilby, R.E., Bisson, P.A., 2000. Riparian ecology and management in the pacific coastal rain forest. BioScience 50 (11), 996–1011. https://doi.org/10.1641/0006-3568(2000)050[0996:REAMIT]2.0.CO;2.
Paerl, H.W., Hall, N.S., Calandrino, E.S., 2011. Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. Sci. Total Environ. 409 (10), 1739–1745. https://doi.org/10.1016/j.scitotenv.2011.02.001.
Perbiche-Neves, G., Ferreira, R.A.R., Nogueira, M.G., 2011. Phytoplankton structure in two contrasting cascade reservoirs (Paranapanema River, Southeast Brazil). Biologia 66, 967. https://doi.org/10.2478/s11756-011-0107-1.
Petesse, M.L., Petrere, M., 2012. Tendency towards homogenization in fish assemblages in the cascade reservoir system of the Tietê river basin, Brazil. Ecol. Eng. 48, 109–116. https://doi.org/10.1016/j.ecoleng.2011.06.033.
Pinto, E., Sigaud-kutner, T.C.S., Leitão, M.A.S., et al., 2003. Heavy metal–induced oxidative stress in algae. J. Phycol. 39 (6), 1008–1018. https://doi.org/10.1111/j.0022-3646.2003.02-193.x.
Poff, N., Olden, J., Merritt, D., et al., 2007. From the Cover: homogenization of regional river dynamics by dams and global biodiversity implications. Proc. Natl. Acad. Sci. U.S.A. 104 (14), 5732–5737. (accessed 3 April 2020). www.jstor.org/stable/25427270.
Poff, N.L., Olden, J.D., 2017. Can dams be designed for sustainability? Science 358 (6368), 1252–1253. https://doi.org/10.1126/science.aaq1422.
Pomari, J., Kane, D., Ferreira, R., et al., 2019. A new tool to assess ecosystem health in large subtropical reservoirs: development and validation of a Planktonic Index of Biotic Integrity. Aquat. Ecosyst. Health Manage. 22 (1), 15–29. https://doi.org/10.1080/14634988.2019.1562837.
Ruaro, R., Gubiani, É.A., 2013. A scientometric assessment of 30 years of the Index of Biotic Integrity in aquatic ecosystems: applications and main flaws. Ecol. Indic. 29, 105–110. https://doi.org/10.1016/j.ecolind.2012.12.016.
Saksena, D.N., 1987. Rotifers as indicators of water quality. Acta Hydrochim. Hydrobiol. 15. https://doi.org/10.1002/aheh.19870150507.
Scott, J.T., Stanley, J.K., Doyle, R.D., et al., 2009. River–reservoir transition zones are nitrogen fixation hot spots regardless of ecosystem trophic state. Hydrobiologia 625, 61–68. https://doi.org/10.1007/s10750-008-9696-2.
SEPA, 2002. Monitoring and Analysis Methods of Water and Wastewater, fourth ed. China Environ. Sci. Press, Beijing.
Shi, Y.L., Zhang, M., Yao, N., et al., 2020. Water pollution status and nitrogen pollution distribution patterns around ion-absorbed rare earth tailings in Dingnan County, Jiangxi Province. Res. Environ. Sci. 33 (1), 94–103. https://doi.org/10.13198/j.issn.1001-6929.2019.07.20.
Song, H., Xu, J., Lavoie, M., et al., 2017. Biological and chemical factors driving the temporal distribution of cyanobacteria and heterotrophic bacteria in a eutrophic lake (West Lake, China). Appl. Microbiol. Biotechnol. 101, 1685–1696. https://doi.org/10.1007/s00253-016-7968-8.
Souza, G.B.G., Vianna, M., 2020. Fish-based indices for assessing ecological quality and biotic integrity in transitional waters: a systematic review. Ecol. Indic. 109, 105665. https://doi.org/10.1016/j.ecolind.2019.105665.
Wennrich, R., Mattusch, J., Morgenstern, P., et al., 2004. Characterization of sediments in an abandoned mining area; a case study of Mansfeld region, Germany. Environ. Geol. 45, 818–833. https://doi.org/10.1007/s00254-003-0942-7.
Wu, N., Cai, Q., Fohrer, N., 2012a. Development and evaluation of a diatom-based index of biotic integrity (D-IBI) for rivers impacted by run-of-river dams. Ecol. Indic. 18, 108–117. https://doi.org/10.1016/j.ecolind.2011.10.013.
Wu, N., Schmalz, B., Fohrer, N., 2012b. Development and testing of a phytoplankton index of biotic integrity (P-IBI) for a German lowland river. Ecol. Indic. 13 (1), 158–167. https://doi.org/10.1016/j.ecolind.2011.05.022.
Yang, N., Li, Y., Zhang, W., et al., 2019. Reduction of bacterial integrity associated with dam construction: a quantitative assessment using an index of biotic integrity improved by stability analysis. J. Environ. Manage. 230 (15), 75–83. https://doi.org/10.1016/j.jenvman.2018.09.071.
Zhang, Y., Ban, X., Li, E., et al., 2020. Evaluating ecological health in the middle-lower reaches of the Hanjiang River with cascade reservoirs using the Planktonic index of biotic integrity (P-IBI). Ecol. Indic. 114, 106282. https://doi.org/10.1016/j.ecolind.2020.106282.
Zhang, H., Ding, S., Zhang, Y., et al., 2015. Assessment of the fish index of biotic integrity and its relationship with environmental factors in the Xiliao River Basin. J. Lake Sci. 27 (5), 829–839. https://doi.org/10.18307/2015.0509.
Zhang, H., Duan, Z., Wang, Z., et al., 2019. Freshwater lake ecosystem health assessment and its response to pollution stresses based on planktonic index of biotic integrity. Environ. Sci. Pollut. Res. 26, 35240–35252. https://doi.org/10.1007/s11356-019-06655-0.
Zhang, F.F., Zhang, M., Liu, Z.G., et al., 2011. A health assessment using a benthic-index of biotic integrity in Ganjiang River basin. Acta Hydrobiol. Sin. 35 (6), 963–971. https://doi.org/10.3724/SP.J.1035.2011.00001.
Zhang, J.L., Zheng, B.H., Liu, L.S., et al., 2010. Seasonal variation of phytoplankton in the DaNing River and its relationships with environmental factors after impounding of the Three Gorges Reservoir: a four-year study. Procedia Environ. Sci. 2, 1479–1490. https://doi.org/10.1016/j.proenv.2010.10.161.
Zhu, W., Liu, Y., Wang, S., et al., 2019. Development of microbial community–based index of biotic integrity to evaluate the wetland ecosystem health in Suzhou, China. Environ. Monit. Assess. 191, 377. https://doi.org/10.1007/s10661-019-7512-2.