ASSESSMENT OF RIVER HEALTH IN THE HAIHE RIVER BASIN BASED ON WATER QUALITY, AQUATIC LIFE, AND PHYSICAL HABITAT

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Abstract. Rivers play a key role in ecosystems and society. With the development of local economies, the Haihe River Basin has been affected and threatened by human activities. It is necessary and important to develop a river health evaluation system and to quantitatively evaluate the river health status. In this study, we collected samples from 37 sites along the Haihe River Basin and assessed the health with ten indices which indicated its physical, chemical, and biological conditions. The weight of each index was estimated by using the principal component analysis (PCA). The integrated index of river health was constructed to assess the health status. The results showed that the whole Haihe River Basin health was in the fair category. The numbers of sites in healthy, sub-healthy, fair, sub-sick and sick categories were 1, 17, 13, 3, and 3, respectively. DO (dissolved oxygen), benthic integrated biotic index and physical habitat had positive effects on the river health, while nutrients and organic matter had negative effects on river health. The research results not only provide scientific basis and technical support for further research but guidance and suggestions for government to improve the river health.
Keywords: *assessment index system, physicochemical parameters, phytoplankton, macroinvertebrate, principal component analysis*

Introduction

Rivers are one of the important natural ecosystems composed of aquatic organism communities and abiotic environments. It is the main channel for material circulation, energy flow and information transmission between terrestrial and aquatic ecosystems, playing an important ecological function (Shan et al., 2021). Rivers are also important natural resources for human development. It not only provides food, production and domestic water for human beings, but also has multiple service functions such as flood control, power generation, shipping, irrigation, tourism, etc. (Carson and Mitchell, 1993; Wilson and Carpenter, 1999; Grizzetti et al., 2019). However, with the rapid growth of population and the intensification of human industrial and agricultural activities, rivers are constantly disturbed and damaged by human activities stress. For example, the development of reservoirs, the transformation of channels, a large number of sewage discharge and overfishing have caused the destruction of river structure, the deterioration of water quality, the reduction of fish resources, the disappearance of species, soil erosion, and other serious ecological and environmental problems (Poff et al., 1997; Yeom et al., 2007; Wang et al., 2014). Therefore, accurate assessment of the health status of river ecosystem has become a hot issue of river management in recent years.

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The concept of river health was early proposed in the Clean Water Act of the United States in 1972, which set river health as the physical, chemical and biological integrity, that is, the state of maintaining the natural structure and function of the ecosystem. Meyer (1997) described this concept as explicitly incorporating both ecological integrity and human values. Fairweather (1999) proposed that river health should be combined with socio-economic objectives. However, to date, the concept of river health has not been unified.

Based on the concept of river health, many countries have established different evaluation methods to guide river health assessment, such as the Index of Stream Condition (ISC) in Australia (Ladson et al., 1999), the Rapid Bioassessment Protocols (RBPs) in the United States (Barbour et al., 1999), Overall Index of Pollution (OIP) in India (Sargaonkar and Deshpande, 2003). In China, Yang et al. (1992) first used EPT (Ephemeroptera, Plecoptera and Trichoptera) taxonomic unit number and FBI (family biological index) to evaluate the water quality of Jiuhuahe River in Anhui Province. After that, scholars pay more attention to river health. The research on river health has been reported in Huai River, Taihu Basin, Liao River, Wei River and urban rivers (Meng et al., 2009; Zhao and Yang, 2009; Deng et al., 2015; Zhang et al., 2018; Wang et al., 2019).

As an important tool for river management, river health assessment has been used worldwide. The methods employed to assess river health can be classified as single factor method and aggregative indicator method. The former is widely used. A number of factors have been used to determine river health such as ecological flow (Ma et al., 2019) or biological monitoring with common indicative species including fish (Karr, 1981), phytoplankton (Reynolds, 2003), macroinvertebrate (Helson and Williams, 2013), periphyton (Murdock et al., 2004). This method is simple and easy to operate, but it is difficult to fully display the complex changes of the river ecosystem. Aggregative indicator method mainly covers biological, physical and chemical factors, which can comprehensively, accurately and objectively reflect the river health status (Zhao and Yang, 2009). Many studies have reported aggregative indicator method to determine the river health assessment (Meng et al., 2009; Kim and An, 2015). To date, a number of river health assessment methodologies have been proposed such as River Pollution Index (RPI) (Liou et al., 2004), the Index of Stream Condition (ISC), Ecological Health Index (EHI) (Yadav et al., 2015), but a universally applicable approach has not developed mainly due to large geographical differences, catchment characteristics and habitat-specific species attributed to river systems (Pinto and Maheshwari, 2014; Singh and Saxena, 2018). It is the development direction of the river health evaluation in the future.

The Haihe River Basin is the political, economic and cultural centre of China, with dense population and numerous large and medium-sized cities. Its health status is of great significance to the integrated development of Beijing-Tianjin-Hebei region and the development of the national economy. However, little work has been done to evaluate river health for the whole Haihe River Basin (Shan et al., 2016; Cheng et al., 2018). Moreover, previous studies have primarily focused on the water physicochemical and biological diversity without focusing on the habitat situation in Haihe River Basin. These limitations of information have rendered it difficult to determine the status of Haihe River Basin. The objective of this paper is to establish a river health assessment index system based on ten indices consisting of water quality, aquatic life, and physical habitat to quantitatively evaluate river health in this basin and propose management strategies for improving river health.

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Materials and methods

Study area and sampling sites

The Haihe River Basin (35-43°N, 112-120°E) is located in northeastern China. The drainage area of Haihe River Basin is approximately 3.18×10^5 km^2, accounting for 3.3% of China's area. The north and west parts of basin are mountains and plateaus, which account for 60% of the whole area; the east and southeast parts are plains, which account for 40% (Wei et al., 2017). The Haihe River Basin contains numerous tributaries, with dispersed river systems, including three primary river systems: the Luan River (the northern part), the Haihe River (the middle part), and the Tuhaimajia River (the southern part) (Xu et al., 2020). Both basins are characterized by temperate semi-humid and semi-arid continental monsoon climates, with mean annual temperature ranging between 1.5°C and 14°C and mean annual rainfall of 527 mm.

The collection of water and biological samples and the investigation of physical habitat were conducted from June to July 2020. Thirty-seven sites were sampled and investigated in the Haihe River Basin (*Fig. 1*). Site selection was based on two principles. Firstly, the sites have sufficient spatial representativeness, covering various habitat types. The sampling sites basically cover the main tributaries and important main streams of the Haihe River Basin. Secondly, the sites can reflect the impact of anthropogenic activities.

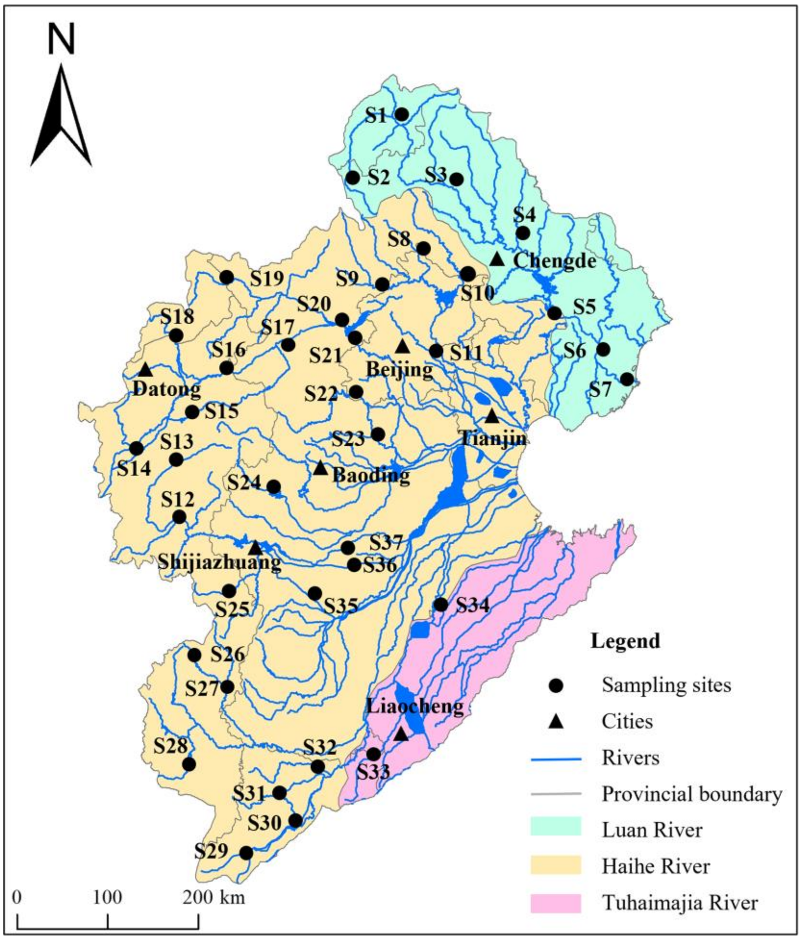

***Figure 1.** Sampling sites in the Haihe River Basin*

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Evaluation index system

In this paper, based on previous studies and the actual situation of the Haihe River basin, we selected ten indices concerning three aspects of water quality, aquatic life, and physical habitat for the health assessment (Meng et al., 2009; Kim and An, 2015; Zhang et al., 2018; Wang et al., 2019).

Water quality

Seven parameters, dissolved oxygen (DO), total nitrogen (TN), total phosphorus (TP), permanganate index (COD_{Mn}), chemical oxygen demand (COD), five-day biological oxygen demand (BOD_5), ammonium nitrogen (NH_3-N) were measured at each site. The DO is an important parameter in water quality assessment and reflects the physical and biological processes prevailing in the water. COD_{Mn}, COD, and BOD_5 mainly reflect the degree of organic pollution of water. TN, TP, and NH_3-N are important parameters that are frequently used to evaluate nutritional pollution.

We measured DO in situ using a portable instrument. Water samples (2L) were collected 0.5 m below the water surface and transported to the laboratory to analyze TN, TP, COD_{Mn}, COD, BOD_5, and NH_3-N. One water sample was collected per site. All these parameters were measured according to Monitoring and Analysis Methods for Water and Wastewater.

Aquatic life

Phytoplankton and macroinvertebrate were used to evaluate river health. As an important primary producer in the river ecosystem, phytoplankton is very sensitive to changes in the water environment, and its diversity directly affects the structure of the upper food chain and the stability of the entire ecosystem (Cellamare et al., 2012). Macroinvertebrate have a long life cycle and are sensitive to different types of pollution and disturbance, which can comprehensively reflect the degree of disturbance caused by long-term human activities on river ecosystem (Dauvin et al., 2007).

Qualitative phytoplankton samples were collected using a 25# plankton net (64 μm mesh) to make "∞" shape reciprocating and slowly dragging at the speed of 20 cm/s-30 cm/s at the surface (0.5 m below the surface) for about 1 min-3 min (Liu et al., 2019). Then the retentate was rinsed into a plastic bottle. The volume of sample was approximately 100 mL. Quantitative phytoplankton samples were collected using a plexiglass water collector to collect 1 L of water to a plastic bottle. Qualitative and quantitative phytoplankton samples were immediately fixed with Lugol's iodine solution (1.0%v/v) in situ. In the laboratory, quantitative phytoplankton samples allowed to settle for 48 h and then concentrated to approximately 50 mL in a sterile glass bottle prior to analysis (Chen et al., 2003). One quantitative and one qualitative sample were collected per site. Phytoplankton species were identified and classified to the lowest possible taxon with the microscope according to Hu and Wei (2006). The Shannon-Wiener index is a typical and commonly used index for phytoplankton biodiversity evaluation. The calculation formula is as follows:

$$H' = -\sum_{i=1}^{S} \frac{n_i}{N} log_2 \frac{n_i}{N} \quad \text{(Eq.1)}$$

Where S is the number of species, n_i is the number of individuals in the i-th species, and N is the total number of individuals.

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Macroinvertebrate samples were collected using D shaped net (0.25 m wide with 425 µm mesh), Surber net (0.3 m wide with 425 µm mesh) or Van Veen grabs from multiple habitat sampled in proportion to their occurrence with 3-4 replications for each site (Barbour et al., 1999). All samples were composited into one sample. The samples were sieved on a 425 µm screen and selected in white porcelain plate. Macroinvertebrate visible to the naked eye were placed into 50-mL sealed plastic containers and fixed with 95% ethanol in the field. One sample was collected per site. In the laboratory, all samples were counted and identified to the lowest taxon as far as possible using the dissecting microscope and microscope (usually species or genus). The benthic integrated biotic index (B-IBI) system was constructed to assess the health condition of Haihe River Basin. Our B-IBI system was modified from Barbour et al. (1996). The metrics were consisted in five major groups as ecological characteristics by community richness, relative abundance, pollution tolerance, functional feeding group and biodiversity index. 21 candidate biological indicators were selected to analyze the distribution range, discriminant ability and Pearson's correlation. Three biological indicators were finally selected for the B-IBI index, including the total number of taxon units, the average score per taxon (ASPT) and Shannon-Wiener diversity index (*Table 1*). Then the ratio method was used to unify the dimensions of biological indicators, and the value of B-IBI was obtained by accumulating the scores of each biological indicator. As the B-IBI increases, the health status of river improves.

Table 1. *Calculation formula of three biological indicators*

Indicators	Calculation formula
Total number of taxon units (M1)	M1/20.10
ASPT (M15)	M15/6.51
Shannon-Wiener diversity index (M18)	M18/3.63

The dominant species were determined by the dominance value (Y) of aquatic life. The species with Y > 0.02 were the dominant species (Liu et al., 2019). The calculation formula is as follows:

$$Y = \frac{n_i}{N} \times f_i \quad \text{(Eq.2)}$$

Where Y is the dominance value of aquatic life, f_i is the frequency of species i, n_i is the individual number of species i, and N is the individual sum of all species.

Physical habitat

We established physical habitat evaluation index system mainly based on modified system of Barbour et al. (1999), which reflects the river morphology and riverbank habitat environment. We assessed ten parameters that include sediment, instream habitat complexity, velocity/depth diversity, bank stability, river channel change, river water volume status, riparian vegetation diversity, water quality status, human activity intensity, and bank land use type. All the parameters were determined by field investigation. Each parameter was divided into four categories including poor (0–5), fair (6–10), good (11–15) or excellent (16–20). Each parameter score was accumulated to obtain the final habitat quality evaluation results ranging from 0-200.

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Assessment method

Determination of the assessment method is the core of ecosystem health assessment. There is not a general understanding and uniform method at present. This study referred to the evaluation method of Meng et al. (2009).

According to the constructed river health evaluation index system, comprehensive river health index was calculated based on the following formula:

$$RH = \sum_{i=1}^{n} H_i W_i \tag{Eq.3}$$

Where RH represents the comprehensive river health index, H_i is the value of the ith index, and W_i is the weight of the ith index.

In order to compare the evaluation indices in a dimensionless way, indices that decrease with a disturbance were standardized according to the following formula:

$$H_i = \frac{H_{max} - H_{fact}}{H_{max} - H_{III}} \tag{Eq.4}$$

Indices which increase with a disturbance were standardized according to the following formula:

$$H_i = \frac{H_{fact}}{H_{III}} \tag{Eq.5}$$

Where H_{max} is the maximum of the index, H_{fact} is the actual value of the index, and H_{III} is the category III value of the index.

The principal component analysis (PCA) was applied to determine the weight of each index (W_i).

The assessment criteria for river health was calculated according to RH. H_{fact} was the values of the standards of category I, II, III, or IV for each index (*Table A1*). The river health status was divided into five categories, namely healthy, sub-healthy, fair, sub-sick and sick.

Statistical analysis

Cluster analysis (CA) was conducted in Primer 6.0 for the classification of the sites on the basis of the water quality. PCA was performed using SPSS software (version 23) to determine the weight of each index. PCA was also used to analyze the correlations among water quality, aquatic life and physical habitat (with using Canoco version 4.5). During the analysis, indices indicating eigenvalues > 1 were retained. Other statistical analysis was completed with Excel.

Results

Water quality

The average, minimum and maximum values of seven water quality parameters were shown in *Table 2*. Depending on the different application functions and protection objectives, the Surface Water Environmental Quality Standard (GB3838-2002) divides the water quality into five categories (category I to category V). Water sources with the

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level of category III and below are suitable for human consumption. The average value of DO, COD and BOD_5 were under category I, TP, COD_{Mn} and NH_3-N under category II. Only TN average value exceeded category III, indicating that the TN pollution in Haihe River basin was the most serious.

Table 2. *Average, minimum and maximum values of the water quality, aquatic life and physical habitat indices and river health assessment score*

Indices	Average	Minimum-maximum
DO	8.26 ± 2.15	2.90-13.90
TN (mg/L)	3.73 ± 3.26	0.28-12.46
TP (mg/L)	0.07 ± 0.08	0.01-0.32
COD_{Mn} (mg/L)	3.16 ± 1.57	1.00-6.50
COD (mg/L)	13.05 ± 6.07	5.00-30.00
BOD_5 (mg/L)	1.85 ± 1.10	0.20-4.40
NH_3-N (mg/L)	0.29 ± 0.39	0.02-1.93
Phytoplankton ($\times 10^6$ cells/L)	4.33 ± 6.62	0.01-37.02
Macroinvertebrate (ind./m^2)	305.49 ± 267.80	3.30-1376.10
Physical habitat	118 ± 22	75-172
River health assessment score	0.79 ± 0.39	0.37-2.22

CA was used to classify the sampling sites which have similar the physicochemical characteristics of the water. According to Bray Curtis similarity, the 37 sampling sites were divided into three clusters (*Fig. 2*). S11, S18, S20, S29 and S35 forming Cluster I were highly polluted with heavy human activities (agricultural production, industrial effluents and domestic sewage). Cluster II comprised the sampling sites S9, S10, S22 and S25-S27, which corresponded to the moderately polluted sites. The other sites were divided into Cluster III which was less polluted.

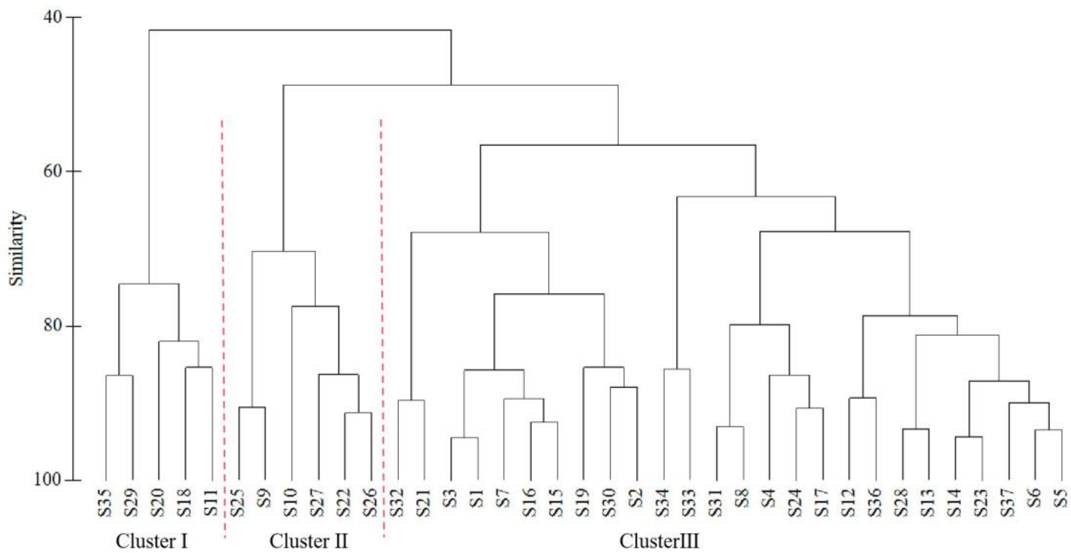

Figure 2. *Dendrogram showing the cluster between the sampling sites depending on the water quality*

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Aquatic life

Phytoplankton

Our study identified 122 phytoplankton taxa comprising 8 phyla: Chlorophyta 47, Bacillariophyta 40, Cyanophyta 22, Euglenophyta 5, Xanthophyta 3, Pyrrophyta 2, Chrysophyta 2, and Cryptophyta 1 taxa. Total phytoplankton abundance over the river of the investigation ranged from 0.01×10^6 cells/L (S13) to 37.02×10^6 cells/L (S20), with an average of $4.33 \pm 6.62 \times 10^6$ cells/L. The dominant phytoplankton taxa were *Anabaena oscillarioides*, *Pseudanabaena* sp., *Cyclotella catenata*, *Cyclotella meneghiniana* and *Synedra acus*, with the dominance of 0.028, 0.101, 0.021, 0.076, and 0.024, respectively. The average value of Shannon-Wiener index was 2.60 ± 0.64, the highest value was observed in the S28 (3.61), and the lowest was in the S35 (0.90).

Macroinvertebrate

A total of 106 macroinvertebrate taxa, assigned to 4 phyla (Platyhelminthes, Annelida, Mollusca and Arthropoda), 8 classes, 20 orders and 50 families, were identified in the Haihe River Basin. At the phylum level, Arthropoda was the most species-abundant macroinvertebrate group (87 taxa, 82.08%), followed by Mollusca (12 taxa, 11.32%) and Annelida (6 taxa, 5.66%), Platyhelminthes was the least species-abundant group (1 taxa, 0.94%). Most of the taxa sampled are moderate to highly tolerant to pollution. 20 taxa regarded as highly and 76 taxa regarded as moderately tolerant to pollution were sampled. Only 10 taxa were sensitive to pollution. The abundance of macroinvertebrate ranged from 3.30 ind./m^2 (S37) to 1376.10 ind./m^2 (S22), with an average of 305.49 ind./m^2. The dominant macroinvertebrate taxa were *Caridina denticulate sinensis*, *Alainites yixiani*, *Chironomus* sp., *Micronecta guttata*, with the dominance of 0.110, 0.023, 0.025, 0.024, respectively. The average value of B-IBI was 1.85 ± 0.55; the highest value was observed in the S27 (2.87), and the lowest was in the S37 (0.51).

Physical habitat

The physical habitat scores averaged 118 ± 22 and ranged from 75 (S5) to 172 (S21). There were only two sites where the physical habitat scores exceeded 150. The scores of 26 sites were between 100-150 and 9 sites scored 50-100. No sites scored below 50. Among the indices of physical habitat, the average scores of bank stability, river channel change, river water volume status, riparian vegetation diversity, water quality status and bank land use type were in the good category (*Fig. 3*). The sediment, instream habitat complexity, velocity/depth diversity and human activity intensity were in the fair category. Instream habitat complexity had the lowest score and was the main factor affecting physical habitat quality.

Comprehensive evaluation results

In this study, ten indices were selected to develop the evaluation index system. The weight of each index was calculated according to PCA, as presented in *Table 3*. Each index had a different weight value, ranging from 0.089 to 0.112 with a small difference. Based on the index weight in *Table 3* and calculation formula, we computed assessment criteria for river health, as presented in *Table 4*. The lower the score, the better the

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evaluation result. The result showed that the river health assessment mean score was 0.79, which belonged to the fair category. Among the 37 sites, S1 had the lowest score and S35 had the highest score. The numbers of sites in the healthy, sub-healthy, fair, sub-sick and sick categories were 1, 17, 13, 3, and 3, respectively (*Fig. 4*). The health status in Haihe River Basin was spatially heterogeneous. The sites in the healthy and sub-healthy categories were mostly located in northern and western mountain areas, while the sites in the plain areas were mainly in the fair category.

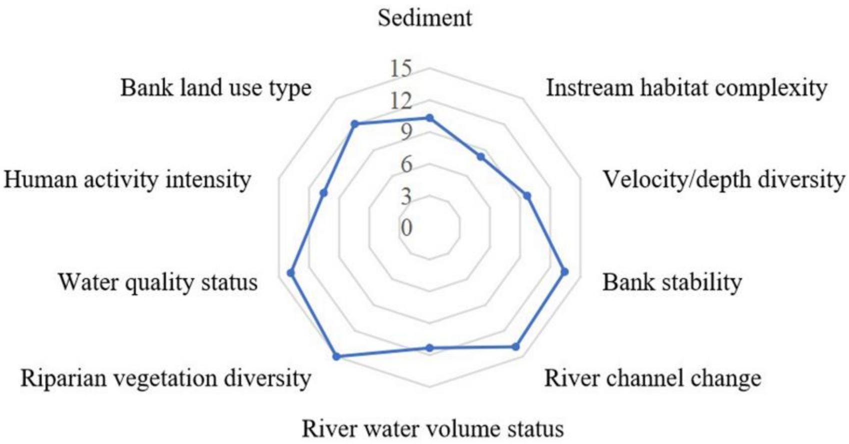

Figure 3. *Distribution of the physical habitat indices score*

Table 3. *Response to disturbances and weight value for the assessment indices*

Index type	Index	Response to disturbances	Weight value
Water quality	DO	Decrease	0.099
	COD_{Mn}	Increase	0.112
	BOD_5	Increase	0.090
	NH_3-N	Increase	0.109
	COD	Increase	0.093
	TN	Increase	0.089
	TP	Increase	0.107
Aquatic life	Shannon-Wiener index of phytoplankton	Decrease	0.102
	B-IBI	Decrease	0.109
Physical habitat	physical habitat index	Decrease	0.091

Table 4. *Assessment criteria of river health*

Assessment criteria	Value assignment
Healthy	RH ≤ 0.39
Sub-healthy	0.39 < RH ≤ 0.65
Fair	0.65 < RH ≤ 1
Sub-sick	1 < RH ≤ 1.44
Sick	RH > 1.44

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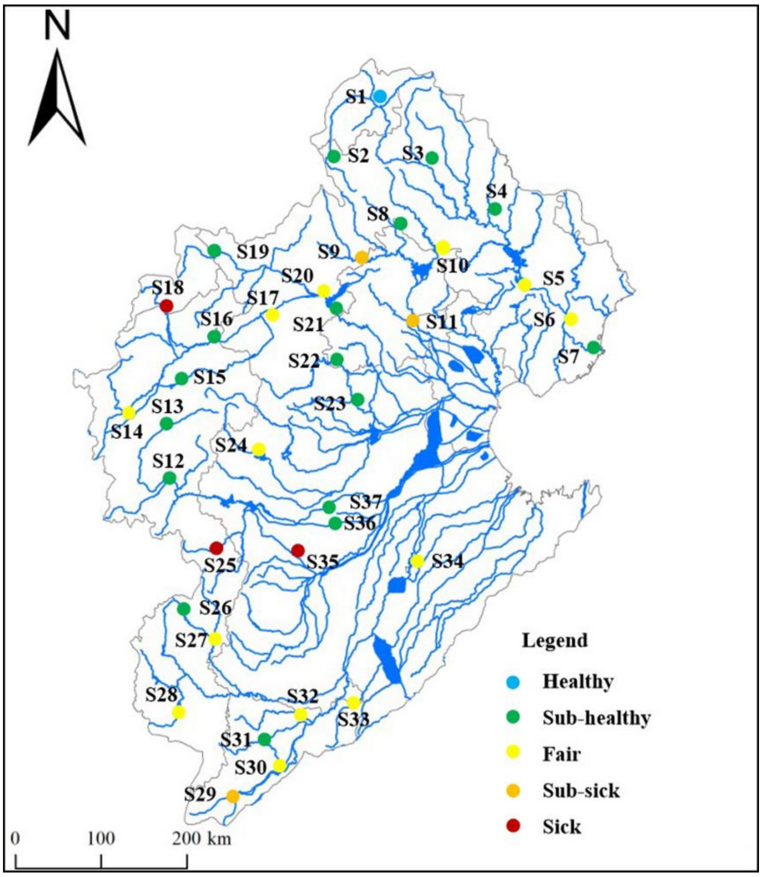

Figure 4. *Category distribution of river health in the Haihe River Basin*

Correlation structure between evaluation indices

The correlation structure between ten indices was visualized in the PCA ordination plot (*Fig. 5*). The first two PCA components accounted for 96.6% of the total variance (eigenvalues of > 1.0). The first component (PC1) represented 89.7% of the variability and was dominated by the physical habitat and B-IBI, while the second component (PC2) represented 6.9% of the variability and was largely influenced by water quality characteristics, with negative impacts from DO, positive impact from other water quality indices. DO was the only water quality index that had a positive correlation with the B-IBI, Shannon-Wiener index of phytoplankton (P-SWI) and physical habitat. The other water quality indices had negative correlations with both groups. The sites with a better status were more located on the right side of the diagram with high DO, B-IBI and physical habitat score, and low nutrients and organic matter, while sites with a worse status were more located on the left side with high nutrients and organic matter.

Discussion

In order to validate the evaluation index system in this study, Ecological Quality Index (EQI) was employed to assess the Haihe River Basin. EQI based on Technical Guidelines for Monitoring and Evaluating the Ecological Environment Quality of River (in Chinese) was calculated using physical habitat, water quality and Shannon-Wiener index of macroinvertebrate indices, with weight values 0.2, 0.4 and 0.4, respectively.

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The evaluation results of whole Haihe River Basin using two methods were in the fair category. But the results of EQI only have 4 categories, and no sites were in the sick category (*Table A2*). Compared to the two methods, the method used in this study can show distinguishing features of river health. Overall, our results are credible.

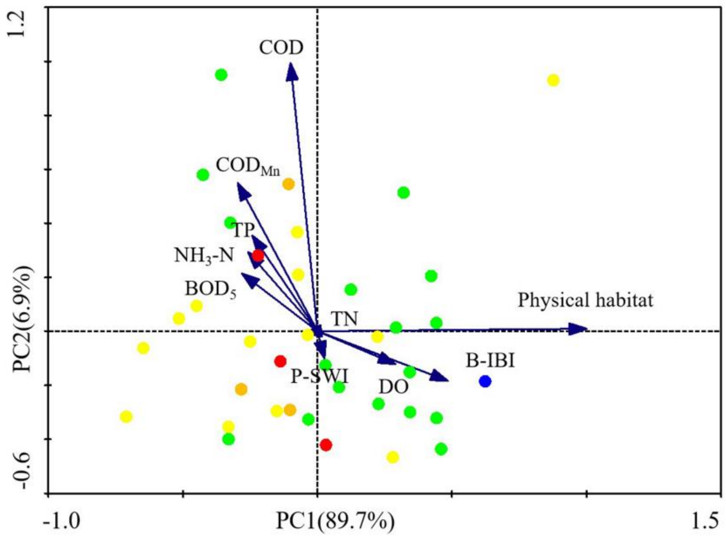

Figure 5. *Principal component analysis of evaluation indices. The blue, green, yellow, orange and red dots indicate sampling sites in the healthy, sub-healthy, fair, sub-sick and sick status, respectively*

Our assessment result of river health in Haihe River Basin was fair, indicating that the river was moderately modified. The rapid population growth, industrialization and urbanization process brought about huge ecological and environmental stress in the Haihe River Basin (Bai et al., 2010). Most of the sites with healthy and sub-healthy status are located at the northern and western mountain areas, while the sites in the plain areas of midstream and downstream are more fair status, which is consistent with the previous results conducted in Haihe River Basin (Cheng et al., 2018). This implies that environmental pollution in Haihe River is mainly concentrated in its plain areas. This may be related to the natural geographical features of the river basin. Due to the undulating terrain in the mountain areas, human activities are greatly hindered. So human activities have little impact on the river ecosystem, and the river health was relatively good. Plain areas are the most affected by human activity. There are many large cities with high population density such as Beijing and Tianjin, and the industrial and agricultural production are developed, which leads to the worse health of this area. Similar phenomena have been observed in many rivers such as Shaying River and Tajan River (Aazami et al., 2015; Luo et al., 2018).

At present, little is known about the health status of Haihe River Basin. Cheng et al. (2018) studied the water ecosystem health research in this basin by using a model based on water physicochemical, nutrient, and macroinvertebrate indices. The assessment results showed that the river ecosystem health was poor overall, and no sites were excellent. Shan et al. (2016) developed a predictive model that used macroinvertebrates as indicator organisms to assess Haihe River Basin ecological status. The river's

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ecological status was determined by calculating the ratio of observed to expected values (O/E). Over half of the sites had poor and bad status, and the proportion of excellent and good was less than 30%. The results of two scholars were worse than ours, which may have two possible explanations. First, this may be caused by the difference of sites we set up. Our sampling sites were relatively few in the plain areas. As has already been mentioned, the health of mountain areas was better than that of plain areas. Second, we conducted the field survey in 2020, while Cheng et al. (2018) and Shan et al. (2016) conducted it in 2013. In recent years, a series of environmental protection works have been carried out. For example, to improve the quality of water environment in China, “Action Plan for Prevention and Control of Water Pollution” was implemented in 2015. China announced the establishment of the Xiong’an New Area in 2017, which is a millennium plan. Xiong’an New Area is located in the Haihe River basin, and extensive attention is paid to the Haihe River basin, which promotes the improvement of health in Haihe River Basin.

Based on the field survey and evaluation results, the health condition of the Haihe River Basin shows a series of problems. For example, pollutants, especially TN, in rivers result in different degrees of pollution in water quality. The increase of nitrogen content was mainly caused by large livestock herds and large mining companies in the northern and western mountain areas, while in the southeast and east of basin, it was due to farmland sewage, human sewage and industrial wastewater (Sun et al., 2013). Habitat complexity is low, usually with only one or two habitats in each sampling site. Moreover, the aquatic biodiversity is relatively low compared with other basins (Meng et al., 2009; Gabyshev and Gabysheva, 2010), and most of them are pollution tolerant species (i.e. Chironomus, Limnodrilus and Lymnaeidae). To alleviate the health condition, we have formulated strategies for future Haihe River Basin health management based on regional characteristics. For water quality, specific measures should be developed to manage the multiple sources of waste discharges such as large mining companies and human and animal feces in the northern and western mountain areas. For example, the use of green manure from human and animal feces could decrease nutrient loading (Sun et al., 2011). In the southeast and east, it is necessary to reduce the use of chemical fertilizers and the intensity of agricultural activities. Centralized collection and treatment of rural sewage and domestic garbage should be carried out to reduce water pollution particularly during the rainy season. Implementation of a strict state policy on environmental pollution control can improve water quality. In order to increase habitat heterogeneity, it is possible to improve river morphology, reduce water conservation projects, strengthen the ecological flow supply and so on. For example, the river channel and bottom were hardened in site S36, which was not conducive to the survival of aquatic life. Ecological restoration and reconstruction in riparian zones should be carried out, building ecological slopes with aquatic plants. River biodiversity can be restored by strictly monitoring water activities such as fishing and damming, reconstructing the important aquatic species and key functional groups in the aquatic ecosystem, and preventing the damage of alien invasive species to indigenous species. In some important sites such as S5, biodiversity can be increased through proliferation and release of fish and shellfish.

Several restrictions of our study for future research should be mentioned. Due to the wide area of the entire Haihe River basin, the number of sites in this study was limited, which failed to fully cover all systems of the Haihe River basin and might not be uniform enough in spatial distribution. And we only investigated once a year, without

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considering the impact of seasonal changes especially water quality and biology. Another restriction is the physical habitat scores were obtained through scoring by experts in field, which may be subjective and uncertain. Therefore, long-term, systematic and objective investigation needs to be further carried out to make evaluation index system more accurately reflect the health status of the Haihe River basin in the future. Furthermore, the assessment criteria was calculated based on the survey data of the Haihe River basin. We cannot claim that assessment criteria would work in other regions as well. Different assessment criteria will be established in various river regions.

Conclusion

In this study, we constructed an integrated method for river health evaluation based on ten indices including DO, TN, TP, COD_{Mn}, COD, BOD_5, NH_3-N, P-SWI, B-IBI and physical habitat, and evaluated the health status of Haihe River Basin. The health assessment result showed that the river was in the fair category, which is consistent with the actual status. Water pollution, low habitat complexity and biodiversity are important factors affecting river health. We proposed restoration strategies for the health status, which can provide a reference for health assessment, management, and protection of Haihe River Basin.

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APPENDIX

Table A1. *Criteria of assessment indices in Haihe River Basin*

Index type	Index	I	II	III	IV
Water quality	DO	7.5	6	5	3
	COD_{Mn} (mg/L)	2	4	6	10
	BOD_5 (mg/L)	3	3	4	6
	NH_3-N (mg/L)	0.15	0.5	1.0	1.5
	COD (mg/L)	15	15	20	30
	TN (mg/L)	0.2	0.5	1.0	1.5
	TP (mg/L)	0.02	0.1	0.2	0.3
Aquatic life	P-SWI	3	2	1	0
	B-IBI	2.14	1.61	1.08	0.55
Physical habitat	Physical habitat index	150	120	90	60

I, II, III, and IV value of water quality are from the Surface Water Quality Standard of China (GB3838-2002)
I, II, III, and IV value of P-SWI are from the Technical Guidelines for Monitoring and Evaluating the Ecological Environment Quality of River (in Chinese)
I, II, III, and IV value of B-IBI were calculated based on the B-IBI evaluation index system.
Physical habitat index referred to Luo et al., 2018

Table A2. *Number of sampling sites with different methods*

Category	This study	EQI
Healthy	1	1
Sub-healthy	17	17
Fair	13	15
Sub-sick	3	4
Sick	3	0

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