Front. Earth Sci. 2021, 15(4): 936–946
https://doi.org/10.1007/s11707-020-0857-6

RESEARCH ARTICLE

Assessment of river ecosystem health in Tianjin City, China: index of ecological integrity and water comprehensive pollution approach

Yan WANG[1], Shang ZHAO[2], Mingdong SUN[1], Xubo LV[1], Wenqian CAI[1], Xiangqin XU (✉)[1], Hongxiang GE (✉)[3], Kun LEI[1]

1 State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China
2 Beijing Jiaotong University, Beijing 100044, China
3 Zhujiang College, South China Agricultural University, Guangzhou 510642, China

Abstract Evaluation of the river ecological environment can provide a basis for river management and ecological restoration. To conduct a comprehensive health assessment of the rivers in Tianjin, their biological, physical, and chemical indicators are investigated on the basis of 32 river monitoring sites from August to September 2018. The comprehensive pollution and ecological integrity indexes of the rivers are analyzed. Results of the two evaluations, compared to achieve the river ecological environment evaluation, are as follows. 1) Index of Ecological Integrity evaluation shows that among the sampling points, 18.8% are "healthy", 28.1% are "sub-healthy", 40.6% are "fair", 6.3% are "poor", and 6.3% are "very poor". 2) The comprehensive evaluation of the chemical properties of the 32 river ecosystems in Tianjin shows severe overall river pollution and low standard water function area. Of the total sampling sites, 16 (50%) are heavily contaminated and 10 (31.3%) are moderately contaminated. Excessive chemical oxygen demand and ammonia nitrogen are the main causes of water pollution. 3) The Index of Ecological Integrity (IEI) has high correspondence with environmental factors. Pearson correlation analysis results show that the IEI index is significantly correlated with permanganate index ($R = -0.453$; $P = 0.023 < 0.05$). Analysis results using BEST show that ammonia nitrogen is the best environmental parameter to explain the changes in IEI ($R_{ho} = 0.154$; $P = 0.02 < 0.05$) and those using RELATE show significant correlation between the biotic index and the environmental parameter matrices ($R_{ho} = 0.154$; $P = 0.034 < 0.05$).

Keywords water ecological function zone, index of water comprehensive pollution, index of ecological integrity, Tianjin

Received June 9, 2020; accepted November 26, 2020

E-mails: 512793156@qq.com (Xiangqin XU)
120920128@qq.com (Hongxiang GE)

1 Introduction

Natural ecosystems have a process of development and evolution that is constantly disturbed by human activities, which result in different directions and trends. The evaluation of the ecosystem integrity is conducive to environmental management, ecosystem protection, and restoration. Water environment and ecosystem health assessment is used worldwide. Such assessment has become an important means to monitor and diagnose the health status of water bodies and guides the restoration and protection of damaged water ecosystems (Walsh, 2000; Cairns et al., 1993).

For river ecological evaluation, the diatom index has been widely used in Europe, the United States, Australia and other places (Prygiel and Coste, 1993; Fore and Grafe, 2002; Chessman et al., 2010;). For example, the EU's Water Framework Directive has established a set of standard methods, including collection of diatom samples, pretreatment, index calculation and evaluation (European Commission, 2000). The index of biotic integrity is also a widely used method. Initially, the method relies on fish index to evaluate the water ecosystem health (Karr, 1981), while the species has gradually extended the different biological classes of bottom-living organisms, symbiotic algae and aquatic plants (Virtanen and Soininen, 2016; Mondy et al., 2012). However, it only reflects the damage status of the biological community, and the results are not comprehensive enough in the areas with excellent water quality but few biological groups.

With the continuous development of modern society, interference of human activities has become an inevitable influence on rivers. As such, the entry point of foreign river health research has changed from biology in the river and water body itself to the natural ecosystem of the river and its surroundings (Karr, 1999; Norris and Hawkins, 2000; MacKay et al., 1995; Meyer, 1997; Simpson and Norris, 2000). Water ecosystem includes biological and abiotic factors and its health involves not only the integrity of biological community, but also its physical and chemical environment. Therefore, the Index of Ecological Integrity (IEI) method is created with the capacity to integrate physical, chemical, biological, hydrological, and other multi-index systems. A typical multi-index system (Ladson et al., 1999) is the Australian River assessment scheme, which evaluates river health using 22 indexes that include hydrology, physical characteristics, riparian condition, water quality, and aquatic organisms (Roland et al., 2002; Robert et al., 2006). Although the IEI is more comprehensive in evaluating water ecological health, this method easily ignores the particularity of different water systems. Water ecosystem has typical regional characteristics. In addition, differences may be observed in the selected evaluation indexes and standards under different water types, regions, and space-time scales (Norris and Thoms, 1999; Dolédec et al., 2010).

Compared with administrative boundaries, ecological zones have biological properties and can better subdivide a province into several sub-units through protection planning. Thus, a solid ecological foundation is provided for function zoning (Omernik and Bailey, 1997). In the mid-1980s, Omernik (1987) first proposed the concept of water ecological zone and its division by function. With the in-depth development of ecology and environmental science theory, this concept is widely applied and popularized in water environment management (Hughes et al., 1986; Hughes et al., 1990; Hughes and Larsen, 1988; Gannon et al., 1996). In China, function zone management of water ecological environment is the development direction and basic control unit. The scientific delineation of this control unit is an important basis to support the transformation of water environmental management. The national program for medium- and long-term scientific and technological development (2006–2020) proposes to “carry out the water ecological function zone in typical river basins,” and the action plan for the prevention and control of water pollution proposes to “study and establish a management technology system for the water ecological environment function zone in river basins”. According to the water ecological function division method mentioned in the 11th and 12th Five-Year Plans, the technical methods of water ecological function division and of setting ecological goals are established.

Therefore, taking Tianjin as an example, this article investigates six types of biological group indicators for the river to obtain a comprehensive and coordinated biotic index data. These indicators include zooplankton, phytoplankton, benthic animal, fish, large aquatic plants, and terrestrial plants. The sampling stations cover the whole Tianjin area, which can fully reflect the status of the river ecosystem in Tianjin. Subsequently, assessment of water environment and ecological integrity is carried out. This study also adds the water ecological zoning, and analyzes the correlation between IEI evaluation results and environmental factors to verify the applicability of the evaluation system.

2 Materials and methods

2.1 Overview of research area

Tianjin is located in the lower reaches of the Haihe River, which is the confluence of five tributaries in the North China Plain and the Bohai Sea in the East with abundant water resources (Fig. 1). Human activities considerably affect the surface water quality of Tianjin. The degraded ecological function of the river mainly shows characteristics of industrial pollution and agricultural non-point

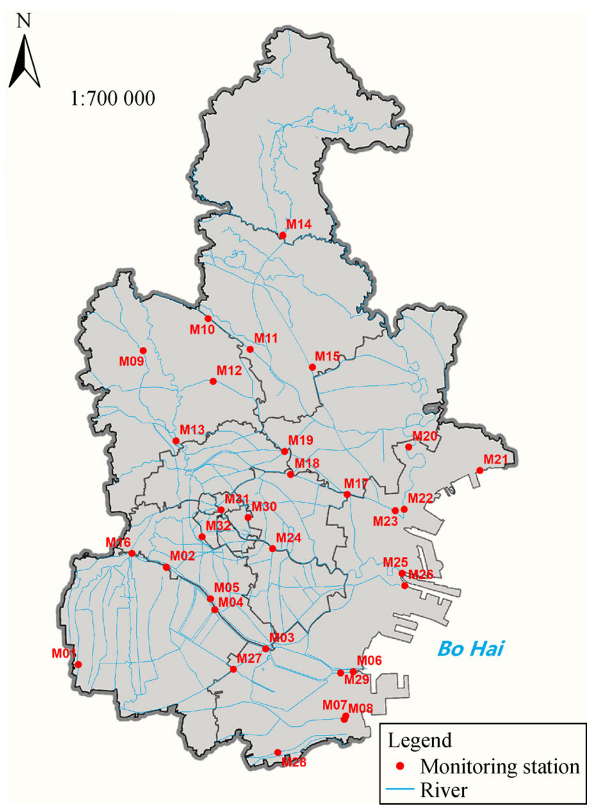

Fig. 1 The monitoring stations in Tianjin.

source pollution. The severity of the main water pollution is such that most of the indicators exceed the surface water quality standard V.

2.2 Division of water ecological functional zones

2.2.1 Partition principle

1) Dominant principle of water ecosystem pressure: division according to the impact of regional land use on water ecosystem

2) Dominant principle of water system structure: structure and function are divided according to water system development

3) Principle of ensuring the integrity of sub-watershed boundary

2.2.2 Partition index

Partition indicators include land use area ratio, river structure index, and human disturbance (Table 1).

2.2.3 Partition method

Using the bottom-up method, the catchment watershed is taken as the basic unit. The land use and water system structure of the catchment basin are calculated, and then the human activity pressure and natural conditions are evaluated. On this basis, the catchment basin is classified using qualitative or quantitative methods.

The area proportion threshold of farmland, urban, forests, grass, construction and other different land use types that can degrade or improve the aquatic community structure can be identified through literature review. The river index threshold that causes the change of aquatic community structure is identified through expert experience or data analysis. The indexes in the catchment basin are divided using qualitative classification tree or quantitative cluster analysis, while the same types of catchment and sub-catchment are merged.

2.3 Sampling

The principles for sampling point selection ensure the representative points in different zones according to the results of the four-level water ecological environment functional zoning in Tianjin. Combining the characteristics of the Tianjin water system, 32 river survey sample points are selected as typical representations (Fig. 1). The above sample points are taken in a water ecological environment survey from August 25 to September 12, 2018. The sampling was carried out under the relatively stable hydrodynamic condition and water quality, while the water ecosystem was basically in a stable state, which belong to instantaneous samples. Analysis includes the characteristics of biological communities, physical characteristics of water environment, and water environment chemical characteristics.

2.4 Data acquisition and analysis

The investigation of water ecological environment mainly includes the general physical, chemical, and biological community indexes (fish, benthos, zooplankton, phytoplankton, macrophyte, and riparian plants).

2.4.1 Physical and chemical index data acquisition

According to the sampling principle of the Code for Water Environment Monitoring, the data indexes potential of hydrogen, conductivity, dissolved oxygen, and water temperature are obtained onsite using the water quality analyzer (YSI Pro2000). Salinity data are obtained using the salinometer while flow rate and water depth are obtained using the flow meter (FP111). The river width is obtained using the distance meter (Leupold RX-IV), and transparency disk (KH05-SD20) is used for data acquisition. The land use type of the riverbank is identified by referring to the 2007 Classification of Land Use Status, and combining the land use characteristics of the area. A total of 800 m of the left and right banks are taken as the boundary. Laboratory test indicators are ammonia nitrogen, total nitrogen, total phosphorus, dissolved phosphate, permanganate index, chemical oxygen demand, nitrite nitrogen, nitrate nitrogen, total dissolved solids, and suspended solids. Two parallel water samples (2 L each) are collected from each sampling point and taken to the laboratory for testing within 48 h. Finally, a single factor evaluation is carried out according to the basic project standard limit of The Environmental Quality Standard for Surface Water (GB3838-2002).

Table 1 Classification and indicators of the water ecological function zones

Index type	Index	Index representation	Whether must choose
Land use	Percentage of land covered by woodlands, grasslands, farmland, urban land, and other construction land	Quantitative	Yes
River structure	Catchment area	Qualitative, quantitative	Yes
	River length, number of nodes, river network density,	Quantitative	Options
Human disturbance	industrial/agricultural/domestic water intensity; industrial/domestic/chemical fertilizer intensity	Quantitative	Options

2.4.2 Data acquisition of biome indicators

Assessment of biological integrity includes quantifiable indicators of biological communities, such as species composition, number of species, biomass, habitat density, biological dominance index, and biodiversity index. Analysis is carried out for the six biological groups of fish, benthic animals, zooplankton, phytoplankton, large aquatic plants, and riparian land plants on the riverbank. Tianjin aquatic samples are collected, fixed, and stored on the basis of the sampling principles of the "Water Environment Monitoring Standards" (SL219-2013), "Guidelines for Monitoring the Environmental Quality of River Water Ecosystems (Trial) (research group of major science, technology program for water pollution control and treatment of China, 2014), and relevant research (Han et al., 2018). Samples that can be easily identified are directly analysed onsite. The remaining samples are brought back to the laboratory for identification and analysis.

2.5 Comprehensive pollution index evaluation method

The comprehensive pollution index method calculates the relative pollution index of each pollution index and obtains the value representing the pollution degree of water body. This method can be used to determine the pollution degree of water body. The comprehensive pollution index of water quality is based on the evaluation of a single pollution index. Considering the characteristics of surface water pollution in Tianjin, representative pollutants are selected, including ammonia nitrogen, total phosphorus, permanganate index, chemical oxygen demand, and potential of hydrogen. Subsequently, the comprehensive water pollution index is calculated as

$$P=\frac{1}{n}\sum_{i=1}^{n}P_i=\frac{1}{n}\sum_{i=1}^{n}\frac{C_i}{S_i}, \tag{1}$$

where P is the comprehensive pollution index, P_i is the pollution index of pollutant i, C_i and S_i are the monitoring concentration and evaluation standard of pollutant i, respectively. n is the number of pollutants. Table 2 shows the comprehensive pollution index standards.

2.6 IEI evaluation method

In this study, the result with the lowest human activity interference intensity is selected as the reference point on the basis of relevant local and international research and considering the water quality and habitat score of each sampling point (Steedman, 1994; Barbour et al., 1996; Maxted et al., 2000; Zheng et al., 2007). The Qualitative Habitat Evaluation Index is used to conduct onsite habitat scoring to rate the quality of river sections at the Tianjin sampling sites. The index screening adopts a standardized method to screen the core parameters (Qu et al., 2012; Kong et al., 2018).

The IEI is calculated by referring to the Technical Guide for Evaluation of River Water Ecological Environment Quality (Trial) after assigning the index.

The specific steps taken to calculate the IEI are adopted from relevant research (Zhang et al., 2019; Zhao et al., 2016):

a) Data normalization

The core parameters that decrease with the increase of interference are normalized by their 95th quantile (Eq. 2), while the parameters that increase with the increase of interference are normalized by Eq. 3. Take the average of the three core parameters in the IEI as their respective scores:

$$V_i' = V_i/V_{95\%}\times 100, \tag{2}$$

$$V_i' = (\mathrm{Max}-V_i)/(\mathrm{Max}-V_{5\%})\times 100, \tag{3}$$

where V_i' is the normalized parameter value; V_i is the parameter value; $V_{95\%}$ is the 95th quantile of the parameter; $V_{5\%}$ is the 5th quantile of the parameter; Max is the maximum of the parameter.

b) Weight coefficient of parameter

The weight of each parameter is calculated by using analytic hierarchy process:

$$W_i=\frac{\sqrt{\Pi a_{ij}}}{\sum_{i=1}^{n}\Pi a_{ij}}, \tag{4}$$

where W_i is the corresponding weight of physical integrity, chemical integrity and biological integrity; a_{ij} is the scale.

Table 2 Comprehensive pollution index classification standards

P	Water quality status	Classification basis
⩽0.20	Very good	Most items are not detected, individual items are detected but within the standard
0.21–0.40	Good	The detected value is within the standard, and several items are close to or exceed the standard
0.41–0.70	Light pollution	Individual items are detected and exceed the standard
0.71–1.00	Moderate pollution	Two of the detected values exceed the standard
1.01–2.00	Heavy pollution	A considerable portion of the detected values exceed the standard
⩾ 2.0	Severe pollution	A considerable portion of the detected values exceed the standard by several or dozens of times

c) IEI

the IEI is got by weighted average of the three parts:

$$\text{IEI} = \sum_{i=1}^{n} (W_i \times I_i), \quad (4)$$

where I_i are the score of physical integrity, chemical integrity and biological integrity.

The evaluation standard of IEI adopts the 25% quantile method of reference point index value distribution, that is, if the index value of a point is greater than the 25% quantile, then that point is subject to limited interference. The distribution range of less than 25% quantile is divided into four equal parts and represents different health levels. In addition, the "Technical Guide for River Water Eco-Environmental Quality Assessment (Trial)" is used as reference to test the environmental pressure sensitivity of the index of biotic integrity. If the "better" ratio of the reference point is above 60%, then the index responds more sensitively and the environmental pressure can be used to evaluate the ecological health of the study area.

3 Results and analysis

3.1 Division of water ecological function zone

The relevant data on the division of water ecological function areas in Tianjin are collected through field research and investigation. Data include those of river network, topography, water environment function areas, administrative regions (township level), and control sections. The division of water ecological function areas in Tianjin prioritizes the separation of water catchment areas, and avoids breaking the jurisdictions to ensure that the tasks and measures of the water quality objective management can finally be implemented. Thus, Tianjin is divided into eight function zones (Fig. 2, Table 3).

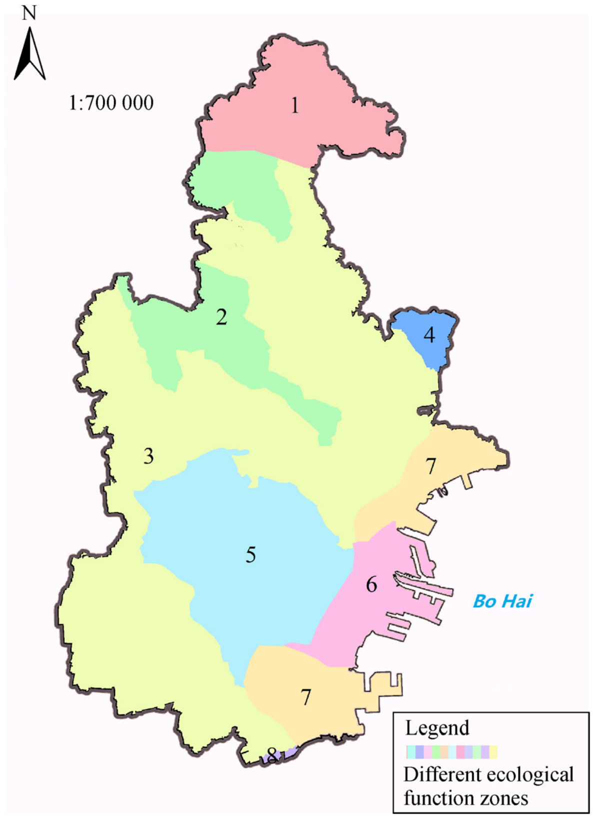

Fig. 2 Water ecological function areas.

3.2 Evaluation results of monitoring stations

3.2.1 Analysis of water quality characteristics

The single factor evaluation of the river water quality at the sampling point is carried out according to the environmental quality standard for surface water (GB 3838-2002). The results show severe overall river pollution in Tianjin, and the standard rate of the water function area is only 46.9%. Water quality among the sampling points are as follows: M15 is class II; M14 and M20 are class III; M2, M9, M10, M11, M12, M13, M16, M22, M23, M30, and M31 points are class IV; M19 and M32 points are class V; and the other 16 points are poor class V (Fig. 3). Ammonia nitrogen and permanganate index exceed the standard levels, comprising the main reason for the low river water quality.

3.2.2 Analysis of river biological community structure characteristics

A total of 127 species of phytoplankton are investigated, with Chlorophyta mainly accounting for 38% of the total. The Shannon–Wiener index range is 1.047–2.974, with the higher values found in M30, M24, and M22.

A total of 72 zooplankton species are investigated, with rotifers accounting for 48% of the total. Rotifers and copepods dominate the majority of sites. The Shannon–Wiener index range is 0–2.271, with the higher values found in M5, M17, M28, and M30.

A total of 32 species of benthic animals are investigated, with gastropods mainly accounting for 37% of the total. The range of Shannon–Wiener index is 0–1.546, with the higher values found in M16 and M10.

A total of 27 species of fish are surveyed and classified into 8 orders and 12 families. Carps mainly account for 43% of the total. Shannon Weiner index range is 0–2.189, with the high distribution values found in M16, M23, and M24.

A total of 26 species of large aquatic plants are surveyed and classified under 23 families and 26 genera. Water-emerging plants mainly dominate with 18 species, accounting for 69.23% of the total. The Shannon–Wiener

Table 3 Description of water ecological function areas

ID	Region
1	Habitat disturbance area in water stress of middle Luanhe river
2	In the lower reaches of Chaobai river, the habitat destruction area of urban polluted main stream is affected by water stress
3	In the lower reaches of the Haihe river, the habitat destruction area of urban polluted main stream is affected by water stress
4	Tangshan urban watershed in the lower reaches of Jiyunhe river basin suffer from water stress and urban complex pollution of the main stream habitat
5	Habitat destruction area of Tianjin urban river basin in the lower reaches of Haihe river
6	Coastal wetland habitat conservation area is polluted by water stress from towns in the lower reaches of Hebei province
7	The water quantity in the lower reaches of north Haihe river stresses agriculture to pollute the habitat disturbance area of coastal wetlands
8	The lower reaches of Ziya river stress the agriculture pollution of the artificial river channel habitat destruction area

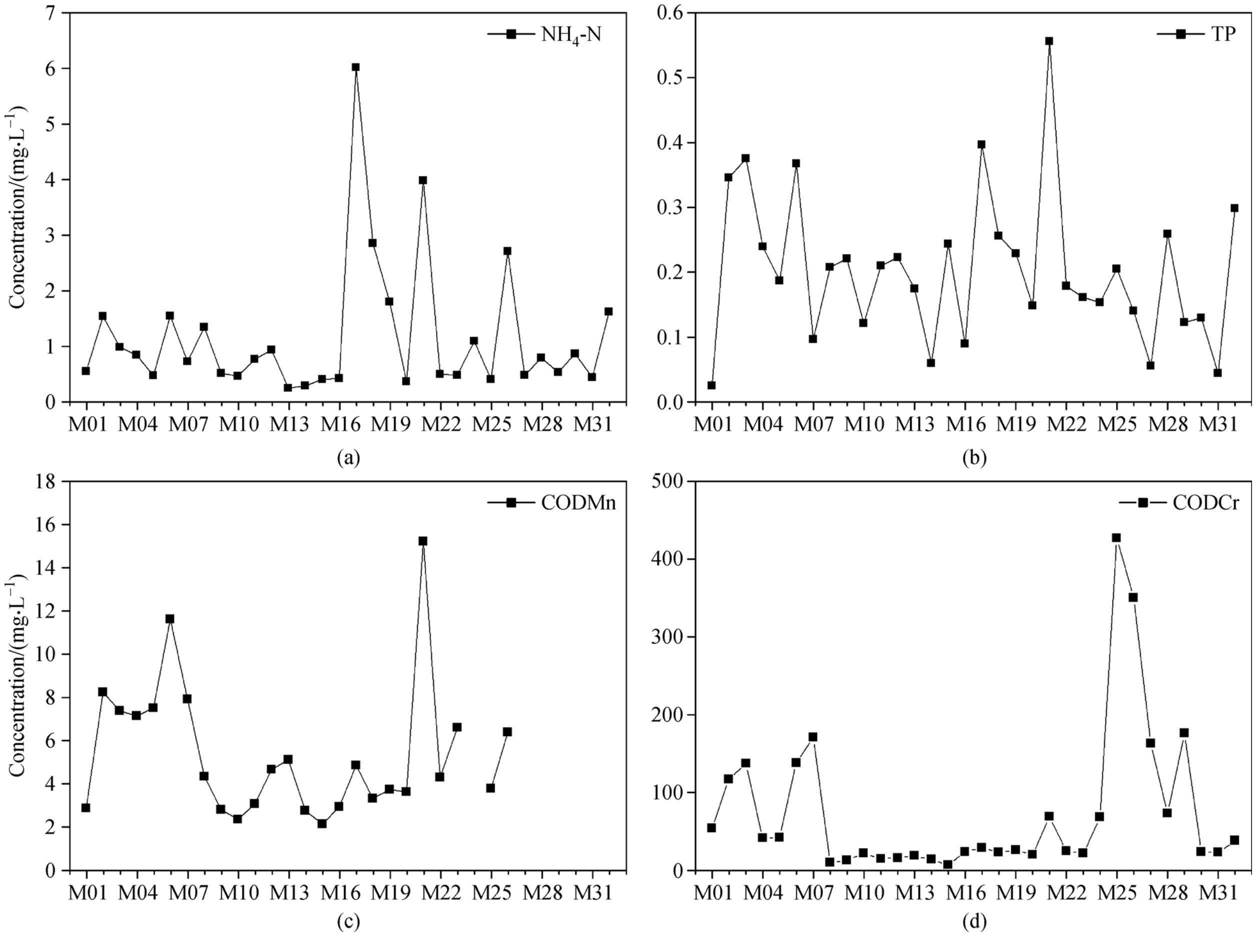

Fig. 3 Water quality of monitoring stations.

Index ranges 0–0.743, and the higher values are found in M12, M11, and M32.

A total of 82 species of herbs (including varieties, variants, and artificial plantings) (25 orders, 29 families, 71 genera), 14 species of vines (6 orders, 8 families, 13 genera), and 23 species of artificial trees (9 orders, 14 families, 20 genera) are investigated. The Shannon–Wiener index range is 0.095–0.998, with the higher values found in M23, M28, M31, and M32.

3.2.3 Comprehensive Pollution Index results

The results of the comprehensive evaluation of 32 rivers in Tianjin show a severe overall river pollution and a low rate of water function areas reaching the standard. Of the total sampling sites, 16 (50%) are heavily contaminated and 10 (31.3%) are moderately contaminated (Table 4). Chemical oxygen demand and ammonia nitrogen are the main causes of water pollution.

Table 4 Results of Comprehensive Pollution Index

Monitoring station	River	Longitude	Latitude	Comprehensive Pollution Index	
M01	Duliujian River	116.75	38.80	0.70	Mild contaminated
M02	Duliujian River	117.02	39.02	1.68	Mild contaminated
M03	Duliujian River	117.30	38.83	1.82	Heavily contaminated
M04	Duliujian River	117.16	38.92	1.13	Heavily contaminated
M05	Hai River	117.15	38.95	0.78	Moderately contaminated
M06	Duliujian River	117.56	38.76	1.98	Heavily contaminated
M07	Jiyun River	117.53	38.66	1.85	Heavily contaminated
M08	Jiyun River	117.53	38.66	1.24	Heavily contaminated
M09	Yongdingxin River	116.97	39.52	1.10	Heavily contaminated
M10	Yongdingxin River	117.17	39.59	0.87	Moderately contaminated
M11	Yongdingxin River	117.29	39.52	0.87	Moderately contaminated
M12	Yongdingxin River	117.18	39.45	1.16	Heavily contaminated
M13	Yongdingxin River	117.06	39.31	0.96	Moderately contaminated
M14	Jiyun River	117.40	39.78	0.79	Moderately contaminated
M15	Yongdingxin River	117.47	39.47	0.72	Moderately contaminated
M16	Duliujian River	116.92	39.05	0.73	Moderately contaminated
M17	Yongdingxin River	117.56	39.17	0.35	Good
M18	Yongdingxin River	117.40	39.22	1.14	Heavily contaminated
M19	Yongdingxin River	117.38	39.28	0.78	Moderately contaminated
M20	Jiyun River	117.75	39.28	0.95	Moderately contaminated
M21	Jiyun River	117.96	39.22	1.45	Heavily contaminated
M22	Jiyun River	117.73	39.13	1.03	Heavily contaminated
M23	Yongdingxin River	117.70	39.13	0.70	Mild contaminated
M24	Hai River	117.33	39.05	1.12	Heavily contaminated
M25	Hai River	117.71	38.99	2.34	Heavily contaminated
M26	Hai River	117.72	38.96	1.32	Heavily contaminated
M27	Duliujian River	117.21	38.78	1.44	Heavily contaminated
M28	Jiyun River	117.33	38.59	1.37	Heavily contaminated
M29	Duliujian River	117.52	38.76	1.27	Heavily contaminated
M30	Hai River	117.27	39.13	0.93	Moderately contaminated
M31	Hai River	117.19	39.15	0.48	Mild contaminated
M32	Duliujian River	117.13	39.09	1.24	Heavily contaminated

3.2.4 IEI evaluation results

The 25th quantile of the reference point IEI score distribution is used as the river "health" evaluation standard, which is divided into five levels: "healthy" ($\geqslant 3$), "sub-healthy" (2.55–3), "fair" (2.12–2.55), "poor" (2.01–2.12), and "very poor" (< 2.01). Table 5 shows that among all the sampling points, 6 (18.8%) are "healthy"; 9 (28.1%) are "sub-healthy"; 13 (40.6%) are "fair"; 2 (6.3%) are "poor"; 2 (6.3%) are "very poor." These results show the uneven distribution of health status of the different regions. The overall ecological statuses are good at the Haihe mainstream water system and the Ji Canal, fair at the Yongdingxin River system, and poor at the Duliujian River system.

3.3 Analysis of IEI and comprehensive pollution index based on water ecological function zones

The IEI evaluation reflects a comprehensive river health after long-term disturbance by human activities. The results show that the IEI has high correspondence with

Table 5 Results of Index of Ecological Integrity (IEI), relevant physicochemical and biological parameters

Monitoring station	Physical integrity			Chemical integrity				Biotic integrity							IEI	IEI Evaluation Results
	Conductivity	pH	Score	TN	TP	COD_{Mn}	Score	Phytoplankton	Zooplankton	Benthic fauna	Fish	Aquatic plants	Terrestrial plants	Index of Biotic Integrity		
M01	0.97	0.55	1.51	0.97	0.89	0.94	2.80	11.58	2.33	0.73	3.50	0.16	2.30	3.43	2.67	Sub-health
M02	0.96	0.33	1.29	0.43	0.68	0.53	1.64	10.18	2.33	0.95	3.50	3.47	1.39	3.64	2.33	Fair
M03	0.95	0.23	1.18	0.38	0.61	0.60	1.59	9.90	3.67	1.00	4.00	0.85	2.02	3.57	2.26	Fair
M04	0.97	0.12	1.09	0.61	0.70	0.62	1.93	8.11	2.33	0.99	3.50	0.73	10.58	4.37	2.65	Sub-health
M05	0.97	0.31	1.28	0.43	0.00	0.77	1.20	7.92	2.33	1.16	4.00	0.55	0.82	2.80	1.86	Very poor
M06	0.91	0.27	1.18	0.70	0.73	0.59	2.02	9.21	2.33	1.00	3.50	0.00	0.96	2.83	2.09	Poor
M07	0.79	0.44	1.23	0.40	0.54	0.28	1.21	12.01	1.00	1.00	4.00	0.55	0.97	3.26	2.03	Poor
M08	0.44	0.67	1.11	0.85	0.49	0.56	1.90	8.07	1.00	1.00	4.00	0.77	3.51	3.06	2.13	Fair
M09	0.99	0.75	1.74	0.64	0.30	0.95	1.89	8.10	1.00	1.13	3.50	1.22	1.72	2.78	2.20	Fair
M10	0.99	0.68	1.68	0.81	0.54	0.98	2.33	12.13	1.00	1.00	3.00	0.36	0.95	3.07	2.43	Fair
M11	0.99	0.40	1.40	0.66	0.66	0.93	2.25	16.39	2.33	0.98	3.00	2.88	0.89	4.41	2.86	Sub-health
M12	0.99	0.33	1.31	0.66	0.66	0.93	2.25	11.53	2.33	1.26	2.50	1.87	1.01	3.42	2.44	Fair
M13	0.99	0.60	1.58	0.64	0.44	0.81	1.88	4.79	2.33	1.30	4.00	2.64	2.13	2.86	2.19	Fair
M14	1.00	0.75	1.74	0.91	0.50	0.95	2.37	5.13	2.33	0.88	4.00	2.12	2.96	2.90	2.39	Fair
M15	0.99	0.36	1.35	0.60	0.74	1.00	2.34	11.38	2.33	0.89	4.00	4.83	2.78	4.37	2.86	Sub-health
M16	0.95	0.51	1.46	0.86	0.72	0.94	2.52	10.39	2.33	0.98	3.00	1.53	2.84	3.51	2.60	Sub-health
M17	0.98	0.85	1.83	0.35	0.01	0.79	1.15	25.57	2.33	0.97	3.00	5.30	1.48	6.44	3.47	Health
M18	0.98	0.76	1.74	0.58	0.61	0.91	2.10	5.52	2.33	0.99	3.00	3.69	3.34	3.15	2.41	Fair
M19	0.98	0.48	1.45	0.63	0.68	0.88	2.19	4.61	1.67	1.14	3.50	4.79	1.92	2.94	2.27	Fair
M20	0.99	0.67	1.66	0.76	0.47	0.89	2.12	12.10	1.67	0.99	3.50	7.52	2.36	4.69	3.01	Health
M21	0.43	0.57	1.00	0.08	0.60	0.00	0.68	11.38	2.33	1.00	4.50	0.00	1.20	3.40	1.86	Very poor
M22	0.98	1.09	2.07	0.71	0.48	0.84	2.02	17.83	2.33	1.00	3.50	2.94	5.32	5.49	3.42	Health
M23	0.97	0.50	1.48	0.74	0.62	0.66	2.02	16.61	2.33	0.99	4.50	3.33	4.54	5.38	3.20	Health
M24	0.99	0.72	1.71	0.75	0.78	0.00	1.53	17.51	2.33	0.96	4.00	0.74	1.45	4.50	2.77	Sub-health
M25	0.43	0.74	1.17	0.67	0.59	0.87	2.14	18.76	3.00	1.00	5.00	0.00	1.64	4.90	2.95	Sub-health
M26	0.58	0.85	1.44	0.77	0.21	0.68	1.66	12.07	1.00	1.00	4.00	0.00	1.50	3.26	2.23	Fair
M27	0.99	0.75	1.74	0.92	0.91	0.00	1.83	23.18	3.67	0.98	3.00	1.15	2.22	5.70	3.35	Health
M28	0.99	0.00	0.99	0.58	0.85	0.00	1.43	9.84	4.33	1.00	3.00	0.54	2.41	3.52	2.13	Fair
M29	0.98	0.61	1.59	0.80	0.87	0.00	1.67	7.82	3.67	1.00	4.50	0.00	1.63	3.10	2.22	Fair
M30	0.99	0.07	1.05	0.79	0.80	0.00	1.60	13.71	3.67	1.00	4.50	1.94	1.97	4.47	2.58	Sub-health
M31	0.99	0.75	1.74	0.51	0.72	0.00	1.23	25.19	3.67	0.90	3.50	0.30	2.67	6.04	3.30	Health
M32	0.98	0.40	1.38	0.93	0.93	0.00	1.86	12.27	3.67	1.30	4.50	0.09	1.84	3.95	2.55	Sub-health

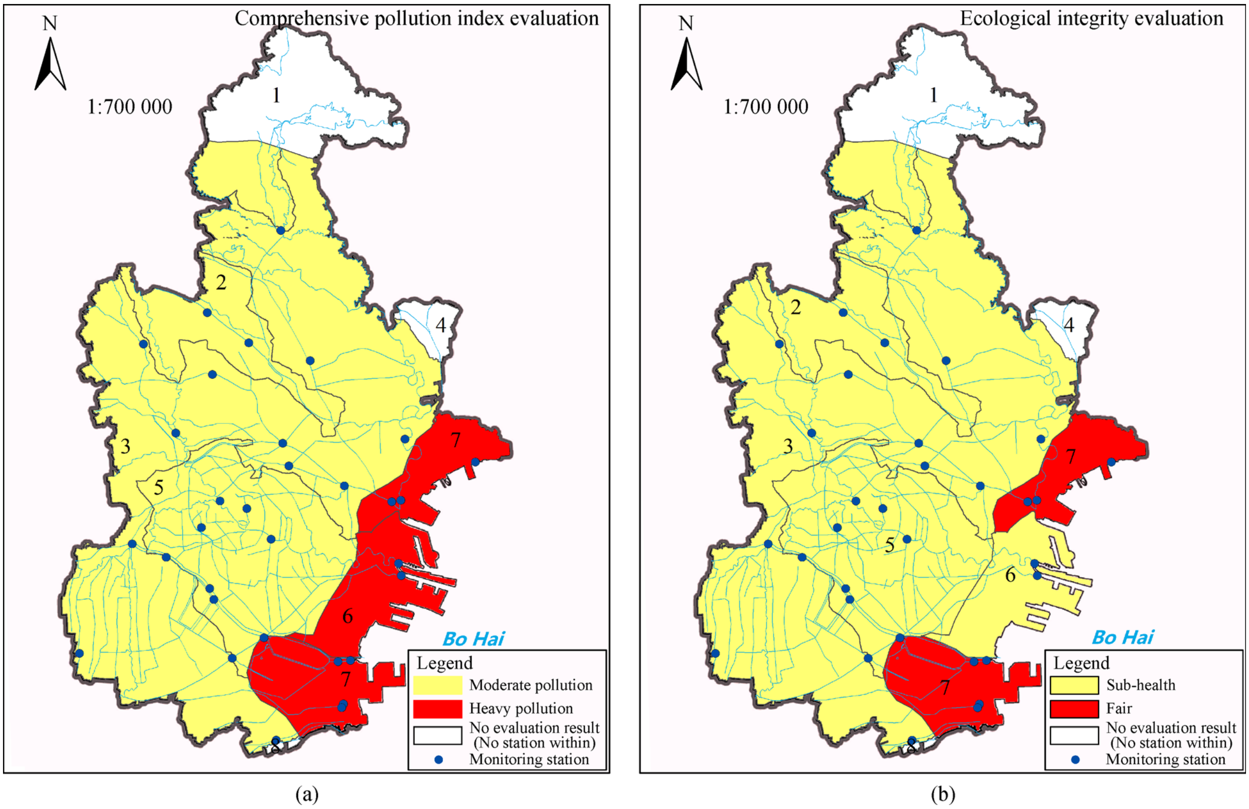

Fig. 4 (a) Comprehensive pollution evaluation and (b) index of ecological integrity evaluation based on water ecological function zones.

environmental factors (Fig. 4). Excessive ammonia nitrogen and permanganate index is the main reason for the water quality failure and the main factor affecting the ecological health of rivers in Tianjin. Thus, the IEI evaluation is a reasonable and feasible determinant of river health. Pearson correlation analysis results show that the IEI index is significantly correlated with permanganate index ($R = -0.453$; $P = 0.023 < 0.05$). Analysis results using BEST show that ammonia nitrogen is the best environmental parameter to explain the changes in IEI ($R_{ho} = 0.154$; $P = 0.02 < 0.05$) and those using RELATE show significant correlation between the biotic index and the environmental parameter matrices ($R_{ho} = 0.154$; $P = 0.034 < 0.05$).

4 Conclusions

In this study, 32 representative river sampling points in Tianjin are selected and evaluated in terms of comprehensive pollution and ecological health status. The evaluation is regarded as an important means and basis for river management and ecological restoration. The results show that:

1) Among all the river survey samples, 18.8% are "healthy", 28.1% are "sub-healthy", 40.6% are "fair", 6.3% are "poor", and 6.3% are "very poor". Thus, Tianjin has a fair overall river ecological health status, with the West banks better than the East. Significant spatial differences are likewise observed. Rivers with good ecological health are generally found in areas far from human activities or natural reserves, and are thus less disturbed. Rivers with poor ecological health are generally found near cultivated lands, residential areas, or river entrances, which are considerably disturbed by human activities. 2) Tianjin has a severe overall river pollution and low water functional area. Excessive ammonia nitrogen and permanganate index are the main reasons for the water quality failure and the main factor affecting the ecological health of rivers in Tianjin. Of the total sampling points, 16 (50%) are heavily contaminated and 10 (31.3%) are moderately contaminated. Excessive chemical oxygen demand and ammonia nitrogen are the main causes of water pollution. 3) The results show that the IEI has high correspondence with environmental factors. Correlation analysis shows that the IEI index is significantly correlated with permanganate index ($R = -0.453$; $P = 0.023 < 0.05$), ammonia nitrogen is the best environmental parameter to explain the changes in IEI ($R_{ho} = 0.154$; $P = 0.02 < 0.05$) and there are significant correlation between the biotic index and the environmental parameter matrices ($R_{ho} = 0.154$; $P = 0.034 < 0.05$).

These findings successfully reflect the environment pressure in the study area. The results indicate that the IEI evaluation is a reasonable and feasible determinant of the ecological health of rivers in Tianjin.

Acknowledgements This study was financially supported by the Major Science and Technology Program for Water Pollution Control and Treatment of China (No. 2018ZX07111002) and the Major Science and Technology Program for Water Pollution Control and Treatment of China (No. 2017ZX07107001). The authors express their sincere thanks for this support.

References

Barbour M T, Gerritsen J, Griffith G E, Frydenborg R, McCarron E, White J S, Bastian M L (1996). A framework for biological criteria for florida streams using benthic macroinvertebrates. J N Am Benthol Soc, 15(2): 185–211

Cairns J Jr, McCormick P V, Niederlehner B R (1993). A proposed framework for developing indicators of ecosystem health. Hydrobiologia, 263(1): 1–44

Chessman C B, Townsend A S (2010). Differing effects of catchment land use on water chemistry explain contrasting behaviour of a diatom index in tropical northern and temperate southern Australia. Ecol Indic, 10(3): 620–626

Dolédec S, Statzner B (2010). Responses of freshwater biota to human disturbances: contribution of J-NABS to developments in ecological integrity assessments. J N Am Benthol Soc, 29(1): 286–311

European Commission (2000). Directive 2000/60/EC of the European Parliament and of the Council-establishing a framework for community action in the field of water policy

Fore S L, Grafe C (2002). Using diatoms to assess the biological condition of large rivers in Idaho (USA). Freshw Biol, 47(10): 2015–2037

Gannon R W, Osmond D L, Humenik F J, Gale J A, Spooner J (1996). Goal-oriented agricultural water quality legislation. Water Resour Bull, 32(3): 437–450

Han J, Zhang J, Song M M, Yin X W (2018). Structure and seasonal changes of fish functional groups in Jinan region. Res Environ Sci, 31 (9): 1537–1544 (in Chinese)

Hughes R M, Larsen D P (1988). Ecoregions: an approach to surface water protection. J Water Pollut Control Fed, 60: 486–493

Hughes R M, Larsen D P, Omernik J M (1986). Regional reference sites: A method for assessing stream potentials. Environ Manage, 10(5): 629–635

Hughes R, Whittier T, Rohm C, Larsen D P (1990). A regional framework for establishing recovery criteria. Environ Manage, 14(5): 673–683

Karr J R (1981). Assessment of biotic integrity using fish communities. Fisheries (Bethesda, Md), 6(6): 21–27

Karr J R (1999). Defining and measuring river health. Freshw Biol, 41 (2): 221–234

Kong F Q, Cui W Y, Zhou X S (2018). Health assessment on Yongding River watershed using benthic index of biotic integrity (B-IBI). Ecol Environ, 27(3): 550–555 (in Chinese)

Ladson A R, White I J, Doolan J A, Finlayson B L, Hart B T, Lake P S, Tilleard J W (1999). Development and testing of an index of stream condition for waterway management in Australia. Freshw Biol, 41 (2): 453–468

MacKay H M, Roux D J, Ashton P J, van Vliet H R, Jooste S (1995). The development of South African water quality guidelines for the natural aquatic environment. Water Sci Technol, 32(5-6): 293–299

Maxted J R, Barbour M T, Gerritsen J, Poretti V, Primrose N, Silvia A, Penrose D, Renfrow R (2000). Assessment framework for mid-Atlantic coastal plain streams using benthic macroinvertebrates. J N Am Benthol Soc, 19(1): 128–144

Meyer J L (1997). Stream health: incorporating the human dimension to advance stream ecology. J N Am Benthol Soc, 16(2): 439–447

Mondy C P, Villeneuve B, Archaimbault V, Usseglio-Polatera P (2012). A new macroinvertebrate-based multimetric index (I2M2) to evaluate Ecological quality of french wadeable streamsful filling the WFD demands: a taxonomical and trait approach. Ecol Indic, 18(4): 452–467

Norris R H, Hawkins C P (2000). Monitoring river health. Hydrobiologia, 435(1/3): 5–17

Norris R H, Thoms M C (1999). What is river health? Freshw Biol, 41 (2): 197–209

Omernik J M (1987). Ecoregions of the conterminous United States (Map Supplement). Ann Assoc Am Geogr, 77(1): 118–125

Omernik J M, Bailey R G (1997). Distinguishing between watershed and ecoregion. J Am Water Resour Assoc, 33(5): 935–949

Prygiel J, Coste M (1993). The assessment of water quality in the Artois-Picardie water basin (France) by the use of diatom indices. Hydrobiologia, 269–270(1): 343–349

Qu X D, Liu Z G, Zhang Y (2012). Discussion on the standardized method of reference sites selection for establishing the Benthic-Index of biotic integrity. Acta Ecol Sin, 32(15): 4661–4672 (in Chinese)

Research group of major science, technology program for water pollution control and treatment of China (2014). Technical guide for monitoring the quality of river water ecological environment. Available at China National Environmental Monitoring Centre website

Robert A, John F, Kim J, Nicholas A (2006). Using multiple indicators to evaluate the ecological integrity of a coastal plain stream system. Ecol Indic, 6(4): 644–663

Roland S, Martin T D, Roland P, Josef W (2002). Ecological integrity: Concept, assessment, evaluation: the traunsee case. Water Air Soil Pollut Focus, 2(4): 249–261

Simpson J C, Norris R H (2000). Biological assessment of river quality: development of AusRivAS models and outputs. In: Wright J F, Sutcliffe D W, Furse M T, eds. Assessing the Biological Quality of Freshwaters: RIVPACS and Other Techniques: 125–142

Steedman R J (1994). Ecosystem health as a management goal. J N Am Benthol Soc, 13(4): 605–610

Virtanen L K, Soininen J (2016). Temporal variation in community-environment relationships and stream classifications in benthic diatoms: implications for bioassessment. Limnologica, 58: 11–19

Walsh C J (2000). Urban impacts on the ecology of receiving waters: a framework for assessment, conservation and restoration. Hydrobiologia, 431(2/3): 107–114

Zhang J, Su H, Sheng C H, Chong X Y, Yin X W, Xu Z X, Zhang Y (2019). Construction of an evaluation system to assess the ecosystem integrity of the Hun-Tai River. Res Environ Sci, 9: 29 (in Chinese)

Zhao Y, Cao N, Wang Y Y, Sun W C (2016). Evaluating the health condition of the river basin water system in China’s central plains economic region using an analytic hierarchy process. Res Environ Sci, 29(6): 936–944 (in Chinese)

Zheng B H, Zhang Y, Li Y B (2007). Study of indicators and methods for river habitat assessment of Liao River basin. Acta Scientiae Circumstantiae, 27(6): 928–936 (in Chinese)