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WATER ECOSYSTEM HEALTH EVALUATION AND INFLUENCING FACTORS ANALYSIS OF AN URBAN RIVER: A CASE STUDY AT BEIYUNHE RIVER, NORTHERN CHINA

Evaluación de la salud del ecosistema acuático y análisis de factores de influencia de un río urbano: estudio de caso en el río Beiyunhe, norte de China

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Key words: comprehensive pollution index method, habitat quality, dam barrier, diffused pollution.

ABSTRACT

The Beiyunhe River is a typical urban river in northern China, and the health status of its ecosystem is degraded by urbanization. To evaluate this health status, a survey was performed throughout the basin. Thirteen indexes were selected to construct an ecosystem health evaluation system, and a composite index method was used to quantify the Beiyunhe River's ecosystem health. Redundancy analysis (RDA) was used to detect the key factors influencing ecosystem health. The results showed that the river's health status was mostly moderate: of the 38 surveyed points, the health status of 10% was Good, 47% was Average, 40% was Poor, and 3% was Very Poor. The upper and middle reaches were in better health than the lower reaches, and the main stream health was better than the tributaries. Among the tributaries, Bahe River (upper and middle reaches) had the best health status, whereas Fenghe River (lower reaches) had the worst. RDA showed that the ratio of hardening of the river, number of water-blocking structures (gates and dams), and population density in the catchment area were the key factors affecting the health of the Beiyunhe River ecosystem. This study can be used as a reference for the evaluation of the health of urban river ecosystems.

Palabras clave: método general del índice de contaminación, calidad del hábitat, dique de contención, contaminación difusa.

RESUMEN

El río Beiyunhe es un típico río urbano en el norte de China y el estado de salud de su ecosistema se ha degradado por la urbanización. Para evaluar dicho estado de salud se realizó una investigación en toda la cuenca. Se seleccionaron trece índices para construir un sistema de evaluación y se utilizó un método de índice compuesto para cuantificar la salud del ecosistema del río Beiyunhe. Se utilizó el análisis de redundancia (AR) para detectar los factores clave que influyen en la salud del ecosistema. Los resultados mostraron que el estado de salud del río fue en general moderado: de los 38 puntos analizados, el estado de salud del 10 % fue bueno, el 47 % promedio, el 40 % pobre y el 3 % muy pobre. Los tramos superior y medio tienen mejor salud que los tramos inferiores, y la salud de la corriente principal es mejor que la de los afluentes. Entre los afluentes, el río Bahe (tramos superior y medio) tuvo el mejor estado de salud, mientras que el río Fenghe (tramos inferiores) el peor. El AR mostró que la proporción de endurecimiento del río, el número de estructuras de bloqueo de agua (puertas y presas) y la densidad de la población en la zona de captación son los factores clave que afectan la salud del ecosistema del río Beiyunhe. Este estudio puede utilizarse como referencia para la evaluación de la salud de los ecosistemas fluviales urbanos.

INTRODUCTION

Since the 1970s, the survival of aquatic organisms globally has been threatened by water pollution and loss of freshwater ecosystems such as rivers and lakes (Zhao et al. 2019, Ding et al. 2020) This issue led to the concept of measuring river health. The Clean Water Act of the United States defines river health as the ability of water bodies to restore and maintain their chemical, physical, and biological integrity (FWPCA 1972). Although this definition has not been uniformly followed, most researchers believe that river health should regard the stability, elasticity, resistance, durability, and resilience of water bodies as important characteristics (Shou-Hua and Xin 2008).

As early as the 1980s, countries began to evaluate the health of river ecosystems using a single hydrochemical index and then moved to a comprehensive evaluation system (Mamun and An 2020) covering multiple indicators such as hydrology, hydrochemistry, aquatic organisms, and habitat. Concurrently, researchers outside China constructed a series of aquatic ecosystem health assessment methods, such as the indicator index, a specific biological integrity index (Dolédec and Statzner 2008, Smith et al. 2010, Mamun and An 2020), and other single index assessments, as well as comprehensive assessment methods, including a multi-species biological integrity index, and a multi-index comprehensive evaluation system (Petesse et al. 2016, Zhao et al 2019). In addition, Friend and Rapport (cited in Li et al. 2019) proposed the pressure-state-response evaluation model (Li et al. 2019), from which the driving force-pressure-state-influence-response and driving force-state-response models were derived. The vitality-organization-resilience model (Zhao et al. 2018) based on the Costanza Health Index, is also widely recognized. After much discussion and research, it was gradually realized that river biological communities have the ability to integrate various chemical, biological, and physical effects on different time scales (Liu et al. 2019). Therefore, a comprehensive assessment method for watersheds with aquatic organisms as the core and considering elements such as hydrology, hydrochemistry, physical habitat, and landscape was developed.

The research on river ecosystem health evaluation in China started late. At the beginning of the 21st century, Chinese researchers began to discuss the concept and connotation of river health (Luo et al. 2018, Wenqi 2018) and carried out a series of studies around the health assessment of river elements such as the physical, chemical, and hydrological properties of water bodies, aquatic organisms, riverbank habitat quality, and human modifications (i.e., hydrological connectivity, channel shape, and hydraulic structures). As the aspects of river ecological health become clearer, specific evaluation indexes are being proposed and improved, and evaluations using comprehensive indexes are also being developed (Mueller et al. 2014, Xue et al. 2020). Zhang et al. (2019) for instance, used indicators of water physical and chemical content, nutrients, algae, macrobenthos, and fish to evaluate the health of 10 key watersheds (Songhua, Liaohe, Haihe, Huaihe, Heihe, Dongjiang, Taihu, Chaohu, Dianchi, and Erhai Rivers) in China and provided technical support for the national aquatic ecosystem health evaluation.

There is a close relationship between urban rivers and human activities. On the one hand, urban development depends on rivers to provide various service functions. On the other hand, urban development has a significant impact on river hydrology, water quality, the water environment, and water ecology (Pan et al. 2015, Zaharia et al. 2016). Continuing urbanization increases the use of water resources and changes the natural ecological characteristics of urban rivers; this is manifested by changes in river hydrology, increases in the number of river-blocking structures (e.g., gates, dams, and bridges), hardening of river courses, increases in water pollution, and changes in land use patterns in river basins. These modifications have led to the continuing destruction of aquatic ecology and habitats, the sharp decline of aquatic species, and the degradation of aquatic ecosystems (Liu et al. 2018, Zhang et al. 2019, Deng et al. 2020). The aquatic ecosystems of urban rivers should not only provide the ecological services required by nature and humans, but also maintain the integrity, stability, and sustainability of the aquatic ecosystem itself (Xia et al. 2010, Wang et al. 2017). A healthy urban river ecosystem needs to be the result of highly coordinated human development and ecological protection (Zhang et al. 2017). Since the concept of river ecosystem health was proposed, the research on urban rivers has focused on water quality and environmental quality assessment and the impact of landscape pattern changes on the ecological risk to river water bodies and aquatic organisms. Relatively fewer studies have focused on the health of urban river ecosystems. In terms of urban river ecosystem health, Zhao and Yang (Zhao and Yang 2005) established an evaluation index system containing five elements (water quantity, water quality, aquatic organisms, physical structure, and riparian zone) and conducted preliminary research evaluating the health of urban river ecosystems. Based on the ecosystem health theory, Zhang et al. (2005) conducted a health evaluation of the vitality, resilience, and organizational structure of urban rivers. Yang et al. (2008), based on the uncertainty of factors in the urban river health evaluation index system, selected indexes for ecological characteristics, overall functions, and social environmental impacts to build an urban river ecosystem health evaluation index system.

At present, China's water environment management is gradually changing from traditional pollution control to watershed ecosystem health management. Scientifically determining the ecological health status of the Beiyunhe River and identifying the main influencing factors is of great significance for constructing a watershed zoning management model that aims to maintain the river's health. In this context, this study considered the problems facing urban river aquatic ecosystems and river characteristics, built an aquatic ecosystem health evaluation system that conformed to the characteristics of urban rivers, and identified and analyzed the factors that affected the health of the Beiyunhe River aquatic ecosystem.

MATERIALS AND METHODS

Study area overview

The Beiyunhe River (115º49′–117º14′ E, 39º11′–40º2′ N) is a first-class tributary of the Haihe River basin. It originates in the Changping District of Beijing and flows through Beijing, Hebei, and Tianjin (**Fig. 1**). The total length of the main stream of the

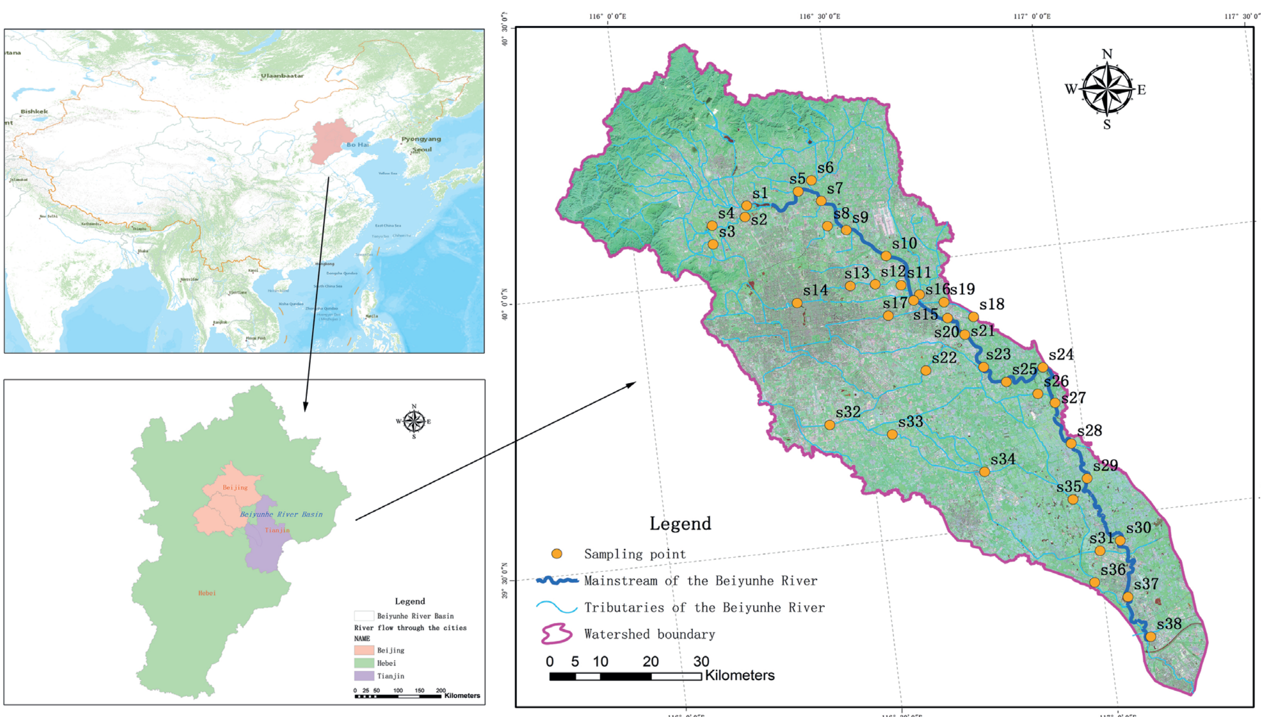

Fig. 1. Map of the sampling points in the Beiyunhe River watershed.

Beiyunhe River is 90.3 km. The river basin has a complicated water system structure and many tributaries. The total population around the river basin is approximately 15.25 million, and built-up land comprises 44.4% of the basin. There are over 80 dams, including nine gate dams and five rubber dams. The Beiyunhe River is a typical multi-dammed city river in northern China (Zhang et al. 2019).

A systematic survey and sampling of the river ecosystem of the Beiyunhe River basin was conducted in June 2019, based on the characteristics of the Beiyunhe River basin, such as the high degree of urbanization and large number of gates and dams in the river channel. In total, 38 typical and representative sites were sampled, including 16 points on the main stream and 22 points on the tributaries, covering all primary tributaries and some secondary tributaries such as the Dongsha, Nansha, Beisha, Tonghui, Liangshui, and Bahe Rivers.

Field sampling and sample analysis

The survey and monitoring samples included the river's hydrological situation, shape, habitat, and water ecology and water quality.

Water quality survey: an EXO-YSI portable multi-parameter water quality monitor (USA) was used for on-site measurement of water quality at sampling points. Data were collected on indicators such as water temperature (WT), dissolved oxygen (DO), conductivity (Cond), and pH. A polyethylene plastic bottle was used to collect 2-L water samples, which were placed in a low-temperature incubator. Within 48 h, the water sample was tested for permanganate index (CODMN), biochemical oxygen demand (BOD_5), suspended matter (TSS), hardness (WH), calcium (Ca), magnesium (Mg), copper (Cu), potassium (K), chromium (Cr), sulfate (SO_4^{2-}), chlorine (Cl), phosphate (PO_4^{3}), nitrate nitrogen ($NO3^-$), nitrite nitrogen ($NO2^-$), ammonia nitrogen (NH_4^+-N), total nitrogen (TN), and total phosphorus (TP). The storage, sampling, and determination methods for the water quality indicators followed Environmental Quality Standards for Surface Water (GB3838-2002) and Water and Wastewater Monitoring and Analysis Methods.

Phytoplankton: Three to five representative habitats were selected within 100 m upstream and downstream of each sampling point. A plexiglass water collector was used to collect 1–2 L of water (the volume was increased when phytoplankton density was too low). Immediately after collection, Luge reagent was added for fixation, and the collected samples were identified under a laboratory microscope.

Zooplankton: The sampling stratification was determined according to the water depth of the sampling point. At a water depth of 5 m, sampling was performed at 0.5 m, 1 m, 2 m, 3 m, and 4 m below the water surface. At a water depth of under 2 m, sampling was performed only at a depth of approximately 0.5 m. A total of 2 L of water was obtained at each sampling point; one bottle of 1L was kept for in vivo observation, whereas the others were fixed in formaldehyde solution and taken to the laboratory for identification.

Zoobenthos: A D-type hand-dip net was used to collect organisms (approximately 6 m^2) from a 20-m transect at the sampling point, in 3–5 habitats. The collected organisms were stored in containers or sealed plastic bags, covered with 70% ethanol, and taken to the laboratory for identification and analysis.

Vascular plants: Three to five 1 × 1-m plots were selected according to habitat conditions, and the emergent plants growing on the shore were directly harvested. Floating leaf plants and submerged plants were sampled using aquatic plant collectors. Floating plants were collected using a handle net (10-mm mesh).

The following principles were followed to build an aquatic ecosystem health evaluation index system for the study area: 1) comprehensiveness, 2) operability, and 3) independent priority (Song et al. 2020).

Initial selection of indicators: According to the three principles, 21 indicators in five categories were preliminarily screened as candidate evaluation indicators (**Table I**).

Ten environmental impact factors were selected from two watershed and river levels. The ecological significance and impact of each environmental impact factor are shown in **table II**.

ANALYSIS

The Shannon-Wiener diversity index was calculated for each monitoring point. Principal component and Spearman rank correlation analyses were used to screen the candidate indicators, and the entropy weight method was used to determine the weight of each indicator. The analyses were performed in SPSS 19.0 of IBM and R software, which was developed at Bell Laboratories by John Chambers and colleagues. The Kriging interpolation method in ArcGIS is used to make spatial analysis of the aquatic ecosystem health assessment of the Beiyunhe River basin. The factors influencing aquatic ecosystem health were

TABLE I. SELECTION OF PRIMARY INDICATORS OF AQUATIC ECOSYSTEM HEALTH ASSESSMENT.

Indicator type	Index	Indicator type	Index
Hydrological indicators	Water temperature (WT)	Physical and chemical water indicators	Conductivity (Cond)
	Multi-year average runoff (AVR)		Total phosphorus (TP)
Biological index	Phytoplankton Shannon-Wiener Diversity Index (PDI)		Total nitrogen (TN)
			Dissolved oxygen (DO)
	Zooplankton Shannon-Wiener Diversity Index (ZDI)		pH
			Suspended matter (TSS)
	Zoobenthos Shannon-Wiener Diversity Index (BDI)		COD_{Mn}
			BOD_5
	Vascular Plant Shannon-Wiener Diversity Index (VDI)		Ammonia nitrogen (NH_4-N)
			Sulfate (SO_4^-2)
			Phosphate (PO_4^3)
Connectivity index	River longitudinal connectivity (RC)		Nitrate nitrogen (NO_3-N)
Habitat indicators	River Habitat Quality Index (QHEI)		Nitrous nitrogen (NO_2-N)

TABLE II. MAIN FACTORS INFLUENCING AQUATIC ECOSYSTEM HEALTH AND THEIR ECOLOGICAL SIGNIFICANCE.

Number	Impact factor	Ecological significance
1	Monthly average flow (MF)	Influences the movement of river material energy and habitat composition, affects the aquatic life process
2	Runoff depth in catchment area (RD)	Reflects the spatial differentiation characteristics of water resources in the catchment area and affects the circulation of biological material and the spatial distribution pattern of the aquatic ecosystem
3	River slope (RRD)	Reflects the stability of river slopes, habitat changes such as deep pools and shoals, and river hydrodynamic conditions
4	River hardening ratio (RHR)	Reflects the characteristics of urban rivers and affects the habitat and species distribution of aquatic organisms
5	Number of water-blocking structures (gates, dams, etc.) (NWBS)	Reflects the characteristics of urban rivers, affects the river hydrodynamic conditions, the transport and transformation of material energy, and affects the aquatic ecosystem process
6	Number of sewage outlets (NSO)	Reflects the characteristics of urban rivers and affects river water environment and aquatic habitat quality
7	Water Quality Pollution Index (WQPI)	Comprehensive reflection of water environment pollution characteristics and water quality pressure of river bodies
8	Forest and grassland area ratio (FAR)	Reflects the characteristics of the natural ecosystem of the catchment area, affects the material cycle and water conservation capacity
9	Construction land ratio (CAR)	Reflects the hardening characteristics of the underlying surface of the catchment area, affecting the hydrological cycle and runoff process
10	Watershed population density (WPD)	Characterizes urban rivers in the catchment area, reflecting the pressure of disturbances caused by human activities in the surrounding area

Note: The data source years of ten environmental impact factors are all in 2019. Among them, MF's data comes from China Hydrological Yearbook. The value of RD is rainfall divided by watershed area, and the rainfall comes from China Hydrological Yearbook. RRD's data comes from DEM data of 12.5m. WPD's data comes from China Statistical Yearbook. Other environmental impact factors' data come from remote sensing image data.

evaluated with a redundancy analysis (RDA) using the 'vegan' package (Wood 2003, Marra et al. 2011) in R.

River longitudinal connectivity: Hydraulic structures such as sluice dams and overflow weirs block the vertical connectivity of the river (Zhao et al. 2010), causing changes in the river's hydrology and seriously impeding material exchange, energy flow, and information transmission within the river; these are important for the structure and function of the aquatic ecosystem. Therefore, the ratio between the number of hydraulic structures in the river basin and the length of the upstream river was used to reflect the longitudinal connectivity of the river as follows:

$$RC = \frac{Ti}{Li},\ i = 1,2,\cdots,n \tag{1}$$

where RC is the vertical connectivity of the river (in km), Ti is the number of breakpoints in the channel upstream of the ith sampling point, and Li is the length of the channel upstream of the ith sampling point. The larger the RC, the worse the vertical connectivity of the river, and vice-versa.

Water ecological health composite index: After obtaining the weight of each evaluation index by using the entropy weight method, the water ecological health composite index (WEHCI) was calculated using the water ecological health evaluation index system for Beiyunhe basin as follows:

$$WEHCI = \sum_{i=1}^{n} (Wi \times li) \tag{2}$$

where the value of $WEHCI$ is 0–1, Wi is the weight value of the ith evaluation index in the composite evaluation index system (0–1), and Ii is the normalized value of the ith evaluation index (0–1). The greater the value of $WEHCI$, the better the aquatic health status, and vice-versa.

At present, there is no unified standard for the classification of river ecological health. Based on the characteristics of the aquatic ecosystem in the Beiyunhe basin, five health grades were determined according to the health scores, namely Excellent (0.8-1.0), Good (0.6-0.8), Average (0.4-0.6), Poor (0.2-0.4), and Very Poor (0-0.2).

Identification of influencing factors: To further identify the factors that influence the health of the aquatic ecosystem of the Beiyunhe River, a quantitative analysis of aquatic ecosystem health and environmental factors was carried out using the correspondence analysis method in a multivariate direct gradient analysis.

RESULTS

Selection of indicators

Principal component analysis among primary indicators: Seven principal components were extracted using the evaluation method. The candidate index factors were screened according to the load value > 0.55 (Gu et al. 2018), resulting in the selection of 15 evaluation indexes (**Table III**).

Correlation analysis between indicators: The index correlation analysis heat map shows that nitrate nitrogen had a significant positive correlation with total nitrogen; thus, to reduce redundancy, only total nitrogen was retained (**Fig. 2**). Suspended matter and sulfate also had a significant positive correlation, and similarly suspended matter was retained. The longitudinal connectivity index was correlated with the multi-year average runoff index; however, as they belong to different index layers, both values were retained. None of the biological and habitat quality indicators and the other types of indicators had a significant correlation, so they were all retained.

The correlation analysis allowed the selection of 13 indicators among the physical, chemical, hydrological, connectivity, biological, and habitat quality indicators for the elaboration of the Beiyunhe River aquatic ecosystem health assessment indicator system. The 13 selected indicators are pH,Cond,COD_{Mn},BOD_5,NH_4-N,TN,TP,WT,PDI,ZDI,QHEI,RC and AVR. The descriptive statistical results of these indicators are counted (**Table IV**).

Determination of evaluation index weight

According to the entropy weight method, the order of the index weights was: Hydrological index > Connectivity index > Biological index > Water physical and chemical index > Habitat quality index (**Table V**). The longitudinal connectivity index had the highest weight (0.252), followed by the multi-year average runoff hydrological index (0.238) (**Fig. 3**). The indexes with relatively small weights were pH, conductivity, and total nitrogen.

The multicollinearity test of 13 indicators was carried out by statistical VIF (Variance inflation factor) values, and the VIF values of 13 indicators were all less than 10, which indicated that there was no multicollinearity among these 13 indicators. Statistical results of VIF values of 13 selected indicators are IN **table VI**.

Evaluation of aquatic ecosystem health

The results of the aquatic ecosystem health surveys (**Fig. 4a**) showed no Excellent evaluation among

TABLE III. PRINCIPAL COMPONENT ANALYSIS RESULTS OF CANDIDATE INDICATORS FOR AQUATIC ECOLOGICAL HEALTH ASSESSMENT OF THE BEIYUNHE RIVER.

Candidate evaluation index	Components						
	1	2	3	4	5	6	7
pH	–0.01	–0.01	**–0.84**	0.00	–0.03	0.26	0.06
DO	0.48	0.45	–0.51	–0.13	0.16	–0.08	0.19
Cond	–0.44	0.07	0.29	**0.55**	0.35	0.21	0.00
TSS	0.18	0.29	0.32	0.10	–0.50	–0.04	–0.19
COD_{Mn}	**–0.66**	–0.05	0.50	–0.14	0.21	–0.12	0.15
BOD_5	0.22	**0.74**	–0.23	0.03	–0.03	0.12	–0.01
SO_4^{2+}	–0.32	0.54	0.26	**0.62**	0.23	0.09	0.00
Phosphate	–0.34	–0.36	–0.15	0.02	0.40	–0.19	–0.49
NO_4^{2-}	**0.77**	0.09	0.06	0.30	0.24	–0.20	0.27
NO_3^-	0.46	–0.13	0.38	0.45	–0.35	0.15	–0.24
NH_4-N	–0.25	–0.27	0.05	0.43	–0.03	–0.20	**0.66**
TN	**0.63**	–0.25	0.14	0.35	0.52	0.10	0.07
TP	–0.06	–0.46	–0.14	–0.23	**0.58**	0.36	–0.17
WT	–0.53	**0.63**	0.04	–0.08	0.03	0.08	–0.08
PDI	0.21	–0.05	–0.02	0.34	–0.16	**0.77**	–0.18
ZDI	**–0.60**	0.25	–0.08	–0.13	–0.21	0.38	0.24
BDI	–0.21	0.20	–0.50	0.07	0.12	0.03	0.09
VDI	0.14	–0.49	0.31	–0.51	–0.19	0.07	0.06
QHEI	0.16	–0.21	0.33	–0.38	0.07	**0.55**	0.45
RC	0.25	**0.58**	0.40	–0.43	0.21	0.04	–0.01
AVR	0.28	**0.61**	0.36	–0.40	0.37	0.03	–0.08

Note: The evaluation indicators selected are shown in bold with their corresponding load values. See **Table I** for an explanation of the variables.

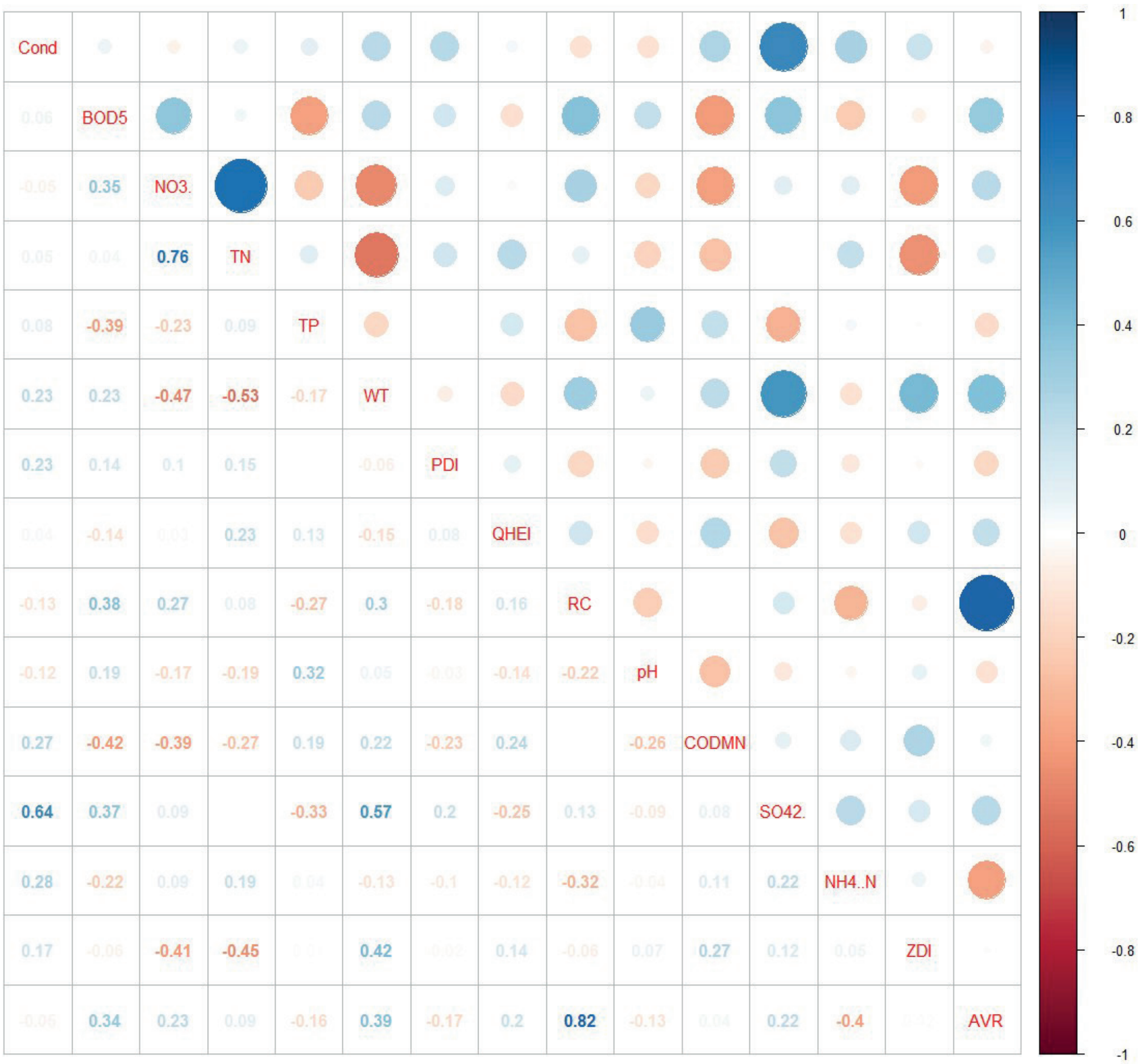

Fig. 2. Correlation analysis heat map of candidate indicators for the assessment of aquatic ecological health in the Beiyunhe River. See **Table I** for an explanation of the variables.

TABLE IV. DESCRIPTIVE STATISTICAL RESULTS OF 13 INDICATORS OF ESTABLISHING THE BEIYUNHE RIVER AQUATIC ECOSYSTEM HEALTH ASSESSMENT INDICATOR SYSTEM.

	Unit	Range	Minimum value	Maximum value	Mean value	Standard deviation
pH		2.70	6.01	8.71	7.36	0.47
Cond	mS/m	820	591	1411	905	190
COD_{Mn}	mg/L	24.26	3.73	27.99	10.48	5.65
BOD_5	mg/L	5.91	0.06	5.97	1.37	1.33
NH_4-N	mg/L	2.12	0.29	2.41	0.85	0.41
TN	mg/L	10.35	0.90	11.25	4.27	2.45
TP	mg/L	0.54	0.42	0.96	0.57	0.12
WT	ºC	13.14	21.62	34.76	27.76	2.70
PDI		3.08	0.54	3.62	2.56	0.73
ZDI		0.46	0.00	0.46	0.21	0.17
QHEI		52	89	141	111	12
RC		0.56	0.00	0.56	0.15	0.15
AVR	$100MBm^3$	6.65	0.24	6.88	3.39	2.69

TABLE V. WEIGHTS OF THE EVALUATION INDICATORS.

Indicator type	Index	Weight	Indicator type	Index	Weight
Hydrological index 0.284	WT	0.046	Physical and chemical water indicators 0.173	COD_{Mn}	0.032
	AVR	0.238		Cond	0.020
Biological index 0.209	PDI	0.049		pH	0.015
	ZDI	0.160		BOD_5	0.032
				TP	0.023
Connectivity index 0.252	RC	0.252		TN	0.023
Habitat quality index 0.082	QHEI	0.082		NH_4-N	0.028

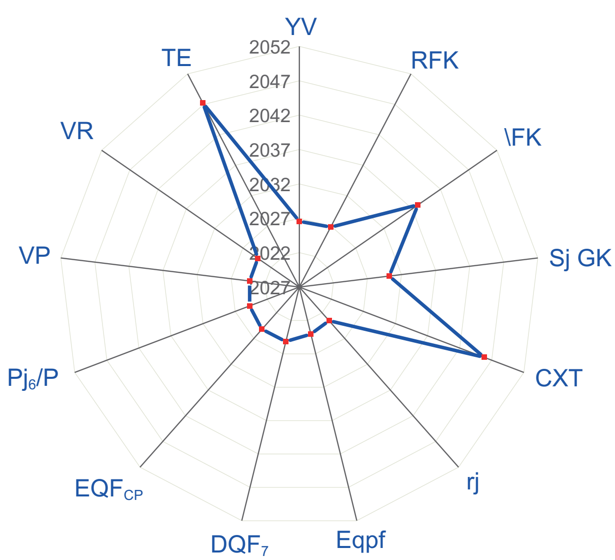

Fig. 3. Radar chart of each evaluation index weight.

TABLE VI. THE VIF VALUES OF 13 SELECTED INDICATORS.

	COD	Cond	pH	BOD5	TP	TN	NH_4-N	WT	AVR	PDI	ZDI	RC	QHEI
VIF	2.64	1.83	1.72	1.73	1.63	2.56	1.77	2.07	4.31	1.56	1.84	3.12	1.79

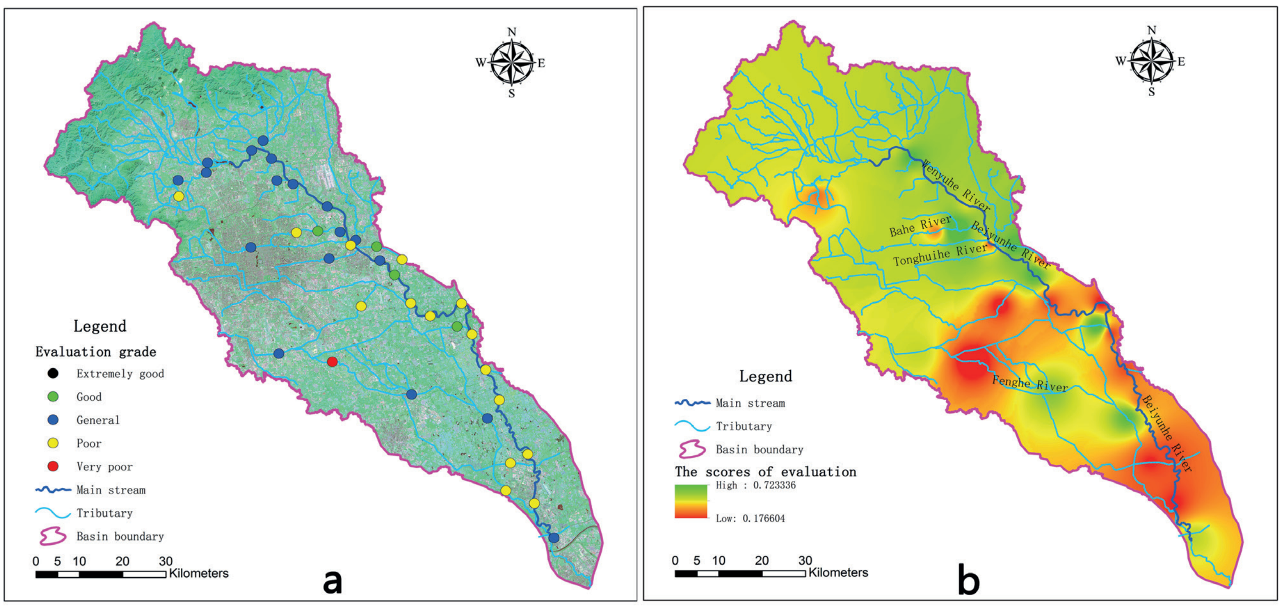

Fig. 4. Results of the evaluation of aquatic ecosystem health. a: Results per sampling point; b: Results of the spatial evaluation.

the sampling points. Four points were rated as Good (10.53%), eighteen as Average (47.36%), fifteen as Poor (39.47%), and one as Very Poor (2.63%). The above indicates that the overall health status of the Beiyunhe River ecosystem is average. The WEHCI was higher for the middle and upper reaches of the river than the lower reaches, and the WEHCI for the main stream was relatively higher than that of the tributaries. Among the latter, the highest WEHCI score (s12) was found for the main stream of the Bahe River, whereas the lowest (s33) was found for the section of Fenghe River in Shaduiying Village. The spatial assessment analysis (**Fig. 4b**) indicated that the aquatic ecosystem health assessment values of the Wenyu River and upstream Beiyunhe River were higher than those of the downstream Beiyunhe River. In addition, the aquatic ecosystems of the tributary Nansha, Fenggang Jianhe, Longhe, Fenghe, and Beijing Paiwu Rivers were relatively poor.

Analysis of influencing factors

Different environmental factors have different effects on the health of aquatic ecosystems. The axial distribution of each indicator reflected the contribution to the health of phytoplankton, zooplankton, and aquatic ecosystems (Politi et al. 2019). **Figure 5** shows that RHR, NWBS, WPD, and WQPI values indicate a significant impact on the aquatic ecological environment. In contrast, the influence exhibited by NSO, CAR, and RD are relatively weak. The comparison between the environmental factors and the characteristics of the aquatic ecological environment showed that MF and WQPI were positively correlated with the health status of zooplankton and that of the aquatic ecosystem. In contrast, the other environmental factors were negatively correlated. However, WQPI, NSO, RRD, NWBS, and WPD positively correlated with phytoplankton, whereas the other indicators negatively correlated with phytoplankton. The RDA showed the order of importance of the 10 environmental factors (**Table VII**): RHR > NWBS > WPD > MR > RRD > FAR > RD > WQPI > CAR > NSO. Among these factors, RHR, NWBS, and WPD significantly impacted the aquatic ecological environment ($P < 0.01$), whereas the other factors had no significant impact.

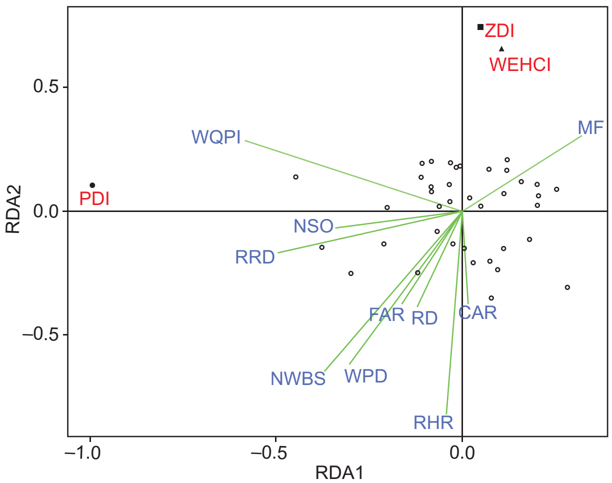

Fig. 5. Redundancy analysis ranking diagram of environmental factors and aquatic environmental characteristics.

TABLE VII. RANKING AND SIGNIFICANCE TEST OF INFLUENCE FACTORS. SEE **TABLE IV** FOR AN EXPLANATION OF THE VARIABLES.

Impact factor	Importance ranking	R^2	P	significance
RHR	1	0.33	0.001	*
NWBS	2	0.29	0.004	*
WPD	3	0.25	0.008	*
WQPI	5	0.08	0.264	
RRD	4	0.09	0.172	
MF	7	0.09	0.209	
FAR	6	0.09	0.207	
RD	8	0.09	0.210	
CAR	9	0.07	0.292	
NSO	10	0.03	0.590	

Note: The symbol " * " indicates significance; No symbol " * " indicates not significant.

DISCUSSION

In this study, we proposed a health evaluation system for the aquatic ecosystem of the Beiyunhe River which considers environmental change, urbanization, and the construction of multi-gate dams. Using the proposed system, we identified the key factors affecting the health of this urban river ecosystem, which are important for its protection.

As one of the five major water systems flowing through Beijing, the health of the Beiyunhe River ecosystem has attracted the attention of many researchers. In 2009, Zhang (2009) evaluated the health of this aquatic ecosystem using 27 indicators including water quantity, water quality, riparian zone status, physical structure, and aquatic organisms using an analytic hierarchy process. In 2011, (Li et al. 2011) used set pair analysis and a variable fuzzy set method to evaluate nine indicators from five water aspects (water quantity, water quality, biological status, water body connectivity, and flood control standards); these indicators were compared with fuzzy comprehensive evaluation and gray comprehensive evaluation methods. In 2012, Gangfu and Bing (2012) proposed an improved "pull grade" method to evaluate the health of the Beiyunhe River aquatic ecosystem, for which they selected 15 indicators, including hydrology, water environment, morphological structure, riparian zone, and aquatic biological conditions. Although these studies use index classification and construction for the evaluation of aquatic ecosystem health, they all lack habitat quality considerations and mainly focus on the comparison and selection of research methods; moreover, they ignore the spatial heterogeneity of the health of the aquatic ecosystem at different points in the basin system and main tributaries. Gu et al. (2019) evaluated the health of the Beiyunhe River ecosystem (Beijing Section) using four types of indicators (aquatic organisms, hydrology, water quality, and habitat). An analysis combining this information with the characteristics of the aquatic ecosystem of urban rivers at the watershed scale will allow for the identification of the spatial characteristics of aquatic ecosystem health in different sections of this urban river.

Based on field survey data, an evaluation system of 13 indicators from five categories including hydrology, aquatic organisms, physical and chemical properties of the waterbody, connectivity, and habitat quality was constructed. Fish indicators were not included among the evaluation indicators. As they are at the top of the food chain in freshwater ecosystems, fish are sensitive to organic and nutrient pollution and habitat degradation (Zhao et al. 2019); therefore, they are common indicators in river ecosystem health assessments (Sheaves et al. 2012, Poikane et al. 2017, Zogaris et al. 2018). Our team obtained 11 fish species (376 individuals) in the Beiyunhe River (**Fig. 6**), the most frequent being the crucian carp (*Carassius carassius*) followed by *Pseudorasbora parva*. Historical data (Wang et al. 1984, Du et al. 2019) showed that 34 fish species were distributed in the Beiyunhe River. Our restricted sampling time, sampling points, and fish survey measures resulted in too few fish to reflect the status of the Beiyunhe River aquatic ecosystem. Nevertheless, the present survey did show that the current fish species in the Beiyunhe River are mostly alien and artificially

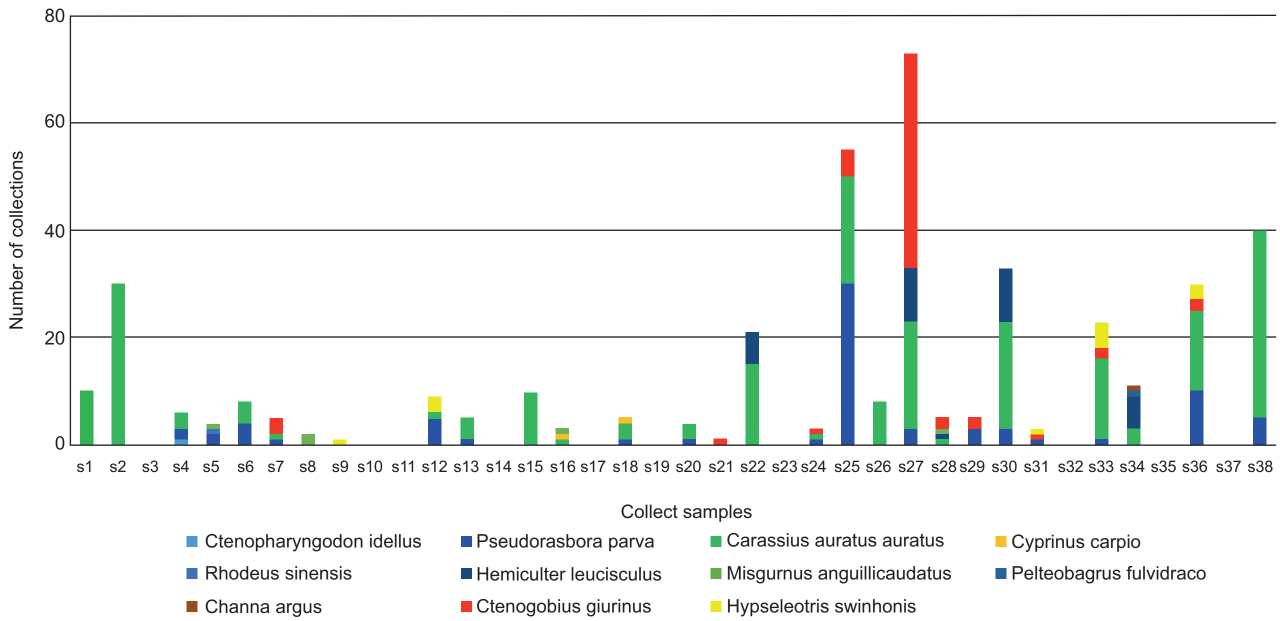

Fig. 6. Fish species and abundance at each sampling point.

stocked species, and that the dominant species are carp, which do not reflect the natural characteristics of the aquatic ecosystem of the basin. Therefore, phytoplankton, zooplankton, benthic animals, and aquatic vascular plants were selected rather than fish as evaluation indicators.

Our study showed that the spatial heterogeneity of the health status of the aquatic ecosystem in the Beiyunhe River is relatively large. The upper and middle reaches of the river were quite healthy, whereas the health of the downstream portion of the river was poor. The results for the upstream portion of the river may be because of the large amount of water, the high proportion of natural runoff in the total amount of water resources, and because it is far from the urban area. The river channel habitats remain relatively natural. Gu et al. (2018) mentioned that the health status of the aquatic ecosystem in the middle reaches of the Beiyunhe River was relatively complex; we found that this portion of the river's health status was relatively good. This difference may result from the fact that the middle reaches of the Beiyunhe River have become navigable from the Beiguan sluice to the Gantang sluice (approximately 11.4 km) since October 2019, and that a series of projects including ecological dredging, river widening, and pipeline network construction have been carried out in the Tongzhou section of the Beiyunhe River. In contrast, the downstream portion of the Beiyunhe River is affected by dam barriers and water reduction/redistribution, which results in a small amount of water in the channel. Moreover, this latter portion contains approximately 70% of the domestic sewage and reclaimed water from Beijing, as both sides of the river are mostly farmland. The use of chemical fertilizers and pesticide spraying leads to increased pollution, which results in even poorer aquatic ecosystem health.

Regarding the relationship between the main stream and its tributaries, the evaluation score of the main stream was generally higher than that of the tributaries, which is related to the greater amount of water resources in the main stream and the greater application of engineering measures such as ecological dredging and widening of river channels. Among the tributaries, the Wenyu River, Tonghui River, and Bahe River have the highest ecological health scores. Beijing has implemented biological measures for improving the environment of urban river and lake water and has implemented measures to prevent water blooms and other projects in the Bahe River basin. This may also be the reason for the high-water ecological health score at the s12 point of the Bahe River. In contrast, the Fenghe River (s33), as the main flood and drainage channel in the Daxing District, accommodates the domestic sewage and garbage from the northern area of Daxing District and Huangcun New Town. Although the health of the aquatic ecosystem has improved recently, it is still suboptimal, and the river is only slowly recovering.

Most of the Beiyunhe River aquatic ecosystem is classified at an Average health status. Compared with previous studies, the health status is following a positive trend. This trend is consistent with previous aquatic ecological monitoring and health assessments conducted by the Beijing Hydrological Station in Beijing in 2019. The weights of hydrological, connectivity, and aquatic biological indicators are relatively large, whereas those of water quality indicators are relatively small. In previous studies (Zhang 2009, Li et al. 2011, Gangfu and Bing 2012, Gu et al. 2018) the weights of water quality and aquatic organisms were more important. This may have occurred because the Beiyunhe River has recently strengthened control measures for pollution sources, increased urban sewage treatment, and strictly prevented the import of external pollution sources. Other measures such as ecological dredging of rivers, control of the release of internal sources, collection of initial rainwater, and more adequate agricultural management measures have been carried out. Therefore, the results of the present study are consistent with the gradual improvement of the water ecological condition of the Beiyunhe River basin.

Research on the health of river ecosystems mostly focuses on the selection of evaluation indicators, construction of evaluation systems, and determination of evaluation methods. However, there are few studies on the factors influencing river aquatic ecosystem health, especially for urban rivers and those disturbed by human activities, where aquatic ecosystem health is affected by a variety of factors (Arthington et al. 2010, Marzin et al. 2014, Zuo et al. 2019). In the past governance model, the primary goal was to ensure the flood control function of the river, which was mainly performed by constructing sluices and dams, river dredging, and slope hardening (Fangyuan et al. 2017, Zhao et al. 2020). At present, more than 43% of the river channels in the Beiyunhe River basin are hardened river channels with a single shape change (mostly box-shaped or trapezoidal), and the habitat of aquatic organisms has been lost. In addition, with the continuous progress of urbanization, population density has increased dramatically, and the disturbance of the river ecosystem has increased dramatically, seriously affecting the health of river ecosystems.

CONCLUSIONS

Based on these factors, we present the following conclusions:

(1) A mathematical evaluation method was used herein to create a health evaluation index system for the Beiyunhe River aquatic ecosystem. The indexes included water temperature, multi-year average runoff, phytoplankton Shannon-Wiener diversity index, zooplankton Shannon-Wiener diversity index, river longitudinal connectivity, river habitat quality, COD, BOD5, conductivity, pH, total phosphorus, total nitrogen, and ammonia nitrogen (13 indicators in five categories). Among these indicators, the vertical connectivity weight of the river was the highest (0.252), followed by the multi-year average runoff (0.238).

(2) The health status of the Beiyunhe River ecosystem was generally Average. Of the 25 evaluation points, 4 were Good, 18 Average, 15 Poor, and 1 Very poor. The proportion of Average and Poor points were estimated to be 86%, but the aquatic ecosystem health status showed an improving trend. A strong spatial heterogeneity was also noted: the upper and middle reaches of the river were healthier than the downstream portion, and the main stream was healthier than its tributaries.

(3) Factors characterizing urban rivers had a large impact on the health of urban river ecosystems. The rate of hardening of the river, the number of water-blocking structures (e.g., gates and dams), and the population density at the catchment area were the key indicators that affected the health of the Beiyunhe River ecosystem.

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REFERENCES

Arthington A. H., Naiman R. J., McClain M. E., Nilsson C. (2010). Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. Freshwater Biology 55(1) 1-16. https://doi.org/10.1111/j.1365-2427.2009.02340.x

Deng X., Xu Y., Zhai X., Liu Y., Li Y. (2014). Establishment and application of the index system for urban river health assessment. Acta Ecologica Sinica 34 993-1001. https://doi.org/10.5846/stxb201209221339

Ding Y., Dong F., Zhao J., Peng W., Chen Q., Ma B. (2020). Non-point source pollution simulation and best management practices analysis based on control units in Northern China. International Journal Of Enveronmental Research And Public Health 17(3) 868. https://doi.org/10.3390/ijerph17030868

Dolédec S., Statzner B. (2008). Invertebrate traits for the biomonitoring of large European rivers: An assessment of specific types of human impact. Freshwater Biology. 53(3) 617-634. https://doi.org/10.1111/j.1365-2427.2007.01924.x

Du L., Xu J., Li Y., Qu X., Liu M., Zhang M., Yu Y. (2019). Fish Community Characteristics and Spatial Pattern in Major Rivers of Beijing City. Research of Environmental Sciences 32(3) 447-457. https://doi.org/10.13198/j.issn.1001-6929.2018.09.05

Fangyuan C., Zhonghua W., Haobo H., Biyu S., Min Z., Jianan Z. (2017). An Environmental Health Risk Assessment of Water Source Based on Uncertainty in the Middle and Lower Reaches of Hanjiang River. River. Environmental Science & Technology 40(4)183-187. https://doi.org/10.3969/j.issn.1003-6504.2017.04.031

Federal Water Pollution Control Act (Clean Water Act) 1972

Gangfu S., Bing S. (2012). Improvement of "scatter degree" method and its application in evaluating river ecosystem health. Yingyong Shengtai Xuebao 23(7) 163-168. https://doi.org/CNKI:SUN:YYSB.0.2012-07-024

Gu X., Xu Z., Liu L., Yin W., Wang M. (2018). Health Assessment of the stream ecosystem in the north canal river basin Beijing China. Environmental Science 39(6): 2576-2587. https://doi.org/10.13227/j.hjkx.201706229

Li W., Qiu L., Chen X., Huang Q. (2011). Assessment model for river ecology health based on Set Pair Analysis and Variable Fuzzy Set. Journal Of Hydraulic Engineering 42(7) 775-782. https://doi.org/10.13243/j.cnki.slxb.2011.07.011

Li Y., Yang W., Shen X.,Yuan G., Wang J. (2019). Water environment management and performance evaluation in Central China: a research based on comprehensive evaluation System. Water 11(12) 2472. https://doi.org/10.3390/w11122472

Liu N., Liu C., Xia Y., Da B. (2018). Examining the coordination between urbanization and eco-environment using coupling and spatial analyses: A case study in China. Ecological. Indicators. 93 1163-1175. https://doi.org/10.1016/j.ecolind.2018.06.013

Liu X., Zhang J., Shi W., Wang M., Chen K., Wang L. (2019). Priority pollutants in water and sediments of a river for control basing on benthic macroinvertebrate community structure. Water 11(6) 1267. https://doi.org/10.3390/w11061267

Luo Z., Zuo Q., Shao Q. (2018). A new framework for assessing river ecosystem health with consideration of human service demand. Science Of The Total Environ. 640 442-453. https://doi.org/10.1016/j.scitotenv.2018.05.361

Mamun M., An K.G. (2020). Stream health assessment using chemical and biological multi-metric models and their relationships with fish trophic and tolerance indicators. Ecological Indicators 111 106055. https://doi.org/10.1016/j.ecolind.2019.106055

Marra G.P, Wood S.N. (2011). Practical variable selection for generalized additive models. Computional Statistics & Data Analysis 55(7) 2372-2387. https://doi.org/10.1016/j.csda.2011.02.004

Marzin A., Delaigue O., Logez M., Belliard J., Pont D. (2014). Uncertainty associated with river health assessment in a varying environment: The case of a predictive fish-based index in France. Ecological Indicators 43 195-204. https://doi.org/10.1016/j.ecolind.2014.02.011

Mueller M., Pander J., Geist J. (2014). A new tool for assessment and monitoring of community and ecosystem change based on multivariate abundance data integration from different taxonomic groups. Environmental Systems Research 3(1) 12. https://doi.org/10.1186/2193-2697-3-12

Pan G., Xu Y., Yu Z., Song S., Zhang Y. (2015). Analysis of river health variation under the background of urbanization based on entropy weight and matter-element model: a case study in Huzhou City in the Yangtze River Delta China. Environmental Research 139 31-35. https://doi.org/10.1016/j.envres.2015.02.013

Petesse M.L., Siqueira-Souza F.K., Freitas C.E.C., Peterre Jr M. (2016). Selection of reference lakes and adaptation of a fish multimetric index of biotic integrity to six amazon floodplain lakes. Ecol. Eng. 97 535-544. https://doi.org/10.1016/j.ecoleng.2016.10.046

Poikane S., Ritterbusch D., Argillier C., Białokoz W., Blabolil P., Breine J., Jaarsma N. G., Krause T., Kubečka J., Lauridsen T. L., Nõges P., Peirson G., Virbickas T. (2017). Response of fish communities to multiple pressures: development of a total anthropogenic pressure intensity index. Science Of The Total Environment 586 502-511. https://doi.org/10.1016/j.scitotenv.2017.01.211

Politi T., Zilius M., Castaldelli G., Bartoli M., Daunys D. E. (2019). Estuarine Macrofauna Affects Benthic

Biogeochemistry in a Hypertrophic Lagoon. Water 11(6) 1186. https://doi.org/10.3390/w11061186

Sheaves M., Johnston R., Connolly R. M. (2012). Fish assemblages as indicators of estuary ecosystem health. Wetlands Ecology And Management 20(6) 477-490. https://doi.org/10.1007/s11273-012-9270-6

Shou-Hua C., Hu X. (2008). Concept of river health and index system for its evaluation. Advances In Science And Technology Of Water Resources. 28(1) 23-27

Smith M.J., Kay W.R., Edward D.H.D., Papas P.J., Richardson K.S., Simpson J.C., Pinder A.M., Cale D.J., Horwitz P.H.J., Davis J.A., Yung F H., Norris R.H., Halse S.A. (1999). AusRivAS: Using macroinvertebrates to assess ecological condition of rivers in Western Australia. Freshwater Biology. 41(2) 269-282. https://doi.org/10.1046/j.1365-2427.1999.00430.x

Song Y., Song X., Shao G., Hu T. (2020). Effects of Land Use on Stream Water Quality in the Rapidly Urbanized Areas: A Multiscale Analysis. Water 12(4) 1123. https://doi.org/10.3390/w12041123

Wang H. (1984). Beijing Fish Journal. Beijing, China, 115 pp.

Wang T., Liu S., Qian X., Shimizu T., Dente S. M. R., Hashimoto S., Nakajima J. (2017). Assessment of the municipal water cycle in China. Science Of The Total Environment. 607 761-770. https://doi.org/10.1016/j.scitotenv.2017.07.072

Wenqi P. (2018). Research on river and lake health assessment indicators, standards and methods. Journal of China Institute of Water Resources and Hydropower Research. 16(5) 394-404. https://doi.org/10.13244/j.cnki.jiwhr.2018.05.008

Wood S.N. (2003). Thin plate regression splines. Journal Of The Royal Statistical Society Series B-Statistical Methodology 65 95-114. https://doi.org/10.1111/1467-9868.00374

Xia T., Zhu W., Xin P., Li L. (2010). Assessment of urban stream morphology: An integrated index and modelling system. Environmental Monitoring And Assessment. 167(1-4) 447-460. https://doi.org/10.1007/s10661-009-1063-x

Xue C., Shao C., Chen S. (2020). SDGs-based river health assessment for small- and medium-sized watersheds. Sustainability 12(5) 1846. https://doi.org/10.3390/su12051846

Yang F., Zeng G., Liu H., Wang L., Cai Q. (2008). Research on the uncertainty of the assessment index system of urban river ecosystem health. Journal of Hunan University(Natural Sciences) 35(5) 63-66

Zaharia L., Ioana-Toroimac G., Cocos O., Ghiţă F. A., Mailat E. (2016). Urbanization effects on the river systems in the Bucharest City region (Romania). Ecosystem Health And Sustainability 2(11) e01247. https://doi.org/10.1002/ehs2.1247

Zhang F., Liu J., Yang Z. (2005). Ecosystem health assessment of urban rivers and lakes for six lakes in Beijing. Acta Ecologica Sinica 25(11) 3019-3027

Zhang G. (2009). The research on ecosystem health evolution and repairing methods of North Canal. B.Sc. Degree. Tianjin University, Tianjin, China, 80 pp.

Zhang K., Shen J., Han H., Jia Y. (2019). Urban river health analysis of the Jialu river in Zhengzhou City using the improved fuzzy matter-element extension model. Water 11(6) 1190. https://doi.org/10.3390/w11061190

Zhang S., Fan W., Yi Y., Zhao Y., Liu J. (2017). Evaluation method for regional water cycle health based on nature-society water cycle theory. Journal Of Hydrology 551 352-364. https://doi.org/10.1016/j.jhydrol.2017.06.013.

Zhang Y., Jiang Y. (2019). Health assessment of water ecosystems in key river basins in China. Beijing, China, 229 pp.

Zhang Y., Liu S., Hou X., Cheng F., Shen Z. (2019). Landscape- and climate change-induced hydrological alterations in the typically urbanized Beiyun River basin, Beijing, China. Stochastic Environmental Research Risk Assessment. 33(1) 149-168. https://doi.org/10.1007/s00477-018-1628-8

Zhao C., Pan T., Yang S., Sun Y., Zhang Y., Ge Y., Dong B., Zhang Z., Zhang H. (2019). Quantifying the response of aquatic biodiversity to variations in river hydrology and water quality in a healthy water ecology pilot city China. Marine And Freshwater Research. 70(5) 670-681. https://doi.org/10.1071/MF18385

Zhao C., Pan X., Xiang H., Yang S., Zhao J., Gan X., Dang B., Ding S. (2020). Determination of priority areas and principal environmental factors for water ecosystem health remediation. Ecohydrology 13(1) e2165. https://doi.org/10.1002/eco.2165

Zhao C., Shao N., Yang S., Ren H., Ge Y., Zhang Z., Zhao Y., Yin X. (2019). Integrated assessment of ecosystem health using multiple indicator species. Ecological Engineering 130 157-168. https://doi.org/10.1016/j.ecoleng.2019.02.016

Zhao C., Sun C., Xia J., Hao X., Li G., Rebensburg K., Liu C. (2010). An Impact Assessment Method of Dam/Sluice on Instream Ecosystem and its Application to the Bengbu Sluice of China. Water Resources Management 24 4551-4565.

Zhao C., Yang S., Liu J., Liu C., Hao F., Wang Z., Zhang H., Song J., Mitrovic S.M., Lim R.P. (2018). Linking fish tolerance to water quality criteria for the assessment of environmental flows: a practical method for streamflow regulation and pollution control. Water Research. 141 96-108. https://doi.org/10.1016/j.watres.2018.05.025

Zhao Y., Yang Z. (2005). A preliminary study on the health assessment of urban river ecosystem. Advances In Water Science 3 349-355. https://doi.org/10.14042/j.cnki.32.1309.2005.03.007

Zogaris S., Tachos V., Economou A.N., Chatzinikolaou Y., Koutsikos N., Schmutz S. (2018). A model-based fish bioassessment index for Eastern Mediterranean rivers: application in a biogeographically diverse area. Science Of The Total Environment 622 676-689. https://doi.org/10.1016/j.scitotenv.2017.11.293

Zuo Q., Han C., Liu J., Li J., Li W. (2019). Quantitative research on the water ecological environment of dam-controlled rivers: case study of the Shaying River China. Hydrological Science Journal- Journal Des Sciences Hydrologiques 64(16) 2129-2140. https://doi.org/10.1080/02626667.2019.1669794