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Not applicable.

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Competing interests

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Qh Y: Conceptualization, Methodology, Software, Investigation, Resources, Data Curation, Writing-Original draft preparation

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Abstract

Ecosystem services provided by river ecosystems rely on healthy ecosystem structure and ecological processes. The Beijing-Tianjin-Hebei urban is a typical water-deficient area. As an important part of the urban-rural integration construction, evaluating the health status of the Beiyun River Basin and discovering the weak links in the water environment is the basis for improving the health of the basin. In this study, Analytic Hierarchy Process was used to establish an evaluation index system for the Beiyun River Basin from 5 aspects including water quality, biology, habitat, hydrology, and social functions, and to assign weights to the index layer. The evaluation results showed that the health evaluation results of the Beiyun River Basin in 2019 are “sub-healthy”, and the overall health status is gradually worsening from northwest to southeast. In the middle reaches of the region, the evaluation result is "healthy", followed by the upstream, and the downstream is the worst. The results showed that areas with less human interference are in better health. The factors that affect the overall health evaluation status in the basin are the level of nutrition, biodiversity, and vegetation coverage. For the comprehensive management of the Beiyun River, the improvement of water quality and habitat ecological restoration is the key to the health of the upstream ecosystem health status. The improvement of the health status of the downstream should focus on equal emphasis on water quality and quantity, restoration of biodiversity, and improvement of the quality of the riparian ecological environment.

Key Words: Beiyun River; Health; analytic hierarchy process; Ecosystem

1. Introduction

River ecosystems provide a variety of ecological services for human society. These ecosystem services rely on a healthy and functionally intact ecosystem. In recent years, the acceleration of China's industrialization and urbanization has increased the disturbance to the natural ecosystem (Rubinato et al. 2020). The discharge of pollutants from industrial production and agricultural activities seriously exceeds the purification capacity of the aquatic environment (Peng and Deng 2020). As a result, the ecosystem of the river basin was destroyed, the water quality of the water body deteriorated, and the biodiversity decreased (Pereda et al. 2021). Urban river pollution negatively affects the stable performance of aquatic ecosystem functions and sustainable social development (Kakar and Khan 2021). Therefore, Sustainable management assessment of river health is necessary.

River health includes the natural health of the river, the ability to provide a good ecological environment, and social service functions (Wu et al. 2020b). Since the concept of river health was put forward, Europe, United States, South Africa, Australia, and others have elaborated various assessment methods. Various concepts such as the stream state index and the biological integrity index have been proposed. Scholars have carried out a lot of work in river health index system and its evaluation methods and applied them in various rivers, and obtained many successful experiences. HaRa et al. (2019) used the chemical pollution index (CPI) and the index of biological integrity (IBI) to diagnose the chemical system (N, P) and the chemical and biological river health of fish in the Gemu River Basin. Zhang et al. (2016) proposed a new concept of lake ecosystem health, a driver-pressure-state-impact-response (DPSIR) management framework, an indicator system of water quality, as well as ecological and socio-economic criteria to evaluate the lake, Nansi Lake in China. The analytic hierarchy process (AHP) (Sun et al. 2019), five-element connection number method (Li et al. 2011), Pressure-State-Response (PSR)

artificial urban canal, affected by flood discharge, water diversion from the Luanhe River, and recreational activities of the population. The river faces increasing sewage discharge year by year, inadequate sewage treatment, and severe tributary pollution, probably exceeding basins carrying capacity regarding resources and environmental integrity (Li and Guan 2018). Zhang et al. (2018) focused on river health evaluations of the Beiyun River for river protection and sustainable water management and used eight indices that included physical, chemical, and biological elements. Wu et al. (2020a) assessed the risk of heavy metal pollution in the soil of the Beiyun River basin associated with land use change. Our previous research assessed the health risks of heavy metals in the Beiyun River basin (Wu et al. 2021) . However, analyze the overall health status of the Beiyun River basin from the aspects of water environment, water ecology, and water resources is still lacking. Therefore, this paper uses the AHP to evaluate the Beiyun River basin with 13 indicators from 5 aspects: water quality, habitat, hydrology, biology, and social functions. The primary purpose of this study is to analyze the overall health of the Beiyun River, identify the main factors affecting its health, and guide the management and supervision of the Beiyun River.

2. Materials and Methods

2.1 Study area

The Beiyun River originates from the eastern foot of Jundu Mountain in Changping District, Beijing and flows through Changping District, Chaoyang District, Shunyi District, Tongzhou District, Xianghe County of Hebei Province, Wuqing District, Beichen District, and Hongqiao District of Tianjin City, and finally merges into Haihe. The Beiyun River has a total length of 238 kilometers and a drainage area of 6,166 square kilometers (Fig. 1). The upper reaches of basin are mainly mountainous and hilly, and the middle and lower reaches are in the plains. The climate in this area is characterized by the continental

monsoon, with an average annual rainfall of about 650 mm, 75% of which is concentrated between July and August (Wu et al. 2020a). The Beiyun River is one of the four major rivers in the Haihe North System. Its upstream tributaries include Wenyu River, Liangshui River, Tonghui River, Ganggou River, Feng River, Yudai River, Xiaozhong River, Zhongba River, Fenggangjian River and Liangshui River. There are three flood diversion and reduction rivers: Yunchaojiang River, Qinglongwan River, and Gangergang River.

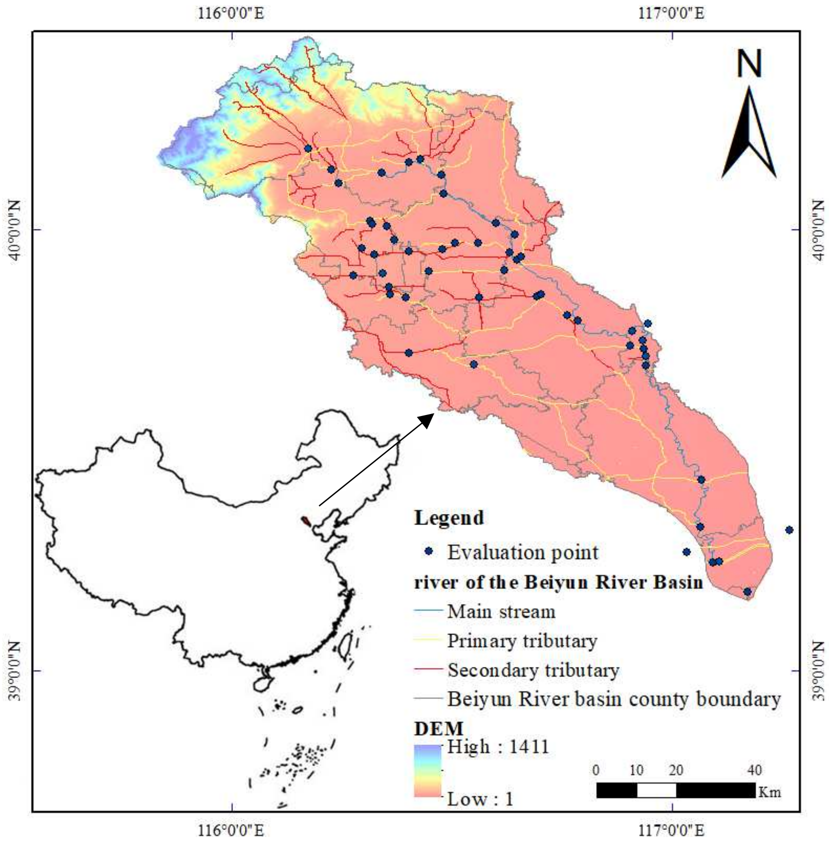

Fig. 1 The maps of Beiyun River Basin

2.2 Analytic Hierarchy Process

AHP is a decision-making method that decomposes the decision-making problem. AHP divides the relevant factors into goals, criteria, plans, and other levels, and then conducts qualitative and quantitative analysis.

The scientificity, rationality, and effectiveness of the used indicators determine the credibility of the

results of river health assessment. The construction of the health evaluation index system of the Beiyun River Basin established in this study follows the principles of scientificity, representativeness, independence, operability, qualitative and quantitative indicators.

2.2.1 Establish a hierarchical structure model

The relevant factors are decomposed into several levels from top to bottom according to different attributes. The factors of the same level are subordinate to or have an influence on the factors of the upper level, and at the same time dominate the factors of the next level or are affected by the factors of the lower level. The top layer is the target layer; the bottom layer is the plan or object layer; the middle is the criterion or indicator layer.

2.2.2 Constructed into a pair comparison matrix

Starting from the second layer of the hierarchical structure model, the pairwise comparison method and the 1-9 comparison scale are used to construct a pair comparison matrix.

$$\mathrm{A} = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} = \left(a_{ij}\right)_{n\times n} \tag{1}$$

Where, a_{ij} represents the importance of the i-th element and the j-th element relative to a factor in the previous layer. Matrix A is the judgment matrix (or paired comparison matrix).

When the matrix $A=(a_{ij})_{n\times n}$ satisfies $a_{ij}>0$ and $a_{ij}=\frac{1}{a_{ij}}$ (i, j=1, 2, …,n), it is called a positive and negative matrix. Compare the values of matrix elements a_{ij} in pairs using numbers 1-9 (See Table 1 for details) and their reciprocals as the scale.

Table 1. The meaning of scale

Scaling	Meaning
1	Indicates that two factors are equally important
3	Indicates that compared with the two factors, the former is slightly more important than the latter

5	Indicates that compared with the two factors, the former is obviously more important than the latter
7	Indicates that compared with the two factors, the former is more important than the latter
9	Indicates that compared with the two factors, the former is extremely important than the latter
2, 4, 6, 8	Represents the intermediate value of the above adjacent judgment
reciprocal	If the importance of factor i and factor j is written as a_{ij}, then the ratio of the importance of factor j to factor i is $a_{ij}=1/a_{ij}$

2.2.3 Hierarchical list sorting and consistency check

The eigenvector of matrix A corresponding to the maximum eigenvalue λ_{max} is called W after being normalized. The element of W is the ranking weight of the relative importance of the corresponding element of the same level relative to the element of the previous level. This process is called hierarchical single sorting.

Whether it is possible to confirm the ordering of the level list requires a consistency test. Proceed as follows:

Calculate the consistency index CI:

$$CI = \frac{\lambda_{max}-n}{n-1} \tag{2}$$

Where, λ_{max} represents the maximum eigenvalue of matrix A.

CI=0 means completely consistent, the larger the CI, the more inconsistent；

Query the random consistency index RI according to Table 2:

Table 2. Random consistency index table

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Calculate the consistency ratio CR：

$$CR = \frac{CI}{RI} \tag{3}$$

When CR＜0.1, the consistency of the matrix is considered acceptable.

2.2.4 Level total ranking and consistency check

The total ranking of levels is to calculate the relative importance of all factors of a level to the highest level. As shown in Table 3.

Where, a_1, a_2, ..., a_m are the m factors A_1, A_2, ..., A_m in the A layer sort the total target Z. b_{1j}, b_{2j}, ..., b_{nj} (j = 1, 2, ..., m) are the hierarchical ordering of factors A_j in layer A by n factors in layer B.

Table 3. Hierarchical total sorting table

Level A / Level B	A_1	A_2	…	A_m	B-level total ranking weight
	a_1	a_2	…	a_m	
B_1	b_{11}	b_{12}	…	b_{1m}	$\sum_{j=1}^{m} b_{1j}a_j$
B_2	b_{21}	b_{22}	…	b_{2m}	$\sum_{j=1}^{m} b_{2j}a_j$
⋮	…	…	…	…	⋮
B_n	b_{n1}	b_{n2}	…	b_{nm}	$\sum_{j=1}^{m} b_{nj}a_j$

The total ranking random consistency ratio of the B layer is:

$$CR = \frac{\sum_{j=1}^{m} CI(j)\, a_j}{\sum_{j=1}^{m} RI(j)\, a_j} \quad (4)$$

Where, CI(j), (j = 1, 2, ..., m) is the consistency index of level single ordering, which is the B level B_1, B_2, ..., B_n to the upper level A factor A_j (j = 1, 2, ..., m).

RI(j), (j = 1, 2, ..., m) are random consistency indicators.

When CR<0.10, it is considered that the total ranking result of the level has a satisfactory consistency and the analysis result is accepted.

The above AHP calculation is conducted in SPSS 22 software.

2.3 Assessment indicator system

In the study, a total of 12 indicator layers including 5 criterion layers including water quality, ecological environment quality, hydrological status, biology, and social function were selected to evaluate the health status of the Beiyun River Basin. It comprehensively reflects the comprehensive health level of the ecosystem of the Beiyun River Basin from two aspects: the integrity of the ecological structure and the integrity of the social functions (Fu et al. 2019).

2.3.1 Water quality

The evaluation of water quality includes conventional water quality indicators, the trophic level indicators, and heavy metal pollution indicators.

The conventional water quality indicators include chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD_5), and dissolved oxygen (DO). COD and BOD_5 measure the content of organic pollutants in the water. DO reflects the oxygen content in the water body. An important indicator to measure the self-purification ability of water bodies (Cao et al. 2020).

The trophic level indicators include ammonia nitrogen (NH_4^+-N) and total phosphorus (TP) (Liao et al. 2020).

The heavy metal pollution indicators include cadmium (Cd), chromium (Cr), lead (Pb), and arsenic (As).

2.3.2 Ecological environment quality

The Ecological environment quality index evaluated riparian environmental quality, vegetation coverage and barriers, and habitat environmental quality.

(1) Riparian environmental quality was scored according to Table 4.

Table 4. Riparian zone environmental quality rating

Riparian index	Indicators of bank erosion	Habitat types in riparian zone	Comfort of the riverine landscape
10, 9	no erosion	forests, swamps	very comfortable
8, 7	slight erosion	shrub, wasteland	comfortable
6, 5	moderate erosion	touristic areas	slightly uncomfortable
4, 3	severe erosion	farmland, villages	very uncomfortable
2, 1	very severe erosion	towns, factories	extremely uncomfortable

(2) The vegetation coverage reflects the density of vegetation in the riparian zone. The vegetation coverage was interpreted using sentinel-2 remote sensing image data. The normalized vegetation index (NDVI) of each pixel was calculated according to formula (5) . Then the maximum likelihood method of supervised classification was used to partition the land types, and then the maximum and minimum NDVI of each land type were calculated separately. The vegetation coverage was calculated according to formula 5.

$$NDVI = \frac{NIR - R}{NIR + R} \tag{5}$$

Where NDVI is the normalized difference vegetation index, NIR is the near-infrared band, and R is the infrared band. The NIR and R bands of Sentinel-2 were band 8 and Band 4, respectively.

$$VFC = \frac{(NDVI - NDVI_{soil})}{(NDVI_{veg} - NDVI_{soil})} \tag{6}$$

Where $NDVI_{soil}$ is the NDVI value of completely bare soil or non-vegetated area, and $NDVI_{veg}$ is the NDVI value of pure vegetation pixels.

(3) As shown in the Table 5, we used the Habitat environmental quality score table to evaluate the Beiyun River Basin habitats. The indicators involved were habitat complexity, bank stability, river form, river water volume status, vegetation diversity, water quality, human activity intensity, riparian land-use type, sediment deposition, and another nine indicators.

Table 5. Habitat environmental quality score table

Habitat quality parameters	20，19，18，17，16	15，14，13，12，11	10，9，8，7，6	5，4，3，2，1，0
1.Habitat complexity	There are various small habitats such as aquatic vegetation, litter, fallen wood, undercut embankments and boulders.	There are small habitats such as aquatic vegetation, litter, and undercut embankments.	There are mainly one or two small habitats.	It is dominated by a small habitat, and the bottom is mostly silt or fine sand.
2.Bank stability	The embankment is very stable with no traces of erosion, and <5% of the embankment has been damaged.	Moderately stable, with severe erosion in small areas, with 5% to 30% of river banks affected.	Moderately unstable, 30% to 60% of the river channels are eroded, and there is severe erosion during the flood season.	Unstable, there are obvious swamps, and more than 60% of the embankments have been eroded.
3. River form	Channelization did not occur or rarely occurs, and the river channel maintains a normal pattern.	Channelization occurs less frequently, usually around the bridge piers, which has little impact on aquatic organisms.	Channelization is relatively extensive, with embankments or bridge pillars appearing on both sides of the bank, which have a certain impact on aquatic organisms.	More than 60% of the embankments within the observation area have been eroded.
4. River water volume status	The amount of water is large, and the river water is submerged on both sides of the river bank, or there is a very small amount of river exposed.	The water volume is large, and the river floods about 75% of the river course.	The amount of water is average, and the river floods 25-75% of the river course.	The amount of water is very small and the river is dry.

Habitat quality parameters	20，19，18，17，16	15，14，13，12，11	10，9，8，7，6	5，4，3，2，1，0
5.Vegetation diversity	There are many types of vegetation around the river bank, with a large area, and more than 50% of the banks are covered with vegetation.	There are many types of vegetation around the river bank, the area is average, 25-50% of the bank is covered with vegetation.	There are fewer types of vegetation around the river bank, with a small area, and 0-25% of the banks are covered with vegetation.	There is almost no vegetation around the river bank, no bank cover, no vegetation.
6. Water quality	It is very clear, without any peculiar smell, and there is no sediment after the river is standing still.	It is clearer, with a small amount of peculiar smell, and there is a small amount of sedimentation in the river water after standing still.	It is turbid, has a peculiar smell, and sediments after the river is allowed to stand still.	It is very turbid, with a lot of irritating gas overflowing, and there are many sediments after the river is standing still.
7.Human activity intensity	There is no human activity interference or little human activity.	Human interference is small, and a small number of pedestrians or bicycles pass.	Human interference is large, and a small number of motor vehicles pass by.	Human interference is great, and the main roads of transportation are the only way to go, and motor vehicles often pass by.
8.Riparian land-use type	There is no cultivated soil on both sides of the river bank, which is rich in nutrients.	There is no cultivated soil on one side of the river bank, and cultivated soil on the other side.	Both sides of the river bank are cultivated soil, which requires the application of chemical fertilizers and pesticides.	On both sides of the river bank is the bare weathered soil layer abandoned by farming, with few nutrients.
9.Sediment deposition	Less than 5% of the riverbed is affected by sediment deposition.	Part of the gravel and fine-grained sediment form a silt dam, and 5% to 30% of the river bed is affected by sediment deposition.	Medium-level particles and fine-particle sediments form sand dams; 30%~50% of the river bed is affected by settlement, and medium-level settlement in areas with slow velocity.	A large amount of fine particulate matter settles, forming a silt dam, and more than 50% of the area is often affected by settlement; the pond disappears due to settlement.

2.3.3 Hydrology

(1) The guaranteed degree of ecological flow is the discharge that must be maintained to maintain ecosystem structure and functioning of the river ecosystem (Lin et al. 2010). The minimum ecological flow was calculated as:

$$EF_1 = min\left[\frac{q_d}{\bar{Q}}\right]_{m=4}^{9} \quad (7)$$

$$EF_2 = min\left[\frac{q_d}{\bar{Q}}\right]_{m=10}^{3} \quad (8)$$

Where: q_d is the measured annual runoff (m^3/s); Q is perennial average runoff (m^3/s); EF_1 is the lowest percentage of annual average runoff from April to September; EF_2 is the lowest percentage of annual average runoff from October to March.

(2) Conditions of river connectivity and barriers represent a comprehensive reflection of the impact of the construction of river dams on the river's longitudinal continuity, which was mainly represented by the characteristics of fish migration barriers, water volumes, and material flow barriers (Bourne et al. 2011). It was assessed according to formula 9.

$$\mathrm{RCr} = 100 + \min\left[(DAMr)_j, (GATEr)_j\right] \quad (9)$$

Where R_{Cr} is the score of the connecting barrier condition of the river; $(DAMr)_j$ is the dam barrier score of the downstream section, j=1~NDAM. NDAM is the number of DAMS from the downstream section to the estuary. j =1~NGATE. NGATE is the number of sluices from the downstream river section to the estuary.

2.3.4 Biology

The fish in the water system of the Beiyun River are dominated by the proliferation of exotic fish

species. The diversity of indigenous fish is affected by human activities, resulting in significant changes in the community structure of local fish. Therefore, fish is not a suitable group of indicator organisms to evaluate the river ecosystem health of the Beiyun River in Beijing (Hou et al. 2015). Microorganisms are more sensitive to changes in the environment, and the microbiological community structure can reflect the water quality and distinguish types and degrees of pollution.

The Shannon-Weaver diversity index reflects the functional relationship between the number of species and the difference in each species' number and can be used as a parameter in ecological monitoring (Etemi et al. 2020). The Shannon-Wiener Diversity Index (H′) was calculated as:

$$H' = -\sum_{i=1}^{S} P_i \log_2 P_i \quad (10)$$

Where $P_i = N_i / N$; N_i: number of individuals of a species (ind. /L); N: total number of species per station (species /L).

2.3.5 Social functions

The social functions of rivers include many factors. The water quality compliance rate and water resources development utilization rate of water function areas were selected in this article (He et al. 2016). Internationally, it is generally believed that the development and utilization of a river should not exceed 40% of its water resources. The water resources development utilization rate C is calculated as:

$$C = \frac{C_0}{C_1} \quad (11)$$

Where C_0 is the total water resource utilization, and C_1 is the total water resource utilization.

2.4 Valuation criteria

Table 6 shows the evaluation criteria for health evaluation indicators in the Beiyun River Basin. In addition, due to the small number of samples collected by benthic animals, approximate values are used to supplement some of the missing values.

Table 6. Evaluation criteria of the health evaluation index in the Beiyun River Basin

Index layer	Scores				
	0	25	50	75	100
Conventional water pollution **I11**	BOD_5、COD、DO V class water environ mental standards	BOD_5、COD、DO IV class water environ mental standards	BOD_5、COD、DO III class water environ mental standards	BOD_5、COD、DO II class water environ mental standards	BOD_5、COD、DO I class water environ mental standards
trophic levels **I12**	NH_4^+-N、TP V class water environmenta l standards	NH_4^+-N、TP IV class water environmental s tandards	NH_4^+-N、TP III clas s water environment al standards	NH_4^+-N、TP II class water environmenta l standards	NH_4^+-N、TP I class water environmental standards
Heavy metal pollution **I13**	Cd、Cr、Pb、As V class water envir onmental standards	Cd、Cr、Pb、As IV c lass water environmen tal standards	Cd、Cr、Pb、As III class water envir onmental standards	Cd、Cr、Pb、As II c lass water environm ental standards	Cd、Cr、Pb、As I c lass water environm ental standards
Riparian condition **I21**	0~6	6~12	12~18	18~24	24~30
Vegetation coverage **I22**	very low coverage	low coverage	moderate coverage	high coverage	sky-high coverage
Habitat status **I23**	0~4	4~8	8~12	12~16	16~20
Degree of ecological flow satisfaction **I31**	<10	10%~20%	20%~30%	30%~50%	>50%
Barrier condition of river connection **I32**	No barrier, 100 points; No fishway, obstructing some fish, 75 points; There is a fishway, general barrier, 25 poi nts; Migration channel completely blocked, 0 points				
Benthic diversity index **I41**	poor	general	good	rich	very rich
Phytoplankton diversity index **I42**	poor	general	good	rich	very rich
The water quality compliance rate **I51**	0~20%	20%~40%	40%~60%	60%~80%	80%~100%
Utilization rate of water resources **I52**	according to the actual situation				

3. Results and discussion

3.1 Analysis of water quality

The monthly water quality monitoring status in 2019 is shown in Fig. 2. The water quality in the middle reaches was the best in terms of conventional water quality parameters and trophic levels and thus the highest indicator score. Upstream reaches had an intermediary score, and downstream reaches had the lowest score. Except for Guanyintang Minggou, Daming Liushugou, and Yudai River, the DO concentration in the Beiyun River drainage area met I Class standard of Environmental Quality Standards for Surface Water of the People's Republic of China (GB 2002-3838), therefore the river have a good self-purification capacity (Wang 2020). Most of the river sections can met the surface water environment IV Class standard of Environmental Quality Standards for Surface Water of the People's Republic of China regarding COD and BOD_5. TP and NH_4^+-N exceeded the standard severely, with an average score of only 22.5. The North Moat, the Kunyu River, and the Tonghui River had an average score of 50, which met the surface water environment Class IV water. In contrast, in most river sections in the entire basin, these two factors did not meet the surface water environment Class V standard. The reason that the upstream and downstream water quality is weaker than that of the midstream is that the area is dominated by rural areas and the sewage collection rate and treatment rate are low. So the water quality is poor (Xu et al. 2020a). The pollution status of heavy metals was different. The downstream scores were high, and the upstream scores were the lowest. The concentration of heavy metals varied greatly between the flood season and the non-flood season. The reason may be due to urban expansion and industrial development in the middle reaches of the region, which have resulted in high heavy metal concentrations (Xu et al. 2020b). During the flood season, most river sections met the environmental standards of surface water Class I. Most of the non-flood season scores exceeded Grade V surface water environmental quality

standards.

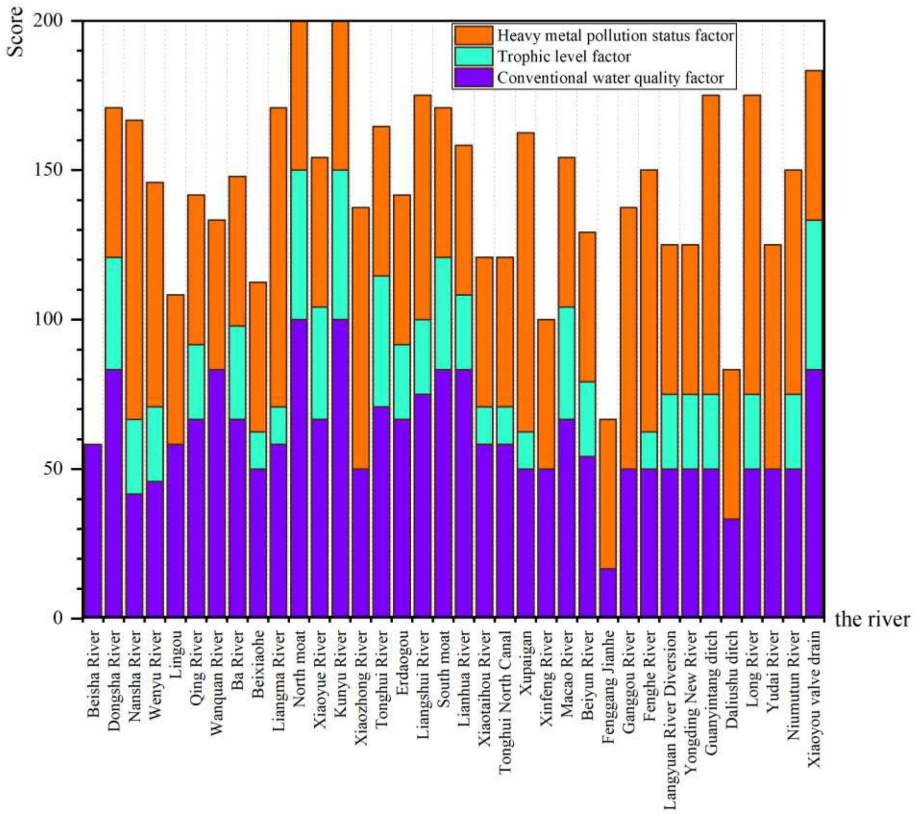

Fig. 2 Water quality distribution map of the Beiyun River Basin

The Beiyun River is the sewage receiving water body of Beijing, and its main stream receives domestic sewage, industrial waste water, sewage treatment plant return water, mixed sewage, and rainwater, etc. Most of its pollutants are BOD_5 and COD, which have a greater impact on the water quality, so the water quality level is average. The upstream is mostly mountain rivers, water diversion channels and core landscape water. The midstream is the development and utilization zone, and the source of wastewater is mainly urban domestic sewage, which is discharged through centralized treatment. Most of the water bodies in this area are landscape waters, which can meet the water quality requirements of landscape water. The downstream is the urban drainage area. There are three reasons for the high level of nutrition and poor water quality in downstream areas. The first is the shortage of water resources; the second is the insufficient supply of new water in the river; the third is the impact of urban

sewage and direct discharge of wastewater from villages and towns (Lyu et al. 2020).

The concentrations of heavy metals vary greatly between the flood season and the non-flood season. During non-flood season, rivers receive less water from their catchments leading to low flow and pollutants are not diluted downstream. For pollutants emitted by human activities in the flood season, the opposite is true. During the flood season, there is more rain and the river's discharge increases, allowing for considerable pollutant dilution. The concentration of heavy metals also decreases accordingly (Cui et al. 2020; Li et al. 2020).

3.2 Habitat quality analysis

The riparian zone's environmental quality evaluation included three indicators: the slope erosion index, riparian habitat type, and water-water landscape comfort. In the evaluation process, the sampling points were evaluated one by one based on a combination of the Baidu map real map and field surveys. The evaluation results are shown in Fig. 3 (a). In general, the upstream evaluation is higher than the midstream, and the downstream is the last, especially in the lower reaches of the Beiyun River, Fenggangjian River, and Xinfeng River. In the densely populated middle reaches of Haidian District, Dongcheng District, and Xicheng District, the environmental quality of the regional riparian zone is also excellent. The overall evaluation average is 63, indicating that the environmental quality level of the riparian zone in the Beiyun River Basin is “healthy”. Among the three indicators, the riparian habitat type had the lowest score, and the slope erosion index and the water-water landscape comfort had relatively high scores.

Fig. 3(b) is the evaluation of habitat quality. In general, the quality of habitat gradually improves from upstream to downstream. The average score is 12, and the overall evaluation level is "healthy", and the downstream is the most suitable area for biological habitat. Among the various indicators, human

activity intensity, habitat complexity, and water quality had the lowest scores, with an average value below 10 points, while the average human activity intensity was only 5.9 points. Embankment stability, sediment deposition, and riparian land-use types had higher scores, with an average value of over 15 points.

Due to the gathering of urban residents, humans have built and reconstructed the slopes and riparian zones in the basin, resulting in higher quality riparian zones and the lowest riparian habitat types. Reconstruction of embankments in densely populated areas has allowed sedimentation to be controlled, and channelization is widespread, and the environmental quality of biological habitats is poor. Conversely, areas with less human activities have less modification of the natural environment and are more suitable for living creatures. It shows that while humans are transforming the riparian zone, they also have a certain impact on the biological habitat. Therefore, when transforming the riparian zone in the future, it is necessary to coordinate economic growth and ecological and environmental protection.

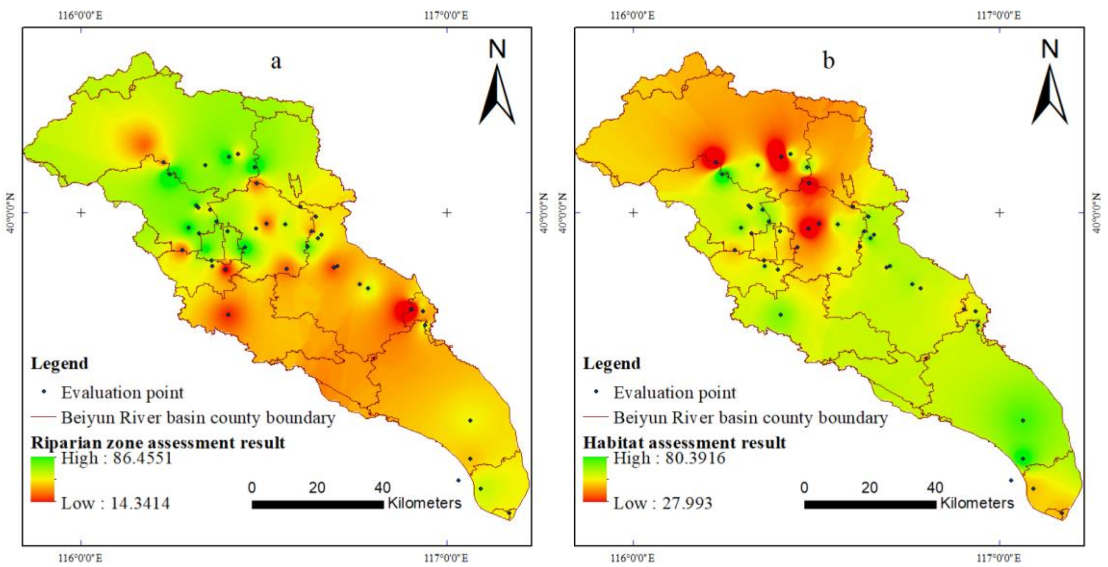

Fig. 3 (a) Environmental quality assessment of the riparian zone, and **(b)** environmental quality assessment of habitat quality

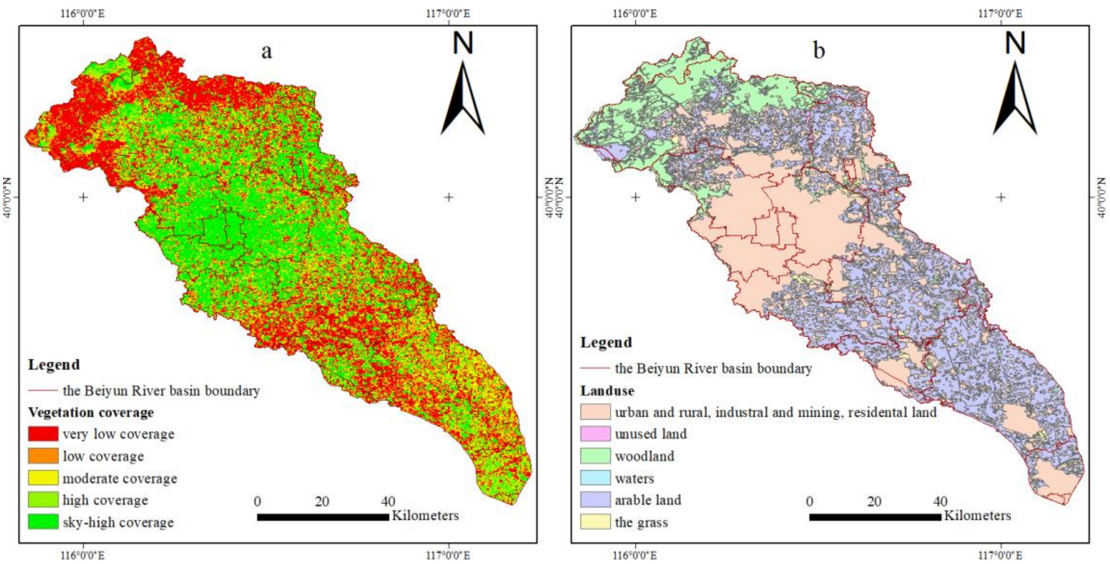

Fig. 4 (a) Vegetation coverage, and **(b)** land use types of the Beiyun River Basin

There was a strong positive correlation between vegetation coverage and land use. There were mountains, woodlands, and villages in the upstream sections. The vegetation coverage was the highest in the woodlands. In the middle reaches of the Beijing center, the surface is mostly impervious surface area and buildings. In the whole Beiyun River Basin, its vegetation coverage was the lowest, and its degree of development and prosperity was the highest. In the downstream sections, where villages and towns dominate, the vegetation coverage was also very low. However, the vegetation coverage was relatively high in places with Low population density and low development degrees, and cultivated land is the primary land-use type. As shown in Fig. 4, the Beiyun River Basin's vegetation coverage was negatively correlated with urban development, utilization, and prosperity. Therefore, during the further development and utilization of the city, the greening construction should be placed in an important position.

3.3 Hydrological index

The degree of ecological flow protection was calculated based on the flow data of relevant sections in 2019. The existing data showed that the ecological flow guarantee rate was relatively high in the

Beiyun River trunk stream, Wenyu River, and Liangshui River. However, it was low in the central part of the city and the downstream area.

The Montana method explains the relationship between aquatic life, river landscape, recreational conditions, and river flow (de Leon and Aguilar-Robledo 2009). The Xinfeng River is 10% of the average flow rate. At this time, the water depth covers 60% of the sediment, and the average water depth is 0.3 m, and the average flow velocity is 0.23 m/s. For most aquatic life forms, it is the recommended minimum instantaneous flow to support short-term habitat. The ecological flow of the five rivers, including the lower section of Qinghe River, the lower section of Wenyu River, the second section of the Beiyun River, the lower section of Tonghui River, and the Liangshui River, is 60% - 100%. At this time, the average water depth is 0.61 m and the average flow velocity is 0.61 m/s, which is a good range of living conditions for aquatic organisms. Most of the river rapids and shoals are submerged, and the beaches on the banks have become areas where fish can swim. There are a wide variety of invertebrates and plenty of water for plants on the banks. It can meet the requirements of fishing, boating, and large yacht sailing. The Mainstream of the Beiyun River and the upper section of the Wenyu River exceed 100% of the average flow. The water depth and velocity may be too high for the suitable living conditions required by most aquatic organisms, but they are good for transferring sediment, bed load, and boating in shallow waters. To meet demands for flow regulation, there are many dams along the Beiyun River. According to the survey, there are 17 flood control gates and 9 rubber dams in the main stream of the Beiyun River (Guo and Wang 2014). There are also many river conservancy projects with the function of power generation. Due to these barriers for matter fluxes and fish migration, the average bonus was 54, and the evaluation level is “sub-healthy”. There were no gate and dam facilities along the North Moat, the Liangma River, and the Dongsha River, and no points are deducted. The Wenyu River, Qinghe River, Tonghui River, and

the mainstream section of the Beiyun River were equipped with many control gates and barrages, so their material circulation has a lot of influence, and the score was low. The Beiyun River is an artificially excavated canal. The river is narrow and the upstream water is insufficient, so that some sections of the downstream were cut off. The construction of sluices and dams in modern times has gradually used the downstream as a channel for flow reduction and flood diversion and sewage discharge, which has a lot of influence on fish migration and material circulation along the way (Li 2015).

3.4 Biological indicators

According to the survey in 2019, a total of 7 phyla and 156 species of phytoplankton organisms were identified in the survey basin, most of which were diatoms and Chlorophyta, such as Cyclotella, Navicula, Pseudanabaena, Nitzschia, Chlamydomonas, and Euglena viridis. A total of 18 species of 3 phyla of benthos were identified, most of which were arthropods. During the survey period, there were two dominant species of river benthos in this area, namely Limnodrilus hoffmeisteri and Branchiura sowerbyi.

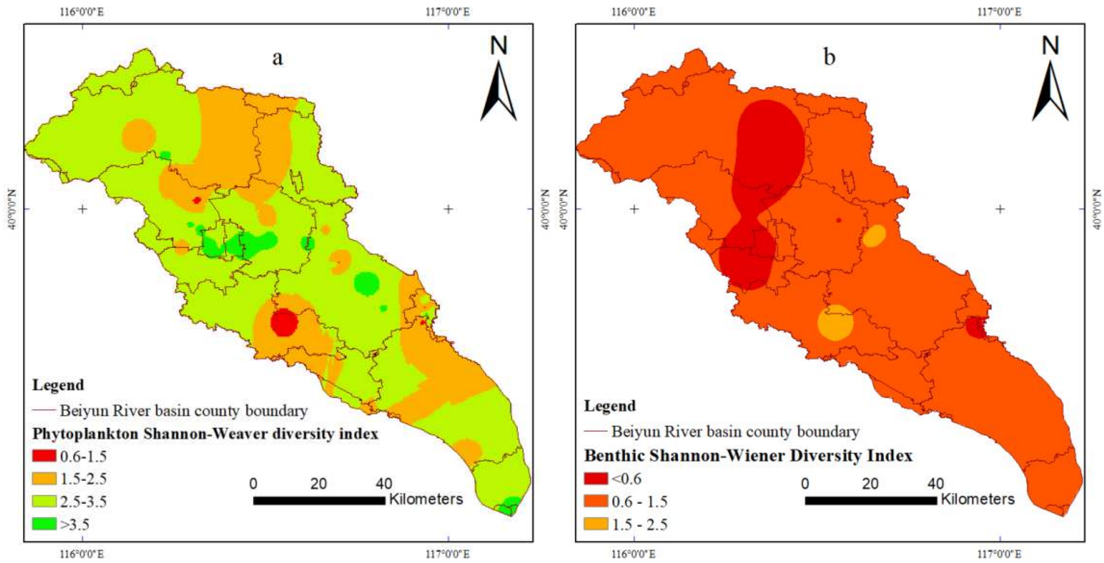

Fig. 5 (a) Distribution of phytoplankton diversity, and **(b)** distribution of benthic diversity

Fig. 5 (a) and (b) show the phytoplankton and benthic community diversity index based on the

survey results from January and February 2019. According to the classification criteria in Table 7, the results showed that the phytoplankton diversity index ranged from 0.85 to 4.07, with an average of 2.73, and the evaluation result was "healthy". As we can be seen in the fig. 5 (a), the community structure of the catchment is rich. In the Wenyu River's upper reaches, the middle reaches of the Beiyun River, and the Xinfeng River, the diversity index was low, and the water quality was poor. The community structure was most abundant in Middle reaches of the Beiyun River Basin. The water body was also cleaner, and the habitat quality was excellent. The benthic diversity index ranged between 0 and 2.06, with an average of 0.83. According to the benthic diversity, it is evaluated as "sick". Compared with the phytoplankton diversity, the benthos diversity index is relatively small, and the evaluated habitat quality type is average.

Table 7. Evaluation criteria of biodiversity thresholds

H′	>3.5	2.6~3.5	1.6~2.5	0.6~1.5	<0.6
State of community structure	very rich	rich	good	average	poor

The results showed that the concentrations of N and P and the ratio of N to P had significant effects on the species and abundance of diatoms, which could better indicate the rivers' trophic state. The survey showed that phytoplankton was mainly composed of diatoms and green algae. The river's trophic level was high and the collected benthos was mostly Limnodrilus, which live in the sewer sludge of sewage and wastewater. The existence of this species indicated that the water body was affected by organic pollution. The diversity of phytoplankton may have been disturbed by other environmental factors. According to this index, the community structure of phytoplankton in the Beiyun River Basin was rich. Considering that the samples were collected in January and February, less benthos was collected this time due to the phenology of some benthos organisms. Compared with phytoplankton, the diversity of benthos was poor.

3.5 Social functions index

According to the water quality management objectives of each river in the Beiyun River Basin, water quality standard rate of water function zone was evaluated according to the water quality category of the river reach released in 2019 (http://www.bjmemc.com.cn/waterenv_riverMore.action). The evaluation result is shown in Fig 6. The average water quality compliance rate is 74%, and the evaluation grade is "healthy". Compared with the water quality management targets set during the Thirteenth Five-Year Plan period, the situation is more optimistic. Some rivers such as Xipaigan, Guanyintang Minggou, Guangou, and Fenghe have low water quality compliance rates. The total amount of water resources in Beijing is 3.55 billion cubie meter, and the total water supply is 2.86 billion cubie meter .The utilization rate of water resources in Beijing reached 80.6 %.

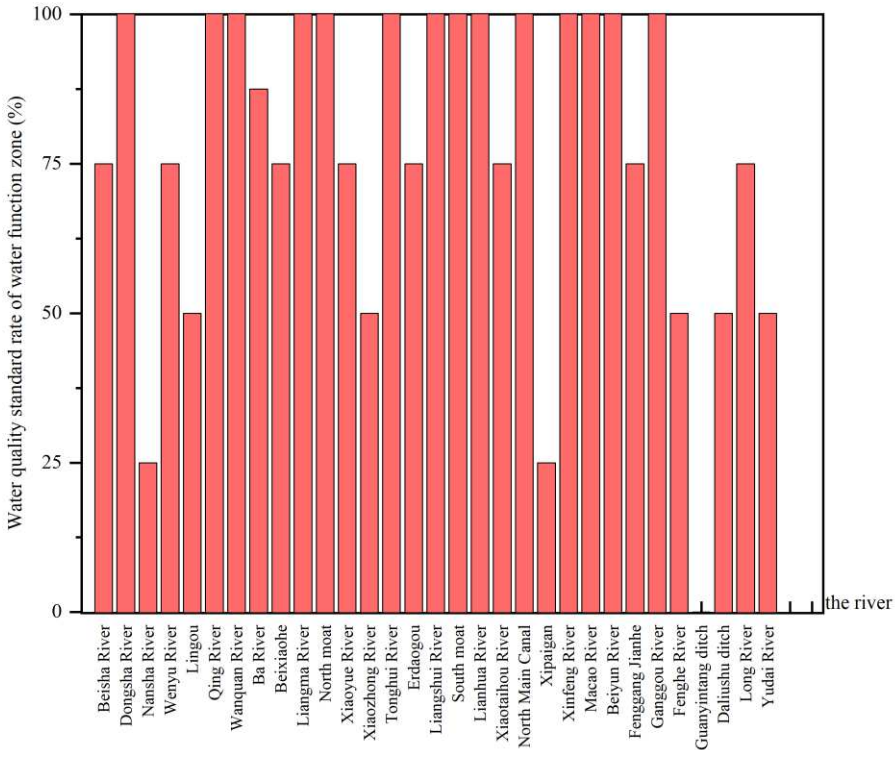

Fig. 6 Water quality standards of each reach in the Beiyun River Basin

During the Thirteenth Five-Year Plan period, it was pointed out that the water quality of the main

rivers and lakes in China should reach 80% or higher and corresponding control measures were put forward by 2020. The water quality of each river in the Beiyun River reached 74% on average. According to the “Water Resources Bulletin”, the development and utilization rate of water resources in Beijing was 80%, which far beyonds the international ecological warning line of 40% water resources development. The Beijing-Tianjin-Hebei region is a typical water-deficient urban agglomeration. Therefore, it is necessary to rely on South-to-North Water Diversion, diversion canals and other projects to transfer water to realize the supply to the city. The sustainable use of water resources has become a strategic issue for China's economic and social development and the core of improving water use efficiency and building a water-conserving society.

3.6 Comprehensive health evaluation results

Taking 2019 as the base year, a comprehensive evaluation of the health of the rivers in the Beiyun River Basin was conducted, with a score of 48, and the overall performance was sub healthy. The upstream section's health status was better than that of the downstream section. The results are shown in Table 8.

Table 8. River health assessment results of the Beiyun River Basin

Evaluating indicator			Level of health		
Target layer	Criterion layer	Index layer	Target layer	Criterion layer	Index layer
River health	water quality	I11	Sub-health	sub-health	healthy (60.6)
		I12			sub-health (22.5)
		I13			healthy (60.5)
	habitat	I21		healthy	healthy (63.2)
		I22			unhealthy (38)
		I23			healthy (68.4)
	hydrology	I31		sub-health	healthy (72)
		I32			sub-health (54.3)
	biology	I41		unhealthy	healthy (71)
		I42			morbid (11)
	social function	I51		sub-health	healthy (71)
		I52			unhealthy (25)

Fig.7 shows the comprehensive health evaluation results of Beiyun River Basin, and the whole basin is in a "sub-healthy" state. In the middle reaches of the area, with a developed economy and the best health in the entire basin, the evaluation result is “healthy”. In upstream areas where land use is mainly woodland and cultivated land, and the health evaluation result is "sub-healthy". In the Xinfeng River (downstream), which is dominated by townships and cultivated land, and the health evaluation result is "unhealthy". The results show that the health status of the areas less disturbed by human activity is better. Therefore, in the future, we can coordinate the relationship between economy and nature through human activities and improve the overall health of the Beiyun River Basin.

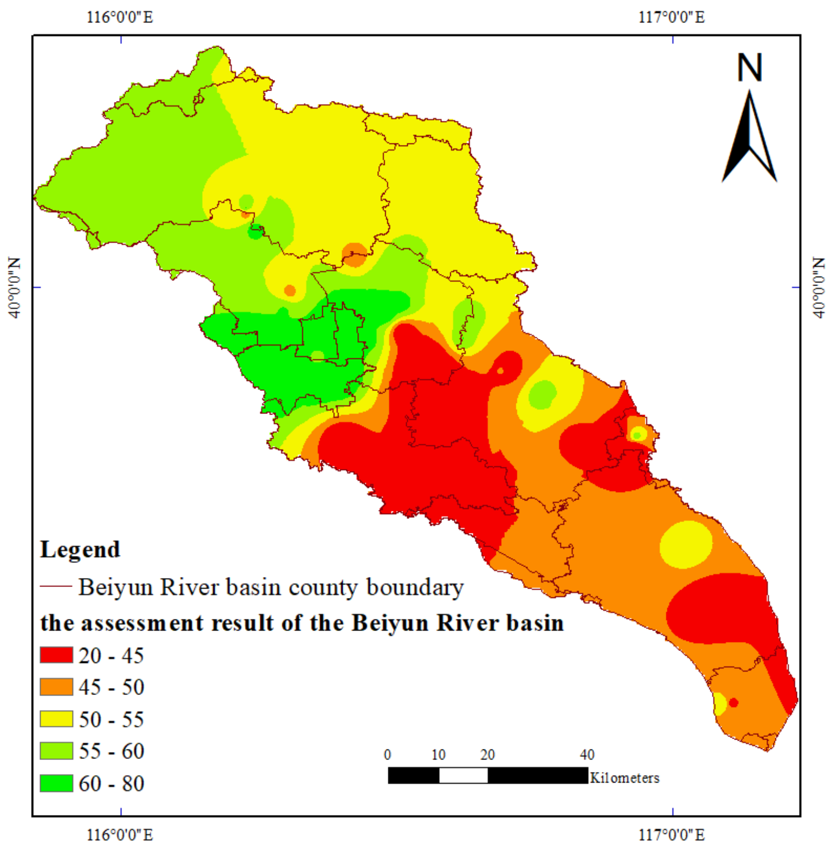

Fig. 7 Comprehensive health assessment of the Beiyun River Basin

4. Conclusions

On the whole, the health assessment result of the Beiyun River Basin is “sub-healthy”, and the

overall health status shows that the northwest mountainous area is better than the southeast plain. Specifically, the evaluation result is "healthy" in the middle reaches of the region, and the upstream evaluation result is "sub-healthy", and the Xinfeng River region located downstream is "unhealthy". In the evaluation results of criterion-level indicators, the factors that affect the overall health evaluation status in the basin are the nutrition, biodiversity, and vegetation coverage. The health evaluation result of water quality, hydrology, and social function status in the basin is "sub-healthy", and the ecological environment quality evaluation result is "healthy", and the biological survival status is "unhealthy".

Based on the analysis of the above evaluation results, the improvement of the health status of the upstream area should focus on the improvement of water quality and the ecological restoration of the habitat. The improvement of the health status of the downstream should focus on equal emphasis on water quality and quantity, restoration of biodiversity, and the quality of the riparian ecological environment. The evaluation of the health status of the basin is of great significance for guiding the management and supervision of the Beiyun River.

Acknowledgements

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Figures

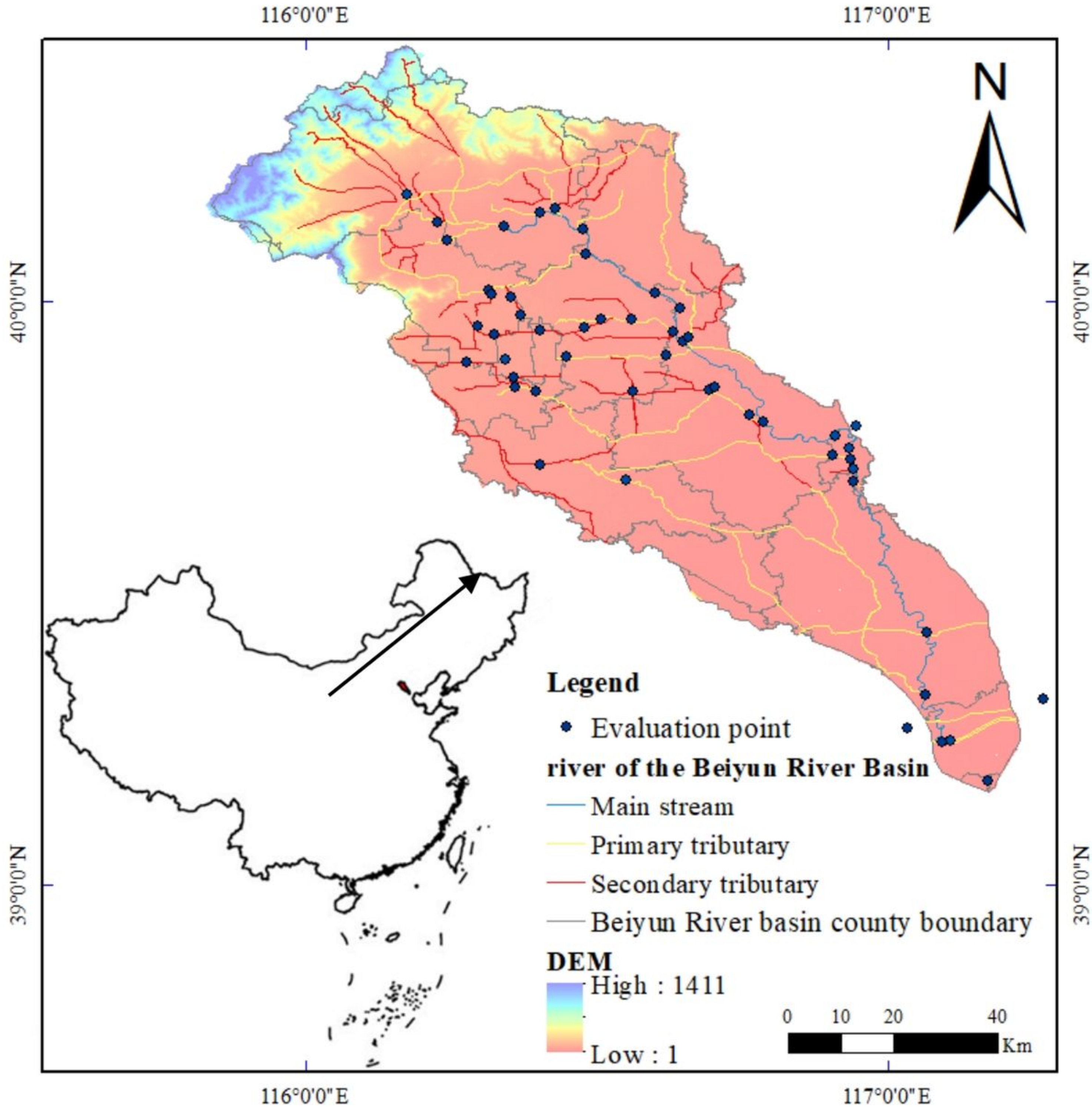

Figure 1

The maps of Beiyun River Basin Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

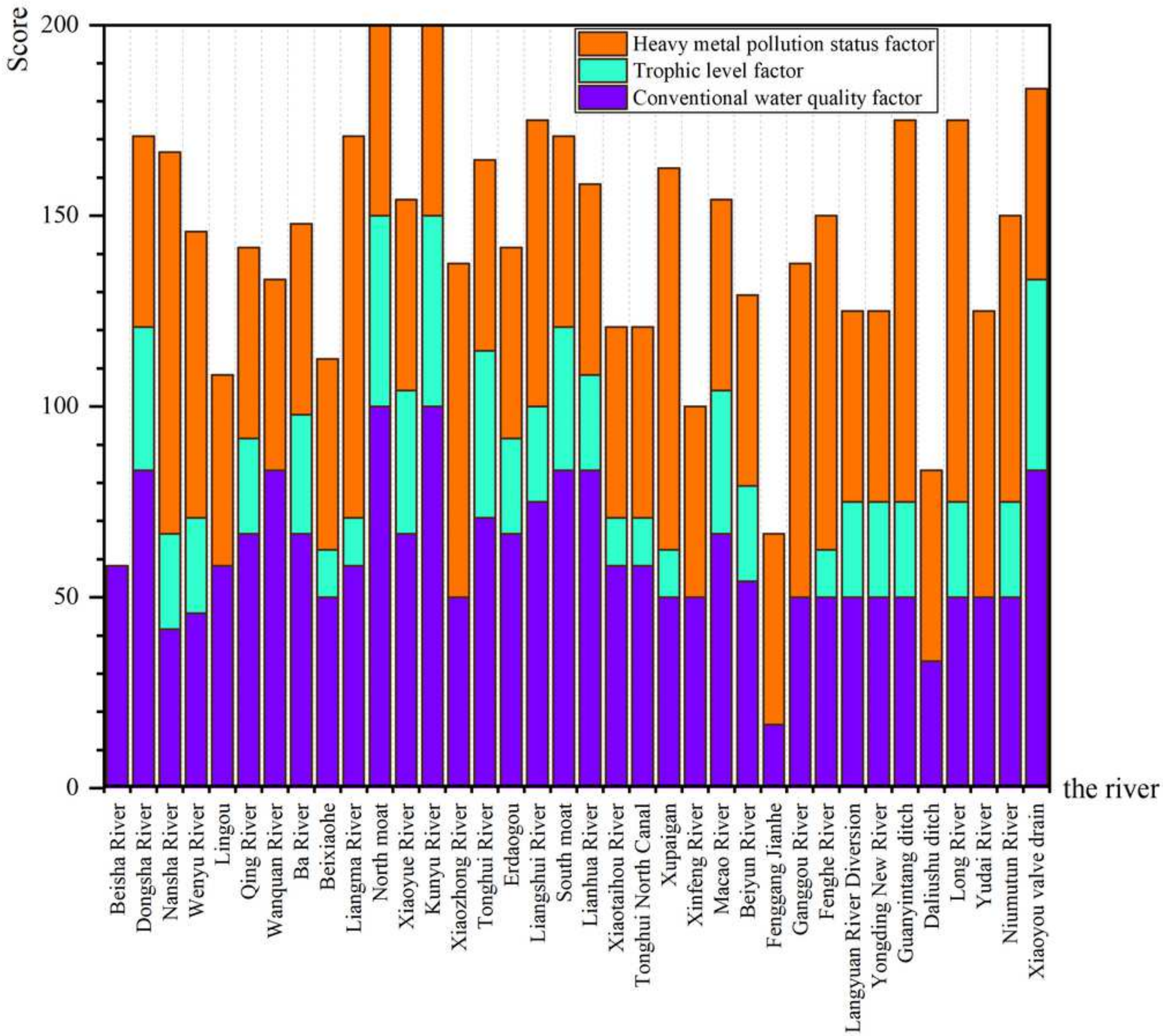

Figure 2

Water quality distribution map of the Beiyun River Basin

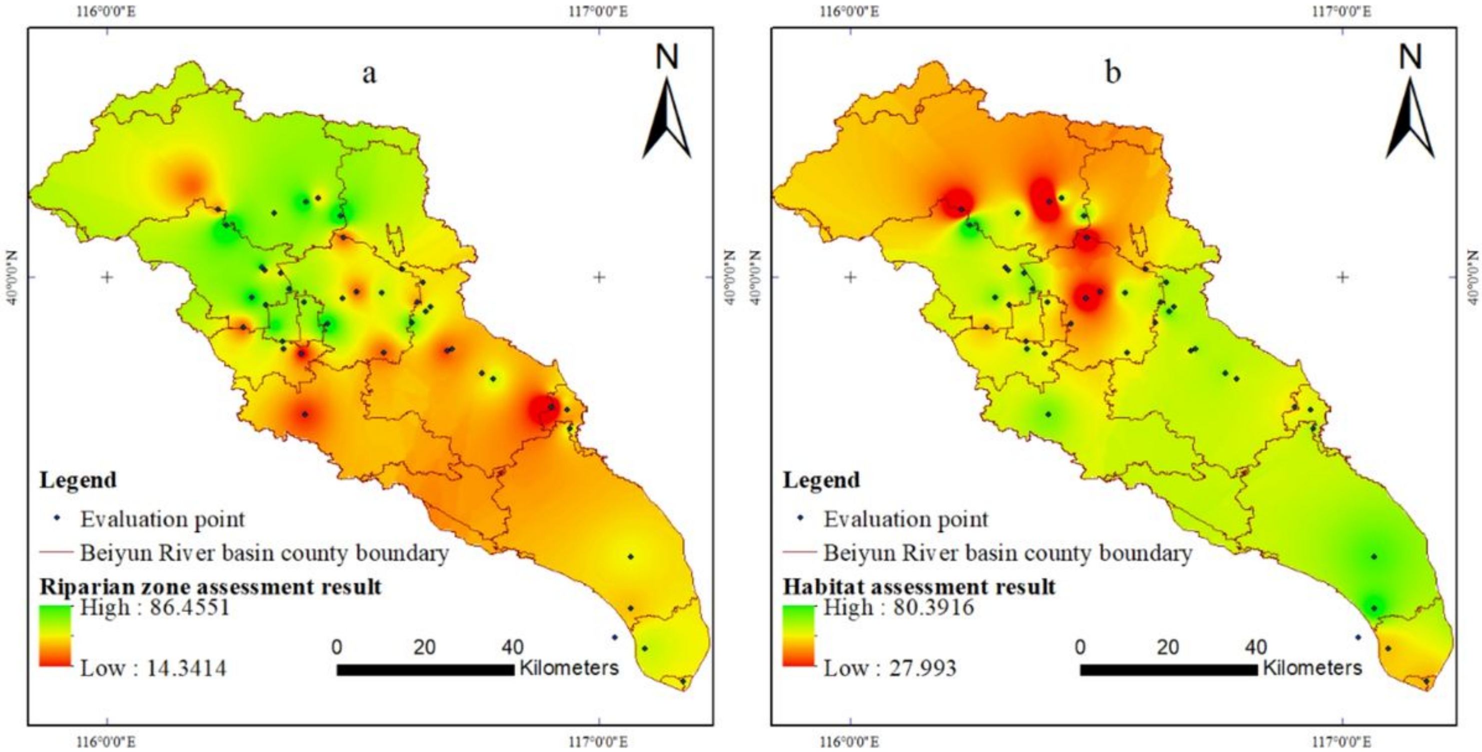

Figure 3

(a) Environmental quality assessment of the riparian zone, and (b) environmental quality assessment of habitat quality Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

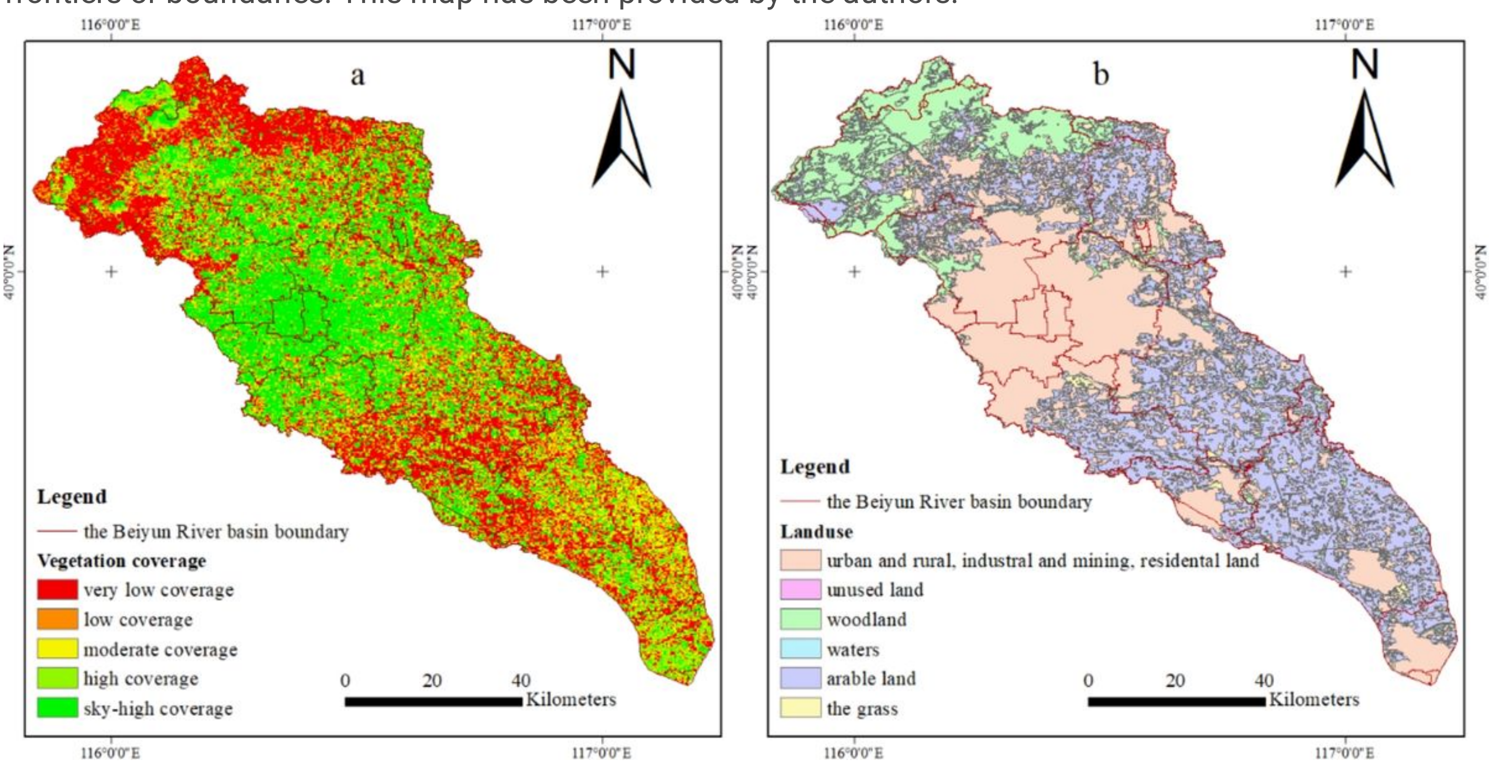

Figure 4

(a) Vegetation coverage, and (b) land use types of the Beiyun River Basin Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

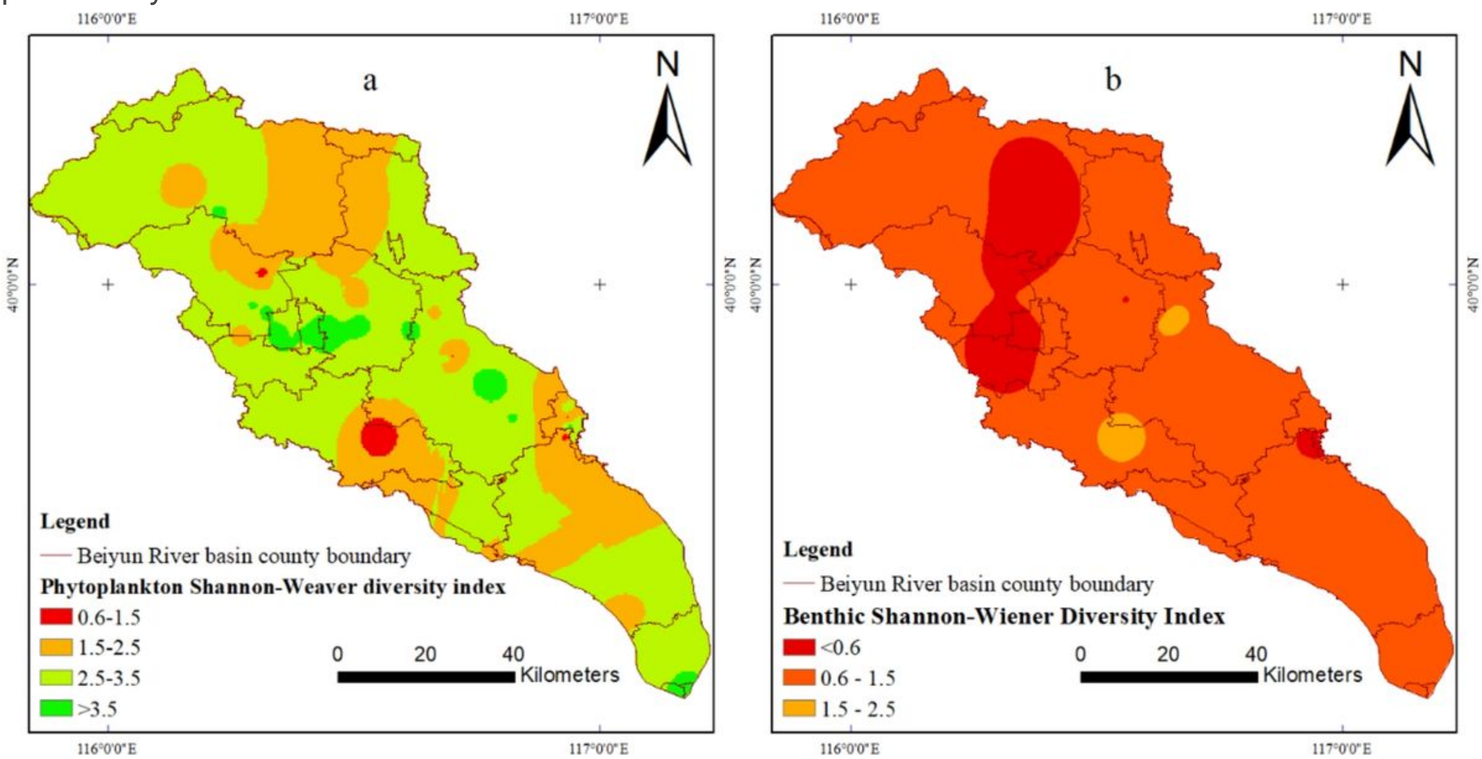

Figure 5

(a) Distribution of phytoplankton diversity, and (b) distribution of benthic diversity Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

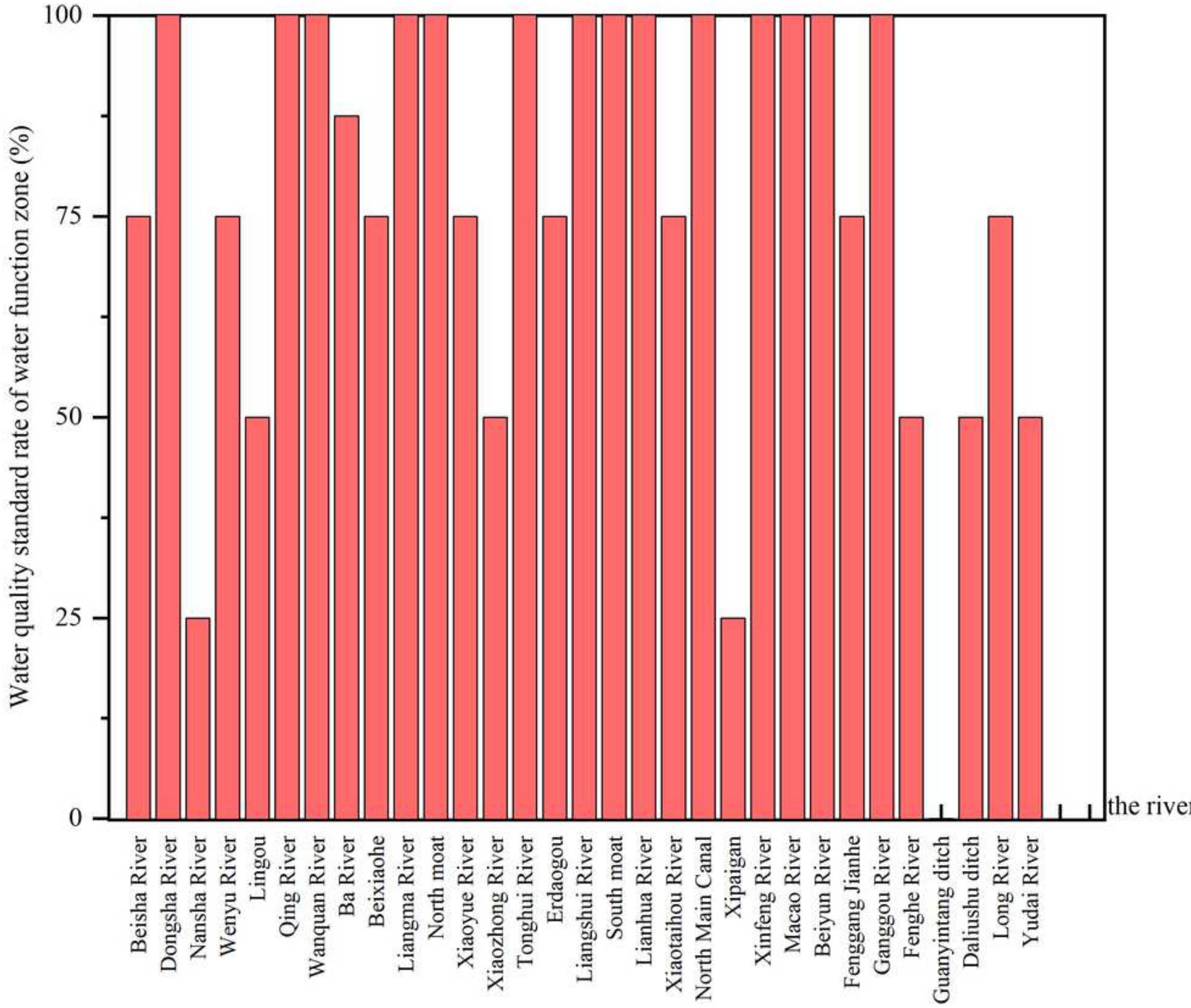

Figure 6

Water quality standards of each reach in the Beiyun River Basin

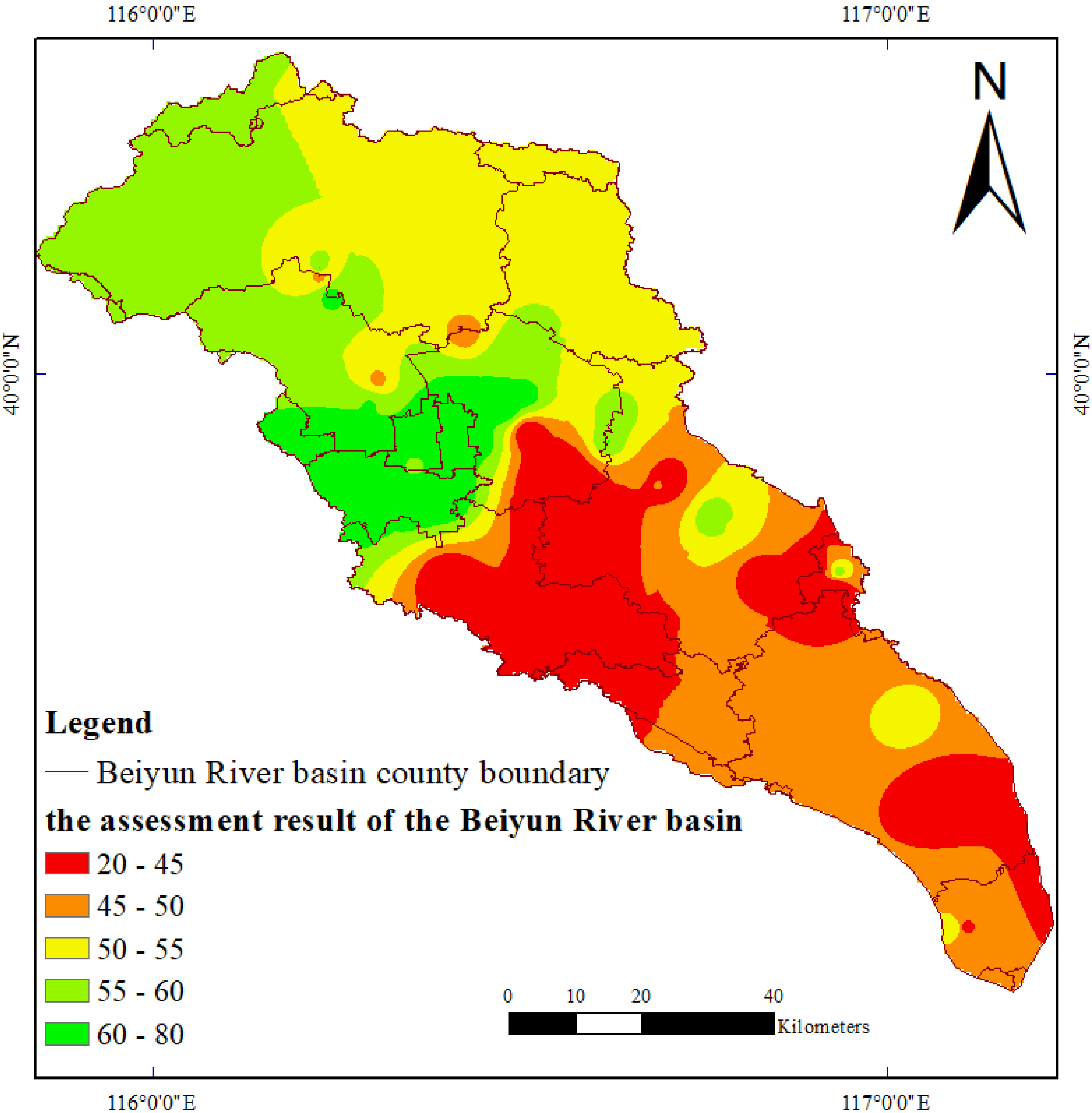

Figure 7

Comprehensive health assessment of the Beiyun River Basin Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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