Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 15 No 2, 868 doi: 10.2166/wcc.2024.653

Ecological health assessment of the Qinghe River Basin: analysis and recommendations

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ABSTRACT

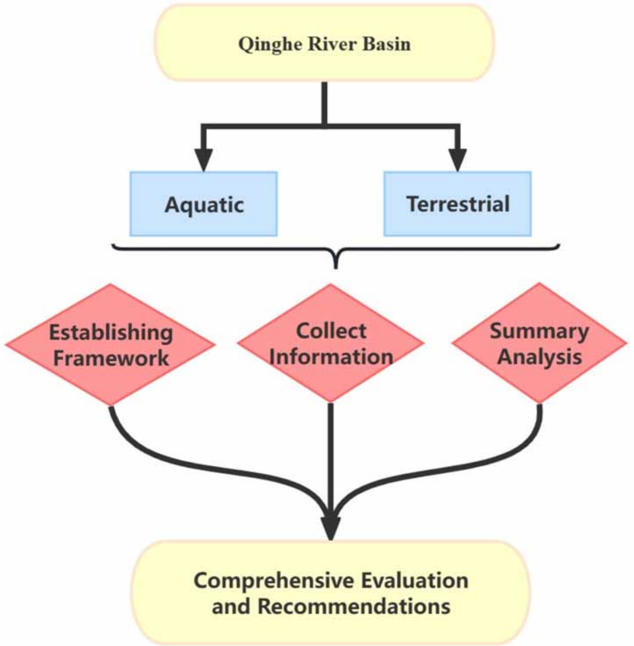
The assessment of ecosystem health at the scale of a large river basin is currently an important direction in environmental science and landscape ecology research. This study focuses on the ecological health assessment of the Qinghe River Basin. Following *the Guidelines for Eco-health Assessment of Basin* (*Trial*), a framework was designed to construct an assessment system. The aquatic and terrestrial systems of the Basin were selected, and the ecological pattern, ecological function, and ecological pressure were evaluated. The comprehensive assessment index, i.e., whole health index (WHI), was used to evaluate the overall situation of the basin, providing a comprehensive reflection of its state. The results indicate that the comprehensive index of ecological health assessment for the Qinghe River Basin is 58.66, indicating an average evaluation grade. By evaluating the health of the ecological system in the Qinghe River Basin, this study has gained an understanding of the current situation and identified major issues in the area. The study also proposes suggestions for future sustainable development and effective management of the Qinghe River Basin. These findings hold significant practical importance for the comprehensive protection and development of the area.

Key words: basin ecological health, environmental protection and management, integrated assessment, Qinghe River Basin

HIGHLIGHTS

- Adopting a comprehensive assessment framework, including aquatic and terrestrial ecosystems, using the whole health index for comprehensive assessment.
- The evaluation covers the entire Qinghe River Basin, providing a comprehensive understanding and evaluation.
- Provided theoretical and practical guidance for sustainable development.
- The evaluation results provide decision-making basis for policymakers.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Rivers are a type of flowing water ecosystem that support abundant natural resources and diverse biodiversity. They play a vital role in the material cycle of the biosphere and are crucial for maintaining environmental security and ensuring sustainable development (Li *et al.* 2022b). The ecological health of basins is closely connected to concepts such as biodiversity and ecological integrity. Monitoring basins plays a crucial role in identifying existing or potential ecological problems and serves as a scientific foundation for pollution and environmental management, as well as protection (Wang *et al.* 2019). Traditionally, water chemistry and toxicity tests have dominated basin monitoring in the past few decades (Bruno *et al.* 2014). However, to enhance the ecological health of basins, it is necessary to develop new monitoring programs. These programs should include prospective evaluations of the area of interest, utilizing multiple metrics that encompass the diverse nature of the ecosystem (Lin *et al.* 2021). Furthermore, the assessment of the ecosystem should consider individual, population, community, and landscape conditions (Martinez-Haro *et al.* 2015).

However, basin ecosystems are complex and variable, making it challenging to accurately assess their ecological status due to a combination of natural and anthropogenic factors (Chen *et al.* 2016). Numerous research studies have suggested various methods and indicators to evaluate the ecological status of basins. Lukin *et al.* (2011) investigated the relationship between fish health and environmental quality. They discovered that fish from the Pechora River experienced various histopathological alterations and acute damage after being exposed to contaminated water and sediments for a short period of time. Yan *et al.* (2016) further enhanced the understanding of ecosystem health assessment by incorporating ecosystem services. They developed the VOR (vigor, organization, resilience) model into the VORS (vigor–organization–resilience–service) model, which added the S (service: soil and water conservation) assessment framework. Fei *et al.* (2017) assessed the ecological safety of the Yuxi River Basin in Hunan Province, China. They examined the spatial and temporal distribution of antimony and other heavy metal pollutants (Pb, Zn, and As), as well as the risk of population exposure. The aim was to determine the ability of ecosystems in maintaining ecological health under different ecological risk scenarios. Zhao *et al.* (2018) focused on the sustainable development of the Liaohe River Basin. They developed an analysis framework called the 'structure–quality–process' to evaluate the ecological safety of the basin, considering both its own development and regional ecological macro-control. Luo *et al.* (2018) proposed an evaluation method for water ecology and environment management. They based their method on the harmony theory, the river prediction model, and the index evaluation method. They considered the perspective of both ecosystem integrity and human service demand. Liu *et al.* (2019) evaluated the ecological and human health risks of heavy metals in the middle reaches of the Fen River Basin. They referred to indicators such as enrichment factor, potential ecological risk index, hazard quotient, and cancer risk in the context of agricultural nonpoint source pollution. Yang *et al.* (2020) examined ecological risk sources, stressors, endpoints, and corresponding response mechanisms in the Weihe River Basin. They developed a conceptual model of risk response and conducted a comprehensive ecological risk assessment using an improved Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) model and a combined weighting method. Wu *et al.* (2020) utilized cluster analysis and canonical correlation analysis to evaluate aquatic ecological health by introducing the fish index of biological integrity and the benthic macroinvertebrate index of biological integrity. Ulaganathan *et al.* (2021) conducted an assessment of ecological and human health risks by detecting changes in pesticide concentrations in water, sediment, and fish in Thamirabarani, a perennial river, in Tamil Nadu, India. Jiang *et al.* (2021) developed an integrated framework to assess the impacts of climate change and human activities on the hydrological health of the Laoha River Basin in northern China. They used a variable infiltration capacity hydrological model, an ecological flow threshold method, and an observation–simulation comparison method to understand the evolutionary characteristics and driving mechanisms of the basin.

The majority of the current studies focus on one element, which makes it difficult to comprehensively assess the status of ecosystems (Cao *et al.* 2023). In addition, there is limited understanding of the structural integrity and health of aquatic ecosystems. Furthermore, the impact of river habitat restoration on ecosystem functions remains poorly understood, and the assessment results offer limited reference value (Lin *et al.* 2020). Therefore, there is an urgent need to develop accurate and comprehensive methods for ecological health assessment in river basins within the field of ecology and environmental management.

This study refers to *the Guidelines for Eco-health Assessment of Basin (Trial)* developed by the State Department of Ecology and Environment in 2013. These guidelines serve as the reference for determining the research scale, indicator system, evaluation model, classification, as well as general principles, methods, content, and technical requirements for assessing the ecological health of basin ecosystems. The development of the evaluation indicator system adheres to the principles of being scientific, systematic, concise, and providing operational guidelines.

This study proposes to use the comprehensive index method to comprehensively evaluate the aquatic and terrestrial ecosystems in the Qinghe River Basin of Liaoning Province, China. The objective is to gain a comprehensive understanding of the ecological status of the basin and provide theoretical and practical support for the development of management and protection strategies. In addition, feasible suggestions will be proposed, and scientific references will be provided for the protection and the management of basin ecosystems.

2. MATERIALS AND METHODS

2.1. Overview of the study area

2.1.1. Geographical location and topography

Being a major tributary of the Liaohe River system, the Qinghe River flows through Qinghe District and Kaiyuan City. The mainstream of the river is the southern branch, which originates from Laohuding Mountain in Qingyuan County. The basin stretches for 217.1 km and covers an area of 5,674.3 km^2. It encompasses eight first-class tributaries, including the Xiaoqing River, Ala River, Tebi River, Kou River, Erdaogou River, Mianpan River, Mazhong River, and Qianma River.

The study area is situated in the low hilly region of the Changbai Mountain range. It has an elevation ranging from 100 to 600 m, with higher topography in the north and lower topography in the south. Around 85% of the basin is mountainous, and it has an average slope drop of 0.93‰. The slope above the Kaiyuan city is approximately 2‰, but it decreases below Kaiyuan due to the flat terrain.

2.1.2. Climatic characteristics

The study area is characterized by a north temperate zone southwest monsoon Continental climate, with hot and rainy summers and cold and dry winters. The annual precipitation ranges from 700 to 800 mm. The frost-free period accounts for 38% of the year, with the first frost typically occurring in late September and the final frost appearing in late April of the following year. The average annual temperature in the region is 6.0 °C, with the lowest temperature being −41 °C, usually experienced in January. The highest temperature reaches 35.7 °C, typically occurring in July and August.

2.2. Establish evaluation system and determine evaluation indicators

Spatially, the evaluation is conducted at two scales. The first scale involves assessing the overall condition of the Qinghe River Basin by considering the entire basin as the evaluation unit. The second scale involves using selected points as evaluation units, where various indicators are calculated (Ge *et al.* 2022). The assessment focuses on the aquatic and terrestrial systems of the basin. The general framework of the assessment consists of three aspects: the ecological structure status, the function status, and the pressure status. The assessment indicator system is divided into two subsystems: aquatic ecosystems and terrestrial ecosystems (Wang 2019). Each subsystem has its own set of indicators.

According to *the Guidelines for Ecological Health Assessment of Basin (Trial)*, there are a total of 17 assessment indicators classified into 6 categories. The explanations and weights for each indicator are presented in Table 1.

The ecological health assessment indicators in the Qinghe River Basin were classified into five levels: excellent, fine, average, fair, and poor. The standard values for each indicator were determined using the data processing method specific to each assessment indicator. The assigned criteria for grading the indicator calculation results are presented in Table 2.

2.3. Evaluation methodology

2.3.1. Data sources

The index system for this assessment consists of 6 categories and a total of 17 items. Each assessment unit in the Qinghe River Basin needs to be evaluated based on this index system. The final evaluation results are obtained using a comprehensive index model. The data sources for this assessment are described as follows:

Table 1 | Basin ecological health assessment index system

Assessment object	Indicator type	Assessment indicator	Indicator interpretation	Weights
Aquatic ecosystem (0.4)	Ecosystem structure (0.4)	Water quality condition index	Percentage of all water quality monitoring sections in the basin that are of class III or above	0.4
		Runoff during the dry period as a proportion of the average annual runoff for the same period	Reflecting the function of basin (flood regulation) to replenish dryness	0.3
		River connectivity	The current status of river connectivity in the region	0.3
	Hydrobiont (0.3)	Macrobenthic diversity composite index	Assessing the species integrity of benthic organisms	0.4
		Composite index of fish species diversity	Assessing the integrity of fish species	0.4
		Conservation rate of endemic (indicative) species	Conservation status of endemic or indicator species within the basin	0.2
	Ecological pressure (0.3)	Intensity of water resources development and utilization	Degree of development and utilization of water resources within the basin	0.5
		Aquatic habitat disturbance index	Reflects the extent to which the basin habitat has been damaged by man-made sand dredging, shipping, tourism, and other activities	0.5
Terrestrial ecosystem (0.6)	Ecological pattern (0.3)	Forest coverage rate	Abundance of forest resources in the region	0.2
		Landscape fragmentation	Degree of fragmentation of ecosystems within the region	0.2
		Rate of important habitat conservation	Riparian zone conditions in the region	0.6
	Ecological function (0.3)	Water source containment function index	Hydrological status of the ecosystem in the area	0.4
		Soil conservation function index	Soil erosion status within the region	0.3
		Proportion of the area of protected areas to the national territory	Reflects the extent to which the basin is protected	0.3
	Ecological pressure (0.4)	Proportion of construction land	Reflects the degree of obstruction to the material cycle and energy flow of natural ecosystems	0.4
		Point source pollution load emission index	Reflects the pressure of pollutants emitted by human activities on basin ecosystems	0.3
		Emission index of nonpoint source pollution	Reflecting the pressure of nonpoint source pollution loads such as agricultural production and livestock and poultry breeding on the basin ecosystem	0.3

Table 2 | Standardized assignment of indicators and grading criteria

Grading criteria	Excellent	Fine	Average	Fair	Poor
Assignment standard value	$N \geq 80$	$60 \leq N < 80$	$40 \leq N < 60$	$20 \leq N < 40$	$N < 20$

(1) The aquatic ecosystem survey is conducted through field sampling, surveys, and questionnaire surveys. The survey of aquatic life is carried out during both the abundant water period and the dry water period, taking into account the hydrological conditions.
(2) The terrestrial ecosystem survey primarily relies on remote sensing interpretation, supplemented by the analysis of sectoral statistical data.
(3) For the water quality and basin pollution load surveys, statistical data from various departments are utilized. In the absence of statistical data, point monitoring methods are employed. Figure 1 illustrates the distribution of the 26 monitoring points.

2.3.2. Indicator calculation method

(1) Water quality condition index

Water quality condition index = basin III and above grade water quality monitoring section number/monitoring section total. Water quality standards are classified according to GB3838-2002 (SEPA, AQSIQ 2002).

(2) Runoff during the dry period as a proportion of the average annual runoff for the same period

Runoff during the dry period as a percentage of the average annual runoff = Runoff during the dry period/Average annual runoff during the dry period.

(3) River connectivity

River connectivity = (Number of hydroelectric projects such as gates and dams, hydropower stations, etc.)/Per 100 km.

(4) Macrobenthic diversity composite index

① Number of taxonomic units (S): The total number of benthic fauna of each type obtained from the samples collected at a point after identification.

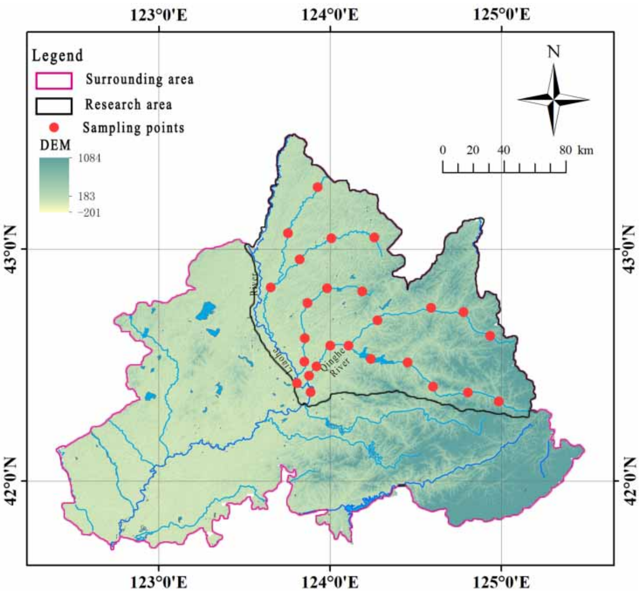


Figure 1 | Sample point distribution map.

② EPT family-level taxonomic unit ratio (EPTr-F): The proportion of the total number of family-level units of the mayfly, Plecoptera, and Trichoptera in the samples collected at a certain location to the total number of family-level units in the samples.

③ Macrobenthic biological monitoring working party (BMWP) index:

$$\text{BMWP index} = \sum t_i$$

where t_i refers to the sensitivity value of the i species in the sample collected at a point based on the family-level taxonomic order element.

④ Berger–Parker dominance index for macrobenthos (D):

$$D = \frac{N_{\max}}{N}$$

where $N_{\max}$ is the number of the most dominant species in the samples collected at a point and N is the number of all individuals identified in the laboratory.

Standardized formulae of ①, ②, ③, and ④ are as follows:

① $S = \dfrac{\text{Measured} - 5\%\,\text{quantile}}{95\%\,\text{quantile} - 5\%\,\text{quantile}}$

② EPT section classification unit ratio (EPTr-F) standardized formula:

Here, E is ephemeroptera, P is plecoptera, and T is trichoptera. These three groups are highly sensitive to environmental interference.

EPT – mountain area:

$$\text{EPTr} - \text{F} > 0.48, \quad \text{EPTr} = 1.0;$$

$$\text{EPTr} - \text{F} < 0.48, \quad \text{EPTr} = 0.0297\text{e}^{7.26019\left(\frac{\text{EPT}}{\text{Total}}\right)}$$

EPT – hilly areas:

$$\text{EPTr} - \text{F} > 0.36, \text{EPTr} = 1.0;$$

$$\text{EPTr} - \text{F} < 0.36, \quad \text{EPTr} = 0.0364\text{e}^{9.1382\left(\frac{\text{EPT}}{\text{Total}}\right)}$$

EPT – plains areas:

$$\text{EPTr} - \text{F} > 0.17, \quad \text{EPTr} = 1.0;$$

$$\text{EPTr} - \text{F} < 0.17, \quad \text{EPTr} = 0.0271\text{e}^{20.635\left(\frac{\text{EPT}}{\text{Total}}\right)}$$

③ $\text{BMWP} = \dfrac{\text{Measured} - \text{Min}}{\text{Max} - \text{Min}}$

④ $D = \dfrac{95\%\,\text{Measured} - \text{Quantile}}{95\%\,\text{Quantile} - 5\%\,\text{Quantile}}$

where 'Measured' refers to the actual data detection value of any one indicator at the sample point; 5% quintile refers to the 5% quantile value of any one indicator detection data; 95% quintiles refers to the 95% quantile value of any one indicator detection data; EPTr-F is the trichoptera of large benthic mayflies (E), plecoptera (P), and trichoptera (T). The number of insect family-level taxonomic units in the total number of all family-level taxonomic units in the sample is as follows: EPTr is the standardized value; Min in the standardized formula of BMWP is 0, and Max is 131 in mountainous areas and 81 in hilly plains.

(5) Composite index of fish species diversity

① Total number of taxonomic units (S), i.e., the number of fish species occurring in the samples collected at a point.
② Shannon–Wiener index (H)

$$H = \sum_{i}^{s} (\mathrm{pi})\log_2(\mathrm{pi})$$

③ Berger–Parker dominance index (D)

$$D = \frac{N_{\max}}{N}$$

where $N_{\max}$ is the number of most dominant species in the samples collected at a site and N is the number of individuals of all species in the site.

Standardized formulae for calculating 'composite index of fish species diversity':

① $$\frac{\text{Measured} - 5\%\,\text{Quantile}}{95\%\,\text{Quantile} - 5\%\,\text{Quantile}}$$

② $$\frac{\text{Measured} - 0}{3 - 0}$$

③ $$\frac{95\%\,\text{Measured} - \text{Quantile}}{95\%\,\text{Quantile} - 5\%\,\text{Quantile}}$$

where 'Measured' refers to the detected value of the actual data of any indicator at the sample point; 5% quintile refers to the value of the 5% quantile of the detected data of any indicator; and 95% quintile refers to the value of the 95% quantile of the detected data of any indicator.

(6) Conservation rate of endemic (indicative) species

Acquired from aquatic life surveys or questionnaires, and then scored according to assessment guidelines.

(7) Intensity of water resources development and utilization

Intensity of water resources development and utilization = industrial, domestic, agricultural, environmental, and other water consumption/total water resources

(8) Aquatic habitat disturbance index

$$\text{Aquatic habitat disturbance index} = \sum_{i=1}^{n} H_i \omega_i$$

where H_i denotes the health score of the ith indicator and ω_i denotes the weight of the ith indicator, where i is 3, with specific reference to the assessment guidelines.

(9) Forest cover rate

$$\text{Forest cover rate} = \text{Forest area}/\text{Inland area of study area} \times 100\%$$

(10) Landscape fragmentation

$$C_i = \frac{N_i}{A_i}$$

where C_i denotes landscape fragmentation, N_i is the number of patches of vegetation in the study area such as forest and grassland, and A_i is the total area of the regional interior.

(11) Rate of important habitat conservation

Rate of important habitat conservation = Proportion of natural embankment × 0.3 + Vegetation integrity index × 0.7.
Percentage of natural embankment = Length of embankment in the basin/Total length of assessment × 100%.

Vegetation structural integrity index = (Standard value of ecosystem type classification × Area of that type)/Total area of important habitats × 100%.

(12) Water source containment function Index

$$\text{Water containment function index} = \sum_{i}^{n} H_i \cdot \omega_i$$

where H_i denotes the health value of the ith assessment indicator and ω_i denotes the weight occupied by the i assessment indicator, where n is 3.

Referring to the theory of the image element dichotomous model, it is obtained that:

$$F_c = \frac{\text{NDVI} - \text{NDVI}_{\text{soil}}}{\text{NDVI}_{\text{veg}} - \text{NDVI}_{\text{soil}}}$$

where F_c refers to the vegetation cover, NDVI_{veg} is the NDVI value obtained when the image element is pure vegetation, and $\text{NDVI}_{\text{soil}}$ is the NDVI value obtained when the image has no vegetation cover at all. NDVI come from remote sensing image interpretation. (NDVI:Normalized Difference Vegetation Index).

(13) Soil conservation function index

Soil function index = area occupied by moderate soil erosion and above/regional land area

(14) Proportion of the area of protected areas to the national territory

$$S = \sum_{i}^{n} A_n/\text{TA}$$

where S is the proportion of the protected area in the national land area; A_n is the total area of the protected area; and TA is the total land area in the basin.

(15) Proportion of construction land

Proportion of construction land = Construction land area/Total land area in the region.

(16) Point source pollution load emission index

Point source pollution load emission index = 0.5 × Point source COD emission/Point source COD target emission + 0.5 × Point source ammonia nitrogen emission/Point source ammonia nitrogen target emission (where COD is the chemical oxygen demand).

(17) Emission index of nonpoint source pollution

Emission index of nonpoint source pollution = 0.5 × Nonpoint source COD emissions/Nonpoint source COD target emissions + 0.5 × Nonpoint source ammonia nitrogen emissions/Nonpoint source ammonia nitrogen target emissions.

2.3.3. Comprehensive basin health assessment

For the assessment of ecological health, the P-S-R (pressure–state–response) model or the VOR model can be chosen. However, no matter which model is used for assessment, the result obtained is a relative value due to the complex composition and integrated nature of the ecosystem. For convenience, the commonly used integrated index method, using the integrated assessment index whole health index (WHI), is therefore used to assess the integrated condition of the basin.

The comprehensive index method was used to conduct a comprehensive evaluation of the ecosystem in the study area. The comprehensive evaluation index, i.e., WHI, was obtained by weighted summation, which was used to reflect the overall health of the study area.

WHI calculation method

$$\text{WHI} = I_A W_A + I_T W_T$$

where I_A is the aquatic ecosystem health score, W_A is the basin ecosystem health index weight, I_T is the terrestrial ecosystem health score, and W_L is the terrestrial ecosystem health index weight, and I_T and I_L are then calculated from the secondary indicators of aquatic and terrestrial areas by weighting.

Aquatic health index value:

$$I_A = \Sigma_i^n W_i \times x_i'$$

Terrestrial health index values:

$$I_T = \Sigma_i^n W_i \times x_i'$$

where W_i is the respective secondary indicator weight value and x_i' is the secondary indicator value.

The grading criteria of basin ecological health assessment results are shown in Table 3.

3. RESULTS AND DISCUSSION

3.1. Analysis of evaluation results

Table 4 shows the standardized allocation results of aquatic, terrestrial, and overall ecosystem health analysis in the Qinghe River Basin. This study evaluates the ecological pressure indicators of the Qinghe River Basin to determine the ecological stress status of its aquatic and terrestrial areas. The findings are represented in the form of radar maps, which visually depict the main limiting factors affecting the ecological health of the basin.

Based on Figure 2, the aquatic ecosystem health of the Qinghe basin is rated as fine. However, there are certain areas that require improvement, as four indicators of the aquatic ecological health status fell below 60 points. Specifically, the

Table 3 | Assessment index values and grading criteria

Grading criteria	Excellent	Fine	Average	Fair	Poor
Assignment standard value	$WHI \geq 80$	$60 \leq WHI < 80$	$40 \leq WHI < 60$	$20 \leq WHI < 40$	$WHI < 20$

Table 4 | Table of standardized assignment results of indicators

Assessment object	Indicator type	Assessment indicator	Weights	Standard value *N*	Overall score
Aquatic ecosystem (0.4)	Ecosystem structure (0.4)	Water quality condition index	0.4	46.15	60.03
		Runoff during the dry period as a proportion of the average annual runoff for the same period	0.3	99	
		River connectivity	0.3	78	
	Hydrobiont (0.3)	Macrobenthic diversity composite index	0.4	32	
		Composite index of fish species diversity	0.4	36	
		Conservation rate of endemic (indicative) species	0.2	50	
	Ecological pressure (0.3)	Intensity of water resources development and utilization	0.5	75	
		Aquatic habitat disturbance index	0.5	60	
Terrestrial ecosystem (0.6)	Ecological pattern (0.3)	Forest coverage rate	0.2	90	57.74
		Landscape fragmentation	0.2	40	
		Rate of important habitat conservation	0.6	44.62	
	Ecological function (0.3)	Water source containment function index	0.4	47	
		Soil conservation function index	0.3	95	
		Proportion of the area of protected areas to the national territory	0.3	0	
	Ecological pressure (0.4)	Proportion of construction land	0.4	90	
		Point source pollution load emission index	0.3	55	
		Emission index of nonpoint source pollution	0.3	56	

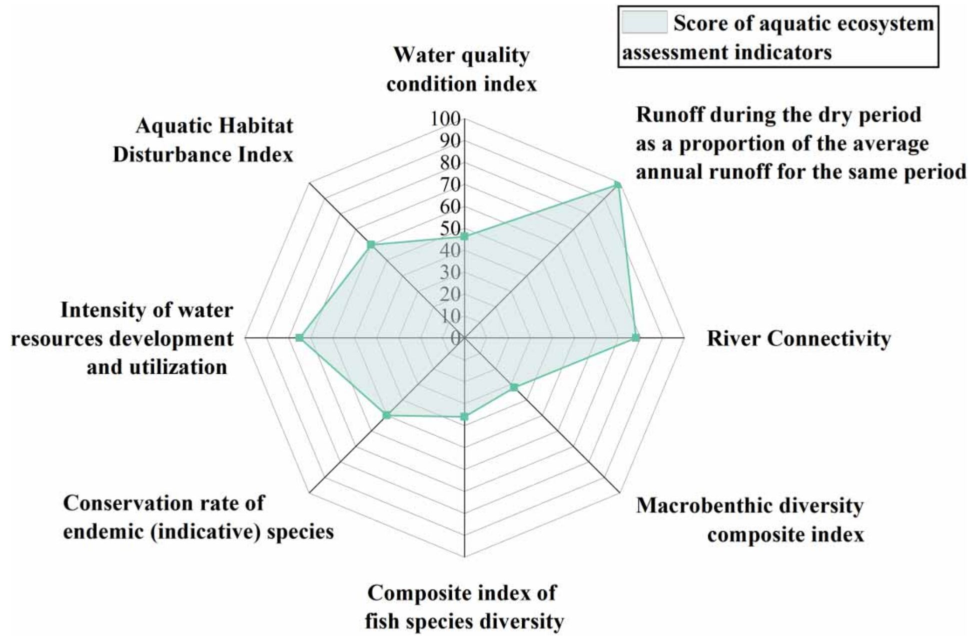


Figure 2 | Results of ecological health status assessment of Qinghe aquatic ecosystem.

macrobenthic diversity composite index and composite index of fish species diversity scored below 40 points, indicating a poor state in these areas. Simultaneously, the conservation rate of endemic (indicative) species in the aquatic ecosystem is also in a poor state, indicating some shortcomings in the conservation of unique species (Johnson *et al.* 2017).

The evaluation grade of the water quality condition index was average, indicating that industrial wastewater and domestic sewage in the basin have a significant impact on the quality of the water environment. The high score of the runoff during the dry period as a proportion of the average annual runoff for the same period suggests that the groundwater condition in the region is favorable, indicating that the basin has a good ecosystem regulation function (Shi 2021). In addition, the good evaluation grade of river connectivity implies that engineering facilities like dikes and hydroelectric power stations have a minimal impact on the ecological environment of the study area.

The primary limitation of the ecological health status of the aquatic in the Qinghe River Basin, as depicted in Figure 2, is the aquatic life index. Specifically, the macrobenthic diversity composite index scores are the lowest, which could be attributed to the water quality in the basin. The quality of water has a significant impact on the structure and function of biological habitats (Lv *et al.* 2014), and human disturbances also disrupt biological habitats to varying extents (Shi *et al.* 2022).

Second, factors influencing fish species diversity include engineering facilities such as dike construction (Guo *et al.* 2018), which may contribute to a composite index of fish species diversity. Another factor affecting fish diversity is fish invasion (Wang *et al.* 2021a). Also, recreational fishing also affects fish diversity (Zachary *et al.* 2018).

Again, endemism or the retention of indicator species refers to the phenomenon where small environmental changes in aquatic ecosystems can result in changes in species populations (Li *et al.* 2022c). This can have a negative impact on fish reproduction (Caldas and Godoy 2019).

The health of the terrestrial ecosystem in the Qinghe River Basin is assessed as being in an average state based on Figure 2. Three indicators of terrestrial ecological health status score above 90 points, reflecting the positive impact of investment in forestry construction and soil protection. Despite these strengths, it is important to note that the basin currently lacks any protected land area, emphasizing the need for strengthened ecological environment protection measures.

Conversely, low scores in landscape fragmentation, rate of important habitat conservation, and water source containment function suggest that human activities are interfering with the balanced development of the ecosystem. In terms of pollution, the point source pollution load emission index and surface source pollution load emission index scores hover around 60, indicating certain achievements in environmental management and governance (Wang *et al.* 2021b). However, further improvements in reducing pollution loads and increasing efforts to enhance environmental quality and protect ecosystems and human health are still required (Shan *et al.* 2015).

The main constraints reflecting the ecological health status of the terrestrial ecosystem of the Qinghe River Basin in Figure 3 include both ecological functions and ecological patterns. The ecological health status of the terrestrial ecosystem of the Qinghe River Basin in Figure 3 is constrained by both ecological functions and ecological patterns. One important factor is the area of protected areas, which is expressed as a percentage of the national land area. This score can vary depending on the regional situation of the basin. The determination of the protected areas is based on relevant laws, policies, and management objectives, using specific assessment and establishment criteria (Wang *et al.* 2023).

The second issue is landscape fragmentation, which is closely related to the pressing environmental concern of soil erosion. Soil erosion poses a threat to the landscape pattern, while the process of human urbanization also significantly impacts it (Luo *et al.* 2020).

The rate of critical habitat maintenance has been affected by human activities, including polder and construction land encroachment. These activities have resulted in a reduction of natural vegetation and wetlands in the riparian zone, leading to a degradation of ecological functions.

The ecological health of the Qinghe River Basin was calculated by assigning a weight of 0.4 to the ecological health of the aquatic and a weight of 0.6 to the ecological health of the terrestrial. The calculation was done using the formula: Ecological health of the basin = Aquatic × 0.4 + Terrestrial × 0.6. The result of this calculation was 58.66, as shown in Table 5.

It can be seen that the overall ecological health evaluation index of the Qinghe River Basin is 58.66, and the evaluation grade is average.

This assessment method may have limitations in comprehensively covering all the factors that influence the ecological health of the watershed. Collecting a large amount of data and ensuring its quality and completeness for calculations are challenging. Furthermore, it may not fully consider the impacts of long-term and complex human activities on the ecological health of the watershed. In addition, it may not fully account for the effects of temporal and spatial scales, such as seasonal and interannual variations in the region. Despite these imperfections, the evaluation results still hold important guiding significance in understanding the regional situation and formulating strategies.

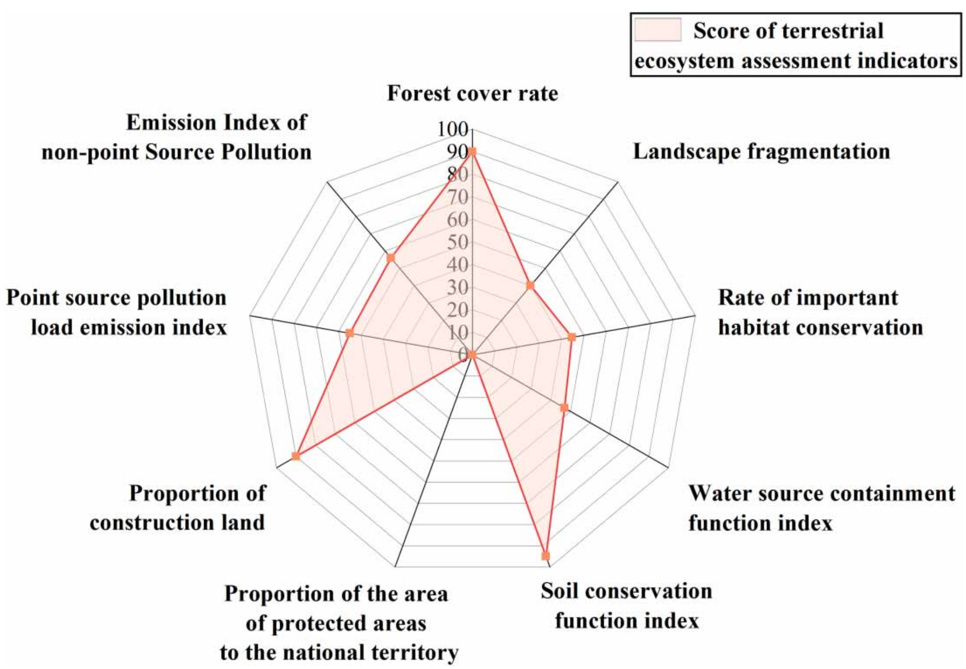


Figure 3 | Results of ecological health status assessment of Qinghe terrestrial ecosystem.

Table 5 | Assigned values of indicators for ecosystem health evaluation in the Qinghe River Basin

Evaluation unit	Water area health index value	Land area health index values	Comprehensive index	Evaluation level
Qinghe	60.03	57.74	58.66	Average

3.2. Regional management and development recommendations

To enhance the management of wastewater, ensure that the wastewater discharged from the wastewater treatment plants in the neighboring towns and cities complies with the required standards. In addition, it is important to enhance environmental awareness education and promote water conservation and wastewater reuse. In agricultural production and daily activities, strict control of point and surface source pollution should be implemented. To improve air quality, effective measures should be taken to reduce emissions and emission concentrations of air pollutants, with stringent limitations placed on sources including coal combustion and dust (Wang 2020). Concurrently, efforts to strengthen greening initiatives and enhance vegetation cover are necessary (Chang and Cui 2023). Actively promote the implementation and execution of national environmental protection policies such as 'garbage classification', 'coal to gas conversion', and high-standard farmland construction. A well-developed waste classification, collection, disposal, and recycling system should be implemented to effectively manage solid waste. Active participation of residents in waste classification and recycling plans can significantly minimize the adverse environmental effects caused by solid waste.

To enhance water resource management and protection, it is essential to promote the rational utilization and management of water resources. In addition, measures should be taken to prevent excessive extraction of groundwater and overexploitation of water resource (Li *et al.* 2020).

To enhance the construction and management of protected areas, such as nature reserves and ecological parks, it is crucial to prioritize the protection and restoration of current biological habitats. Specifically, it is important to give special attention to the habitats of large benthic animals, with the goal of minimizing human interference and preserving the natural state of aquatic environments. These efforts are essential for creating suitable habitat conditions and safeguarding rare species and their habitats (Hu *et al.* 2022).

In addition to establishing protected areas, it is crucial to implement effective measures to prevent land erosion and soil degradation. This involves proper planning and management of land use practices, ensuring that exploitation is carried out sustainably and does not contribute to environmental degradation (Li *et al.* 2022a). By integrating these land management strategies, to enhance the supervision and punishment of illegal land use, it is crucial to promote the adoption of sustainable agricultural practices like crop rotation and organic agriculture, reduction of the utilization of fertilizers and pesticides, and conduction of ecological restoration of degraded land. This research can further support the preservation of ecosystems and the long-term wellbeing of habitats and species.

To safeguard the diversity of native species, it is crucial to manage and limit the spread of invasive alien species. This should be complemented by enhancing the regulation and management of engineering structures, like dikes, to prevent nonnative fish from invading and disturbing local ecosystems (Johnson *et al.* 2018). At the same time, it is important to strengthen the enforcement of laws against illegal angling and recreational angling as these activities can cause harmful impacts on aquatic ecosystems.

Relevant departments should conduct scientific monitoring and evaluation to assess pollution monitoring and control within their jurisdiction. They should establish and improve ecological monitoring networks and assessment systems for ecological environment departments. In addition, regular evaluation of ecological and environmental indicators is necessary. The survey results should be used to develop effective management measures, optimize and adjust plans in real time, and make timely and local deployments. Strengthening scientific research is also important to enhance understanding of watershed ecosystems and improve the professional capabilities of staff (Yu *et al.* 2022).

The department concerned establishing a regional cooperation mechanism is crucial to enhance collaboration among various departments. It is essential for all relevant departments to strengthen communication and coordination. Departments should actively coordinate the cooperation among various departments within their jurisdiction. In addition, they should actively collaborate with other departments in their jurisdiction to carry out collaborative work. They should work together to promote ecological environmental protection and sustainable development of the basin. It is important to actively encourage public participation to increase awareness and protection of ecological environmental preservation in the basin. This will help in creating a collaborative framework for advancing ecological civilization.

4. CONCLUSION

(1) The health of the aquatic ecosystem in the Qinghe River Basin is considered fine, while the health of the terrestrial ecosystem is rated as average. Overall, the ecological health of the Qinghe River Basin is evaluated at an average level.

(2) The poor aquatic life indicators in the aquatic ecosystem and the degradation of ecological functions and patterns in the terrestrial ecosystems can be attributed to water pollution, dike construction, soil erosion, and reclamation activities. These issues are ultimately a result of the environmental damage caused by human production and lifestyle.
(3) This study aims to enhance our comprehension of basin ecological health assessment and offers valuable insights for assessing other expansive watersheds. In the future, it is crucial to focus on monitoring long-term changes and trends in the region.

5. LIMITATIONS AND SHORTCOMINGS OF THE STUDY

The assessment of basin ecological health should be further improved and optimized. The index system should be continuously refined to enhance representativeness and scientific validity. However, there is still subjectivity in the evaluation models and determination of parameters, which requires further improvement. In addition, it is important to consider integrating socioeconomic factors into the evaluation framework to achieve a more comprehensive and sustainable development of the basin.

FUNDING

The work was supported by the Liaoning Provincial Education Department's Service Local Project (LFW202002) and the Liaoning Provincial Education Department's Service Local Project People's Republic of China.

AUTHORS' CONTRIBUTION

Jingcheng Lei: writing – original draft and writing – editing; Jinfeng Zhang: data analysis, software, and draw figure; Peiying Li: review and editing; Chengbin Xu: supervision, writing – review and editing, funding acquisition, and project administration. All authors read and approved the final manuscript.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 19 November 2023; accepted in revised form 16 January 2024. Available online 31 January 2024