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Original Research

Comprehensive River Health Evaluation Indicator System and Its Application

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Abstract

Maintaining a healthy state of rivers is the basis for their functions, and the scientific evaluation of river health has significant implications for the environment, ecology, and socio-economics. In this study, the practical needs of river management and the need to establish a new type of human-water relationship were considered, resulting in the construction of a river health evaluation indicator system with 13 indicators based on the criteria of hydrology and water quality, habitat structure, aquatic organisms, social services, and river management. Additionally, a comprehensive index of river health assessments was proposed to judge the health level of the river. The comprehensive river health evaluation indicator system was applied to the Taihu Lake Basin, and the results indicated that the evaluation indicator system could objectively and scientifically reflect the health level of the river. The comprehensive index of river health assessment was calculated to be 73.38, indicating that the overall health of the river was in a “healthy” state. However, further improvements were needed in areas such as river connectivity. The study presents a new evaluation system and methodology that facilitate the development of effective strategies for river conservation and management.

Keywords: River health evaluation, Indicator system, Taihu Lake Basin, Aquatic ecology

Introduction

Rivers are valuable water resources, crucial ecosystems, and essential for supporting economic development; they are primarily utilized for water supply, flood control, navigation, power generation, and other ecological services [1, 2]. However, the intensification of industrialization, improvements in human living standards, and global climate change, among other pressures, have resulted in imbalances in river water supply and demand, water quality degradation, and the deterioration of river ecosystems.

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These issues render rivers “unhealthy” and pose threats to the human living environment [3-5]. Therefore, it is vital to undertake an assessment of river health.

Currently, scholars from both domestic and international institutions have conducted research on river health from different perspectives, proposing many methods and applying them to the assessment of river health. Xu et al. [6] constructed a new aquatic ecological health evaluation system composed of water quality, ecosystems, and ecological landscapes for the evaluation of small rivers in Shanghai, China. Fu et al. [7] took the Xiaoqing River in Shandong Province as an example, established a multi-level multifunctional river evaluation indicator system composed of environmental functions, ecological functions, social functions, and economic functions, and carried out a health evaluation of the Xiaoqing River in Shandong Province. Wang et al. [8] combined the improved gray occurrence rate model to construct a comprehensive evaluation model including physical habitats, chemical conditions, and biological structures. They chose the Wei River basin in China as a case study to evaluate the health status of the river ecosystem. Azarnivand et al. [9] used two risk-based multi-criterion decision-making methods, ordered weighted average and compromise programming, for the health evaluation of the Taleghan River. Jiao et al. [10] established a comprehensive evaluation indicator system for river health with the health concepts and evaluation standards of regions characterized by significant human activities. The study specifically introduced the River Health Index (RHI) for areas with frequent human activities and evaluated the health status of the Qingliang River section in Cangzhou, China. In summary, the health evaluations of rivers and lakes carried out domestically and internationally mostly focus on natural ecological conditions (for example, hydrology, water quality, and physical and biological structures), and management, monitoring, and conservation measures are also gradually included in the river health evaluation system to reflect the role of basin management in river health [11].

The development and utilization of water resources by human activities directly impact the quantity, quality, and hydrological conditions of rivers. Factors such as pollutant emissions from production and daily life and changes in land use, among others, also have a direct influence on the water quality and ecosystem of rivers. Proper management of water resources to ensure water supply and agricultural irrigation needs is essential for maintaining the health of rivers. Studying the human-water relationship can help reduce sources of pollution, restore damaged ecosystems, and promote the ecological health of rivers. Rivers provide various services to society, such as water supply, irrigation, and transportation, but the demands for social services can also put pressure on the river’s health. Balancing social service needs with ecological health is a key challenge that requires scientific research guidance. However, there is a lack of research on river health involving human-water relationships and social service functions, which cannot reflect the public’s cognition, participation, and feedback [12].

The Taihu Lake Basin, situated in the middle and lower reaches of the Yangtze River, is a plain river network area with a dense river network and complex hydrological systems. Its socio-economic development is advanced, the population density is high, and the river ecosystems have been significantly affected by human activities. Eutrophication has already become the main issue for the Taihu Lake Basin water environment. At present, research on the health of the rivers in the Taihu Lake Basin is still in its nascent stages [13-15], with evaluations largely reliant on criteria like hydrological quality and biological habitats, characterized via Z-IBI [16], P-IBI [17], or water quality indices [18]. Existing multi-criteria evaluation systems involve difficulties in obtaining some indicator data, intricate data computations, and cumbersome evaluation processes, rendering them hard to adapt to the practical needs of government management [19].

This study comprehensively considered five aspects: hydrology and water quality, habitat structure, aquatic organisms, social services, and river management. It constructed a comprehensive indicator system for assessing river health and applied it to the Taihu Lake Basin. The aim was to provide decision-making references for river water resource protection and ecological restoration and support future research and conservation efforts for river health in the basin.

Material and Methods

The River Health Evaluation Indicator System

The establishment of a scientific and reasonable evaluation indicator system is the prerequisite and foundation for the study of river health. River health is generally understood to encompass two aspects: the natural attributes of the river, which focus on the integrity of the structure and function of the river ecosystem, including the interrelationship between the living and non-living systems of the river [20]; and the river’s ability to serve human society, including its capacity to provide continuous water resources, flood control, irrigation, navigation, and fishing services [21, 22]. In 2020, the Ministry of Water Resources issued the “Technical Guidelines for River and Lake Health Assessment (SL/T 793-2020)” (hereinafter referred to as the “Guidelines”). It mainly constructs the river health evaluation indicator system from four aspects: hydrology and water quality, morphological structure, biological integrity, and social service functions. Various provinces and cities have also issued relevant documents on river health assessments. The evaluation of management, monitoring, and conservation efforts, as well as the evaluation of the relationship between humans and water and the social service functions related to the target river, are important components of assessing river health. The utilization of indicators such as water quality status, shoreline ecology, adaptability of control capacity, completeness of monitoring systems, and advancement of management measures in research can comprehensively reflect the status of the human-water relationship. Additionally, indicators including flood control project compliance rate, water function zone compliance rate, and public satisfaction level can be employed to assess the execution of social service functions. Considering the above, a river health assessment indicator system was established, as shown in Table 1. The target layer in the system represented river health assessments, while the criterion layer included hydrology and water quality, habitat structure, aquatic organisms, social services, and river management, with each evaluation indicator as follows:

(1) Hydrology and Water Quality Criterion: Hydrology and water quality criteria can illustrate the water quality and abundance of the river, representing the current status of the natural environment of the river. It includes two main indicators: the satisfaction of basic ecological flow and water quality status. Specifically, the ecological flow refers to the minimum flow required to maintain the basic ecological function and the fundamental morphology of a river, which is of significant importance for maintaining river health [23, 24]. On the other hand, water quality status reflects the physical and chemical properties of river water, and its evaluation enables the identification of water pollution status and facilitates the promotion of river health [25].

(2) Habitat Structure Criterion: River habitat is an integral component of river ecosystems, linking aquatic organisms with the natural environment. Habitat structure criterion can provide basic support for the protection and restoration of river ecosystems [26]. It includes three indicators: river longitudinal connectivity, shoreline ecology, and ecological buffer zone width. Firstly, longitudinal connectivity plays a significant role in the movement of matter, energy, and organisms, and changes in this connectivity have a notable impact on regional ecosystems and river health [27]. Secondly, the shoreline serves as an ecological connection zone between the river and the land, Secondly, the shoreline serves as an ecological connection zone between the river and the land, playing a crucial role in river habitat composition and meeting the requirements of the "River Chief System" for ecological assessment [28]. Lastly, the ecological buffer zone acts as a barrier to protect the water body, reducing the inflow of pollutants. The width of the buffer zone represents the level of protection for the ecological buffer [29].

(3) Aquatic Organism Criterion: The aquatic organism criterion is indicative of the current status and integrity of aquatic organisms, representing the biodiversity of river ecosystems. It includes two indicators: the indigenous fish retention index and benthic macroinvertebrate diversity. Among them, the indigenous fish retention index is capable of representing the community structure and composition of river ecosystems, and the evaluation of this index is beneficial for the recovery of fish biodiversity and the conservation of resources [30]. The large benthic invertebrates are the predominant biological group in river ecosystems, participating in the supply of nutrients, material cycling, and other important ecological processes, and their diversity can reflect the situation of the river water environment [31].

(4) Social Services Criterion: The social service functions of rivers are bestowed by humans and can have an impact on the ecological functions of rivers, so the social services criterion reflects the social attributes of the river and the requirements of constructing a new type of human-water relationship [32]. It includes the compliance rate of flood control projects, the compliance rate of water functional zones, and public satisfaction. The flood control project is the focus of water conservancy construction, which is of great significance for safeguarding the safety of life and property of the residents around the river and economic and social development [33]. Water functional zones are the basic unit of water resources management, enabling the classification, management, and protection of water bodies and facilitating the coordinated development of the social economy and water carrying capacity [34]. The indicator of public satisfaction can illustrate the degree of public recognition of the health of the river and its management [35].

(5) River Management Criterion: Effective river management is a prerequisite for ensuring river health. The river management criterion helps promote the achievement of river health goals. It includes three indicators: adaptability of control capacity, completeness of the monitoring system, and advancement of management measures. The adaptability of control capacity focuses on the current management status of river protection and utilization planning, project approval, and related aspects. The completeness of the monitoring system evaluates the completeness of the monitoring projects within the scope of river and lake management. The advancement of management measures reflects the sophistication of spatial control measures for rivers and the timeliness of identifying and addressing issues.

Scoring Criteria for Each Indicator

The quantitative evaluation of various indicators in the river health evaluation system includes two parts: scores and assigned points. It should be noted that the assigned points of an indicator are obtained through a calculation formula and converted according to the corresponding scoring criteria outlined in the relevant documents. In some cases, the score value is equal to the assigned point value. The scoring criteria for each criterion are as follows:

Table 1. River health evaluation indicator system.

Target Layer	Criterion Layer	Indicator Layer	Meaning
River Health Assessment (A)	Hydrology and Water Quality (B_1)	Satisfaction of Basic Ecological Flow (C_1)	Characterizing the extent to which minimum flow levels are met.
		Water Quality Status (C_2)	Assessing the impact of human activities on water quality.
	Habitat Structure (B_2)	River Longitudinal Connectivity (C_3)	Characterizing the integrity and stability of river ecosystems.
		Shoreline Ecology (C_4)	Characterizing the health status, biodiversity, and functional integrity of shoreline ecosystems.
		Ecological Buffer Zone Width (C_5)	Characterizing the functionality, benefits, and protection level of ecological buffer zones.
	Aquatic Organisms (B_3)	Indigenous Fish Retention Index (C_6)	Characterizing the conservation status and diversity of indigenous fish populations in aquatic environments.
		Benthic Macroinvertebrate Diversity (C_7)	Characterizing the ecological status of benthic macroinvertebrates.
	Social Services (B_4)	Compliance Rate of Flood Control Project (C_8)	Assessing the impact of human activities on flood risk management.
		Compliance Rate of Water Functional Zones (C_9)	Evaluate the effectiveness of water quality management and protection.
		Public Satisfaction (C_{10})	Public perception and evaluation of riverine environments.
	River Management (B_5)	Adaptability of Control Capacity (C_{11})	Characterization of river managers' ability to adapt and adjust to changes in rivers in uncertain environments.
		Completeness of Monitoring System (C_{12})	Assessing the effectiveness and trends of management measures.
		Advancement of Management Measures (C_{13})	Characterization of the advanced nature and efficiency of river management.

Table 2. Scoring criteria for hydrology and water quality criterion indicators.

Scoring	100	80	60	40	20	0
Water Quality Status	I	II	III	IV	V	Inferior V
Satisfaction of Basic Ecological Flow (%)	≥95	80	--	70	60	<50

Note: "--" indicates that the indicator does not have a measure under the current score. Followers are the same.

(1) The hydrology and water quality criterion includes two indicators: the satisfaction of basic ecological flow and water quality status. The scoring criteria for each indicator are detailed in Table 2.

(2) The habitat structure criterion includes three indicators: river longitudinal connectivity, shoreline ecology, and ecological buffer zone width. The scoring criteria for each indicator can be found in Table 3.

(3) The aquatic organism criterion includes two indicators: indigenous fish retention index and benthic macroinvertebrate diversity. The scoring criteria for each indicator are presented in Table 4.

(4) The social services criterion encompasses three indicators: the compliance rate of flood control projects, the compliance rate of water functional zones, and public satisfaction. The scoring criteria for the compliance rate of flood control projects and the compliance rate of water functional zones are provided in Table 5, while the scoring criteria for public satisfaction can be found in Table 6.

(5) The river management standards include three indicators: adaptability of control capacity, completeness of the monitoring system, and advancement of management measures. This criterion does not involve quantitative calculations; instead, it relies on subjective scoring based on the presence and implementation of relevant management measures. The scoring criteria for this criterion were obtained using the Delphi method and are specified in Tables 7 and 8.

Table 3. Scoring criteria for habitat structure criterion indicators.

Scoring	Longitudinal Connectivity Index (per·10 km^{-1})	Riparian Buffer Width (m)	Shoreline Type
100	0	>100	Natural shoreline
80	0.1	30	Slopes protected by vegetation and natural materials such as riprap, dry masonry at the foot
60	--	10	Slopes protected by natural materials such as riprap, dry masonry, etc.
40	0.25	3	Slopes protected by vegetation and hardened materials such as masonry, concrete at the foot
20	0.5	--	--
0	>1	0	Slopes protected by hardened materials such as masonry, concrete, etc.

Table 4. Scoring criteria for aquatic organism criterion indicators.

Scoring	Indigenous Fish Retention Index (%)	Benthic Macroinvertebrate Diversity Index
100	100	[2.0,3.0]
80	80	[1.0,2.0)
60	60	[0,1.0)
40	40	--
0	0	--

Table 5. Scoring criteria for compliance rate of flood control project and water functional zones.

Scoring	Compliance Rate of Flood Control Project (%)	Compliance Rate of Water Functional Zones (%)
100	≥95	100
80	90	80
40	80	60
20	70	40
0	50	0

Weight Allocation for Each Criterion and Indicator

Based on the content of relevant documents, the weights of various criteria and indicators were determined in combination with the Delphi method and the expert consultation method. The sum of the weights of the hydrology and water quality criterion, habitat structure criterion, and aquatic organism criterion was 0.6, while the weights of the social services criterion and river management criterion were both 0.2. The weights of various criteria and indicators in the river health evaluation indicator system are shown in Table 9.

River Health Comprehensive Classification

Calculation of a Comprehensive Index for River Health Assessment

The comprehensive index of river health assessment was calculated using the compound comprehensive index model, and the specific calculation was as follows:

$$B_j = \sum C_i \times \alpha_i \quad (1)$$

Table 6. Scoring table for public evaluation of each option.

Options	Almost No Improvement	Slightly Changed and Not Very Good	Some Improvement	Improved Remarkably and Excellent
Scoring	0	35	65	100

Table 7. Scoring criteria for adaptability of control capacity.

Scoring	100	80	40	20	0
River Management Capability Fulfillment Level	All requirements are met	One requirement is met	Two of the requirements is met	three of the requirements is met	None of the requirements are met

Note: Control Requirements 1) Complete the utilization management planning of river channels and banks or the formulation of one river one policy; 2) Standardize the approval of projects involving rivers and dikes; 3) No "four disturbances" phenomena on banks; 4) No electric fishing, poisoning fish and other behaviors that damage ecology.

Table 8. Scoring criteria for monitoring system completeness and advanced management measures.

Scoring	Integrity of Monitoring System	Advancement of Management Measures
100	The layout and frequency of hydrological and water quality monitoring conform to the relevant technical requirements	Full video surveillance coverage for key river sections, with full-river patrol using drones, remote sensing imagery
80	The layout and frequency of hydrological and water quality monitoring conform to the relevant technical requirements; no aquatic ecological monitoring	Full video surveillance coverage for key river sections, with full-river patrol using drones, remote sensing imagery etc. no less than twice a year
40	The number of hydrological and water quality monitoring stations meets the requirements, but the monitoring frequency is lower than the relevant technical requirements; no aquatic ecological monitoring	Video surveillance does not cover the entire river section; drones or remote sensing imagery are used for patrol but less than twice a year
20	The number of hydrological and water quality monitoring stations is less than the relevant technical requirements, and the monitoring frequency is lower than the relevant technical requirements, no aquatic ecological monitoring.	Patrol inspection relies mainly on manpower, with no video surveillance for key river sections and no full-coverage patrol using drones or remote sensing imagery
0	No hydrological, water quality or aquatic ecological monitoring	No patrol and protection measures have been taken

Table 9. Weights for river health assessment criteria and indicators.

Target Layer	Criterion Layer	Weights of Criterion Layer	Indicator Layer	Weights of Indicator Layer
A	B_1	0.15	C_1	0.65
			C_2	0.35
	B_2	0.20	C_3	0.10
			C_4	0.45
			C_5	0.45
	B_3	0.25	C_6	0.50
			C_7	0.50
	B_4	0.20	C_8	0.30
			C_9	0.30
			C_{10}	0.40
	B_5	0.20	C_{11}	0.30
			C_{12}	0.40
			C_{13}	0.30

$$A = \sum_{j=1}^{5} B_j \times \beta_j \tag{2}$$

In the formula, A represents the comprehensive index of river health assessment; B_j is the score of the j criterion; C_i is the score of the i index; α_i is the weight corresponding to the i index; β_j is the weight corresponding to the j criterion, where j = 1, 2, 3, 4, 5.

River Health Comprehensive Classification

To accurately assess and classify river health levels, ensuring their applicability and rationality, the study based the classification of river health assessment grades on the guidelines provided in relevant documents. The river health grades were divided into five categories: Very Healthy, Healthy, Sub-healthy, Unhealthy, and Morbid. The river health level is divided according to the score range, as shown in Table 10. The interval in which the comprehensive index of river health evaluation fell determined the corresponding health grade of the river.

Application of the River Health Evaluation Indicator System

The established river health evaluation indicator system was applied to the Taihu Lake Basin. Taihu Lake, the third largest freshwater lake in China, is located in the Taihu Plain of the Yangtze River Delta, with geographical coordinates of 30°05’-32°08’N, 119°08’-121°55’E. The Taihu Lake Basin is crisscrossed

Table 10. Criteria for river health comprehensive classification.

Health Grade	Scoring Range	Introduction	Color
Very Healthy	[80, 100]	Meets or basically meets the reference status or expected results	Blue
Healthy	[60, 80)	Approaching the reference status or expected results of treatment	Green
Sub-healthy	[40, 60)	Moderate difference from the reference status or expected results of treatment	Yellow
Unhealthy	[20, 40)	Significant difference from the reference status or expected results of treatment	Orange
Morbid	[0, 20)	Obvious difference from the reference status or expected results of treatment	Red

with rivers and dotted with numerous lakes, covering a water area of 6134 square kilometers, accounting for 17% of the total area. The total area of the basin is 36895 km^2, with a river length of approximately 120,000 km. The Taihu Lake Basin spans Jiangsu, Zhejiang, Fujian Province, and Shanghai, serving various functions such as flood retention, water supply, irrigation, transportation, and tourism. It is an important water source for the basin. Currently, the Taihu Lake Basin still faces prominent structural and regional pollution issues, mainly stemming from the sizeable traditional industries such as printing and dyeing and chemical production. There is inefficiency in urban sewage collection systems, with issues of pipeline leaks and mismatches. Moreover, less than two-thirds of administrative villages have sewage treatment facilities, and less than 30% of them operate properly. Sediment accumulation in the lakebed is a major internal source of eutrophication, yet there are bottlenecks in the treatment and disposal of such sediments. Therefore, conducting a river health assessment in the Taihu Lake Basin can effectively identify pollution and ecological issues in the rivers and enable targeted protective measures to safeguard the water environment in the basin.

The Changxinggang River is an important urban river in the Taihu Lake Basin, located in the northern part of Changxing County, Huzhou City, Zhejiang Province. It has a total length of 31.58 km and belongs to the Sian Water System. It originates from the western mountainous area of Changxing County, goes through the main urban area of Changxing from west to east, connects with the urban water system, and finally flows into Taihu Lake Basin, with the water level basically equal to that of Taihu Lake Basin. Thus, the Changxinggang River has multiple features, such as a plain river network, urban rivers, and lake-inlet rivers. It can be selected as a typical river for the health assessment of rivers in the Taihu Lake Basin. Therefore, this study selected the chosen river for conducting a case study on the river health assessment indicator system in the Taihu Lake Basin. The location relationship between the Changxinggang River and relevant reservoirs and dams is illustrated in Fig. 1.

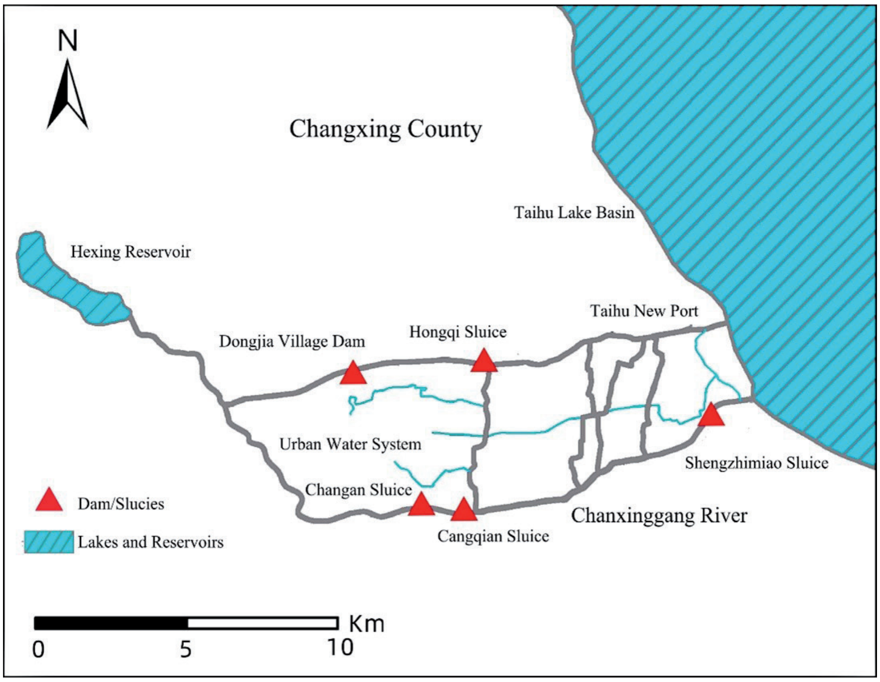

Fig. 1. Location of Changxinggang River and related reservoir, gate dams.

Results and Discussion

Rationality Analysis of the Evaluation Indicator System

A well-designed evaluation system with reasonable criteria ensures that the evaluation results are accurate and comprehensive and provides decision-makers with decision support and reference to help them make wise decisions, optimizations, and improvements. From the perspective of constructing the indicator system, it is based on national and local relevant standards, considering hydrology and water quality, habitat structure, aquatic organisms, social services, and river management aspects. The construction process incorporates scientific and logical strategies and methods with the involvement of experts' consultations. Regarding the determination of weights, the indicator system refers to the guidelines and relevant standards, aligning with industry policies, thus ensuring the authority and applicability of the weights. Additionally, the Delphi method allows for the full utilization of experts' knowledge and experience, eliminating personal biases and pressures in opinion exchange, and achieving consensus opinions or predictions. It demonstrates good operability and is conducive to river management practices. Moreover, the scoring experts involved in the Delphi method have extensive experience in river management and river health assessment, thus ensuring the accuracy and effectiveness of the determined weights. Furthermore, a qualitative evaluation of the health status of the Changxinggang River (a typical river in the Taihu Lake Basin) selected for this study was compared with the opinions of relevant departments, experts, and the general public. The conclusion drawn from this qualitative evaluation aligns closely with the health status determined by the indicator system. Based on these findings, the evaluation system constructed by the study can objectively reflect the health status of rivers and provide a scientific basis for watershed water resource protection, aquatic ecosystem restoration, and further implementation of the river chief system.

Scores for Each Criterion and Its Indicators

The quantitative evaluation of the various indicators in the river health assessment system includes two parts: scores and assigned points. The assigned points are the score obtained by the indicator through a calculation formula and converted according to the aforementioned allocation criteria. For some indicators, the score value is equal to the allocation value. The scores for each criterion are based on the scores for the indicators within the criterion and further calculated by considering the weights of the indicators. The scores of various aspects of the river health assessment system are presented in Table 11.

(1) Hydrology and water quality criterion: The hydrology and water quality criterion include Satisfaction of Basic Ecological Flow and Water Quality Status. The Satisfaction of Basic Ecological Flow indicator is calculated based on the proportion of days that meet the basic ecological flow; the specific calculation formula is shown in Equation (3).

Table 11. River health assessment score of the Changxinggang River.

Target Layer	Criterion Layer	Scoring	Indicator Layer	Scoring
A	B_1	85.41	C_1	99.1
			C_2	60.0
	B_2	65.36	C_3	2.0
			C_4	70.0
			C_5	74.8
	B_3	50.25	C_6	66.7
			C_7	33.8
	B_4	74.67	C_8	100.0
			C_9	53.2
			C_{10}	71.8
	B_5	100.0	C_{11}	100.0
			C_{12}	100.0
			C_{13}	100.0

$$C_1' = (D_m/D) \times 100\% \tag{3}$$

where C'_1 represents the satisfaction of the basic ecological flow; D_m is the number of days that the basic ecological flow is met in the evaluation year; D is the total number of days in the evaluation year.

The average flow rate of the driest month with a 90% guarantee rate, based on the ten-year hydrological data of the Changxinggang River, was determined to be 0.71 m^3/s. The ecological flow rate calculation yielded a satisfaction rate of 94.1% for the ecological flow rate of the Changxinggang River in 2020. By employing linear interpolation, the score for this indicator (C_1) was determined to be 99.1. The water quality index was assigned scores based on the river water quality classification. According to the "Surface Water Environmental Quality Standard (GB3838-2002)", the water quality of the Changxinggang River in 2020 was classified as Class III. Referring to the allocation criteria in Table 2, the score for this indicator (C_2) was determined to be 60.0. Based on the scores of the two indicators and considering the weights of each indicator as shown in Table 9, the score for the hydrology and water quality criterion (B_1) was calculated as 85.41 using Formula (1).

(2) Habitat structure criterion: The habitat structure criterion includes indicators for river longitudinal connectivity, shoreline ecology, and ecological buffer

zone width, with the specific calculation formulas as follows:

$$C_3' = (N/M) \tag{4}$$

$$C_4' = \sum(P_{bi}L_{bi})/L \tag{5}$$

$$I_{bz} = \sum(P_{wi}L_{wi}C_{wi})/L \tag{6}$$

In the formula, C'_3 represents the number of buildings or facilities affecting river connectivity per unit river length, per 10 km; C'_4 is the score of the river shoreline ecological index; I_{bz} is the ecological buffer zone index; N is the number of buildings or facilities affecting river connectivity; M is the evaluated river length, 10 km; P_{bi} is the score of type i shoreline; L_{bi} is the length of type i shoreline, km; P_{wi} is the average width score of the ecological buffer zone of type i width; L_{wi} is the length of the ecological buffer zone of type i width, km; C_{wi} is the vegetation coverage percentage of the ecological buffer zone of type i width; and L is the total length of the evaluated river section shoreline, km.

The river longitudinal connectivity indicator was evaluated based on the number of structures that affected river connectivity within every 10 km segment of the river. The shoreline ecological indicator was calculated based on the proportion of different types of shoreline lengths. The ecological buffer zone indicator was collectively determined by the width of the river ecological buffer zone and its vegetation coverage. According to relevant data from Changxing County and combined with the scoring standards in Table 3, the scores of indicator (C_3), indicator (C_4), and indicator (C_5) were calculated as 2.0, 70.0, and 74.8, respectively, using linear interpolation. Based on the scores of the three indicators and the weights in Table 9, the score of the habitat structure criterion layer (B_2) was calculated to be 65.36 points through formula (1).

(3) Aquatic organism criterion: The aquatic organism criterion includes indicators for the indicator of indigenous fish retention and benthic macroinvertebrate diversity. The indigenous fish retention indicator was obtained by comparing the existing species of fish with historically recorded native species using the specific calculation formula shown in equation (7):

$$C_6' = \left(S_{fo}/S_{fe}\right) \times 100\% \tag{7}$$

In the formula, C'_6 represents the proportion of native fish retention in rivers, %; S_{fo} represents the number of native fishes retained during the evaluation period, species; S_{fe} represents the number of native fishes retained during the historical period, species.

According to the relevant fish monitoring data and the statistical data on the diversity of large benthic invertebrates in Changxinggang River, the proportion of native fish retention was 66.7%, and the diversity index was 0.845. Combined with the scoring standards in Table 4, using linear interpolation, the scores of indicator (C_6) and indicator (C_7) were respectively assigned as 66.7 and 33.8. Based on the scores of the two indicators and the weights of the two indicators in Table 9, the score of the aquatic organism criterion layer (B_3) was calculated as 50.25 using formula (1).

(4) Social services criterion: The social services criterion includes indicators such as the compliance rate of flood control projects, the compliance rate of water functional zones, and public satisfaction. The specific calculation formulas were as follows:

$$C_8' = (RLA/RL) \times 100\% \tag{8}$$

$$C_9' = (FG/FN) \times 100\% \tag{9}$$

$$C_{10}' = \sum_{i=1}^{4}(A \times a_{ai} + B \times b_{bi} + C \times c_{ci} + D \times d_{di})/4 \tag{10}$$

In the equation, C'_8 represents the flood control engineering compliance rate; C'_9 represents the water function area compliance rate; C'_{10} represents public satisfaction; RLA is the length of the dike that meets the flood control standards, km; RL is the total length of the river section under evaluation, km; FG is the number of compliant functional areas; FN is the total number of functional areas under evaluation; A, B, C, D each represent the scores assigned to each option in Table 5; a_{ai}, b_{bi}, c_{ci}, d_{di} each represents the proportion of respondents who chose A, B, C, D in the i-th question, where i = 1, 2, 3, 4;

According to the relevant data for Changxinggang River, the compliance rate of flood control projects was 100%, and the compliance rate of water functional zones was 66.7%. Based on the allocation criterion in Table 5, the scores for indicator (C_8) and indicator (C_9) were 100.0 and 53.2, respectively. A total of 150 formal questionnaires were distributed for the public satisfaction survey, and 123 valid samples were obtained. The respondents included students, service industry practitioners, freelancers, public institution personnel, workers, etc. More than half of the respondents had been living in Changxing County for more than ten years, so it can be considered that the respondents were representative. The final questionnaire statistics results are shown in Fig. 2. The final calculated score for the public satisfaction indicator (C_{10}) was 71.8. Based on the scoring results of the above three indicators, combined with the weights in Table 9, the score for the social services criterion (B_4) calculated through formula (1) was 74.67.

Fig. 3 shows the scores for each criterion layer. From a criterion perspective, the scores for hydrology and water quality, habitat structure, social services, and river management criteria were relatively high, indicating that Changxinggang River had achieved significant progress in ensuring river flow, protecting water quality, and enhancing river management capabilities. The habitat structure had become more intact, and the social services function had continued to improve. However, the score for the aquatic organism criterion was below 60.0, indicating that the biodiversity of Changxinggang River had to some extent degraded compared to previous years and that ecological restoration was needed.

Fig. 4 displays the scores for each evaluation indicator. From an indicator perspective, the scores for satisfaction of basic ecological flow, adaptability of control capacity, completeness of monitoring system, advancement of management measures, public satisfaction, compliance rate of flood control project, indigenous fish retention index, compliance rate of water functional zones, shoreline ecology, and water quality status were relatively high. Changxing County was the first county in Zhejiang Province to establish a "River Chief System + Inspection" coordinated supervision mechanism. Therefore, remarkable achievements were made in the river management criterion, and all three indicators scored 100.0. The public satisfaction indicator was 71.8, indicating that, under the efforts of the relevant management departments, the public could feel the improvement of the aquatic ecosystem and health status of Changxinggang River in recent years,

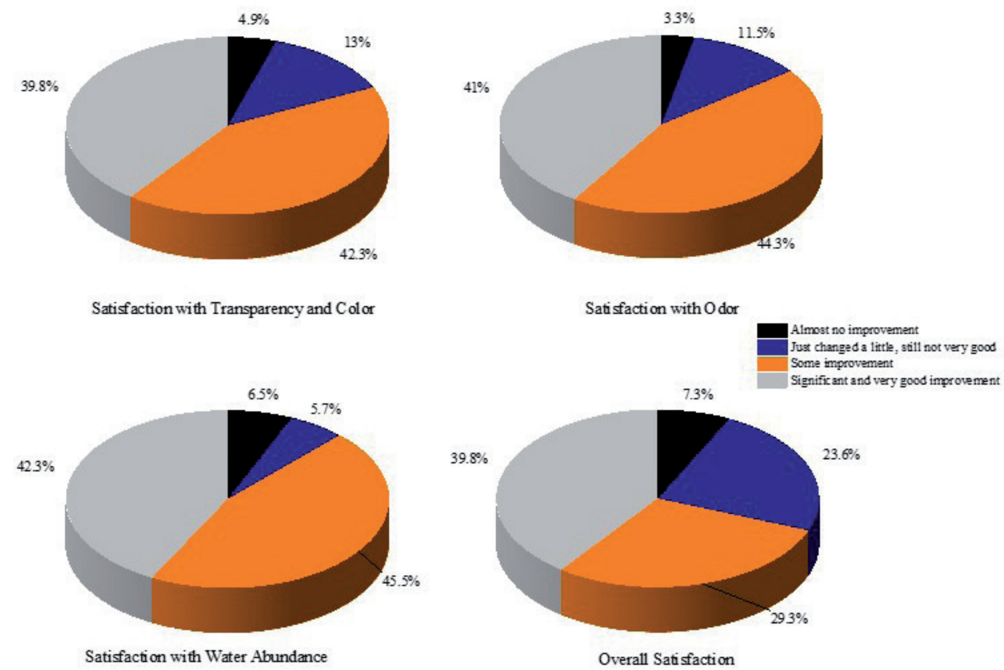

Fig. 2. The results of public satisfaction questionnaire.

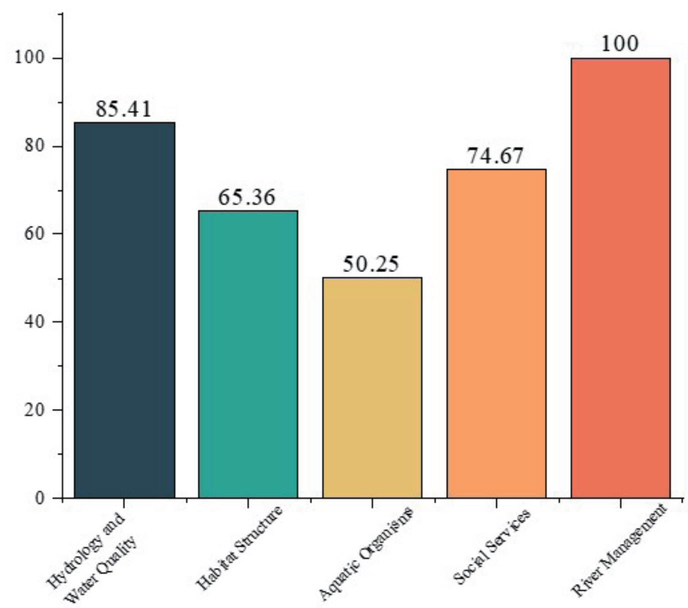

Fig. 3. Bar chart of scores for each criterion of Changxinggang River.

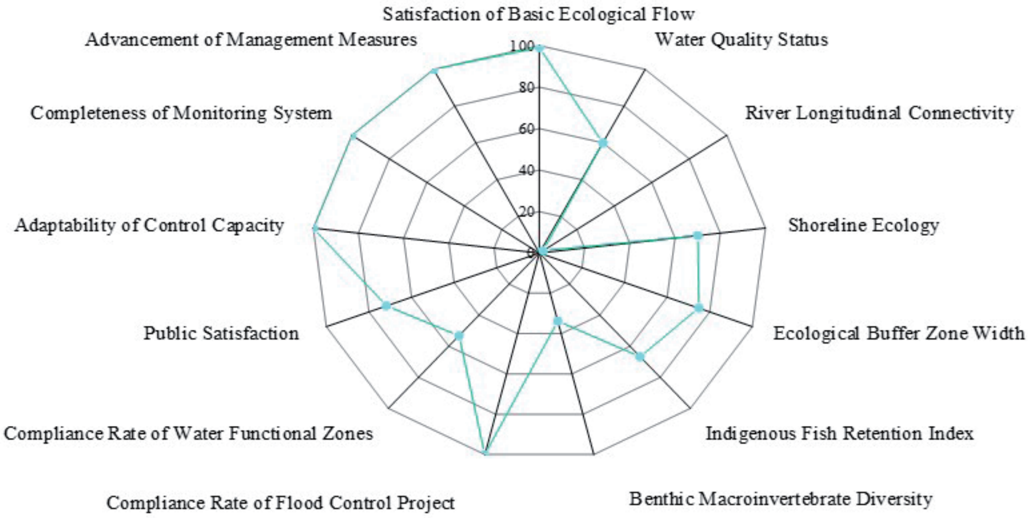

Fig. 4. Evaluation indicator scoring radar map of Changxinggang River.

and they have great expectations for Changxinggang River becoming a "happy river". However, the scores of three indicators, namely river longitudinal connectivity, benthic macroinvertebrate diversity, and compliance rate of water functional zones, were below 60, indicating that there is still room for improvement in the health level of Changxinggang River.

Based on the mentioned issues, here are some suggestions for further work: 1) Study the impact of Changxing Port river connectivity on the river's ecological environment, improve the sluices and dams on the river, and provide suitable passages for fish and other organisms; 2) Strengthen the monitoring of large benthic invertebrate populations and related aquatic animal communities, study their community characteristics and spatiotemporal distribution, and apply them to river management; 3) Green the hardened shoreline and carry out ecological restoration of the ecological buffer zone; 4) Control non-point source pollution in agricultural water use areas and optimize the configuration of sewage treatment and reclaimed water utilization facilities in the Changxing urban area. These actions will contribute to the improvement and sustainable management of the ecological environment in the Changxinggang River.

Conclusions

The study referred to the river health assessment criteria in the relevant published documents, taking into consideration both the practical requirements of river management and the need to establish a new type of human-water relationship. It constructed a comprehensive river health assessment indicator system with the river health assessment as the target level and hydrology and water quality, habitat structure, aquatic organisms, social services, and river management as the evaluation criteria. The indicator system included 13 specific indicators, such as satisfaction with basic ecological flow, adaptability of control capacity, completeness of the monitoring system, and so on. The weights of each criterion and indicator were determined through the Delphi method and the expert consultation method. Additionally, a comprehensive river health evaluation indicator was proposed to determine the classification of river health. This evaluation indicator system can objectively and scientifically reflect the level of river health.

The comprehensive river health assessment index system was applied to the Changxinggang River, a representative river in the Taihu Lake Basin, and it received a score of 73.38, placing it in the "green" health level overall. However, improvements are still needed in terms of river longitudinal connectivity, diversity of large benthic invertebrates, and compliance rate of water functional zones. In the future, based on the practical application of this system and in conjunction with the "one city, one examination" and "one river, one strategy" initiatives, it is suggested to gradually expand the application of the evaluation indicator system to the river health assessment work in various river basins, taking into account local conditions. Moreover, it is recommended to further refine the criteria and indicators in the comprehensive river health assessment indicator system to more accurately and scientifically evaluate the health of rivers in accordance with their actual conditions.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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