

Update of river health assessment indicator system, weight, and assignment criteria in China

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ABSTRACT

Comprehensive assessment of river health is challenging due to the diversity of rivers, the complexity of their ecosystem and functional service. This paper updates the river health assessment indicator system, weight, and assignment criteria in China by reviewing and examining the peer-reviewed literature. We propose an indicator system, weight, and criteria, validated by nine case studies and able to assess the country-scale river health. Our analysis shows that the rule layer of indicator system includes hydrology, water quality, aquatic organism, physical habitats, and functional service; its corresponding weights are set to 0.15, 0.21, 0.18, 0.22, and 0.24, respectively. The ten most representative indicators are selected that incorporates the indicator layer with their corresponding weights. The evaluation based on case studies shows that in eight out of nine cases, our results are consistent with those obtained in previous studies. Therefore, the suggested index system, weight, and three-assessment criteria are well suited for the complex cases in China. This paper can serve as a reference for a river health assessment and present a comprehensive listing of assessment criteria.

Key words | assessment criteria, indicator, river health, weight

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HIGHLIGHTS

- We propose an indicator system which can provide an objective and universally applicable way to evaluate river health.
- We classify the rivers into three types, and the corresponding assignment criteria are proposed, respectively. With this method, the health status of rivers of different types can be determined more accurately and compared horizontally.

INTRODUCTION

Ecosystem and river health has gradually become an important research field, especially river health assessment for sustainable river management (Wang 2014). Hence, river management and conservation, originally assessed with water quality index and organic pollutants, is now using the framework of river health assessment more often (Singh & Saxena 2018). A series of studies on river health

assessment started in 1972. For example, one can refer to the Rapid Bioassessment Protocols (Buss & Vitorino 2010), the River Habitat Survey (Szozskiewicz 2006), the Australian River Assessment System Parsons *et al.* 2002), the EU Water Framework Directive (Voulvoulis 2017), the Blind Number Theory (Wang 2014), and the Definition and Connotation (Wen 2007). These studies provide numerous indicators and assignment criteria.

However, problems in river health assessments remain. Large spatiotemporal variations in rivers make the multi-scale evaluation more complex, as the river geospatial

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components increasingly differ from each other (southern and northern, inland and outer, urban channel and natural rivers, mainstream and tributary). Other challenges include the evaluation and assignment criteria, and data availability. Some researchers think that the social functional service of rivers is more important (Meyer 1997), while others consider their natural properties essential (Frey 1977). These issues make the task even more difficult to carry out river health evaluations properly and compare the health status of rivers horizontally and vertically. Adverse consequences can affect the decision-making, the management, and the ecological river restoration. Currently, two methods are able to solve these problems related to the river health assessment. One method is to classify different rivers according to their different attributes or characteristics. For example, rivers are divided into large categories (ecological (You 2009), mountain (Xiao 2014), urban (Deng et al. 2014)), as well as specific rivers (the Yangtze River (Zheng & Wang 2007), the Yellow River, and the Pearl River (Lin et al. 2006)). Through the principle of neighboring (also called similarity), the evaluation indicators of one river are transplanted to a neighbor or similar river. However, because this approach is limited, it does not allow a comparison of different types of rivers. An alternative approach is to adopt an universal evaluation index for the health assessment of rivers and lakes at the country level (Hao & Guo 2018). However, there are very limited studies on weight and assignment criteria in the country-scale approach.

This paper attempts to use statistical methods to handle the data from papers related to Chinese river health assessments, published between 2000 and 2018. These include articles, Masters and PhD theses from China National Knowledge Infrastructure, as well as SCI journals about China river health assessment. These statistical methods can provide more comprehensive and reliable results. The work will undergo these following steps: (1) propose an objective and fair indicator system of river health assessment and the corresponding weight to be used at country scale; (2) propose a set of indicator assignment criteria for three different types of rivers (urban, ecological reserve, and casual rivers); (3) use nine case studies to validate the performance of the suggested indicator system, weight, and criteria, and examine the pros and cons of our system with respect to previous studies. With our proposed method,

the river health status can be evaluated by a comprehensive score, and the horizontal comparison of the health status of different types of rivers can be implemented.

METHODS

Comprehensive evaluation of river health

According to the analytic hierarchy process (AHP), indicator, weight, and assignment criteria are three decisive factors for comprehensive assessment of river health. If these three factors are given, the health index based on them can be calculated as:

$$R = \sum R_i = \sum W_i \cdot E_i \quad (1)$$

where R is the comprehensive degree of river health in five-point scale, R_i is the integrity score of the indicator, W_i is the weight of indicator i , and E_i is the score of the indicator i , which is determined by the assignment criteria according to the value.

For further evaluation, the score is transformed into a centesimal system according to Equation (2):

$$F = \frac{R}{5} \times 100 \quad (2)$$

where F is the comprehensive score in centesimal system. The health level of rivers is divided into five grades: very healthy, healthy, sub-healthy, unhealthy, and morbid, according to the comprehensive score. See Table 1 for details.

Determination of indicator, weight, and assignment criteria

The three decisive factors of river health assessment vary with the river type, which is inevitably subjective. Therefore, in this paper, we assume that their objective existence is endowed by the subjective.

Method to obtain the indicator system

We analyzed statistically how many times an indicator is used in river health assessment in order to build a new

Table 1 | Classification and description of rivers in different health level

Health level	Comprehensive score	Description
Very healthy	(85,100)	Rich in water resources, good water ecological environment, satisfied the reasonable needs of human social and economic development for the basin resources.
Healthy	(75,85)	Relatively good status in hydrology and water environment, basically satisfied the reasonable demand of human social and economic development for basin resources.
Unhealthy	(30,50)	Threatened health status of the basin, scarce water resources, fragile water ecological environment, maladjusted system structure, damaged function, but some functions can be maintained.
Morbid	(0,30)	Basically, loss of every function, or some indicators are extremely low.

indicator system for China. This new indicator system should be quantifiable, easy to use, and be representative of the physical and chemical characteristics of the river health. Representativeness, universality, quantification, and data availability are therefore essential for the indicator to be relevant. For similar names, connotations, or expressions, they are listed as the same indicator. For example, fish diversity index, retention rate, and loss index; sensitive, indigenous, and alien fish species; fish dominance index; individual abnormal fish species; and fish biological integrity index are all classified as fish index. The most used indicators are combined, classified, and analyzed. Correlation between indicators and repetitiveness are considered, and indicators that are significantly correlated excluded.

Weights calculation

Weights indicate the importance of various indicators of river health assessment, while it also reflects the importance of people's attention to each indicator of river health under certain social and economic conditions. Therefore, it is fixed during a certain period.

This paper builds statistics on the indicator weight of the representative multi-index river health assessment in China, and calculates its mathematical expectation as the weight of each indicator as follows:

$$E(x) = \int_{-\infty}^{+\infty} xf(x)dx \quad (3)$$

where $E(x)$ is the mathematical expectation, and $f(x)$ is the probability density function of weight x .

Method to summarize assignment criteria

River health reflects the public expectation about rivers. Assignment criteria are determined by some critical threshold recognized by the public, with excellent, well, fair, poor, very poor criteria (Su & Jia 2019), which does not satisfy a uniform standard and varies with the river type. For urban rivers, water quality can score 4 or more (out of 5) when it meets the requirements of class III (Surface Water Environmental Quality Standard, GB3838-2002), because class III has already met the public expectation. However, for ecological reserve rivers, water quality can only score 3 or less due to the higher public expectation to water quality. While comparing two types of rivers mentioned above, the difference lies in the assignment criteria: with the same water quality, one scores 4 while the other scores 3. The similarity is that people always care about water quality. In other words, the assignment criteria of indicators have changed; however, the weights of indicators have persisted.

In this paper, a river – when determining indicator assignment criteria – is first classified, and then the literature is classified according to the river type. Next, statistical methods determine the assignment criteria for each indicator. More specifically, we count, summarize, and combine similar assignment criteria and indicators from different literature sources.

RESULTS AND DISCUSSION

Indicator system

The statistical result based on the literature review are shown in Table 2. This table shows that the assessment

Table 2 | Indicators and their frequency usage in river health assessment

Layer 1 (OL)	Layer 2 (RL)	Layer 3 (IL) Indicator and its frequency
River health comprehensive index	Hydrology	Flow process variation degree (37), sediment transport change (19), flow velocity and state (17), water level change (13), cutoff ratio (7).
	Water quality	Achievement ratio of ecological water demand (45), achievement ratio of water quality in water functional area (40), comprehensive pollution index of water quality (37), DO (29), salinity (22), water temperature (21), total phosphorus (16), status of sediment pollutants (15), BOD ₅ (14), pH (14), ammonia nitrogen (11), integrated pollution index of heavy metals (10), permanganate index (10).
	Aquatic organism Physical habitats	Fish species (33), benthic index (28), zooplankton (25), phytoplankton (23), survival status of rare animals (20), basin biodiversity index (15), aquatic plant (11), alien species (7). Riverbank vegetation coverage ratio (47), stability of river bed (43), stability of riverbank (38), longitudinal connectivity (38), wetland conservation ratio (22), natural vegetation coverage (25), meandering degree (23), habitat quantity and quality (20), soil erosion (15), river stability (14), slope (12), river shading rate (12), habitat condition (11).

indicator system is usually composed of three layers. Layer 1 is the objective layer (OL), layer 2 is the rule layer (RL) with RL indicators, and layer 3 is the indicator layer (IL) with IL indicators (Su & Jia 2019). Furthermore, there is a widely accepted classification in more than 90% of the literature about river health in China in which the RL is classified into five RL indicators: hydrology (R_1), water quality (R_2), aquatic organism (R_3), physical habitats (R_4), and functional service (R_5). In addition, the ten most used IL indicators are selected to construct the indicator layer, and we grouped all IL indicators on the basis of the RL indicator. Next, according to the RL group, we introduced the IL indicators and the equations to calculate their values.

Hydrology

The hydrology indicator contains one IL indicator, I_1 -Flow process variation degree (FVD), which refers to the percentage of the annual discharge to average annual discharge (Li 2019) and is calculated using Equation (4):

$$FVD = \left\{ \sum_{m=1}^{12} \left(\frac{q_m - Q_m}{Q_m} \right)^2 \right\}^{1/2}; \bar{Q}_m = \frac{1}{12} \sum_{m=1}^{12} Q_m \quad (4)$$

where q_m is the measured monthly runoff of the assessment year, Q_m is the natural monthly runoff of the assessment, and \bar{Q}_m is the mean value of natural monthly runoff in the assessment year.

Water quality

The water quality indicator contains one IL indicator, I_2 -Achievement ratio of water quality in water functional area (ARWA), which refers to the proportion of water function area in which the water quality reaches the target value of the water function area (Li 2019). It shows whether the water quality is up to the standard which meets the requirements of water resources development, utilization and ecological environment protection at the same time. ARWA is calculated as follows:

$$ARWA = \frac{n}{N} \times 100\% \quad (5)$$

where n is the number of water function zones with water quality up to standard, and N is the total number of water function zones.

Aquatic organism

We use two indicators to describe the status of aquatic organisms. The first one is the I_3 -Shannon–Wiener diversity (S_h) index. Biodiversity is the total diversity, variability of organisms and their systems, which directly affects the survival, reproduction, and development of human beings (Zhang 2007), and S_h is a commonly used biodiversity index to characterize aquatic organisms. It

can be calculated as:

$$S_h = - \sum (p_i/P) \ln (p_i/P) \quad (6)$$

where S_h is the Shannon–Wiener diversity index, P is the total number of the samples, and p_i is the number of the i -th organism.

The second indicator is related to benthos live. Since they live for a long time at the bottom of the rivers, their mobility is weak and any change in water body directly influences the richness of benthos. The change of water body in a certain place directly influences the richness of benthos (Fu et al. 2018). The I_4 -Benthic index of biotic integrity (B - IBI) reflects the river health. The B - IBI is calculated by:

$$B-IBI = \frac{n_n}{N_b} \times 100\% \quad (7)$$

where n_b is the B - IBI value of the assessment river, and N_b is the optimal expectation of B - IBI in the water ecological zone near the river.

Physical habitats

Three indicators are used to represent the state of physical habitats. One is the I_5 -Riverbank vegetation coverage ratio (VCR). Riverbank vegetation benefits rivers in various ways by reducing soil erosion, preventing river erosion, purifying water, improving river microclimate, and providing habitat for aquatic organisms (Zhang 2007; Wei 2018). VCR is calculated as:

$$VCR = \frac{S_p}{S} \times 100\% \quad (8)$$

where S_p is the vegetation area of the riverbank, and S is the total area of vegetation that grows in the riverbank.

I_6 -Longitudinal connectivity (LC) is the second IL indicator, which refers to the connectivity of river branches, lakes, wetlands, and other water systems, and reflects the continuity of water flow and the vertical continuity of the river

(Wei 2018). It is calculated as:

$$LC = \frac{L}{100} \quad (9)$$

where L is the number of gates or dams per 100 km of river.

I_7 -Wetland conservation ratio (WCR) is the third IL indicator. Wetland is the main air purifier in the river basin and can also discharge flood and stored water. It provides a habitat and breeding place for animals. Wetlands are gradually shrinking in size as humans acquire the land (Zhang 2007; Wei 2018). WCR is obtained by:

$$WCR = \frac{a}{A} \times 100\% \quad (10)$$

where a is the current wetland area, and A is the wetland area in the reference period.

Functional service

Functional service contains two IL indicators. Flood control and disaster reduction depends on the safe flood discharge capacity of the river. The completion of a flood control project is one of the important signs of the safe flood discharge of the river (Yang 2012; Li 2019). I_8 -Flood control project completion ratio (FPR) can be selected to reflect the flood control and disaster reduction capacity of the river. The calculation formula is:

$$FPR = \frac{h}{H} \times 100\% \quad (11)$$

where h is the number of the completed flood control projects, and H is the flood control projects to be completed.

I_9 -Utilization ratio of water resources (URW) is an indication of the degree of water resources development and utilization and represents a river's use. Experience shows that if a river basin is rich in water, the rate of human development increases appropriately; however, its ratio should be controlled within a certain range. It is calculated as:

$$URW = \frac{U}{C} \times 100\% \quad (12)$$

where U is the water consumption of the area and C is the total water resources.

I_{10} -Riverbank landscape suitability (RLS) includes the satisfaction of the people in the basin with the river dominated landscape, and also the satisfaction of the public with the production and living environment directly related to the river. The scores are generally obtained by questionnaire and related materials.

Weights of indicator

We selected 47 typical evaluation cases from the literature, according to the number of downloads, citations, journal quality, and weight. We also analyzed and sorted the indicator weights.

Weights of RL

Figure 1 shows the probability density function of weights of RL indicators. Although the variation of the extreme values of the five RL indicators is relatively large, the probability distribution is still rather small. The weights for hydrology, water quality, aquatic organism, physical habitat, and functional service were set to 0.15, 0.21, 0.18, 0.22, and 0.24, respectively. The results of the RL indicator weights are shown in Figure 2.

Weights of indicator layer

The weights of IL indicators are obtained through two steps:

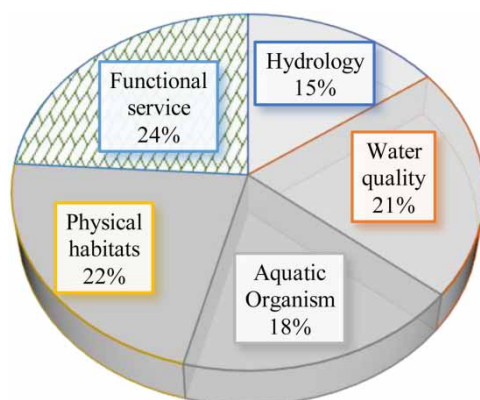


Figure 1 | Probability density function of weights of RL indicators.

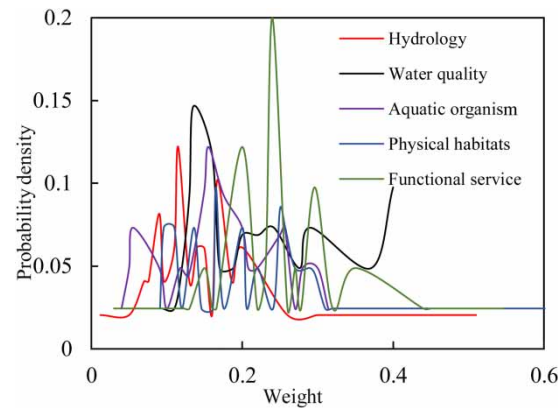


Figure 2 | Weights of RL indicators.

- (1) Calculate mathematic expectation of the weights of IL indicators of reviewed cases, and then count each IL indicator proportion under the same RL; and
- (2) Allocate the weights of RL indicators obtained in the RL weights according to the IL indicator proportion.

For the aquatic organism example:

- (1) We calculated the mathematic expectation of the weights of S_h and B-IBI of reviewed cases, which were 0.10 and 0.06, respectively, then we obtained the weights proportion, which is 5:3 under the aquatic organism rule layer; and
- (2) We allocated the weight of aquatic organism (the weight is 0.18) to S_h and B-IBI. As a result, the weights of S_h and B-IBI were 0.11 and 0.07, respectively.

We obtained the weights of all IL indicators, including FVD (0.15), achievement ratio of water quality in water functional area (0.21), fish species diversity index (0.11), B-IBI (0.07), VCR (0.09), LC (0.07), WCR (0.06), FPR (0.09), URW (0.08) and RLS (0.07). The index system, framework, and weights constructed in this paper are shown in Figure 3.

Indicator assignment criteria

This paper classifies rivers into urban (UR), ecological reserve (ERR), and casual (CR) rivers. UR mostly refers to rivers or their sections that originate from or flow through urban areas, including some canals that have been manually excavated in the past and have the characteristics of natural

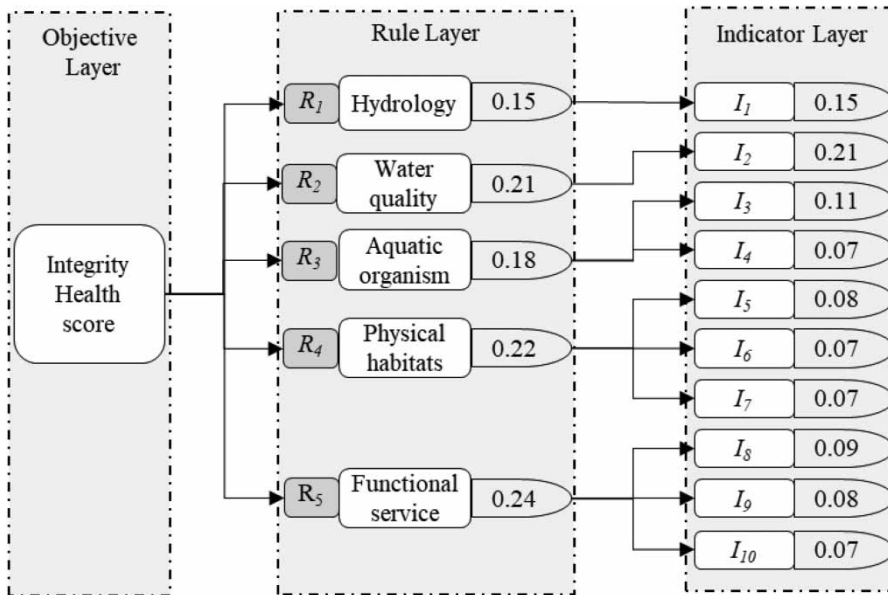


Figure 3 | Indicator system, framework, and weight.

rivers (Deng *et al.* 2014). ERR refer to rivers or their reaches that originate from or flow through the protected areas. Based on the studied references, we proposed the assignment criteria of UR, ERR, and CR, which is a five-point scale and is summarized in Table 3.

CASE STUDIES

By comparing the river health level obtained with our methods and that in the literature, nine cases were used to validate our proposed methods and results. The values of IL indicators were obtained for further assessment in two ways. First, for the indicators for which we had original data, Equations (4)–(12) were used to calculate their values. Second, for the indicators for which the original data was difficult to obtain, we used the IL indicator values of the selected literature because most equations are the same. There was a problem when comparing the values because most of the time the river health assessment system in the selected reference was not exactly the same as that proposed in our study, which means the selected IL indicators were not consistent in the selected literature and our study. Thus we uses various strategies to deal

with it. First, the choice of IL indicator was important. We must ensure that at least one IL indicator exists for each group, thus the IL indicator was selected dynamically according to the actual situation of the river. The second strategy involved the weights. Based on our assessment system, there was more than one IL indicator for some groups, and the values of some indicators were hard to get, thus we allocated the weights of IL indicators with missing data to other IL indicators in the same group in proportion. The third strategy was about the score. When we could not obtain the original data to calculate the value of IL indicator, if the equation in the reference was different to our study, or if the IL indicator to describe the state of RL indicator was different to our study, we scored the IL indicator using the five-point evaluation system based on the IL indicator grade of the reference.

Urban rivers

Case 1: Jing-Hang Grand Canal

The Beijing Hangzhou Grand Canal is the oldest and longest man-made canal in the world. Zhang (2016) established

Table 3 | Threshold values used for the score of river health of different types

River type	Score	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}
Urban rivers	5	(0,0.1)	(0.8,1)	≥ 3	≥ 2.7	(0.8,1)	(0,3)	(0.85,1)	(0.95,1)	(0,0.3)	≥ 90
	4	(0.1,0.15)	(0.7,0.8)	(2,3)	(2,2.7)	(0.6,0.8)	(3,8)	(0.7,0.85)	(0.9,0.95)	(0.3,0.4)	(80,90)
	3	(0.15,0.3)	(0.5,0.7)	(1,2)	(1.35,2)	(0.4,0.6)	(8,10)	(0.5,0.7)	(0.8,0.9)	(0.4,0.5)	(70,80)
	2	(0.3,3.5)	(0.2,0.5)	(0.5,1)	(0.67,1.35)	(0.2,0.4)	(10,20)	(0.3,0.5)	(0.7,0.8)	(0.5,0.6)	(60,70)
	1	≥ 3.5	(0,0.2)	< 0.5	< 0.67	(0,0.2)	≥ 20	(0,0.3)	(0,0.3)	(0,0.7)	≥ 0.6
Ecological reserve rivers	5	(0,0.07)	(0.95,1)	≥ 4	≥ 3.66	(0.95,1)	(0,0.3)	(0.95,1)	(0.95,1)	(0,0.1)	≥ 75
	4	(0.07,0.09)	(0.8,0.95)	(3,4)	(2.75,3.66)	(0.85,0.9)	(3,0.5)	(0.8,0.95)	(0.8,0.9)	(0.1,0.2)	(60,75)
	3	(0.09,0.15)	(0.7,0.8)	(2,3)	(1.83,2.75)	(0.6,0.85)	(5,0.8)	(0.7,0.8)	(0.65,0.8)	(0.2,0.3)	(50,60)
	2	(0.15,0.3)	(0.5,0.7)	(1,2)	(0.92,1.83)	(0.4,0.6)	(0.8,1.2)	(0.5,0.7)	(0.5,0.65)	(0.3,0.4)	(30,50)
	1	≥ 0.3	(0,0.5)	< 1	< 0.92	(0,0.4)	≥ 1.2	(0,0.5)	(0,0.5)	≥ 0.4	≥ 0.4
Casual rivers	5	(0,0.08)	(0.85,1)	≥ 3.6	≥ 3.59	(0.85,1)	(0,1)	(0.9,1)	(0.95,1)	(0,0.2)	≥ 80
	4	(0.08,0.15)	(0.75,0.85)	(2,7,3.6)	(2,7,3.59)	(0.65,0.85)	(1,3)	(0.75,0.9)	(0.85,0.95)	(0.2,0.3)	(70,80)
	3	(0.15,0.25)	(0.6,0.75)	(1.8,2.7)	(1.8,2.7)	(0.45,0.65)	(3,5)	(0.6,0.75)	(0.7,0.85)	(0.3,0.4)	(60,70)
	2	(0.25,1.5)	(0.3,0.6)	(0.9,1.8)	(0.9,1.8)	(0.3,0.45)	(5,10)	(0.4,0.6)	(0.6,0.7)	(0.4,0.5)	(40,60)
	1	≥ 1.5	(0,0.3)	< 0.9	< 0.9	(0,0.3)	≥ 10	(0,0.4)	(0,0.6)	≥ 0.5	≥ 0.5

the health assessment index system of river health, which is composed of 11 indexes obtained by AHP, and evaluated the health of Jing-Hang Grand Canal in Huai'an urban section. The Huai'an section is 23.0 km long, with a high-level channel standard. It is an important channel for material transportation. The assessment process and results are shown in Table 4.

The value of I_1 is qualitatively evaluated as 'satisfied', which is in the second class according to the criteria of Case 1, and thus the score of I_1 is 4 in this paper. I_6 is described by the fluidity index with the value of 75%, which is in the third level according to the criteria of case 1, and thus the score is 3. The data of I_4 is missing, thus its weight is assigned to I_3 . The data of I_7 is missing, and thus its weight is allocated to I_5 and I_6 in proportion. This is the same for I_9 , with the weight being assigned to I_8 and I_{10} in proportion.

Converting the total score into a percentage system, the comprehensive score is 87. Thus, the Jing-Hang Grand Canal in Huai'an section can be classified as 'very healthy'. The health status of Case 2 is also 'very healthy', which is consistent with the evaluation result of this paper. The comparison of the indicator scores between this paper and case 1 is shown in Figure 4.

Case 2: The Yangtze River in Wuhan sector

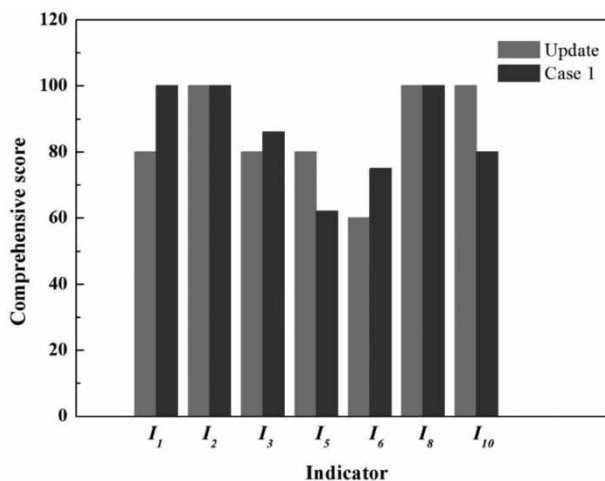
As the largest river in China, the Yangtze River Basin has a prominent social, economic, and ecological status. Zhang (2007) proposed different health evaluation index systems according to river section, and evaluated the health of three typical river sections. The Yangtze River in Wuhan section is selected as Case 2 to test the proposed river health assessment system. Wuhan is located in the middle reaches of the Yangtze River, with a permanent population of more than 11 million. The evaluation process and results are shown in Table 5 for this case.

The selected indicators and their weights are handled in the same way as Case 1: Jing-Hang Grand Canal. Converting the total score into a percentage system results in the comprehensive score of 67.4. Thus, the health degree of the Wuhan section of the Yangtze River is 'sub-healthy'. The evaluation result of Case 2 is also 'sub-healthy', which is consistent with the evaluation result of this paper.

Table 4 | Results of the health assessment of the Jing-Hang Grand Canal in the Huaifan section

Rule layer		Indicator layer		Assessment		
RL indicator	Weight	IL indicator	Weight	IL indicator value	IL indicator score	Integrity score
R_1	0.15	I_1	0.15	Satisfied*	4	0.6
R_2	0.21	I_2	0.21	100%	5	1.05
R_3	0.18	I_3	0.18	2.06	4	0.72
R_4	0.22	I_5	0.12	62%	4	0.48
		I_6	0.1	75%*	3	0.3
R_5	0.24	I_8	0.13	100%	5	0.65
		I_{10}	0.11	80	5	0.55
Total	1		1			4.35

Note: '*' means that the equation used for the IL indicator in the selected reference for the case study, or the RL indicator in the selected reference was different to our study. We used the IL indicator's grade in the reference to assign the IL indicator score.

**Figure 4** | Comparison of the indicator score between this study (denoted by 'update') and Case 1 from Zhang (2016).**Table 5** | Results of the health assessment of the Yangtze River in the Wuhan section

Rule layer		Indicator layer		Assessment		
RL indicator	Weight	IL indicator	Weight	IL indicator value	IL indicator score	Integrity score
R_1	0.15	I_1	0.15	0.08	4	0.6
R_2	0.21	I_2	0.21	99.5%	5	1.05
R_3	0.18	I_3	0.18	2.94	3	0.54
R_4	0.22	I_5	0.09	25%	2	0.18
		I_6	0.07	0.7	4	0.28
		I_7	0.06	2nd level*	4	0.24
R_5	0.24	I_{10}	0.24	70	2	0.48
Total	1		1			3.37

Note: '*' means that the equation used for the IL indicator in the selected reference for the case study, or the RL indicator in the selected reference was different to our study. We used the IL indicator's grade in the reference to assign the IL indicator score.

Case 3: The Simao River

The Simao River, located in the Pu'er City, is the only drainage channel for the Simao District. It originates in Dajianshan Mountain, and finally merges into the Lancang River. Li (2019) established the health assessment index system for rivers in southwest mountainous cities, and evaluated the Simao River's health. The assessment process and results are shown in Table 6.

With the comprehensive score of 64.8, the health degree of the Simao River is 'sub-healthy'. The evaluation result of Case 3 is also 'sub-healthy', which is consistent with the evaluation result of this paper. See Figure 5 for the comparison of the indicator score between this paper and Case 3.

Table 6 | Results of the health assessment of the Simao River

Rule layer		Indicator layer		Assessment		
RL indicator	Weight	IL indicator	Weight	IL indicator value	IL indicator score	Integrity score
R_1	0.15	I_1	0.15	0.74*	2	0.3
R_2	0.21	I_2	0.21	60%	3	0.63
R_3	0.18	I_4	0.18	1.35*	2	0.36
R_4	0.22	I_5	0.12	57%	3	0.36
		I_6	0.1	0	5	0.5
R_5	0.24	I_8	0.13	100%	5	0.65
		I_9	0.11	38%	4	0.44
Total	1		1			3.24

Note: "*" means that the equation used for the IL indicator in the selected reference for the case study, or the RL indicator in the selected reference was different to our study. We used the IL indicator's grade in the reference to assign the IL indicator score.

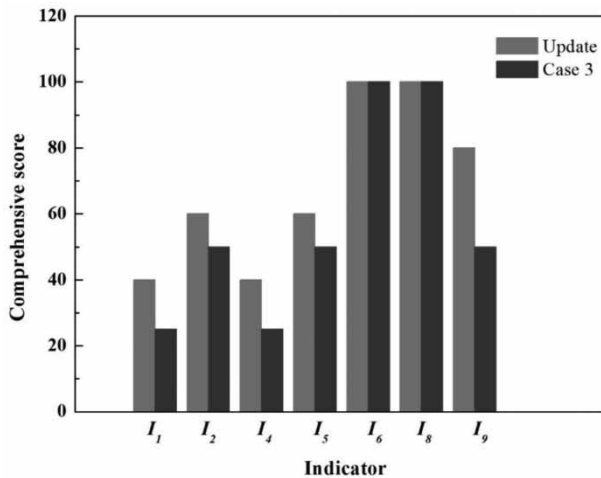


Figure 5 | Comparison of the indicator score between this paper and Case 3 from Li (2019).

Ecological reserve rivers

Case 4: The Songhua River

The Songhua River is the largest tributary on the right bank of the Heilongjiang River and the largest river in Heilongjiang Province. Wei (2018) established the health evaluation index system of the main stream of the Songhua River, and evaluated the health of the Songhua River in 2006 and 2015 in sections. The river section mainly includes the Sanjiangkou fish reserve and buffer zone of Tongjiang City. There are Fujin and Suibin wetlands along the river, both of which are provincial natural reserves. The evaluation process and results are shown in Table 7.

Table 7 | Results of the health assessment of the Songhua River

Rule layer		Indicator layer		Assessment		
RL indicator	Weight	IL indicator	Weight	IL indicator value	IL indicator score	Integrity score
R_1	0.15	I_1	0.15	1.19	1	0.15
R_2	0.21	I_2	0.21	67.50%	2	0.42
R_3	0.18	I_3	0.11	0.95*	4	0.44
		I_4	0.07	1.92	3	0.21
R_4	0.22	I_5	0.09	30%	1	0.09
		I_6	0.07	0	5	0.35
		I_7	0.06	69%	2	0.12
R_5	0.24	I_8	0.09	57%	2	0.18
		I_9	0.08	47%	1	0.08
		I_{10}	0.07	63	4	0.28
Total	1		1			2.32

Note: "*" means that the equation used for the IL indicator in the selected reference for the case study, or the RL indicator in the selected reference was different to our study. We used the IL indicator's grade in the reference to assign the IL indicator score.

The comprehensive score of river health is 46.4, thus it is classified as ‘morbid’. However, the evaluation result in Case 4 is ‘healthy’, which is different from the result we obtained. The reason for the inconsistency is that the standard used in Case 4 cannot be applied for an ecological reserve river and should be stricter. This leads to an optimistic evaluation result, which is incorrect for river management. Figure 6 shows the comparison of the indicator score between this paper and Case 4. In Case 4, with a value of 30%, the score of I_5 is 78, and with the value of 47%, the score of I_9 is 68, which is not correct.

Case 5: The Buyuan River

The Buyuan River is an important tributary of the lower Lancang River. Yang (2012) selected seven key indexes

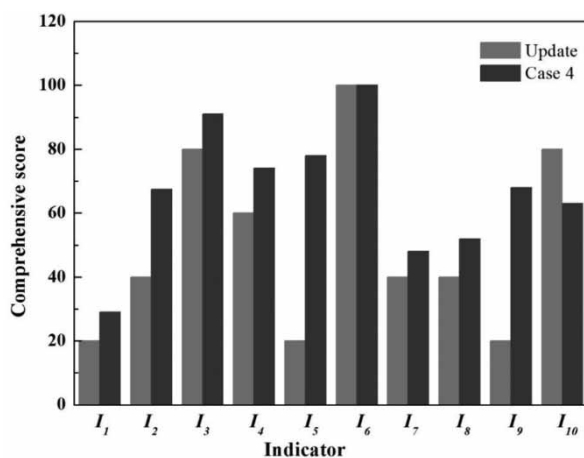


Figure 6 | Comparison of the indicator score between our results and Case 4.

Table 8 | Results of the health assessment of the Buyuan River in the Nanban sector

Rule layer		Indicator layer		Assessment		
RL indicator	Weight	IL indicator	Weight	IL indicator value	IL indicator score	Integrity score
R_1	0.15	I_1	0.15	16.6%*	5	0.75
R_2	0.21	I_2	0.21	98%	5	1.05
R_3	0.18	I_3	0.18	11*	4	0.72
R_4	0.22	I_5	0.12	68%	3	0.36
		I_6	0.1	0	5	0.5
R_5	0.24	I_9	0.24	12%	4	0.96
Total	1		1			4.34

Note: ‘*’ means that the equation used for the IL indicator in the selected reference for the case study, or the RL indicator in the selected reference was different to our study. We used the IL indicator’s grade in the reference to assign the IL indicator score.

from 60 references related to the river health evaluation index system and verified them using the Buyuan River. In this paper, the Buyuan River in the Nanban river section was selected as Case 5 for validation. In this section, a fish nature reserve will mitigate the adverse impact of the cascade power station construction on aquatic organisms and their habitats, while maintaining the connectivity of fish habitats. The evaluation process and results are reported in Table 8.

The comprehensive score of the Buyuan River in the Nanban sector is 86.8, thus it is classified as ‘very healthy’, which is consistent with the ‘very healthy’ status of the river in Case 5.

Case 6: The Lhasa River

The Lhasa River is a tributary of the Yarlung Zangbo River. Chen (2019) constructed a river health assessment index system including 11 indexes based on the characteristic of the Lhasa River, and applied it to the main stream of the Lhasa River. The upper reaches of the Lhasa River were selected for Case 6 for validation. The river source is the Medica wetland, which is a national natural reserve. The evaluation process and results are given in Table 9.

The comprehensive score of the Lhasa River in the upper reaches is 81.6, and thus it is classified as ‘healthy’, which is consistent with the results obtained in Case 6 according to Chen (2019).

Table 9 | Results of the health assessment of the Lhasa River in the upper reaches

Rule layer		Indicator layer		Assessment		
RL indicator	Weight	IL indicator	Weight	IL indicator value	IL indicator score	Integrity score
R_1	0.15	I_1	0.15	Original*	5	0.75
R_2	0.21	I_2	0.21	50%	2	0.42
R_3	0.18	I_3	0.18	8%*	4	0.72
R_4	0.22	I_6	0.22	0	5	1.1
R_5	0.24	I_8	0.13	95%	5	0.65
		I_9	0.11	10%	4	0.44
Total	1		1			4.08

Note: '*' means that the equation used for the IL indicator in the selected reference for the case study, or the RL indicator in the selected reference was different to our study. We used the IL indicator's grade in the reference to assign the IL indicator score.

Casual rivers

Case 7: The Daxi River

The Daxi River is a tributary on the left bank of the Wujiang River. The interaction between the natural environment and human activities of the Daxi River has increased, and the basin environment is fragile and sensitive. Zhang (2012) constructed a river health assessment index system with 18 indicators, and evaluated the health of the Daxi River in the Nanchuan section based on AHP. The evaluation process and results are shown in Table 10.

The comprehensive score of the Daxi River is 61.2, thus the river status is 'sub-healthy', which is consistent with the

evaluation result in Case 7 obtained by Zhang (2012). Figure 7 shows the indicator score of this paper compared to Case 7 by Zhang (2012).

Case 8: The Qi River

The Qi River is a first-class tributary on the right bank of the upper reaches of the Yangtze River. The Qi River basin is rich in iron, and forest and tourism resources. The health of the Qi River directly affects the socio-economic development and ecological stability of the basin. Li (2015) established a river health assessment index system based on 16 indicators and a multi-level gray clustering evaluation system which were applied to the Qi River. Case 8 is selected for validation in this

Table 10 | Results of the health assessment of the Daxi River

Rule layer		Indicator layer		Assessment		
RL indicator	Weight	IL indicator	Weight	IL indicator value	IL indicator score	Integrity score
R_1	0.15	I_1	0.15	0.124	4	0.6
R_2	0.21	I_2	0.21	58%	2	0.42
R_3	0.18	I_4	0.18	1.23	2	0.36
R_4	0.22	I_5	0.12	Pretty good*	4	0.48
		I_6	0.1	0.85	5	0.5
R_5	0.24	I_8	0.13	Weak*	2	0.26
		I_9	0.11	21%	4	0.44
Total	1		1			3.06

Note: '*' means that the equation used for the IL indicator in the selected reference for the case study, or the RL indicator in the selected reference was different to our study. We used the IL indicator's grade in the reference to assign the IL indicator score.

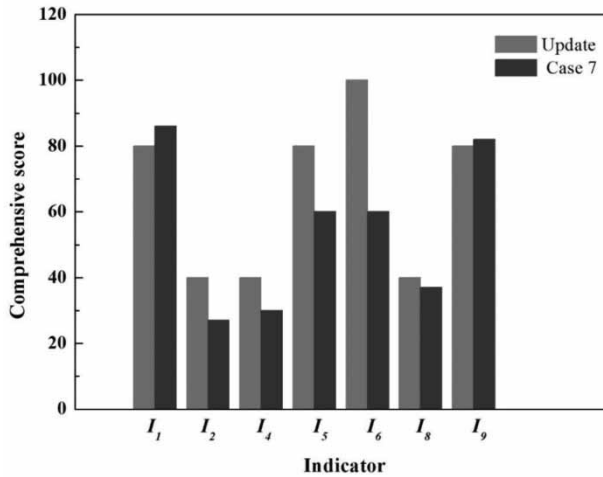


Figure 7 | Comparison of the indicator score between this paper and Case 7.

paper. The evaluation process and results are shown in Table 11.

The comprehensive score of the Qi River is 76.6, and thus it is classified as ‘healthy’, which is consistent with the evaluation result obtained by Li (2015) in Case 8.

Case 9: The Yellow River in Inner Mongolia

The Yellow River is the second largest river in China and the birthplace of Chinese civilization. This river’s health directly affects the economic development of Inner Mongolia. Tian (2016) established a river health assessment index system in line with the characteristics of the Yellow River in Inner Mongolia, and evaluated its

Table 11 | Results of the health assessment of the Qi River

Rule layer		Indicator layer		Assessment		
RL indicator	Weight	IL indicator	Weight	IL indicator value	IL indicator score	Integrity score
R_1	0.15	I_1	0.15	0.06	4	0.6
R_2	0.21	I_2	0.21	86%	5	1.05
R_3	0.18	I_3	0.11	1.78	2	0.22
		I_4	0.07	1.9	4	0.28
R_4	0.22	I_6	0.22	2.5	4	0.88
R_5	0.24	I_8	0.09	87.5%	4	0.36
		I_9	0.08	45%	2	0.16
		I_{10}	0.07	77	4	0.28
Total	1		1			3.83

Table 12 | Results of the health assessment of the Yellow River in Inner Mongolia

Rule layer		Indicator layer		Assessment		
RL indicator	Weight	IL indicator	Weight	IL indicator value	IL indicator score	Integrity score
R_1	0.15	I_1	0.15	0.83*	2	0.3
R_2	0.21	I_2	0.21	12%	1	0.21
R_3	0.18	I_3	0.18	1.12	2	0.36
R_4	0.22	I_5	0.13	42%	2	0.26
		I_7	0.09	73%	3	0.27
R_5	0.24	I_9	0.13	42%	2	0.26
		I_{10}	0.11	80	4	0.44
Total	1		1			2.1

Note: ‘*’ means that the equation used for the IL indicator in the selected reference for the case study, or the RL indicator in the selected reference was different to our study. We used the IL indicator’s grade in the reference to assign the IL indicator score.

health with fuzzy evaluation method. We use this study as Case 9. The evaluation process and results are shown in Table 12.

The comprehensive score is 42, meaning that the Yellow River is classified as 'unhealthy'. This is consistent with the evaluation result in Case 9 obtained by Tian (2016).

CONCLUSION

This paper reviews and examines the previous literature on river health assessment. It also proposes an indicator system and assignment criteria for three types of river. We use nine case studies to evaluate our suggested method for river health assessment. The main outcomes are as follows. (1) The proposal of a novel indicator system of river health assessment based on statistics and mathematical analysis. This system incorporates five RL indicators and ten IL indicators including their corresponding weights. With fixed indicators and weights, the assessment system can provide an efficient, clear, and concise evaluation method. (2) The establishment of three types of assignment criteria for three types of rivers (urban rivers, ecological reserve rivers, and casual rivers) which will improve more accuracy and comparison with different rivers. (3) The nine validation cases show that the novel method is reliable, rational, and widely usable.

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DATA AVAILABILITY STATEMENT

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

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