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Health Assessment of the Waterway from Chongqing to Yibin in the Upper Yangtze River, China

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Abstract: Ecological waterway construction and waterway health protection have become a trend and requirement of waterway development worldwide. How to assess the health status of a waterway is a fundamental concern for waterway sustainable development. This study established a comprehensive framework for health assessment of the waterway from Chongqing to Yibin in the upper reach of the Yangtze River, focusing on the coordinated development of river functions or services including navigation, flood discharge, sediment transport, water supply, self-purification, ecology, and recreation. This framework consists of a hierarchical indicator system, a weight determination method with analytic hierarchy process (AHP), an assessment model considering cask short board effect, and a sensitive analysis method. The waterway health in this river section in the periods 2016–2017 and 2018–2020 were assessed. The results showed that the river functions of navigation, flood discharge, water supply, ecology, and recreation had improved, while sediment transport had deteriorated from "Fair" to "Poor", and self-purification remained at "Excellent" condition. The overall health of the waterway from Chongqing to Yibin has improved but remained in a "Fair" state during 2016–2020, at roughly the same healthy state as the other three waterways in the middle, middle-lower, and lower reaches. The results are conducive to understanding the health status of the whole Yangtze River waterway. They can serve as an important reference for ecological protection and development of high quality in the Yangtze River basin.

Keywords: the Yangtze River; waterway health; AHP; assessment; ecological waterway

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1. Introduction

Inland waterways are essential for transportation due to benefits such as large navigation capacity, low cost, less energy consumption, less pollution, and less land occupation [1]. With the rapid development of the water transportation industry, the waterway construction has entered a golden period of development. Aside from meeting the increasing demand for passenger and goods transport, an accumulating body of research has revealed that the essence of creating inland waterways is to bring about regional socio-economic development that is also comprehensive, coordinated, and sustainable [2]. Coordination of navigation and environmental and ecological protection of a waterway is getting more and more attention from researchers, governmental administrators, and practitioners.

Waterway health assessment is useful for guiding inland waterway construction and realizing the sustainable development of the nexus between waterways, nature, society, and the economy. As a result, the current research mainly focused on the assessment of river health [3–5]. A series of agreements, plans, assessment systems and prediction models of river health have been established in the United States (Rapid Bioassessment Protocols, RBPs) [6], Britain (a system for evaluating rivers for conservation, SERCON) [7], Australia (AUSRIVAS) [8] and South Africa (River Health Program, RHP) [9]. River health assessment methods include model methods and multi-index evaluation methods [4]. Waterway health is affected by multiple factors. A multi-metric approach is more commonly used because it can assess waterway health in an objective and comprehensive way [10]. Numerous mathematical approaches, such as analytic hierarchy process (AHP) [11], fuzzy comprehensive assessment [12], artificial neural network [13] and so on, have also been applied to river health assessment. Among them, the AHP, which was proposed by Saaty, has been widely used and proved useful in multi-index evaluation and multi-object decision making [14].

The Yangtze River is the longest river in China and the third longest river in the world. The ecological functions of Yangtze River, such as bio-diversity preservation, water supply security, and pollution reduction, have significant implications well beyond the local environment. It is important for the regional environment as environmental fluxes transporter and ecosystem provider [15]. On the other hand, the Yangtze River waterway plays an important role in China's economy and even the world's industrial chain [16]. The Yangtze River waterway has become the busiest inland waterway in the world since 2006, and carries much larger freight transport than any other inland waterway [17]. The efforts of China to protect the ecological system in the waterway development could be useful for other developing regions relying on inland water transportation. So far, the existing research pertinent to waterway ecological protection mainly focused on the middle and lower reaches of the Yangtze River, proposing the concept and evaluation indicator system of the ecological waterway [18–21]. Located in the upper reaches of the Yangtze River, the waterway from Chongqing to Yibin has different riverbed features, has experienced different kinds of waterway regulation projects, and plays a critical role in the comprehensive transportation system of western developing areas in China and the ecological security of the middle and lower reaches of Yangtze River [22]. Nevertheless, waterway health in this river reach has not been reported. This, therefore, hinders forming a holistic picture of the waterway health in the Yangtze River.

The main aims of this paper are: (1) to construct a comprehensive framework of waterway health assessment for the reach from Chongqing to Yibin in the upper Yangtze River based on the principle that the navigation function should be developed in harmony with other river functions; (2) to compare the waterway health changes between the periods of 2016–2017 and 2018–2020 and comprehensively assess the effect of the waterway regulation projects during the Thirteenth Five-Year Plan period (from 2016 to 2020); (3) to reveal the health status of the whole Yangtze River waterway for the first time by comparative analysis with previous studies on waterway assessment in the other reaches. This work is thus expected to provide scientifical support for sustainable exploitation and ecological protection of the Yangtze River.

2. Materials and Methods

2.1. Study Area

Located in the southern margin of Sichuan Basin, the waterway from Chongqing to Yibin in the upper Yangtze River primarily flows through Chongqing and through Yibin and Luzhou in Sichuan (Figure 1). The waterway from Chongqing to Yibin has a total length of 384 km. The area has a subtropical monsoon climate, which is characterized by distinct patterns of four seasons, notably being hot and wet in summer, cold and dry in winter. Sufficient rainfall in the upper reaches of the Yangtze River can easily induce geological disasters such as collapse and landslides. The reach passes through canyons, hills, and mountains. The waterway in this section is narrow and steep in canyons, open in hilly areas, and has a width of 500~1000 m during the flood season, 300~400 m during the dry season. The average current velocity is 1.5–3.0 m/s in the dry season, 3.0–5.0 m/s in the flood season, and the maximum frequently exceeds 6.0 m/s. There are more than 30 navigation-obstructing beach sections, which have become a serious hindrance to the development and health of the waterway.

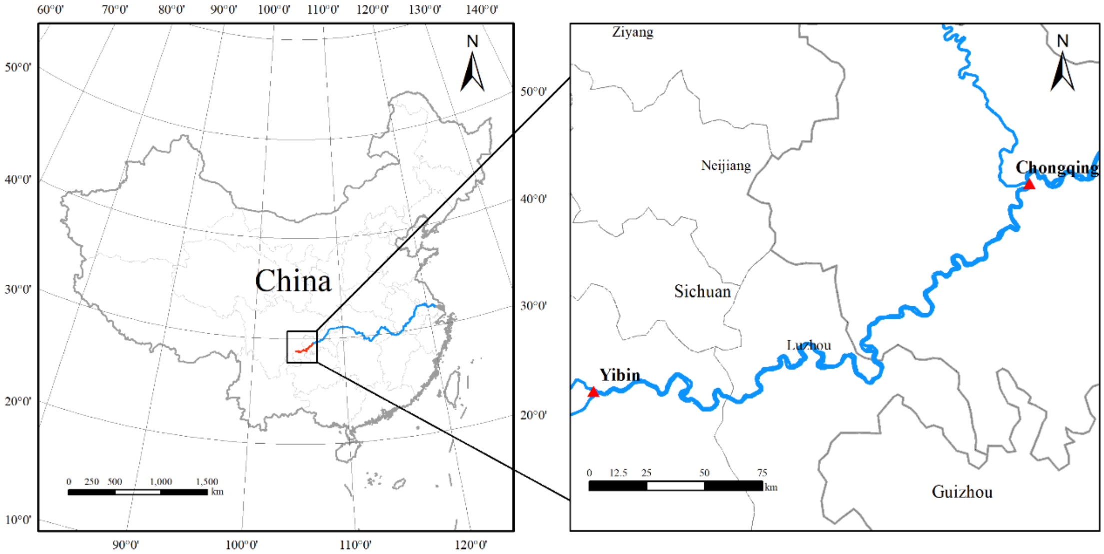

Figure 1. Location of the Chongqing to Yibin waterway.

A series of waterway regulation projects had been carried out in this river reach in order to produce and maintain a more favorable channel dimension which is normally represented by Water depth × Waterway width × Bend radius. Dredging and reef blasting are the most common waterway regulation projects between Chongqing and Yibin. At present, the channel dimensions of the waterway from Chongqing to Yibin have already been enlarged from 1.8 m × 40 m × 400 m to 2.9 m × 50 m × 560 m, which has effectively improved its navigation capacity[23]. The navigable conditions in the reach can meet the standards for class-III, with a navigation capacity for ships up to 1000 tons throughout the year.

2.2. Indicator System Construction for Waterway Health Assessment

A waterway usually has both natural and social functions, and a healthy waterway should maintain its natural functions while meeting societal needs [21]. Previous pieces of research have already pointed out that the river system has a variety of functions or services, such as flood discharge, water supply, sediment transport, purification, landscape, navigation, power generation and so on [24]. In response to the new changes of water and sediment conditions caused by the joint operation of the Three Gorges Project and the upstream reservoirs, new requirements for the Yangtze Golden Waterways have also been developed, including for flood control, shipping, power generation, water supply and ecology [25]. A healthy waterway must ensure that navigation and other river functions are developed in a coordinated manner.

The waterway health assessment indicator system consists of three layers: (a) the state layer (indicates the comprehensive health status of the waterway); (b) the function layer (includes the major functions or services of the waterway); (c) the indicator layer (which includes indicators to represent a certain function or service). Based on previous research [19–21] and the actual situation of the study area, seven functions or services were chosen for the function layer including navigation, flood discharge, sediment transport, water supply, self-purification, ecology, and recreation. The indicators were selected following the principles that they should be clear, simple, and independent, and the data needed to assess them is available. Table 1 shows the proposed indicator system to assess the health of the waterway from Chongqing to Yibin in the upper Yangtze River. The proposed indicator system will be described in detail after Table 1.

Table 1. Indicator system for health assessment of the waterway from Chongqing to Yibin.

State Layer	No.	Function Layer	No.	Indicator Layer	Description and Calculation Method

The Waterway Health	B1	Navigation	C1	Navigable depth and width (m)	Navigable depth and width of the waterway [24]
			C2	Rate of navigation aid facilities in service to the total (%)	$\frac{\text{number of navigation marks in service}}{\text{total number of navigation marks}} \times 100\%$ (GB50139-2004)
			C3	Annual accident occurrences	Accidents occurred within a year [20]
	B2	Flood discharge	C4	Maximum flood discharge capacity	The maximum flood level that the waterway can resist. (GB 50201-94) [26]
			C5	Proportion of flood control works meeting the criterion to the total (%)	$\frac{\text{number of flood control works meet the criterion}}{\text{total number of flood control works}} \times 100\%$ [27]
	B3	Sediment transport	C6	The variation rate of water used for sediment transportation in a certain year relative to the average value (%)	$\frac{\text{water used for sediment transportation in a certain year}}{\text{the average water used for sediment transportation in several years}} \times 100\%$ $W_c = \frac{0.1 \times nS_t}{\sum_i^n max(C_{ij})}$ Where W_c represents water used for sediment transportation (10^8 m^3); S_t is average sediment discharge in a year(10^4); C_{ij} is average sediment concentration in the jth month of the ith year; n indicates the number of years [28].
			C7	The variation rate of the suspended sediment load in a certain year relative to the average value (%)	$SCr = \frac{\lvert W_s - W_{s0} \rvert}{W_{s0}} \times 100\%$ Where SCr represents the rate of change of suspended sediment load, W_s is the suspended sediment load in a certain year, W_{s0} is average sediment load over years [29].
	B4	Water supply	C8	Rate of water resource utilization (%)	$\frac{\text{volume of water supply}}{\text{the total water resource}} \times 100\%$ [30,31]
			C9	Rate of reaching water quality standard in function zones (%)	$\frac{\text{number of function zones reaching water quality standards}}{\text{total number of water function zones}} \times 100\%$ [32]
			C10	Water quality comprehensive index	$P = \sqrt{\frac{\bar{P}_i^2 + P_{max}^2}{2}}$ $P_i = \frac{C_i}{C_0}$ Where P represents comprehensive water quality index; P_i is pollutant index; C_i is the concentration of pollutant; C_0 is the reference value of pollutant concentration [18].
	B5	Self-purification	C11	Dissolved oxygen concentration(mg/L)	Dissolved oxygen concentration (mg/L) [33]
			C12	The variation rate of water used for self-purification in a certain year relative to the average value (%)	Average minimum monthly flow over the past decade (GB3839-83)
	B6	Ecology	C13	Degree of satisfaction of ecological water demand (%)	$EF = min\, [\frac{q_d}{Q}]_{m=1}^{m=12}$ Where EF represents degree of satisfaction of ecological water demand(%), q_d is the measured daily flow in evaluation year, Q is the average flow for several years [34].
			C14	Fish integrity index	$H = -\sum_{j=1}^{n}(h_j) \times ln\,(h_j)$ Where H represents fish integrity index; n is the number of biological species, h_j is the proportion of number of species j to the total fish species [35,36].
			C15	Survival of rare species	Investigation of rare species numbers and survival situation [37–39]
	B7	Recreation	C16	Landscape diversity index	$H_l = -\sum_{j=1}^{n}(h_j) \times ln\,(h_j)$

		Where H_l represents landscape diversity index; n is the number of landscape species, h_j is the areal parentage of type j landscape over the total area [40].
C17	Normalized difference vegetation index	$NDVI = \frac{R_{NIR}-R_{Red}}{R_{NIR}+R_{Red}}$ Where $NDVI$ represents normalized difference vegetation index; R_{NIR} is the intercalibrated data in near-infrared bands; R_{Red} is the intercalibrated data in red bands [41].

(1) Navigation

The Yangtze River shipping plays an irreplaceable role in the national shipping system [42]. The Yangtze River port completed a cargo throughput of 3.5 billion tons in 2021, an increase of more than 6% year by year, a record high. This includes a container throughput of 22.82 million standard containers, an increase of 16.3%. The upper reaches of the Yangtze River have large ports such as Chongqing, Yibin, and Luzhou. In recent years, the shipping capacity of the three ports has been greatly improved, which provides an effective guarantee for the economic development of the upper reaches. The navigation function is expressed by 3 indicators: navigable depth reliability, proportion of navigation aid facilities in service, and annual accident occurrences.

(2) Flood discharge

One of the river's primary functions is to regulate runoff between regions through flood discharge. In recent years, engineering measures such as channelization, reservoir construction, embankment, flood storage and detention areas, and underground rivers are quite commonly used for recharge, regulation, and discharge [43]. For a long time, flood control projects such as the Yangtze River embankment, flood storage and detention area have been mainly distributed in the middle and lower reaches, while flood defense in the upstream is relatively weak. Two indicators were selected to represent flood discharge, namely, the maximum flood discharge capacity and the proportion of flood control works that meet flood control criteria stipulated by the Chinese government.

(3) Sediment transport

The abnormal sediment transport function will lead to river siltation, runoff reduction, and flow interruption, as well as threaten the safety of surrounding areas. Regional sediment transport could be severely affected by numerous factors, such as climate change, vegetation coverage, human interventions and so on [44,45]. The historical changes in land use brought an increase in sediment discharge [46,47]. However, the trends have now gone into reverse due to anthropogenic factors including construction of dams, water diversion and sand mining [48–50]. The main source of suspended sediment in the Yangtze River Basin is in the upstream reaches. The rate of variation in suspended sediment transport reflects the change in river sediment concentration and sediment deposition in the river channel, and indirectly reflects the state of the river structure and ecological environment [51]. The rate of variation in suspended sediment transport is expressed by the ratio of the value of river sediment transport in the assessment year and value of the average river sediment transport over a longer period. The greater the value, the greater the impact on the river ecosystem. The sediment transport function is represented by 2 indicators: the variation rate of water used for sediment transportation in a certain year relative to the average value and the variation rate of the suspended sediment load in a certain year relative to the average value.

(4) Water supply

Water is the source for life, and hence it gets diverted for human and animal use, such as farmland irrigation, industrial production, and landscape ecology. The Yangtze River provides abundant water resources for the areas it flows through. With the acceleration of urbanization, it is of great importance for the waterway from Chongqing to Yibin to meet the growing demand for water quantity and water quality. In this context, water function zoning has implemented to set water-quality target and improve water ecological environment. Different function zones are stipulated according to conditions of social and economic development, natural endowment, and environmental and ecological functions.. The water resource utilization ratio, comprehensive index of water quality and rate of reaching water quality standards in the function zones were chosen to indicate the function of water supply.

(5) Self-purification

The self-purification capacity of river water is an essential indicator for a healthy river [52]. Pollutants in rivers can be eliminated by natural dilution, diffusion, oxidation, or metabolism, as well as by absorption and degradation of aquatic organisms. Domestic sewage and industrial wastewater have been the primary pollution source along the reaches from Chongqing to Yibin. To assess the waterway's self-purification, two indicators were used, specifically, dissolved oxygen concentration and the variation rate of water used for self-purification in a certain year relative to the average value.

(6) Ecology

As the breeding habitat of numerous aquatic organisms, the waterway plays an important role in maintaining biodiversity. From Chongqing to Yibin, a reserve covering some of the upper reaches of the river have been designated as the Yangtze River Rare Fish National Nature Reserve to protect rare freshwater fishes such as *Acipenser dabryanus*, *myxopyronins asiaticus*[53]. The ecology function of the waterway is represented by 3 indicators: degree of satisfaction on ecological water demand, fish or biological integrity index, and survival of rare species.

(7) Recreation

In order to realize the harmonious coexistence of man and nature, the river is also attributed a recreation service function. It is critical that improvements in the surrounding ecological environment, increasing vegetation coverage, enriching people's lives, and stimulating the local economy are considered during the waterway regulation implementation process. The recreation function is indicated by 2 indicators: landscape diversity index and normalized difference vegetation index (NDVI). Land cover data retrieved by the 30 m resolution Landsat 8 data (USGS, Reston, VA, USA) was used to calculate landscape diversity index. Seven types of landscape were used in this study, namely, built up, forest, arable land, grassland, water bodies, traffic land, and barren land. To represent the recreation function of the waterway, a 2-km buffer belt along the river banks from Chongqing to Yibin is used when calculating the two indicators.

2.3. Determination of Indicator Weight

Waterway health assessment is a multi-objective evaluation process, and the rationality and accuracy of the weights directly affect the evaluation results. In this study, the corresponding weights were calculated by the analytic hierarchy process (AHP) method. AHP is a subjective weighting method with the advantages of ease of use, strong systematicity, and high flexibility. A complex problem is structured hierarchically by AHP, which descends from a goal to criteria, sub-criteria, and alternatives in successive levels [54]. The essence of AHP is pairwise comparison. The numbers 1–9 and their reciprocals are used to indicate the relative importance of different indicators, with '9' indicating that one indicator is much more important than the other. Indicators are pairwise compared according to 9 level-scales to derive their weights, developing a pairwise comparison matrix $A = \left(a_{ij}\right)_{n\times n}$ for the function layer and the index layer. For each comparison matrix, we obtained the maximum eigenvalue(λ_{max}), consistency index (CI), consistency ratio (CR), and normalized eigenvector. The corresponding normalized eigen vector obtained from the pairwise comparison matrix was regarded as relative weight. The consistency of the pairwise comparison was assessed by the consistency ratio (CR), a scalar value defined as the ratio between CI and a reference value called the random index (RI). It is widely accepted that the pairwise comparison matrix passes the consistency check with a CR ≤ 0.1 [54–56].

To define the pairwise comparisons in this study, 18 experts from universities, the Yangtze River waterway administrations, research institutes for water transportation engineering, hydrobiology and water conservancy, and inland river port and navigation center, and harbor consultants, were consulted with questionnaires. These experts have extensive knowledge and several years of practical experience in water ecological environment, hydrology and water resources management, Yangtze River aquaculture, and hydropower among others. The total $CR = 0.0158 < 0.1$, indicating that consistency check is satisfactory. The derived weights obtained from our study can be used in health assessment for the waterway from Chongqing to Yibin in the upper Yangtze River.

$$CR = \frac{CI}{RI} \tag{1}$$

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

where λ_{max} is the principal eigen value, which was obtained from the sum of the products between each element of the eigen vector and the sum of columns of the pairwise matrix; n is the size of the pairwise comparison matrix.

RI is the random consistency index, as shown in Table 2 [57].

Table 2. Average random consistency index (RI).

n	1	2	3	4	5	6	7	8
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41

2.4. Waterway Health Index

Waterway health index has been used to determine the health condition of the waterway. The weight of each indicator from AHP analysis is required for *WHI* estimation. Previous studies have defined the relationship between *WHI* and indicator weights through Equation (3) [58,59].

$$WHI = \sum_{i=1}^{n} I_i \times w_i \tag{3}$$

where I_i represents the information amount of the ith indicator by 5-points scores, and w_i indicates the weight of the ith indicator. For the sake of avoiding unit influence between different indicators, the dimensionless processing of the indicator is performed first before calculating *WHI*. The values of each indicator have been normalized into integers [1,5]. Hence, the value of *WHI* should be within the interval of [1,5], and it can be divided into five levels, in descending order: "Excellent," "Good," "Fair", "Poor," and "Bad". Equation (3) is also applicable for function level when the status of every function is assessed.

In order to determine the classification criteria of waterway health, it is important to conduct threshold research of different indicators. In this study, each indicator threshold was determined according to following methods: (a) Adopt existing national, local, industrial, or international standards; (b) Refer to the index classification of previous researches in similar study areas; (c) Expert consultation. Table 3 lists the indicator assignment standards for each indicator.

Table 3. Five-grade waterway health assessment standard.

Index Layer	Unit	Excellent (5)	Good (4)	Fair (3)	Poor (2)	Bad (1)	Threshold Based on

C1	m/m	≥4/100	≥3.5/80	≥2.6/50	≥1.8/30	<1.8/30	National standards(GB50139-2004)
C2	%	≥95	≥85	≥75	≥60	<60	National standards(GB50139-2004)
C3		≤30	≤80	≤160	≤250	>250	Maritime Bureau statistics
C4		Once in a thousand years flood	Once-in-a-century flood	Flood once in 50 years	Flood once in 20 years	Flood once in 10 years	National standards (GB 50201-94)
C5	%	≥95	≥80	≥65	≥60	<60	Literature[60]
C6	%	≤10	≤25	≤40	≤60	>60	Literature[61]
C7	%	≤20	≤35	≤50	≤70	>70	Literature[20]
C8	%	≤10	≤20	≤30	≤40	>40	Literature[12]
C9	%	≥95	≥80	≥60	≥40	<40	Literature[62]
C10		≤0.5	≤1	≤1.5	≤2	>2	National standards (GB 3838-2002)
C11	mg/L	≥7.5	≥6	≥5	≥3	≥2	National standards (GB 3838-2002)
C12	%	≤5	≤15	≤30	≤50	>50	Historical hydrological data
C13	%	≥65	≥45	≥35	≥15	<15	Literature[63]
C14		58–60	48–52	40–44	28–34	12–22	Literature[35,36]
C15		Better	Good	Ordinary	Bad	Poor	Literature[37]
C16		≥1.8	≥1.2	≥0.7	≥0.3	<0.3	Literature[12]
C17		≥0.8	≥0.6	≥0.4	≥0.2	<0.2	Literature[64]

Considering that the functions of the waterway interact and influence with each other, the functional failure can bring serious influence on the entire ecosystem. The *WHI* obtained by weighted calculation cannot reflect the cask short board effect on waterway health. Therefore, a logarithmic function is used to represent the short-term effect of a functional collapse on the ecological waterway system, using the following Equation (4) [65].

$$WHI_c = \sum_{i=1}^{n} log_5 I_i \times w_i \tag{4}$$

In Equation (4), the function of log5 is used to convert the 5-point scale into the following grades as shown in Table 4. Thus, the linear split points of "Excellent," "Good," "Fair", "Poor," and "Bad" in *WHI* was non-linearized to reflect the cask short board effect. This method not only provides more reasonable waterway health assessment results but also allows for timely action to avoid further damage to river health.

Table 4. Health condition interval marking of waterway assessment.

Level	Excellent	Good	Fair	Poor	Bad
WHIc	1 ($\log_5 5$)	0.86 ($\log_5 4$)	0.68 ($\log_5 3$)	0.43 ($\log_5 2$)	0 ($\log_5 1$)

2.5. Sensitivity Analysis

Weighting is a factor that has great influence on the evaluation result. In this study, single parameter sensitivity analysis was used to verify the reliability of the indicator system. The weight of each function was manually increased or decreased by 20% and the weights of the other functions changed proportionally to ensure that the sum of all weights always adds up to 1. We obtained the new *WHIc* after changing the weight value of one factor at a time to identify the impacts of single parameter. The weight calculation is as shown in Equations (5) and (6).

$$w_i^{'}=w_i\times(1\pm c\ \%) \tag{5}$$

where $c\%$ represents the rate-of-change of the weight, $w_i^{'}$ represents the weight of ith index after change.

$$w_j^{'}=\frac{1\text{-}w_i^{'}\times w_i}{1\text{-}w_i} \tag{6}$$

2.6. Data Source and Preprocessing in 2016–2017 and 2018–2020

During the Thirteenth Five-Year Plan (from 2016–2020), China vigorously advanced the Yangtze River golden waterway construction. Based on this background, data collected was split into two time periods: 2016–2017 and 2018–2020. We assessed and compared these time periods to better understand the health status of the waterway from Chongqing to Yibin in the upper Yangtze River. Most of the basic data comes from:

(1) Reports about Yangtze River Channel regulation and construction, including Environmental Impact Report of the "13th Five-Year" Waterway Management and Construction Planning of the Yangtze River Trunk Line, Environmental Impact Report on Development Planning of Yangtze River Main Channel.
(2) Statistics and Related Website. China Hydrological Yearbook, National Bureau of Statistics of China (accessed on 28 February 2022 http://www.stats.gov.cn/), Changjiang Waterway Bureau (accessed on 13 December 2021 http://www.cjhdj.com.cn), Changjiang Hydrology (accessed on 3 November 2020 http://www.cjh.com.cn), Changjiang Water Resources Commission of The Ministry of Water Resources (accessed on 6 September 2021 http://www.cjw.gov.cn), Changjiang Maritime Safety Administration (accessed on 8 March 2022 https://cj.msa.gov.cn), Chongqing Water Resources Bureau (accessed on 28 January 2020 http://slj.cq.gov.cn), Yibin Water Resources Bureau (accessed on 30 September 2021 http://ybsswj.yibin.gov.cn).
(3) Extensive monitoring and sampling in the study area.

3. Results and Discussion

3.1. Indicator Assessment

AHP was used to calculate the weights of each indicator and function of waterway health. Figure 2 shows the weights for waterway health assessment.

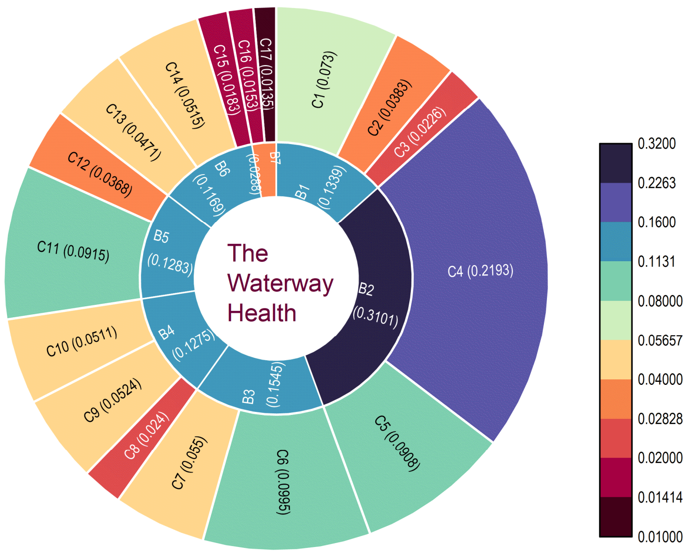

Figure 2. Weights for waterway health assessment.

According to the waterway maintenance plan published by Changjiang Waterway Bureau, the navigable width/depth has been kept at 2.9/50 m from 2016 to 2020. C1 was set to 3 for both 2016–2017 and 2018–2020. The proportion of navigation aid facilities in services reached 100%, and C2 was set to 5 for both. Reef running is the main type of accidents in the upper Yangtze River due to the special terrain topography. Based on the accident records by Changjiang Maritime Safety Administration, C3 was set to 4 and 5 for 2016–2017 and 2018–2020, respectively. The number of accidents has decreased significantly due to the construction of the waterway and the outbreak of COVID-19.

With the guidance of the comprehensive plan for the Yangtze River Basin, the flood control standard has been remarkably upgraded in the reach from Chongqing to Yibin. The flood control standard has been improved to once in 50–100 years in major districts of Chongqing, once in 20–50 years in Yibin and Luzhou. C4 was set to 2 for 2016–2017 and to 3 for 2018–2020. From the 14th Five-Year Plan for Water Security in Chongqing, Luzhou and Yibin, the flood control measures have been gradually perfected within the region and the compliance rate was increased from ≥65% to ≥80%. Therefore, C5 was set to 3 and 4 for 2016–2017 and 2018–2020, respectively.

According to the Yangtze River Sediment bulletin, the sediment transportation data gauged at Zhutuo and Cuntan hydrological stations within the waterway from Chongqing to Yibin experienced a sharp increase of the water used for sediment transfer and a decrease of the sediment concentration in 2018. C6 was set to 4 and 1 for 2016–2017 and 2018–2020, respectively. The proportion of the suspended sediment load relative to the average value was 69.47% in 2016–2017 and 42.41% in 2018–2020. C7 was set to 2 and 3 for 2016–2017 and 2018–2020.

Based on the Yangtze River water resources bulletin, water resource utilization rate was 11.63% and 12.94% in 2016–2017 and 2018–2020. For both periods, C8 was set to 4. The water quality of the Yangtze River has got better year by year during the 13th Five-Year Plan period as several environmental protection measures have been taken. The rate of reaching water quality standard in functional districts increased from more than 60% in 2016–2017 to more than 80% in 2018–2020, with C9 increased from 3 to 4. C10 was set to 4 for 2016–2017 and 5 for 2018–2020. Throughout the evaluation period, the dissolved oxygen concentration basically kept above 7.5 mg/L. C11 was set to 5 for 2016–2017 and 2018–2020.

The hydrologic data at Cuntan and Zhutuo hydrologic stations were obtained from Hydrological Yearbook of the People’s Republic of China. The proportion of water used for self-purification relative to the average value was lower than 5%, hence C12 was set to

5 for both 2016–2017 and 2018–2020.The degree of satisfaction on ecological water demand (C13) was set to 3 for the two periods.

Based on data from sampling in the study area, the fish or biological integrity index was calculated, and C14 was set to 3 for 2016–2017 and 2018–2020. The living environment of rare species has improved as a result of numerous policies aimed at recovering fish stocks and aquatic biodiversity throughout the Yangtze River Basin. C15 was set to 3 for 2016–2017 and 4 for 2018–2020.

The landscape diversity index (C16) and normalized difference vegetation index (NDVI, C17) of the buffer were calculated. The landscape diversity indicator was 0.94 in 2016–2017 and 1.30 in 2018–2020. Thus, C16 was set to 3 and 4, respectively. For 2016–2017 and 2018–2020, NDVI was maintained above 0.6. C17 was set to 4 for both 2016–2017 and 2018–2020.

The results of assessment of the indicators of the waterway from Chongqing to Yibin are displayed in Table 5.

Table 5. Assessment of the indicators of the waterway from Chongqing to Yibin.

Indicator	2016–2017	2018–2020	Index	2016–2017	2018–2020
C1	3	3	C10	4	5
C2	5	5	C11	5	5
C3	4	5	C12	5	5
C4	2	3	C13	3	3
C5	3	4	C14	3	3
C6	4	1	C15	3	4
C7	2	3	C16	3	4
C8	4	4	C17	4	4
C9	3	4			

3.2. Function Health Assessment

Based on the indicator system constructed to evaluate waterway health, the comprehensive Waterway Health Index was used to calculate the health condition of the waterway from Chongqing to Yibin in upper Yangtze River. The specific results are shown in Figure 3.

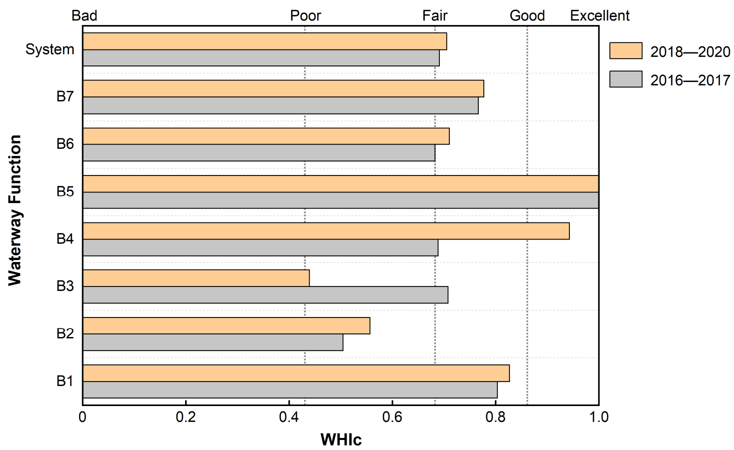

Figure 3. Assessment of the waterway from Chongqing to Yibin.

As shown in Figure 3, the *WHIc* of the reach from Chongqing to Yibin was 0.6914 and 0.7053 for 2016–2017 and 2018–2020, respectively. The results indicated that the health of the waterway from Chongqing to Yibin belonged to the "Fair" level during 2016–2017 and 2018–2020. Comparing two time periods we assessed, the *WHIc* of the reaches from Chongqing to Yibin increased during the evaluation period. The scores of different functions show that there was an increase in 2018–2020 compared to 2016–2017 except for B3 and B5. The sediment transport (B3) was assigned "Fair" in 2016–2017 but "Poor" in 2018–2020. During the evaluation period, the self-purification (B5) remained in "Excellent" condition.

(1) Navigation

The waterway from Chongqing to Yibin in the upper Yangtze River usually holds poor natural conditions for navigation such as sharp corners, narrow channels, shallow water depth, fast flow rate, and a disordered flow regime [66]. For the sake of navigation capacity and safety, Changjiang Waterway Bureau has moved forward the implementation of improvement and dredging projects. The Ministry of Transport has incorporated the waterway regulation project from Yibin to Chongqing in the upper reaches of the Yangtze River into the "Thirteenth Five-year Plan for Waterway Regulation and Construction of the Yangtze River". Three projects have completed preliminary work between 2016 and 2020 (including the reaches from Yangshipan to Shangbaisha in Sichuan, Hejiangmen to Jieshipan and Jieshipan to Jiulongpan in Chongqing). Because of these works, the navigation function of the reaches from Chongqing to Yibin increased from 0.8035 to 0.8269, while remaining in the "Fair" state.

(2) Flood discharge

In terms of the flood discharge function, the waterway from Chongqing to Yibin in the upper Yangtze River has been improved from 0.5044 to 0.5567 but remained in "Poor" category in 2016–2017 and 2018–2020. The major measures that have been taken to improve the flood discharge function of the waterway from Chongqing to Yibin are improving the flood control standard and constructing flood control projects. Regional flood control standards in the upper reaches have been further improved during the "Thirteenth Five-year" period, but failed to meet the standards set by the comprehensive plan for the Yangtze River Basin. In this case, controlling reservoirs is of great importance. The world's largest reservoir group with the Three Gorges Reservoir at its core has been built along the upper reaches of the Yangtze River. In order to control the floods occurring in July/August 2020 in the Yangtze River Basin, the number of controlled reservoirs in the upper and middle reaches of the Yangtze River increased to 41. The joint application of the reservoir group and improvement of city flood control standards will increase the flood control capacity [67,68].

(3) Sediment discharge

As the sole function showing a negative trend, the sediment transport function index fell from 0.7080 ("Fair") to 0.4396 ("Poor"). Under the dual influence of climate variations and human activities, the water discharge and sediment load have been significantly altered [69]. Sediment loads in this river have shown a progressive decline since the 1970s; the Yangtze River's average annual sediment load transported at Cuntan and Zhutuo hydrological station decreased to 922 Mt/year and 553 Mt/year between 2016–2020, only 21.48% and 18.27% of the 1956–2002 level (before the three Gorges Dam was filled). In addition, the fluvial suspended sediment concentration has declined by an order of magnitude, from 1.0 to 0.1 kg/m^3 [70], and even to 0.01 kg/m3. Variation of the sediments transport function is affected by climate change and anthropogenic activities [71]. Over 50,000 dam reservoirs including the Three Gorges Dam, one of the world's largest dams, and many waterway regulation projects have been constructed in the Yangtze River catchment since the 1950s, and many researches have suggested that these human activities might be the major driving factors for sediment load reduction [72,73]. The sediment transport function situation in the waterway from Chongqing to Yibin may have profound impacts on the morphology and ecology of the downstream Yangtze River including its delta.

(4) Water supply

The water supply function improved from 0.6887 (“Fair”) in 2016–2017 to 0.9430 (“Good”) in 2018–2020. Based on these monitoring and statistical data, researchers found that the water quality of the reaches from Chongqing to Yibin declined during 2000–2010 and then gradually improved in 2010–2020 [74,75]. During the 13th Five-Year Plan period, all sections in the reaches from Chongqing to Yibin met the quality of class II [76]. The improvement of the water quality should benefit from the national policies adopted by Chinese government, such as urban sewage treatment.

(5) Self-purification

The self-purification function was measured as “Excellent” both in 2016–2017 and 2018–2020. During the evaluation period, the dissolved oxygen concentration of the reaches exceeded surface water Class II water standard. On account of the big vertical drop in elevation together with large discharge and some ecology restoration projects carried out during the evaluation period, the waterway from Chongqing to Yibin has a strong self-purification ability.

(6) Ecology

The sampling results showed that the biodiversity of the reaches from Chongqing to Yibin had increased from 0.6826 to 0.7105 during 2016–2020, despite which the ecology function remained in a “Fair” state. The Yangtze River is one of the biodiversity hotspots in the world for its diverse assemblages [77]. However, the threats to the health of the Yangtze River ecosystem are many, such as habitat loss, alternations of hydrological regimes, water pollution and overexploitation. For this reason, the protection of endemic species especially the rare and endangered, has been given great importance. Starting from 2015, the rescue actions for endangered species, such as Chinese sturgeon, Yangtze finless porpoise and Yangtze sturgeon, have been put into effect. In order to comprehensively improve the biodiversity of Yangtze River, a long-term fishing-ban policy began to be implemented. Faced with the complexities of ecological interactions, the response of the ecological environment to the ecological measures has temporal hysteresis, which needs to assessed for the long-term.

(7) Recreation

In terms of the landscape recreation function, it has improved from 0.7665 to 0.7774 but remained “Fair” in 2016–2017 and 2018–2020. There is a increase in the landscape diversity index and NDVI in the waterway from Chongqing to Yibin, which was consistent with the model evaluation results in previous studies [78]. Comprehensively considering the multi-functional needs of the waterway, many wetlands protection parks and wetland nature reserves have been built along the reaches from Chongqing to Yibin. These ecological restoration projects are expected to further improve the landscape recreation function of the waterway.

3.3. Sensitivity Analysis

WHIc values when their weight factors are fluctuated ±20% from their original values as per Figure 2 are shown in Table 6. The results indicated that the assessment results are not sensitive to the weight floating by 20%. The waterway health assessment results of the reaches from Chongqing to Yibin are stable and reliable.

Table 6. Fluctuation of *WHIc* with the increase or decrease of the weight by 20%.

Function	Weight Increase 20%				Weight Decrease 20%			
	2016–2017	**Grade**	**2018–2020**	**Grade**	**2016–2017**	**Grade**	**2018–2020**	**Grade**
B1	0.6948	Fair	0.7091	Fair	0.6879	Fair	0.7015	Fair
B2	0.6746	Fair	0.6920	Fair	0.7082	Fair	0.7187	Fair
B3	0.6920	Fair	0.6956	Fair	0.6908	Fair	0.7150	Fair
B4	0.6913	Fair	0.7123	Fair	0.6914	Fair	0.6984	Fair
B5	0.7004	Fair	0.7140	Fair	0.6823	Fair	0.6966	Fair

B6	0.6911	Fair	0.7054	Fair	0.6916	Fair	0.7052	Fair
B7	0.6918	Fair	0.7057	Fair	0.6909	Fair	0.7049	Fair

3.4. Health Comparison with Waterways in the Other Reaches of the Yangtze River

In previous research, health of waterways in the middle, middle-lower, and lower reaches of the Yangtze River have been assessed. Although the indicator systems in the different reaches were not the same, and the assessment years were not consistent with each other, they are very helpful to understand the overall health conditions of the Yangtze River waterway. The assessment results of waterway health in different reaches are shown in Table 7. In terms of the Jingjiang reach in the middle portion of the Yangtze River, the waterway health index has increased but remained in "Fair" state from 2011 to 2014 with the waterway regulation project started in 2013. It was predicted to be in "Good" level after the project completed. The results indicated that the channel regulation projects offered the waterway health benefits. Considering different functions of the waterway, the navigation function, flood discharge function, sediment transport function and ecology function have been improved but the water supply and self-purification function experienced a downward trend [20]. The evaluation for the Wuhan-Anqing reach in the middle-lower part of the Yangtze River revealed that the health status was "Fair" in 2018. The ecological function was "Poor" and the other functions including navigation, flood discharge, landscape and entertainment and self-purification were at a "Good" level, even "Excellent" [21]. As for the lower reaches of Yangtze River, the research reported that Nanjing-Liuhekou reach was "Fair". From the perspective of the specific functions, the navigation function, self-purification function, and the landscape and entertainment function were "Excellent", and the ecological function was "Bad" [63].

Based on the earlier research and our study that applied a comparable indicator system, the overall waterway health status of the Yangtze River was "Fair". In the past decade, there is a significant improvement in the navigation, flood discharge, water supply, and recreation function in the waterway health of the Yangtze River. The health status progress might be attributed to the national policies adopted by Chinese government, such as waterway regulation projects [75]. The degradation of sediment discharge only occurred in the upper reaches and has not been assessed in the other reaches of Yangtze River. Sediment discharge across the vast basin has long been recognized as a complicated issue for the distinct geographic features and climate change. Human activities have further complicated this issue [79]. A part of the study has attributed the change of sediment discharge to human activities especially the dam construction, which plays the primary role in trapping sediment and reducing downstream sediment load [80]. However, the ecological impacts due to the change of sediment discharge have not yet been studied extensively. The long-lasting effects caused by changes in the sediment discharge still need further assessment.

From the experiences of different rivers in the world, the ecological challenge in waterway development could change over time, which requires constant reflection and actions as response. For example, numerous programs in last decades have been launched to improve the River Rhine ecosystem from different perspectives, including Room for the River, the Delta Program for Rivers, Sustainable Fairway Rhine Delta, and the Water Framework Directive, according to [81]. In order to restore a healthy Mississippi River ecosystem, the Upper Mississippi River Restoration program has been implemented since 1986, which initially targeted specific restoration objectives through habitat rehabilitation projects. While addressing the complexity in multiple factors of the river ecological system, physical process modeling of existing conditions may be used to evaluate alternative restoration measures [82]. Compared to these rivers, the Yangtze River in China has experienced a much more dramatic development in recent decades, leaving less time to address all the ecological challenges. To strengthen the protection and restoration of the ecological environment in the Yangtze River basin, Law of the Protection of the Yangtze River was enacted in December 2020, and put into force in March 2021. The present study provides a dynamic method and an integrated assessment framework to cover a wide range of ecological concerns for follow-up assessment. This may enable the further institutionalization of waterway health protection for the Yangtze River. The health assessment framework of the present study would also apply to other waterways of large rivers which usually have multiple natural and social functions besides navigation.

Table 7. Waterway health assessment of the Yangtze River waterway.

Function	The Upper Reaches		The Middle Reaches			The Middle-Lower Reaches	The Lower Reaches
	Form Chongqing to Yibin		Jingjiang [21]			From Wuhan to Anqing [22]	From Nanjing to Liuhekou [23]
	2016–2017	2018–2020	2011	2014	2015 (Predicted)	2018	2016
Navigation	Fair	Fair	Fair	Fair	Good	Good	Excellent
Flood discharge	Poor	Poor	Fair	Good	Good	Good	Good
Sediment transport	Fair	Poor	Poor	Fair	Good	Fair	Fair
Water supply	Fair	Good	Fair	Fair	Good	Fair	Fair
Self-purification	Excellent	Excellent	Fair	Good	Excellent	Excellent	Excellent
Ecology	Fair	Fair	Fair	Poor	Fair	Poor	Bad
Recreation	Fair	Fair	Poor	Poor	Fair	Good	Excellent
System	Fair	Fair	Fair	Fair	Good	Fair	Fair

4. Conclusions

With a comprehensive health assessment framework, the waterway health from Chongqing to Yibin in the upper Yangtze River between 2016–2017 and 2018–2020 were assessed and compared. Basically, the health index of the waterway from Chongqing to Yibin has increased but remains in “Fair” category in the studied period. Owing to the ecological measures and actions taken during this period, the functions of the waterway including navigation, flood discharge, water supply, ecology and recreation have been improved. Sediment transport function showed a degradation from “Fair” to “Poor”. The sensitivity analysis shows that the results obtained in this study are not sensitive to weighting fluctuations within a narrow range of rates. Although the conditions of seven functions in the upper, middle, middle-lower, and lower reaches were different, ranging from “Poor”, “Fair”, to “Good”, the overall health of the four waterways were all assessed as “Fair” in recent years which implies that systematic efforts should be continued in the future.

Several limitations of the study also warrant mention. (1) For the purpose of coordinating development of the navigation function with other functions, a waterway health assessment system was constructed based on AHP methods in this study. The coordination of the navigation function with other functions was considered in an indirect way. More extensive work is therefore needed to directly explore the coupling and coordination of this relationship as well as the interaction mechanisms between different functions in the future. (2) This study assessed the health status of the upper river reach from Chongqing to Yibin in the context of the Yangtze River and the Thirteenth Five-Year Plan. Considering the delayed effect of regulation projects, especially on the ecological aspects, the waterway health assessment could be conducted at a longer time scale. (3) The sediment discharge function remains a complex issue that involves soil erosion, climate change, anthropogenic activities and so on. There is still some controversy concerning the choice of evaluation method and indicator of sediment discharge function. Further research is needed for choosing more suitable indicators of the sediment transport function and for clarifying the response of variation of the indicators to waterway health.

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