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Assessment of the Happy River Index as an Integrated Index of River Health and Human Well-Being: A Case Study of the Yellow River, China

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Abstract: Acceleration urbanization and industrialization has resulted in challenges such as river ecosystem degradation and water scarcity that have hindered sustainable development in China. Healthy rivers provide ecosystem services that improve human well-being. The Happy River Index (HRI) integrates trends in river health and human well-being. This study aimed to establish an HRI assessment framework. The assessment framework was applied to the Yellow River, China at three spatial scales in which the analytic hierarchy process (AHP)-entropy weight and single index quantification-multiple indices syntheses-poly-criteria integration (SMI-P) methods were utilized. Limiting factors were diagnosed by the obstacle degree model and approaches to improve the HRI in regions along the Yellow River are suggested. The results showed that: (1) the overall HRI of the Yellow River was relatively low, with some differences among different regions; (2) the HRI for the upper, middle, and lower reaches of the Yellow River showed a decreasing trend from 0.77 to 0.65; (3) Sichuan had the highest HRI at the regional scale, followed by Gansu and Qinghai, whereas Inner Mongolia had the lowest; (4) scarcity of water resources and the fragility of the ecological environment were the two dominant factors restricting the improvement of the HRI in regions along the Yellow River. The results of this study can provide a valuable reference for protection of river health and improvement of human well-being in China.

Keywords: Happy River Index; Happy river assessment; river health; human well-being; Yellow River

1. Introduction

Rivers are analogous to blood vessels of the Earth and are recognized to have played a crucial role in the development of human civilization, as rivers have supported human development through provision of fresh water, agriculture, fisheries, and transport [1]. With increased human development, there has been a concurrent increase in the exploitation of rivers for water supply, flood control, transportation, electricity generation, and other ecological services [2,3]. However, pressures from rapid globalization, increased population, higher standards of living, industrialization, and changes in the global climate have converged and resulted in a sharp imbalance between water supply and demand, a deterioration in water quality, and degradation of river ecosystems [4–6]. These challenges have hindered the realization of sustainable development. Unsustainable regional economic development has become a profound challenge of widespread concern, particularly in less developed countries still in the early stage of economic development [7,8].

Given the role of rivers in human evolution and development, it is no surprise that there is a close connection between human well-being and rivers, as rivers interweave human, habitats, and other living beings together, supporting and sustaining the diverse cultural beliefs and national confidence [1]. Achieving sustainable development requires a deep understanding of the close and complex relationship between human society and river ecosystems. The majority of developed countries have entered a post-industrial era in which there has been increasing attention to river protection, and these countries have gained considerable experience in the restoration and management of rivers. Already in 1997, the importance of riverside communities' involvement in river management was emphasized in the amendment of the River Law in Japan [9]. The provision of the sufficient supply of good quality water as needed for sustainable, balanced, and equitable water use was included in the purpose of the EU Water Framework Directive [10]. Lately, the supporting role of aquatic ecosystem on human, economy, culture, sustainable development, and well-being was emphasized in the newly revised Brisbane Declaration and Global Action Agenda on environmental flows, in which those relationships were incorporated into the river management [11]. All those actions above are seek to link water and social relations explicitly. However, many developing countries are currently undergoing a stage of rapid industrialization and population growth. These countries urgently need to increasingly exploit water resources to consolidate development and ensure water supply and food security. While some countries such as China have achieved remarkable and rapid economic development, these achievements had come at environmental costs. In particular, there has been increasing pressure on river systems. Achieving a sustainable balance between the protection of river ecosystems and regional economic development has become a key issue of concern in these countries. This issue is particularly urgent in China in which water resources are becoming under increasing pressure while the country remains in a period of rapid economic development, the quality of life of the Chinese people is increasing, and there is a growing recognition of the benefits of healthy rivers to human well-being. A rigorous and comprehensive consideration of the complex relationship between the protection of river ecosystems, social development, and human well-being is of great significance for advancing river management [1,12]. Recognition of this relationship has led to the development of some frameworks that have attempted to integrate complex and interdependent societal issues, such as river health [13,14] and the human-water harmony [12,15].

The term "river health" originated from a consideration of the health of a river ecosystem, and was proposed for achieving improved river management. River health has been evaluated from various aspects. The original assessments of river health assessment were mainly based on an assessment of the ecological functions of rivers [16]. The River Habitat Survey (RHS) [17], the Index of Stream Condition (ISC) [18], the River Invertebrate Prediction and Classification System (RIVPACS) [19], and the Index of Biological Integrity (IBI) [20] are the most widely used indices for river health assessment and integrate physical, chemical, and biological aspects of rivers [14,21–24]. Some recent studies have begun to integrate the water demands of economic activities and societal development into river health assessment. The ecosystem health of the Lancang River was assessed with consideration of the ecosystem, ecosystem services, and human activities [25]. Luo [22] integrated river ecosystem integrity with servicing of human water demand in an assessment of river ecosystem health of the Shaying River. However, few studies have attempted to develop a comprehensive river assessment framework that integrates hydrology, water quality, water ecology, land use, and ecosystem services. Achieving sustainable development has become an increasingly urgent goal widely pursued by human societies, and consequently, this goal has become a focus of many scholars across the world. The relationship between water, ecology, and human society was comprehensively analyzed by Falkenmark et al. [26] based on the connection between water and ecological systems. Hoff [27] defined the global water system to be a general term relating to water resources available to human society and the physical, biological, and biogeochemical components of these water resources and interactions between them. "Unity of Man and Nature" is an important concept in Chinese traditional culture and recognizes elements of sustainable development in integrating river health and human well-being. The concept

of harmony between humans and water has gradually become of increasing academic interest in China since Wang first proposed the idea in 1999 [28]. The Human-Water Harmony evaluation model was proposed by Zuo [29] to analyze the relationship between humans and water. A human-water harmony index evaluation system was established by Ding [30], and was applied in some cities of China. Zhang [31] proposed the River-Human Harmony (RHH) theory, which refers to a coordinated and sustainable cycle between rivers and human systems. However, despite the recent inclusion of a human social perspective in the theory of river health and the river-human harmony theory, few studies have considered the links between rivers and human well-being that integrate human happiness, cultural identity, and sense of place within assessments of river health made during river management.

During a symposium on ecological protection and high-quality development of the Yellow River Basin (YRB) in September 2019, the Chinese government emphasized the importance of the principles of ecological priority and green development, as well as the urgent need to sustainably develop the Yellow River so as to maintain the ecological integrity of the river for the benefit of the people, or "a happy river" [32]. Subsequently, the concept of a happy river has aroused widespread attention in both scientific research and management practice in China. There have since been many studies on happy river in China. For example, Zuo et al. [33] first discussed the concept, connotation, and the criteria of happy river based on river management in China. Chen et al. [34] discussed the basic requirements of happy river that integrated humans and rivers. To commemorate the 28th "World Water Day" and the 33rd "China Water Week", the Chinese government proposed the principle of "sticking to water conservation and building happy rivers and lakes". The challenge of how to construct and evaluate a happy river has attracted widespread attention. Gu [35] discussed the issues related to the construction of a happy river and suggested some key directions. Li [36] emphasized that scientific understanding of river health is the basis for defining a happy river and discussed the key issues and recommendations for river health management. Tang [37] proposed a hierarchical, multi-dimensional method for assessing a happy river. Han et al. [38] constructed an evaluation index system of a happy river that integrated natural properties of watersheds, socio-economic attributes, and human-water harmony based on the research of river health. However, given that the concept of happy river is a relatively new theory, the study of the happy river remains at a theoretical exploration stage, and few systematic studies have been conducted on the evaluation of the happy river.

The present study discusses the concept and connotation of "happy river" aims to achieve the following goals: (1) propose an assessment framework for the evaluation of the HRI that integrates river health and human well-being; (2) assess the HRI of the Yellow River Basin (YRB) at different spatial scales; (3) validate the assessment framework based on the assessment results; (4) analyze the limiting factors of HRI in the YRB and establish the associations between river health and human well-being to guide high-quality development of rivers and promote human well-being.

2. Methodology

2.1. Definition and Implications of Happy River

The term "happy river" was first proposed in China in September 2019 to promote the ecological protection and high-quality development of the YRB and other major rivers in China. Many researchers in China have since discussed the concept of happy river. Despite there being no clear and unified concept of happy river, the majority of studies emphasized the core importance of river health and the need to take human well-being into consideration. The generally accepted understanding of happy river is guided by the Human-Water Harmony theory and the concept of sustainable development, and envisions harmonious coexistence between rivers and human beings [32,33,37]. The concept of happy river, which is proposed based on river health, is becoming increasingly important due to the complexity of challenges facing water security and China's current stage of economic development. The focus of an assessment of whether a river is a happy river is not only on the river itself, but also on the economic and social services that support high-quality development of the rivers. This high-quality development

integrates the sustainability of both the river health and the human well-being. The understanding of happy river is subjective and varies across space and time, and integrates, but is not limited to, water security, water resources, water quality, water ecology, economic society, science and technology, culture, and education.

The authors of the current study have previously discussed the understanding of happy river [33]. The promotion of a river to achieve the status of a happy river can limit damage resulting from river-related disasters through dual intervention of nature functions and human activities. A happy river has a relatively intact physical structure and stable natural functions, thereby increasing resilience to floods and droughts. Secondly, happy rivers can sustainably provide water resources to support the development of the economy and society if the water supplied is within the carrying capacity of the river. Thirdly, happy rivers have a sufficiently good water quality to sustain a strong aquatic ecosystem that is sustainably able to support the natural water purification function of rivers. Happy rivers are resilient to external interference, have healthy ecosystems, and can sustainably support river ecosystem services. Fourthly, the understanding of a happy river is subjective and varies across regions and time. A happy river falls within a balanced state between river health and human exploitation. The purpose of further examining happy river is to realize sustainable development that integrates the health of the river ecosystem and the well-being of society. In general, happy river emphasizes a balance between the protection of river ecological health and human exploitation of rivers.

Accordingly, the authors of the current study defined the happy river in a previous study as [33]: "in the process of river development and protection, a happy river refers to a river in which conservancy facilities are safe, river water flow is smooth, and the river ecosystem is healthy". Based on this, happy rivers emphasizes the need to achieve a sustainable balance between water resources supply and demand while maintaining the natural structure and function of rivers.

2.2. Framework for the Assessment of Happy River

Given the understanding of happy river, assessment of a river should integrate both river ecological health and human well-being. One important social aspect of understanding the concept of a happy river is the communication of the results of the assessment to water resource managers. The happy river assessment framework (Figure 1) was proposed for the evaluation of the HRI of a river. This framework provides useful guidance at the managerial level and includes two main parts: (1) the relationships between a river ecosystem and human society considered in the assessment; (2) procedures used in the happy river assessment.

The first part demonstrates the inseparable relationships between the river ecosystem and human society. The river ecosystem can provide a variety of services to support the development of human society, including human livelihoods, production, ethics, culture, education, and human happiness. However, the rapid development of human society over recent decades has resulted in enormous pressure on river ecosystems through human activities such as hydraulic engineering infrastructure, overexploitation of water resources, and sewage and wastewater discharge. The development of human society is closely integrated with the services provided by rivers, particularly in relation to economic and cultural development, and the demands made by human society on rivers are increasing. Modern society is increasingly recognizing both the material benefits of rivers and the benefits of healthy river ecosystems to human happiness. However, achieving a state of river health that promotes human well-being requires the exploitation and utilization of rivers by humans to be based on the primary premise of maintaining the ecological health of rivers.

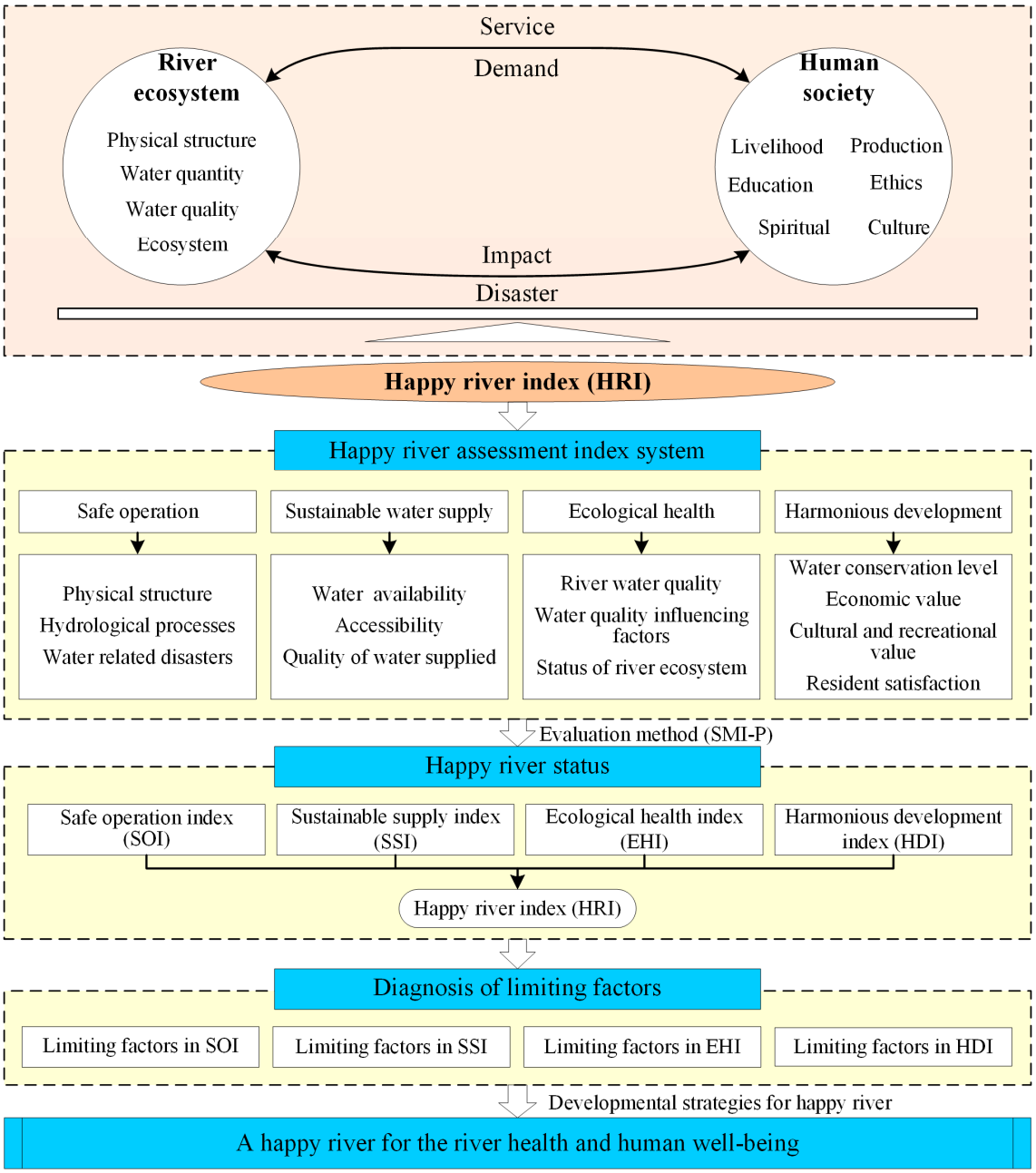


Figure 1. A proposed framework for the happy river assessment.

The second part of the framework demonstrates the procedures required for the happy river assessment. (1) Based on the understanding of happy river, there are four dimensions within the happy river assessment indicator system, namely safe operation, sustainable water supply, ecological health, and harmonious development of rivers. (2) The HRI and the values of the four dimensions are calculated based on the evaluation and calculation methods outlined in the framework. (3) After the assessment, factors limiting the protection of the river ecosystem and human development are identified through the degree of limitation model. (4) Regulations required for constructing happy river are proposed.

2.3. River Happiness Assessment Index System

2.3.1. Indicator Selection

The selection of appropriate indicators is the first step within the HRI evaluation process. Clarification of the relationship between river health and human well-being is very important. The comprehensive analysis of river happiness requires the concept of happy river to be described quantitatively. In an effort to integrate constitutional and structural characteristics within the happy river concept, the current study selected indicators according to four dimensions: (1) safe operation; (2) sustainable water supply; (3) ecological health; (4) harmonious development of rivers and humans. The specific steps followed are described below.

(1) Data collection and screening. Take the four dimensions above as the basic framework, indicators were collected widely from related references containing complete and reliable index systems, including systems for assessing happy river, river health, the rigor of water resources management systems, human-water harmony, and water resources carrying capacity, a total number of 1, 365 indicators were collected.

(2) Preliminary selection of the indicators. Relevance between the evaluation indicators in the selected references and the four dimensions were sequentially analyzed, and irrelevant and duplicate indicators were then eliminated. Those indicators closely related to the dimensions were retained, and the frequency of those indicators occurrence in the related references were statistically analyzed. 126 indicators highly related to the four dimensions and those show high frequency of occurrence were selected as the preliminary indicators.

(3) Final screening of the indicators. The indicators in the relevant documents were also collected from the administrative departments. Based on the results of step (2), indicators were further selected within a scientific, complete, representative, operable, and objective way, while advice from experts was also taken into consideration. Finally, the happy river assessment index system was established and included 16 basic indicators and 34 alternative indicators (Table 1). Within practical application, the basic indicators are those recommended for selection, whereas the alternative indicators can be selected according to the specific situation of a particular time or region.

2.3.2. Development of the Indictor Standards

The indicator standards represent the scales with which to evaluate the index levels. The classification of standards and the determination of standard values provided in the present study (Table 2) were based mainly on the following documents: (1) the existing national recommendation standards in related evaluation systems; (2) target value of water resources within economic and social planning for the basin; (3) corresponding index standards in relevant references; (4) expert consultation. The happy river evaluation standards were divided into five levels: (I) excellent; (II) good; (III) moderate; (IV) poor, and; (V) very poor. Since the happy river standards are spatiotemporally dynamic, evaluation of the rivers under unified standards poses a challenge, and the standards proposed in the present study can act as a reference for similar regions. It is recommended that researchers choose suitable standards according to the conditions and demands of a specific region.

Table 1. Indicators selected within a Happy River Index (HRI) evaluation framework.

Dimensions	Indicators	Characteristic [a]	Unit	Type [b]	Calculation	Reference
SOI	Security and stability of riparian zone and riverbed (H1)	+	%	B	(The length of river with safe and stable riparian and the riverbed/Total length of the river section investigated) × 100 or Expert scoring method	[39]
	Index of connectivity status (H2)	-	/100 km	A	Number of barriers such as breakpoints or nodes (gates, dams)/Total length of the river section	[39]
	Requirement rate of bank-full discharge (H3)	+	%	A	(Actual bank full discharge of the river section/Critical bank full discharge under the corresponding water and sediment conditions without channel shrinkage) × 100	[40]
	Change in sediment carrying capacity (H4)	-	%	A	(Sediment concentration variation in value after 10 years/Sediment concentration under the same conditions 10 years ago) × 100	[41]
	Extent of variation in flow process (H5)	-	-	A	The average deviation between the monthly measured runoff and the natural monthly runoff during the assessment year	[39]
	The ratio of harnessed water and soil erosion area (H6)	+	%	A	(Area of soil erosion that has been treated/Total area of soil erosion) × 100	[42]
	Index of hydrological regulation (H7)	+	-	A	Regulation storage capacity of various water conservancy engineering facilities in the river/The annual average total runoff of the river	[42]
	The flood control and drainage attainment rate (H8)	+	%	B	1/2 × ((Length of embankment that up to the flood control standards/Length of the total planned embankment) + (Area up to the drainage standard/Total area of areas with drainage standards)) × 100	[42]
	Rate of intact hydraulic engineering facilities (H9)	+	%	B	(Number of intact hydraulic engineering facilities/Total number of hydraulic engineering facilities) × 100	[43]
	Rate of population affected by floods (H10)	-	%	B	(The number of people suffered by floods/Regional population) × 100	[44]
	Flood losses as a percentage of gross domestic product (GDP) (H11)	-	%	A	(Economic losses caused by floods/Regional GDP) × 100	[44]
SSI	Water resources per km^2 (H12)	+	10^4 m^3/km^2	A	Total amount of water resources/Study area	[45]
	Water resources per capita (H13)	+	m^3/per	A	Total amount of water resources/Total population	[45]
	Water supply guarantee rate (H14)	+	%	B	(The number of years when the water supply can meet the demand/The total years of water supply) × 100	[41]
	Tap water provision coverage rate (H15)	+	%	A	(Population of the city with access to piped water supply/City population) × 100	[42]
	Safety of drinking water (H16)	+	%	A	(The number of days in a year that drinking water up to the standard/365) × 100	[41]
	Rate of qualified drinking water sources (H17)	+	%	B	(The number of monitored drinking water sources that up to the standards/The total number of monitored drinking water sources) × 100	[42]
	Irrigation guarantee rate (H18)	+	%	A	(The number of years that the expected irrigation water consumption can be fully satisfied in the years of irrigation/The total number of years) × 100	[41]
	The degree of total water consumption exceeding the standard (H19)	-	%	B	((Actual total water consumption - the total water consumption target in Chinese "three red line strategy")/the total water consumption target in Chinese "three red line strategy") × 100	[42]
	Groundwater over-exploitation rate (H20)	-	%	A	(The area of groundwater over-exploitation/Total regional area) × 100	[42]
	Utilization ratio of water resources (H21)	±	%	B	(Total water consumption/Multi-year average water resources) × 100	[39]
EHI	Pollution load index (H22)	-	-	A	0.5 × (COD discharge/COD discharge target + Ammonia nitrogen discharge/Ammonia nitrogen discharge target)	[46]
	The ratio of water functional regions with up-to-standard water quality (H23)	+	%	B	(The number of water function regions that reach the water quality standard/The total number of water function regions) × 100	[39]
	Percentage of monitored river sections with water quality equal to or better than Class III (H24)	+	%	A	(The number of monitoring sections with water quality equal to or better than grade III/The total number of river monitoring sections) × 100	[39]
	Compliance rate of industrial wastewater discharge (H25)	+	%	A	(Industrial wastewater standard discharge/Total industrial wastewater discharge) × 100	[47]
	Concentrated treatment rate of sewage (H26)	+	%	A	(Annual municipal wastewater treatment capacity/Annual municipal wastewater production) × 100	[47]
	Eutrophication status of lakes and reservoirs (H27)	-	-	A	$w(chl) \times TLI\ (chl) + w(TP) \times TLI(TP) + w(TN) \times TLI(TN) + w(SD) \times TLI(SD) + w(COD) \times TLI(COD)$ [c]	[48]

Table 1. *Cont.*

Dimensions	Indicators	Characteristic [a]	Unit	Type [b]	Calculation	Reference
	Sediment pollution index (H28)	-	-	A	$I = \frac{1}{m}\sum_{j=1}^{m}\frac{1}{n}\sum_{i=1}^{n}\frac{C_i}{C_{0i}}$ [d]	[39]
	Minimum ecological flow demand guarantee rate (H29)	+	%	B	(The number of months that the section flow is greater than or equal to the ecological base flow/Total statistical months) × 100	[42]
	Rate of river ecological bank protection (H30)	+	%	A	(The length of the river ecological revetment that have been built/The total length of artificial revetment) × 100	[42]
	Index of biological integrity (H31)	+	%	A	$IBI = \frac{\frac{TY_{plankton}}{JTY_{plankton}} + \frac{TY_{benthos}}{JTY_{benthos}} + \frac{TY_{fish}}{JTY_{fish}} + \frac{TY_{plants}}{JTY_{plants}} + \frac{TY_{amphibians}}{JTY_{amphibians}}}{5} \times 100$ [e]	[42]
	Natural wetland retention rate (H32)	+	%	A	(Water surface area at the average annual water level/The total basin area) × 100	[39]
	Water space ratio (H33)	+	South China, % North China, %	A	(The area carrying the function of the water body/The total area) × 100	[42]
HDI	Water consumption per 10,000 Yuan RMB of GDP (H34)	+	m^3/10,000 RMB	B	Water consumption of regional economic and societal development/The total GDP (unit: 10,000 Yuan RMB)	[45]
	Water consumption per 10,000 Yuan RMB of industrial added value (H35)	+	m^3/10,000 RMB	B	Industrial water consumption/Industrial GDP (unit: 10,000 Yuan RMB)	[45]
	Utilization coefficient of agricultural irrigation water (H36)	+	-	B	(Actual net irrigation water consumption in the field/The gross irrigation water consumption in the field) ×100	[42]
	Pipe network leakage rate (H37)	-	%	A	(Water leakage from the pipe network/Total water supply) × 100	[42]
	Rate of water-saving technology uptake (H38)	+	%	A	(The number of water-saving appliances used in public facilities and residents' lives/Total number of water appliances) × 100	[42]
	Repeated utilization ratio of industry water (H39)	+	%	A	(Repeated industrial water consumption/Total industrial water consumption) × 100	[47]
	Hydropower resources development rate (H40)	-	%	A	(Total installed capacity of hydropower stations in the river basin/Hydropower resources that can be developed) × 100	[49]
	The degree of human-water harmony (H41)	+	-	A	SMI-P	[29]
	Guaranteed rate of navigable water level (H42)	+	%	A	(The number of days that the water level is higher than the designed lowest navigable water level in a year/365) × 100	[41]
	Landscape diversity index (H43)	+	%	A	(The number of different ecological types in the landscape/Maximum possible ecological types in the landscape) × 100	[46]
	Hospitable landscape construction intensity (H44)	+	%	B	Questionnaire, Annual average construction length of the hydrophilic trail, guardrail, lighting, pavement, etc.	[46]
	The number of river culture carriers (H45)	+	set	A	The number of water conservancy facilities, protected areas, museums, and non-material culture, which has the function of cultural inheritance	[42]
	Degree of construction of water laws and regulations (H46)	+	-	A	Questionnaire	
	Water resources monitoring capability index (H47)	+	%	A	1/4 × (Metering rate of water consumption + monitoring rate of water quality in water function area + monitoring rate of sewage outlet to the river + warning and forecast rate of water disaster) × 100	[42]
	Degree of water culture excavation and protection (H48)	+	%	B	Questionnaire, degree of water culture protection, integration of hydraulic engineering facilities and water culture, and industrialization level of water culture were scored	[50]
	Public awareness of river ecological protection (H49)	+	%	A	Questionnaire, ((Number of participants in publicity and education activities related to river protection + the number of visitors to the water culture carrier)/Regional population) × 100	
	Public satisfaction with the degree of the happy river (H50)	+	%	B	Questionnaire, (The number of people who are satisfied with the natural and social functions of the river/Total number of people surveyed) × 100	

Notes: [a] The column "Characteristic" represents the effect of the evaluation indicator on the HRI, "+" represents a positive action and "−" represents a negative action; [b] in the "Type" column, "B" represents Basic Indicators, "A" represents Alternative Indicators; [c] "*TLI(chl)*", "*TLI(TP)*", "*TLI(TN)*", "*TLI(SD)*", "*TLI(COD)*" are the trophic level index of chlorophyll, total phosphorus, total nitrogen, water transparency , and chemical oxygen demand, respectively. W_j is the weight of the *jth* parameter; [d] "m" is the number of river sections, "n" is the number of sediment quality indicators, "C_i" is the concentration of pollutions in the sediment, and "C_{0i}" is the background concentration of pollutants; [e] "TY_i" is the number of aquatic organisms for different species, "JTY_i" is the number of aquatic organisms for different species in the base year.

Table 2. Evaluation standards of the Happy River Index (HRI) Evaluation Framework.

Indicators Code	Grade				
	I (Excellent)	II (Good)	III (Moderate)	IV (Poor)	V (Very Poor)
H1	[98,100]	[85,98)	[70,85)	[50,70)	<50
H2	[0,0.3]	(0.3,0.5]	(0.5,0.8]	(0.8,1.2]	>1.2
H3	[95,100]	[80,95)	[60,80)	[30,60)	<30
H4	[0,5]	(5,10]	(10,15]	(15,25]	>25
H5	[0,0.1]	(0.1,0.3]	(0.3,1.5]	(1.5,3.5]	(3.5,5]
H6	[95,100]	[80,95)	[60,80)	[40,60)	<40
H7	≥40	[30,40)	[20,30)	[10,20)	<10
H8	[95,100]	[80,95)	[75,80)	[50,75)	<50
H9	[98,100]	[90,98)	[75,90)	[60,75)	<60
H10	[0,2]	(2,5]	(5,10]	(10,20]	>20
H11	[0,1]	(1,2.5]	(2.5,4]	(4,5.5]	>5.5
H12	≥60	[35,60)	[20,35)	[15,20)	<15
H13	≥10,000	[1670,10,000)	[1000,1670)	[500,1000)	<500
H14	[95,100]	[80,95)	[65,80)	[50,65)	<50
H15	[95,100]	[80,95)	[60,80)	[40,60)	<40
H16	[95,100]	[80,95)	[65,80)	[50,65)	<50
H17	[98,100]	[85,98)	[75,85)	[60,75)	<60
H18	[95,100]	[80,95)	[65,80)	[50,65)	<50
H19	≤0	(0, 5]	(5,10]	(10,20]	>20
H20	[0,2]	(2,10]	(10,15]	(15,20]	>20
H21	[25,30]	[20,25)(30,40]	[10,20)(40,50]	[5,10)(50,60]	<5>60
H22	[0,0.5]	(0.5,0.9]	(0.9,1.1]	(1.1,1.5]	>1.5
H23	[95,100]	[80,95)	[60,80)	[40,60)	<40
H24	[95,100]	[80,95)	[60,80)	[40,60)	<40
H25	[95,100]	[90,95)	[85,90)	[70,85)	<70
H26	[85,100]	[80,85)	[70,80)	[60–70)	<60
H27	≤20	(20,50]	(50,60]	(60,80]	>80
H28	[0,0.1]	(0.1,0.3]	(0.3,0.5]	(0.5,1]	>1
H29	[98,100]	[90,98)	[80,90)	[60,80)	<60
H30	[95,100]	[80,95)	[60,80)	[30,60)	<30
H31	[85,100]	[70,85)	[50,70)	[30,50)	<30
H32	[95,100]	[85,95)	[70,85)	[45,70)	<45
H33 (North China)	≥30	[20,30)	[10,20)	[6,10)	<6
H33 (South China)	≥15	[10,15)	[6,10)	[4,6)	<4
H34	[95,100]	[85,95)	[70,85)	[50,70)	<50
H35	[95,100]	[85,95)	[70,85)	[50,70)	<50
H36	≥0.65	[0.55,0.65)	[0.5,0.55)	[0.45,0.5)	<0.45
H37	≤8	(8,12]	(12,18]	(18,25]	>25
H38	[95,100]	[80,95)	[70,80)	[50,70)	<50
H39	[95,100]	[75,95)	[40,75)	[30,40)	<30
H40	≤50	(50,60]	(60,70]	(70,80]	>80
H41	[0.98,1]	[0.8,0.98)	[0.6,0.8)	[0.3,0.6)	[0,0.3)
H42	[95,100]	[80,95)	[65,80)	[50,65)	<50
H43	[95,100]	[80,95)	[70,80)	[50,70)	<50
H44	[95,100]	[80,95)	[60,80)	[30,60)	<30
H45	≥8	[6,8)	[3,6)	[1,3)	0
H46	[90,100]	[70,90)	[40,70)	[20,40)	<20
H47	[90,100]	[75,90)	[60,75)	[40,60)	<40
H48	[95,100]	[80,95)	[60,80)	[30,60)	<30
H49	≥20	[15,20)	[10,15)	[5,10)	[0,5)
H50	[95,100]	[80,95)	[60,80)	[30,60)	<30

2.4. The HRI Assessment Method

The assessment of the HRI is a comprehensive process incorporating multiple indices, multiple criteria, and multiple dimensions. Many methods are suitable for use within the happy river assessment, including matter element analysis, artificial neural network, fuzzy comprehensive evaluation, and grey correlation analysis. All these methods show unique advantages and shortcomings, and while some are simple and easy to calculate, others are computationally complex. The method of "single index quantification-multiple indices syntheses-poly-criteria integration" (SMI-P) proposed by Zuo [29] has

been widely used in China within water resource and water quality assessment and management, and is based on the Human-Water Harmony theory [13,22,51–53]. A reasonable assessment index system can be established by analyzing the relationships between the indicators and dimensions and between the dimensions and the final target. The quantitative relationships between each indicator and dimension, and between each dimension and the final target can thus be clearly identified. Using this approach, the final target can be deconstructed and refined layer by layer to facilitate quantitative and rational results. The SMI-P method incorporates three steps: (1) calculate the degree of membership of a single indicator by a fuzzy membership function; (2) calculate the synthesis value of each dimension by the weighted average of each indicator in each dimension; (3) obtain an overall HRI by the weighted average of each dimension. Using the Happy River Index system, evaluation standards, and the SMI-P method, the procedures for happy river assessment were as follows:

Step1: single index quantification

To calculate the membership value of each indicator, the five nodal points a, b, c, d, and, e representing Very Poor, Poor, Moderate, Good, and Excellent, respectively were set (Table 2). The membership value for x of each single indicator was calculated by a fuzzy membership function ($\mu_k(x)$) with $\mu_k \in [0\ ,\ 1]$ and the membership value was calculated using the following equations [22]:

$$\text{for positive indicators } \mathrm{H}_i = \begin{cases} 0\ , & x_i \le a_i \\ 0.3\left(\frac{x_i - a_i}{b_i - a_i}\right), & a_i < x_i \le b_i \\ 0.3 + 0.3\left(\frac{x_i - b_i}{c_i - b_i}\right), & b_i < x_i \le c_i \\ 0.6 + 0.2\left(\frac{x_i - c_i}{d_i - c_i}\right), & c_i < x_i \le d_i \\ 0.8 + 0.2\left(\frac{x_i - d_i}{e_i - d_i}\right), & d_i < x_i \le e_i \\ 1\ , & e_i < x_i \end{cases}, \tag{1}$$

$$\text{for appropriate indicators } H_i = \begin{cases} 0, & x_i \le a_i \\ 0.3\left(\frac{x_i - a_i}{b_i - a_i}\right), & a_i < x_i \le b_i \\ 0.3 + 0.3\left(\frac{x_i - b_i}{c_i - b_i}\right), & b_i < x_i \le c_i \\ 0.6 + 0.2\left(\frac{x_i - c_i}{d_i - c_i}\right), & c_i < x_i \le d_i \\ 0.8 + 0.2\left(\frac{x_i - d_i}{e_i - d_i}\right), & d_i < x_i \le e_i \\ 1, & e_i < x_i \le f_i \\ 0.8 + 0.2\left(\frac{g_i - x_i}{g_i - f_i}\right), & f_i < x_i \le g_i \\ 0.6 + 0.2\left(\frac{h_i - x_i}{h_i - g_i}\right), & g_i < x_i \le h_i \\ 0.3 + 0.3\left(\frac{i_i - x_i}{i_i - h_i}\right), & h_i < x_i \le i_i \\ 0.3\left(\frac{j_i - x_i}{j_i - i_i}\right), & i_i < x_i \le j_i \\ 0, & x_i > j_i \end{cases}, \tag{2}$$

$$\text{for negative indicators } \mathrm{H}_i = \begin{cases} 1, & x_i \le e_i \\ 0.8 + 0.2\left(\frac{d_i - x_i}{d_i - e_i}\right), & e_i < x_i \le d_i \\ 0.6 + 0.3\left(\frac{c_i - x_i}{c_i - d_i}\right), & d_i < x_i \le c_i \\ 0.3 + 0.2\left(\frac{b_i - x_i}{b_i - c_i}\right), & c_i < x_i \le b_i \\ 0.3\left(\frac{a_i - x_i}{a_i - b_i}\right), & b_i < x_i \le a_i \\ 0, & a_i < x_i \end{cases}, \tag{3}$$

In Equation (1) to Equation (3), H_i is the membership degree value of the i^{th} indicator and $H_i \in [0, 1]$; a_i, b_i, c_i, d_i, e_i are node values of the i^{th} indicator.

Step2: Weight determination

During the assessment process, the determination of the weight of each indicator and each dimension plays an important role in the accuracy assessment. Since the single-weighting method has limitations, a combination of the subjective and objective weighting methods (the AHP-entropy weight method) was used in the present study to calculate the weights of the indicators and dimensions. The steps were as follows:

• AHP-based weight

Four steps were included to calculate the AHP-based weight. First, a hierarchical model was constructed by analyzing the relationship between HRI and safe operation index (SOI), sustainable supply index (SSI), ecological health index (EHI), and harmonious development index (HDI) in the YRB. Secondly, the comparative matrices were constructed. The scales of SOI, SSI, EHI, and HDI were determined to be 2, 1, 2, and 1, respectively, according to the 1–9 comparative scale method. Thirdly, the weight vector was calculated and assessed for consistency. The maximum eigenvalue and corresponding eigenvector of each pairwise comparison matrix was constructed. A consistency ratio < 0.1 indicated the weight to be reasonable, and the weight was obtained by normalizing the eigenvector. Finally, the AHP-based weights of SOI, SSI, EHI, and HDI were calculated as 0.33, 0.17, 0.33, and 0.17, respectively, in the present study. The weights of the indicators were obtained using the same approach.

• Entropy-based weight

The statistical indicators required standardization due to differences in unit among of the indicators. The standardization equations are described below.

$$\text{For positive indicators } U_{ij} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j}, \tag{4}$$

$$\text{For negative indicators } U_{ij} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j}, \tag{5}$$

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m}\frac{U_{ij}}{\sum_{i=1}^{m} U_{ij}}\ln\frac{U_{ij}}{\sum_{i=1}^{m} U_{ij}}, \tag{6}$$

$$w_j'' = \frac{1 - e_j}{\sum_{j=1}^{n}(1 - e_j)}, \tag{7}$$

In Equation (4) to Equation (7), x_{ij} is the set of the j^{th} indicator of the i^{th} region, U_{ij} is the standardized value of x_{ij}, e_j is the entropy of the i^{th} indicator, w_j'' is the weight of i^{th} indicator, and n is the number of indicators.

• Combination of the AHP and entropy weight

The calculation of AHP-entropy-based weight is as follows [54]:

$$w_j = \frac{w_j' \times w_j''}{\sum_{j=1}^{n}(w_j' \times w_j'')} \tag{8}$$

In Equation (8), w_j and w_j' are the combined AHP-entropy weight and the objective weight of i^{th} indicator, respectively.

Step3: synthesis of multiple indices

The four dimensions in the HRI system are SOI, SSI, EHI, and HDI. The values of the four dimensions were determined using Equations (9)–(12).

$$SOI = \sum_{i=1}^{n_1} W_{iO} \cdot H_{iO} \tag{9}$$

$$SSI = \sum_{i=1}^{n_2} W_{iS} \cdot H_{iS} \tag{10}$$

$$EHI = \sum_{i=1}^{n_3} W_{iE} \cdot H_{iE} \tag{11}$$

$$HDI = \sum_{i=1}^{n_4} W_{iH} \cdot H_{iH} \tag{12}$$

In Equations (9)–(12), n_1, n_2, n_3, n_4 are the number of indicators for the four dimensions, respectively, W_{iO}, W_{iS}, W_{iE}, W_{iH} are the weights of each single indicator in each dimension, and $\sum_{i=1}^{n_1} W_{iO} = \sum_{i=1}^{n_2} W_{iS} = \sum_{i=1}^{n_3} W_{iE} = \sum_{i=1}^{n_4} W_{iH} = 1$.

Step 4: poly-criteria integration

HRI is the weighted average of the four dimensions calculated above and the value of HRI can be calculated by:

$$HRI = W_O \cdot SOI + W_S \cdot SSI + W_E \cdot EHI + W_H \cdot HDI \tag{13}$$

In Equation (13), HRI is the Happy River Index, HRI ∈ [0,1] and W_O, W_S, W_E, W_H are the weights of each dimension. The value of HRI is between 0 and 1, and Table 3 shows the grading of the HRI, with the higher the HRI, the better the river status.

Table 3. Classification of the Happy River Index (HRI).

HRI	Type
1	Very happy
[0.8,1)	Happy
[0.6,0.8)	Sub-happy
[0.4,0.6)	Medium
[0.2,0.4)	Sub-medium
(0,0.2)	Unhappy
0	Very unhappy

2.5. Diagnosis of Limiting Factors

The dominant limiting factors restricting the HRI of the YRB can be diagnosed by the obstacle degree model [55], and targeted suggestions for addressing these limiting factors can be proposed to decision makers. Factors limiting the HRI were calculated by factor contribution degree (V_j), indicator deviation degree (h_{ij}), and obstacle degree (y_{ij}) [56]:

$$V_j = W_i \cdot W_{ij}, \tag{14}$$

$$h_{ij} = 1 - H_{ij}, \tag{15}$$

$$y_{ij} = \frac{h_{ij} \times V_{ij}}{\sum_{j=1}^{n} \left(h_{ij} \times V_{ij} \right)} \times 100\%, \quad (16)$$

In Equation (14) to Equation (16), W_i and W_{ij} are the weights of the dimension to the total target and the single indicator to each dimension, respectively and H_{ij} is the standardized value of the individual indicator calculated by Equation (1) to Equation (3).

3. Case Study

3.1. Study Area

The Yellow River is the second-longest river in China and the sixth-longest globally [57], with a total length of 5464 km and draining a catchment area of ~795,000 km^2. The Yellow Rover originates from the Bayan Har Mountains and stretches from west to east across the provinces and regions of Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong in northern China, finally flowing into the Bohai Sea near the city of Dongying in Shandong Province. The river can be divided into the upper, middle, and lower reaches. The upper reach area extends from the Bayan Har Mountains to the town of Hekou, Inner Mongolia. The middle reach extends from the town of Hekou to the Peach Blossom Valley, Henan. The lower reach extends from the Peach Blossom Valley to Dongying (Figure 2). The Yellow River is widely considered to be the birthplace of Chinese civilization. The Yellow River Basin (YRB) hosts 150 million people and water from the Yellow River irrigates ~15% of China's arable land, feeding approximately 12% of the country's population and supports 14% of the national GDP. Coal production within the YRB accounts for ~70% of China's total coal production. Therefore, it is clear that the Yellow River plays an important role in ecological security, socio-economic development, and human well-being in China.

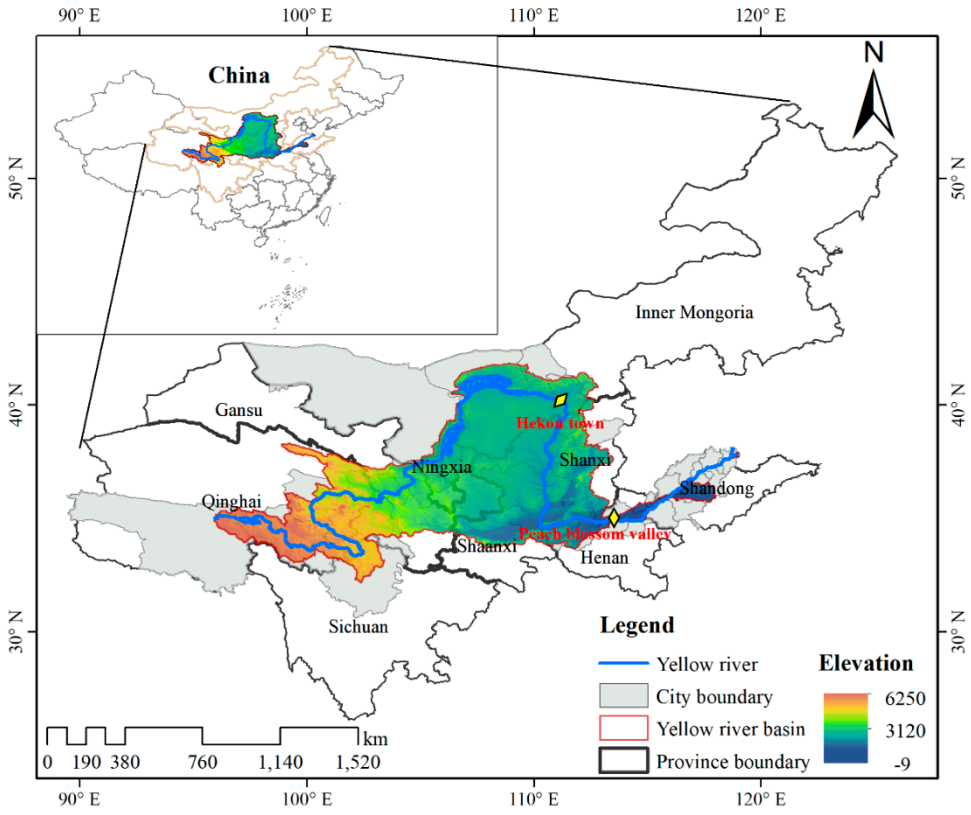


Figure 2. Map of the Yellow River Basin, China.

However, the YRB faces many challenges due to climate change and intensive human activities, including water scarcity, serious water pollution, a fragile ecological environment, unevenly distributed natural resources, and water deficits. Since water resources in the YRB are mostly concentrated in the upper reaches, most of which are plateau and mountainous regions, whereas this region only contains less than 10% of the total farmland of the YRB, there is a spatial mismatch between available water resources and demand. The per-capita water resources in the YRB is only 27% of China's national average. In contrast, the rate of water resources utilization is as much as 80%, far exceeding the global guideline of 40% for preventing ecological damage [58]. The Yellow River is also known as the most sediment-laden river in the world. This is because the middle reaches of the river flow through the Loess Plateau, which is characterized by serious soil erosion, resulting in vast quantities of mud and sand being deposited in the river. Economic development in the YRB is also uneven, with the GDP of Qinghai being only 3.6% of that in Shandong. The challenges facing the YRB mentioned above severely affect the ecological health of the Yellow River and greatly restrict high-quality development of regions within the YRB. Assessment of the status of the Yellow River with consideration of river health and human well-being is vital for promoting both river health and high-quality development in the YRB.

3.2. Data Sources and Processing

Research data for the present study were collected from the statistical yearbooks (2018) and water resources bulletins (2017) of the nine provinces and regions compiled by the provincial or regional bureau of statistics and department of water resources, respectively, the city statistical yearbook, and the 2018 water statistical yearbook of China compiled by the national bureau of statistics and ministry of water resources, P.R. China. In addition, the present study conducted expert consultation and questionnaire surveys on some subjective indicators. The data were processed using Microsoft Excel 2016 and analyzed using Origin 2020. Maps were generated using ArcGIS 10.4.1.

The happy river assessment framework was applied to evaluate the HRI of the YRB over three spatial scales in 2017: (1) river-reach scale; (2) main-stem scale; and (3) regional scale. The four dimensions and the basic indicators comprised the fixed part of the framework. The indicators for the happy river assessment of the YRB were then further screened according to the index screening principles and data availability. Data for each indicator were then collected, either from a government report or the questionnaire survey. The SMI-P and AHP-entropy weight methods were then applied. Finally, the factors limiting the HRI were identified and corresponding improvement measures were proposed for improving river health and the human well-being within the YRB.

4. Results

4.1. Happy River Assessment of the Yellow River at the River-Reach Scale

A total of 16 basic indicators and six alternative indicators (change in sediment carrying capacity, extent of variation in flow processes, water resources per capita, tap water provision coverage rate, concentrated treatment rate of sewage, and percentage of monitored river sections with water quality equal to or better than Class III) were selected for the happy river assessment in the Yellow River at the river-reach scale. The original data for the 22 assessment indicators for each reach were quantified by Equation (1) to Equation (3) accordingly (see Figure 3). The SOI, SSI, EHI, HDI, and HRI were then calculated by aggregating the membership values and AHP-entropy-based weights of the indicators using Equation (4) to Equation (13), with the results presented in Figure 4.

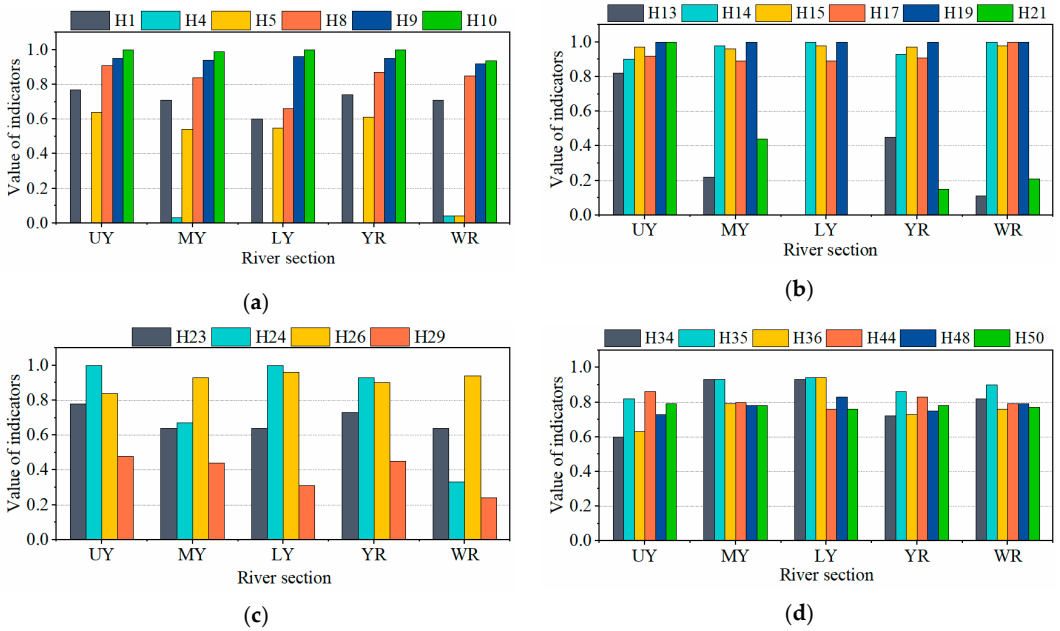


Figure 3. Membership degree values of happy river indicators for different reaches of the Yellow River and the Wei River: (**a**) indicators for safe operation index (SOI) dimension; (**b**) indicators for sustainable supply index (SSI) dimension; (**c**) indicators for ecological health index (EHI) dimension; (**d**) indicators for harmonious development index (HDI) dimension. The codes of the indicators have the prefix 'H' (see Table 1), the labels "UY", "MY", and "LY" refer to the upper, middle, and lower reaches of the Yellow River, respectively, whereas "YR" and "WR" refer to the Yellow River and Wei River, respectively.

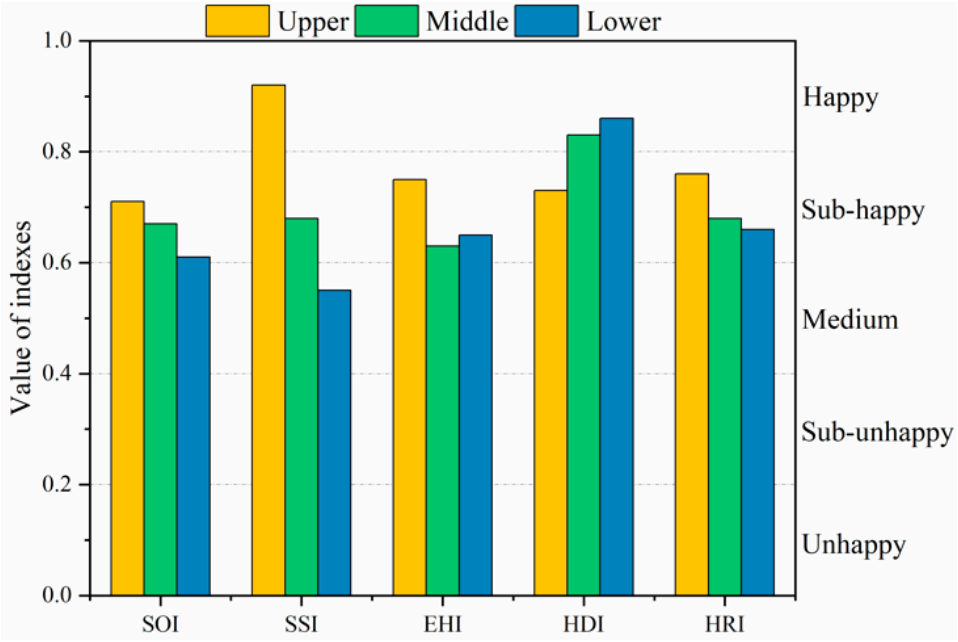


Figure 4. Results of the happy river evaluation for the upper, middle, and lower reaches of the Yellow River.

There was a decrease in HRI for the Yellow River from the upper to lower reaches, with HRI decreasing from 0.77 to 0.65, and all reaches falling within the Sub-happy level. SOI, SSI, and EHI had the highest values of the four dimensions in the upper reaches, whereas HDI had the lowest value (Figure 4). In contrast, SOI and SSI showed the lowest values in the lower reaches, whereas

HDI showed the highest value. As shown in Figure 3, the membership values of H1, H5, and H8 in dimension SOI, H13 and H21 in dimension SSI, H24 in dimension EHI, H34, and H36, and H48 in dimension HDI showed significant differences among different river reaches, and all displayed the same trends with corresponding dimensions, which were relatively important factors within the happy river assessment. On the one hand, the natural water resources of the upper reach are relatively abundant and of better quality, with a healthier ecological environment. On the other hand, socio-economic development of the upper reach is lower, with lower water resources utilization efficiency (H34, H35, and H36). The middle reach is located in arid and semi-arid areas in which precipitation is low and evaporation is high. The river flows through the loess plateau characterized by water scarcity, serious soil erosion, and ecosystem fragility. Therefore, the SOI and SSI were lower in the middle reach than in the upper reach. However, the middle reach is an important energy base with higher economic development and higher water use efficiency compared to that in the upper reach, resulting in a higher HDI compared to the upper reach. However, greater loads of pollutants are generated in the middle reach, thereby contributing to a low EHI level. Although the lower reach of the Yellow River is the most developed section of the Yellow River with a high population density and high water use efficiency, the sharp mismatch between supply and demand within the lower reaches has resulted in serious water shortages, thereby contributing to the lowest SSI. Moreover, the river channel of the lower reach is continually undergoing a process of siltation and shrinkage, resulting in the riverbed being higher than the catchment on both sides, and thereby contributing to the lowest SOI among all the reaches. Collectively, these factors resulted in the performance of high economic development but low HRI in the lower reach.

4.2. Happy River Assessment at the Overall Main-Stem Scale within Both the Yellow and Wei Rivers

As the largest tributary of the Yellow River, the Wei River drains a typical arid/semi-arid area of northwest China. The present study discusses the HRI for both the Yellow and Wei rivers to verify the applicability of the happy river assessment framework to tributaries. The indicators selected for the river mainstem-scale assessment were the same as those selected for the river-reach scale assessment. The original data of each of the 22 indicators were quantified by Equations (1)–(3) (see Figure 3). Figure 5 presents the assessment results of SOI, SSI, EHI, HDI, and HRI for the Wei and Yellow rivers. The HRI values for the Wei and Yellow rivers were 0.62 and 0.71, respectively, with both falling in the Sub-happy level. The dimensions of SOI, SSI, and EHI in the Yellow River were all higher than those in the Wei River, except for the HDI (Figure 5). As shown in Figure 3, the membership values of H5 in dimension SOI, H13 in dimension SSI, and H24 and H29 in dimension EHI showed significant differences, and all displayed the same trend with corresponding dimensions, which were relatively important factors for the happy river assessment. The membership values of indicators in the dimension HDI showed no significant differences. The Wei River originates from Gansu, flows through the Loess Plateau and then into the Yellow River in Shaanxi, with these areas constituting the most severe soil erosion areas in the YRB. While the sediment concentrations of both the Wei and Yellow rivers are high, their sources of water and sediment are different. In addition, flood disasters occur more frequently in the Wei River compared to in the Yellow River. Moreover, the Wei River Basin was once the most developed area in China with a large population density [31]. With the acceleration of urbanization and industrialization, maintenance of the ecological health of the river could not be guaranteed, which ultimately led to a continuous deterioration of the ecosystem in the Wei River Basin. On the other hand, cities along the Wei River occupy an important position in the regional economic development of China and have relatively higher water use efficiencies. Thus, the level of HDI in Wei River was higher than that in the entire Yellow River.

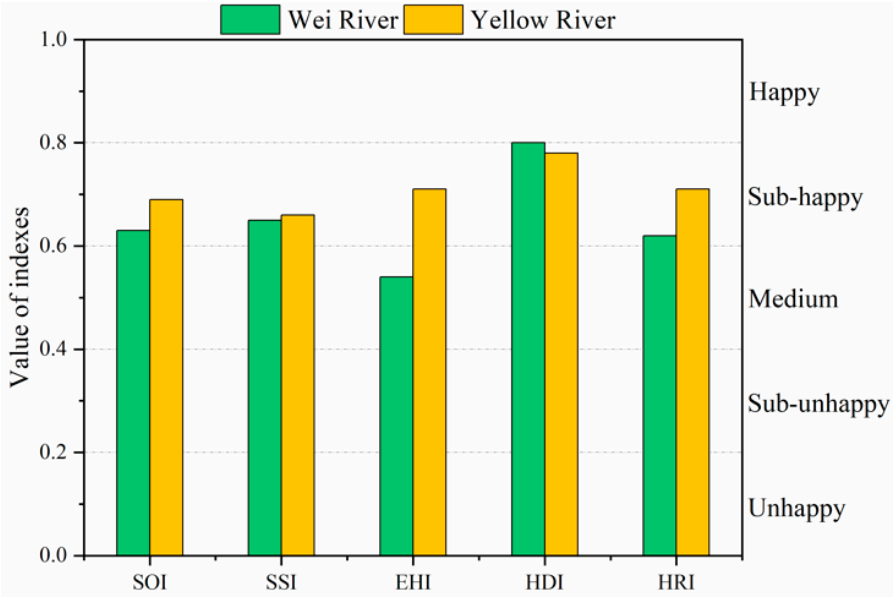


Figure 5. Results of the happy river evaluation of the Yellow and Wei Rivers.

4.3. Happy River Assessment of the Yellow River at the Regional Scale

A total of 16 basic indicators and six alternative indicators (index of connectivity status, the ratio of harnessed water to soil erosion area, water resources per-capita, tap water provision coverage rate, concentrated treatment rate of sewage, natural wetland retention rate) were selected for the regional scale assessment along the Yellow River. Data for the indicators were collected as outline in Section 4.1. Figure 6 shows the membership values of the indicators, while the SOI, SSI, EHI, HDI, and HRI assessment results at the regional scale are presented in Figure 7.

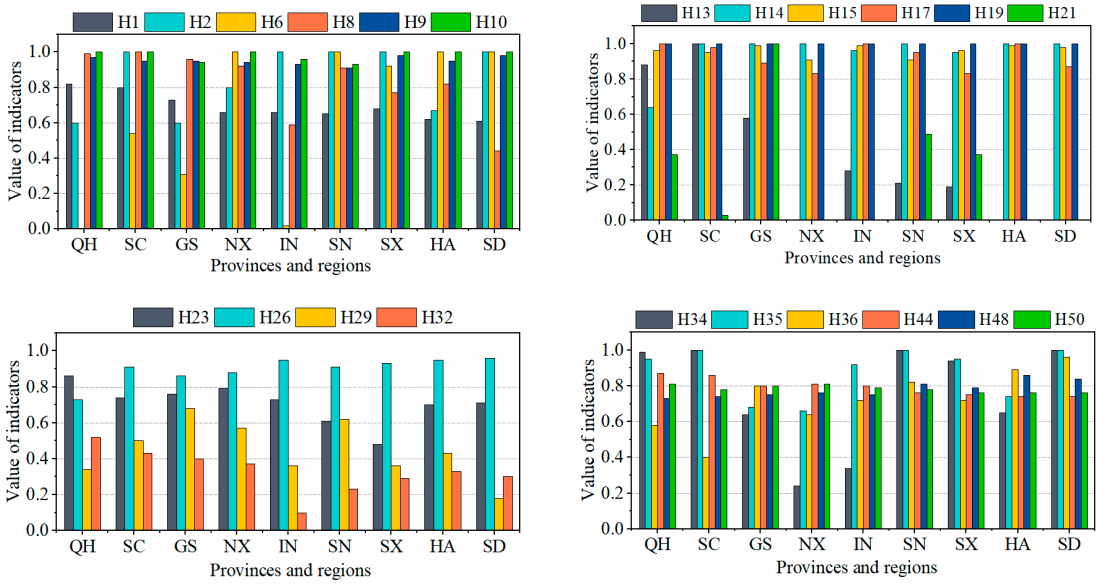


Figure 6. Membership degree values of happy river indicators for different provinces and regions along the Yellow River mainstem. Here, the labels "QH", "SC", "GS", "NX", "IM", "SN", "SX", "HA", and "SD" refer to the provinces and regions of Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong, respectively.

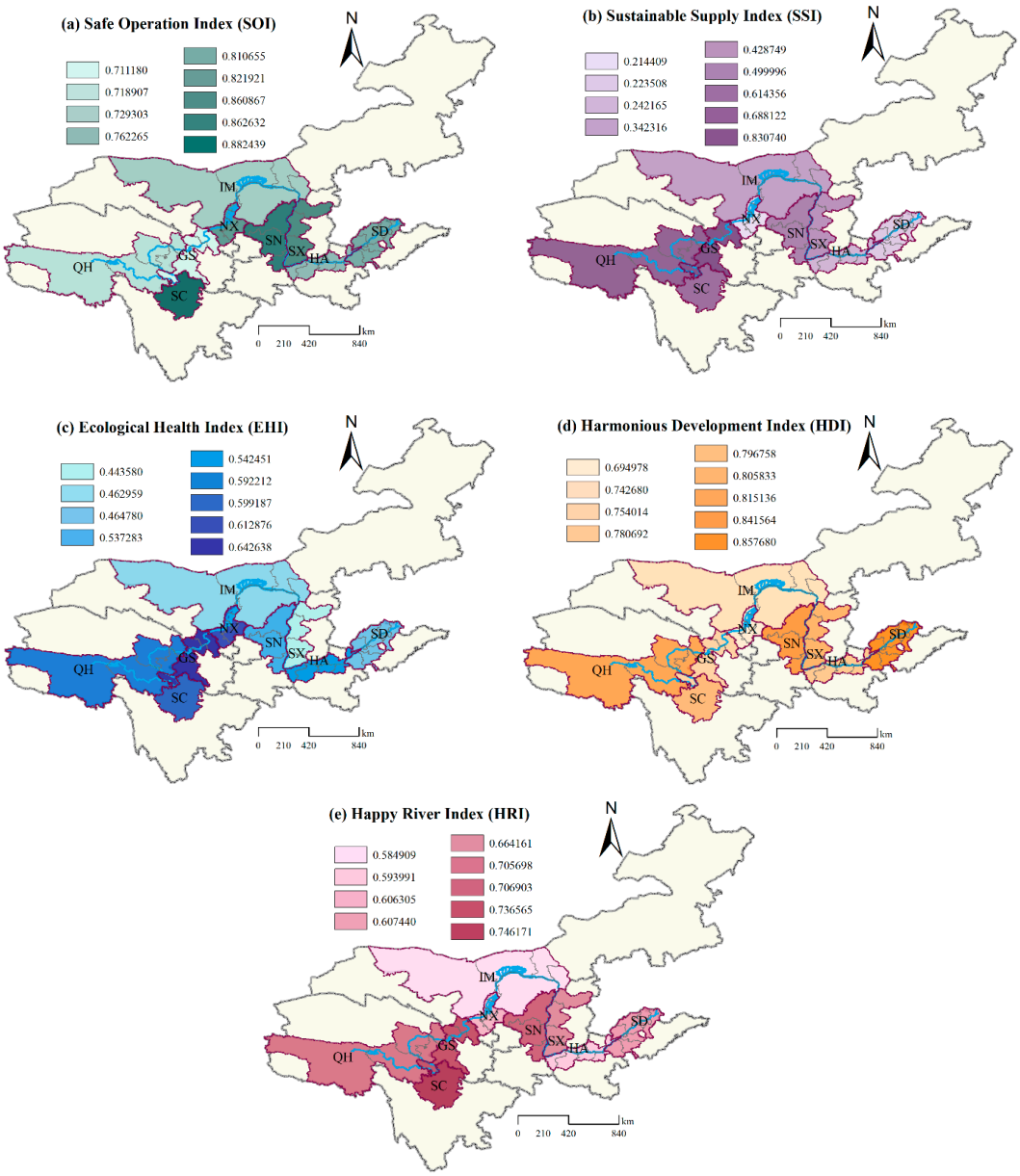


Figure 7. Maps showing the spatial distributions of (**a**) the safe operation index; (**b**) sustainable water supply index; (**c**) ecological health index; (**d**) harmonious development index; and (**e**) happy river index. Here, the labels "QH", "SC", "GS", "NX", "IM", "SN", "SX", "HA", and "SD" refer to the provinces and regions of Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong, respectively.

There were relatively significant differences in HRI among the nine provinces and regions (Figure 7e). The rank of provinces in terms of HRI was Sichuan > Gansu > Shaanxi > Qinghai > Shanxi > Shandong > Ningxia > Henan >Inner Mongolia, with HRI ranging from 0.58 to 0.75.

Among the provinces, Henan and Inner Mongolia had HRI values below 0.6, thereby falling within the medium level, whereas the HRI of all other regions fell within the Sub-happy level. The dimension levels of SSI and EHI showed clear regional differences among the nine provinces and regions, ranging from 0.21 to 0.83 and 0.44 to 0.64, respectively. The lowest values were for SSI in the majority of regions, except in Qinghai, Sichuan, and Gansu (Figure 7b). Regional differences in SOI and HDI were relatively insignificant, ranging from 0.71 to 0.88 and 0.69 to 0.86, respectively. These findings indicated that the level of HRI in the Yellow River is mainly influenced by the sustainability of water resources and

river ecological health. As shown in Figure 6, the membership values of H2, H6, and H8 in dimension SOI, H13, and H21 in dimension SSI, H29, and H32 in dimension EHI, and H36 in dimension HDI showed significant differences, which were the relatively important factors for the regional scale happy river assessment. The harnessing of the Yellow River has played an important part in the stabilization and rejuvenation of China. After more than 70 years of governance, the mainstem of the Yellow River has become highly developed and managed for water conservancy, and these developments play an important role in flood control, silt reduction, and maintaining the stability of the mainstem of the Yellow River. Therefore, the SOI values in the nine provinces and regions along the Yellow River were relatively high with little variation. The regions along the Yellow River experience water shortages, with the average annual river runoff in the YRB constituting only 2% of the national total and the region's per-capita water resources far below the national average, except for in Qinghai. Given the uneven distribution of water resources and the fragile ecosystem in the region, the values of SSI and EHI was relatively low and showed large spatial variations. Shandong clearly had the highest HDI followed by Shanxi, Qinghai, and Henan. On the one hand, Shandong had the highest water efficiency as this is the most developed region along the Yellow River, and the degree of river health protection is relatively high. On the other hand, Qinghai is situated in the northwest and is heavily resource dependent. Although this is an underdeveloped region in China, the ecological environment of the region is relatively better than that in developed regions, and the residents are more satisfied with the river. Ultimately, the factors described above affect the HRI of those regions.

4.4. Analysis on Factors Decreasing HRI

Equations (14)–(16) were used to calculate the degree of limitation on indicators and dimensions at a reach/regional scale. Figures 8 and 9 show degrees of limitation on the four dimensions and main indicators at the reach scale, respectively. In general, there were large differences in the degree of limitation to the HRI among the different dimensions, in which the EHI was the dimension posing the biggest limitation for the middle and lower reaches of Yellow River, followed by SOI, SSI, and HDI (Figure 8). This was attributed to the relatively greater abundance of water resources in the upper reach compared to that in the middle and lower reaches. The degree of limitation to the HRI over the entire lengths of the Yellow and Wei rivers showed the same trend as that at the reach scale, with the degree of limitation posed by the EHI in Wei River slightly higher. As shown in Figure 9, the main indicators of limitation to the HRI across the entire lengths of the Yellow and Wei rivers were change in sediment carrying capacity (H4), the ratio of water functional regions with up-to-standard water quality (H23), and minimum ecological flow demand guarantee rate (H29), among which H23 posed the highest limitation, implying that the ecological health of the river is the main challenge to realizing sustainable development across the entire YRB. Although there were similarities in the main factors limiting the HRI among different reaches, differences persisted between the upper reach and the lower reaches. Water resources per capita (H13) and utilization ratio of water resources (H21) were the factors limiting HRI for the majority of reaches, except within the upper reach in which the economy is less developed, population density is relatively low, and the utilization of water resources is lower. In addition, in contrast to the reaches of the Yellow River, the percentage of monitored river sections with water quality equal to or better than Class III (H24) was the main factor limiting the HRI for the Wei River, implying that this tributary of the Yellow River has been more disturbed by human activities compared to the mainstem of the Yellow River. The factors limiting the HRI for the upper reaches of the Yellow River were ecological and socio-economic development, while that for the downstream reaches was mainly the natural ecological environment. The results showed that the ecosystem of the Wei River is in a worse state than that of the Yellow River mainstem.

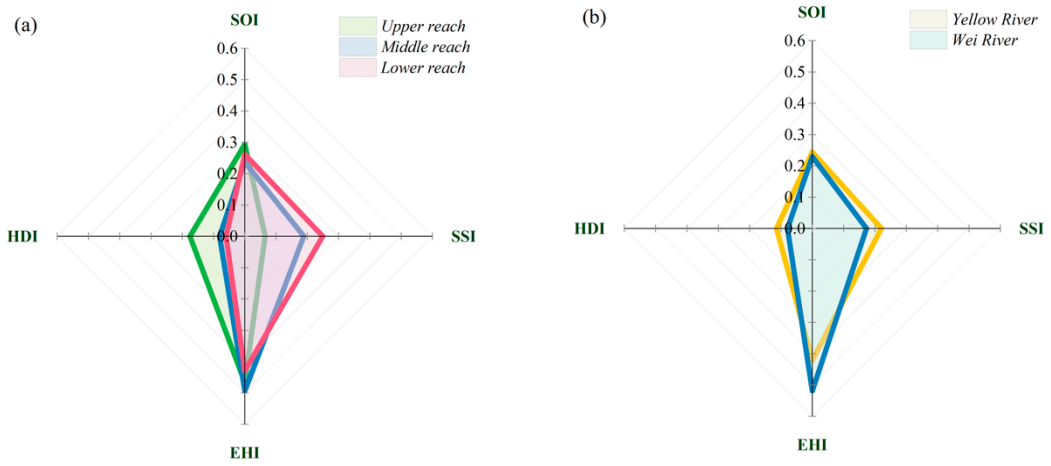


Figure 8. The degrees of limitation to the Happy River Index posed by the four dimensions: (**a**) at a river-reach scale of the Yellow River, and (**b**) at the mainstem scale.

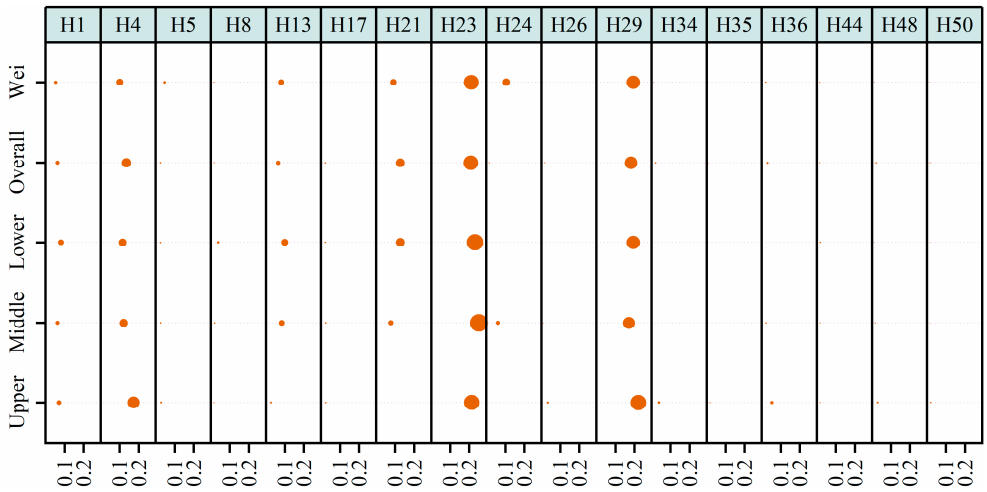


Figure 9. The degrees of limitation to the Happy River Index posed by the assessment indicators of each reach in the Yellow and Wei rivers. Here, the labels "Upper", "Middle", "Lower", and "Overall" refer to the upper, middle, lower, and overall reaches of the Yellow River, respectively, whereas "Wei" refers to the Wei River.

The dimensions posing the main limitation to HRI at the regional scale were SSI and EHI, except for that in Qinghai and Gansu, and were different to those at the reach and mainstem scales (Figure 10). The relatively lower limitations to HRI in Qinghai and Gansu were due to their relatively abundant water resources. Even though water resources in Sichuan in the upper reach were comparable to those of Qinghai and Gansu, the spatial-temporal distribution of water resources in Sichuan is uneven, with most area in Sichuan consisting of plateau and mountains, thereby making it difficult to improve water use efficiency. The rate of water resources utilization in Sichuan was less than 10%, far less than the internationally acknowledged rational utilization of water resources of 30% [59]. The dimension posing the least resistance to HRI among almost all the regions was HDI. Even though socio-economic development in these regions was quite uneven, the indicators in HDI are set to relative values, which reflected the dynamics of the HRI. In other words, the indicators achieving the requirement of the corresponding stage would result in a high HDI. As shown in Figure 11, the indicators limiting HRI in all the provinces and regions along the Yellow River were the security and stability of the riparian zone and riverbed (H1), minimum ecological flow guarantee rate (H29), and the natural wetland retention rate (H32), of which the highest were H29 and H32, implying that ecological health was the

main factor limiting HRI among the nine provinces and regions. There were both similarities and differences in the main factors limiting the HRI among the different provinces and regions. The index of connectivity status (H2) and the ratio of harnessed water and soil erosion area (H6) were the unique factors limiting HRI in Qinghai and Gansu in the upper reach, whereas water resources per-capita (H13) was the main factor limiting HRI in the other regions, except for in Qinghai and Sichuan. The factors limiting the HRI in provinces and regions along the upper reaches of the Yellow River were ecological and social-economic development. The results showed that Sichuan and Gansu face challenges related to barriers to economic and social development, while the other regions face challenges related to ecological river health.

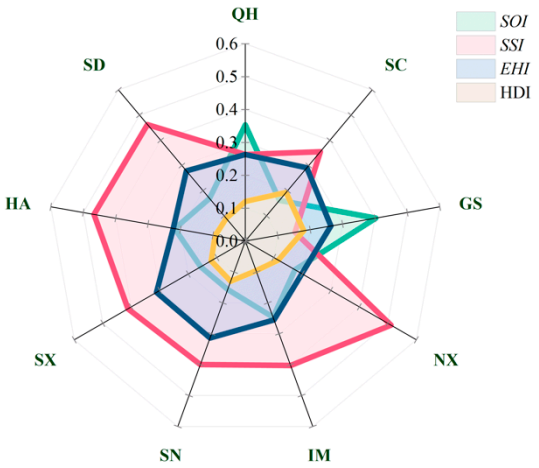


Figure 10. The degrees of limitation of the four dimensions to the Happy River Index (HRI) at the regional scale along the Yellow River. Here, the labels "QH", "SC", "GS", "NX", "IM", "SN", "SX", "HA", and "SD" refer to the provinces and regions of Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong, respectively.

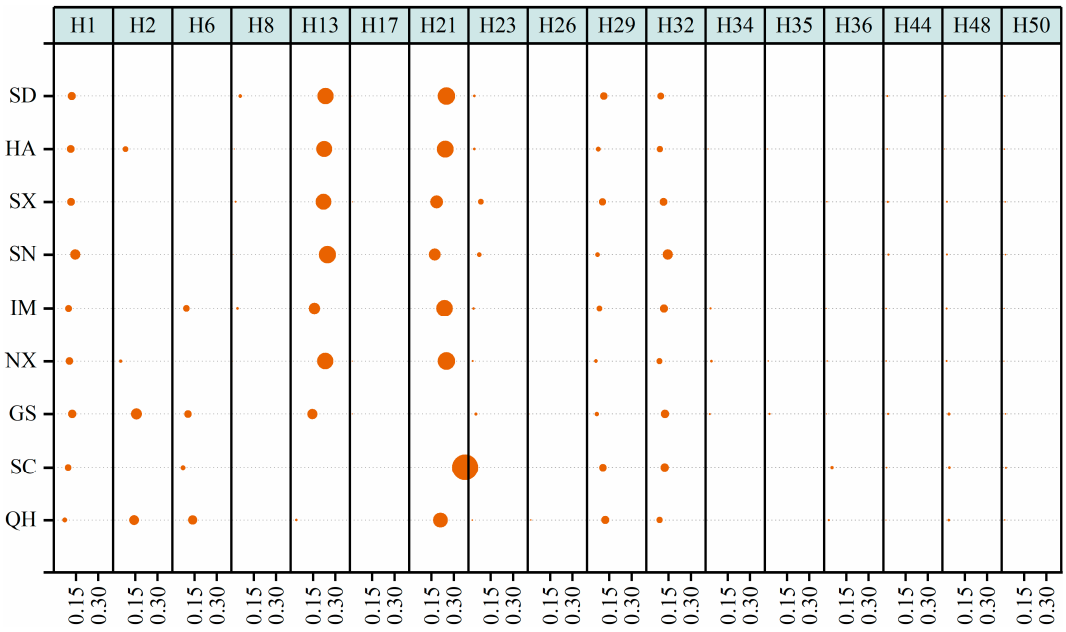


Figure 11. The degree of limitation to the Happy River Index of the assessment index of each provinces and region along the Yellow River. Here, the labels "QH", "SC", "GS", "NX", "IM", "SN", "SX", "HA", and "SD" refer to the provinces and regions of Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong, respectively.

5. Discussion

5.1. Appropriateness of Happy River Assessment Index System for Application to the Yellow River

Achieving a Happy River status among China' rivers is a new major strategic target proposed by the Chinese government to promote ecological protection and high-quality development in the YRB, and similar approaches have been applied within river management in other developing countries. As yet, few studies have conducted a happy river assessment. The present study presents a preliminary attempt to propose a set of universally applicable indicators for assessing the HRI status of a catchment, comprising of four dimensions and 50 indicators. The indicators were further screened based on an application to the Yellow River and data availability. HRI assessments of the Yellow River were conducted at the river-reach scale, overall mainstem scale, and the regional scale. The construction of the assessment index system was mainly based on an in-depth analysis of river health and human well-being, and integrated river ecosystem services, river health, water security, green development, and river-human harmony, as well as the four dimensions of safe operation, sustainable supply, ecological health, and harmonious development. The dynamics of a happy river were also taking into consideration by including both basic indicators and alternative indicators in the assessment index system. The basic indicators were regarded as the primary indicators, whereas the alternative indicators could be selected according to differences in spatial and temporal characteristics.

Within the specific indicators, the proportion of people affected by floods and hydraulic engineering facilities were both take into consideration, besides for indicators related to the river itself. Within the sustainable supply dimension, the indicators related to supplied water quantity and quality were closely related to human well-being, and so were both included. In particular, within the harmonious development dimension, in addition to water conservation indicators that reflect the level of economic development in the existing index system, the intensity of hospitable landscape construction, the degree of water culture excavation and protection, and the degree of public satisfaction with the state of the river were included to reflect the human psychological and cultural dependencies on rivers. In addition, indicators reflecting water-saving technology and management level were included as alternative indicators for assessment at different development stages. Of particular relevance to the Yellow River due to the uneven spatial distribution of water resources and socio-economic development, indicators included the ratio of harnessed water and soil erosion area, water resources per capita, utilization ratio of water resources, and the indicators of water use efficiency, which are more aligned with the natural and social situation in China.

5.2. The Overall HRI of the Yellow River

The assessment of the HRI of the Yellow River at three scales conducted in the current study showed significant differences among reaches and regions, and that the dimensions most responsible for differences were SSI and EHI. On the one hand, besides basic indicators, there were differences in the indicators used for the HRI assessment among the reach and regional scales, leading to different weights of the dimensions. On the other hand, the span of the divided river reaches was larger than that of the regions in the present study, resulting a situation in which the regions that obtained the worst HRI values did no correspond with the reaches that obtained the worst HRI values. Despite these differences, the results among the three spatial scales were compatible and complemented each other to facilitate a better understanding of the HRI status of the Yellow River. Overall, the upper reach of the Yellow River maintained the highest HRI, followed by the middle and lower reaches. Sichuan and Gansu in the upper reaches of the Yellow River similarly had the highest HRI values. Some common characteristics between Sichuan and Gansu in terms of river health and human well-being were evident: (1) they are both situated in the northwest with relatively abundant water and other natural resources, and in which per-capita water resources are above the average level for the YRB; (2) they show relatively low urbanization and industrial development, but show good ecological health. In contrast, the HRI for Ningxia was vastly different. Ningxia is situated in the arid inland of China,

characterized by little precipitation and strong evaporation and in which water resources are scarce [59]. In addition, the region has low overall economic development, with energy, heavy chemicals, and other industries with high water consumption accounting for a large proportion of the industry in Ningxia [2], thereby resulting in the low HRI level. Within the middle reach, Inner Mongolia among the regions had the lowest HRI. The region of Inner Mongolia lies in the arid/semi-arid climatic zone, and the Yellow River flows through the Loess Plateau when flowing through Inner Mongolia. This results in serious soil erosion and sediment transport in a fragile ecological environment [60,61]. The problem of inefficient utilization of water resources has also contributed to the low level of HRI in this region. The regions of Henan and Shandong in the lower reaches of the Yellow River are relatively developed with high population density, particularly in Shandong. As the only coastal area among all the regions along the Yellow River with a large extent of open area, Shandong has obvious geographical advantages for social-economic development. The regions in the lower reaches have relatively higher socio-economic development due to economic growth [62]. However, urbanization has resulted in a high population density and extreme water scarcity in this area, which is not conducive to the sustainable development of society and human well-being. Therefore, the HRI values for these regions with a good economic foundation were not as high. Ultimately, water shortage was the main factor limiting the HRI along the YRB. Future climate change and social development will further aggravate the disparity between water supply and demand in the Yellow River. The deterioration of the ecological environment resulting from natural factors and social development are secondary factors restricting the HRI of the Yellow River.

5.3. Suggestions for the Happy River Construction of the Yellow River

According to the overall assessment results of the HRI for the Yellow River, some suggestions are proposed to guide the happy river construction within the Yellow River as follows:

First, water resources should be utilized in a more economical and intensive way. According to the assessment results, water scarcity is the most prominent problem that restricts the improvement of HRI in Yellow River. Especially in Shandong, where the water resources are seriously short and uneven, the water resource per capita in Shandong is less than 1/6 of China's national average [63]. Besides, the utilization of water resources in agriculture within the upper reach is coarse with low efficiency, which would restrict the sustainable development seriously. So, in the future, regions within the YRB need to improve the efficiency of water utilization. Some measures can be taken, such as strengthening integrated management in the utilization of water resource, rational programming the population, urban and industrial development along the Yellow River to avoid the excessive development and utilization of water resources, adjusting the industrial structure, developing water-saving industries and techniques, energetically promote water-saving agriculture, intensifying the publicity and education on water conservation, and so on, promoting the transformation of regional water utilization from an extensive way to economical and intensive way.

Secondly, the ecological environment protection should be strengthened within the regions along the Yellow River. According to the present study, the overall EHI was the secondary factor that restricts the improvement of HRI in those regions. The ecological environment is fragile due to the unique natural environment. The ecosystem degeneration in the upper reach, soil erosion and serious pollution in the middle reach, and the unguaranteed ecological basic flow in the lower reach synthetically result in the low EHI in those regions. To improve the ecological health within the YRB, vegetation coverage should be expanded to increase the water conservation capacity and soil conservation capacity in the upper and middle reaches. Regions in the middle reach should pay more attention to the pollution prevention and control in both the main-stem and tributary of Yellow River. Accelerate the construction and reconstruction of centralized sewage treatment facilities, and their supporting pipe networks. Besides, the allocation of water resources in the Yellow River should be optimized, priorities should be given to the ecological water use of the rivers and wetlands, especially in the lower reach.

Thirdly, the water and sediment regulation system should be improved to ensure the safety along the Yellow River. According to the assessment, security and stability of riparian zone and riverbed, and the attainment rate of flood control and drainage were both limiting factors in the lower reach. The issues of soil erosion in the upper and middle reaches will lead to the siltation of the river sediment and the continuous elevation of the river bed in the lower reach. Especially in Henan and Shandong, where the riverbeds are higher than the ground elevation outside banks, also called "perched river". This potential issue is inevitable to bring security hidden trouble to the lower reach. From the perspective of systematic governance, it is an important measure to strengthen the control of soil erosion in the upper reaches and improve the water and sediment regulation system to reduce such kind of hazards.

Finally, the strategic positioning of ecological priority and green development must be firmly adhered to promote the high-quality development of the YRB and improve the human well-being. According to the results, the highest HRI value is not in the most developed regions along the Yellow River, which indicated that the aim of the happy river lies not on the river health or economic development alone, but the well-being of both. So, a new path of high-quality development with regional characteristics should be explored according to the local conditions. Regions with low economic development in the upper reach should enhance their economic development by creating more ecological products, while the major grain-producing areas in the middle reach should develop modern agriculture and improve the quality of agricultural products. For the highly developed regions within the lower reach, intensive development is advocated to improve the economic and population carrying capacity. Besides, the Yellow River culture is an important part of Chinese civilization, and the root and soul of the Chinese nation. With the development of society and the improvement of humans living standards, humans' demands for mental and cultural service of the rivers become increasing. It is important to promote the protection of the cultural heritage of the Yellow River and dig out the historical value of the Yellow River culture, make the Yellow River a happy river for the benefit of the river itself, and the well-being of people both on economic lives and cultural.

6. Conclusions

In this study, a framework for happy river assessment was established to comprehensively assess the river health and human well-being, and the happy river status was assessed along the Yellow River. The results were concluded as follows:

(1) The proposed happy river assessment framework is a new perspective for evaluating river health. Compared to the existing framework, the happy river assessment framework is based on the notion that the natural river system is a sub-system of the whole river system. It is essentially an extension of river health and transcends the limitations of the traditional concept of river health, which led by the ecological environment.

(2) The AHP-entropy weight method considering both subjective and objective weights, and the SMI-P method were used for the happy river assessment, which is flexible and reliable for river assessment. Even though not all indicators provided could help for the happy river assessment, this study can undoubtedly provide the decision-makers with useful information on integrated river management.

(3) The assessment results showed that the overall HRI was low and the shortage of water resources was the dominant obstacle factor in the regions along the Yellow River. The HRI in Yellow River at the river-reach scale in descending order was upper, middle, and lower reach. The HRI in Sichuan was the highest at the regional scale, followed by Gansu and Shaanxi, respectively. While the lowest HRI was that in Inner Mongolia, indicating that the aim of the happy river lies not on the river health or economic development alone, but the well-being of both.

Despite that, limitations also exist in the present study which could be further improved. First, the happy river is a strategic target of river management in China in the new era, with abundant connotations. The assessment indicators should be updated with a further understanding of the happy river and the increase of available data to make the results more scientific and systematic. Second, the HRI for different rivers and regions, and for the Yellow River in different years should be studied to further explore the driving mechanism and the limiting factors accurately. Finally, it is not universally applicable for each assessment method and might result in different results when assessing with different methods. So, more assessment methods should be used to analyze the happy river status and reach a decision more comprehensively.

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References

1. Anderson, E.P.; Jackson, S.; Tharme, R.E.; Douglas, M.; Flotemersch, J.E.; Zwarteveen, M.; Lokgariwar, C.; Montoya, M.; Wali, A.; Tipa, G.T.; et al. Understanding rivers and their social relations: A critical step to advance environmental water management. *WIREs Water* **2019**, *6*, e1381. [CrossRef] [PubMed]
2. Bian, J.; Ren, H.; Liu, P. Evaluation of urban ecological well-being performance in China: A case study of 30 provincial capital cities. *J. Clean Prod.* **2020**, *254*, 120109. [CrossRef]
3. Xie, Z.H. China's historical evolution of environmental protection along with the forty years' reform and opening-up. *Environ. Sci. Ecotechnol.* **2020**, *1*, 100001. [CrossRef]
4. Babel, M.S.; Shinde, V.R.; Sharma, D.; Dang, N.M. Measuring water security: A vital step for climate change adaptation. *Environ. Res.* **2020**, *185*, 109400. [CrossRef] [PubMed]
5. Habersack, H.; Hein, T.; Stanica, A.; Liska, I.; Mair, R.; Jäger, E.; Hauer, C.; Bradley, C. Challenges of river basin management: Current status of, and prospects for, the River Danube from a river engineering perspective. *Sci. Total Environ.* **2016**, *543*, 828–845. [CrossRef]
6. Shi, T.; Yang, S.Y.; Zhang, W.; Zhou, Q. Coupling coordination degree measurement and spatiotemporal heterogeneity between economic development and ecological environment—-Empirical evidence from tropical and subtropical regions of China. *J. Clean Prod.* **2020**, *244*, 118739. [CrossRef]
7. Gimelli, F.; Rogers, B.C.; Bos, J.J. Linking water services and human well-being through the fundamental human needs framework: The case of India. *Water Altern.* **2019**, *12*, 715–733.
8. Luo, P.P.; Sun, Y.T.; Wang, S.T.; Wang, S.M.; Lyu, J.Q.; Zhou, M.M.; Nakagami, K.; Takare, K.; Nover, D. Historical assessment and future sustainability challenges of Egyptian water resources management. *J. Clean Prod.* **2020**, *263*, 121154. [CrossRef]
9. Keigo, N.; Klement, T.; Kunihiko, A. River and wetland restoration: Lessons from Japan. *BioScience* **2006**, *56*, 419–429.
10. The European Parliament and the Council of the European Union. Directive 2000/60/EC of the European Parliament and of the Council Establishing a Framework for Community Action in the Field of Water Policy. *OJEC* **2000**, *43*, 1–72.
11. Arthington, A.H.; Bhaduri, A.; Bunn, S.E.; Jackson, S.E.; Tharme, R.E.; Tickner, D.; Young, B.; Acreman, M.; Baker, N.; Capon, S.; et al. The Brisbane declaration and global action agenda on environmental flows. *Front. Environ. Sci.* **2018**, *6*, 45. [CrossRef]
12. Costanza, R. Valuing natural capital and ecosystem services toward the goals of efficiency, fairness, and sustainability. *Ecosyst. Serv.* **2020**, *43*, 101096. [CrossRef]

13. Sadat, M.A.; Guan, Y.Q.; Zhang, D.R.; Shao, G.W.; Cheng, X.M.; Yang, Y.J. The associations between river health and water resources management lead to the assessment of river state. *Ecol. Indic.* **2020**, *109*, 105814. [CrossRef]
14. Wang, S.; Zhang, Q.; Yang, T.; Zhang, L.Q.; Li, X.P.; Chen, J. River health assessment: Proposing a comprehensive model based on physical habitat, chemical condition and biotic structure. *Ecol. Indic.* **2019**, *103*, 446–460. [CrossRef]
15. Dunham, J.B.; Angermeier, P.L.; Crausbay, S.D.; Cravens, A.E.; Gosnell, H.; McEvoy, J.; Moritz, M.A.; Raheem, N.; Sanford, T. Rivers are social-ecological systems: Time to integrate human dimensions into riverscape ecology and management. *WIREs Water* **2018**, *5*, e1291. [CrossRef]
16. Singh, P.K.; Saxena, S. Towards developing a river health index. *Ecol. Indic.* **2018**, *85*, 999–1011. [CrossRef]
17. Raven, P.J.; Dawson, F.H.; Fox, P.J.A.; Rouen, K.J. *River Habitat Quality the Physical Character of Rivers and Stream in the UK and Isle of Man*, 2nd ed.; Environment Agency: Bristol, UK, 1998; pp. 1–32.
18. Ladson, A.R.; White, L.J. *An Index of Stream Condition: Reference Manual*, 2nd ed.; Department of Natural Resources and Environment: Melbourne, Australia, 1999; pp. 1–40.
19. Wright, J.F. Development and use of a system for predicting the macroinvertebrate fauna in flowing waters. *Austral. Ecol.* **1995**, *20*, 181–197. [CrossRef]
20. An, K.G.; Park, S.S.; Shin, J.Y. An evaluation of a river health using the index of biological integrity along with relations to chemical and habitat conditions. *Ecol. Indic.* **2002**, *28*, 411–420. [CrossRef]
21. Marzin, A.; Delaigue, O.; Logez, M.; Belliard, J.; Pont, D. Uncertainty associated with river health assessment in a varying environment: The case of a predictive fish-based index in France. *Ecol. Indic.* **2014**, *43*, 195–204. [CrossRef]
22. Luo, Z.L.; Zuo, Q.T.; Shao, Q.X. A new framework for assessing river ecosystem health with consideration of human service demand. *Sci. Total Environ.* **2018**, *640*, 442–453. [CrossRef]
23. Cox, B.; Sue, O.; Taffs, K. A comparison of macroinvertebrate-based indices for biological assessment of river health: A case example from the sub-tropical Richmond River Catchment in northeast New South Wales, Australia. *Ecol. Indic.* **2019**, *106*, 105479. [CrossRef]
24. Ma, D.Y.; Luo, W.G.; Yang, G.L. A study on a river health assessment method based on ecological flow. *Ecol. Model.* **2019**, *401*, 144–154. [CrossRef]
25. Wen, Z.Q.; Li, X.; Li, T.H. Comprehensive study on freshwater ecosystem health of Lancang River Basin in Xishuangbanna of China. *Water* **2020**, *12*, 1716. [CrossRef]
26. Falkenmark, M.; Rockstroem, J. The new blue and green water paradigm: Breaking new ground for water resources planning and management. *J. Water Res. Plan. Man.* **2006**, *132*, 129–132. [CrossRef]
27. Hoff, H. Global water resources and their management. *Curr. Opin. Environ. Sus.* **2009**, *1*, 141–147. [CrossRef]
28. Wang, S.C. *Resource-Oriented Water Management: Towards Harmonious Coexistence Between Man and Nature*, 1st ed.; China Water&Power Press: Beijing, China, 2003; pp. 121–141.
29. Zuo, Q.T.; Zhang, Y.; Lin, P. Index system and quantification method for human-water harmony. *J. Hydraul. Eng.* **2008**, *39*, 440–447.
30. Ding, Y.F.; Tang, D.S.; Dai, H.C.; Wei, Y.H. Human-water harmony index: A new approach to assess the human water relationship. *Water Resour. Manag.* **2014**, *28*, 1061–1077. [CrossRef]
31. Zhang, J.X.; Tang, D.S.; Ahmad, I.; Wamg, M. River–human harmony model to evaluate the relationship between humans and water in river basin. *Curr. Sci.* **2015**, *109*, 1130–1139. [CrossRef]
32. Xi, J.P. Speech at the symposium on ecological protection and high-quality development of the Yellow River Basin. *China Water Resour.* **2019**, *20*, 1–3.
33. Zuo, Q.T.; Hao, M.H.; Ma, J.X.; Tao, J. Happy river: The concept, connotation and judgement criteria. *Yellow River* **2020**, *42*, 1–5.
34. Chen, M.S.; Wang, J.P.; Qiao, G.P. Understanding and Reflection on "Happy River" connotation and Evaluation System. *Water Resour. Dev. Res.* **2020**, *20*, 3–5.
35. Gu, S.Z. Thoughts on the build of happy rivers and lakes. *China Water* **2020**, *6*, 13–14.
36. Li, Y.; Dai, J.Y.; Fan, Z.W. The connotation of river and lake health and the management of key issues. *China Water* **2020**, *6*, 17–20.
37. Tang, K.W. Reflections on "Happy River" concept and evaluation methods. *China Water* **2020**, *6*, 15–16.

38. Han, Y.P.; Xia, F. Evaluation of happy river based on hierarchy of needs theory. *South-to-North Water Transf. Water Sci. Technol.* **2020**, *18*, 1–7+38.
39. Ministry of Water Resources of the People's Republic of China. *National River Health Assessment Indicators, Standards and Methods*; (Office Resources [2010] No. 484); General Office of the Ministry of Water Resources: Beijing, China, 2010; pp. 22–71.
40. Hu, C.H.; Chen, J.G.; Sun, X.L.; Guo, Q.C. Health assessment of river course in Lower Yellow River and measures for regulation. *J. Hydraul. Eng.* **2008**, *39*, 1189–1196.
41. Geng, L.H.; Liu, H.; Zhong, H.P.; Liu, C.S. Indicators and criteria for evaluation of healthy rivers. *J. Hydraul. Eng.* **2006**, *37*, 253–258.
42. Ministry of Water Resources of the People's Republic of China. *Evalution Guide of Water Ecological Civilization Construction: SL/Z738-2016*; China Water Conservancy and Hydropower Press: Beijing, China, 2016; pp. 3–15.
43. Yang, Z.; Yang, K.; Su, L.W.; Hu, H. Two-dimensional grey cloud clustering-fuzzy entropy comprehensive assessment model for river health evaluation. *Hum. Ecol. Risk Assess* **2020**, *26*, 726–756. [CrossRef]
44. Jin, J.L.; Wu, K.Y.; Wei, Y.M. Connection number based assessment model for watershed water security. *J. Hydraul. Eng.* **2008**, *39*, 401–409.
45. Zhang, J.; Zhang, C.L.; Shi, W.L.; Fu, Y.C. Quantitative evaluation and optimized utilization of water resources-water environment carrying capacity based on nature-based solutions. *J. Hydrol.* **2019**, *568*, 96–107. [CrossRef]
46. Zhao, Y.W.; Zhou, L.Q.; Dong, B.Q.; Dai, C. Health assessment for urban rivers based on the pressure, state and response framework-A case study of the Shiwuli River. *Ecol. Indic.* **2019**, *99*, 324–331. [CrossRef]
47. Wang, X.S.; Li, X.N.; Wang, J.W. Urban water conservation evaluation based on multi-grade uncertain comprehensive evaluation method. *Water Resour. Manag.* **2018**, *32*, 417–431. [CrossRef]
48. Ministry of Water Resources of the People's Republic of China. *National Lake Health Assessment Indicators, Standards and Methods, (Office Resources [2011] No. 223) [Z]*; General Office of the Ministry of Water Resources: Beijing, China, 2011; pp. 24–67.
49. Yu, Y.; Wang, C.; Wang, P.F.; Hou, J.; Qian, J. Assessment of multi-objective reservoir operation in the middle and lower Yangtze River based on a flow regime influenced by the Three Gorges Project. *Ecol. Inform.* **2017**, *38*, 115–125. [CrossRef]
50. Tang, K.W. Discussion on concept and assessment system of aquatic ecological civilization. *Water Resour. Prot.* **2013**, *29*, 1–4.
51. Zuo, Q.T.; Luo, Z.L.; Ding, X.Y. Harmonious development between socio-economy and river-lake water systems in Xiangyang City, China. *Water* **2016**, *8*, 509. [CrossRef]
52. Wang, D.Y.; Huang, K.; Mo, C.X.; Wu, W.X.; Feng, S.W. Quantitative evaluation of human-water harmony in Guangxi based on comprehensive weight SMI-P method. *Water Sav. Irrig.* **2018**, *7*, 107–112.
53. Luo, Z.L.; Zuo, Q.T. Evaluating the coordinated development of social economy, water, and ecology in a heavily disturbed basin based on the distributed hydrology model and the harmony theory. *J. Hydrol.* **2019**, *574*, 226–241. [CrossRef]
54. Yang, T.; Zhang, Q.; Wan, X.H.; Li, X.P.; Wang, Y.Y.; Wang, W. Comprehensive ecological risk assessment for semi-arid basin based on conceptual model of risk response and improved TOPSIS model-a case study of Wei River Basin, China. *Sci. Total Environ.* **2020**, *719*, 137502. [CrossRef]
55. Zhou, B.; Zhong, L.S.; Chen, T.; Zhang, A.P. Spatio-temporal pattern and obstacle factors of ecological security of tourism destination: A case of Zhejiang province. *Sci. Geogr. Sin.* **2015**, *35*, 599–607.
56. Ou, Z.R.; Zhu, Q.K.; Sun, Y.Y. Regional ecological security and diagnosis of obstacle factors in underdeveloped regions: A case study in Yunnan Province, China. *J. Mt. Sci.* **2017**, *14*, 870–884. [CrossRef]
57. Huang, S.Z.; Huang, Q.; Chang, J.X.; Zhu, Y.L.; Leng, X. Drought structure based on a nonparametric multivariate standardized drought index across the Yellow River basin, China. *J. Hydrol.* **2015**, *530*, 127–136. [CrossRef]
58. Chen, Y.P.; Fu, B.J.; Zhao, Y.; Wang, K.B.; Zhao, M.M.; Ma, J.F.; Wu, J.H.; Xu, C.; Liu, W.G.; Wang, H. Sustainable development in the Yellow River Basin: Issues and strategies. *J. Clean Prod.* **2020**, *263*, 121223. [CrossRef]
59. Tong, S.Y.; Zhou, Z.Y.; Peng, H.Y. Spatial pattern of scarcity of water and it's shortage types in China. *Ecol. Econ.* **2016**, *32*, 168–173.

60. Li, D.J.; Xu, D.Y.; Wang, Z.Y.; You, X.G.; Zhang, X.Y.; Song, A.L. The dynamics of sand-stabilization services in Inner Mongolia, China from 1981 to 2010 and its relationship with climate change and human activities. *Ecol. Indic.* **2018**, *88*, 351–360. [CrossRef]
61. Gang, C.C.; Zhao, W.; Zhao, T.; Zhang, Y.; Gao, X.R.; Wen, Z.M. The impacts of land conversion and management measures on the grassland net primary productivity over the Loess Plateau, Northern China. *Sci. Total Environ.* **2018**, *645*, 827–836. [CrossRef]
62. Long, X.L.; Ji, X. Economic growth quality, environmental sustainability, and social welfare in China—Provincial assessment based on genuine progress indicator (GPI). *Ecol. Econ.* **2019**, *159*, 157–176. [CrossRef]
63. Liu, Y.; Zhang, Z.X.; Zhang, F.X. Challenges for water security and sustainable socio-economic development: A case study of industrial, domestic water use and pollution management in Shandong, China. *Water* **2019**, *11*, 1630. [CrossRef]

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