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Article

Evaluation of Regional Water Ecological Economic System Sustainability Based on Emergy Water Ecological Footprint Theory—Taking the Yellow River Basin as an Example

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Abstract: In the article, on the basis of quantifying the emergy water ecological footprint, a sustainability evaluation system for the overall water ecological economic system of the basin and each province (region) was proposed. And using the subjective and objective combination of the Analytic Hierarchy Process (AHP) and Entropy Weight Method (EWM) to determine the weight of the indicator system, a TOPSIS model for sustainability evaluation was constructed. And taking the Yellow River Basin as an example, the results indicate that (1) Throughout the entire basin, the sustainability of the water ecological economic system showed a fluctuating upward trend year by year during the study period, from 0.37 to 0.51. (2) In each province (region), the sustainability of the water ecological economic system had gathered in space. The overall sustainability level of the upstream Sichuan, Qinghai and Gansu provinces is high, always at level (I). The overall sustainability level of the midstream Ningxia and Neimenggu was low, always at level (IV). The overall sustainability level of the downstream Shaanxi, Shanxi, Henan and Shandong provinces is high, rising gradually over time, from level (III) to level (II) or (I). Against the backdrop of the rapid development of the economy and society, the contradiction between economic and social development, ecological environment protection, and sustainable utilization of water resources is becoming increasingly severe, which has become a key factor restricting the sustainable development of the ecological economic system in Yellow River Basin. Multidimensional comprehensive evaluation of the sustainability level of the regional water ecological economic system is a prerequisite for identifying sustainable development issues in the Yellow River Basin, and also the basis for formulating targeted policies for sustainable utilization of regional water resources and high-quality economic development.

Keywords: sustainability; emergy water ecological footprint; water ecological economic system; Yellow River Basin

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1. Introduction

The ecological restoration and economic development of the Yellow River Basin are related to the construction of China's socialist cause. The biggest problem in the Yellow River Basin is to achieve high-quality development under the rigid constraints of water resources and ecology. The basic way to solve the development problem of the Yellow River Basin is to take the road of sustainable development, and its core is to realize the sustainable development of water ecological economic system.

The sustainability evaluation of regional water ecological economic system is the primary issue of sustainable development, an important indicator to measure the sustainability of water resources, the basic basis for efficient allocation of water resources, and the premise for formulating regional socio-economic sustainable development planning [1].

There is still relatively little research on the sustainability of water ecological economic systems abroad, mainly from the perspective of water resource utilization and management.

After 2000, although there were a large number of articles on sustainable water resource management, there were still relatively few evaluations of sustainability. Sustainability evaluation is an important link in sustainable development and an important basis for formulating environmental and ecological protection and high-quality development strategies in river basins. Weigert et al. [2] proposed a method for evaluating the advantages and disadvantages of water resources management schemes under the Sustainable Development Goals. Jin et al. [3] established a nonlinear relationship between evaluation indicators and the level of sustainable water resource utilization through an improved ideal interval method (IIM) based on an accelerated genetic algorithm. Choi et al. [4] explored the connotation of sustainable development and management of water resources and provided corresponding generalized evaluation indicators. Simon et al. [5] used the ecological impact assessment of the German urban water management strategy in the 14 parts of the surface water system as an example to illustrate that sustainability assessment needs to consider spatial differences. Morrison et al. [6] used 20 Sustainable Development (SDI) indicators to evaluate the sustainability of water supply systems in medium-sized cities in South Africa. Russo et al. [7] assessed the level of sustainable water management in urban, agricultural and Systema Naturae sectors.

There is relatively rich research on the sustainability of water ecological economic systems in China. There are two types of evaluation models of sustainability: conventional models and unconventional models. The conventional model is mainly based on water volume. The unconventional model is mainly based on the water's ecological footprint.

Conventional models: In 2012, Cui et al. [8] established the evaluation index system and evaluation criteria for the sustainable development of water resources in water rich areas by using the analytic hierarchy process (AHP). On this basis, the GRNN neural network was used to build an evaluation model. Taking Wenshan Prefecture as an example, the results show that the method has a good rate of convergence and is not easy to fall into the local minimum. In 2014, Kang et al. [9] introduced the Random Forest model for an example study to solve the problems of multiple indicators, nonlinearity and complex noise in the evaluation of sustainable development of water resources. The results show that the model is more robust than SP interpolation, artificial neural network (ANN) and support vector machine (SVM) methods. In 2015, Li [10] constructed the AHP fuzzy comprehensive evaluation model for Quanzhou City. In 2018, Men et al. [11] used the combination method of rough set and fuzzy theory to determine the index weight, and, respectively, applied the Fuzzy set analysis method based on attribute recognition and the same difference opposite hierarchy to evaluate the sustainable development of water resources in the "resourceful" water shortage area (Beijing Tianjin wing area), and the results proved that the model was feasible. In 2020, Liu et al. [12] utilized cloud models to simultaneously consider the characteristics of fuzziness and randomness, and introduced them into the evaluation of sustainable development of water resources, establishing an entropy weight normal cloud evaluation model. In 2020, Ayadi et al. [13] established the AHP entropy weight method fuzzy comprehensive evaluation method, taking the urban area of Xi'an as an example, and the results showed that the model was reliable.

Unconventional models: Fan [14], Leng [15], Zhu [16], Wang [17], Wu [18], Zhang [19], Xiong [20], Tao [21], etc., based on the analysis of water ecological footprint, have given the qualitative analysis of sustainability and have not yet formed a comprehensive evaluation model.

Literature analysis shows that the current models for the sustainability evaluation of the water ecological economic system are all conventional water resources consumption (i.e., surface and underground water consumption), and there is no study on the comprehensive evaluation of emergy water ecological footprint based on emergy water ecological footprint theory.

Therefore, in this article, from the perspective of the water ecological economic system (w-eco-economic system), this paper divides the emergy water ecological footprint into accounts. Based on the newly divided emergy water ecological footprint, this paper constructs the sustainability evaluation model of the w-eco-economic system in the Yellow River Basin and discusses the overall sustainability of the Yellow River Basin and the sustainability of provinces (regions). Specifically, the innovations of this study are the following: (1) In traditional sustainability evaluation, the consideration of water resource usage in the system is relatively rough, which makes it difficult to reflect the exact water usage of the system, resulting in incorrect evaluation of sustainability. Based on this, the article uses the emergy water ecological footprint to replace traditional water resource usage. (2) Based on the emergy water ecological footprint, taking into account the differences in material energy flow and function in economic, social, and water ecology and combining the PSR (pressure-state-response) model, the sustainability evaluation index system of the economic-social-water ecological subsystem was established, and a comprehensive evaluation model for the sustainability of the water ecological economic system was established on this basis. (3) To overcome the subjective impact of weight determination and fully consider the impact of data itself on sustainability, a subjective and objective indicator weighting method was established.

By exploring sustainability of the water ecological economic system, the research conclusions of this study are of more practical significance, providing an empirical reference for the high-quality development of the Yellow River Basin and providing experience references for other regions to explore the coupling-coordinated development of the w-eco-economic system.

2. Materials and Methods

2.1. Study Area

The Yellow River is the second largest river in China and the fifth longest river in the world. From the source of Qinghai to the estuary of Shandong, the Yellow River (Figure 1) flows through 9 provinces and regions: QingHai, SiCuan, GanSu, NingXia, NeiMengGu, ShaanXi, and ShanXi, HeNan, ShanDong, with a drainage area of over 750,000 square kilometers, most of which are located in the central and western regions of China. The upstream environment is good and water resources are abundant, but the population is small and the economic and social development is backward. The middle reaches are rich in energy resources, but ecologically fragile. The downstream land is fertile, agriculture is developed, and the level of development is relatively high, but economic development is greatly constrained by the scarcity of water resources [22].

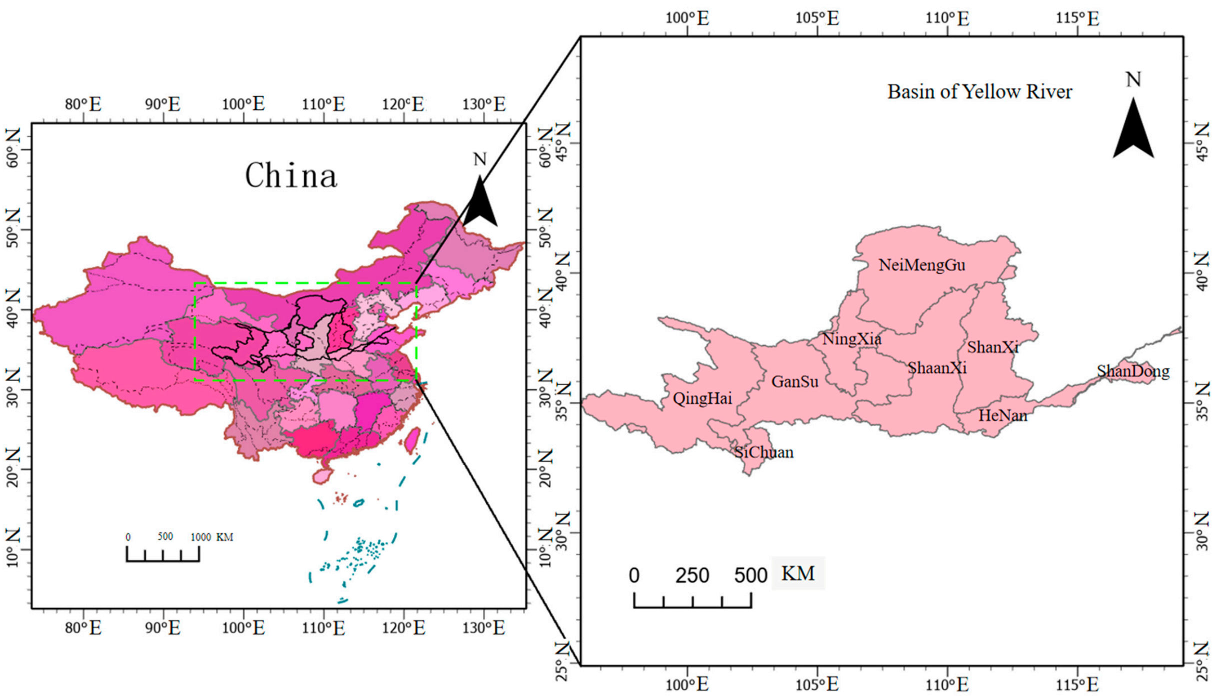

Figure 1. Map of the Yellow River Basin Area.

At present, there are some problems in the Yellow River Basin [23], such as the contradiction between water supply and demand. The Yellow River belongs to a resource-based water shortage river, so the basic characteristic of the Yellow River Basin is that there are more people and less water, with a per capita water resource of 383 cubic meters, only 18% of the national average level. The current water supply has far exceeded the carrying capacity of the Yellow River's water resources. Overall, there are three main issues [24–26]: (1) From the perspective of water resource development and utilization rate, the international standard is no more than 40%, but the Yellow River Basin has already approached 80%. In the case of contradiction between supply and demand of water, industrial and farm water have seriously occupied ecological water, resulting in insufficient self-purification capacity of the water environment; (2) The spatial distribution of water and sediment is uneven. A total of 50% of the runoff in the Yellow River Basin comes from the upstream, and 90% of the sediment comes from the middle reaches. This uneven and mismatched spatial distribution of water and sediment leads to the Yellow River being prone to sedimentation, serious soil erosion, and flood disasters; (3) There is a high risk of environmental pollution. The economic development model of the Yellow River Basin is broad, and the increase in industrial, agricultural, and domestic water consumption has led to an increase in wastewater discharge. In addition, natural climate reasons in the Yellow River Basin have led to less rainfall and smaller water volume, resulting in low pollutant degradation capacity of the water body and a decrease in water quality. The water resources of the Yellow River only account for 2% of the country, but the wastewater discharge accounts for about 6% of the country, and the chemical oxygen demand (COD) discharge accounts for 7% of the country.

The main data sources include the *Yellow River Water Resources Bulletin 2011–2021* [27], the *Water Resources Bulletin 2011–2021* of various provinces (regions) in SiChuan, QingHai, GanSu, NingXia, NeiMengGu, ShaanXi, ShanXi, HeNan, and ShanDong [28–35], the *China Urban Rural Construction Statistical Yearbook 2011–2021* [36], and the *China Statistical Yearbook 2011–2021* [37].

2.2. Emergy Water Ecological Footprint Model

The emergy water ecological footprint refers to the amount of water resources consumed by regional development and the amount of water resources needed to absorb domestic and production wastes when the economic scale and population develop to a certain degree in a specific geographical region and is the productive land area calculated based on this [38,39].

From the perspective of realizing the function of the w-eco-economic system, the emergy water ecological footprint primary account is divided into three secondary accounts: the emergy water ecological footprint (em-wef) of the economic subsystem, the em-wef of the social subsystem, and the em-wef of the water ecological subsystem (w-ecological subsystem). The specific division of secondary accounts is shown in Table 1 below.

According to the composition of the emergy water ecological footprint, the emergy analysis method is used to convert the consumption of water resource material flow and energy flow in the water ecological economic system into virtual land area. The basic conversion formula is:

$$\mathrm{WEF} = \frac{\gamma \mathrm{B}}{\mathrm{P}} \tag{1}$$

where, WEF refers to the emergy water ecological footprint, hm^2. P represents the regional emergy density, sej/km^2; γ represents the emergy conversion rate, sej/J or sej/g, and B is energy or substance, J or g. The specific expression can be found in Table 1.

The abbreviations and formulas of Accounts of WEF of the w-eco-economic system are as follows.

Table 1. Emergy water ecological footprint constitutions.

Primary Account	Secondary Account	Abbreviation	Tertiary Account	Abbreviation	Formula
Water ecological economic system (EFW)	Economic subsystem	WEF_{econ}	Primary industry	WEF_{pri}	$WEF_a + WEF_f + WEF_h + WEF_{fi}$
			Secondary industry	WEF_{sec}	$W_i \times \tau_{en}/P_W$
			Tertiary industry	WEF_{tri}	$W_{tri} \times \tau_{en}/P_W$
	Social subsystem	WEF_{soci}	Urban life	WEF_{UL}	$W_{UL} * \tau_{en}/P_W$
			Rural life	WEF_{RL}	$W_{RL} * \tau_N/P_W$
	Water ecological subsystem	WEF_{ecol}	Biodiversity conservation	WEF_{bd}	$N \times R \times \tau_B/P_W$
			Environmental purification	WEF_P	$(M_1\tau_1 - M_2\tau_2)/P_W$
			Climate regulation	WEF_W	$(2507.4 - 2.39t) \times G \times \tau_q/P_W$
			Convey	WEF_t	$PE_{recol} \times \frac{\tau_r}{P_W}$

Note: WEF_a represents the emergy ecological footprint of agricultural water use (km^2), WEF_f represents the emegy ecological footprint of forestry water use (km^2), WEF_h represents the emergy ecological footprint of animal husbandry water use (km^2), and WEF_{fi} represents the emergy ecological footprint of fishery water use (km^2). W_i is the water used in the manufacturing industry (m^3), W_{tri} is water for the service industry (m^3), τ_{en} is the energy density of the engineering water body (sej/m^3). W_{UL} is urban domestic water (m^3), W_{RL} is rural domestic water use (m^3). Number of aquatic species N in the region, ratio of biological activity area R (%), τ_B is the species energy conversion rate (sej/unit). The amount of pollutants emitted by the region is M_1 (g), energy conversion rate τ_1 (sej/g), the amount of pollutants after a certain period of time M_2 (g), energy conversion rate τ_2 (sej/g). t is the annual average temperature of the region (°C), G is the evaporation capacity (g), τ_q is the conversion rate of steam energy value (sej/g). PE_{recol} (J) represents the ecological part of river potential energy. τ_r is the conversion rate of river runoff energy value (sej/J).

2.3. Sustainability Evaluation Model of Water Ecological Economic System

2.3.1. The Construction Method of the Index System—The Combination of the PSR Model and Ecological Economics Theory

From the perspective of reflecting the structure function of the water ecological economic system, the index system is divided into three parts, and the indicators are selected, respectively, from the aspects of economy, society and water ecology combined with the PSR model [40]. The model includes pressure, state, and response. The evaluation index system of water resources sustainable utilization of the PSR model is divided into three systems: pressure factor, state factor and response factor. It contains the causality of "what happened? Why happened? how to deal with". It is comprehensive, intuitive, and operable, and helps to improve the application effect of the index system.

Overall, there are two steps to establishing an indicator system: (1) By reviewing the indicators selected in previous sustainability evaluations and using the PSR model as a framework, combined with the functions of each subsystem, the article selects representative, accessible, and highly repetitive indicators [41–49]. (2) using the emergy water ecological footprint replaces the regular water resources consumption indicators that can be replaced.

2.3.2. Evaluation Method

Comprehensive Evaluation Method—The AHP-EWM-TOPSIS Model

Multi-index comprehensive evaluation refers to the evaluation method of "synthesizing" multiple evaluation indexes into a whole through a certain mathematical model (or algorithm). There are many methods of multi-index comprehensive evaluation. In practical application, a more appropriate method should be selected according to the evaluation purpose (or criteria) and the characteristics of the evaluated system. In this study, the TOPSIS method is selected, which is based on subjective and objective weighting and comprehensively considers the relative distance from the worst solution in each dimension (i.e., index). The observation value far from the worst solution has high sustainability. The method is simple in principle, easy to operate, and has no strict requirements on the number of indicators and has a wide range of applications. The evaluation model is the following:

$$x_{ijr} = w_r \times z_{ijr} \tag{2}$$

$$x_{rmin} = min(x_{ijr}) \quad (3)$$

$$x_{rmax} = max(x_{ijr}) \quad (4)$$

where, z_{ijr} is the normalized observed value of r index in j years in i region, x_{ijr} is a pair of Weighted value of z_{ijr}, and the sum of weight w_r is 1. x_{rmin} is the minimum of the observed values of r index, and x_{rmax} is the maximum of the observed values of r index.

Calculate the Euclidean distance between the year j of region i and the positive ideal solution $\{x_{rmin}\}$ and the negative ideal solution $\{x_{rmax}\}$:

$$d_{ij}^{+} = \sqrt{\sum_{r=1}^{k}(x_{ijr} - x_{rmax})^2} \quad (5)$$

$$d_{ij}^{-} = \sqrt{\sum_{r=1}^{k}(x_{ijr} - x_{rmin})^2} \quad (6)$$

Calculate the comprehensive evaluation index (paste progress):

$$s = \frac{d_{ij}^{-}}{d_{ij}^{+} + d_{ij}^{-}} \quad (7)$$

The larger the calculation result, the stronger the sustainability.

Method for Determining Index Weights—The AHP-EWM Method

At present, there are two weighting methods used in the research: the subjective weighting method and the objective weighting method. The two methods have their own advantages and disadvantages. The subjective weighting method, based on expert experience, takes into account the preferences of researchers, which fails to take into account the information contained in the index data. The objective weighting method, starting from the index data itself, greatly reflects the information carried by the index data, which is more objective and stable. Because the sustainability evaluation index system of the water ecological economic system is a complex evaluation system involving the economic subsystem, social subsystem and water ecological subsystem, the research period is long and there are a lot of data. In order to fully reflect the information carried by the data and the judgment of experts on the importance of the index, the subjective and objective method of combining analytic hierarchy process (AHP) and entropy weight method (EWM) is selected for weighting.

Combined weight calculation combines the results of the analytic hierarchy process and entropy weight method to obtain the weights of the two weighting methods comprehensively considered ω_r:

$$\omega_r = a\omega_{1r} + (1 - a)\omega_{2r} \quad (8)$$

where, ω_{1r} is the weight calculated by AHP, and ω_{2r} is the weight calculated by entropy weight method. The combination weight changes with the change of A. When a = 1, it represents the subjective weight (AHP); when a = 0, it represents the objective weight (EWM).

(1) Analytic hierarchy process (AHP)

① The first step is to establish a judgment matrix, which uses the Analytic Hierarchy Process (AHP) to calculate subjective weights. It is necessary to manually determine the relative importance of indicators. The criteria for establishing a judgment matrix are as follows:

Using expert scoring to construct a judgment matrix for each subsystem $X = (x_{ij})_{n \times n}$, x_{ij} represents the importance of the i-th indicator relative to the j-th indicator. The results are shown in Table 2.

Table 2. Method of Scaling between Elements of Judgment Matrix.

Scale	Meaning
1	two factors are equally important
3	factor i is slightly more important than factor j
5	factor i is significantly more important than factor j
7	factor i is more important than factor j
9	factor i is extremely important compared to factor factor i is extremely important compared to factor j
2, 4, 6, 8	the median of the two adjacent judgments mentioned above
reciprocal	factor j is more important than factor i

② The second step is consistency testing, which logically tests the relative importance between indicators.

Finding consistency *RI* by following Table 3, calculating the consistency index *CI* and the consistency ratio of each subsystem, *CR*:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{9}$$

$$CR = \frac{CI}{RI} \tag{10}$$

when $CR < 0.10$, it is considered that the judgment matrix logically passes; the consistency of the judgment matrices for each subsystem is passed. In the equation, λ_{max} is the maximum eigenvalue of the subsystem judgment matrix X.

Table 3. Average random consistency indicators.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14
RI	0	0	0.52	0.89	1.12	1.24	1.36	1.41	1.46	1.49	1.52	1.54	1.56	1.58

③ The third step is to calculate the subjective weights of each subsystem in the Yellow River Basin and province (region).

Geometric average method:

$$w_i = \frac{\left(\prod_{j=1}^{n} x_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} x_{ij}\right)^{\frac{1}{n}}} \tag{11}$$

Arithmetic averaging method:

$$w_i = \frac{1}{n}\sum_{j=1}^{n}\frac{x_{ij}}{\sum_{k=1}^{n} x_{kj}} \tag{12}$$

Eigenvector method:

$$XW = \lambda_{max} W \tag{13}$$

Least squares method:

$$minZ = \sum_{i=1}^{n}\sum_{j=1}^{n}\left(x_{ij}w_j - w_i\right)^2 \tag{14}$$

$$s.t.\sum_{i=1}^{n} w_i = 1 \tag{15}$$

$$w_i > 0,\ i = 1,\ 2,\ \ldots,\ n \tag{16}$$

In Equation (11)–(16), $i = 1, 2, \ldots, n$ represents the subsystem index, and w_i is the weight of the i indicator. Equation (13) involves normalizing the W vector, whose components are the subsystem indicator weights. In Equation (14)–(16), the vector W that satisfies the minimum Z value is the subsystem weight vector.

Linearly weight the results of the above four methods in equal proportions to obtain the comprehensive AHP weights of the subsystems.

(2) Entropy weight method (EWM)

① The first step in calculating the weight of evaluation indicators for each subsystem in a basin, province, or region is to calculate the entropy values of each subsystem in the basin and provinces (regions).

$$p^s_{ijr} = \frac{z_{ijr}}{\sum_{i=1}^{m}\sum_{j=1}^{n} z_{ijr}} \tag{17}$$

$$h^s_r = -\sum_{i=1}^{m}\sum_{j=1}^{n} p^s_{ijr} \cdot lg\left(p^s_{ijr}\right) \tag{18}$$

② The second step is to calculate weights based on the order of indicators.

$$w_r = \frac{1 - h^s_r}{\sum_{r=1}^{N_s}(1 - h^s_r)} \tag{19}$$

The objective weight calculation of each subsystem in the watershed: when m is taken as 1, it is the watershed weight formula.

In the equation, for $p^s_{ijr} = 0$, Assign 0 to $p^s_{ijr} \cdot lg\left(p^s_{ijr}\right)$. $s = \{1,2,3\}$ represents each subsystem, where $s = 1$ represents the economic subsystem, $s = 2$ represents the social subsystem, and $s = 3$ represents the water ecological subsystem; N_s represents the indicator in the s system. The objective weights are obtained by incorporating the indicator values of each subsystem into the above formula.

3. Results

3.1. Establishment of Indicator System

In current research, the indicators related to water resource consumption used in the sustainability evaluation system of the water ecological economic system are all conventional water resource consumption (i.e., surface water and groundwater consumption). However, conventional water resources consumption is not enough to reflect the actual water use in the region. In order to more accurately reflect the current situation of local water resources utilization and more comprehensively evaluate the sustainability of water resources, the concept of emergy water ecological footprint is introduced in this study. The evaluation index system for measuring the entire Yellow River Basin and each province (region) has been extracted, as shown in Tables 4–6.

Table 4. Index system for sustainability of the economic subsystem.

Indicator Layer	Unit	Data Source and Calculation	Nature
C.1. economic benifits of unit secondary industry wef	10^4 CNY/km^2	$\frac{\text{Gdp.sec}}{\text{WEF}_{\text{sec}}}$	+
C.1. economic benifits of unit tertiary industry wef	10^4 CNY/km^2	$\frac{\text{Gdp.ter}}{\text{WEF}_{\text{ter}}}$	+

Table 4. *Cont.*

Indicator Layer	Unit	Data Source and Calculation	Nature
C.3. Propotion of secondary industry	%	$\frac{WEF_{sec}}{WEF_{econ}}$	+
C.4. Modulo of economic subsystem wef	Dimensionless	$\frac{WEF_{econ}}{Area}$	−
C.5. Industrial water recycling rate	%	Statistical Data	+
C.6. Module of Water conservancy fixed assets investment	Dimensionless	$\frac{Inv.wcon}{Area}$	+

Note: Unit (Dimensionless) represents unitless. The formulas not listed in the table can be found in the statistical data or are commonly used indicators; Gdp.sec represents the gross domestic product of the Secondary sector of the economy (10^4 CNY), Gdp.ter represents the gross domestic product of the Tertiary sector of the economy (10^4 CNY), Area represents the area (km^2), and Inv.wcon represents the fixed investment in water conservancy (10^4 CNY). The symbols not indicated in the formula are shown in Table 1.

Table 5. Index system for sustainability of social subsystem.

Indicator Layer	Unit	Data Source and Calculation	Nature
C.7. Per Capita Disposable Income	CNY/(people·year)	Statistical Data	+
C.8. Proportion of rural population	%	Statistical Data	+
C.9. Rural Engel's coefficient	%	Statistical Data	+
C.10. Growth rate of urban residents' life wef	%	$\frac{WEF_{UL}-WEF_{UL-typ}}{WEF_{UL-typ}}$	+
C.11. Growth rate of rural residents' life wef	%	$\frac{WEF_{RL}-WEF_{RL-typ}}{WEF_{RL-typ}}$	+
C.12. Modulo of urban residents' life wef	Dimensionless	\	+
C.13. Water supply pervasion	%	Statistical Data	+
C.14. Per water storage capacity	m^3/people	$\frac{Cap.rev}{Pop}$	+
C.15. Population benefits of unit rural residents' life wef	people/km^2	$\frac{Pop.rur}{WEF_{RL}}$	+
C.16. Population benefits of unit urban residents' life wef	people/km^2	$\frac{Pop.ur}{WEF_{UL}}$	+

Note: The formulas not listed in the table can be found in the statistical data or are commonly used indicators; WEF_{UL-typ} represents the emergy ecological footprint of urban residents' domestic water in the base year, WEF_{RL-typ} represents the emergy ecological footprint of domestic water for rural residents in the base year, Cap.rev represents the reservoir capacity (including large, medium and small reservoirs, 10^8 m^3), Pop.rur represents the rural permanent population (10^4 people), Pop.ur represents the urban permanent population (10^4 people), and the symbols not indicated in the formula are shown in Table 1.

Table 6. Index system for sustainability of the water ecological subsystem (w-ecological subsystem).

Indicator Layer	Unit	Data Source and Calculation	Nature
C.17. Forest vegetation coverage	%	Statistical Data	+
C.18.Modulo of convey wef	Dimensionless	$\frac{WEF_t}{Area}$	−
C.19.Modulo of Climate regulation wef	Dimensionless	$\frac{WEF_w}{Area}$	−
C.20. Reservoir regulation coefficient	Dimensionless	$\frac{Cap.rev}{Vol.riv}$	+
C.21. Proportion of groundwater supply	%	Statistical Data	−
C.22. Cv in water ecological carrying capacity	Dimensionless	Statistical Data	−
C.23. Water production coefficient	%	$\frac{WEF_{und}+WEF_{sur}}{ECW}$	+
C.24. Surplus rate of wef	%	$\frac{WEC-WEF}{WEC}$	+
C.25. Comprehensive Water Pollution Index	%	$\frac{WEF_p}{WEC}$	−

Note: $WEC(und/sur) = \left(Poe.rai(und/sur) * \tau_{Poe.rai(und/sur)} + Che.rai(und/sur) * \tau_{Che.rai(und/sur)}\right)/P_w$ (km^2), Poe.rai(und/sur) represents rainwater (ground/surface water) potential energy (J), Che.rai(und/sur) represents rainwater (ground/surface water) Chemical energy (J), $\tau_{Poe.rai(und/sur)}$ represents the conversion rate of rainwater (ground/surface water) potential energy value (SEJ/J), $\tau_{Che.rai(und/sur)}$ represents rainwater (ground/surface water) Chemical energy emergy conversion rate (SEJ/J), *Vol.riv* represents runoff (10^8 m^3), P_w represents the energy density of regional water resources (SEJ/km^2), and the meaning of *Cap.rev* is shown in Table 3, Index C.14 calculation formula, and symbols that are not indicated in the formula are shown in Table 1. The formulas not listed in the table can be found in the statistical data or are commonly used indicator.

3.2. Determination of Indicator Weight

The weights of each subsystem in the criterion layer, considering the ecological fragility of the Yellow River Basin and the relatively small amount of water resources, suggest that in the criterion layer of the sustainability evaluation index system for w-eco-economic system, economic subsystem: social subsystem: water ecological subsystem = 0.2: 0.2: 0.3 and the sum of weights for the three subsystems is 1.

The weight of the indicator layer is combined with the entropy weight method and expert scoring method, as shown in Section 2.3.2 AHP-EWM method. The final results are shown in Table 7.

Table 7. Mixed Weights for Sustainability Evaluation of the Water Ecological Economic System (w-eco-economic system).

Goal	Criterion Layer	Indicator Layer	Hybrid Weight	
			Basin	Provinces (Regions) in the Basin
W-eco-economic System	Economic subsystem			
	0.2	C.1	22.351	25.0635
		C.2	17.449	17.473
		C.3	11.1495	10.8815
		C.4	12.4755	4.886
		C.5	20.4175	15.3945
		C.6	16.1575	26.302
	Social subsystem			
	0.2	C.7	8.666	8.6975
		C.8	6.139	4.1165
		C.9	7.417	2.275
		C.10	6.719	3.995
		C.11	11.158	4.454
		C.12	11.399	8.693
		C.13	9.479	6.8465
		C.14	11.356	34.3195
		C.15	12.4175	13.0495
		C.16	15.25	13.5535
	W-Ecological subsystem			
	0.3	C.17	6.934	8.326
		C.18	14.246	5.2015
		C.19	12.797	9.1565
		C.20	9.219	17.235
		C.21	11.1885	9.548
		C.22	\	10.1385
		C.23	14.2445	20.495
		C.24	16.0025	10.339
		C.25	15.3825	9.5605

3.3. 2011–2021: Assessment on the Sustainability of the Water Ecological Economic System of the Yellow River Basin as a Whole and Provinces (Regions)

3.3.1. Sustainability Evaluation of Water Ecological Economic System in the Entire Basin

To further evaluate the differences in the sustainability of the water ecological economic system in the Yellow River Basin, this study used data from the sustainability index of the water ecological economic system in the basin, and divided sustainability into five levels using equal intervals: high level (I), higher level (II), medium level (III), lower level (IV), and low level (V).

The sustainability assessment model established above was used to evaluate the overall ecological economic system sustainability of the Yellow River Basin. The specific results are shown in Figure 2.

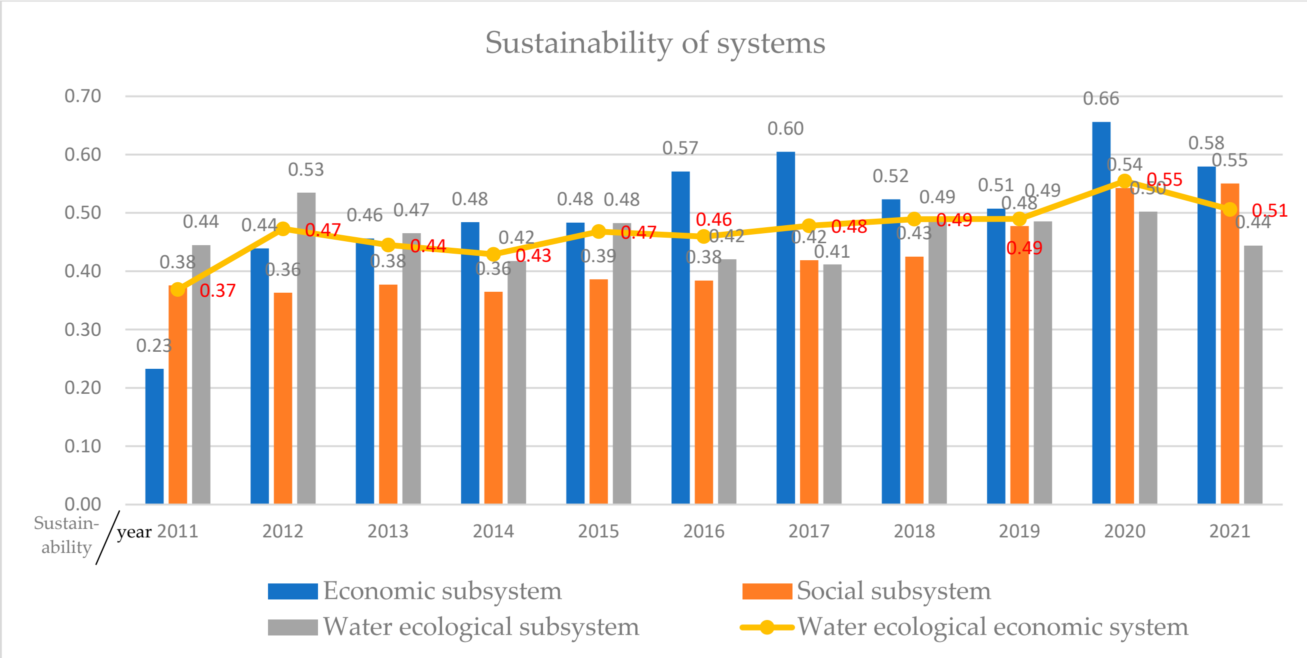

Figure 2. Sustainability for the water ecological economic system (w-eco-economic system) of Basin.

(1) The sustainable level of the water ecological economic system in the Yellow River Basin has been increasing year by year. In 2011, it was at a low level of sustainability, in 2013–2014 it was at a medium level of sustainability, in 2012 and 2015–2016 it was at a high level of sustainability, and in 2017–2021 it was at a high level of sustainability.

(2) The sustainability level of the economic subsystem has been increasing year by year and the growth rate is significant. In 2018, there was a certain decrease, followed by an increase. The reason is that in 2019, the major national strategy of "Ecological Protection and High Quality Development of the Yellow River Basin" proposed that the focus of economic construction in the Yellow River Basin has shifted from high water consuming industries such as heavy industry, energy industry, and agriculture to low water consuming and high value-added industries such as service industry and high-tech industry. The sustainable level of the social subsystem remained almost unchanged from 2011 to 2017, but there was some growth after 2018, thanks to the rapid development of the economy in 2019; The sustainability of the water ecosystem experienced periodic fluctuations during the research period, mainly due to the correlation between water resource renewal and rainfall. In 2012, there was a large increase because the strictest water resources management system was put forward that year, which defined the three red lines of water resources utilization—the red line of total development, the red line of water use efficiency, and the red line of water function zone restriction on pollution reception.

Overall, the sustainable level of the water ecological economic system is showing an increasing trend year by year. Although the sustainable improvement of each subsystem affects the overall sustainability of the system, the promoting effect of the economic subsystem is more obvious.

3.3.2. Sustainability Evaluation of the Water Ecological Economic System in Various Provinces (Regions)

Sustainability Evaluation of Total System in Various Provinces (Regions)

From Figure 3, it can be seen that during the research period, water ecological economic systems in Qinghai and Sichuan provinces remained at a high level of sustainability for a long time (I). The water ecological economic system in Gansu Province has been at a high level of sustainability for a long time (II) and has shown slow growth from 2011 to 2018. The water ecological economic systems of Ningxia and Neimenggu have been at a low level and sustainable for a long time (V). From 2011 to 2018, the water ecological economic system in Shaanxi Province remained at a medium level of sustainability for a long time (III), and gradually developed into a high level of sustainability (II) after 2019. The water ecological economic systems in Shanxi Province have long been moderately sustainable (III). The water ecological economic systems in Henan Province have been improving year by year, with a moderate level from 2011 to 2015 (III), a high level from 2016 to 2019 (II), and a high level from 2020 to 2021 (I). The water ecological economic system in Shandong Province was consistently at a moderate sustainable level (III).

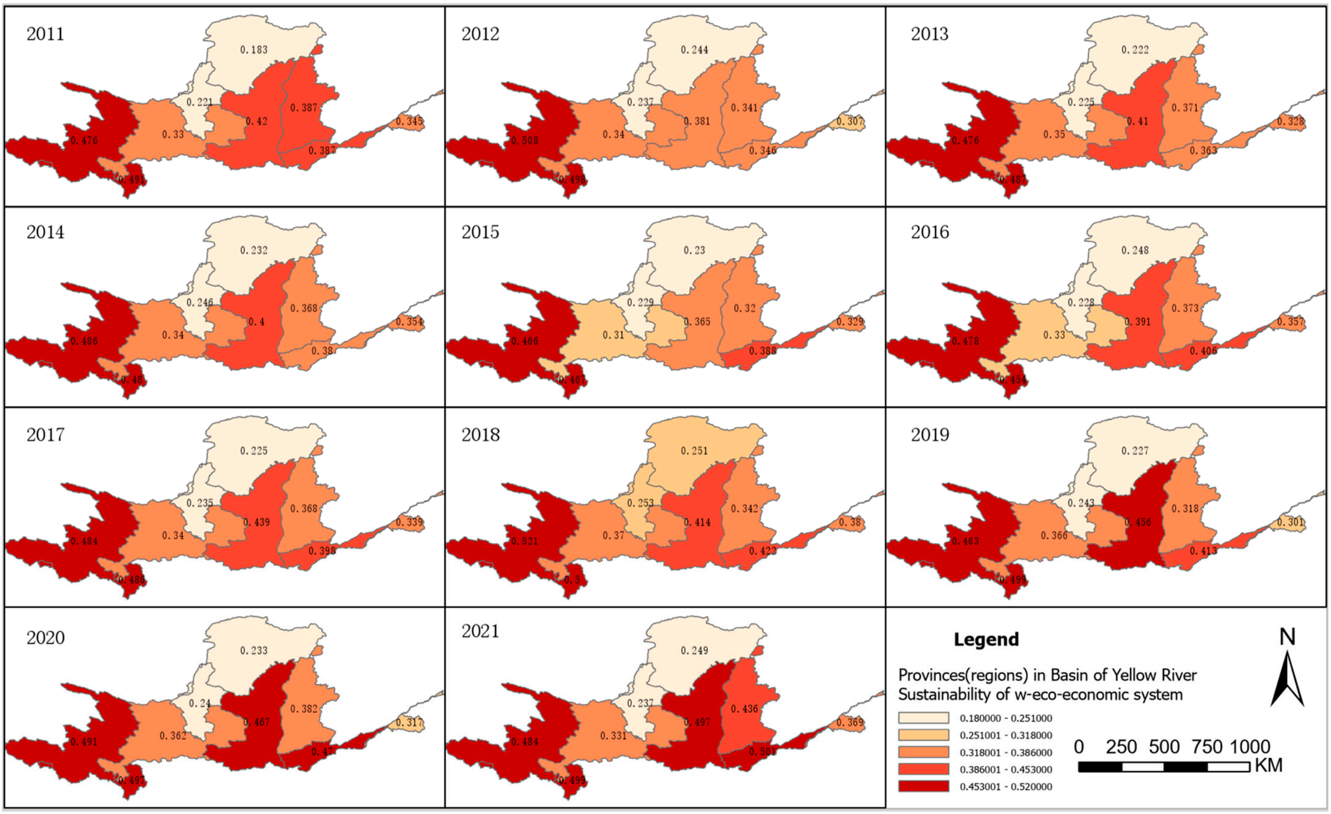

Figure 3. Sustainability evaluation of the water ecological economic system in various provinces (regions).

Sustainability Evaluation of the Economic Subsystem in Various Provinces (Regions)

The sustainability evaluation results of the economic subsystem are shown in Figure 4. It can be seen that during the research period, the sustainability of the economic subsystem in each province (region) has improved, but the speed of improvement varies. Generally, the downstream development speed was faster than the upstream, and the upstream was faster than the middle.

Specifically, in terms of upstream regions, the sustainability of the economic subsystems in each province (region) was at a low level (V) and a relatively low level (IV). The sustainability of the economic subsystem in Sichuan was consistently at a low level (II), with a rapid increase year by year. Qinghai was consistently at a low level (II), but it has been increasing rapidly year by year.

From the perspective of the middle reaches, the sustainability of the economic subsystems in Gansu, Ningxia, and Neimenggu was at a relatively low level (IV), gradually improving over time.

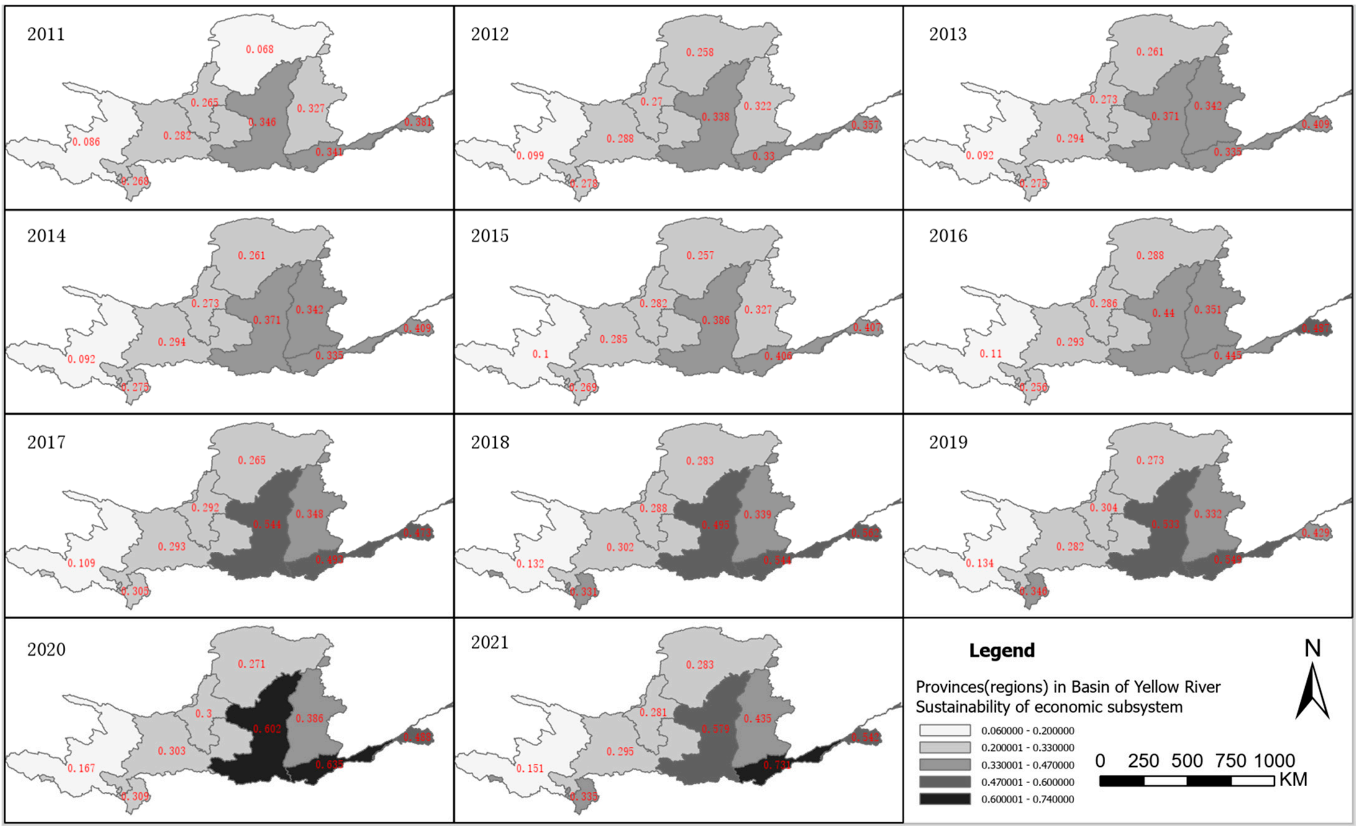

Figure 4. Sustainability evaluation of the water ecological economic system in various provinces (regions).

From the perspective of downstream regions, the sustainability of the economic subsystem in each province (region) was at a medium level (III) and a relatively low level (IV) in the early stage of the study, while in the later stage, each province (region) gradually transitioned to a high level (I) and a relatively high level (II). Overall, the improvement speed was relatively fast. Shaanxi and Henan developed from a medium level (III) at the beginning of the study period to a high level (I) at the end of the study period, with a fast development speed. Shanxi has developed rapidly from a relatively low level at the beginning of the research period (IV) to a medium level at the end of the period (III). Shandong has developed rapidly from a medium level (IV) at the beginning of the research period to a higher level (III) at the end of the period.

Sustainability Evaluation of the Social Subsystem in Various Provinces (Regions)

The sustainability evaluation results of the social subsystem are shown in Figure 5. It can be seen that during the research period, the sustainability of the social subsystems in the upstream and downstream provinces (regions) has improved, but the speed of improvement varies. The sustainability of the social subsystems in the midstream provinces (regions) has remained stable.

Specifically, in terms of upstream regions, the sustainability of the social subsystems in Sichuan and Qinghai has been at a relatively low level—(IV) and (V)—for a long time, and the development speed of the subsystems was relatively slow.

From the perspective of the middle reaches, the sustainability of the social subsystems in Gansu, Ningxia, and Neimenggu has been at a medium level (III) and a relatively low level (II) for a long time. Except for Neimenggu, which has shown significant growth, the sustainability of the subsystems was relatively stable.

From the perspective of downstream regions, the social subsystems of Shaanxi, Shanxi, Henan, and Shandong had good sustainability and have been at a high level—(II) and

(I)—for a long time. The sustainability of the subsystems has been significantly improved. Shaanxi and Shanxi have gradually transitioned from medium level (III) and low level (IV) to high level (I) and high level (I), while Henan and Shandong have gradually transitioned from high level (II) to high level (I).

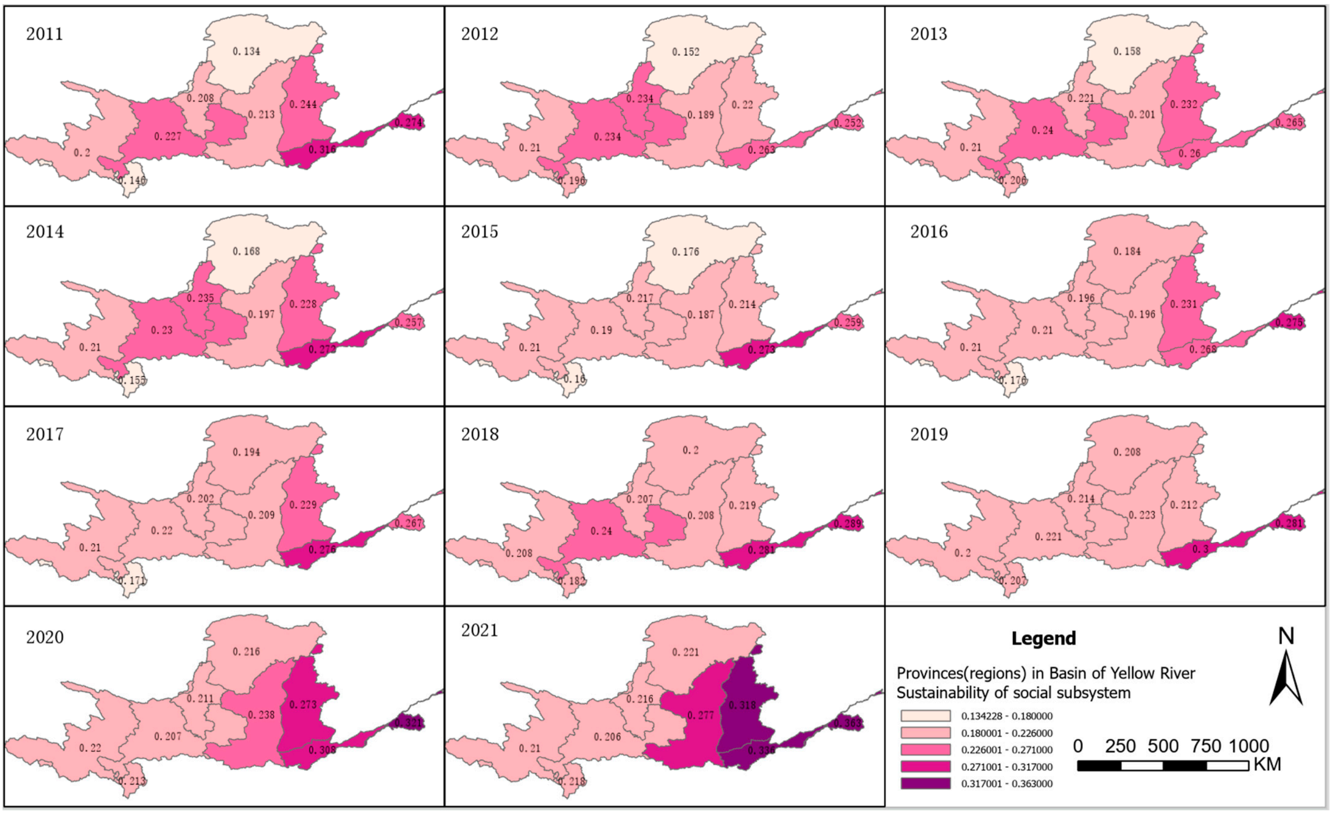

Figure 5. Sustainability evaluation of the water ecological economic system in various provinces (regions).

Sustainability Evaluation of Water Ecological Subsystems in Various Provinces (Regions)

The sustainability evaluation results of the water ecological subsystem are shown in Figure 6. It can be seen that during the research period, the sustainability of the water ecological system in each province (region) remained basically stable except for a few provinces. Specifically, in terms of upstream regions, the sustainability of water ecological subsystems in Sichuan and Qinghai has been at a high level for a long time (I), but Sichuan has slightly decreased.

In the middle reaches, the sustainability of water ecological systems in Gansu, Ningxia, and Neimenggu was poor, with long-term low levels (IV) and (V). Except for Neimenggu, which was relatively stable, the sustainability of subsystems has slightly improved.

From the perspective of downstream regions, the sustainability of the water ecological subsystems in Shaanxi, Shanxi, Henan, and Shandong was average, with a long-term moderate level (II). The sustainability of subsystems decreases slightly over time. Shaanxi was at a medium level (III) all year round, Shanxi was at a lower level (IV) all year round, Henan gradually degraded from a higher level (II) to a medium level (III), and Shandong gradually degraded from a higher level (II) to a lower level (IV).

There are two main reasons for the above phenomenon. Firstly, the supply of regional water resources is constrained by natural conditions, and the water resources in different provinces (regions) are limited and stable; On the one hand, economic and social development has put pressure on the ecological environment, and on the other hand, the improvement of technology has alleviated the pressure, achieving a stable state of dynamic balance between the two.

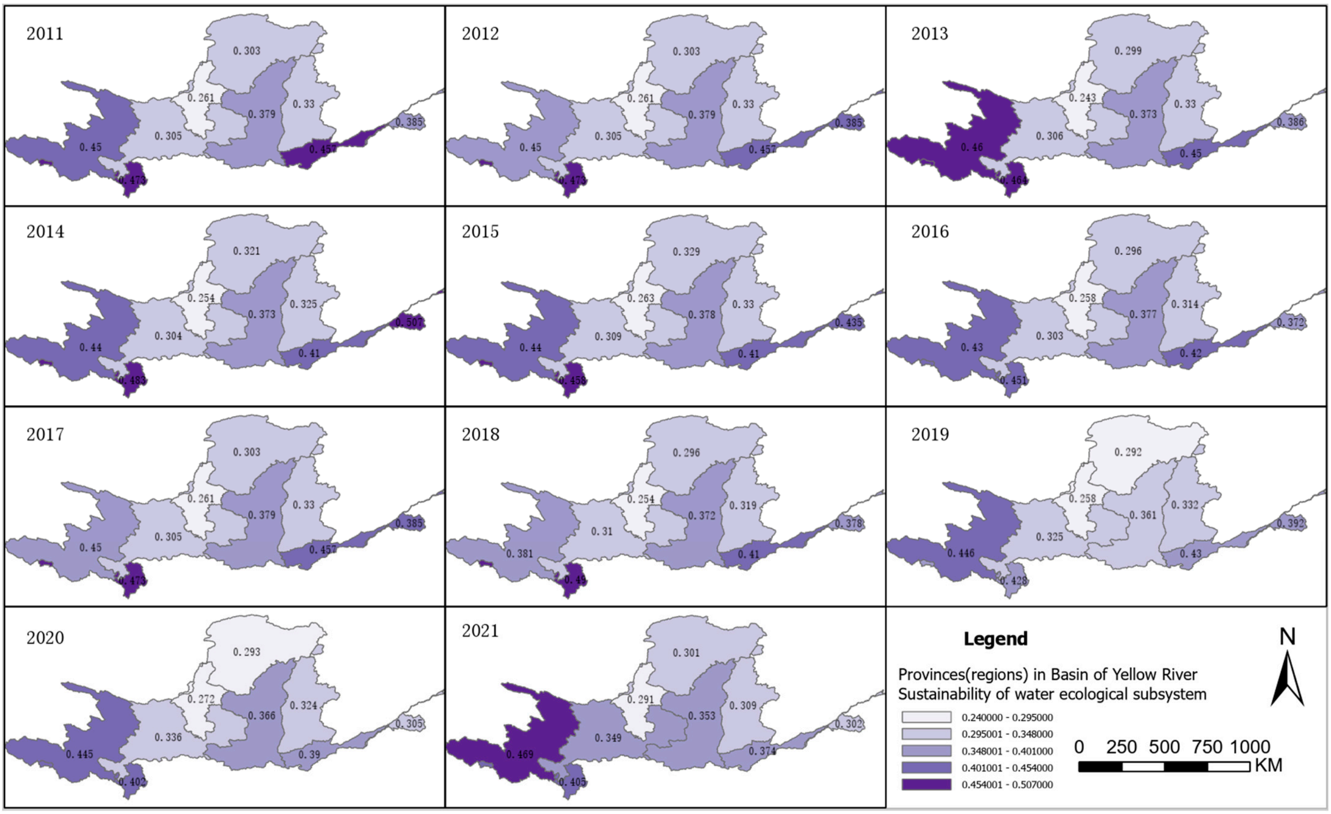

Figure 6. Sustainability evaluation of the water ecological economic system in various provinces (regions).

4. Discussion

The study of sustainable development is inevitably inseparable from the sustainable utilization of water resources, therefore quantifying the use of water resources is very important. The article mainly quantifies water resources from the perspective of ecological and economic systems, using emergy as an intermediate quantity.

In order to better reflect the utilization of water resources in water ecological economic system sustainability evaluation, the emergy water ecological footprint is combined to consider the structure function and corresponding material energy flow of the water ecological economic system. Referring to the PSR model framework, a sustainability evaluation index system is established from three aspects: the economic, social, and water ecological subsystems. Using a combination of subjective and objective weights, an AHP-EWM-TOPSIS model for sustainability evaluation of each subsystem was established, and based on this, an AHP-EWM-TOPSIS model for the overall system was established. Taking the Yellow River Basin as an example, it has been proven that the model is effective and reliable. Sustainability about the Yellow River Basin in the article that mainly combined the two parts of are as follows:

(1) Sustainability of the water ecological economic system in the entire basin

The sustainability of the water ecological economic system in the Yellow River Basin has been increasing year by year, from 0.37 at the beginning of the research period to 0.51 at the end of the period, with an increase rate of 0.378. But the impact of the three major subsystems on sustainability varies. The economic subsystem has developed rapidly, with sustainability increasing from 0.23 to 0.58 during the research period, and its impact on the overall system sustainability has gradually increased year by year. The development of the social subsystem is relatively delayed compared to the economic system, but the growth rate has improved since 2018, with sustainability increasing from 0.43 to 0.55, an increase rate of 0.279. Its impact on the overall system sustainability is relatively stable. The sustainability of the water ecological subsystem is relatively stable, with fluctuations mainly occurring around 0.43. From the above analysis, it can be seen that the economic subsystem has the greatest impact on the overall sustainability improvement of the system, followed by the social system. To achieve sustainable development in the Yellow River Basin, economic development is essential, which is in line with the high-quality development concept of the Yellow River Basin.

(2) Sustainability of the water ecological economic system in various provinces (regions)

From the upstream region, the sustainability of the water ecological economic system in Qinghai and Sichuan has been at a high level (I) for 11 years, increasing from 0.455 to 0.484 and 0.453 to 0.499, respectively. Sustainability has been growing slowly year by year, with growth rates of 0.068 and 0.101. From the perspective of the middle reaches, the sustainability of the water ecological economic systems in Gansu, Ningxia, and Neimenggu is at a relatively low level in the Yellow River Basin but has slowly increased over time. The sustainability of water ecological economic systems in Gansu has been at a medium level for many years (III), while the sustainability of the water ecological economic systems in Ningxia and Neimenggu has been at a relatively low level for many years (IV), with an average of 0.342, 0.236, and 0.231, respectively. The growth rates are 0.02, 0.07, and 0.36, respectively. From the perspective of downstream regions, the sustainability of water ecological economic systems in Shaanxi, Shanxi, Henan, and Shandong has grown rapidly. At the beginning of the research period, Shaanxi and Henan were at a moderate level (III), but gradually transitioned to a high level (I) over time, with sustainability increasing rapidly from 0.387 to 0.501. At the beginning of the research period, Shanxi and Shandong were at a relatively low level (IV), but gradually transitioned to a higher level (III) over time, with sustainability increasing from 0.387 to 0.501 and from 0.345 to 0.369, respectively.

Obviously, there is a spatial structure of accumulation in the overall system sustainability of each province (region), with upstream ≈ downstream > midstream. Secondly, the overall system sustainability of each province (region) has improved, but the growth rate of each province (region) varies, with downstream > upstream ≈ midstream. Specifically, the reasons for the formation and improvement of the overall sustainability spatial pattern in each province (region) are different. In the upstream region, the sustainability of water ecological subsystems in Qinghai and Sichuan is relatively high and has remained stable at around 0.456 and 0.450 for a long time (I). However, the development of economic and social subsystems is relatively backward, at a low level (V) and a lower level (IV). In the downstream region, in the early stage of the study, the economic subsystem of each province (region) generally improved rapidly. Shaanxi and Henan developed rapidly from a medium level (III) at the beginning of the study period to a high level (I) at the end of the study period, with growth rates of 0.33 and 0.862, respectively, from 0.346 to 0.579 and from 0.341 to 0.731. Shanxi has developed from a relatively low level at the beginning of the research period (IV) to a medium level at the end of the period (III), with a rapid development rate of 0.327 to 0.435, with a growth rate of 0.33. Shandong has developed from a medium level (IV) at the beginning of the research period to a relatively high level (III) at the end of the period, with a rapid growth rate of 0.423, from 0.381 to 0.542. The social subsystem in the downstream region is also at a high level in the watershed, but the development speed is slower than the economic subsystem. The social subsystems of Shaanxi, Shanxi, Henan, and Shandong have good sustainability and have been at a high level—(II) and (I)—for a long time. The sustainability of the subsystems has significantly improved, with rates of 0.30, 0.303, 0.063, and 0.32, respectively. Among them, Shaanxi and Shanxi have gradually transitioned from medium level (III) and low level (IV) to high level (I) and high level (I), while Henan Shandong has gradually transitioned from a higher level (II) to a higher level (I).

Overall, in future research on sustainability, the following aspects should be strengthened: (1) The establishment of a sustainability evaluation index system should test its completeness. (2) Although the overall sustainability of the watershed was considered in mass articles; there is still insufficient research on the synergy between subsystems.

5. Conclusions

The article introduced the emergy water ecological footprint, then constructed an AHP-EWM-TOPSIS model for sustainability of the Yellow River Basin and provinces (regions) and computed it. The main conclusions are as follows:

(1) The sustainability of the water ecological economic system in the entire basin is on the rise year by year, but the main reason for the improvement of the overall system sustainability level is the improvement of the economic subsystem sustainability. The improvement of the social subsystem sustainability level is attributed to the development of the economy and the improvement of social welfare. Although the sustainability of the water ecological subsystem is influenced by the economic and social subsystem, it is more importantly constrained by natural conditions, The sustainability level showed periodic changes during the study period.

(2) The overall system sustainability of each province (region) and watershed continues to improve. Although the specific reasons for improving sustainability vary among different provinces (regions), almost all are affected by the development of economic subsystems. Secondly, there is a mismatch between the economic and social development of the basin and the ecological status of water resources. The upstream economy with good water resources and ecology is relatively poor, while the downstream water resources with good economic development are relatively few. The midstream economy is generally developed, but the ecology is fragile. The specific situation is as follows:

The sustainability of the water ecological economic system and various subsystems has shown a clustering phenomenon. The overall sustainability level of the upstream Sichuan and Qinghai provinces is relatively high, while the overall sustainability level of the midstream Ningxia Hui Autonomous Region and Neimenggu Autonomous Region is relatively low. The overall sustainability level of the downstream Shaanxi, Shanxi, Henan, and Shandong provinces is relatively high. The high sustainability level of the upstream overall system is caused by the high sustainability level of the water ecological subsystem, while the high sustainability level of the downstream overall system is caused by the high sustainability level of the economic subsystem. This is consistent with the actual economic and social development status and the distribution of available water resources, indicating that the model is true and reliable.

(3) From the above analysis, it can be seen that in order to improve the sustainability of the overall system of the Yellow River Basin, while developing the economy, attention should be paid to the sharing of development achievements and their application in the sustainable use of water resources and ecological protection, in order to achieve coordinated development of the economy's society water resource ecology. Consider leveraging the strengths of each province (district), avoiding their own weaknesses, and achieving coordinated and orderly coordination among provincial (district) subsystems to promote the overall sustainability of the watershed.

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