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Evaluation of the Coupled Coordination of the Water–Energy–Food–Ecology System Based on the Sustainable Development Goals in the Upper Han River of China

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Abstract: Water, energy, food, and ecology are essential for achieving sustainable development in a region, and in order to achieve the Sustainable Development Goals, their security is also essential at a river basin scale. This study investigated the interrelationships among the water system, food system, energy system, and ecosystem in China's Upper Han River, in alignment with Goals 2, 6, 7, and 15 of the United Nations' Sustainable Development Goals (SDGs). To evaluate the achievement of the SDGs in the Upper Han River, this water–energy–food–ecology system was evaluated by a thorough evaluation index system according to Goals 2, 6, 7, and 15, and the weights of the indices were given using a combination of the CRITIC weighting method and entropy approach. The level of coupling coordination of the system from 2000 to 2021 was quantitatively evaluated by using a coupling coordination degree model. The autoregressive integrated moving average model was built to forecast the process of the indices from 2022 to 2041, and the predicted processes of the system were evaluated by the coupling coordination degree model. The degree of coupling coordination improved from 0.396 to 0.845, and the comprehensive assessment development index increased by 113% from 2000 to 2021, demonstrating that it was a stable development period in general. The fragile support capacity of the water system for the energy system, food system, and ecosystem had a great impact on the overall comprehensive evaluation index. SDG2 (food system), SDG6 (water system), SDG7 (energy system), and SDG15 (ecosystem) all have higher levels of internal conflict. These bi-directional dynamics tended to converge in the sufficiency development mode in the future period as well as the historical period. The analysis of the relationship showed that there were inherent connections and interactions between the four goals, as presented by the high level of coupling that persisted between SDG2, SDG6, SDG7, and SDG15. In the process of promoting the achievement of these goals, the coupling degree also tends to be coordinated from 2022 to 2041. The results offer a view for the river basin's sustainable development and management.

Keywords: sustainable development goals; comprehensive evaluation index; ARIMA forecast; coupling coordination

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1. Introduction

Water, energy, food, and ecology are interconnected and inseparable resources, and the relationships among these four resources are close and complex [1,2]. In surveying the complexity of the water–food–energy nexus, it is necessary to look at the specific processes of regional resource use, which are often based on the ecosystem and linked to ecosystem services [3]. The entire hydrological process is impacted by the quality of the ecosystem, and maintaining healthy water ecosystems depends critically on the availability of ecological water; energy is used up during the extraction, transportation, use, and treatment of water resources, and vice versa. Water resources are also used in the production and use of energy; water resources are highly demanded due to food production, handling, as well as use. There is a cross-regional and cross-system transmission effect associated with the risk of ecological degradation and a lack of water and energy [4–6].

Among the many challenges currently facing the world, the issues of water scarcity, energy supplies, food security, and ecological degradation have become prominent [7]. With the backdrop of growing environmental constraints and human activity, ecological vulnerability has been made worse by the notable rise in the demand for food, energy, and water [8,9], has reduced the natural environment's ability to self-regulate and repair, and has increased the pressure on the external environment [10]. This has resulted in environmental externalities of resource management [11], which, in turn, impede water, energy, and food security. Therefore, in the face of regional sustainable development, it is necessary to build a framework for water–energy–food–ecosystem linkages. In recent years, the synergistic water–energy–food–ecosystem (WEFC) model has attracted much attention as an integrated program. Some scholars believe that WEFC linkages have become a theory, a tool [5], and even a new discipline [12] for alleviating regional tensions. However, the current research mostly constructs WEFC linkages from the perspectives of individual regions [13], and in recent years, the linkage framework established by the international community is currently not being applied very much in China [2]. For the purpose of building evaluation models, there have not been any thorough reviews of the ecological properties of land and water combined with the mechanisms underlying the relationships between water, energy, and food indicators.

In April 2020, GRID-Arendal released a report entitled "The Water-Energy-Food-Ecosystems Nexus Approach", which stated that each trans-basin or aquifer faces specific challenges related to management and that the water–food–energy–ecosystems nexus approach provides a more solid basis for equitable water allocation for all uses. By increasing resource efficiency, reducing exchange, creating synergies, and improving management while protecting ecosystems, this approach will also help harmonize development goals across different sectors and make progress towards the United Nations Sustainable Development Goals (SDGs) [14]. The main objective of the 2030 Agenda for Sustainable Development, which was approved by the UN General Assembly in 2015, is to create a society that is more just, egalitarian, peaceful, and prosperous, aiming to promote multidimensional and balanced development and to achieve sustainable human societies [15].The SDGs include four goals that are particularly closely linked to water, energy, food, and ecology. Any action performed toward any one of these four objectives is probably going to directly affect the others. Janouskova et al. constructed an evaluative framework based on 60 indicators across the 17 SDGs to measure the development of China's Yangtze River Economic Zone (YRED) and to identify the key factors affecting its development [16]. In order to achieve zero hunger, SDG 2 has five targets: tripling agricultural productivity, establishing resilient and sustainable food production systems, eliminating hunger and malnutrition, and attaining food security and sustainable agriculture [17]. SDG6 relates to access to clean water and sanitation, with targets revolving around water security [18–20]. SDG7 aims to achieve reliable and clean energy so the targets are closely related to energy [21]. SDG15 seeks to stop and reverse land degradation, stop the loss of biodiversity, battle desertification, and preserve, restore, and promote the sustainable use of terrestrial ecosystems [22]. So far, there are some case studies on the evaluation of the 17 SDGs at a regional scale or river basin scale. However, a generalized index system is still lacking. A case study of different regions all over the world is necessary.

The objective of this study is that a quantitative method is used to establish evaluation indicator systems for food, water, energy, and ecology based on Sustainable Development Goals 2, 6, 7, and 15, respectively, to grasp the regional characteristics and to expand the indicator system in order to bring a thorough evaluation closer to the sustainable development subject and make it more scientific. The quantification of the interactions among the four goals in combination with the regional status quo enriches the research perspective for the further quantification of the interactions among the SDGs.

The Han River in China is the water source of the middle route of the National South-to-North Water Diversion Project, and it is also the water supply source of the local counties. Therefore, the upper Han River is the study area in this work, and a comprehensive development evaluation index is computed by combining the ecological indicators of land and water bodies to create the indicator assessment of the WEFC system. In order to quantify the comprehensive development assessment index for the years 2000–2021 and the anticipated years 2022–2041, the coupling coordination degree model is finally introduced. The indicators for 2022–2041 are predicted using the ARIMA model. The linked coordination analysis will support the region's sustainable growth in decision-making.

2. Materials and Methods

2.1. Study Area

A significant tributary in the middle course of the Yangtze River is the Han River; it originates from Panzhong Mountain, Ningqiang County, Hanzhong City, with a main stream length reaching 15,332 km, an 873 mm yearly precipitation total, and a 159,000 km^2 basin, as shown in Figure 1, where the mean annual rainfall is from 700 mm to 1700 mm [23]. The Han River Basin is in a subtropical monsoon zone, with a mild and humid climate and abundant water; however, the distribution is uneven over the year, and the runoff from May to October accounts for about 75% of the annual runoff, with large inter-annual variations, which makes it the most varied river among the major tributaries of the Yangtze River [24]. The basin is rich in hydropower resources. As seen in Figure 1, the study area was in the upper reach of the Shiquan Hydrological Station in the Han River, which has a diverse and complex topography that is dominated by mountains with few plains. Shiquan is the study area's lowest elevation; the terrain is high in the west and low in the east, and it is high in the north and low in the south. In the main channel, there are four hydrological stations along the main stream in Wuhouzhen, Hanzhong, Yangxian, and Shiquan. The basin has three large reservoirs, namely, Sanhekou, Huangjinxia, and Shiquan.

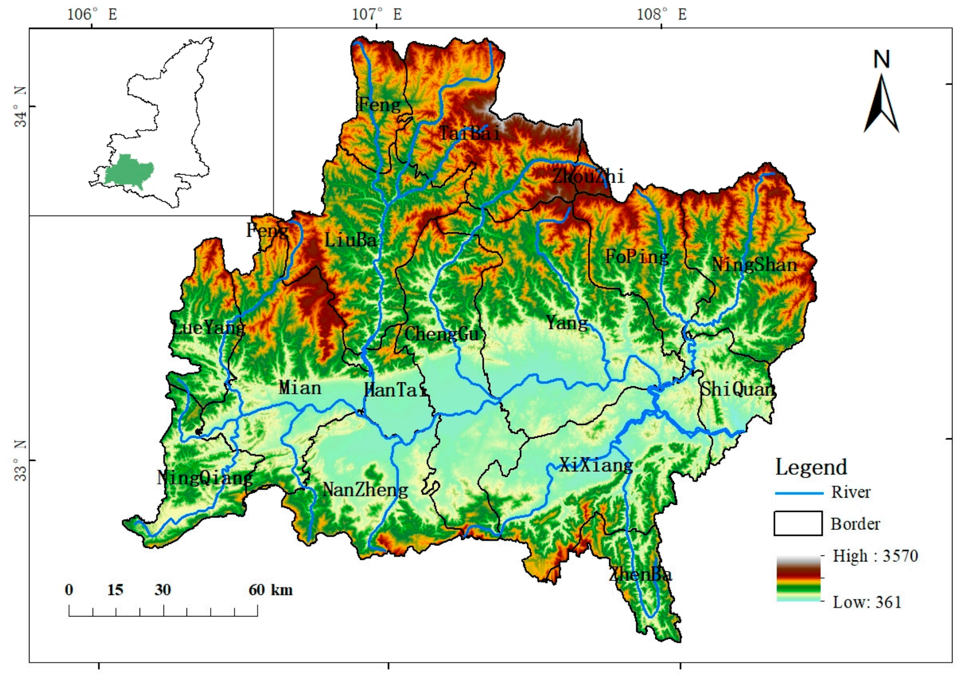

Figure 1. Topography of the upper Han River basin.

2.2. Data

The data used in this study came from the Shaanxi Province Water Resources Bulletin, the China Urban Statistical Yearbook, the National Economic and Social Development Statistical Bulletin of each district and county from 2000 to 2021 [25,26], the ERA5-Land dataset [27], and the China Natural Flow Grid Point dataset [28]. To increase the completeness of the data, some missing data are converted from province data to county data based on the area percentages of the counties.

Due to the nature of the selected indicators, there were large differences in orders of magnitude and in the quantitative levels. Normalizing the original data was required to guarantee the accuracy and validity of the outcomes of the data processing from a scientific standpoint. At the same time, normalizing the data to the same quantitative level was performed in order to solve the problem of comparability between the data [29]. Equation (1) normalizes positive indicators, and Equation (2) normalizes negative indicators. These are the normalization techniques and formulas:

$$Y_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})} \tag{1}$$

$$Y_{ij} = \frac{\max(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})} \tag{2}$$

where Y_{ij} is the standardized value of indicator j in year i; X_{ij} represents the initial data, and $\max(X_{ij})\min(X_{ij})$ are the maximum and minimum values, respectively.

2.3. Methodology

Through the preliminary data collection, a comprehensive evaluation index model was established based on Sustainable Development Goals, and the coupling coordination degree of the whole system was analyzed to evaluate the coupling and coordination development of the upper reach of the upper Han River. The flowchart of the study approach is shown in Figure 2, and it shows the comprehensive procedure of this study.

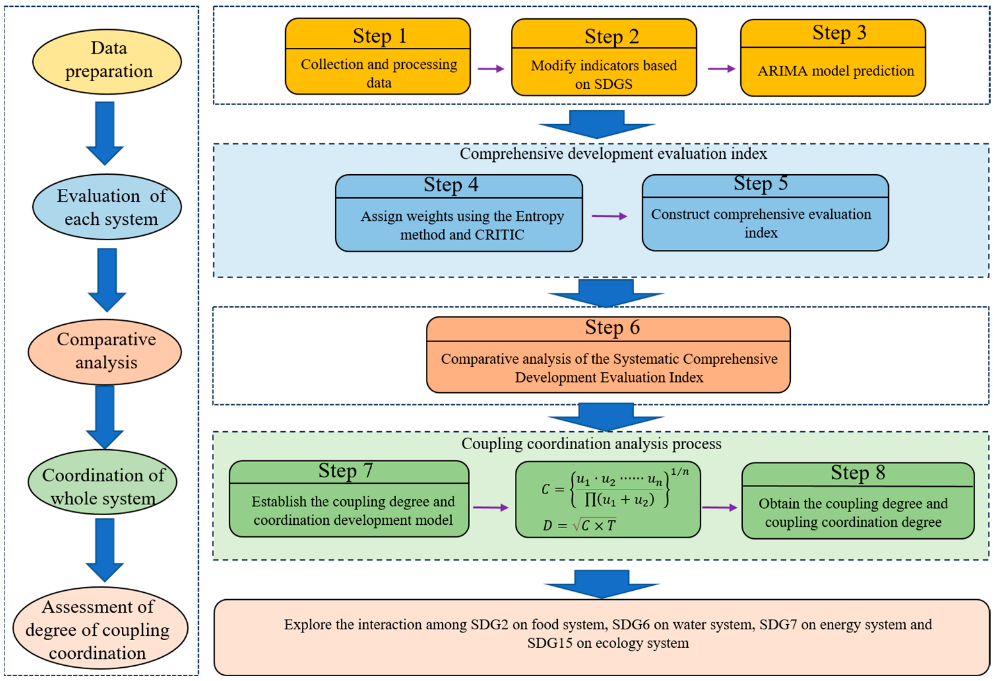

Figure 2. The flowchart of study approach.

2.3.1. Localization of the Indicators of the System

The United Nations has proposed corresponding targets and indicators for each of the goals, but not all of them are clear. It was discovered during the process of interpreting the content of the four goals that the indicators do not accurately reflect the goals' entirety and that different regions have varying degrees of access to statistics and different standards of statistical data, making it challenging to gather all the information needed for these indicators and to compare the computation results. Indicators have to match the objectives, and data should be readily available. This study transformed the four SDGs by three methods [15]: (1) adoption (A): without changing the name, definition, and calculation method of the original indicators, they could be used directly; (2) modification (M) refers to when the original indicator name, definition, and calculation method needed to be replaced with other indicators; (3) extension (E): supplementary indicators were used when the connotation of the goals could not be fully expressed. Based on the relevant foundations of SDG2, SDG6, SDG7, and SDG15, a comprehensive evaluation index system for China's food system (SDG2), water resource system (SDG6), energy system (SDG7), and ecosystem (SDG15) was constructed and they are shown in Table 1.

Table 1. Transformation of the food, water, energy, and ecological indicator systems in line with SDGs 2, 6, 7, and 15.

Goal	System	Connotation	Original Indicators	Methods	Transformed Indicators
Goal 6	Water	Ensuring security of water supply	6.1.1 Proportion of population using safely managed drinking water services	E	Residential water consumption
				E	Per capita water consumption
			6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	M	Annual precipitation
				M	Total water resources
			6.3.2 Proportion of bodies of water with good ambient water quality	A	Total water usage
		Improving water-use efficiency	6.5.1 Degree of implementation of integrated water resource management	M	Average acre-foot water use for irrigated farmland
			6.4.1 Change in water-use efficiency over time	A	Water consumption per 10,000 GDP
		Improving water quality	6.3.1 Proportion of domestic and industrial wastewater flows that are safely treated	A	Centralized wastewater treatment plant rate
				A	Industrial wastewater emissions
Goal 7	Energy	Optimizing the energy mix	7.1.1 Proportion of population with access to electricity	M	Night light data
				E	Energy consumption
				E	Electricity consumption
		Improving energy efficiency	7.2.1 Renewable energy share in the total final energy consumption	E	Energy consumption
				E	Energy utilization efficiency
			7.3.1 Energy intensity measured in terms of primary energy and GDP	E	Per capita GDP
				A	Gross output value of agriculture, forestry, livestock, and fisheries
				A	Gross domestic production
				E	Per capita net income of rural residents
				M	Comprehensive utilization rate of general industrial solid waste

Table 1. *Cont.*

Goal	System	Connotation	Original Indicators	Methods	Transformed Indicators
Goal 2	Food	Increasing food production	2.1.2 Prevalence of moderate or severe food insecurity in the population based on the Food Insecurity Experience Scale	M	Food production
				M	Pesticide usage
				A	Area affected by crops
				E	Agricultural fertilizer use
		Improving food productivity	2.4.1 Proportion of agricultural area under productive and sustainable agricultural use	M	Area sown for food
				E	Cropland irrigated area
				E	Engel's coefficient for rural inhabitants
			2.3.1 Volume of production per labor unit by class of farming/pastoral/forestry enterprise size	E	Gross power of agricultural machinery
				M	Total value of primary sector
				M	Food production per capita
Goal 15	Ecology	Conservation of biodiversity	15.1.2 Proportion of total water resources used, annual change in forest area, and land under cultivation	M	Zooplankton density
				M	Zooplankton biomass
				M	Dominant species
				A	Shannon–Wiener index
				A	Species richness index
				A	Species evenness index
			15.4.1 [Indicator of the conservation of mountain ecosystems]—to be developed	E	Yearly average temperature
				E	NDVI
		Curbing biodiversity loss	15.5.1 Red List Index	M	Chemical Composite Pollution Index
				E	Degree of variability in river flow processes

2.3.2. Entropy and CRITIC Weighting Methods

The determination of indicator weights has a significant impact on evaluation results, and the commonly used methods include hierarchical analysis, the entropy value method, the independent weight method, and the factor analysis method, etc. This study combines the entropy [30] value method and the CRITIC weighting method to determine the comprehensive weights. The uncertainty is expressed as the entropy value. If the information is larger, the entropy is lower and the uncertainty is lower; conversely, if the information is smaller, the entropy higher and the uncertainty is higher [31]. Thus, the information carried by the entropy value is utilized for weight calculation. In combination with the degree of variation in each indicator, the information entropy is utilized as a tool for calculating the weight of each indicator, which provides the basis for the comprehensive evaluation of multiple indicators. The calculation formula is as follows:

$$p_{ij} = \frac{X_{ij}}{\sum\limits_{i=1}^{m} X_{ij}} \tag{3}$$

$$e_j = -k\sum_{i=1}^{n} p_{ij}\ln(p_{ij}), j = 1, \ldots, m \tag{4}$$

$$d_j = 1 - e_j, j = 1, \ldots, m \tag{5}$$

$$w_j = \frac{d_j}{\sum\limits_{j=1}^{m} d_j}, j = 1, \ldots, m \tag{6}$$

$$S_i = \sum_{j=1}^{m} w_j x_{ij}, i = 1, \ldots, n \tag{7}$$

where X_{ij} represents the normalized data, p_{ij} represents the normalization results for the judgment matrix, e_j is the information entropy redundancy or information utility value, d_j is also the information entropy redundancy or information utility value, w_j represents weights of indicators, and S_i is the composite score for each sample.

The CRITIC [32] weighting method is an objective assignment method. The idea lies in using two indicators: the contrast strength and conflictability. For the comprehensive evaluation of multiple indicators and multiple objects, the CRITIC method eliminates the influence of some indicators with strong correlations, reduces the overlap of information between indicators, and is more conducive to obtaining credible evaluation results [33]. The calculation process is

$$\overline{x}_j = \frac{1}{n}\sum_{i=1}^{n} x_{ij} \tag{8}$$

$$S_j = \sqrt{\frac{\sum_{i=1}^{n}(x_{ij}-\overline{x}_j)^2}{n-1}} \tag{9}$$

$$R_j = \sum_{i=1}^{p}\left(1 - r_{ij}\right) \tag{10}$$

$$C_j = S_j \sum_{i=1}^{p}\left(1 - r_{ij}\right) = S_j \times R_j \tag{11}$$

$$W_j = \frac{C_j}{\sum_{j=1}^{p} C_j} \tag{12}$$

where S_j is the jth indicator's standard deviation, R_j is the indicator's jth standard deviation, C_j is the degree of knowledge, and W_j is the weight of the jth indicator objectively.

2.3.3. Comprehensive Development Evaluation Index Model

The water, energy, food, and ecosystem evaluation indices were calculated by using the weight values and the normalized values from the processed data [34]. The formula is

$$W(x) = \sum_{d=1}^{m} W_d \times X_{id} \tag{13}$$

where $W(x)$ is the indicator for integrated water resource development evaluation, W_d is the indices of water resources' weighting, and X_{id} shows the water resource indicators' normalized values for year i.

$$E(y) = \sum_{f=1}^{m} W_f \times D_{if} \tag{14}$$

where $E(y)$ is the indicator for integrated energy resource development evaluation, W_f is the weighting of the energy resource indicators, and D_{if} shows the energy resource indicators' normalized values for year i.

$$F(z) = \sum_{v=1}^{m} W_v \times G_{iv} \tag{15}$$

where $F(z)$ is the indicator for integrated food resource development evaluation, W_v is the indices of food resources' weighting, and G_{iv} shows the food resource indicators' normalized values for year i.

$$C(h) = \sum_{g=1}^{m} W_g \times R_{ig} \tag{16}$$

where $C(h)$ is the indicator for integrated ecological resource development evaluation, W_g is the indices of ecosystem resources' weighting, and R_{ig} shows the ecological resource indicators' normalized values for year i.

$$T = \alpha W(x) + \beta E(y) + \gamma F(z) + \omega C(h) \tag{17}$$

where T is the integrated water–energy–food–ecosystem development assessment index, and α, β, γ, and ω are the weighting coefficients for each respective system. In this study, with reference to previous research [2] and other relevant information, we took $\alpha = \beta = \gamma = \omega = 0.25$.

2.3.4. Coupled Coordination Degree Model and Classification Criteria

The degree of coordinated development was examined using the coupling coordination degree model [35]. The dynamic correlative relationship between two or more systems that interact and influence one another to accomplish coordinated development is referred to as the coupling degree. This relationship can show the degree of dependency and mutual restrictions between systems. The coupling degree refers to the size of the degree of benign coupling in a coupled interaction relationship, and it can reflect the coordination status. Three index values must be calculated in order to use the coupling coordination degree model: the coupling degree C, the coordination degree T, and the coupling coordination degree D. Table 2 shows the classification criteria of different types of coupling coordination degree [36]. Their formulas are

$$C = \left\{ \frac{u_1 \cdot u_2 \cdot \cdots \cdot u_n}{\prod (u_1 + u_2)} \right\}^{1/n} \tag{18}$$

$$u_i = \sum_{i=1}^{m} \omega_{ij} \times u_{ij} \tag{19}$$

$$T = \beta_1 U_1 + \beta_2 U_2 + \beta_3 U_3 + \cdots \tag{20}$$

$$D = \sqrt{C \times T} \tag{21}$$

where C is the coupling, T is the coordination, and D is the coupling coordination.

Table 2. Standards for categorizing coupling coordination level.

Interval of D-Values for Coupling Coordination	Harmonization Levels	Degree of Coupling Harmonization
0.0–0.2	1	Severe disorder
0.2–0.4	2	Mild disorder
0.4–0.6	3	General coordination
0.6–0.8	4	Medium coordination
0.8–1.0	5	High-quality coordination

2.3.5. ARIMA Forecasting Model

The autoregressive integrated moving average model, or ARIMA for short, is a popular technique for time series analytical forecasting [37]. The "autoregressive" AR, the "sliding average" MA, amount of phrases that are autoregressive p, how many words make in a sliding average q, and the ARIMA (p, d, q) model is comprised of the number of differences (order) d. An expansion of the ARMA (p, q) model is the ARIMA (p, d, q) model. Three essential processes are involved in developing an ARIMA model: estimating the parameters, testing the model, and identifying and ordering the model.

2.3.6. Comparative Analysis Method of Evaluation Index of Systematic Comprehensive Development

The Sustainable Development Goals are not independent of one another, and the goals may be synergistic or antagonistic to each other. The coupled relationship of water, energy, food, and ecology reflects the structural dynamics of the human–land relationship on the basis of a long time series and portrays an evolutionary pattern. In order to be able to sensitively capture the dynamic changes in and directions of the sub-elemental interrelationships and to portray the direction of the evolution of the WEFC system, the development evaluation indices for each system were compared two by two, and a time series comparison was performed to compute the coefficients of comparison by applying the following formula.

$$l_{SDG6,SDG7} = \frac{W(x)}{E(y)} \tag{22}$$

$$l_{SDG6,SDG2} = \frac{W(x)}{F(z)} \tag{23}$$

$$l_{SDG6,SDG15} = \frac{W(x)}{C(w)} \tag{24}$$

$$l_{SDG7,SDG2} = \frac{E(y)}{F(z)} \tag{25}$$

$$l_{SDG7,SDG15} = \frac{E(y)}{C(w)} \tag{26}$$

$$l_{SDG2,SDG15} = \frac{F(z)}{C(w)} \tag{27}$$

3. Results

3.1. Evaluation Index System for the Degree of Coupling and Coordination in the WEFC System in the Upper Han River

Based on the interactions among SDGs 2, 6, 7, and 15, the relationships among water–energy–food–ecosystems in the upper Han River were explored, and an evaluation index system for the degree of coupling and coordination degree in the WEFC system was constructed. Under the premises of scientific validity, representativeness, completeness, and data availability, in combination with the actual situation of the region and keeping close to the Sustainable Development Goals, a total of 31 indicators were selected from the four systems to construct the evaluation system. Because of their solid scientific foundation and objective outcomes, the entropy value approach and the CRITIC method of objective empowerment were chosen for this study's comprehensive weight calculations of the indicators. The indicators were positively and negatively orientated for directional unification in order to represent the optimization effect's worth and account for nature's positive and negative contributions to human life [38]. The results are shown in Table 3.

In Table 3, W_{j1} is the weight of the entropy method, W_{j2} is the weight of CRITIC, and W_j is the composite weight index. If the index property is positive and noted by +, the larger the data, the better; if it is negative and noted by $-$, the smaller the value, the better.

Table 3. Evaluation indicators and their weights for the Sustainable Development Goals in the upper Han River.

Standardized Layer	Indicator Layer	W_{j1}	W_{j2}	W_j	Directions	Units
Water (Goal 6)	Precipitation	0.1225	0.0794	0.1010	+	mm
	Total water resources	0.1300	0.0756	0.1028	+	billion m^3
	Residential water consumption	0.0872	0.1021	0.0947	−	billion m^3
	Water consumption per capita	0.2268	0.1268	0.1768	−	m^3/person
	Water consumption per 10,000 GDP	0.0962	0.1413	0.1188	−	m^3/10,000 yuan
	Average acre-foot water use for irrigated farmland	0.0382	0.0793	0.0588	−	m^3/acre
	Centralized wastewater treatment plant rate	0.0715	0.1263	0.0989	+	%
	Industrial wastewater emissions	0.1299	0.1335	0.1317	−	10 kt
	Total water consumption	0.0977	0.1356	0.1167	−	billion m^3
Energy (Goal 7)	Gross domestic production	0.1532	0.0918	0.1225	+	10^8 CNY
	Gross output value of agriculture, forestry, livestock, and fisheries	0.1455	0.0883	0.1169	+	10^4 CNY
	Per capita GDP	0.1489	0.1053	0.1271	+	CNY
	Per capita net income for rural residents	0.1833	0.0905	0.1369	+	CNY
	Nighttime lighting data	0.031	0.074	0.0525	+	—
	Energy consumption	0.0783	0.1628	0.1206	−	million tons of coal equivalents
	Energy efficiency	0.0963	0.136	0.1162	+	tons of coal equivalents/ 10 yuan
	Electricity consumption	0.1077	0.1751	0.1414	−	kw·h
	Comprehensive utilization rate of general industrial solid waste	0.0558	0.0761	0.0660	+	%
Food (Goal 2)	Total power of agricultural machinery	0.106	0.1104	0.1082	+	W·kW
	Food production	0.0704	0.0684	0.0694	+	10 kt
	Food production per capita	0.0597	0.1032	0.0815	+	kg/person
	Total value of primary industry	0.1535	0.1216	0.1376	+	10^8 CNY
	Agricultural fertilizer applications	0.1208	0.1103	0.1156	−	10 KT
	Pesticide usage	0.1292	0.1128	0.1210	−	t
	Food cultivation area	0.1101	0.0671	0.0886	+	k·hm^2
	Irrigated area of cultivated land	0.1101	0.0671	0.0886	+	k·hm^2
	Engel's coefficient for rural residents	0.0903	0.1317	0.1110	−	%
	Crop-affected area	0.0498	0.1074	0.0786	−	k·hm^2
Ecosystem (Goal 15)	Average temperature per year	0.3841	0.3850	0.3846	+	°C
	NDVI	0.3434	0.3031	0.3233	+	—
	Degree of variability in river flow processes	0.2725	0.3019	0.2872	−	—

3.2. Analysis of the Comprehensive Development Evaluation Index for the WEFC System

We forecasted the initial 31 indicators for the years 2000–2021 using the ARIMA model with a long time series in order to understand the WEFC correlation system's developmental tendency; by adjusting the model parameters, the model passed the test, and the model's setting was basically correct. The data for the indicators for the years 2022–2041 were anticipated using the well-established ARIMA model, and the predicted data were then subjected to a coupling analysis.

The ARIMA model is used to predict the data of 31 indicators in 2022–2041, and we take the water consumption per 10,000 GDP and the gross output value of agriculture, forestry, livestock, and fisheries as examples in Figures 3 and 4.

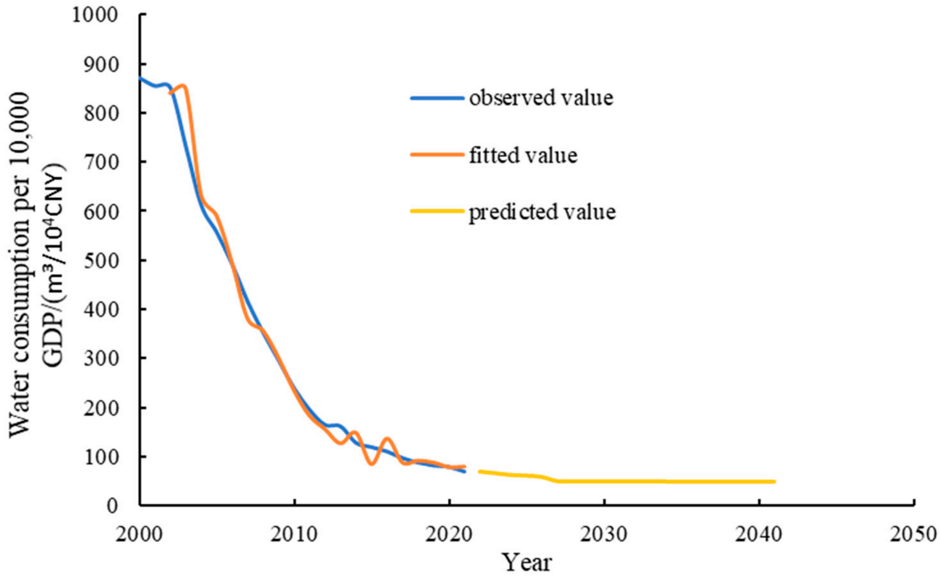

Figure 3. Forecast results of water consumption per 10,000 CNY GDP.

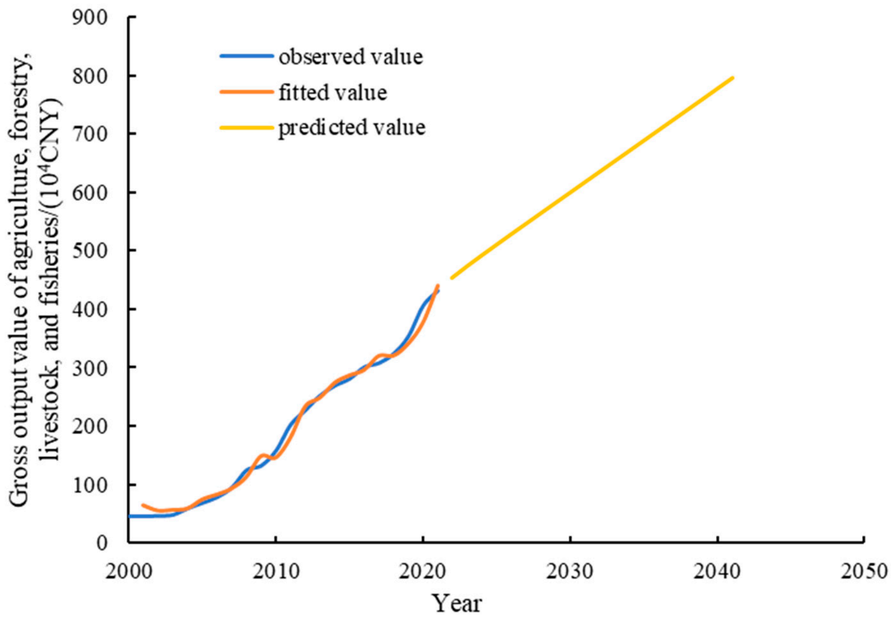

Figure 4. Forecast results of gross output value of agriculture, forestry, livestock, and fisheries.

The integrated development evaluation index was calculated for each system and for SDGs 2, 6, 7, and 15 in the upper Han River for the period of 2000–2021 and the projected period of 2022–2041, and the results are shown in Figures 5 and 6.

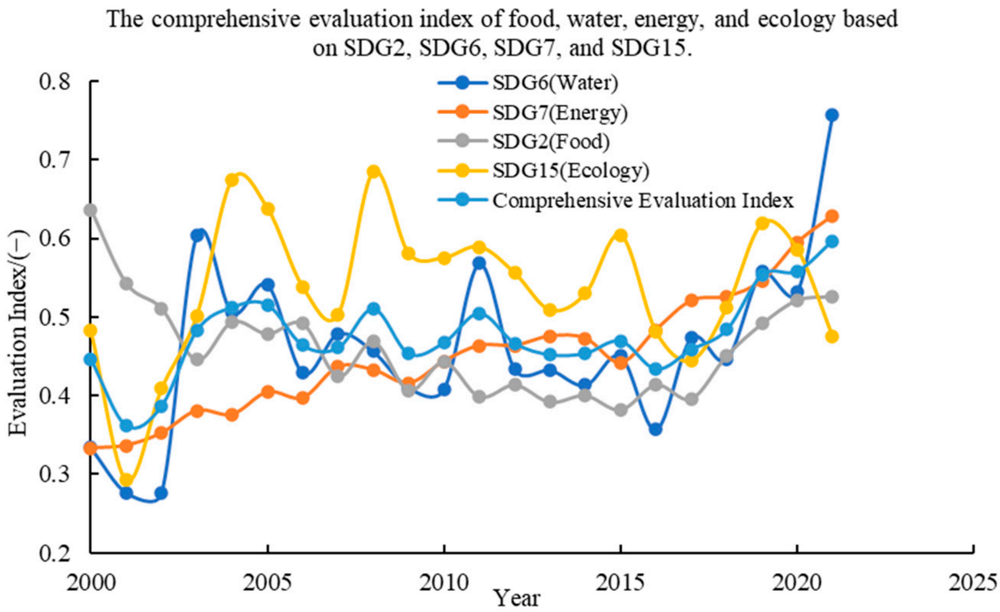

Figure 5. The development evaluation index and composite development index of the WEFC system for 2000–2021.

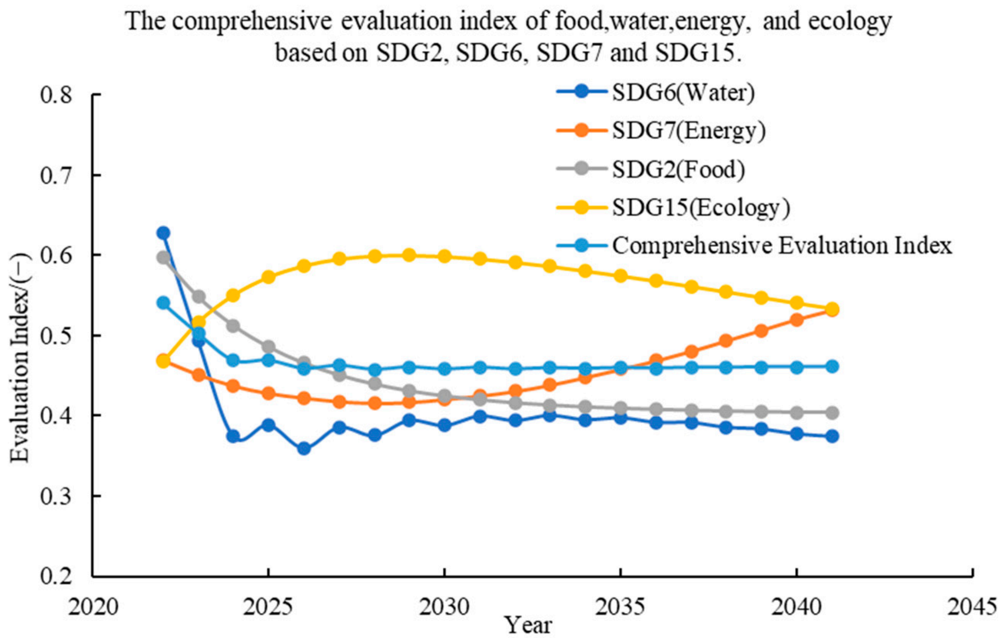

Figure 6. The development evaluation index and composite development index of the WEFC System for 2022–2041.

As shown in Figure 5, in the last 22 years, in the upper Han River, the comprehensive evaluation indicators for SDG2 (food system), SDG6 (water system), SDG7 (energy system), and SDG15 (ecosystems), showed fluctuating changes, and the comprehensive development evaluation index tended to be on an upward trend. Its trend was most affected by the evaluation indices for the water resource system. This was mostly caused by the water resource system's explosive growth as well as the energy, food, and ecological systems' instability.

The evaluation indicators for the food system (SDG2) showed a decreasing and then increasing trend in these 22 years, which was the same as the pattern of development in local agriculture. As the economy has grown, the total power of machinery continued to rise, while there was a gradual decrease in the sown area of grain and irrigated area of arable land in 2000–2017, as well as a downward trend in grain production. After 18 years, the grain production and sown area increased year by year. The state strengthened its support for agriculture and significantly improved agricultural infrastructure, with per capita grain production rising by 7%, and the total value of the primary sector steadily rising, increasing more than sevenfold in 22 years.

The indicators for the evaluation of the water resource system (SDG6) fluctuated considerably. The total amount of water resources dropped sharply in 2015 and 2016, and then it resumed a steady rise. The total water consumption increased year by year, with the lowest comparisons being found in 2006 and 2016, which was mainly due to the decreases in precipitation in 2006 and 2016, as well as the increase in water consumption for agriculture, which led to a decrease in the evaluation indices for water resource development. During the 22-year period, the water consumption represented by 10,000 yuan of GDP fell by more than 90%, industrial wastewater discharge fell by 78%, and the sewage treatment rate significantly increased, which was related to the national policy of optimizing the industrial structure and focusing on environmental protection. During this 22-year period, the water consumption per capita increased by 16%, and the water consumption per mu of irrigated farmland has decreased by 16 percentage points. These factors caused fluctuations in the overall evaluation indicators.

The indicators for evaluating the energy system (SDG7) maintained an upward trend over the 22-year period, with an increase of 88%, and they basically remained between 0.3 and 0.6, with energy consumption increasing nearly threefold and electricity consumption more than twofold over this period, showing a significant negative pull effect. The energy-use efficiency rose year by year, and the gross product, total output value of agriculture, forestry, animal husbandry, and fisheries, energy-use efficiency, night lighting data, and general rate of comprehensive utilization of industrial waste all steadily rose year by year, which indicated that the upper Han River Basin steadily improved in the optimization of its energy structure and improved its energy efficiency. The energy evaluation indices were largely influenced by scientific and technological progress and policies.

The impact on ecosystems (SDG15) fluctuated considerably, and the terrestrial ecological indicators—except for the yearly average temperature, which increased year by year, the NDVI, and the degree of variability of river flow processes—showed unstable and fluctuating changes, and they did not increase much in the last 22 years.

On the basis of this quantitative assessment, a process perspective was used to assess the future development evaluation indices for water, food, energy, and ecology [39]. As shown in Figure 6, the water system fluctuated and then tended to stabilize, though it fluctuated the most. The energy system tended to steadily rise, while the comprehensive development index for food and ecosystems showed a downward trend; the exploitation and use of energy and the production and consumption of food caused the system's comprehensive performance capacity to be slightly lower, and there is a need to continue to optimize the energy structure, improve energy utilization, ensure high-quality arable land and grassland, and set up a highly efficient and low-pollution sustainable agricultural model.

3.3. Comparative Analysis of the Systematic Comprehensive Development Evaluation Index

Based on a previous study [40], the types of associations between each system are listed in Table 4, and the comparison coefficients of water and energy, water and food, water and ecology, energy and food, energy and ecology, and food and ecology are plotted in Figures 7 and 8.

Table 4. Comparison coefficients for each system and the classification of correlation types.

Subsystem Comparison	Comparison Coefficient	Comparison of Association Types
Water system, energy system	SDG6/SDG7 < 0.6	Extreme water impairment energy development mode
	0.6 ≤ SDG6/SDG7 < 0.8	Severe water impairment energy development mode
	0.8 ≤ SDG6/SDG7 < 1	Water supply scarcity energy development mode
	1 ≤ SDG6/SDG7 < 1.5	Adequate water supply energy development mode
	1.5 ≤ SDG6/SDG7	Particularly abundant water resources energy development mode
Water system, food system	SDG6/SDG2 < 0.6	Extreme water impairment food development mode
	0.6 ≤ SDG6/SDG2 < 0.8	Severe water resource impairment food development mode
	0.8 ≤ SDG6/SDG2 < 1	Water supply scarcity food development mode
	1 ≤ SDG6/SDG2 < 1.5	Adequate water supply food development mode
	1.5 ≤ SDG6/SDG2	Particularly water sufficient food development mode
Water system, ecosystem	SDG6/SDG15 < 0.6	Extreme water impairment eco-development mode
	0.6 ≤ SDG6/SDG15 < 0.8	Severe water impairment eco-development mode
	0.8 ≤ SDG6/SDG15 < 1	Water supply shortage eco-development mode
	1 ≤ SDG6/SDG15 < 1.5	Water resource adequacy eco-development mode
	1.5 ≤ SDG6/SDG15	Particularly water sufficient eco-development mode
Energy system, food system	SDG7/SDG2 < 0.6	Extreme energy impairment food development mode
	0.6 ≤ SDG7/SDG2 < 0.8	Severe energy impairment food development mode
	0.8 ≤ SDG7/SDG2 < 1	Energy supply shortage food development mode
	1 ≤ SDG7/SDG2 < 1.5	Adequate energy supply food development mode
	1.5 ≤ SDG7/SDG2	Particularly energy sufficient food development mode
Energy system, ecosystem	SDG7/SDG15 < 0.6	Extreme energy impairment eco-development mode
	0.6 ≤ SDG7/SDG15 < 0.8	Severe energy impairment eco-development mode
	0.8 ≤ SDG7/SDG15 < 1	Energy supply shortage eco-development mode
	1 ≤ SDG7/SDG15 < 1.5	Energy resource adequacy eco-development mode
	1.5 ≤ SDG7/SDG15	Particularly energy sufficient eco-development mode
Food system, ecosystem	SDG2/SDG15 < 0.6	Extreme food impairment eco-development mode
	0.6 ≤ SDG2/SDG15 < 0.8	Severe food impairment eco-development mode
	0.8 ≤ SDG2/SDG15 < 1	Food supply shortage eco-development mode
	1 ≤ SDG2/SDG15 < 1.5	Food resource adequacy eco-development mode
	1.5 ≤ SDG2/SDG15	Particularly food sufficient eco-development mode

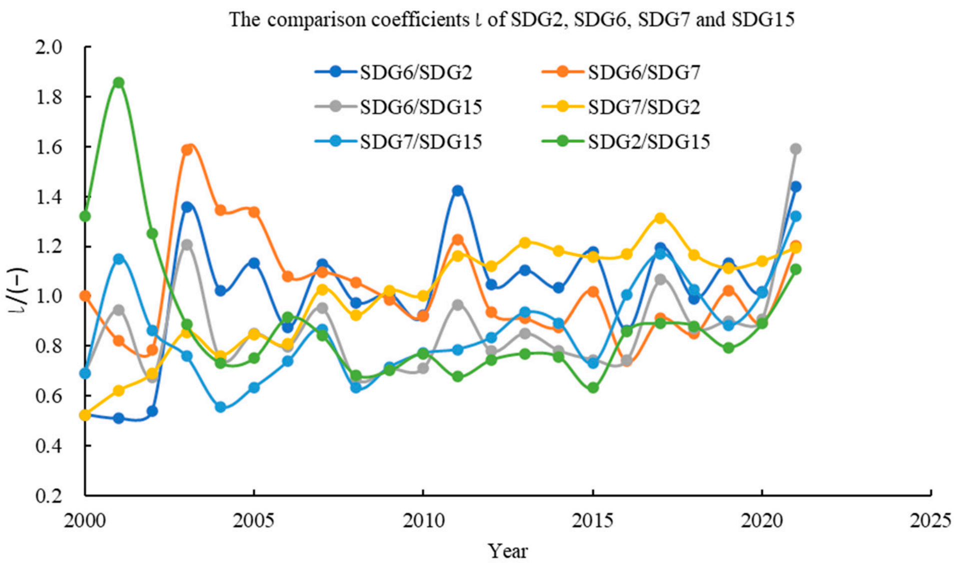

Figure 7. Comparison coefficients for SDGs 2, 6, 7, and 15 in 2000–2021.

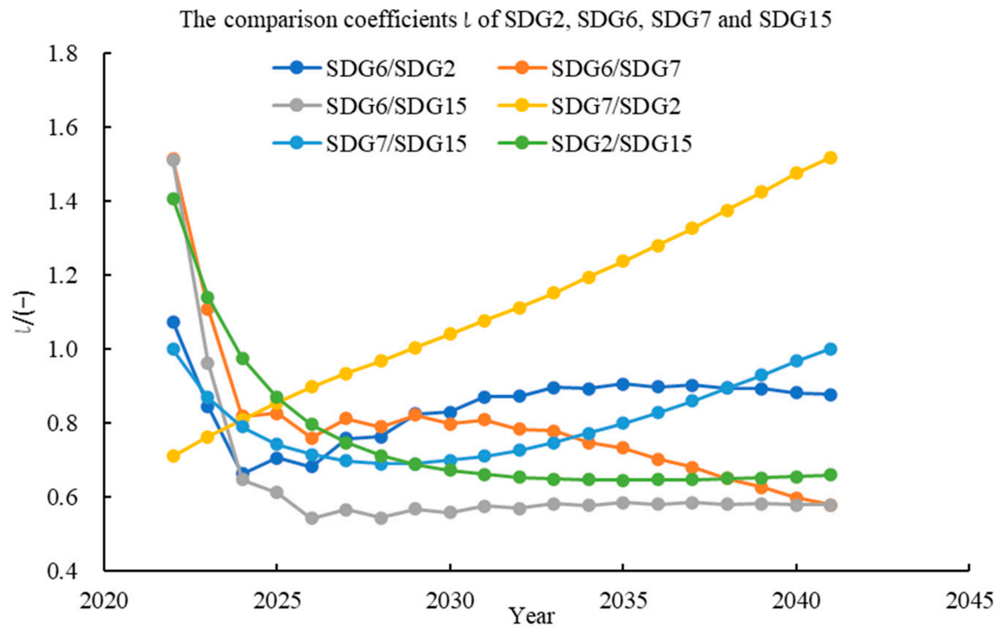

Figure 8. Comparison coefficients for SDGs 2, 6, 7, and 15 in 2022–2041.

According to the results shown in Figure 7, the comparison coefficients of the evaluation indicators for SDG6 and SDG7 basically stayed near 1, placing them in the category the energy development mode with a sufficient supply of water resources, and the coefficient of 1.588 indicated that the energy development mode with particularly sufficient water resources was reached in 2003. The comparison coefficients from 2003 to 2008 were always greater than 1, meaning that the energy development mode with a sufficient supply of water resources was achieved, which indicated that the development of the water system was superior to that of the energy system during this period of time.

SDG2 and SDG6 comparison coefficients revealed that the food development mode with severely degraded water resources typified the three years between 2000 and 2002. In 2001, the lowest value of 0.509 was attained, and this suggested that the water system was severely impaired in accordance with SDG6. Compared to SDG2, SDG6's development was more constant after 2003; the comparison coefficient was nearly 1, showing that the growth of SDG6 and SDG2 was balanced in the upper Han River. The development mode in 2003–2005, 2007, 2009, 2011–2015, and 2019–2021 was that of sufficient water resources. This was due to the high relative utilization efficiency of water resources. That is, the development of SDG6 (water system) was better than of SDG2 (food system).

The coefficients of the evaluation indicators of SDG2 and SDG15 showed that the years 2000–2002 and 2021 were characterized by the eco-development mode with an adequate food supply, and the eco-development mode with exceptional food sufficiency was reached in 2001. However, the years 2008–2015 were characterized by severely impaired food resources, as the irrigated area of arable land and the sown area of grain decreased year by year, while use the of pesticides and fertilizers increased year by year. Although the grain output increased year by year, the food development lagged behind the ecological development of the whole food system. After 2016, according to the assessment indices, there was a shift from the ecological development mode with seriously degraded food resources to the ecological development mode with an adequate supply of food.

The comparison coefficients of SDG7 and SDG2 showed an upward trend during the 22-year period. They began in the development mode of extremely impaired food, changed to the food development mode with an energy supply sufficiency, transitioned to the food development mode with energy supply sufficiency stabilized, and then reached the food development mode with energy supply sufficiency in 2021, which indicated that the development of the energy system was better than that of the food system, benefiting from the national to ecological development.

The comparison coefficients of SDG7 and SDG15 showed large fluctuations during the 22-year period. From 2003 to 2011, they were initially identified as having a severely energy-impaired food development mode, which later changed to a food development mode with a sufficient energy supply, as structural optimization was performed, and energy efficiency was increased.

SDG6 and SDG15 comparison coefficients revealed that only the years 2003, 2017, and 2021 were able to attain the ecological development mode with an adequate supply of water, and the remaining years' comparison coefficients were less than 1, suggesting that throughout this time, the development of local water supplies fell behind that of the environment.

According to Figure 8, the coefficients of SDG6, SDG7, SDG2, and SDG15 showed changes, and the changes in energy and food were slightly larger. SDG7 and SDG2 were characterized by the food development mode with sufficient energy supply after 2031, and they tended to be stably rising, which indicated that the development of SDG7 was sufficient in this period. The coefficients of SDG6 and SDG2 were shown to be characterized by the mode of water supply shortage in the next 20 years, and they showed a decreasing trend. SDG6 and SDG7 were shown to be in the energy development mode with severe water resource impairment in the next 20 years; the coefficients decreased, increased, and then stabilized, indicating that SDG7 was in a period of sufficient development. SDG6 and SDG15 were shown to be characterized by the ecological development mode with severe water resource impairment in the next 20 years, indicating that the development of water resources in the region will lag behind eco-friendly development in the future. The ecological growth mode with substantial food impairment was demonstrated to define SDG2 and SDG15 over the next 20 years, after which they tended to drop until stabilizing.

3.4. Analysis of the Degree of System Coupling and Coupling Coordination

The coupling and coordinated coupling of SDG2, SDG6, SDG7, and SDG15 for the upper Han River in 2000–2021 and 2022–2041 were obtained and are shown in Figures 9 and 10.

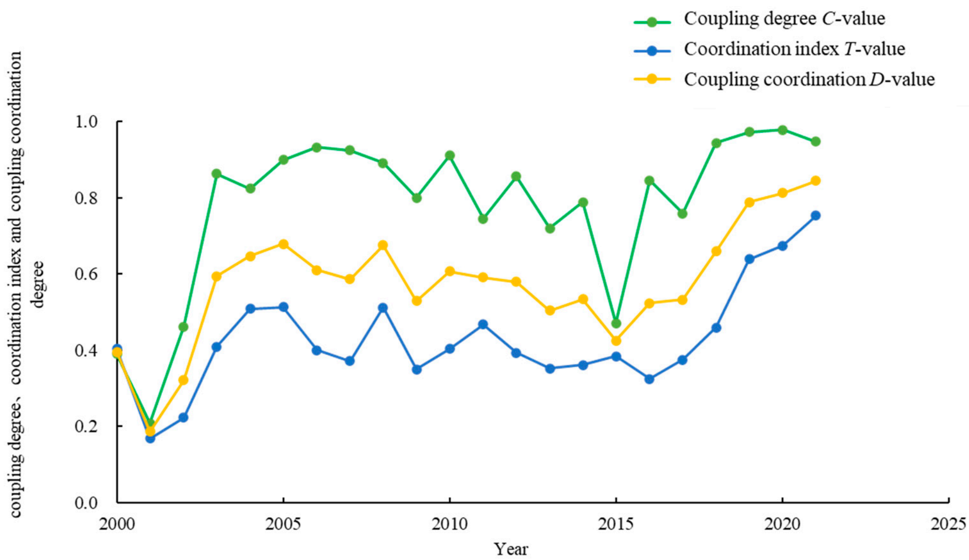

Figure 9. Coupled coordination charts for 2000–2021.

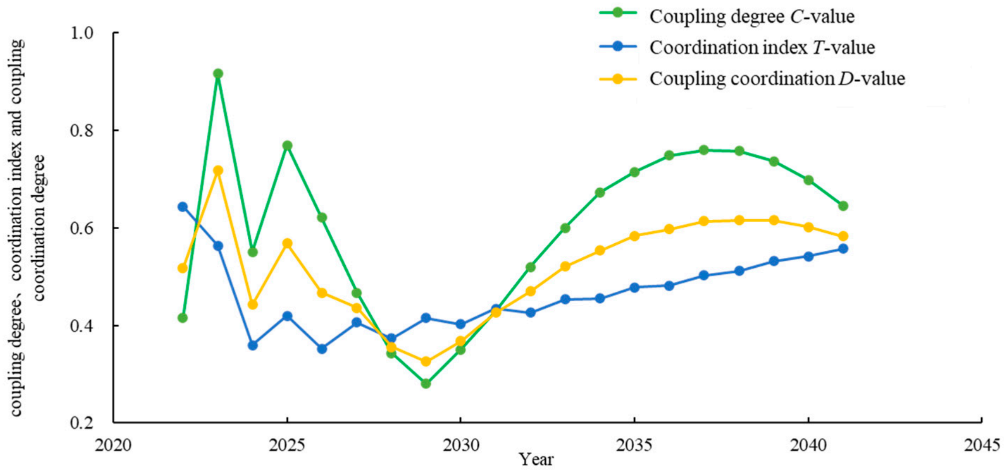

Figure 10. Coupled coordination charts for 2022–2041.

According to the results of the analysis in Figure 9, from 2000 to 2021, the upper Han River's ecosystems, food, energy, and water coupling degree varied and fluctuated, and the overall trend was gradually increasing. The degree of coupling and coordination went from serious dysfunctions to high-quality coordination during this period, and the *C*-value fluctuated within the range of 0.72 to 0.98 after 2003 except for 2015, indicating a high level of coupling, so the degree of coupling of the water, energy, food, and ecosystems within this system was high. The subsystems were associated with a high degree of coupling, and there was an overall trend of increasing for the water system and comprehensive evaluation index for energy, which was conducive to the improvement of the degree of coupling within the whole system [41].

The coupled coordination degree of the WEFC system in the upper Han River from 2000 to 2021 can be divided into three stages. The first stage was in 2000–2002 as the WEFC system in the upper Han River was in a state of dislocation in this time period. The second stage was in 2003–2019, as the coupled coordination degree fluctuated and changed, presenting a state of basic coordination or medium coordination. The third stage was in 2020–2021, when the model reached a state of high-quality coordination. The degree ranged from 0.396 in 2000 to 0.845 in 2021, with an increase of 113% from 2000 to 2021.

From 2022 to 2041, the coupling coordination degree of the WEFC system in the upper Han River first showed a decreasing trend, as shown in Figure 10. Then, in 2029, it started to show an increasing trend from 0.326 to 0.583, an increase of 79%, followed by a smaller increase, but a stable developmental trend was maintained in the overall coordination of the system, which developed from a barely coordinated state to a well-coordinated state. Overall, the interrelated status of the coupling coordination in the WEFC system based on SDG2, SDG6, SDG7, and SDG15 will be further strengthened and optimized in the future, which will promote the continuous improvement of the WEFC system.

4. Discussion

Overall, the upper reaches of the Han River typically have a strong coupling coordination degree. This study provided a comprehensive understanding of the WEFC system in a historical period and a future period. However, this method of making future predictions is based on historical data and ignores the impact of outside variables, such as laws and the significant exchange of materials and energy with the outside of the region. There are some uncertainties in the results of the future predictions, particularly in the long-term prediction [42]. It is important to consider the uncertainty of the prediction in the decision-making regarding development policies based on the evaluation, and attention should be paid to the interaction between the WEFC system and the outside too. The upper Han River basin is the water source region of the middle route of the National South-to-North Water Diversion Project, and also the water source region of the Han-to-Wei Water Diversion Project in Shaanxi Province too. After the implementation of the Han-To-Wei Water Diversion Project in the next several years, the water resources situation will change, and a change in the ecosystem and energy system will follow it. This is a typical interaction of socio-hydrological processes and can be studied based on socio-hydrological modeling [25].

5. Conclusions

In this study, a coupled and coordinated evaluation system for water, energy, food, and ecology was constructed based on the Sustainable Development Goals. We classified different WEFC associations, identified key indicators, and selected 31 indicators that captured the characteristics of the system of the upper Han River basin in China. Continuous data of 22 years (from 2000 to 2021) were collected, and the data series for the next 20 years were predicted using the ARIMA model to analyze the results of the coupled model on a long time series. We considered the regional limitations, the actual situation, and changes in the data themselves in the analysis.

In this study, SDG2, SDG6, SDG7, and SDG15 were selected to provide scientific guidance for the assessment of the WEFC system in order to enhance the sustainability of the region and promote the coordinated development of the resources and the achievement of the SDGs at the regional level.

In this study, the weights of the indices were computed using the entropy weight method and the CRITIC weighting method, and the comprehensive evaluation indices were used to analyze the degree of system coupling and coordination from 2000 to 2041.

The comprehensive development index of the upper Han River based on SDG2, 6, 7, and 15 increased by 113% during the period of 2000–2021, and the degree of coupling coordination increased from 0.396 to 0.845, demonstrating stable development in general. The water system fluctuated the most, and the fragile support capacity of the water system for the energy system, food system, and ecosystem had a great impact on the overall comprehensive evaluation index. There were differences in the development status of the four systems in SDG2, SDG6, SDG7, and SDG15; therefore, the degree of coordinated development of the respective goals needs to be improved.

SDG2, 6, 7, and 15 have prominent internal conflicts, which are mainly between food systems and water systems, between food systems and energy systems, and between food systems and ecosystems. These bi-directional dynamics tended to converge on the sufficiency development mode in both the historical period and the projected period.

The coupling among SDG2, 6, 7, and 15 remained at a high level, indicating that there were intrinsic linkages and interactions among the four goals. In the process of vigorously promoting the achievement of the goals, the coupling degree also tended to be coordinated in 2022–2041, but it was still not stable enough. It is necessary to further improve the level of coupling and coordination among the goals, which is socially important to guide the integrated management of regional resources and the promotion of their sustainable development.

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Data Availability Statement: Date will be made available on request. All relevant data are within the paper.

Conflicts of Interest: Author Guanghui Ming was employed by the company Key Laboratory of Water Management and Water Security for Yellow River Basin (Ministry of Water Resources), Yellow River Engineering Consulting Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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