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Abstract: In this paper we take 30 provinces and cities in China (excluding Tibet, Hong Kong, Macao and Taiwan) as the research object, and construct a comprehensive evaluation system for the water-energy-food nexus (WEF Nexus). Then we use the entropy method to assign weights to various indicators. At last, we combine the indicators with coordination model (including the coupling model and the coupling coordination model) to measure the comprehensive evaluation index and coupling coordination degree of 30 provinces in China from 2005 to 2017 and conduct quantitative evaluation and analysis. The results showed that: 1) The WEF Nexus comprehensive evaluation index of 30 provinces in China showed a slow upward trend. The comprehensive evaluation index of the southern region was higher than that of the north, and the comprehensive evaluation index of the eastern region was higher than that of the west; 2) The coordination degree of WEF Nexus in China's 30 provinces has reached high level in the horizontal coupling stage, the overall degree of coupling coordination is on the rise. As of 2017, the WEF Nexus coupling coordination degree of most provinces in China has reached 0.700 or more, which belongs to the intermediate coordinated development type. In the six selected years, 30 provinces have experienced five types of development: near coordinated, barely coordinated, primary coordinated, intermediate coordinated, and well-coordinated.

Keywords: water-energy-food; nexus; comprehensive evaluation index; coupling degree; coupling coordination degree; China;

1 Introduction

Water, energy, and food are three basic elements that support the normal operation of human survival and development. Human need food and water to survive and long-term using of external energy sources to meet basic life needs. Water, energy, and food are interconnected, influenced and restricted each other. That is, the production and consumption of any one of them will affect the other two resources (Zhang Lixiao et al, 2019). In response to rapid population growth, globalization, rapid economic development, and urbanization's pressure on the three resources of water, energy and food, the German "Water-Energy-Food Security Negative Relations Conference" firstly proposed the concept of "Water-Energy-Food Nexus" which summarizes the relationship between water security, energy security, and food security as "nexus"(Chang Yuan et al, 2016). After the Bonn Conference, more and more scholars have focused their attention on the research of "Water-Energy-Food Nexus" and conducted qualitative or quantitative analysis of the intricate relationship between water, energy and food from different angles.

At present, the research contents of WEF Nexus is mainly divided into three aspects: 1) Research on the relationship between WEF Nexus; 2) Research on the internal mechanism of WEF Nexus; 3) Research on quantitative prediction of WEF Nexus.

Tony Allan et al. (2015) introduced the concept of the "water-energy-food nexus" from a global perspective, and established a conceptual framework that includes two interacting systems, namely the water-food-trade system and the energy-climate change system. And list the challenges faced by those who wish to use this concept in arid regions around the world. Wang Huimin et al. (2019) used the method of Nexus analysis and the "pressure-state-response" (PSR) model proposed by OECD and UNEP[5] to construct a "water-energy-food-economic society" PSR model, and summarized the processes of transmission and interaction of the information flow, material flow, and policy flow among the four systems of water, energy, food, and economic society. On this basis, the WEF collaborative security framework is proposed. Hong-Mei Deng et al. (2001) explored the hidden connection between water, energy and food resources by determining important final demands based on input-output models and structural path analysis.

In China, water security is the most prominent issue in WEF Nexus that manifested in the competitive relationship between water for food and energy production. En Hua et al. (2020) improved the existing water footprint accounting method for food and energy production, and calculated the food water footprint (blue water footprint and green water footprint) of 31 provinces in mainland China in 2015, and the main energy nexus blue water footprint. The research also proposes the Index of Water Stress (IWS), Food and Energy Stress for Water Contribution Rate (WCR), Food and Energy Water

Consumption Rate (n) and Water-Energy-Food Competitive Composite Index (CCI) to evaluate the consumption and the intensity of competition for water resources in food and energy production in different regions. Sun Caizhi et al. (2018) used methods such as Logistic curve, coupling coordination degree model and exploratory spatial data analysis to conduct safety assessment and spatial correlation analysis on China's Water-Energy-Food Nexus.

Li Guijun et al. (2016) constructed a causality network of complex system with WEF Nexus as the main body and covering social, economic, and environmental systems, and used system dynamics technology to simulate the dynamics of Beijing WEF Nexus and predict the trend of change. Jian Chai et al. (2020) used the Bayesian network model to propose a quantitative analysis framework based on the relationship between water-energy-food-economy-society-environment, and predicted the demand for water, energy, and food from the perspective of system interaction. Venla Niva et al. (2020) carried out a quantitative spatial scenario analysis to determine the provinces that are expected to experience changes in water stress under the situation where the food and energy sectors compete for water resources.

Since the concept of WEF Nexus was first proposed, the field has experienced a rapid development stage, but so far there is no clear and unified definition of the concept, and the conceptual framework of Nexus has not been proposed. For now, this is still the direction that researchers need to work on. Exploring the driving force of WEF Nexus pressure from the perspective of open systems is the direction that the follow-up research needs to consider and improve this research (2018). The various systems within WEF Nexus influence and restrict each other. Social, economic, demographic and ecological factors will also affect the WEF relationship. Therefore, for countries or regions, how to realize the coordinated development of resources is the future of this field. One of the research directions.

At present, China is facing serious resource shortages, uncoordinated resource development, and continuous deterioration of the environment. In-depth research on water, energy, and food issues can provide good theoretical and technical support for dealing with these problems. At present, most of the research on WEF Nexus in China is concentrated on the national or city level. This article takes 30 provinces of China (excluding Tibet, Hong Kong, Macao and Taiwan) as the research object, selects relevant data from 2005 to 2017, and combines the coordination and coupling model to analyze the WEF Nexus of 30 provinces in China. The coordinated development of Nexus has been quantitatively analyzed to further understand the development status of WEF Nexus in various provinces in China and can propose targeted measures for different problems in various provinces. This will help the country formulate and implement strategies to promote water, energy, and food resources sustainable development. The coordinated development of the nexus has very important practical significance.

2 Methodology

There is more and more literature focus on quantitative methods to research WEF Nexus. For example, Input-Output Model, Life-Cycle Assessment, Water Footprint Accounting Method etc. are always used to understand and quantify the relationship between water, energy, and food. Yuhan Liang et al.(Liang et al., 2020) use EE-MRIO model to investigate how the final demand of WEF products drives the extraction the resources of WEF Nexus and analyze how the primary inputs of sectors that experience water withdrawals, energy extraction, and food harvest enable the extraction of WEF Nexus resources. En Hua et al. (2020) use water footprint accounting method to assess the degree of competition between food and energy for water by using indicators such as Competition Composite Index (CCI) of WEF and analyze the water resources competition in food and energy production in different provincial administrative regions of China. Pei-Chiun Li et al. (2020) evaluate the embodied resource consumption in WEF nexus in Taiwan and to distinguish resource flows into direct and indirect consumption based on LCA method. Hong-Mei Deng et al. (2020) aim to quantify and capture the critical final demand categories that have an important impact on embodied water-energy-food uses in China by applying Environmentally Extended Input-Output (EEIO) model and Structural Path Analysis (SPA) methods. Based on Eora MRIO database, Anne Owen et al. (2017) use input-output analysis techniques to investigate the interaction between the water energy, and food impacts of products at different points along their supply chains, from the extraction of material and burning of energy, to the point of final consumption and then identify the twenty most important final products whose large energy, water and food impacts could be captured by various demand-side strategies such as reducing food waste or dietary changes. Tasnuva Mahjabin et al. (2020) focus on America, based on virtual water trade network provide a quantitative estimation of the virtual water embodied in the internal US food and energy transfers and analyze the associated interdependence of these connections.

Some researchers also pay attention to the system simulation field to evaluate and predict the WEF Nexus from different perspectives. The main methods used by researchers are System Dynamic model, Simultaneous Equations Model, Bayesian networks, MIFCP ect. Wa'el A. Hussien et al. (2017) use system dynamics-based model to present the structure of a developed integrated model for water, energy and food consumption at a household scale. The developed model addresses the impact of lifestyle change (user behaviour), family size, household income, appliances efficiency and climate change (increase/decrease the duration of summer season) on the future demand for water, energy, and food. Wa'el A. Hussien et al. (2018) investigate the impact of seasonal variability on the demand for water, energy, and food, using a previously developed WEF model (a system dynamic-based model). Albert Wicaksono et al. (2019) propose a novel Water-Energy-Food Nexus Simulation Model (WEFSiM) to identify the critical factors affecting the availability of certain resources through feedback analysis Various types of water resources, power plants, and food categories are implemented in the model to provide more accurate and detail simulation. Huang Daohan et al. (2020) develop and estimate a Simultaneous Equations Model with structural equations to explain an urban WEF structure from a process perspective and explored synergies in the urban WEF nexus. Jialin Yi et al. (2020) construct a composite index, combining single WEF sector indicators and WEF linkage indicators that reflect the characteristics of the nexus to develop a composite sustainability index for the WEF nexus that provides theoretical advances by combining single WEF sector indicators with WEF linkage indicators and explore the divergence of assessment results when weak and strong sustainability criteria are applied, and consider the practical ramifications of these concepts using Jiangsu Province, China, as a case study.

Optimal management is also an important field of WEF Nexus to connect the theoretical research with practical management. Researchers are trying to use system integration methods to deeply explore the relationship between water, energy and food and propose optimized management plans. An integrated model analysis framework and tool called WEFO is developed by Xiaodong Zhang et al. (2017) to support the decisions of the water-energy-food nexus management. The WEFO model is capable of simultaneously addressing interactions among the water, energy, and food subsystems, as well as their effects on the decision alternatives and strategies for supporting nexus management. L.Yu et al. (2020) propose a multi-level interval fuzzy credibility-constrained programming (MIFCP) method for planning the regional-scale water-energy-food nexus (WEFN) system. MIFCP can not only deal with uncertainties expressed as interval parameters and fuzzy sets, but also handle conflicts and hierarchical relationships among multiple decision departments.

All in all, with the development of WEF Nexus field, there will be more and more comprehensive methods to be proposed. In matter of fact, most of the existing papers use some traditional methods to quantify the WEF relationship without considering its complexity, comprehensive and interdisciplinary. Thus, the traditional methods are not much appropriate to use. Although some scholars have initially proposed optimization models for the WEF Nexus and the coordinated management of WEF Nexus at the basin scale, there is still a gap between these theoretical studies and practical management. There is an urgent need to develop models and tools that can integrate WEF Nexus with society, economy and ecosystem, etc. Especially in the effective management of the urban WEF relationship, there is no general model or tools can be used yet.

2.1 Concepts

Coupling coordination degree is an index used to evaluate the coupling coordination development level of WEF Nexus. Related concepts include coupling degree and comprehensive evaluation index.

The concept of coupling comes from the field of physics. It refers to a measure that two or more entities depend on each other. The effect and degree of coupling determine the trend of the system from disorder to order (Cong Xiaonan et al, 2019). The key to the mechanism of the system from disorder to order lies in the synergy between the order parameters within the system. The synergy affects the characteristics and laws of the phase transition of the system, and the degree of coupling is a measure of this synergy (Wu Yuming et al, 2018). That is, the degree of coupling reflects the degree of mutual influence and interaction between the various subsystems of WEF Nexus.

Coordination refers to the benign relationship between different systems or elements. Coupling coordination measures the degree of harmony between different systems in the development process. Therefore, the concept of coupling coordination degree is introduced in the research to reflect the coordinated development level of WEF Nexus.

The comprehensive evaluation index is a technical process that quantifies the evaluation results. It integrates multiple indexes and finally forms a general index. Through index comparison, the evaluation goal is achieved. The comprehensive evaluation index reflects the comprehensive development level of WEF Nexus and each subsystem. Its value range is [0,1]. When the index falls at (0,0.3], it indicates that the system has a low level of development; it falls at (0.3, 0.7], indicating that the level of development of the system is average; when the index belongs to (0.7, 1], it indicates that the development level of resource is relatively high (Li Chengyu et al, 2020). The comprehensive evaluation index of each province's WEF Nexus subsystem will affect the overall evaluation value of WEF Nexus. If the development level of a certain subsystem lags behind, it will affect the overall WEF comprehensive evaluation index, and then affect the level of coupling coordination in the province.

2.2 Model's structure

2.2.1 Construction of an evaluation index system

Constructing a scientific and reasonable evaluation index system is the basis for evaluating the level of WEF's coordinated development (Deng Peng et al, 2017). Based on the existing literatures (Bi Bo et al, 2018; Liu Jing et al, 2019; Yin Qingmin et al, 2019; Zhang Hongfen et al, 2019; Zhang Hongfen et al, 2019) and following the principles of scientific, objectivity and dynamic, this paper selects the comprehensive evaluation indicators of water resources system, energy system and food system (Table 1).

Table 1 WEF Nexus Comprehensive Evaluation System

Subsystem	Evaluation index	Property

Water resources	Water resources per capita	Positive
	Water consumption per capita	Negative
	Total water consumption in each region	Negative
	Total wastewater discharge	Negative
	Water production modulus	Positive
	Proportion of agricultural water	Negative
	Proportion of industrial water	Negative
	Proportion of ecological water	Positive
	Water consumption per ten thousand Yuan GDP	Negative
Energy	Energy production	Positive
	Total energy consumption	Negative
	Growth rate of total energy consumption	Negative
	Energy self-sufficiency rate	Positive
	Energy consumption elasticity coefficient	Negative
	Energy consumption per ten thousand Yuan GDP	Negative
	Decrease rate of energy consumption per ten thousand Yuan GDP	Positive
Food	Per capita food production	Positive
	Effective irrigation area	Positive
	Grain planting area	Positive
	Grain production	Positive
	Total grain production volatility	Negative
	Food consumer price index	Negative
	Agricultural fertilizer application rate	Negative

Note: If the indicator type is positive, the larger the indicator value is, the better; if the indicator type is negative, the smaller the indicator value is, the better.

2.2.2 Determination of the index weight

According to the established evaluation system, the weighting method used in this paper is the entropy method. The entropy method is an objective weighting method which determines the index weight according to the information provided by the observation value of each index, and avoids the deviation caused by human factors. The calculation steps are as follows:

(1) Calculate the proportion of the j-th index in the i-th year P_{ij} :

$$P_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{m} X'_{ij}}$$

(2) Calculate the information entropy of the j-th index e_j :

$$e_j = -\frac{1}{ln_m}\sum_{i=1}^{m}(P_{ij}\, lnP_{ij})$$

(3) Calculate the difference coefficient of the j-th index g_j:

$$g_j = 1 - e_j$$

(4) Calculate the index weight W_j:

$$W_j = \frac{g_j}{\sum_{j=1}^{n} g_j}$$

Where, m represents the number of years to be counted; n represents the number of indicators of each system; $0 \le e_j \le 1$, the greater the entropy value, the smaller the index difference coefficient, when $P_{ij} = 0$, e_j=0; the greater the g_j value the more important the indicator.

2.2.3 Comprehensive evaluation index model

The comprehensive evaluation index is used to measure the development level of WEF Nexus and each system, and to improve its own status by comparing and analyzing the development level of each subsystem.

$$f(x) = \sum_{i=1}^{9} w_i X_{it}$$

$$g(y) = \sum_{j=1}^{7} w_j Y_{jt}$$

$$h(z) = \sum_{k=1}^{7} w_k Z_{kt}$$

X_{it}、Y_{jt}、Z_{kt} represent the standardized values of the indicators in the water, energy, and food systems; w_i、w_j、w_k represent the weights of the indicators in the water, energy, and food systems; $f(x)$、$g(y)$、$h(z)$ are the comprehensive evaluation indexes of water resources, energy and food systems in year t. The higher the index, the higher the level of development. On the contrary, the level of development is relatively lagging.

2.2.4 Coupling coordination degree model

The degree of coupling reflects the degree of association between WEF Nexus and the strength of the interaction, while the degree of coupling coordination reflects the level of development of WEF Nexus and the relationship between the interactions between systems and each other. For measuring the coordination of WEF Nexus The degree of development has certain applicability. Based on the relevant research of Liao Chongbin (1999) and other scholars, combined with the research objects of this article, the coupling degree model is constructed as follows:

$$C = \frac{3\sqrt[3]{f(x)g(y)h(z)}}{f(x)+g(y)+h(z)}$$

Among them, C represents the degree of coupling, and C ∈ [0, 1]. When C=0, it means that the coupling degree between systems is the smallest and the system is in an irrelevant state; C=1 means that the coupling degree between the systems reaches the maximum, and the system reaches a benign coupling state. According to relevant literature and the law of coupling development of WEF Nexus in the research area, the coupling degree is divided into 4 levels.

Table 2 Classification of coupling degree

Coupling coordination degree	**0~0.3**	**0.3~0.5**	**0.5~0.8**	**0.8~1.0**
Stage	Low	Antagonism	Run-in	High

The degree of coupling coordination can reflect the level of coordinated development of the three systems of water resources, energy and food. The coupling coordination degree model is constructed as follows:

$$D = \sqrt{C * T}$$

$$T = \alpha f(x) + \beta g(y) + \gamma h(z)$$

D represents the degree of coupling coordination, D∈[0,1]; T represents the comprehensive evaluation index of WEF Nexus; α, β, and γ represent the weight of each system, that is, the importance of each system. This article sets α=β=γ= 1/3. Combining related literature (Sun Caizhi et al, 2018; Li Gunjun et al, 2016), the coupling coordination degree is divided as follows (Table 3):

Table 3 Types of Coupling and Coordinated Development

<table>
<tr><th>Coordination degree</th><th>Stage</th><th>D Value</th><th>coordination type</th></tr>
<tr><td rowspan="4">Coordinated development（Acceptable interval）</td><td rowspan="2">Highly coordinated</td><td>0.90~1.00</td><td>High-quality coordinated</td></tr>
<tr><td>0.80~0.89</td><td>Well-coordinated</td></tr>
<tr><td rowspan="2">Basic coordination</td><td>0.70~0.79</td><td>Intermediate coordinated</td></tr>
<tr><td>0.60~0.69</td><td>Primary coordinated</td></tr>
<tr><td rowspan="2">Transition class（Transition zone）</td><td rowspan="2">Transition class</td><td>0.50~0.59</td><td>Barely coordinated</td></tr>
<tr><td>0.40~0.49</td><td>On the verge of coordinated</td></tr>
<tr><td rowspan="4">Dysregulation（Unacceptable interval）</td><td rowspan="2">On the verge of maladjustment</td><td>0.30~0.39</td><td>Mild dysregulation</td></tr>
<tr><td>0.20~0.29</td><td>Moderate Disorder Recession</td></tr>
<tr><td rowspan="2">Dysregulation</td><td>0.10~0.19</td><td>Severe dysregulation</td></tr>
<tr><td>0~0.09</td><td>Extremely maladjusted recession</td></tr>
</table>

2.3 Data source and processing

In order to measure the level of WEF Nexus coupling and coordination degree among China's provinces, this paper selects data on relevant indicators from China's provinces (excluding Tibet, Hong Kong, Macao and Taiwan) from 2005 to 2017. Because there is no available data of 2018-2019, we choose the data between 2005-2017. The main data comes from China Statistical Yearbook, China Energy Statistical Yearbook and Provincial Statistical Yearbook, etc. Some data are calculated using relevant formulas and basic data.

Standardize the original data to eliminate the inconvenience of data processing caused by different dimensions of the original data. The processing method is as follows:

Positive indicators:

$$X'_{ij} = (X_{ij} - minX_j)/(maxX_j - minX_j)$$

Negative indicators:

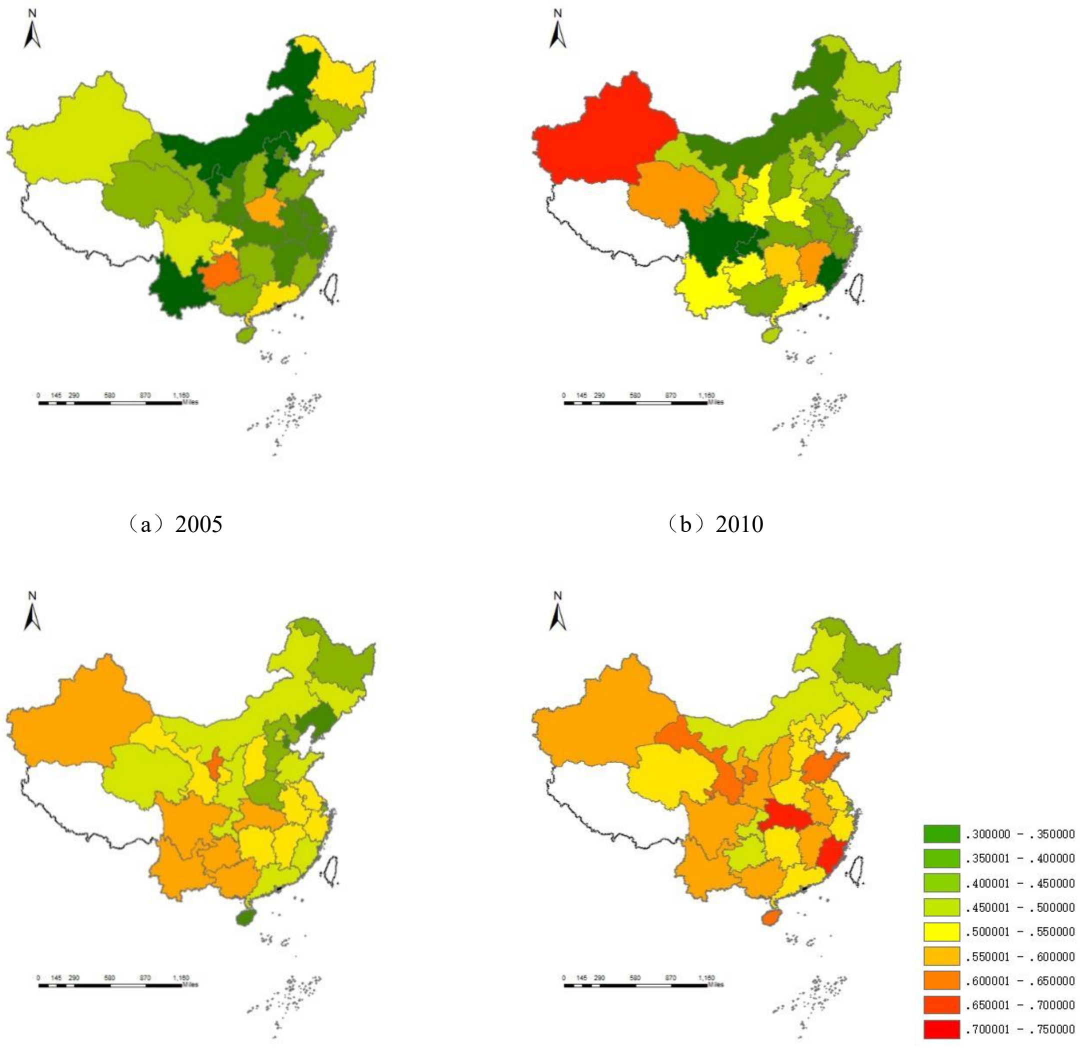
$$X'_{ij} = (maxX_j - X_{ij})/(maxX_j - minX_j)$$

Among them, X'_{ij} represents the standardized value, and X_{ij} is the original value; $maxX_j$、$minX_j$ are the maximum and minimum values of j index over the years.

3 Results

3.1 Comprehensive evaluation analysis

The comprehensive evaluation index of 30 provinces in China is calculated according to the corresponding model mentioned above. And the results are presented in ARC GIS. Figure 1 shows the comprehensive evaluation index of 30 provinces in 2005, 2010, 2015 and 2017 from left to right.



（a）2005　　（b）2010

（c）2015　　（d）2017

Figure 1 Comprehensive Evaluation Index of 30 Provinces in China

It can be seen from Figure 1 that the WEF Nexus comprehensive evaluation index of 30 provinces in China is generally showing a slow upward trend. The comprehensive evaluation index of the southern region is higher than that of the north, and the comprehensive evaluation index of the eastern region is higher than that of the western region. From 2005 to 2017, the provinces with a comprehensive evaluation index above 0.200 include Hubei, Yunnan, Shandong, Fujian, Ningxia, Hainan and Anhui. Among them, the province with the largest increase in the comprehensive evaluation index value between 2005 and 2017 was Hubei and the value of comprehensive evaluation index in 2017 was 0.663 with an added value of 0.270. The reason may be related to the further development of the food system in Hubei Province during 2005-2017. The evaluation index of the food system in Hubei Province increased from 0.325 in 2005 to 0.824 in 2017. This is due to the large increase in the province's per capita grain output during the study period, and the fluctuating and upward trend in total grain output, and a large grain yield per unit. Promote. The six provinces and cities of Heilongjiang, Shanghai, Henan, Guangdong, Chongqing, and Guizhou all have different degrees of decline in the comprehensive evaluation index between 2005 and 2017. The province with the largest decline in the index is Heilongjiang, and the comprehensive evaluation index of this province in 2017 was 0.408, A decrease of 0.137 from 2005. During the study period, the comprehensive evaluation index of the province's water resources system decreased from 0.672 in 2005 to 0.304 in 2017; the comprehensive evaluation index of the energy system decreased from 0.563 in 2005 to 0.291 in 2017; the comprehensive evaluation index of the food system showed a slight upward trend, Increased from 0.400 in 2005 to 0.628 in 2017. The food system was affected by the lagging development of energy and water resources systems, which led to a decline in the province's comprehensive evaluation index. In addition, in 2017, the top five provinces in the comprehensive evaluation index were Hubei, Fujian, Shandong, Hainan and Gansu, and the comprehensive evaluation indexes were 0.663, 0.652, 0.648, 0.643 and 0.603. The average comprehensive evaluation in 2005, 2010, 2015 and 2017 The indexes are 0.431, 0.471, 0.498, and 0.547 respectively, and it can be concluded that China's WEF Nexus comprehensive evaluation index is on the rise.

3.2 Coupling and coordination analysis

Based on the coupling coordination degree model and the results of the comprehensive evaluation index, the WEF Nexus coupling degree and coupling coordination degree of 30 provinces in China are calculated. Due to the large amount of data, this paper selects the coupling degree calculation results in 2005, 2010, 2015, and 2017 as shown in Figure 2, and selects the coupling coordination degree calculation results in 2005, 2008, 2010, 2013, 2015 and 2017 as shown in Figure 3.

It can be seen from Figure 2 that the coupling degree of WEF Nexus in China's 30 provinces is above 0.900, which has reached a high level of coupling, which indicates that the three subsystems have a high degree of correlation. During the study period, the fluctuation range of the WEF Nexus coupling degree was small and the change was relatively stable. As of 2017, the provinces with a low degree of coupling are Gansu, with a degree of coupling of 0.903, and the provinces with a higher degree of coupling are Tianjin, Henan, Hunan, and Sichuan.

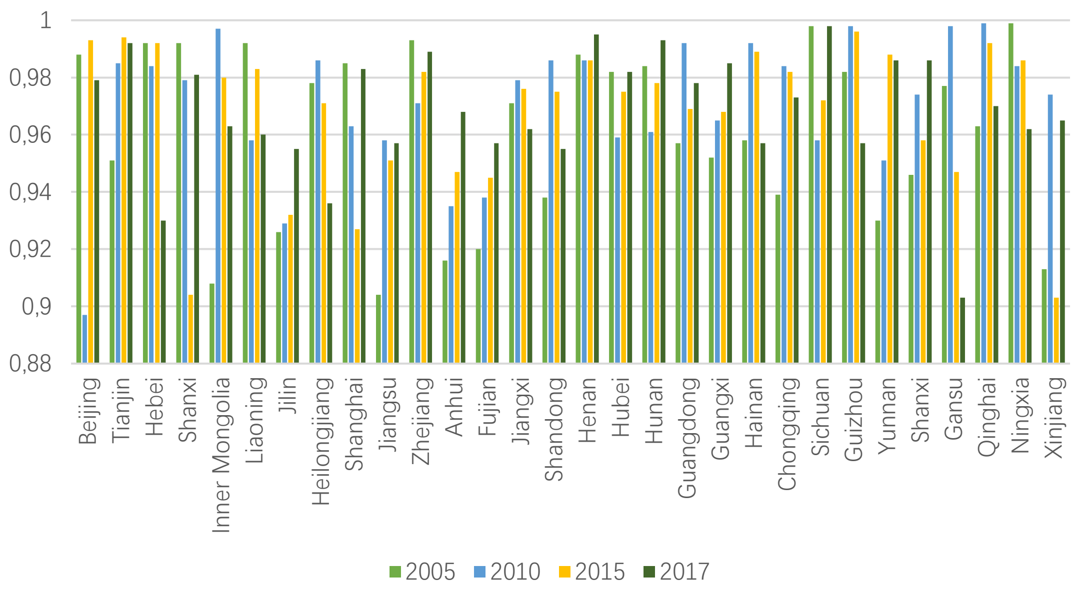
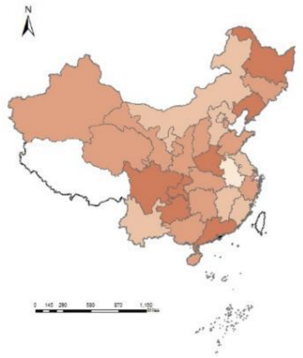


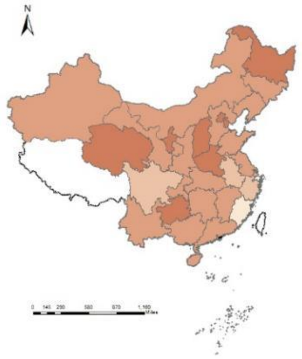
Figure 2 WEF Nexus coupling degree in 30 provinces of China

It can be seen from Figure 3 that the overall WEF Nexus coupling coordination degree of 30 provinces in China is on the rise. As of 2017, the WEF Nexus coupling coordination degree of most provinces in China has reached 0.700 or more which belongs to the intermediate coordinated development type. Hubei Province has the highest coupling coordination degree with a value of 0.807 that reaching a high level of coordination. There are also some provinces and cities with a degree of coupling coordination between 0.600-0.700. Among them, Heilongjiang Province has the lowest degree of coupling coordination with a value of 0.618, which belongs to the primary coordinated development stage. Industrial water consumption accounts for a large percentage of total water consumption, and water consumption per unit of GDP is year by year. The increase in energy production and the increase in energy consumption per unit of GDP have led to a low comprehensive evaluation index for the province's water resources and energy systems, which in turn affects the coupling and coordination degree of the province. It also indicates that the province's water resource utilization efficiency is low and water resources the shortage is serious.

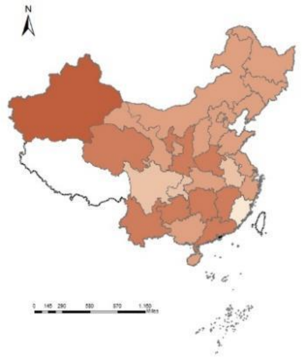
In the six selected years, 30 provinces have developed five types of development: near coordination, barely coordination, primary coordination, intermediate coordinated, and well-coordinated (Table 4). In the selected years, the number of provinces belonging to the primary coordinated development category were 14, 18, 16, 16, 16, and 8, respectively; the number of provinces belonging to the intermediate coordinated development and above categories were 7, 8, 10, 6, 13, and 22. Among them, in 2013, 2010, 2008, and 2005, there were 2, 1, 1, and 1 provinces and cities that were on the verge of coordinated development.



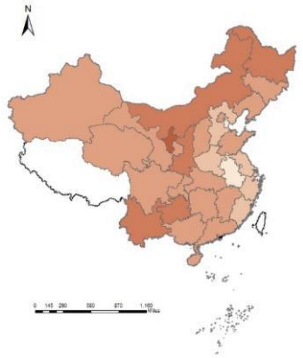
（a）2005



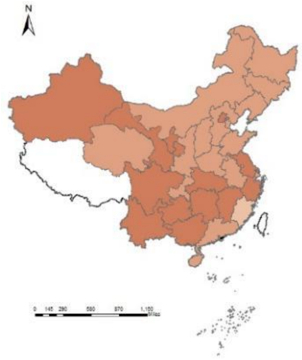
（b）2008



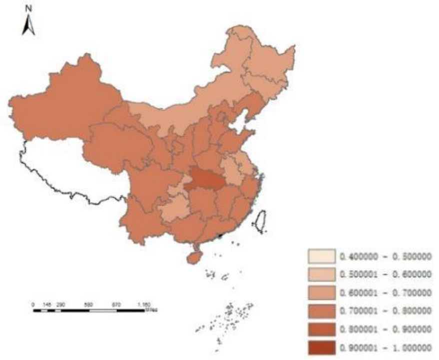
（c）2010



（d）2013



（e）2015



（f）2017

Figure 3 The coupling coordination degree of WEF Nexus in 30 provinces of China

The number of provinces in the barely coordinated and primary coordinated development stage is gradually decreasing, and provinces with the intermediate and well-coordinated development have shown an increasing trend year by year. In 2017, 21 provinces belonged to the intermediate coordinated development type, accounting for 70%, an increase of 46.7% over 2005; the remaining 8 provinces are in the primary coordinated development stage, accounting for 26.7%. In short, China's 30 provinces have entered the basic coordination stage in 2017, and most of them are in the intermediate coordinated development stage. This shows that as time goes by, more and more people begin to pay attention to the coordinated development of WEF Nexus and other issues, and the degree of coupling and coordination among provinces is getting higher and higher.

In the selected years, the coupling coordination degree of WEF Nexus in most provinces has gradually increased over time which indicates that when faced with water shortages, low resource utilization efficiency, energy depletion, and declining cultivated land area, local governments have realized the urgency of the problem and taken corresponding measures to solve a series of problems. Such as introducing advanced equipment to improve water resource efficiency, looking for alternative energy sources, adjusting industrial structure, improving energy efficiency and increasing food crop yields.

Table 4 The coupling and coordination degree in China's 30 provinces from 2005 to 2017

Year	On the verge of coordination	Barely coordinated	Primary coordination	Intermediate coordination	Well-coordinated
2005	Anhui	Fujian, Inner Mongolia, Yunnan, Ningxia, Hebei, Jiangsu, Jiangxi, Beijing	Jilin, Shanxi, Hubei, Shandong, Zhejiang, Qinghai, Hunan, Shanxi, Guangxi, Gansu, Hainan, Tianjin, Xinjiang, Shanghai	Liaoning, Guangdong, Sichuan, Chongqing, Heilongjiang, Henan, Guizhou	——
2008	Fujian	Anhui, Zhejiang, Sichuan	Jilin, Inner Mongolia, Shanxi, Guangxi, Hainan, Hubei, Liaoning, Shanghai, Chongqing, Guangdong, Gansu, Hebei, Jiangsu, Hunan, Shandong, Jiangxi, Yunnan, Xinjiang	Heilongjiang, Shanxi, Tianjin, Henan, Beijing, Qinghai, Ningxia, Guizhou	——
2010	Fujian	Anhui, Sichuan, Chongqing	Beijing, Hubei, Jiangsu, Inner Mongolia, Liaoning, Guangxi, Shanghai, Shanxi, Zhejiang, Tianjin, Jilin, Hebei, Hainan, Shandong, Heilongjiang, Gansu	Yunnan, Henan, Guangdong, Hunan, Shanxi, Guizhou, Ningxia, Jiangxi, Qinghai	Xinjiang
2013	Anhui, Tianjin	Henan, Fujian, Shanghai, Zhejiang, Hebei, Jiangsu	Hubei, Xinjiang, Chongqing, Shandong, Guangxi, Beijing, Sichuan, Jiangxi, Qinghai, Hunan, Jilin, Liaoning, Shanxi, Gansu, Guangdong, Hainan	Shaanxi, Guizhou, Heilongjiang, Yunnan, Inner Mongolia	Ningxia
2015	——	Fujian	Tianjin, Liaoning, Anhui, Hainan, Shanghai, Hebei, Henan, Heilongjiang, Shandong, Shaanxi, Chongqing, Jilin,	Beijing, Jiangsu, Gansu, Xinjiang, Zhejiang, Hunan, Jiangxi, Hubei, Sichuan, Guizhou,	——

			Inner Mongolia, Shanxi, Qinghai, Guangdong	Guangxi, Yunnan, Ningxia	
2017	——	——	Heilongjiang, Shanghai, Anhui, Jilin, Inner Mongolia, Guizhou, Jiangsu, Chongqing	Hebei, Liaoning, Guangdong, Beijing, Hunan, Fujian, Henan, Jiangxi, Qinghai, Ningxia, Zhejiang, Tianjin, Gansu, Xinjiang, Yunnan, Shanxi, Shaanxi, Sichuan, Guangxi, Hainan, Shandong	Hubei

4 Conclusion and policy recommendations

Based on the existing data we collected and corresponding methodology, we got the results of China's provincial WEF Nexus coupling coordination. And the relevant conclusions are as follows:

The WEF Nexus comprehensive evaluation index of 30 provinces in China is generally showing a slow upward trend. The comprehensive evaluation index of the southern region is higher than that of the north, and the comprehensive evaluation index of the eastern region is higher than that of the west. Each subsystem of WEF Nexus influences and restricts each other. The lagging development of a certain system may affect the comprehensive evaluation index in the region. Therefore, all provinces should pay attention to the coordinated development of the three systems of water, energy and food to improve the coupling and coordination of WEF Nexus.

The coupling coordination degree of WEF Nexus in China's 30 provinces has reached a high level and the degree of coupling coordination is on the rise. As of 2017, the WEF Nexus coupling coordination degree of most provinces in China has reached 0.700 or more, which belongs to the intermediate-coordinated development type. In the six selected years, 30 provinces have experienced five types of development: near coordination, barely coordination, primary coordination, intermediate coordination and well-coordinated development. Provinces with barely coordination and primary coordination development are gradually decreasing, and intermediate and well-coordinated development provinces have shown an increasing trend year by year. In 2017, 21 provinces belonged to the intermediate coordinated development type which accounting for 70%, an increase of 46.7% over 2005. The remaining 8 provinces are in the primary coordinated development category, accounting for 26.7%.

As the three basic elements supporting human survival and development, water, energy and food play an important role in the process of economic and social development and based on the conclusions obtained, we propose the following recommendations:

1) The three subsystems of WEF Nexus are interconnected and restricted. The production and consumption of any one resource will affect the other two resources. When designing the national development strategy, government departments need to consider the coordination and contact of relevant departments, also need to formulate a layout plan that can coordinate the economic and social development to promote the coordinated development of WEF Nexus.

2) Improve resource utilization efficiency. Inefficient use of resources is one of the main factors affecting resource consumption. Therefore, it is necessary to accelerate the process of related technology research and encourage innovation. Actively introduce advanced equipment, production techniques, technologies, and methods, establish water-saving mechanisms and resource recycling techniques to improve the efficiency of energy and water use and promote sustainable social development.

3) At the same time, all provinces should adjust the industrial structure according to the distribution of resources, eliminate outdated equipment, reduce high-energy-consuming industries, actively seek alternative energy sources, develop low-carbon new energy and other corresponding measures to avoid affecting overall coordinated development level of one region due to the lagging development of a certain system.

Reference

Allan, T. and M. Keulertz, et al. (2015) The water – food – energy nexus: an introduction to nexus concepts and some conceptual and operational problems. International Journal of Water Resources Development 31 (3): 301-311.

Chai, J. and H. Shi, et al. (2020) Quantifying and predicting the Water-Energy-Food-Economy-Society-Environment Nexus based on Bayesian networks - A case study of China. Journal of Cleaner Production 256: 120266.

Deng, H. M. and C. Wang, et al. (2020) Managing the water-energy-food nexus in China by adjusting critical final demands and supply chains: An input-output analysis. Sci Total Environ 720: 137635.

Deng, H. M. and C. Wang, et al. (2020) Managing the water-energy-food nexus in China by adjusting critical final demands and supply chains: An input-output analysis. Sci Total Environ 720: 137635.

Heinonen, S. and P. Jokinen, et al. (2001) The ecological transparency of the information society. Futures 33 (3): 319-337.

Hua, E. and X. Wang, et al. (2020) The competitive relationship between food and energy production for water in China. Journal of Cleaner Production 247: 119103.

Huang, D. and G. Li, et al. (2020) Exploring interactions in the local water-energy-food nexus (WEF-Nexus) using a simultaneous equations model. Science of The Total Environment 703: 135034.

Hussien, W. A. and F. A. Memon, et al. (2017) 2017-A integrated model to evaluate WEFnexus at a houshold scale. Environmental Modelling & Software.

Hussien, W. A. and F. A. Memon, et al. (2018) A risk-based aeeseement of the household WEF nexus under the impact of seasonal variability. Journal of Cleaner Production.

Li, P. and H. Ma (2020) Evaluating the environmental impacts of the water-energy-food nexus with a life-cycle approach. Resources, Conservation and Recycling 157: 104789.

Liang, Y. and Y. Li, et al. (2020) Quantifying Direct and Indirect Spatial Food-Energy-Water (FEW) Nexus in China. Environ Sci Technol 54 (16): 9791-9803.

Mahjabin, T. and A. Mejia, et al. (2020) Integrating embedded resources and network analysis to understand food-energy-water nexus in the US. Sci Total Environ 709: 136153.

Niva, V. and J. Cai, et al. (2020) China's sustainable water-energy-food nexus by 2030: Impacts of urbanization on sectoral water demand. Journal of Cleaner Production 251: 119755.

Owen, A. and K. Scott, et al. (2017) Identifying critical supply chains and final products-an input-output approach to exploring the WEF nexus. Applied Energy.

Wicaksono, A. and D. Kang (2019) Nationwide simulation of water, energy, and food nexus: Case study in South Korea and Indonesia. Journal of Hydro-environment Research 22: 70-87.

Yi, J. and J. Guo, et al. (2020) Sustainability assessment of the water-energy-food nexus in Jiangsu Province, China. Habitat International 95: 102094.

Yu, L. and Y. Xiao, et al. (2020). Planning water-energy-food nexus system management under multi-level and uncertainty. Journal of Cleaner Production 251: 119658.

Zhang, X. and V. V. Vesselinov (2017) Integrated modeling approach for optimal management of water, energy and food security nexus. Advances in Water Resources 101: 1-10.

Zhang Lixiao, Zhang Pengpeng, Hao Yan,et al (2019) Urban food-energy-water (FEW) nexus: conceptual frameworks and prospects. Acta Ecologica Sinica, 39(04): 1144-1153.

Chang Yuan, Xia Peng, Wang Jianping (2016) Overview of the water-energy-food nexus and its

enlightenment to China. Water Resources Development Research, 16(05): 67-70.
Tony Allan, Keulertz Martin, Woertz Eckart (2015) The water–food–energy nexus: an introduction to nexus concepts and some conceptual and operational problems. International Journal of Water Resources Development, 31(3): 301-311.
Wang Huimin, Hong Jun, Liu Gang (2019) Simulation research on different policies of regional green development under the nexus of water-energy-food. China Population,Resources and Environment, 29(06): 74-84.
Sirkka Heinonen, Jokinen Pekka, Kaivo-oja Jari (2001) The ecological transparency of the information society. Futures, 33(3): 319-337.
H-M Deng, Wang C, Cai W-J, et al. (2020) Managing the water-energy-food nexus in China by adjusting critical final demands and supply chains: An input-output analysis. Sci Total Environ, , 720137635.
En Hua, Wang Xinyu, Engel Bernard-A, et al. (2020) The competitive relationship between food and energy production for water in China. Journal of Cleaner Production, 247119103.
Sun Caizhi, Yan Xiaodong (2018) Security evaluation and spatial correlation pattern analysis of water resources-energy-food nexus coupling system in China. Water Resources Protection, 34(05): 1-8.
Li Gunjun, Li Yulong, Jia Xiaojing, et al. (2016) establishment and simulation study of system dynamic model on sustainable development of water-energy-food nexus in Beijing. Management Review, 28(10): 11-26.
Jian Chai, Shi Huiting, Lu Quanying, et al. (2020) Quantifying and predicting the Water-Energy-Food-Economy-Society-Environment Nexus based on Bayesian networks - A case study of China. Journal of Cleaner Production, 256120266.
Venla Niva, Cai Jialiang, Taka Maija, et al. (2020) China’s sustainable water-energy-food nexus by 2030: Impacts of urbanization on sectoral water demand. Journal of Cleaner Production, 251119755.
Bai Jingfeng, Zhang Haijun, et al. (2018) Spatio-temporal Variation and Driving Force of Water-Energy-Food Pressure in China. Scientia Geographica Sinica,38(10):1653-1660.
Y Liang, Li Y, Liang S, et al. (2020) Quantifying Direct and Indirect Spatial Food-Energy-Water (FEW) Nexus in China. Environ Sci Technol, 54(16): 9791-9803.
Pei-Chiun Li, Ma Hwong-wen, et al. (2020) Evaluating the environmental impacts of the water-energy-food nexus with a life-cycle approach. Resources, Conservation and Recycling, 157104789.
H-M Deng, Wang C, Cai W-J, et al. (2020) Managing the water-energy-food nexus in China by adjusting critical final demands and supply chains: An input-output analysis. Sci Total Environ, , 720137635.
Anne Owen, Scott Kate, Barrett John (2017) Identifying critical supply chains and final products-an input-output approach to exploring the WEF nexus. Applied Energy.
T Mahjabin, Mejia A, Blumsack S, et al. (2020) Integrating embedded resources and network analysis to understand food-energy-water nexus in the US. Sci Total Environ, 709136153.
Wa'el-A Hussien, Memon Fayyaz-A, Savic Dragan-A (2017) A integrated model to evaluate WEFnexus at a houshold scale. Environmental Modelling & Software.
Wa'el-A Hussien, Memon Fayyaz-A, Savic Dragan-A (2018) A risk-based aeeseement of the household WEF nexus under the impact of seasonal variability. Journal of Cleaner Production.
Albert Wicaksono, Kang Doosun, et al. (2019) Nationwide simulation of water, energy, and food nexus: Case study in South Korea and Indonesia. Journal of Hydro-environment Research, 2270-87.
Daohan Huang, Li Guijun, Sun Chengshuang, et al. (2020) Exploring interactions in the local water-

energy-food nexus (WEF-Nexus) using a simultaneous equations model. Science of The Total Environment, 703135034.
Jialin Yi, Guo Jie, Ou Minghao, et al. (2020) Sustainability assessment of the water-energy-food nexus in Jiangsu Province, China. Habitat International, 95102094.
Xiaodong Zhang, Vesselinov Velimir-V (2017) Integrated modeling approach for optimal management of water, energy and food security nexus. Advances in Water Resources, 1011-10.
L Yu, Xiao Y, Zeng X-T, et al. (2020) Planning water-energy-food nexus system management under multi-level and uncertainty. Journal of Cleaner Production, , 251119658.
Cong Xiaonan, et al. (2019) Expression and Mathematical Property of Coupling Model, and Its Misuse in Geographical Science. Economic Geography, 39(04): 18-25.
Wu Yuming, Zhang Yan, et al. (2008) Analyzing coupled regional economic growth and environmental conservation in China. Resources Science.
Li Chengyu, Zhang Shiqiang, et al. (2020) Chinese provincial water-energy-food coupling coordination degree and influencing factors research. China Population, Resources and Environment.
Deng Peng, Chen Jing, Chen Dan, et al. (2017) The evolutionary characteristics analysis of the coupling and coordination among water, energy and food: take Jiangsu Province as an example. Journal of Water Resources and Water Engineering, 28(06): 232-238.
Zhang Hongfen, Zeng Jingjing, Qu Jiansheng, et al. (2019) Research on the coupling coordination degree among water-energy-food system in high-intensity flow areas——A case study of Beijing, Tianjin and Hebei Province. China Rural Water and Hydropower, (05): 17-21.
Zhang Hongfen (2019) Comprehensive evaluation and coordination analysis of water, energy and food nexus in China. Lanzhou University.
Yin Qingmin, Wu Yi, et al. (2019) Case studies on water-energy-food coupling coordinated development in China. Resources & Industries.
Liu Jing, Liu Cuishan, Li Xiao, et al. (2019) Security evaluation of water-energy-food nexus system in China. Hydro-Science and Engineering (in Chinese).
Bi Bo, Chen Dan, Deng Peng, et al. (2018) The evolutionary characteristics analysis of coupling coordination of regional water-energy-food. China Rural Water and Hydropower, (02): 72-77.
Liao Chongbin (1999) Quantitative judgement and classification system for coordinated development of environment and economy: A case study of the city group in the Pearl River Delta. Tropical Geography, (02): 76-82.