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Evaluation and Scenario Prediction of the Water-Energy-Food System Security in the Yangtze River Economic Belt Based on the RF-Haken Model

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Abstract: As an important agricultural production area in China, the Yangtze River Economic Belt has a large amount of water resources and rich types of energy. Water and energy resources are the supporting basis of food production, and the production and use of energy also need to consume a large amount of water resources. The three affect each other and are interdependent. Paying attention to the synergistic security of water-energy-food system in the Yangtze River Economic Belt is important for regional economic development. This paper uses the pressure-state-response (PSR) model and selects 27 indicators to build an evaluation index system of the regional water-energy-food system. We use the random forest model to evaluate the security level of the Yangtze River Economic Belt from 2008 to 2017, and the Haken model is employed to identify the driving factors that dominate the synergistic evolution of the system. Then we take the identified factors as the key control variables under each scenario and launch a scenario simulation of some provinces in the Yangtze River Economic Belt in 2025. The results show that due to the improvement of water and energy utilization efficiency and the advancement of agricultural production technology, the level of water-energy-food security in the Yangtze River Economic Belt improved significantly from 2008 to 2017. Each province performs differently in different subsystems, with water resources security being better in the upper reaches and Zhejiang and Shanghai in the lower reaches, and food security being better in the middle and lower reaches. The level of energy security is high in Sichuan, Yunnan, and Guizhou in the upper reaches and Shanghai and Anhui in the lower reaches. According to the results of scenario prediction for Jiangsu Province and Hubei Province in 2025, implementing moderate management in accordance with current management objectives can increase the overall security of the system to level 4. The two provinces should focus on controlling water resources and energy consumption and improving the utilization efficiency of water and energy in agricultural production.

Keywords: Yangtze River Economic Belt; water-energy-food; security evaluation; scenario prediction; random forest-Haken model (RF-Haken)

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1. Introduction

Water, energy and food security are related to the survival and development of human beings and social progress, and are essential basis resources in the advancement of human society. Food production, circulation, processing and storage are inseparable from water and energy support. The purification and deployment of water will inevitably lead to the consumption of energy, and the production and supply of energy also need to consume a large amount of water. There is a close and complex relationship among the three, in which they influence and depend on each other. The water-energy-food (W-E-F) nexus was first described as an overview of concepts related to the nexus at the World Economic Forum in 2011, and W-E-F risk was listed as one of three major risk groups that received much attention at the Bonn Conference in 2011. Against the background of world-class issues such as the rapid global population growth, severe climate change, and resource shortages, the world has gradually realized the importance of rational and effective use of water, energy and food resources for the sustainable development of various countries and regions. In 2013, the UN Economic and Social Council for Asia and the Pacific (ESCAP) released the W-E-F nexus report for the Asia-Pacific region, focusing on the close relationship between water-energy-food system in time and space. In 2015, the United Nations proposed the "2030 Sustainable Development Goals", which include water, energy and food as key elements. This is conducive to shifting international attention to environmental issues to resource systems and placing these concerns within the policy framework of sustainable development [1].

As an important region for China's economic development during the "13th Five-Year Plan" period, the Yangtze River Economic Belt has great economic development value and is a pivotal strategic location for China's economic, social and ecological civilization construction. At the symposium on comprehensively promoting the development of the Yangtze River Economic Belt chaired by General Secretary Jinping Xi in November 2020, it was pointed out that the integrity of ecosystem and the systematic nature of river basin should be taken into consideration to enhance the coordinated governance of the upper, middle and lower reaches of the Yangtze River, and comprehensively improve resource utilization efficiency. The Yangtze River basin is rich in water resources, but its oversized population base makes the per capita water possession very low. The extensive industrial water use pattern and the discharge of industrial and domestic sewage have also caused damage to the water environment. The entire Yangtze River region is relatively short of energy and cannot be self-sufficient, with a primary energy self-sufficiency rate of only about 50%. High energy consumption industries such as steel and petrochemical are highly concentrated along the Yangtze River, and consume huge amounts of energy [2]. In addition, the Yangtze River Economic Belt is also an important agricultural production area in China. However, the situation of food supply and demand in the region has been severe in recent years. In 2016, the sown area of early rice and double-season late rice in the Yangtze River economic Belt decreased by 10.90% and 18.23%, respectively, compared with 2000, while the sown area of medium rice and one-season late rice increased by 9.96%. The aggravation of agricultural non-point source pollution, tighter resource constraints, and obvious degradation of ecosystem all pose threats to food security [3]. Therefore, paying attention to water, energy and food security in the Yangtze River Economic Belt is of great significance to the future economic development and social stability of the region.

To date, domestic and foreign scholars have conducted research on water-energy-food under different spatial and temporal scales, including countries [1,4,5], provinces [6,7], and river basins [8], and the research methods have been expanded from the initial qualitative analysis to quantitative research. Qualitative research mainly considers the relationship between complex systems [9,10], conceptual connotations [11,12], and explores the research framework of synergistic management [13]. Quantitative research analyzes the coupling coordination relationships and security levels of water-energy-food systems, performs system prediction and policy simulation, etc. The coupling coordination degree model [14,15], logistic curve [16], extension matter-element model [17], system dynamics [7,18,19] have been applied to the quantitative study. For example, Bassel T. Daher [20] established a new water-energy-food Nexus modeling tool (WEF Nexus Tool 2.0), which offers a common platform to evaluate scenarios and identify resource allocation strategies. Tong Zhang [21] developed a synergistic assessment model of water-energy-food relationships based on logistic curves, and the study indicated that water supply may have an important impact on system stability. Guijun Li [22] constructed a system dynamics model for the sustainable development of water-energy-food in Beijing. The study found that the energy system is a breakthrough point for improving the comprehensive sustainability of W-E-F in Beijing at the present stage. In addition to focusing on the relationship between the three themselves, some studies have taken the water-energy-food nexus as an entry point for studying water resources security [23,24], food security [25], and agricultural production efficiency [26,27], and the research scope has been further enriched to consider climate change, land use, etc. [28–30]. However, few studies have been conducted on the water-energy-food system of the Yangtze River Economic Belt, basically focusing on the study of individual systems of food [31]. Among them, Jiazhong Zheng et al. [26] studied agricultural productivity in the middle and lower reaches of the Yangtze River from the perspective of water-energy-food using three-stage data envelopment analysis. The study showed that technological innovation, agricultural structure, etc., have significant effects on regional agricultural productivity. In combination with previous studies, it can be found that: (1) There have been few water-energy-food system security evaluations in the Yangtze River Economic Belt, and more discussions have been conducted at the national and provincial scales; (2) The evaluation index lacks a reliable grading standard, and the mean method is often used or the evaluation results are simply divided based on subjective experience; (3) The evaluation tool is relatively simple, basically using the linear weighting method, resulting in the evaluation results relying on index weights, and the evaluation process is cumbersome; (4) The research on the key factors affecting the level of synergistic security of the system is insufficient, and lacks targeted policy recommendations; and (5) There are relatively few predictions on water-energy-food security, and the evaluation of current situation is more, without considering the influence of policy regulation and management tools on the future situation.

Based on the actual situation of Yangtze River Economic Belt, this paper constructed a water-energy-food evaluation index system for Yangtze River Economic Belt and gave the threshold division criteria for each index. The random forest model was constructed to evaluate the security and the main driving factors affecting the synergistic security of the water-energy-food system were found by using the Haken model of synergetics. These driving factors were taken as key regulatory variables for scenario prediction to predict the system security level in 2025 under different scenarios, so as to provide a management basis for improving the security level of the water-energy-food system in the Yangtze River Economic Belt.

2. Study Area and Methods

2.1. Overview of the Study Area

The Yangtze River Economic Belt is a macro collaborative economic belt based on the Yangtze River basin, with the Yangtze River as the link and urban economic zones as the basic unit. It spans three major regions, the east, middle and west, with a land area of about 2.05 million square kilometers, accounting for 21.4% of the national area, covering 11 provinces (municipalities), including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Guizhou and Yunnan. Among them, Chongqing, Sichuan, Guizhou and Yunnan belong to the upper reaches of the Yangtze River; Jiangxi, Hubei and Hunan belong to the middle reaches, and Shanghai, Jiangsu, Zhejiang and Anhui belong to the lower reaches (as is shown in Figure 1). The Yangtze River Economic Belt is rich in water resources and arable land resources, with six major plains: Taihu Lake, Poyang Lake, Dongting Lake, Jianghuai, Jianghan and Chengdu. The area of rivers, lakes, wetlands and reservoirs accounts for 20% of the country. The grain production accounts for about 38.5%, and the gross agricultural product accounts for about 40% of the country, making it an important commodity food production base in China. At the same time, the Yangtze River Economic Belt is one of the support areas of mineral resources, with large reserves and various kinds of mineral resources. With the rapid development of the economy, a large number of industrial industries with high energy and water consumption have gathered in the region, and agricultural production also has a high demand for water and energy, which inevitably puts huge pressure on water, energy and food security. The Yangtze River Economic Belt is characterized by many topographical features and obvious spatial variation in resource conditions. Therefore, it is of great practical significance to study the water-energy-food security issues in the region.

Figure 1. Geographical distribution map of the Yangtze River Economic Belt.

The data used in this study are obtained from China Statistical Yearbook, China Environmental Statistical Yearbook, China Energy Statistical Yearbook, China Rural Statistical Yearbook, China Grain Statistical Yearbook, Water Resources Bulletin and provincial statistical yearbooks from 2009–2018, where missing data for some years are filled in using mathematical methods such as the mean method.

2.2. Establishment and Grading of Evaluation Index System

In this paper, the pressure-state-response (PSR) model is adopted to establish the structural indicator model of the water-energy-food system. This model is better able to show the dynamic interaction and change of the system under the combined effect of multiple factors [32], which is commonly used to study the impact of human activities on resources and environment. Pressure refers to the influence factors that threaten the system security and change the original state of the system. So pressure indicators mainly reflect the intensity and quantity of resource consumption by human activities, including pressures on water, energy and food consumption, and damage to the natural environment; State represents the status of resources, state indicators mainly reflect the performance of resources under the combined effect of human activities and the current natural environment, including the supply capacity of water, energy, and food under the current use intensity and socioeconomic dependence; Response represents the efforts made to improve system safety and relieve system pressure, so response indicators reflect the measures taken by human society to the current resource situation, including the economical use of resources and the investment and development of new technologies. Considering the scientificity of the indicators and the availability of data, the final established indicator system is shown in Table 1 below. Water, energy, and food security are the first-level indicators, and the second-level indicators of PSR are established under each first-level indicator [16,33]. The subsystem security status is determined by these three types of indicators, and then affect the overall security status of the water-energy-food system.

There is currently no unified standard for the grading of the water-energy-food security index. In this paper, the security level is divided into five levels, from the level 1 (extreme insecurity) to level 5 (security). The higher the value is, the higher the safety is. Among them, the utilization rate of water resources, per capita water resources, per capita grain possession, Engel's coefficient, etc., refer to relevant international and domestic standards such as the United Nations; while proportion of effective irrigation area, proportion of water-saving irrigation area, etc., are set with reference to documents issued by the Ministry of Agriculture and the Ministry of Water Resources. Some indicators such as energy consumption per 10,000-yuan GDP, proportion of energy consumption in primary industry, per capita energy consumption, per capita grain sown area, etc., are divided by the standard deviation and mean of the corresponding data, assuming that the standard deviation is σ and the mean is μ. For the negative indicators, (0, μ-σ] is level 5, (μ-σ, μ] is level 4, (μ, μ+σ] is level 3, (μ+σ, μ+2σ] is level 2, (μ +2σ,∞] is level 1, and the opposite is true for the positive indicators. Other indicators refer to existing studies [34–36] and are combined with the situation of the Yangtze River Economic Belt itself. The classification criteria applicable to the Yangtze River Economic Belt region are shown in Table 2, below.

Table 1. Evaluation index system of the water-energy-food system security.

Evaluation Index System			Attribute
Water Security	Pressure	Proportion of water used for industry and agriculture A_1	negative
		Water consumption per 10,000-yuan GDP A_2	negative
		Per capita water consumption A_3	negative
	State	Per capita water resources A_4	positive
		Utilization rate of water resources A_5	negative
		Water yield per km^2 A_6	positive
	Response	Treatment rate of urban sewage A_7	positive
		Proportion of water-saving irrigation area A_8	positive
		Reuse rate of urban industrial water A_9	positive
Energy Security	Pressure	Energy consumption per 10,000-yuan GDP B_1	negative
		Proportion of energy consumption in primary industry B_2	negative
		Per capita energy consumption B_3	negative
	State	Rate of energy self-sufficiency B_4	positive
		Elasticity coefficient of energy consumption B_5	negative
		Proportion of electricity generated from clean energy sources B_6	positive
	Response	Investment intensity of resource exploration B_7	positive
		Investment intensity of energy industry B_8	positive
		Comprehensive utilization rate of industrial solid waste B_9	positive
Food Security	Pressure	Disaster rate of production area C_1	negative
		Fluctuation rate of grain yield C_2	negative
		Per capita food consumption C_3	negative
	State	Engel's coefficient C_4	negative
		Per capita grain possession C_5	positive
		Per capita grain sown area C_6	positive
	Response	Proportion of effective irrigation area C_7	positive
		Power input per unit sown area C_8	positive
		Investment proportion of agriculture, forestry and water conservancy C_9	positive

2.3. Random Forest Model

Random forest (RF) is a fusion algorithm based on the decision tree classifier proposed by Leo Breiman [37], which consists of multiple decision trees, with no association between each tree in the forest. The final output of the model is jointly determined by all decision trees. The basic idea is based on statistical learning theory, using bootstrap resampling method to extract multiple samples from the original sample, and construct decision trees for each bootstrap sample. When dealing with classification problems, the voting result with the most occurrences in all decision trees is regarded as the final prediction result; in the regression problem, the mean value the decision tree output is the final result.

The random forest model has the advantages of fewer adjustment parameters, high prediction accuracy and good generalization ability, which can effectively avoid the phenomenon of "overfitting", and has good robustness in extracting the features of the data set. It has great advantages in dealing with large-scale data sets and high-dimensional feature vector space, and has been widely used in the fields of medicine and economics [38,39]. This paper involves processing of multiple data from several indicators, and the application of this method for safety evaluation and scenario prediction is more accurate. Moreover, this method does not need to calculate indicator weights, which can improve the evaluation efficiency.

Table 2. Evaluation indicator standards for water-energy-food system security.

Indicator	Grading Standard of Security				
	Extreme Insecurity (1st Level)	Not Security (2nd Level)	General Security (3rd Level)	Relative Security (4th Level)	Security (5th Level)
A1	(90, 100]	(85, 90]	(80, 85]	(75, 80]	(65, 75]
A2	(280, 340]	(180, 280]	(80, 180]	(40, 80]	(0, 40]
A3	(700, 800]	(550, 700]	(400, 550]	(250, 400]	(150, 250]
A4	(0, 1000]	(1000, 2000]	(2000, 3500]	(3500, 5000]	(5000, 6500]
A5	(60, 650]	(40, 60]	(20, 40]	(10, 20]	(0, 10]
A6	(15, 40]	(40, 65]	(65, 90]	(90, 120]	(120, 145]
A7	(0, 40]	(40, 60]	(60, 80]	(80, 90]	(90, 100]
A8	(0, 40]	(40, 60]	(60, 75]	(75, 85]	(85, 100]
A9	(0, 40]	(40, 60]	(60, 80]	(80, 90]	(90, 100]
B1	(1.39, 2.24]	(1.07, 1.39]	(0.75, 1.07]	(0.43, 0.75]	(0, 0.43]
B2	(4.53, 5.96]	(3.33, 4.53]	(2.13, 3.33]	(0.93, 2.13]	(0, 0.93]
B3	(4.2, 5]	(3.4, 4.2]	(2.6, 3.4]	(1.8, 2.6]	(1, 1.8]
B4	(0, 40]	(40, 60]	(60, 80]	(80, 100]	(100, 160]
B5	(1, 1.5]	(0.5, 1]	(0, 0.5]	(−0.5, 0]	(−1.5, −0.5]
B6	(0, 30]	(30, 60]	(60, 70]	(70, 80]	(80, 100]
B7	(0, 0.5]	(0.5, 1]	(1, 1.5]	(1.5, 2]	(2, 2.5]
B8	(0, 2]	(2, 4]	(4, 7]	(7, 10]	(10, 13]
B9	(0, 40]	(40, 60]	(60, 80]	(80, 90]	(90, 100]
C1	(32, 40]	(24, 32]	(16, 24]	(8, 16]	(0, 8]
C2	(11, 20]	(7, 11]	(4, 7]	(1, 4]	(0, 1]
C3	(190, 220]	(165, 190]	(140, 165]	(120, 140]	(90, 120]
C4	(60, 100]	(50, 60]	(40, 50]	(20, 40]	(0, 20]
C5	(0, 260]	(260, 400]	(400, 540]	(540, 680]	(680, 800]
C6	(0, 0.04]	(0.04, 0.07]	(0.07, 0.1]	(0.1, 0.13]	(0.13, 0.16]
C7	(0, 20]	(20, 40]	(40, 55]	(55, 75]	(75, 100]
C8	(0, 3]	(3, 5]	(5, 7]	(7, 9]	(9, 11]
C9	(0, 1]	(1, 2]	(2, 3]	(3, 4]	(4, 5]

2.4. Haken Model

According to the synergetics theory of the German scholar Haken, there is usually only one or a few slow variables in a complex system, but they control the entire process of evolution. The slow variables dominate most of the fast variables and determine the structure, function and direction of the evolution of complex system, and drive the system evolving from disorder to order, from low level to high level. In other words, the evolution of complex systems is controlled by a few slow variables, that is, order parameters. Therefore, when studying the evolution of complex systems, we only need to focus on order parameters instead of paying attention to all variables and factors.

The Haken model [40] is a mathematical equation used to describe the process of synergistic evolution of a system due to the interaction between different variables within the system under certain external conditions. The Haken model can be used to express the relationship between driving forces and identify fast variables and slow variables. Assuming that q_1 is the internal force of a certain subsystem and parameter, and q_2 is the variable controlled by this internal force, the model expression is as follows:

$$\dot{q}_1 = -\gamma_1 q_1 - a q_1 q_2 \tag{1}$$

$$\dot{q}_2 = -\gamma_2 q_2 + b q_1^2 \tag{2}$$

where γ_1 and γ_2 represent the damping coefficients of the two subsystems and q_1 represents the order parameter. The model is required to satisfy the "adiabatic approximation assumption", namely, $|\gamma_2| \gg |\gamma_1|$ and $\gamma_2 > 0$. Since the physical equations are set for continuous random variables, their application to economic analysis usually requires discretization. The expression of the processed equation is as follows:

$$q_1(t) = (1-\gamma_1)q_1(t-1) - a q_1(t-1) q_2(t-1) \tag{3}$$

$$q_2(t) = (1-\gamma_2)q_2(t-1) + b q_1^2(t-1) \tag{4}$$

The water-energy-food system is a multivariate, open and unstable nonlinear complex system, where the variables interact with each other, both competitive and synergistic, and constitute the driving force for the synergistic evolution of the system. There are always active and dominant slow variables in the dynamic evolution of the system, and the system is guided by these slow variables so that the synergistic evolution process of the whole system continues in an orderly manner. The equations established in the Haken model can identify the slow variables that dominate the synergistic evolution of the system through two-by-two comparisons between variables, which is suitable for the study of complex systems. In this paper, we attempt to identify the slow variables in the water-energy-food system from the perspective of the variables that control the synergistic evolution of the system through Haken model, and make these variables the key control objects of regulation to provide a basis for the setting of variables in the scenario simulation. Attaching importance to the management of these factors can not only improve the safety level of the system, but also promote the improvement of the system to a more advanced direction of synergistic and orderly development.

2.5. Random Forest-Haken Model

This paper adopts the random forest and Haken models to construct the security evaluation and prediction model of water-energy-food system. The flow chart is shown in Figure 2, and the main steps are as follows:

Step 1: Construct an evaluation index system and divide the index threshold;
Step 2: Use the random generation method to generate the sample data of each level;
Step 3: Standardize the positive and negative index data respectively in order to improve the accuracy of the model;
Step 4: Use the standardized sample data as the input vector and the corresponding safety level values as the output vector to construct the random forest evaluation and prediction model, and bring in the actual data to obtain the evaluation results;
Step 5: Apply the Haken model to identify the variables in two by two to find out slow variables of the system;
Step 6: Use the identified slow variables as the main regulation variables, set different prediction scenarios, and input the data into the random forest model to obtain the prediction results.

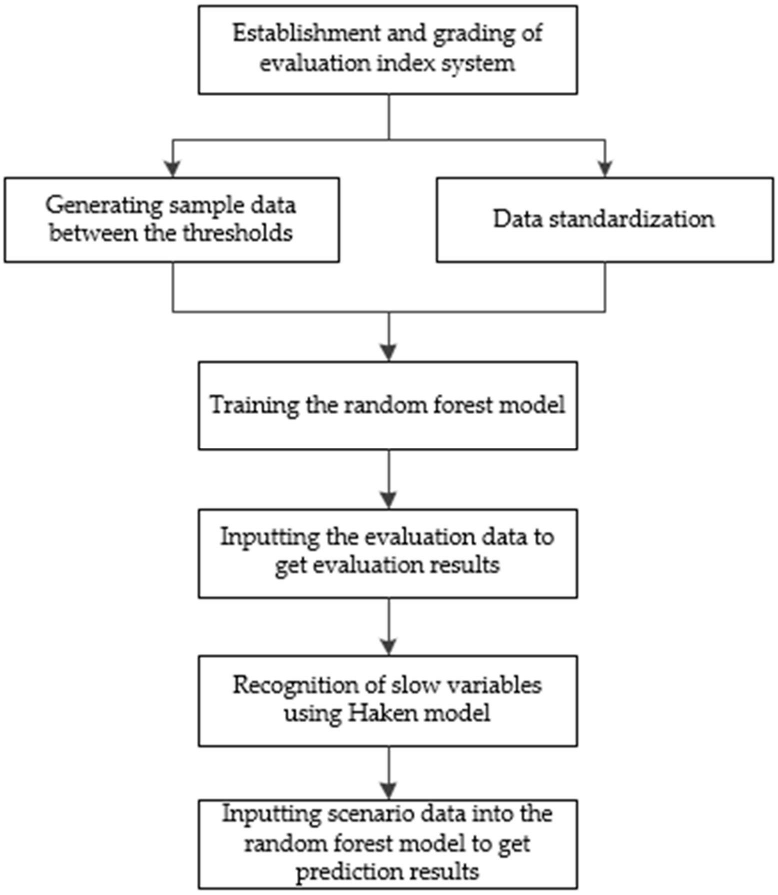


Figure 2. Flow chart of water-energy-food system security evaluation.

3. Results and Discussion

3.1. Security Evaluation Based on Random Forest

According to the constructed evaluation index system and grading criteria, the random forest evaluation model is established. Firstly, the training samples should be generated among the grades as the source of training data. Then, the data should be standardized to improve the accuracy of the model. Finally, the generated samples and grade values are used as the input and output data of the model for training and testing to obtain the classification criteria of the evaluation grades, and bring in the actual data to obtain the results of safety evaluation.

3.1.1. Generation of Training and Test Samples

The random generation method is used to generate 100 sets of samples between the thresholds of each grade, and a total of 500 sets of samples are obtained, which is completed by Python's numpy function.

3.1.2. Data Standardization

In order to eliminate the influence of different dimensions of evaluation indicators on the evaluation results, the indicator data are standardized. Positive indicators are processed according to Equation (5), and negative indicators are processed according to Equation (6).

$$\hat{x} = \frac{x - x_{min}}{x_{max} - x_{min}} \tag{5}$$

$$\hat{x} = \frac{x_{max} - x}{x_{max} - x_{min}} \tag{6}$$

where $\hat{x}$ represents the standardized data, x represents the original data, x_{max} represents the upper limit of each index threshold, x_{min} represents the lower limit of each index threshold. The processed data range lies within 0~1, which is conducive to network training.

3.1.3. Construction of Random Forest Model

In this paper, we use the Random Forest Regressor toolkit in Python to construct the training model. The randomly generated samples are taken as the input vector of the model, and the grade values are taken as the output vector, of which 500 sets are divided into two categories: 250 sets are used as training samples and the other are used as test samples. In the random forest model, the larger the ntree value is, the better the accuracy of the model is. In order to test the reliability of the training results, this paper adopts 10-fold cross-validation. Using 10 randomly selected samples as 10 training sets, one of which is the test set and the remaining 9 are the training sets, and so on for 10 cycles, so that each sample can be one test set. Subsequently, 10 Mean Square Errors (MSE), Normalized Mean Squared Errors (NMSE) and deterministic coefficients (R^2) are calculated for the 10 test sets, and then the mean values of these 10 MSE, NMSE and R^2 are derived. The corresponding error test formulas are as follows:

$$MSE = \frac{1}{n}\sum\left(\hat{y}_i - y_i\right)^2 \tag{7}$$

$$NMSE = \frac{\sum\left(y_i - \hat{y}_i\right)^2}{\sum\left(y_i - \overline{y_i}\right)^2} \tag{8}$$

$$R^2 = 1 - \frac{\sum_i\left(\hat{y}_i - y_i\right)^2}{\sum_i\left(\hat{y}_i - \overline{y_i}\right)^2} \tag{9}$$

where $\hat{y}_i$ represents the test value of the i-th sample, y_i represents the expected value of the i-th sample. The calculated value of MSE is 0.0002591, $NMSE$ is 0.0001319, and R^2 is 0.999868, indicating that the model has very good generalization ability and evaluation accuracy.

3.1.4. Evaluation of the Current Situation of the Water-Energy-Food System

Running the model above, the classification results of each system are obtained, as is shown in Table 3 below. Level 1 represents extreme insecurity, level 2 represents lack of security, level 3 represents general security, level 4 represents relative security and level 5 represents security. The higher the value is, the higher the security is.

Table 3. Classification results of security evaluation of each system.

Security Level	Classification Results			
	Water-Energy-Food SYSTEM	Water Subsystem	Energy Subsystem	Food Subsystem
1	≤1.615	≤1.640	≤1.623	≤1.596
2	(1.615, 2.507]	(1.640, 2.504]	(1.623, 2.508]	(1.596, 2.524]
3	(2.507, 3.497]	(2.504, 3.556]	(2.508, 3.474]	(2.524, 3.436]
4	(3.497, 4.542]	(3.556, 4.534]	(3.474, 4.444]	(3.436, 4.573]
5	>4.542	>4.534	>4.444	>4.573

In the previous sections, we divided the thresholds of indicators into different levels, and generated sample data of five levels. Then, the sample data were taken as the input data and the corresponding grade value as the output data to construct the random forest model, and the model had good accuracy. By summing and averaging the relevant index data of 11 provinces in each year, we obtained the data of the overall Yangtze River Economic Belt from 2008 to 2017, and brought them as input data into the random forest model. When calculating the security level of the three subsystems, the data for the nine indicators involved in each subsystem are taken into account, while the data for the 27 indicators are taken into account when calculating the security level of the water-energy-food system. The security values obtained are shown in Figure 3 below. Similarly, the actual data of 11 provinces from 2008 to 2017 are taken into the model as input data to obtain the security values of the water-energy-food system and the subsystems of each province, as shown in Figures 4–7 below. The overall security level of the Yangtze River Economic Belt has improved significantly since 2008. Among these improvements is the fact that the food security level is relatively high and the development speed is the fastest. The security level was upgraded from level 3 to level 4, with an average annual growth rate of 3.35%. The level of water resources security is the lowest, rising from level 2 to level 3 since 2010, with large fluctuations before 2013, and a significant improvement after 2013. Although the security level of the energy subsystem has also improved, the growth rate is slower than that of the other two subsystems, and the security level remains at level 3, with an average annual growth rate of only 1. 38%.

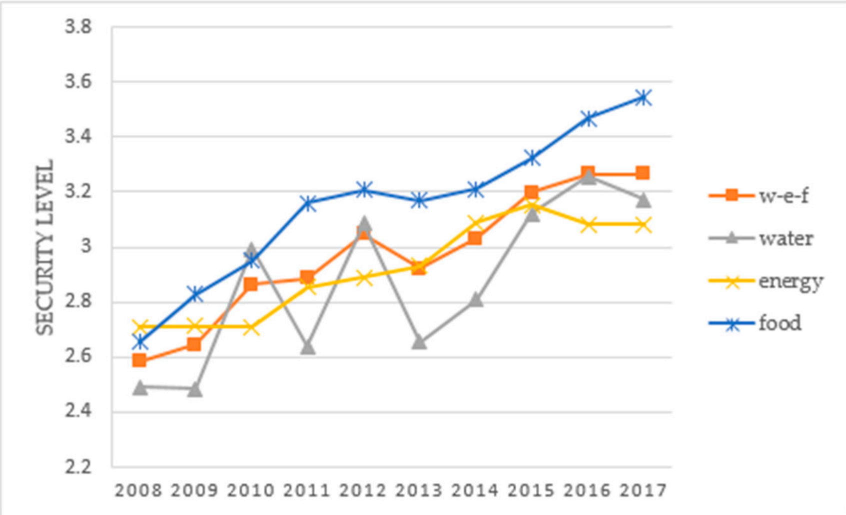


Figure 3. Trend graph of system security in the Yangtze River Economic Belt during 2008–2017.

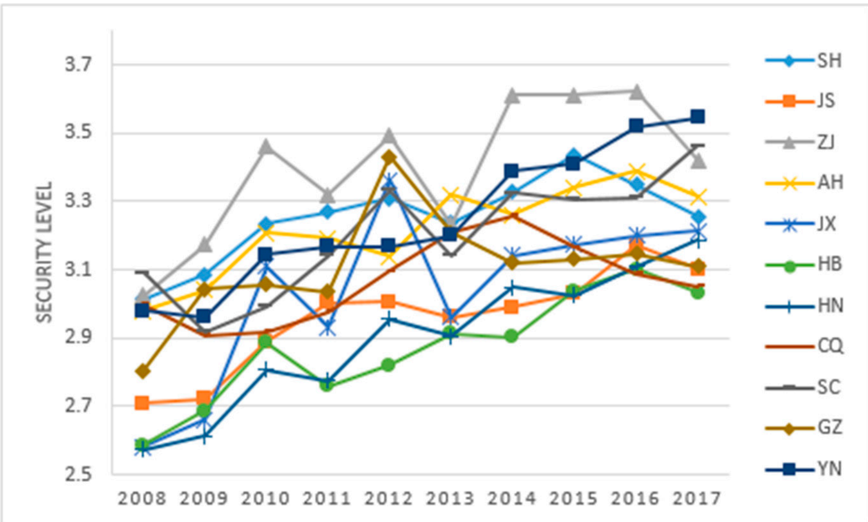


Figure 4. Trend graph of W-E-F security of each province (municipality) in the Yangtze River Economic Belt during 2008–2017.

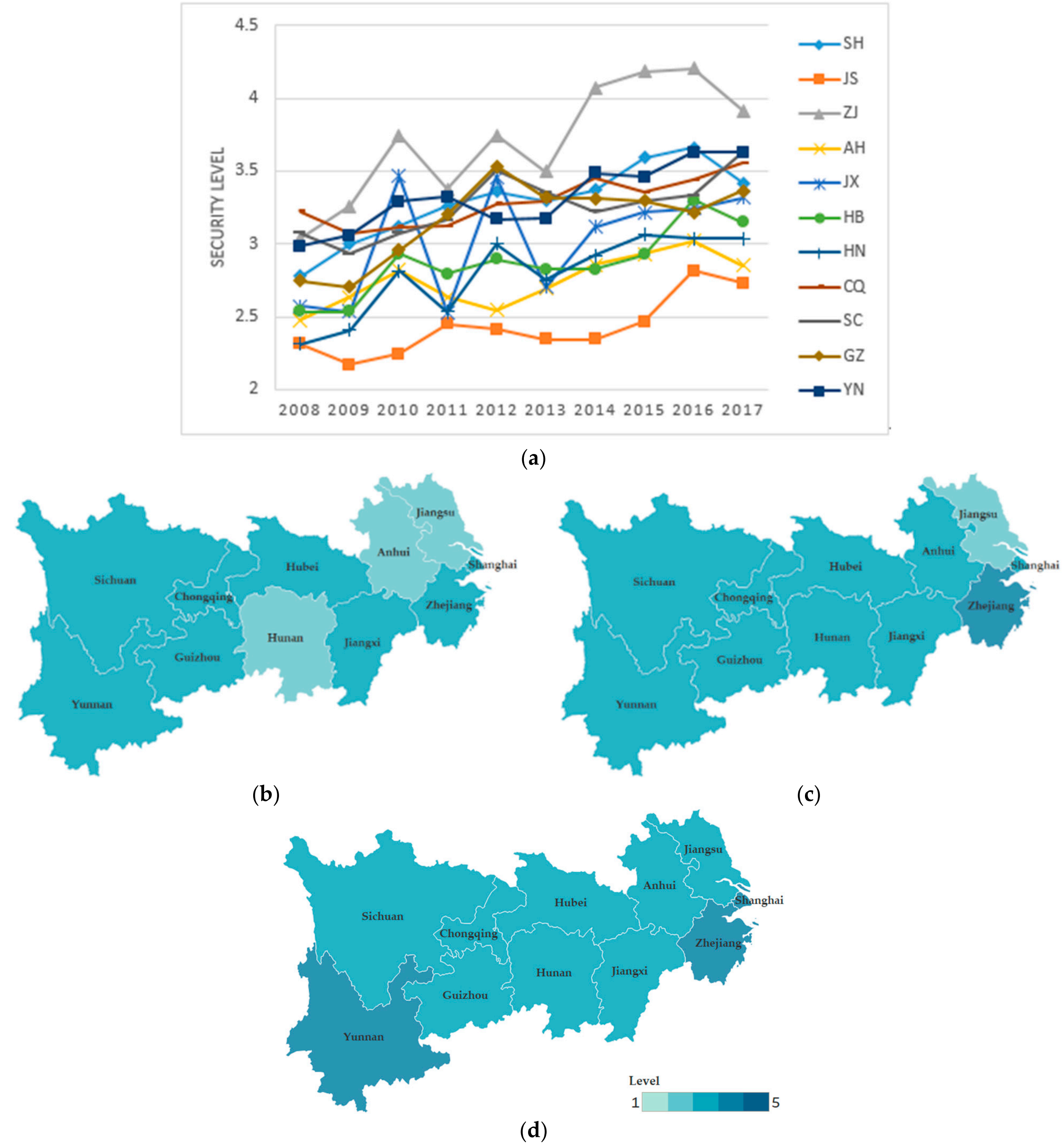


Figure 5. Water resources subsystem evaluation results: (**a**) Trend graph of water subsystem security of each province (municipality) in the Yangtze River Economic Belt during 2008–2017; (**b**) Distribution of water resources security in 2008; (**c**) Distribution of water resources security in 2012; (**d**) Distribution of water resources security in 2016.

The water-energy-food system of all provinces (municipalities) in the Yangtze River Economic Belt shows an overall fluctuating upward trend. The security of Zhejiang, Shanghai, Anhui and the four provinces (municipalities) in the downstream area is relatively high, while the three midstream provinces and Jiangsu Province perform relatively poorly. However, the three provinces in the middle reaches of the Yangtze River have been growing rapidly in recent years, especially Jiangxi Province, which has a good development trend with an average annual growth rate of 2.46%. In contrast, Jiangsu performs a relatively slower development trend, with an annual growth rate of only 1.45%. The following is a further analysis of the resource status of each province from each subsystem.

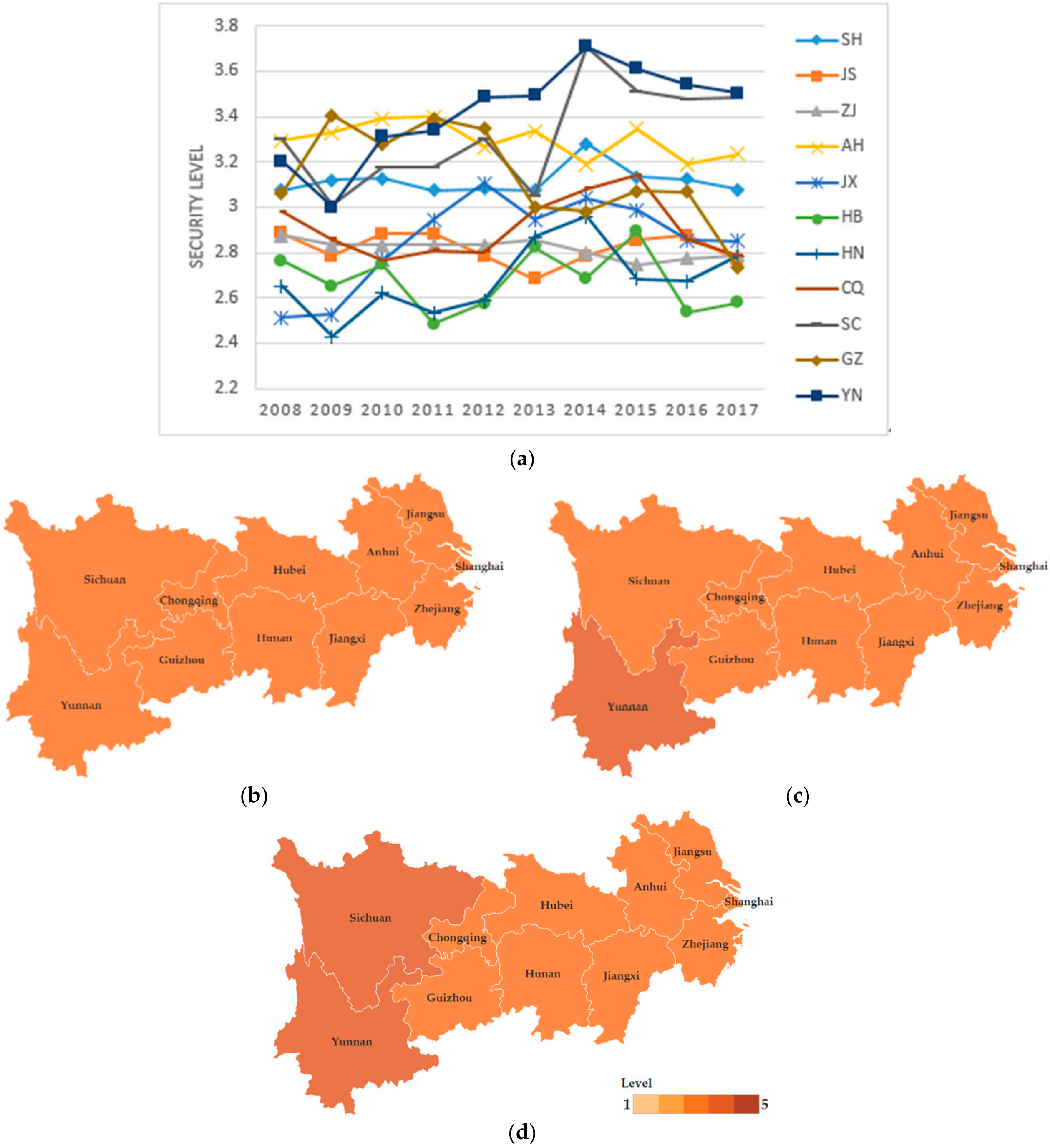
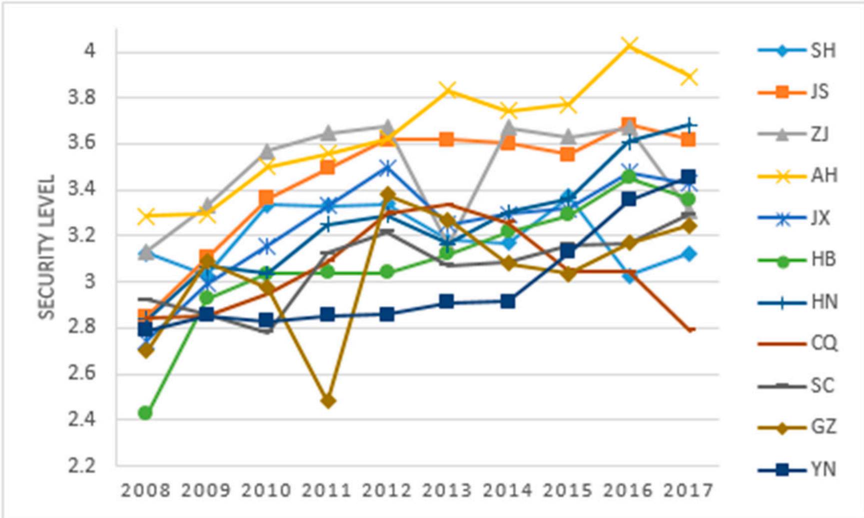


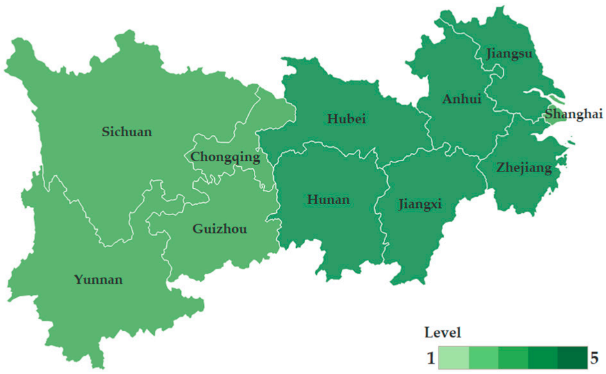
Figure 6. Energy subsystem evaluation results: (**a**) Trend graph of energy subsystem security of each province (municipality) in the Yangtze River Economic Belt during 2008–2017; (**b**) Distribution of energy security in 2008; (**c**) Distribution of energy security in 2012; (**d**) Distribution of energy security in 2016.



(**a**)

(**b**)

(**c**)



(**d**)

Figure 7. Food subsystem evaluation results: (**a**) Trend graph of food subsystem security of each province (municipality) in the Yangtze River Economic Belt during 2008–2017; (**b**) Distribution of food security in 2008; (**c**) Distribution of food security in 2012; (**d**) Distribution of food security in 2016.

1. Evaluation of the water resources subsystem

Overall, from 2008 to 2017, the water subsystems of the provinces (municipalities) in the Yangtze River Economic Belt showed a clear fluctuating upward trend. The efficiency of water resource utilization in the region has been continuously improving, and sewage treatment has also been greatly improved. The urban sewage treatment rate of all provinces (municipalities) has reached more than 90%. The four provinces (municipalities) in the upper reaches, as well as Shanghai and Zhejiang in the lower reaches of the Yangtze

River have relatively high safety levels, among which Zhejiang Province has the highest safety value. The upstream region is dominated by plateaus and mountains, with large per capita water resources, less developed industries, relatively backward economy and low overall water demand, so the development and utilization rate of water resources is low. The water security of the three provinces in the middle reaches is at the medium level, where the water demand of industry and agriculture is large, so there is still a lot of room for improvement in the promotion and use of water-saving technologies. Its rapid development in recent years has resulted in a substantial reduction in water consumption per 10,000-yuan GDP and an almost doubling of the urban sewage treatment rate. The downstream regions of Anhui and Jiangsu have the lowest security level and slow growth rates. The economic development of the two provinces is more dependent on water resources, and the proportion of water-saving irrigation area is low. In Jiangsu Province, in particular, the total amount of water resources is insufficient, with less than 600 m^3 per capita in most years and over-exploitation of water resources.

2. Evaluation of the Energy Subsystem

Compared to the water and food subsystems, the development of the energy subsystem is generally slower. Although the dependence of economic production on energy in each province is declining, per capita energy consumption is still expanding. In the case of no significant increase in energy production, the external dependence on energy still shows an upward trend in most regions. Sichuan, Yunnan and Guizhou in the upstream region and Shanghai and Anhui in the downstream region have relatively high levels of energy security, among which Yunnan and Sichuan reach Level 4 in some years. The upstream region of the Yangtze River and the downstream Anhui are rich in energy reserves, and the energy output and self-sufficiency rates are much higher than in other regions. The upstream region, in particular, is rich in hydropower resources and less dependent on traditional energy for power generation. Except for Anhui Province, the energy reserves in the middle and lower reaches of the Yangtze River are relatively small, while rapid economic development needs to consume a large amount of energy resources, resulting in a high degree of external dependence on energy. Hubei and Hunan Provinces with low security levels account for a relatively high proportion of agriculture, and the proportion of energy consumption in the primary industry is much higher than that of Jiangsu, Anhui and other provinces which have a similar proportion of agriculture. The energy utilization efficiency still needs to be improved in the process of agricultural development.

3. Evaluation of the food subsystem

The security level of the food subsystem in the provinces (municipalities) of the Yangtze River Economic Belt is on the rise, with provinces continuously increasing their investment in agriculture. The disaster control and production technology have also been significantly improved. The four downstream provinces have a higher level of food security among the 11 provinces, while the four upstream provinces are lagging behind. However, the development trend of Sichuan, Guizhou and Yunnan is fast in recent years. The advantages of economy and technology in the lower reaches of the Yangtze River have effectively ensured food security, with advanced agricultural production technology, complete power machinery supporting facilities and a better consumption structure than those in the middle and lower reaches. The middle reaches are vulnerable to flood disasters, which affects food production. In recent years, the disaster prevention and management in this area have been significantly improved, and food security has been raised. The security level of Hunan Province reached Level 4 in 2016, and Hubei and Jiangxi are also close to Level 4. In the upper reaches of the Yangtze River, soil erosion is serious, and the land for crop production has been significantly destroyed, with per capita food possession being less than 400 kg. The supporting agricultural technology and water conservancy facilities are not sufficiently optimal. At present, Sichuan, Guizhou and Yunnan provinces have already made significant improvements in water and soil control, and increased the proportion of investment in agriculture and water conservancy.

3.2. Identification of Slow Variables in Systems Based on the Haken Model

There are a total of 27 variables in the water-energy-food system constructed in this paper, and the Haken model can only identify two variables. Therefore, the 27 variables are analyzed in pairs. The basic steps include the following points: the first step is to put forward the variable hypothesis; the second step is to construct the motion equation and judge whether the equation is valid; the third step is to judge whether the equation satisfies the "adiabatic approximation hypothesis ($|\gamma_2| \gg |\gamma_1|$ and $\gamma_2 > 0$)", and the order parameters of the system can be obtained. The model equations are solved by using Eviews 10.0. This paper involves a total of 27 × 26 = 702 sets of equations. Due to space limitations, only the following results that meet the conditions are listed (see Table 4). In a system, there may be more than one slow variable that dominates evolution and more than one fast variable that is influenced by it. In this study, the slow variables include proportion of water-saving irrigation area A_8, per capita water consumption A_3, energy consumption per 10,000-Yuan GDP B_1, per capita grain possession C_5, per capita grain sown area C_6, and proportion of effective irrigation area C_7, a total of six variables, which dominate the evolutionary development of the system and make the system continue to improve in a more advanced synergistic and orderly direction. Among them, proportion of water-saving irrigation area, energy consumption per 10,000-Yuan GDP, per capita grain possession and per capita grain sown area all dominate several fast variables. For example, per capita grain possession is the dominant variable, which also affects power input per unit sown area and reuse rate of urban industrial water. In the following study, scenario simulations will be conducted with these six slow variables as key regulatory variables, which can promote the synergistic development of the system while improving the safety level.

Table 4. Variables and parameter results of Haken model.

Slow Variable	γ_1	a	Fast Variable	γ_2	b
A8	−0.036	0.037	B7	0.144	0.074
	−0.0035	−0.048	B3	0.0333	−0.009
A3	0.025	−0.058	A1	0.0615	0.07
B1	−0.003	−0.037	A5	0.024	0.0311
	−0.056	0.0278	A9	0.088	0.1054
	−0.0813	0.0908	C4	0.267	0.2518
C5	0.001	−0.0396	C8	0.01	0.044
	0.018	−0.04	A9	0.05	0.118
C6	−0.009	0.0156	C9	0.023	0.085
	0.0153	−0.0247	B3	0.061	0.0368
C7	−0.0069	−0.0323	B4	0.01	−0.0096

3.3. Scenario Prediction

In this paper, Jiangsu Province in the lower reaches of the Yangtze River and Hubei Province in the middle reaches are selected as the provinces for scenario simulation. Hubei Province has the lowest overall security level among the provinces, and Jiangsu Province, while it is a strong economic province in China, has a security level that is low and develops slowly. In the "National Agricultural Sustainable Development Plan (2015–2030)", these two provinces were listed as priority areas for development. Under the dual advantages of economic conditions and policy support, Hubei and Jiangsu should be able to make a breakthrough on the level of security. We take 2017 as the base year and 2025 as the scenario year, and set up three scenarios: Scenario 1, Scenario 2 and Scenario 3.

Scenario 1: The strength of resource management is weak, the growth of science and technology level is relatively slow, and the growth of resource utilization efficiency is slow. In order to reduce the workload of prediction, we set the improvement value of the target variable in this scenario to only reach 1/3 of the target value in scenario 3;

Scenario 2: The intensity of resource management is medium, the level of social economy and science and technology is greatly improved, and resource utilization is more efficient. In this scenario, we set the improvement value of variables to reach 2/3 of the target value in scenario 3;

Scenario 3: As a result of being strictly managed and implemented according to the target planning, all indicators have fully reached their target values, the technological progress is relatively significant, and the resource utilization efficiency is greatly improved. Significant investment is made in water resources protection and energy use, and agricultural production conditions and technologies are further improved. Based on the slow variables identified above, the proportion of water-saving irrigation area and per capita water consumption of the water subsystem, energy consumption per 10,000-yuan GDP of energy subsystem, and per capita grain possession, per capita grain sown area and proportion of effective irrigation area of food subsystem are taken as the key control variables. The proportion of water-saving irrigation area and the proportion of effective irrigation area are set according to the "National Agricultural Sustainable Development Plan (2015–2030)". Per capita grain possession, per capita grain sown area, energy consumption per 10,000-yuan GDP, and per capita water consumption are set according to the actual development trends of the two provinces, taking into account the policy preference and the technology development. The specific data is shown in Table 5. For other indicators, the optimal value in the observed years of the regions in which each province is located are taken as the data for 2025. That is, the optimal value in the middle reaches and lower reaches of the Yangtze River are taken for Hubei and Jiangsu respectively. Indicators such as per capita water resources are largely determined by the regional resource base and geological conditions, and the values are taken in conjunction with the actual situation of each province over the years.

Table 5. Data for key variables.

Province	A_3	A_8	B_1	C_5	C_6	C_7
Jiangsu	550	80	0.2	500	0.07	95
Hubei	450	60	0.3	580	0.1	65

We brought the data of each indicator into the random forest model to derive the prediction results of Jiangsu and Hubei in 2025, and 2017 was taken as the base year to calculate the change ratio of the safety level of each system. These results are reported in Tables 6 and 7. The results show that, according to the current management objectives, the resource situation of Jiangsu and Hubei will be significantly improved in 2025.

Table 6. Evaluation results of water-energy-food system security under various scenarios in 2025.

		Security Value				Level			
		W-E-F	**Water**	**Energy**	**Food**	**W-E-F**	**Water**	**Energy**	**Food**
Jiangsu	Scenario 1	3.481	3.208	3.155	3.969	3	3	3	4
	Scenario 2	3.765	3.387	3.703	4.102	4	3	4	4
	Scenario 3	3.955	3.615	3.947	4.191	4	4	4	4
Hubei	Scenario 1	3.406	3.353	3.165	3.761	3	3	3	4
	Scenario 2	3.633	3.426	3.458	4.025	4	3	3	4
	Scenario 3	3.937	3.587	3.973	4.230	4	4	4	4

Scenario 1: In this scenario, the security level of water-energy-food system in Jiangsu Province and Hubei Province are improved to a certain extent, but it is still at Level 3. Except for food security, the other two systems do not reach level 4.

Scenario 2: Water-energy-food security in the two provinces are able to reach the relatively safe level of Level 4 when moderate control measures are adopted, compared to Level 3 before 2017. In this scenario, the energy security of Jiangsu Province is able to reach Level 4, and the energy security of Hubei Province is very close to Level 4, with a difference of only 0.016. The water system is still at level 3.

Table 7. Change rate of system security value under each scenario.

	Jiangsu				Hubei			
	W-E-F	**Water**	**Energy**	**Food**	**W-E-F**	**Water**	**Energy**	**Food**
Scenario 1	12.20%	17.41%	14.04%	9.65%	12.36%	6.29%	22.67%	11.97%
Scenario 2	21.36%	23.94%	33.85%	13.33%	19.83%	8.69%	34.05%	19.84%
Scenario 3	27.48%	32.31%	42.65%	15.79%	29.87%	13.86%	54.00%	25.93%

Scenario 3: In this scenario, the security of the water-energy-food system is greatly improved. In Jiangsu Province and Hubei Province, it has been increased by 27.48% and 29.87%, respectively. The security level of each subsystem reaches Level 4, and the security of water resources in Jiangsu Province is improved by more than 30%. The energy system of the two provinces improves the most, and the grain system is close to level 5.

According to the results of the three scenarios above, to reach Level 4, the water-energy-food systems of the two provinces need to be improved by about 20%. The grain subsystem of the two provinces is in the best condition, relatively, and can reach level 4 under the weakest management, so the two provinces should strengthen the management of water and energy security. Only by maintaining a relatively large increase can the subsystem security level reach level 4 in the future.

4. Conclusions

In this paper, firstly, we established an index system for water-energy-food security evaluation based on the pressure-state-response model, and completed the division of index thresholds for the Yangtze River Economic Belt as the criteria for its security evaluation. Secondly, by constructing a random forest model, the water, energy and food security status of the Yangtze River Economic Belt from 2008 to 2017 was evaluated and comparatively analyzed in two dimensions of time and space. Finally, the Haken model of synergetics was introduced to identify the driving factors affecting the synergistic security of the system, and these were used as the key control variables for scenario prediction. Jiangsu Province and Hubei Province, which have poor performance, were selected to set up three scenarios to predict the security level in 2025, respectively.

The following conclusions are drawn from the study: (1) The overall security level of all systems in the Yangtze River Economic Belt is on the rise, with water resources security being the lowest and food security being the highest. The level of water resources security has risen from level 2 to level 3, and food security has risen from level 3 to level 4. Energy security is developing the slowest, with an average annual growth rate of only 1.38%. (2) Specific to the analysis of different regions of the Yangtze River Economic Belt, it can be found that the development levels of each subsystem are not very coordinated. For example, the security levels of water and energy systems in the upper Yangtze River region are relatively good. However, the advantages of water and energy resources do not provide a strong guarantee for food security, which is directly related to the mountainous geographical distribution of the upper reaches of the Yangtze River, where the land suitable for growing food is limited. The economy of the lower Yangtze River plain is in the leading position in China, with developed industrial, high technological level, and superior topographic conditions, so food security is relatively good. But at the same time, the rapid economic development has brought great pressure on water and energy security. Provinces should formulate targeted measures based on the characteristics of resources. (3) According to the screening results of Haken model, the main factors affecting the synergistic security of the water-energy-food system in the Yangtze River Economic Belt are per capita water consumption, proportion of water-saving irrigation area, energy consumption per

10,000-yuan GDP, per capita grain possession, proportion of effective irrigation area and per capita grain sown area. (4) Under the current management objectives and efforts, it is still very difficult for provinces (municipalities) of the Yangtze River Economic Belt to achieve level 5 of the water-energy-food system, as they are especially restricted by water and energy subsystems. It is necessary to strengthen the development of water-saving technology, carry out technological upgrades to industries with large amounts of water and energy consumption, gradually transform to green and environmental protection industries, improve the water and energy utilization, and encourage the development of new energy.

This paper has some innovations in research content and research methods: (1) From the perspective of system synergy, the Haken model is introduced to identify the slow variables of system. And the slow variables are used as the key regulatory variables for scenario prediction, considering the impact of policy regulation rather than pure trend prediction. Previous studies have not identified the driving factors of the system, and the system prediction is always based on the trend of previous years, which lacks policy guidance significance. (2) This paper draws on the indicators established in previous studies, and considers the characteristics of the water-energy-food system to compare and screen the indicators, so that the evaluation index system established can accurately reflect the water-energy-food system in the Yangtze River Economic Belt. The security evaluation index system is constructed using the PSR model, which can clearly reflect the impact of the natural environment and human activities on the system. Additionally, this paper divides the thresholds, and different indicators are divided on different bases to ensure the accuracy and fit the actual situation in the Yangtze River Economic Belt as much as possible. (3) Different from the previous simple linear weighting method, this paper constructs an evaluation and prediction model based on random forest, which improves the efficiency and accuracy of the evaluation, and makes it more convenient for future scenario simulation.

The research in this paper focuses on security evaluation, scenario prediction and identification of driver factors (slow variables) of the water-energy-food system; there are also some study limitations: (1) In this paper, we combine the actual situation of the Yangtze River Economic Belt in the division of index thresholds in order to conduct spatial comparison and analysis. When the study area changes, this standard may not be applicable, and the division standard needs to be redefined. (2) External factors such as climate change, carbon emissions, forest ecosystems, and land use changes will all have an impact on water-energy-food security. The above factors were not taken into consideration in this study, which could be further improved in the future on the basis of more data and information support.

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