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Original Research

Spatio-Temporal Evolution Measurement and Obstacle Factors of the Vulnerability of Water-Energy-Food-Ecology Nexus in the Yangtze River Economic Belt

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Abstract

The vulnerability of the water-energy-food-ecology nexus in the Yangtze River Economic Belt greatly impacts regional sustainable development. This study aimed to conduct a quantitative assessment and temporal and spatial evolution analysis of the vulnerability of the water-energy-food-ecology nexus in the Yangtze River Economic Belt from 2008 to 2018 and diagnose the main factors that hinder the vulnerability reduction. Firstly, the vulnerability assessment index system was constructed according to the Vulnerability-Scoping-Diagram framework. Then, SPA-TOPSIS and ArcGIS10.7 were comprehensively used to evaluate the vulnerability of the water-energy-food-ecology nexus. Finally, the obstacle degree model was used to diagnose the main factors that hinder the vulnerability reduction of the water-energy-food-ecology nexus from the index and subsystem levels. The results showed that the vulnerability level of the water-energy-food-ecology nexus in the Yangtze River Economic Belt decreased from 2008 to 2018, and the overall trend was improved. The vulnerability level of the upstream region was generally lower than that of the middle and lower reaches. The main obstacles are the comprehensive utilization rate of solid waste, the primary industry energy consumption ratio, energy consumption intensity, water consumption per 10,000-yuan GDP, domestic water consumption per capita and fertilizer application per unit grain sowing area. The energy subsystem is the primary obstacle system, followed by the food, ecology, and water subsystem.

Keywords: Yangtze River Economic Belt, water-energy-food-ecology nexus, vulnerability, obstacle degree model

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Introduction

The Yangtze River Economic Belt covers 11 provinces (municipalities), including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Guizhou, and Yunnan [1] (as is shown in Fig. 1). It spans China's east, middle, and west plates [2]. It covers an area of about 2.05 million square kilometers, and both population and GDP account for more than 40 percent of the whole country [3]. With industrialization and urbanization, the social economy has developed rapidly in recent years. However, the Yangtze River Economic Belt confronts problems such as uneven distribution of water resources, the prominent contradiction of local water supply [4], continuous increase in total energy consumption [5], increasing difficulty in balancing food supply and demand [6], and increasingly severe soil erosion [7]. Overall, the water, energy, food, and ecology system of the Yangtze River Economic belt has shown prominent vulnerability characteristics.

Water, energy, and food are the basics for human survival and development. In 2011, the Bonn Conference in Germany first proposed the concept of the water-energy-food nexus, which clarified the relationship between the three [8]. Subsequently, the water-energy-food nexus attracted attention from all walks of life, and its internal mechanism and application research has gradually become a research hot spot [9]. From the research progress at domestic and foreign, the commonly used research methods mainly include coupling coordination degree model [10], life cycle assessment model [11], computable general equilibrium model [12], system dynamics model [13], climate, land, energy and water resources strategy [14]. In terms of research content, it mainly includes the sustainable research of resources, the analysis of the interaction between various subsystems and the external environment [15], such as the research on the core relationship of the three. On this basis, some scholars add climate [16], land [17], ecology [18], and other factors for more profound research. Ecology system is an important part of achieving sustainable development and corresponds to many SDG15 targets [19], such as SDG15.1 (Protection, restoration, and sustainable use of terrestrial and inland freshwater ecosystems, and their services), SDG15.4 (Protection of mountain ecosystems, including biodiversity). Under the increasingly intensified human activities, the demand for water, energy, and food has greatly increased, and the massive consumption of resources may hurt the ecological environment, increase environmental pressure, reduce the self-regulation and repair capacity of the ecological environment, thereby increasing the vulnerability of the ecosystem, which in turn affects resource availability, threatening water, energy and food security [20]. For this

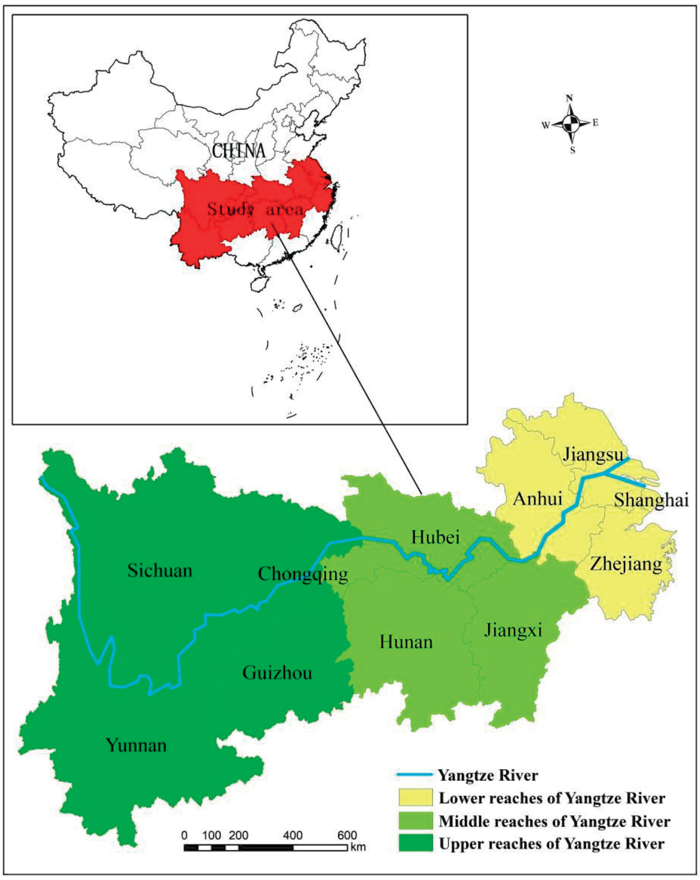

Fig. 1. Geographic location of the Yangtze River Economic Belt.

reason, some scholars have studied the water-energy-food-ecology nexus from the perspectives of coupling and coordination [21], collaborative management [22], and water resource utilization [23] to alleviate the problems of resource scarcity. The water-energy-food-ecology nexus is enormous and complex. Vulnerability is an inherent attribute of the nexus [24]. Any change in the vulnerability of any subsystem must affect the entire system. At present, vulnerability research has expanded from natural disasters to social, economic, and other fields [25]. The research perspective has gradually expanded from a single system to related systems, and the research methods have become increasingly diversified. The index evaluation method is a commonly used vulnerability evaluation method. The main steps include the construction of the evaluation index system, the standardization of the index, the determination of the index weight, and the application of the evaluation results [26]. At present, the index system recognized at home and abroad mainly includes "Pressure-State-Response" [27], "Vulnerability-Scoping-Diagram" [28], "Sensitivity-Resilience-Pressure" [29]. When constructing the index system, it is necessary to consider the system's internal structure and function, and take the interaction between the external environment and the system into account. For example, selecting indexes such as water consumption per 10,000-yuan GDP and per capita domestic water consumption to reflect the impact of economic development and human activities on the vulnerability of water resources. However, the research on the vulnerability of the water-energy-food-ecology nexus is still mainly focused on individual subsystems, especially the water subsystem [30-31] and ecology subsystem [32-35], only a few scholars have studied the vulnerability of the water-energy-food nexus [36]. Based on the definition of vulnerability [26], this research believes that the vulnerability of the water-energy-food-ecology nexus is caused by the unbalanced development of the internal system and the disturbance of the external environment, such as human activities and natural conditions. Then, the system's structure, state, and function tend to change toward imbalance and present an unstable state.

Based on the above analysis, it can be seen that the research on the vulnerability of the water-energy-food nexus and its subsystems at home and abroad has achieved fruitful research results. However, in the background of sustained global population growth and increasing pressure on resources, only considering the interaction among water, energy, and food resources, emphasizing that the traditional water-energy-food nexus is the key to the sustainable development can not fully reflect the relationship between the ecology system and the three. Therefore, taking ecology system as the core elements into the water-energy-food nexus and exploring the temporal and spatial evolution trend of the vulnerability of water-energy-food-ecology nexus will become a necessary measure to promote the rational development and utilization of resources, enhance the self-regulation and restoration ability of ecological environment, promote the stable development of the related system and realize sustainable development. The main objectives of this study are to (1) construct the vulnerability assessment index system of the water-energy-food-ecology nexus according to the "Vulnerability-Scoping-Diagram" framework. (2) use SPA-TOPSIS and ArcGIS10.7 to quantitatively evaluate and analyze the spatial and temporal evolution of the vulnerability of water-energy-food-ecology nexus in the Yangtze River Economic Belt from 2008 to 2018. (3) use the obstacle degree model to diagnose the obstacle factors that hinder vulnerability reduction. To a certain extent, this research helps to fill the gap in the research field of the vulnerability of the Yangtze River Economic Belt. It broadens the existing research perspective of the water-energy-food-ecology nexus to provide a reference for formulating relevant policies.

Material and Methods

Data Sources

Most of the data in this study were obtained from the China Statistical Yearbook, China Energy Statistical Yearbook, China Environment Statistical Yearbook, China Soil and Water Conservation Bulletin, and statistical yearbooks of provinces (municipalities) from 2009 to 2019 where missing data were filled by interpolation method of adjacent years.

Research Methods

The research in this study is roughly divided into the following steps: the first step is to construct a vulnerability evaluation index system of the water-energy-food-ecology nexus based on the VSD framework, and the second step is to use the CRITIC (Criteria Importance Through Intercriteria Correlation) to assign weights to the index. In the third step, SPA-TOPSIS is used to evaluate the vulnerability of the water-energy-food-ecology nexus. The fourth step is to use the obstacle degree model to diagnose the obstacle factors that hinder the reduction of the vulnerability of the water-energy-food-ecology nexus. The specific process is shown in Fig. 2.

Establish the Vulnerability Assessment Index System of Water-Energy-Food-Ecology Nexus

The VSD framework believes that the vulnerability of the system can be divided into three dimensions: exposure, sensitivity, and adaptability [37]. Exposure refers to the degree to which the system is affected by unbalanced internal development and external conditions such as the natural environment [38]. Sensitivity refers to the degree to which the structure, state, and function of the system are affected.

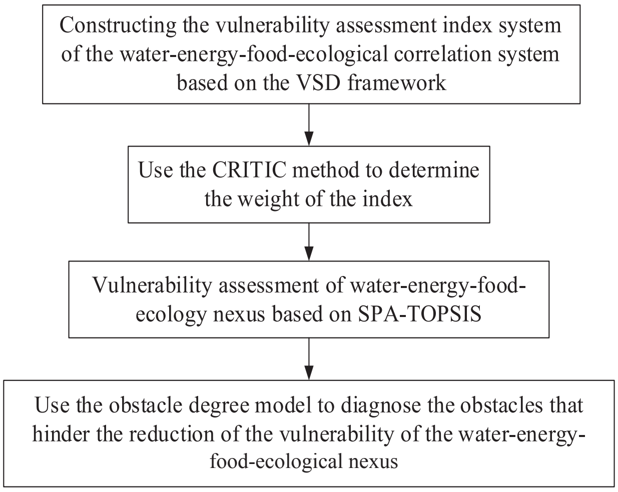

Fig. 2. Flow chart of vulnerability assessment of the water-energy-food-ecology nexus.

Adaptability refers to the self-recovery ability of the system. Under the guidance of scientificity, systematization, and practicability principles, the vulnerability evaluation index system of the water-energy-food-ecology nexus is constructed, as is shown in Table 1. When the value of the positive index is larger and the negative index is smaller, the water-energy-food -ecology nexus of the Yangtze River Economic Belt is more vulnerable.

Method for Determining the Weights of the Vulnerability Assessment Index System of the Water-Energy-Food-Ecology Nexus

The CRITIC method was first proposed by Diakoulaki et al. [39]. This method determines the weight through the conflict of the index and the intensity of contrast. The correlation coefficient determines the conflict of the index. The more significant the correlation coefficient, the smaller the weight. The standard deviation determines the contrast strength of the index, the more significant the standard deviation, the greater the weight. Based on the principle of CRITIC, the original data is firstly standardized to eliminate the influence of different dimensions on the evaluation results.

Table 1. Vulnerability evaluation index system of water-energy-food-ecology nexus.

Evaluation Index System			Impact	Mean	Max	Min	Std.Dev
Vulnerability of water subsystem	Exposure	Domestic water consumption per capita W_1	+	64.01	106.57	37.71	16.64
		Water consumption per 10,000-yuan GDP W_2	+	123.38	335.96	30.93	68.91
		Wastewater discharge per 10,000-yuan GDP W_3	+	12.68	25.05	5.76	3.80
	Sensitivity	Per capita water resource W_4	-	2144.84	5099.72	88.28	1244.92
		Utilization rate of water resources W_5	-	56.46	600.39	6.61	97.31
		Water production module W_6	-	65.57	141.92	26.45	25.29
	Adaptability	Storage capacity of water conservancy project W_7	-	1.71	5.30	0.04	1.39
		Complete investment in wastewater treatment W_8	-	43918.00	198111.00	1508.00	38898.70
		Afforestation area W_9	-	221975.55	713478.00	710.00	188126.96
Vulnerability of energy subsystem	Exposure	Per capita energy consumption E_1	+	2.73	4.90	1.22	0.89
		Proportion of energy consumption in primary industry E_2	+	2.12	6.48	0.52	1.21
		Intensity of energy consumption E_3	+	0.73	1.99	0.34	0.32
	Sensitivity	Primary energy production E_4	-	6606.17	20143.90	57.66	5151.61
		Rate of energy self-sufficiency E_5	-	54.86	167.94	0.52	44.64
		Energy market liquidity E_6	-	32.59	61.75	13.13	12.07
	Adaptability	Investment intensity of resource exploration E_7	-	0.89	2.15	0.32	0.47
		Investment intensity of energy industry E8	-	3.82	12.84	0.51	2.78
		Comprehensive utilization rate of industrial solid waste E_9	-	74.14	99.94	37.18	20.07

Table 1. Continued.

Vulnerability of food subsystem	Exposure	Per capita food consumption F_1	+	167.08	238.65	118.10	24.48
		Per capita grain sown area F_2	+	0.07	0.12	0.01	0.03
		Fertilizer application per unit grain sowing area F_3	+	0.52	0.86	0.28	0.15
	Sensitivity	Per capita grain possession F_4	+	0.36	0.64	0.04	0.14
		Proportion of grain sown area F_5	+	61.59	83.90	44.66	8.48
		Engel's coefficient F_6	+	40.33	51.05	29.31	4.78
	Adaptability	Area of arable land protected by embankments F_7	-	1287.10	5904.00	64.00	1265.94
		Investment intensity of grain and material reserves F_8	-	0.13	0.65	0.03	0.10
		Investment proportion of agriculture, forestry and water conservancy F_9	-	2.43	5.36	0.56	1.25
Vulnerability of ecological subsystem	Exposure	Proportion of forest disaster area C_1	+	0.01	0.19	0.00	0.03
		Industrial smoke and dust emissions C_2	+	33.66	93.26	1.45	16.71
		Sulfur dioxide emissions C_3	+	53.59	110.43	1.11	25.50
	Sensitivity	Annual precipitation C_4	-	130.99	411.87	4.66	112.07
		Crop disaster rate C_5	-	0.08	0.38	0.00	0.07
		Forest coverage rate C_6	-	37.81	61.16	9.08	15.52
	Adaptability	Urban sewage treatment rate C_7	-	87.35	97.70	40.21	10.40
		Intensity of investment in energy conservation and environmental protection C_8	-	0.61	1.41	0.18	0.27
		Soil erosion control area C_9	-	3811.73	9961.80	0.00	2479.00

The non-dimensional standardization processing formula of the positive index is as follows:

$$x_{pt}=\frac{X_{pt}-\min\left(X_{pt}\right)}{\max\left(X_{pt}\right)-\min\left(X_{pt}\right)} \tag{1}$$

The non-dimensional standardization processing formula of the negative index is as follows:

$$x_{pt}=\frac{\max\left(X_{pt}\right)-X_{pt}}{\max\left(X_{pt}\right)-\min\left(X_{pt}\right)} \tag{2}$$

In the formula, X_{pt} represents the original value of the t th index in the p th region; x_{pt} represents the standard value of the t th index in the p th region in a certain year; max(X_{pt}) represents the maximum value of the index; min(X_{pt}) represents the minimum value of the index. Then calculate the weight w_t of the t th index according to formula (3):

$$w_t=\frac{\delta_t\sum_{p=1}^{m}\left(1-r_{pt}\right)}{\sum_{t=1}^{n}\left[\delta_t\sum_{p=1}^{m}\left(1-r_{pt}\right)\right]} \tag{3}$$

In the formula, r_{pt} represents the correlation coefficient of the p th row and the t column, δ_t represents standard deviation.

Vulnerability Assessment Model of Water-Energy-Food-Ecology Nexus

SPA (Set Pair Analysis) is a method that explores the influence of randomness and ambiguity on the system by constructing two sets related to each other [40] and analyzing the relationship between certain and uncertain objects [41]. Connection degree is a common SPA tool used to express the dialectical relationship of the set pairs. The formula is as follows:

$$\sigma=\frac{A}{N}+\frac{B}{N}i+\frac{C}{N}j=a+bi+cj \tag{4}$$

In the formula, N is the total number of set pair features. A, B, C respectively represent the same characteristic number, different characteristic number, and opposite characteristic number. a, b, c represent the degree of identity, difference, and opposition of the two sets, $a+b+c=1$, $i\in[-1,1]$, $j=-1$.

TOPSIS is suitable for solving the multi-objective decision-making problem with limited schemes and can reflect the changing trend of evaluation objects more comprehensively [42]. SPA-TOPSIS method presents the internal correlation between sets through the degree of connection to evaluate the uncertain problems. To eliminate the situation that "the solution closer to the euclidean distance of the positive ideal solution may be closer to the negative ideal solution" [43], which is in the traditional TOPSIS method, the contact vector distance [44] is used to make the evaluation result more reasonable and accurate. Specific steps are as follows:

Step 1: Determine positive ideal solution and negative ideal solution.

When the index direction is positive, $r_t^+ = \max\limits_{1\le p\le m}\{x_{pt}\}$, $r_t^- = \min\limits_{1\le p\le m}\{x_{pt}\}$; When the index direction is negative, $r_t^+ = \min\limits_{1\le p\le m}\{x_{pt}\}$, $r_t^- = \max\limits_{1\le p\le m}\{x_{pt}\}$,there are positive ideal solutions $R^+ = \{r_k^+ \mid k = 1, 2, ..., n\}$ and negative ideal solutions $R^- = \{r_k^- \mid k = 1, 2, ..., n\}$.

Step 2: Calculate the degree of connection.

Take the positive index as an example. Suppose there are a total of m schemes like S_1, S_2, ..., S_m. Scheme S_p and positive ideal solution R^+ form set pair $S^+ = (S_p, R^+)$, and negative ideal solution R^- form set pair $S^- = (S_p, R^-)$. Suppose the degree of connection between S_p and the positive ideal solution R^+ is σ_p^+, and the degree of connection between R^- and the negative ideal solution R^- is σ_p^-, then:

$$\sigma_p^+ = a_p^+ + b_p^+ i + c_p^+ j = w_1\sigma_{p1}^+ + w_2\sigma_{p2}^+ + ... + w_n\sigma_{pn}^+ \tag{5}$$

$$\sigma_p^- = a_p^- + b_p^- i + c_p^- j = w_1\sigma_{p1}^- + w_2\sigma_{p2}^- + ... + w_p\sigma_{pn}^- \tag{6}$$

where, $\sigma_{pt}^+ = a_{pt}^+ + b_{pt}^+ i + c_{pt}^+ j$, $\sigma_{pt}^- = a_{pt}^- + b_{pt}^- i + c_{pt}^- j$. In the formula (5), when $x_{pt} = r_t^-$, $a_{pt}^+ = b_{pt}^+ = 0$ is formulated, then $c_{pt}^+ = 1$; when $x_{pt} \in (r_t^-, r_t^+]$, $a_{pt}^+ = \frac{x_{pt}}{r_t^+}$ is formulated, then $b_{pt}^+ = 1 - a_{pt}^+$, $c_{pt}^+ = 0$. In the formula (6), when $x_{pt} = r_t^+$, $a_{pt}^- = b_{pt}^- = 0$ is formulated, then $c_{pt}^- = 1$; when $x_{pt} \in (r_t^-, r_t^+]$, $a_{pt}^- = \frac{r_t^-}{x_{pt}}$ is formulated, then $b_{pt}^- = 1 - a_{pt}^-$, $c_{pt}^- = 0$; when $r_t^- = 0$, $x_{pt} = 0$, $a_{pt}^- = 1$ is formulated, then $b_{pt}^- = c_{pt}^- = 0$; when $r_t^- = 0$, $x_{pt} \neq 0$; $a_{pt}^- = \frac{r_t^+ - x_{pt}}{r_t^+}$ is formulated, then $b_{pt}^- = 1 - a_{pt}^-$, $c_{pt}^- = 0$.

If the index direction is negative, calculate the connection degree between S_p and R^+ according to formula (6), and calculate the connection degree between S_p and R^- according to formula (5).

Step3: Calculate contact vector distance.

When the contact vector of R^+ is $\overrightarrow{\sigma} = (1, 0, 0)$ the corresponding contact vector of S_p is $\overrightarrow{\sigma} = (a_p^+, b_p^+, c_p^+)$ [39], then the contact vector distance between S_p and R^+ is:

$$d_p^+ = \sqrt{\left(1 - a_p^+\right)^2 + \left(b_p^+\right)^2 + \left(c_p^+\right)^2} \tag{7}$$

Similarly, the contact vector distance between S_p and R^- is:

$$d_p^- = \sqrt{\left(1 - a_p^-\right)^2 + \left(b_p^-\right)^2 + \left(c_p^-\right)^2} \tag{8}$$

Step 4: Calculate the relative closeness degree.

In this study, the relative closeness degree D_p represents the vulnerability of the water-energy-food-ecology system. The larger D_p, the higher the vulnerability of the water-energy-food-ecology system. The specific formula is as follows:

$$D_p = \frac{d_p^-}{d_p^- + d_p^+} \tag{9}$$

To further understand the changes in the vulnerability of the water-energy-food-ecology nexus and its subsystems, 2008, 2013, and 2018 are selected as the critical years. Then, using ArcGIS 10.7 Natural Breaks to divide the vulnerability of the water-energy-food-ecology nexus into five levels, from low to high that is no vulnerable, low vulnerable, moderate vulnerable, highly vulnerable, and extremely vulnerable.

Diagnosis Model of Obstacle Factors of Vulnerability of Water-Energy-Food-Ecology Nexus

The obstacle degree model is used to calculate the obstacle degree by introducing factor contribution degree V_t, index deviation degree Y_t, and obstacle degree H_t to diagnose the obstacle factors that hinder the decline of the vulnerability of the water-energy-food-ecology nexus. Specific formulas are as follows:

$$Y_t = 1 - x_{pt} \tag{10}$$

$$H_t = \frac{Y_t \times V_t}{\sum_{t=1}^{n}\left(Y_t \times V_t\right)} \times 100\% \tag{11}$$

In the formula, Y_t is the gap between the actual value and the optimal value of the index; V_t is the contribution degree of the index to the vulnerability of the water-energy-food-ecology nexus, which is generally expressed by the index weight w_t. H_t is the obstacle degree of index or subsystem to reduce the vulnerability of the water-energy-food-ecology nexus.

Results and Discussion

Analysis of the Temporal and Spatial Evolution of the Vulnerability of the Water-Energy-Food-Ecology Nexus

Vulnerability Analysis of Water-Energy-Food-Ecology Nexus

According to the formula, the comprehensive evaluation results of the water-energy-food-ecology nexus vulnerability in the Yangtze River Economic Belt from 2008 to 2018 are calculated (Table 2.). The vulnerability of the water-energy-food-ecology nexus in all provinces (municipalities) of the Yangtze River Economic Belt shows a fluctuating downward trend. The vulnerability of Sichuan, Guizhou, and Yunnan provinces in the upper reaches of the Yangtze River is relatively low, which is opposite to that of Shanghai and Jiangsu in the lower reaches. In recent years, the vulnerability of the water-energy-food-ecology nexus in Shanghai has decreased rapidly, from 0.5664 in 2013 to 0.4943 in 2018, a decrease of about 12.73%, while Jiangsu Province showed a fluctuating downward trend. The following is a further analysis of the spatio-temporal evolution of vulnerability in the water-energy-food-ecology nexus in 2008, 2013 and 2018.

From the perspective of the temporal and spatial evolution (Fig. 3), the most vulnerable provinces distribute in the lower reaches of the Yangtze River Economic Belt. In 2008, the most vulnerable provinces (municipalities) mainly included the lower reaches of Jiangsu and Shanghai, and their vulnerability evaluation values are 0.5713 and 0.5624, respectively, while the less vulnerable provinces concentrated in the upper and middle reaches. From 2008 to 2013, the spatial pattern of the vulnerability of the water-energy-food-ecology nexus in the Yangtze River Economic Belt has changed. Opposite to province Hunan and Zhejiang, the vulnerability of Sichuan, Chongqing, Anhui, Hubei, and Guizhou has increased, while Yunnan, Jiangsu, Shanghai, and Jiangxi remain unchanged. The spatial distribution of vulnerabilities in 2018 has changed more significantly than in the previous period. The number of provinces (municipalities) at the highly vulnerable level has increased (Table 3), but the three provinces of Sichuan, Yunnan, and Guizhou still maintain low vulnerability. On the whole, the upper reaches of the Yangtze River Economic Belt are generally in low vulnerability, while the middle reaches are mainly in a moderate vulnerable state, and the downstream areas are in a highly vulnerable and extremely vulnerable state.

Vulnerability Analysis of Water Subsystem

From 2008 to 2018, the temporal and spatial distribution of the vulnerability of the water subsystem

Table 2. Results of vulnerability assessment of water-energy-food-ecology nexus.

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Shanghai	0.5624	0.5585	0.5568	0.5795	0.5584	0.5664	0.5342	0.5244	0.5108	0.4975	0.4943
Jiangsu	0.5713	0.5509	0.5551	0.5447	0.5436	0.5540	0.5539	0.5465	0.5349	0.5464	0.5467
Zhejiang	0.5140	0.5100	0.5008	0.5064	0.4895	0.4778	0.4834	0.4637	0.4722	0.4821	0.4790
Anhui	0.4970	0.4981	0.4925	0.5015	0.4936	0.4936	0.4952	0.4836	0.4754	0.4776	0.4875
Jiangxi	0.4891	0.4856	0.4644	0.4791	0.4429	0.4640	0.4639	0.4504	0.4498	0.4567	0.4602
Hubei	0.4985	0.5111	0.4937	0.5051	0.4995	0.4897	0.4911	0.4785	0.4670	0.4718	0.4671
Hunan	0.5235	0.5290	0.5013	0.5103	0.4896	0.4819	0.4876	0.4787	0.4653	0.4679	0.4721
Chongqing	0.4982	0.5173	0.5049	0.4885	0.4802	0.4901	0.4765	0.4734	0.4796	0.4936	0.4810
Sichuan	0.4793	0.4809	0.4789	0.4809	0.4570	0.4738	0.4730	0.4669	0.4606	0.4529	0.4601
Guizhou	0.4897	0.4874	0.4699	0.4557	0.4451	0.4470	0.4412	0.4396	0.4282	0.4341	0.4374
Yunnan	0.4748	0.4698	0.4482	0.4734	0.4462	0.4554	0.4609	0.4336	0.4443	0.4540	0.4484

Table 3. Number of provinces (municipalities) in different vulnerability levels of water-energy-food-ecology nexus.

	No vulnerable	Low vulnerable	Moderate vulnerable	Highly vulnerable	Extremely vulnerable
2008	2	2	3	2	2
2013	2	1	3	3	2
2018	2	2	2	4	1

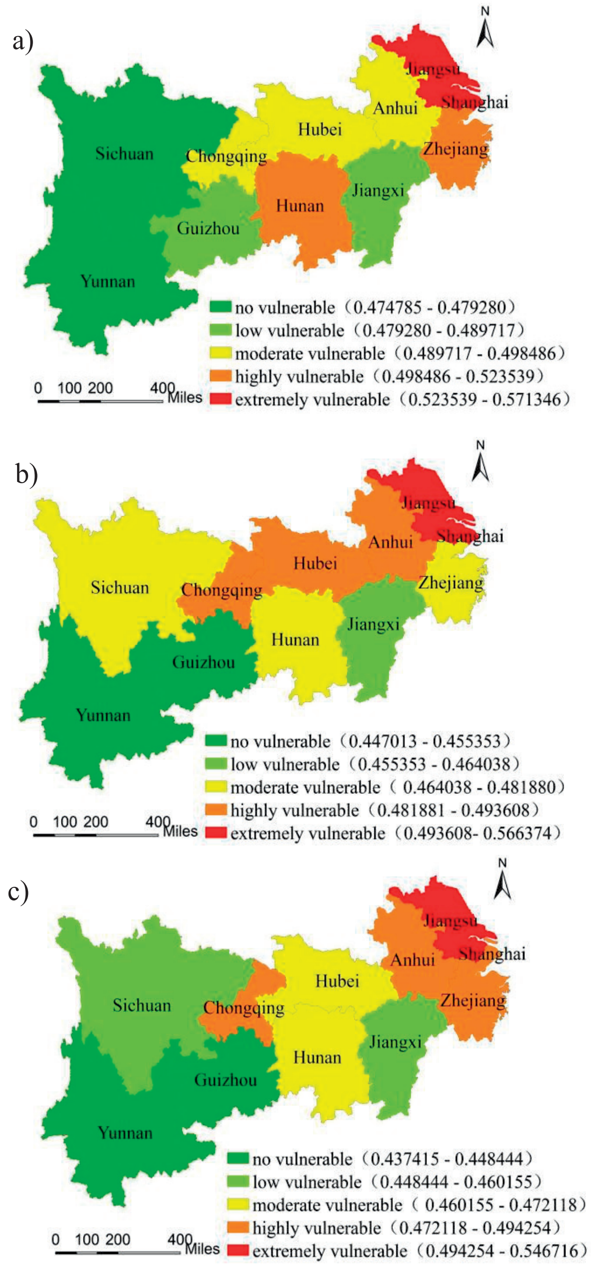

Fig. 3. Spatial-temporal evolution of the vulnerability of water-energy-food-ecology nexus: a) 2008, b) 2013, c) 2018.

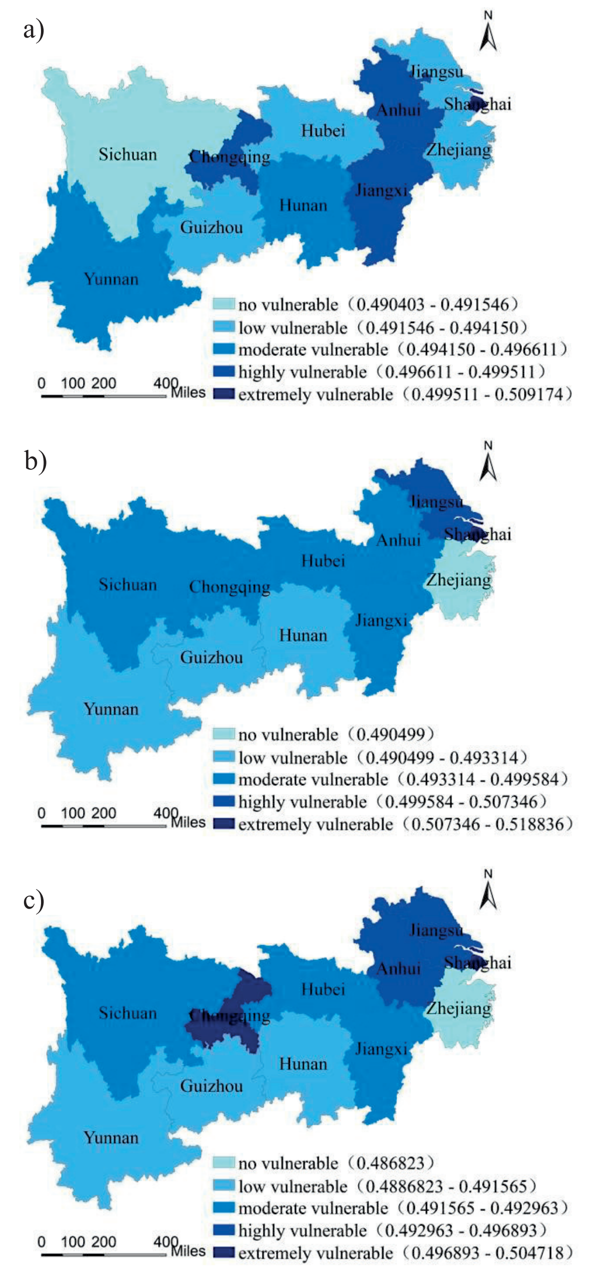

Fig. 4. Spatial-temporal evolution of the vulnerability of water subsystem: a) 2008, b) 2013, c) 2018.

is quite different (Fig. 4). From 2008 to 2013, the provinces(municipalities) with reduced vulnerability levels mainly included Yunnan, Chongqing, Jiangxi, Hunan, Anhui, and Zhejiang, which is opposite to Hubei, Sichuan, and Jiangsu. The vulnerability levels of Shanghai and Guizhou were maintained constant. From 2013 to 2018, only Chongqing and Anhui increased vulnerability levels. In general, the number of provinces (municipalities) in the no vulnerable and highly vulnerable levels decreased during the research period (Table 4), while the number of provinces (municipalities) in the low and moderate vulnerability levels increased relatively. Spatially, the upper and middle reaches are developing towards low and moderate vulnerable, and the lower reaches are developing towards highly vulnerable. It may be caused by unbalanced regional development and unreasonable industrial layout.

The four provinces (municipalities) of Yunnan, Guizhou, Sichuan, and Chongqing, located in the upper reaches of the Yangtze River, are dominated by plateaus and mountainous terrain. Their social and economic development is relatively backward, and both the level of productivity and the utilization rate of water resources are low. In 2008, the water consumption per 10,000-yuan of GDP in Yunnan and Guizhou provinces was about 286.11 m^3 and 268.97 m^3. In 2018, it dropped to 87.07 m^3 and 72.13 m^3. It shows that water use

Table 4. Number of provinces (municipalities) in different vulnerability levels of water subsystem.

	No vulnerable	Low vulnerable	Moderate vulnerable	Highly vulnerable	Extremely vulnerable
2008	1	4	2	3	1
2013	1	3	5	1	1
2018	1	3	3	2	2

efficiency has improved, but there is still a huge gap compared with downstream provinces such as Shanghai and Zhejiang. In the middle reaches, the industrial and agricultural water consumption is relatively large, and the heavy chemical industries with high water consumption concentrate in the areas along the Yangtze River, and the industrial structure transformation is not timely. The economic development of the downstream areas has a higher demand for water resources, and the contradiction between supply and demand of water resources is prominent, especially in Jiangsu Province. In recent years, the water resources have been over-exploited, and the per capita water resources are less than 600 m^3, resulting in the increasing vulnerability of water subsystem in Jiangsu Province. To strengthen the protection of water subsystem and promote the high-quality economic development, in 2016, the Central Committee of the Communist Party of China reviewed and approved the Outline of the Development Plan for the Yangtze River Economic Belt [45]. When interpreting the outline, the relevant person in charge of the Ministry of Water Resources pointed out that in the face of still high waste and sewage discharge and serious eutrophication of lakes and reservoirs, it is necessary to strict water resource management system, implement an ecological environment protection system, and encourage and guide water rights trading between the upper and lower reaches to provide a good development environment for the middle and lower reaches.

Vulnerability Analysis of Energy Subsystem

From 2008 to 2018, the vulnerability of the energy subsystem showed an upward trend. In space, it shows the characteristics of transferring from the upper reaches of the Yangtze River to the middle and lower reaches. The classification results show that (Fig. 5), from 2008 to 2013, only Yunnan, Guizhou, Hubei and Zhejiang provinces decline the vulnerability levels. Among them, the vulnerability evaluation value in Guizhou decreased from 0.4984 in 2008 to 0.4836 in 2013, with the largest decline of about 3%. From 2013 to 2018, the number of provinces(municipalities) above the moderate vulnerability level increased (Table 5). The provinces with increased vulnerability levels mainly included Anhui, Jiangxi, Hubei, Guizhou, Yunnan, while Sichuan, Chongqing, Hunan, Shanghai, and Jiangsu showed a downward trend. On the whole, the vulnerability of the energy subsystem in the upper reaches of the Yangtze River Economic Belt is low, the vulnerability of the middle reaches is high, and the lower reaches are declining. Compared with the

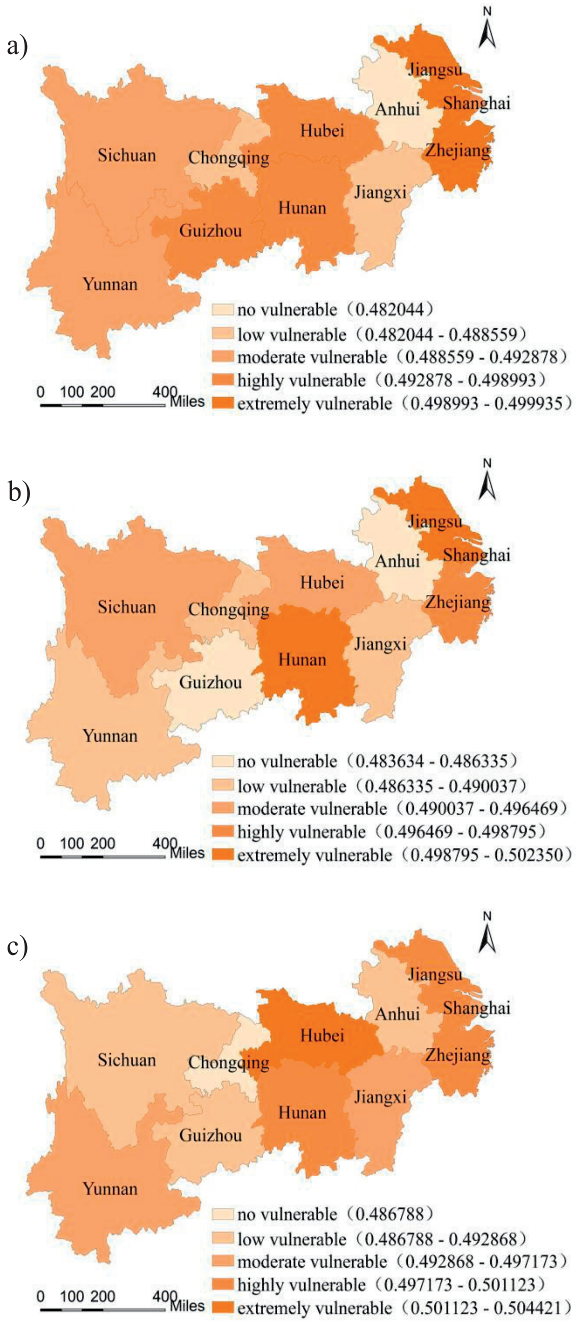

Fig. 5. Spatial-temporal evolution of the vulnerability of energy subsystem: a) 2008, b) 2013, c) 2018.

Table 5. Number of provinces (municipalities) in different vulnerability levels of energy subsystem

	No vulnerable	Low vulnerable	Moderate vulnerable	Highly vulnerable	Extremely vulnerable
2008	1	2	2	4	2
2013	2	3	2	1	3
2018	1	3	3	3	1

upstream regions, the middle and downstream regions have a higher social and economic development level and an advanced level of industrial development. The increasing energy demand has put tremendous pressure on the energy subsystem. In addition, with the continuous adjustment of the industrial structure, industries with high energy consumption in the downstream areas are gradually shifting to the upper and middle regions. However, the problems of low energy utilization efficiency in the upper and middle regions have not been solved yet, increasing the vulnerability of the energy subsystem. In recent years, the capacity of the provinces (municipalities) in the upper reaches of the Yangtze River to treat and reuse solid waste has changed significantly. For example, the comprehensive utilization rate of solid waste in Sichuan Province has dropped from 61.67% in 2008 to 41.28% in 2018. While in Guizhou, it has increased from 40.02% to 55.56% but is still far below the lower reaches of the Yangtze River. Therefore, all provinces (municipalities) should rationally manage energy resources, improve energy consumption structure, increase energy utilization efficiency, and reduce the adverse effects of economic development and industrialization on sustainable development.

Vulnerability Analysis of Food Subsystem

From 2008 to 2018, the vulnerability of food subsystems in the Yangtze River Economic Belt reduced slightly (Fig. 6). The classification results show that from 2013 to 2018, only Sichuan and Anhui provinces have increased vulnerability levels. In recent years, the provinces with no vulnerable or low vulnerable account for only about 30% of all in the Yangtze River Economic Belt (Table 6), indicating that the overall situation of food vulnerability is not optimistic. It is mainly affected by natural conditions. At present, the arable land resources in the Yangtze River Economic Belt are mainly distributed in the middle and upper reaches. In 2018, the per capita grain sown area of Sichuan, Yunnan, Guizhou, and other provinces was about 0.0751, 0.0761, and 0.0864 hectares, with a decrease of 4.94%, 4.13%, and 6.25% compared with 2008, but it still far exceeded Shanghai, Zhejiang and other places in the lower reaches. However, the large-scale use of chemical fertilizers and pesticides in the food production process will increase soil erosion, resulting in a decline in arable land quality and thus affecting food production. Compared with the middle and upper reaches, the superior natural conditions in the lower reaches are conducive to food production. However, the per capita grain sowing area in Shanghai in 2018 was only 0.0054 hectares, indicating that the

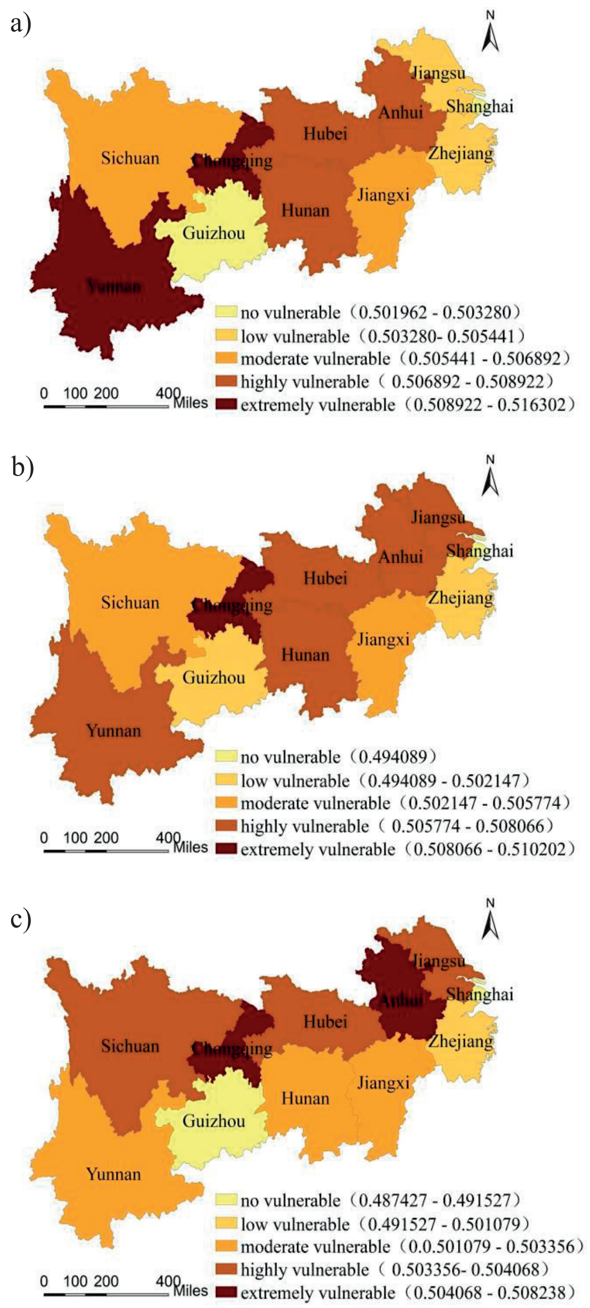

Fig .6. Spatial-temporal evolution of the vulnerability of food subsystem: a) 2008, b) 2013, c) 2018.

Table 6. Number of provinces (municipalities) in different vulnerability levels of food subsystem

	No vulnerable	Low vulnerable	Moderate vulnerable	Highly vulnerable	Extremely vulnerable
2008	2	2	2	3	2
2013	1	2	2	5	1
2018	2	1	3	3	2

rapid development of urbanization and industrialization has caused changes in the scale and structure of labor. Besides, construction land occupies a large amount of arable land, which reduces the resource advantage of food production and increases the vulnerability of the food subsystem. Therefore, the provinces (municipalities) in the Yangtze River Economic Belt need to increase investment in the innovation of agricultural technology, reduce the amount of fertilizer and pesticide application, increase food production capacity, and ensure the security of food supply and the efficient use of arable land resources.

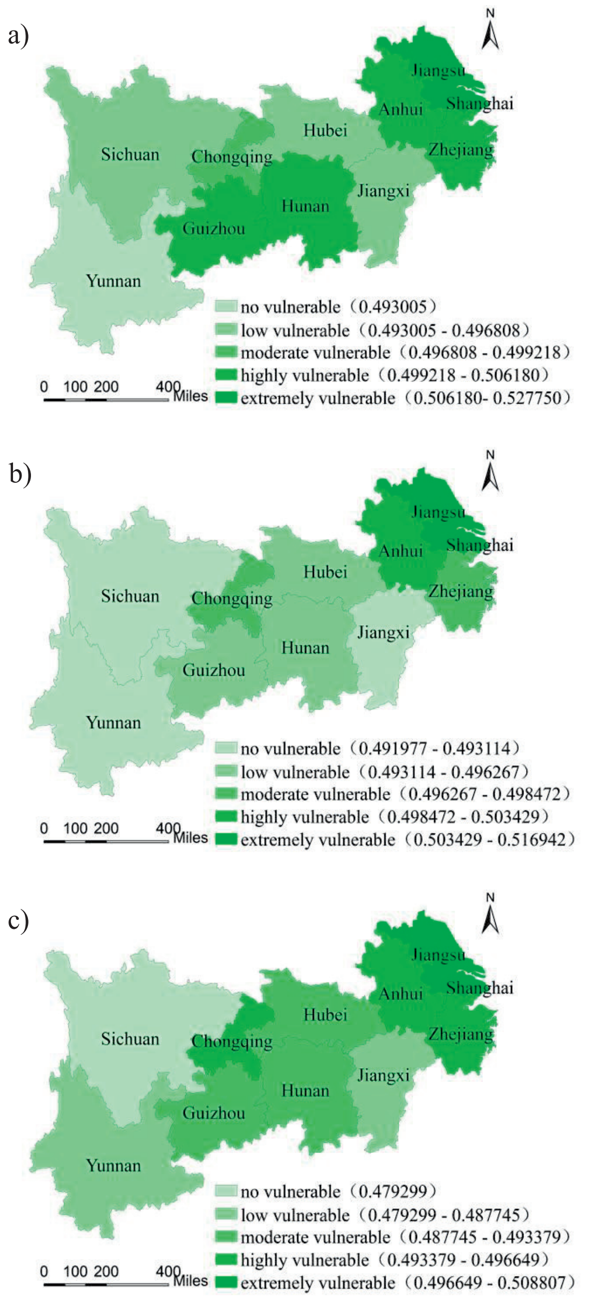

Fig. 7. Spatial-temporal evolution of the vulnerability of ecology subsystem: a) 2008, b) 2013, c) 2018.

Vulnerability Analysis of Ecology Subsystem

From 2008 to 2018, the overall vulnerability of the ecology subsystem showed a downward trend. The classification results show that (Fig. 7), from 2008 to 2013, the number of provinces(municipalities) in the upper and middle reaches of the Yangtze River with moderate vulnerability and below has increased (Table 7). From 2013 to 2018, the vulnerability of ecology subsystems in the Yangtze River Economic Belt showed a pattern of the highest vulnerability in the lower reaches and low vulnerability in the upper reaches. It indicates that the ecological development level of the upper, middle, and lower reaches of the Yangtze River Economic Belt is quite different, and the lower reaches are still facing a severe ecological situation. In 2018, the average forest coverage rate of the provinces (municipalities) in the Yangtze River Economic Belt was 39%, about double the national average. Jiangxi, Zhejiang, Yunnan, Hunan, Guizhou, Chongqing, and other upper and midstream provinces (municipalities) rank in the top 6. The forest coverage rate of Jiangxi Province is as high as 61.16%, and Jiangxi now has become a demonstration area for ecological civilization construction. However, in Shanghai and Jiangsu, which are located in the lower reaches of the Yangtze River, the forest coverage rate is only 14.04% and 15.2%, compared with 9.41% and 10.48% in 2008, the growth rate is more than 30%. It shows that although the ecological environment has been improved, it is still at a relatively fragile level. Therefore, upper reaches should rationally develop resources to coordinate economic development and environmental protection in future construction. The Middle reaches should accelerate industrial upgrading and vigorously develop a circular and low-carbon economy. Lower reaches need to take advantage of economic advantages, increase environmental protection and pollution control, and use resources efficiently.

Table 7. Number of provinces (municipalities) in different vulnerability levels of ecology subsystem.

	No vulnerable	Low vulnerable	Moderate vulnerable	Highly vulnerable	Extremely vulnerable
2008	1	3	1	4	2
2013	3	3	2	1	2
2018	1	2	3	3	2

Diagnosis of Vulnerability Obstacle Factors of Water-Energy-Food-Ecology Nexus in the Yangtze River Economic Belt

Analysis of the Obstacle Factors in the Index Layer

According to the obstacle degree model, the obstacle degree of each index is calculated. To reflect the criticality, top eight obstacle factors of each year are selected for analysis (Table 8). From the perspective of common obstacle factors, the comprehensive utilization rate of solid waste (E_9) is the primary obstacle factor, with the high frequency and obstacle degree, followed by the proportion of energy consumption in the primary industry (E_2), energy consumption intensity (E_3), water consumption per 10,000-yuan GDP (W_2), per capita domestic water consumption (W_1), chemical fertilizer application per unit grain sowing area (F_3), etc. The obstacle factors are mainly concentrated in energy, food, and water subsystems in the past decade from the distribution of obstacle factors. Since 2015, the improvement of the ranking of obstacle factors such as forest coverage (C_6) and urban sewage treatment rate (C_7) shows that the impact of ecology subsystem on the

Table 8. Obstacle degree of index layer in the Yangtze River Economic Belt.

Year	Program	Ranking of index							
		1	2	3	4	5	6	7	8
2008	Index	E_9	E_2	E_1	W_1	F_3	C_6	E_3	F_2
	Obstacle degree	6.772%	6.205%	5.575%	4.624%	4.267%	3.579%	3.560%	3.513%
2009	Index	E_9	E_2	E_1	W_1	F_3	E_3	C_6	F_5
	Obstacle degree	6.819%	6.177%	5.322%	4.444%	4.396%	3.704%	3.683%	3.476%
2010	Index	E_9	E_2	E_1	W_1	F_3	E_3	C_6	F_5
	Obstacle degree	6.869%	5.876%	4.621%	4.096%	4.092%	3.854%	3.537%	3.437%
2011	Index	E_9	E_2	E_1	E_3	W_1	F_3	W_2	C_6
	Obstacle degree	6.429%	6.002%	4.394%	4.287%	4.235%	4.100%	3.991%	3.778%
2012	Index	E_9	E_2	E_3	W_1	W_2	E_1	F_3	F_1
	Obstacle degree	10.350%	5.588%	4.184%	4.117%	3.904%	3.818%	3.816%	3.564%
2013	Index	E_9	E_2	E_3	W_2	E_1	W_1	F_3	C_6
	Obstacle degree	6.254%	5.691%	4.642%	4.176%	4.170%	3.987%	3.917%	3.746%
2014	Index	E_9	E_2	E_3	W_2	E_1	F_3	W_1	C_6
	Obstacle degree	6.362%	5.725%	4.794%	4.404%	4.072%	3.988%	3.937%	3.824%
2015	Index	E_9	E_2	E_3	W_2	F_3	E_1	C_6	C_7
	Obstacle degree	6.107%	5.519%	4.734%	4.357%	3.930%	3.821%	3.730%	3.659%
2016	Index	E_2	E_9	E_3	W_2	F_3	C_6	C_7	E_1
	Obstacle degree	5.403%	5.304%	4.767%	4.425%	3.854%	3.731%	3.688%	3.615%
2017	Index	E_2	E_9	E_3	W_2	F_6	C3	F_3	W_3
	Obstacle degree	5.501%	5.305%	4.980%	4.619%	4.253%	4.049%	3.883%	3.881%
2018	Index	E_2	E_9	E_3	W_2	C3	F_6	F_3	W_3
	Obstacle degree	5.459%	5.208%	5.114%	4.692%	4.544%	4.379%	4.069%	4.038%

vulnerability of the nexus is gradually increasing. From the top three obstacle factors each year, the top three in 2008-2013 were the comprehensive utilization rate of solid waste (E_9), the proportion of energy consumption in the primary industry (E_2), and per capita energy consumption. In 2012, energy consumption intensity (E_3) became the third obstacle factor, and the ranking remained unchanged in subsequent years. In recent years, the rapid development of the social economy and the continuous progress of industrialization technology have improved the problems of large-scale discharge of wastewater, and low utilization rate of water resources development. However, problems such as excessive consumption of water and improper treatment of industrial wastewater and low comprehensive utilization rate of solid waste still hinder the sustainable development of the water-energy-food-ecology nexus. In the future, it is necessary to continue to strengthen technological innovation, improve the utilization rate of water resources and urban sewage treatment rate, adjust the energy consumption structure of the three industries and reasonably control the application amount of chemical fertilizer, to reduce the vulnerability of water-energy-food-ecology nexus.

Analysis of the Obstacle Factors in the Subsystem Layer

In terms of the specific value, the annual average obstacle degree of water, energy, food, and ecology subsystem is 22.92%, 29.97%, 25.41%, and 24.5%, and the order is energy subsystem>food subsystem> ecology subsystem>water subsystem. In terms of the changing trends (Fig. 8), from 2008 to 2016, the obstacle degree of the water subsystem showed an obvious upward trend, while the food subsystem fluctuated between 24.07% and 27.4%, with a small range of change. From 2016 to 2018, opposite to the water subsystem,

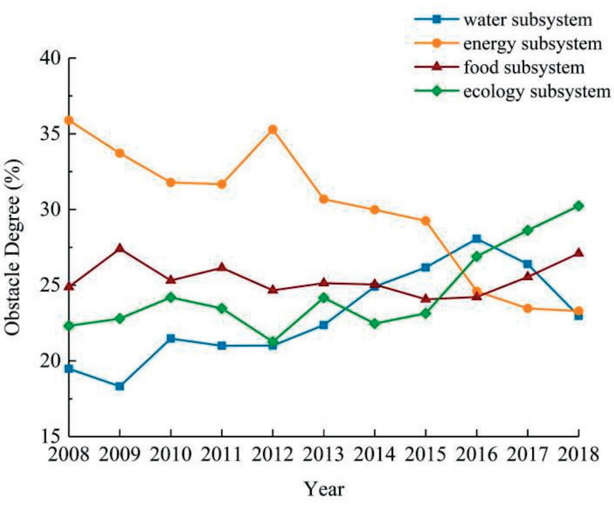

Fig. 8. Obstacle degree of subsystem layer in the Yangtze River Economic Belt.

the obstacle degree of the food subsystem increased rapidly. Except for the slight fluctuation in 2012, the obstacle degree of the energy subsystem showed a downward trend, from 35.89% in 2008 to 23.29% in 2018, with a decrease of about 35.1%. While in the ecology subsystem, it has been increasing year by year in the recent five years. In 2016, the obstacle degree had exceeded its annual average of 24.5%, and now, it has reached 30.23%, indicating that the ecological situation of the Yangtze River Economic Belt is still dire, and the hindrance effect of the ecology subsystem on reducing the vulnerability of the associated system is gradually increasing. From the changing trend and rate of the obstacle degree of each subsystem, the years with higher obstacle degrees of the energy subsystem (more than the annual average of 29.97%) are mostly before 2015. In 2016, the obstacle degree of the water subsystem surpassed that of the energy subsystem and ranked first for the first time. In combination with the analysis results of the index layer, it can be seen that it is important to focus on food and ecology subsystems in future development. At the same time, taking the energy and water subsystems into account is necessary.

Conclusions and Policy Recommendations

Conclusions

Based on the basic characteristics of vulnerability, this study firstly constructs the vulnerability evaluation index system. Then, the vulnerability of the water-energy-food-ecology nexus and its subsystems in the Yangtze River Economic Belt from 2008 to 2018 is evaluated, and its spatial and temporal evolution characteristics are studied. Finally, the obstacle degree model is used to diagnose the obstacle factors that hinder vulnerability reduction.

The following conclusions are obtained through the research: (1) From the nexus perspective, from 2008 to 2018, the vulnerability of the water-energy-food-ecology nexus in the Yangtze River Economic Belt decreased, showing an overall trend of improvement and presenting the spatial distribution characteristics of upper reaches < middle reaches < lower reaches. From the perspective of subsystems, except for the food subsystem, other subsystems showed a trend of developing to low and moderate vulnerable in the upper and middle reaches, and developing to highly and extremely vulnerable in the lower reaches. (2) The obstacle factors that hinder the reduction of the water-energy-food-ecology nexus vulnerability mainly include the comprehensive utilization rate of solid waste, the proportion of energy consumption in the primary industry, the intensity of energy consumption, water consumption per 10,000-yuan GDP, per capita domestic water consumption, fertilizer application per unit grain sowing area, etc. From the perspective of subsystems, the changing trend of obstacle degree of each subsystem are different. The energy subsystem is the main obstacle system to reduce the vulnerability of the water-energy-food-ecology nexus, followed by the food subsystem, ecology subsystem, and water subsystem. The annual average obstacle degrees are 29.97%, 25.41%, 24.5%, and 22.92%, respectively. Future development needs to focus on the ecology and food subsystem with a rapid increase in obstacle degree, meanwhile, taking the water resources system and energy subsystem into account.

Policy Recommendations

Through the research, we can also find that the vulnerability level of each province (municipalities) subsystem of the Yangtze River Economic Belt is not consistent. For example, the vulnerability of water, energy, and ecology subsystems in the upper reaches of the Yangtze River is relatively low. However, the resource advantages do not effectively ensure the security of the food system, which is mainly affected by the mountainous and plateau terrain in the upper reaches. Therefore, all provinces should formulate targeted measures according to the characteristics of resources. In this regard, the following policy suggestions are put forward. Firstly, upper reaches shall develop resources rationally, improve the development and utilization rate of water resources and the comprehensive utilization rate of solid waste, and promote the coordination between economic development and environmental protection. Secondly, middle reaches should promote the transformation and upgrading of industrial structure, improve water efficiency, control chemical fertilizers and pesticides, and develop a circular and low-carbon economy. Thirdly, lower reaches need to take advantage of economic advantages, increase agricultural innovation and technology investment, strengthen environmental protection and pollution control, and advocate green GDP. In recent years, Yunnan Province, located in the upper reaches, has strictly controlled sewage discharge, prevented soil erosion and water pollution. Now, the province has effectively improved the ecological environment, reflecting effectiveness of the recommendations.

To verify the scientificity and rationality of this research, it is necessary to compare the research conclusions of the vulnerability of each subsystem with those of other relevant studies from the perspective of the Yangtze River Economic Belt and various provinces (municipalities). For example, in terms of water vulnerability, it is compared with the research conclusions of Jiangsu, Shanghai, Anhui, Jiangxi, and other provinces in 2013 [46], while energy and food vulnerability is compared with the research conclusions of security evaluation of the Yangtze River Economic Belt [47] and Guizhou province, respectively [48]. Ecological vulnerability is compared with that in Yunnan Province from 2008 to 2018 [49]. The results all show that the conclusions are highly consistent. Besides, this research also has some innovations and features, for example, considering the significant role of the ecology system in sustainable development and the inseparable relationship between water, energy, food, and ecology system, emphasizing the integration of the ecology system into the water-energy-food nexus. Based on the definition of vulnerability, the study explores spatial and temporal patterns of vulnerability evolution of water-energy-food-ecology nexus in the Yangtze River Economic Belt, which will help fill the existing research gaps in the Yangtze River Economic Belt and broaden the existing research perspectives of the water-energy-food-ecology nexus, thus providing new ideas for regional governance.

When studying the vulnerability of the water-energy-food-ecology nexus in the Yangtze River Economic Belt, this study focuses on analyzing the temporal and spatial evolution characteristics of the vulnerability of the water-energy-food-ecology nexus and each subsystem after the addition of the ecology system. The interaction between subsystems and changes in external factors such as climate, land, and vegetation coverage will impact the vulnerability of the water-energy-food-ecology nexus. In the future, these factors will be added for further analysis based on the support of more data and information.

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Conflict of Interest

The authors declare no conflict of interest.

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