Water resource security evaluation of the Yangtze River Economic Belt

Junlong Liu, Jin Chen, Zhe Yuan, Jijun Xu, Yongqiang Wang and Yuru Lin

ABSTRACT

To reasonably evaluate the water resource security state, this research built a water resource security evaluation index system of the Yangtze River Economic Belt (YREB) based on the driving force-pressure-state-impact (DPSI) concept framework, established a water resource security evaluation model by combining the entropy weight method with the fuzzy set pair analysis method and conducted quantitative evaluations of the water resource security states from 2008 to 2016. All the work above was based on the comprehensive consideration of the water resource characteristics in different areas of the YREB, following the index system construction principles. The results have shown that on the whole, the water resource security state of the YREB has generally undergone a process from getting worse to getting better in the latest nine years. From the aspect of the percentages of the water resource security grades, the spatial distribution of water resource security in the YREB is highest in the downstream area, second in the middle reaches, and lowest in the upper reaches. From the aspect of the DPSI security evaluation results, the driving force and state of the water resource are the important factors affecting the water resource security of the YREB.

Key words | DPSI concept framework, entropy weight method, fuzzy set pair analysis method, water resource security, Yangtze River Economic Belt

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INTRODUCTION

Water resource security is one of the important concepts proposed by the international community at the end of the 20th century. It is closely related to food security, ecological security and environmental security (Zou & An 2012) and it is a basic conditional guarantee for national and areal development (Jiang & Yang 2015). To research the water resource security state in an area (a basin) has important significance for relieving the contradiction between the supply and demand of water resources, further enhancing the development and utilization level of water resources and harmoniously developing the water resources and social economy.

The objective of the Yangtze River Economic Belt (YREB) as one of China's three major strategies in the new era is to promote the harmonious development of the east part, central part and west part of China and build a new economic support belt for China relying on the Yangtze River, a golden waterway (Chen 2016a). The central government and local governments have paid great attention to it. In recent years, because the population has been increasing constantly in the areas along the Yangtze River, urbanization progress has been accelerating and the economy has been quickly developing, a series of non-negligible problems such as water resource shortage, water quality deterioration and wetland area reduction (Zhai *et al.* 2019; Zhang *et al.* 2019) have appeared in the Yangtze River Economic Belt and the water eco-environment of the YREB has been facing a serious challenge. Therefore, only by clearly understanding the water resource security state of the YREB and strengthening water resource management and ecological restoration can it be ensured that the water of the Yangtze River will be kept clear from generation to generation,

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making the strategic goal of the YREB entitled 'Ecology First and Green Water Development' achievable and enabling the construction and development of the YREB to be sustained.

In consideration of this, taking the YREB as the research area, combining the actual conditions in different areas, following the index system construction principles such as representativeness, scientific nature, operability and systematicity, and referring to the research results related to the water resource security evaluation, this paper has built a water security evaluation index system for the YREB based on the driving force-pressure-state-impact (DPSI) concept model, determined the evaluation index weights by using the entropy weight method, further built a water resource security evaluation model by using the fuzzy set pair analysis method and quantitatively evaluated the water resource security conditions of the YREB from 2008 to 2016. The research results can provide reference bases and decision support for the water resource planning and management of the YREB and provide references for water resource security research in other similar areas.

STUDY AREA AND DATASETS

Study area

The Yangtze River Economic Belt stretches across the three major areas of China: East China, Central China and Southwest China, covering nine provinces and two municipalities directly under the central government – Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan and Guizhou – with a total area of 2.05 million square kilometres, accounting for 21% of the total area of China. The population and the gross domestic product (GDP) of the nine provinces and two municipalities directly under the central government both account for over 40% of the population and GDP of China. The YREB is the basin economic belt with the most population, the largest industrial scale and the most complete urban system in the world (Zhai *et al.* 2019). It is also one of the areas with the strongest strategic support for China. Because the social and economic development, natural resource conditions, etc. in different areas are quite different, generally the YREB is divided into three areas: the Upstream Area, the Midstream Area and the Downstream Area. From the upstream to the midstream and then the downstream, six city clusters with different scales – the Central Yunnan City Cluster, the Central Guizhou City Cluster, the Chengdu-Chongqing City Cluster, the Yangtze River Midstream City Cluster, the Yangtze River and Huai River City Cluster, and the Yangtze River Delta City Cluster – have now formed and they are in different development stages (Fang *et al.* 2015), which play very important roles in the economic and social development of the YREB. The position of the YREB is shown in Figure 1.

Datasets

The basic data adopted in the research are derived from the year-by-year statistical data on various indexes of all the provinces and municipalities of China provided by the website of the National Bureau of Statistics (http://data.stats.gov.cn/). In consideration of the data integrity and availability, the statistical data of the 11 provinces and municipalities of the YREB from 2008 to 2016 are selected as the basic data for the research work of the paper. However, there are no specific statistical data for some indexes and the indexes have been obtained by using some index algorithms.

METHODOLOGY

Index system construction

The construction of a water resources evaluation index system is the basis of water resources safety evaluation. However, due to the distribution of water resources having regional characteristics, water resources evaluation index systems in different regions should be different. This study refers to the existing driving force-pressure-state-impact-response (DPSIR) concept frameworks (Cao *et al.* 2012) on water resource security, combines the water resource characteristics and actual situations of the different areas of the YREB, follows the index system construction principles such as representativeness, scientific nature, operability and systematicity, and refers to the relevant results of the existing water resource security evaluation research (Wang *et al.* 2010). The water resource security evaluation index system of the YREB based on the DPSI conceptual model is constructed, as shown in Table 1.

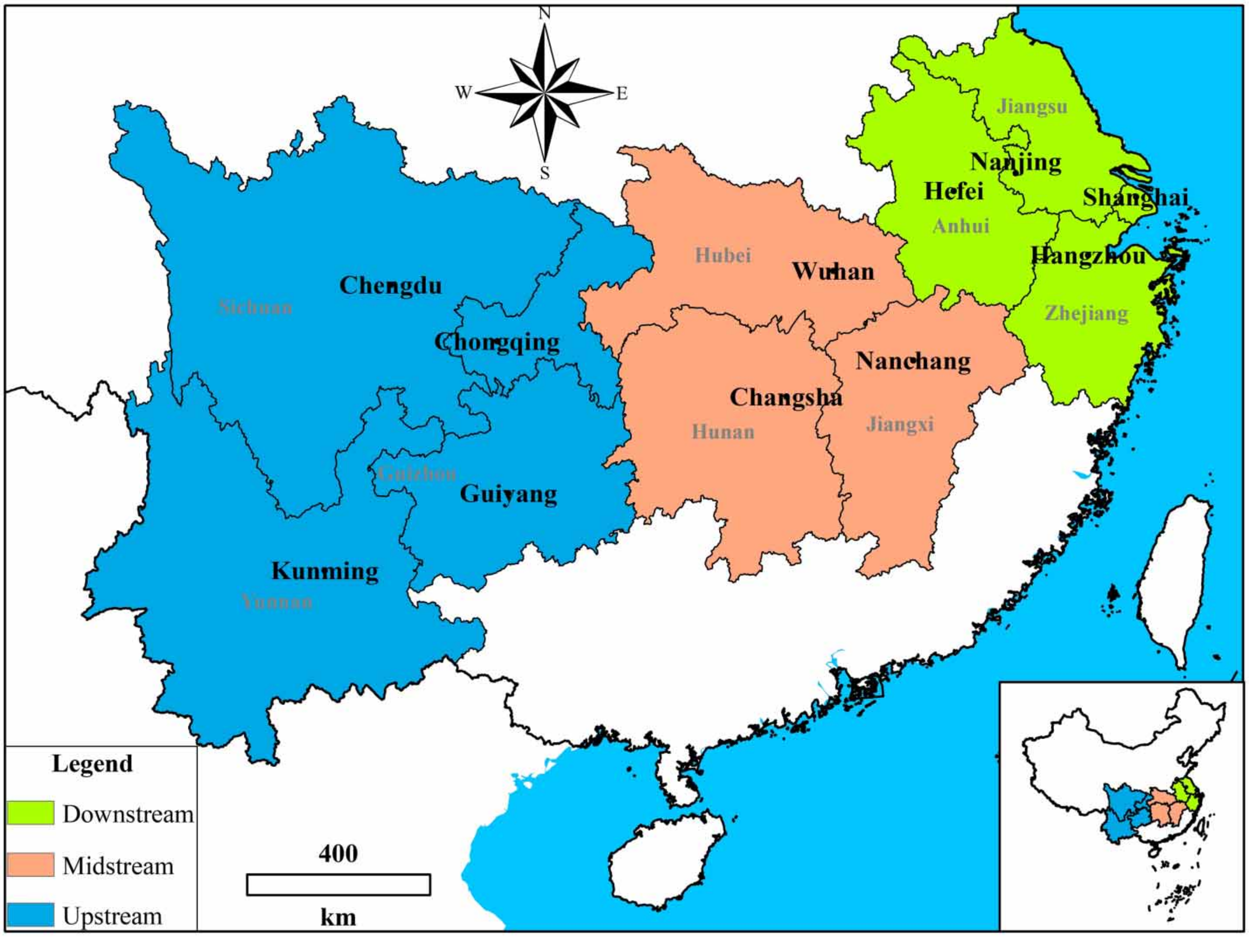

Figure 1 | The schematic diagram of the spatial range of the YREB.

Evaluation grade standard

The grading standard of the water resource security indexes varies from area to area, based on comprehensive consideration of the actual conditions of the different areas of the YREB, referring to research results on the critical values of domestic and foreign water security indexes, water security evaluation standards, the standards and planning objectives issued by local governments, and the requirements for river system protection, etc. (Jin *et al.* 2008). In this paper, the water resource security assessment level of the YREB is divided into five levels: safe, generally safe, barely safe, unsafe and very unsafe. The specific water resource security grading standards are shown in Table 2.

Fuzzy set pair evaluation model

Calculation of index connection degree

Assume that the water resource security evaluation index system is X. The index value x_l ($l = 1, 2, \ldots, n$) of the evaluation objects can be regarded as a set A_l. B_K is the set of the K^{th} level of the grading standard, then the set pair constituted by A_l and B_K is $H(A_l, B_K)$. If the B_K is designated as the first-level set B_1 of an index in the evaluation standard during an evaluation period, then the constituted set pair $H(A_l, B_K)$ can enhance the accuracy of the evaluation conclusion and prevent different evaluation index roles from making differences (Wang *et al.* 2011). Because the boundary of the threshold value s_t ($t = 1, 2, \ldots, K - 1$) is fuzzy, the

Table 1 | Water resource security indexes and their meanings

Target level	Factor level	Index level	Meaning of index	Index type
Water resource security	Driving force (D)	Per capita GDP (yuan/person) D1	It indicates the driving force of the economic development state applied on water resource security.	Negative
		Population density (person/km^2) D2	It indicates the driving force of the population aggregation extent applied on water resource security.	Negative
		Urbanization rate (%) D3	It indicates the driving force of the areal development applied on water resource security.	Negative
		Percentage of irrigation area in cultivated land area (%) D4	It indicates the driving force of the agricultural development applied on water resource security.	Positive
		Annual GDP growth rate (%) D5	It indicates the driving force of the economic development intensity applied on water resource security.	Negative
	Pressure (P)	Water consumption for each 10,000 yuan of GDP (m^3/10,000 yuan) P1	It indicates the pressure of the economic development intensity on water resource quantity.	Negative
		Water consumption for each 10,000 yuan of industrial output (m^3/10,000 yuan) P2	It indicates the pressure of the industrial water consumption on water resource quantity.	Negative
		Water consumption for each 10,000 yuan of agricultural output (m^3/10,000 yuan) P3	It indicates the pressure of the agricultural water consumption on water resource quantity.	Negative
	State (S)	Per capita water resource quantity (m^3/person) S1	It indicates the per capita water resource state.	Positive
		Per unit area water resource quantity (10,000 m^3/km^2) S2	It indicates the per unit area water resource state.	Positive
	Impact (I)	Loss rate due to agricultural drought (%) I1	It indicates the impact on agriculture.	Negative
		Percentage of the people who have difficulty to drink due to drought (%) I2	It indicates the impact on human drinking water.	Negative
		Percentage of the animals that have difficulty to drink water due to drought (%) I3	It indicates the impact on livestock and poultry farming.	Negative

Table 2 | Grades of water resource security evaluation of the YREB

Target level	Factor level	Index level	Safe	Generally safe	Barely safe	Unsafe	Very unsafe
Water resource security	Driving force (D)	D1	<2,000	2,000–5,000	5,000–8,000	8,000–12,000	>12,000
		D2	<400	400–800	800–2,000	2,000–5,000	>5,000
		D3	<10	10–20	20–30	30–50	>50
		D4	>60	50–60	40–50	30–40	<30
		D5	<3	3–5	5–8	8–10	>10
	Pressure (P)	P1	<300	300–600	600–1,000	1,000–1,500	>1,500
		P2	<200	200–400	400–600	600–1,000	>1,000
		P3	<500	500–1,000	1,000–1,500	1,500–2,000	>2,000
	State (S)	S1	>3,000	3,000–2,300	2,300–1,700	1,700–1,000	<1,000
		S2	>200	200–150	150–100	100–50	<50
	Impact (I)	I1	<2.75	2.75–7.50	7.50–16.25	16.25–23.30	>23.30
		I2	0.01	0.01–0.08	0.08–0.85	0.85–2.38	>2.38
		I3	0.01	0.01–0.64	0.64–5.98	5.98–16.66	>16.66

$$\mu A_l - B_1 = \begin{cases} 1 + 0I_1 + 0I_2 + \cdots + 0I_{K-2} + 0J, & x_l \leq s_1 \\ \dfrac{s_1 + s_2 - 2x_l}{s_2 - s_1} + \dfrac{2x_l - 2s_1}{s_2 - s_1} I_1 + 2I_2 + \cdots + 0I_{K-2} + 0J, & s_1 < x_l \leq \dfrac{s_1 + s_2}{2} \\ 0 + \dfrac{s_2 + s_3 - 2x_l}{s_3 - s_1} I_1 + \dfrac{2x_l - s_1 - s_2}{s_3 - s_1} I_2 + \cdots + 0I_{K-2} + 0J, & \dfrac{s_1 + s_2}{2} < x_l \leq \dfrac{s_2 + s_3}{2} \\ \cdots & \\ 0 + 0I_1 + \cdots + \dfrac{2s_{K-1} - 2x_l}{s_{K-1} - s_{K-2}} I_{K-2} + \dfrac{2x_l - s_{K-2} - s_{K-1}}{s_{K-1} - s_{K-2}} J, & \dfrac{s_{K-2} + s_{K-1}}{2} < x_l \leq s_{K-1} \\ 1 + 0I_1 + 0I_2 + \cdots + 0I_{K-2} + 1J, & x_l > s_{K-1} \end{cases} \quad (1)$$

$$\mu A_l - B_1 = \begin{cases} 1 + 0I_1 + 0I_2 + \cdots + 0I_{K-2} + 0J, & x_l \geq s_1 \\ \dfrac{2x_l - s_1 - s_2}{s_1 - s_2} + \dfrac{2s_1 - 2x_l}{s_1 - s_2} I_1 + 2I_2 + \cdots + 0I_{K-2} + 0J, & \dfrac{s_1 + s_2}{2} < x_l \leq s_1 \\ 0 + \dfrac{2x_l - s_2 - s_3}{s_1 - s_3} I_1 + \dfrac{s_1 + s_2 - 2x_l}{s_1 - s_3} I_2 + \cdots + 0I_{K-2} + 0J, & \dfrac{s_2 + s_3}{2} < x_l \leq \dfrac{s_1 + s_2}{2} \\ \cdots & \\ 0 + 0I_1 + \cdots + \dfrac{2x_l - 2s_{K-1}}{s_{K-2} - s_{K-1}} I_{K-2} + \dfrac{s_{K-2} + s_{K-1} + 2x_l}{s_{K-2} - s_{K-1}} J, & s_{K-1} < x_l \leq \dfrac{s_{K-2} + s_{K-1}}{2} \\ 1 + 0I_1 + 0I_2 + \cdots + 0I_{K-2} + 1J, & x_l < s_{K-1} \end{cases} \quad (2)$$

connection degree $\mu A_l - B_1$ can be obtained by using Equations (1) and (2) to calculate.

Under normal conditions, the indexes of water resource security evaluation can be grouped into negative indexes (cost-type indexes) and positive indexes (benefit-type indexes). If a negative index is better when it is smaller, as $K > 2$, the K-element connection of the set pair $H(A_l, B)$ is as defined in Equation (1).

If a positive index is better when it is larger, as $K > 2$, the K-element connection of the set pair $H(A_l, B)$ is as defined in Equation (2).

Data standardization

To remove the impact brought by the evaluation dimensions, it is necessary to remove all the dimensions from various indexes before the evaluation is conducted. In the research, the interval value method was adopted to remove all the dimensions from the original data. If the m-year water resource security state of an area with n indexes is evaluated, a matrix (Zhang et al. 2015) with $m \times n$-order index characteristic values is formed:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & & & \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (3)$$

If the evaluation index is a positive index, its standardization method is:

$$y = \frac{X_{ij} - \min x_j}{\max x_j - \min x_j} \quad (4)$$

If the evaluation index is a negative index, its standardization method is:

$$y = \frac{\max x_j - X_{ij}}{\max x_j - \min x_j} \quad (5)$$

In the above equations, $x_{\max}$ is the maximum value of the index and $x_{\min}$ is the minimum value of the index.

Determination of index weights

Because the index weights determined by using the entropy weight method have absolute objectivity and subjective randomness can be effectively avoided, the method of entropy weight was used to calculate the weight of the water resource security evaluation index system in the paper (Zhang & Wang 2015). In a water resource security evaluation system consisting of m-year n evaluation objects, the entropy H_i of the i^{th} index is defined as:

$$H_i = -k\sum_{i=1}^{n} f_{ij}\cdot \ln f_{ij}, \quad f_{ij} = y_{ij}/\sum_{i=1}^{n} y_{ij}, \quad k = 1/\ln n \tag{6}$$

In the above equation, as $f_{ij} = 0$, $f_{ij}\ln f_{ij} = 0$.

The entropy weight ω_i of the index can be obtained by calculating the following equation:

$$\omega_i = \frac{1 - H_i}{\sum_{i=1}^{m} 1 - H_i} \tag{7}$$

Calculation of sample connection

Assume that A is an evaluation sample set and B is the set of the l^{th}-level evaluation grading standard for all the indexes, then the K-element connection of the constituted set pair $H(A, B)$ is:

$$\begin{aligned}\mu_{A-B} = \sum_{i=1}^{n}\omega_i\mu_{A_t-B_1} = \sum_{i=1}^{n}\omega_i a_i + \sum_{i=1}^{n}\omega_i b_{i,1}I_1 + \\ \sum_{i=1}^{n}\omega_i b_{i,2}I_2 + \cdots + \sum_{i=1}^{n}\omega_i b_{i,K-2}I_K - 2 + \sum_{i=1}^{n}\omega_i c_i J\end{aligned} \tag{8}$$

Let $f_1 = \sum_{i=1}^{n}\omega_i a_i$, $f_1 = \sum_{i=1}^{n}\omega_i b_i, 1, \ldots, f_{K-1} = \sum_{i=1}^{n}\omega_i b_{i,K-2}$, $f_K = \sum_{i=1}^{n}\omega_i c_i$, then Equation (8) can be transformed into:

$$\mu_{A-B} = f_1 + f_2 I_1 + f_3 I_2 + \cdots + f_{K-1}I_{K-2} + f_K J \tag{9}$$

In the above equation, $f_1, f_2, \ldots, f_K$ respectively represent the possibilities that the evaluation sample belongs to the first level, the second level, … and the K^{th} level evaluation standard.

Determination of evaluation grades

The determination of the connection difference uncertainty component coefficients has some subjectivity. To reduce the evaluation result errors caused by the subjective factors and enhance the accuracy of the sample evaluation grade, the confidence level grading method was adopted in the research to judge what grade a sample belongs to (Cheng 1997), i.e.:

$$h_k = (f_1 + f_2 + \cdots + f_k) > \lambda, \quad k = 1, 2, \ldots, K \tag{10}$$

In the above equation, h_k is the property measure and λ is the confidence level. If the value of λ is too great, the evaluation results tend to be reserved and reliable. If the value of λ is too small, the reliability of the results becomes worse and the risks become large. It is suggested that λ should be between 0.5 and 0.7; λ is 0.55 in this research.

RESULTS AND DISCUSSION

Water resource security evaluation

In this paper, the 2016 data of Jiangsu Province are taken as an example to describe the meanings of various parameters and their calculation processes. First, place the negative indexes and positive indexes of the 2016 water resource security evaluation in Equations (1) and (2), calculate the connection degrees of various indexes and according to Equations (3)–(7) calculate their corresponding weights, as shown in Table 3. Then combine various index connection degrees with the weights and place them into Equations (8) and (9), and all the 2016 grade connection degrees can

Table 3 | Various index connection degrees and their weights for Jiangsu Province in 2016

Connection degree	B_1	B_2	B_3	B_4	B_5	Weight
$\mu(x_1)$	0	0	0	0	1	0.07
$\mu(x_2)$	0	0.82	0.18	0	0	0.10
$\mu(x_3)$	0	0	0	0	1	0.10
$\mu(x_4)$	0	0.78	0.22	0	0	0.05
$\mu(x_5)$	0	0	0.48	0.52	0	0.12
$\mu(x_6)$	1	0	0	0	0	0.06
$\mu(x_7)$	1	0	0	0	0	0.05
$\mu(x_8)$	1	0	0	0	0	0.09
$\mu(x_9)$	0	0	0	0	1	0.09
$\mu(x_{10})$	0	0	0	0.77	0.23	0.09
$\mu(x_{11})$	1	0	0	0	0	0.11
$\mu(x_{12})$	1	0	0	0	0	0.05
$\mu(x_{13})$	0	0.85	0.15	0	0	0.04

be obtained, as shown in Table 4. Let the confident level $\lambda = 0.55$. As for 2016, $h_2 = f_1 + f_2 = 0.5 < \lambda$, $h_3 = f_1 + f_2 + f_3 = 0.59 > \lambda$, and the water resource security of Jiangsu Province in 2016 belongs to the third level according to the confidence criterion, which is barely safe. Similarly, the water resource security grades of the other provinces and municipalities of the YREB from 2008 to 2016 can be calculated, and the results shown in Figure 2 are obtained.

This research divided the YREB into three major areas – the Yangtze River Downstream Area (Shanghai, Jiangsu, Zhejiang and Anhui), the Yangtze River Midstream Area (Jiangxi, Hubei and Hunan) and the Yangtze River Upstream Area (Chongqing, Sichuan, Yunnan and Guizhou) – and analyzed their water resource security. As shown in Figure 2, on the whole, the water resource security state of the YREB has generally undergone a process from getting worse to getting better in those nearly nine years. In the period from 2008 to 2013, the overall water resource security state gradually became worse and worse, and in the period

Table 4 | Comprehensive evaluation connection degree (f_n) of the water resource security of Jiangsu Province in 2016 and their h_K values

Year	f_1	f_2	f_3	f_4	f_5	h_1	h_2	h_3	h_4	h_5	Security grade
2016	0.35	0.15	0.09	0.13	0.28	0.35	0.5	0.59	0.72	1	Barely safe

Figure 2 | Temporal and spatial variation of the water resource security of the YREB from 2008 to 2016.

from 2010 to 2013, the decreasing trend in the upstream and midstream areas was most significant, the security of most areas of all the provinces and municipalities was very unsafe and unsafe, and only a few areas were barely safe. In the period from 2014 to 2016, the water resource security state gradually improved as a whole, and the upstream area, the midstream area and most of the downstream area all changed their security states from unsafe states to barely safe states.

Viewing the spatial distribution of the water resource security grades from 2008 to 2016, in the Yangtze River Downstream Area, the area that belonged to the unsafe grade range (very unsafe state and unsafe state) accounted for 64% and the area that belonged to the safe grade range (barely safe state, generally safe state and safe state) accounted for 36%; the percentage of the area of Zhejiang Province that belonged to the safe grade range was the highest and in the nine years all the area of Zhejiang Province was in the safe grade range; the percentage of the area of Shanghai that belonged to the unsafe grade range was the highest (100%). In the Yangtze River Midstream Area, the area that belonged to the unsafe grade range accounted for 67% and the area that belonged to the safe grade range accounted for 33%; the percentage of the area of Jiangxi Province that belonged to the safe grade range was relatively the highest (67%) and the percentage of the area of Hubei Province that belonged to the unsafe grade range was the highest (89%). In the Yangtze River Upstream Area (a vast area), the area that belonged to the unsafe grade range accounted for 69% and the area that belonged to the safe grade range only accounted for 31%; the areas of Sichuan Province and Guizhou Province mostly belonged to the safe grade range; the percentage of the area of Chongqing that belonged to the unsafe grade range was the lowest; in the nine years, all the area of Chongqing belonged to the unsafe grade range. To sum up, viewing the water resource security grade range percentages of the three major areas in those nearly nine years, the security grade of the downstream area was the highest, that of the midstream area was the second highest and that of the upstream area was the lowest in the spatial distribution of the water resource security of the whole YREB.

Water resource DPSI security evaluation

Referring to the calculation process of the 2016 water resource security grade of Jiangsu Province, the water resource driving force security grade, pressure security grade, state security grade and impact security grade of each province and municipality from 2008 to 2016 can be calculated. The calculation results are shown in Figures 3, 4, 5 and 6.

Water resource driving force security

It can be found in Figure 3 that the water resource driving force security of the YREB was not in a good state as a whole in the period from 2008 to 2016. Most of the area was in a very unsafe state or an unsafe state and only the areas of a few provinces and municipalities were in a barely safe state. This is consistent with the current situation of the YREB, which only accounts for 21% of the national land, bears more than 40% of the population and contributes over 40% of the GDP, has rapid socio-economic development, and has a relatively large driving impact on water resources and the ecological environment.

Water resource pressure security

Viewing the water resource pressure security shown in Figure 4, the water resource pressure security of the YREB was relatively stable in those nearly nine years and there was no obvious temporal and spatial variation. The water resource pressure security of Guizhou and Jiangxi belonged to the generally safe grade three times in the period from 2008 to 2009, but the water resource pressure security of all the other provinces and municipalities belonged to the safe grade in the nine-year period. Viewing the three water resource pressure indexes selected in the research, this has shown that the economic structure and industrial structure of the YREB were reasonable in the research period. Meanwhile, this has also shown that the water resource utilization rate of each industry was high (Chen & Liu 2018) and the impact of each industry on water resource pressure security was weak. This result was mainly caused by Central Government Document No. 1 of 2011, which clearly proposed to implement the strictest water resource management system

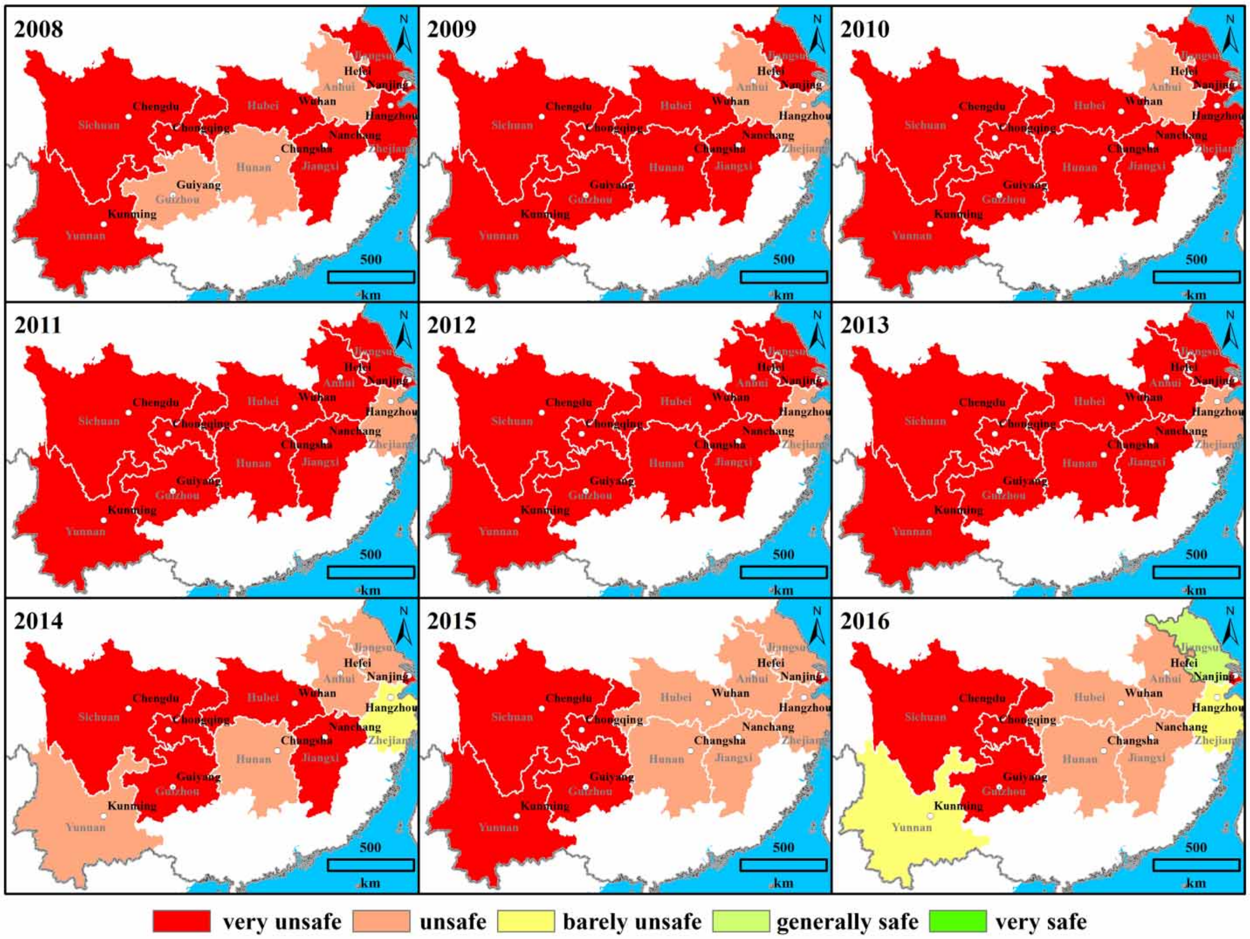

Figure 3 | Temporal and spatial variation of the water resource driving force security of the YREB from 2008 to 2016.

to strongly promote water saving society construction in all the regions of the YREB.

Water resource state security

It can be found from Figure 5 that the water resource state security of the YREB showed no obvious change trend in the period from 2008 to 2016, most of the area belonged to the very unsafe grade or the unsafe grade and only a little of the area belonged sometimes to the barely safe grade. The water resource states of Shanghai and Jiangsu belonged to the very unsafe grade in those nearly nine years, which is related to the rapid economic development in Shanghai and Jiangsu and the dense population. In addition, it can be found that the water resource state security of most of the midstream and upstream provinces and municipalities was not in a good state. This could be mainly explained from the following two aspects. In one aspect, the whole area mainly consisted of hilly regions, the surface water storage condition was poor, the water conservancy projects of the hilly regions for water control lagged behind, the surface water resource adjustment and control ability was weak and the water storage problem was severe (Chen 2016b). In the other aspect, to some extent this is related to the spatial distribution of the precipitation of the Yangtze River Basin that gradually decreases in the direction from the downstream to the upstream.

Water resource impact security

Viewing the water resource impact security shown in Figure 6, the water resource impact security underwent

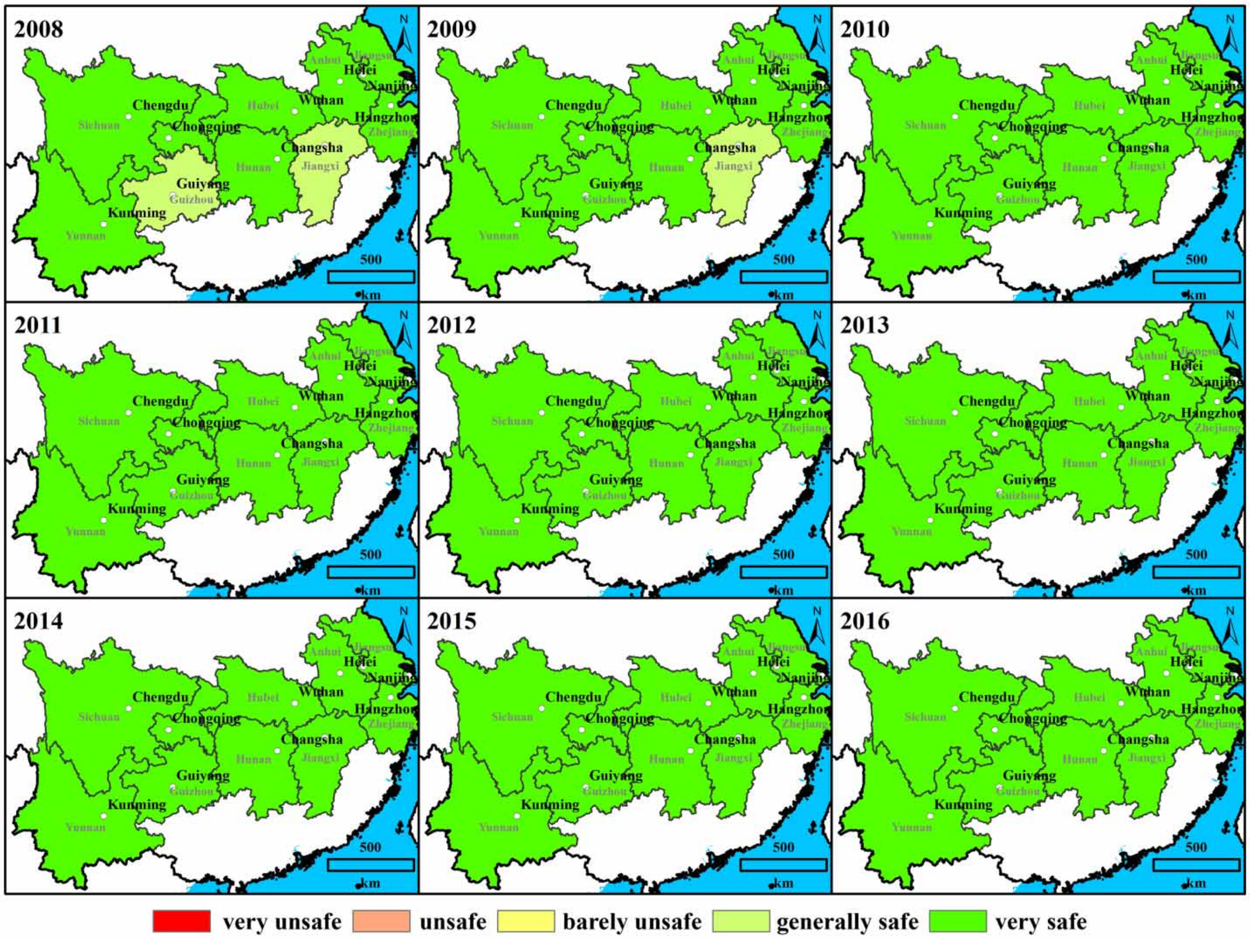

Figure 4 | Temporal and spatial variation of the water resource pressure security of the YREB from 2008 to 2016.

a process from getting worse to getting better in those nearly nine years. In the period from 2010 to 2011, the water resource impact security grades of Southwest China and most provinces of the Yangtze River Midstream Area belonged to the very unsafe grade or the unsafe grade, which was closely related to the great drought of Southwest China and the drought of the Yangtze River midstream and downstream areas that occurred in the period. According to the *Bulletin of Flood and Drought Disasters in China* (Ministry of Water Resources of the People's Republic of China 2011, 2012), in 2010, the population that had difficulty getting drinking water had been the second highest since 1995, and the number of people in Southwest China who had difficulty getting drinking water reached 23.349 million, accounting for 70.02% of people in China who had difficulty getting drinking water. In 2011, in China, 28.9545 million people had difficulty getting drinking water. The people in Guizhou, Yunnan, Sichuan and Hubei who had difficulty getting drinking water accounted for 59.2% of the total in China. In the first half-year of 2011, in some of the Yangtze River midstream and downstream regions, the accumulated precipitation was over 50% less than that of the same period in multiple years and it had been the lowest for the period in the past 60 years. In addition, it can also be found that the 2013 water resource impact security of the Yangtze River midstream and upstream areas was not in a good state. It was mainly caused by the severe, high-temperature summer drought that occurred in some places south of the Yangtze River and some places around the Han River, and the earlier winter

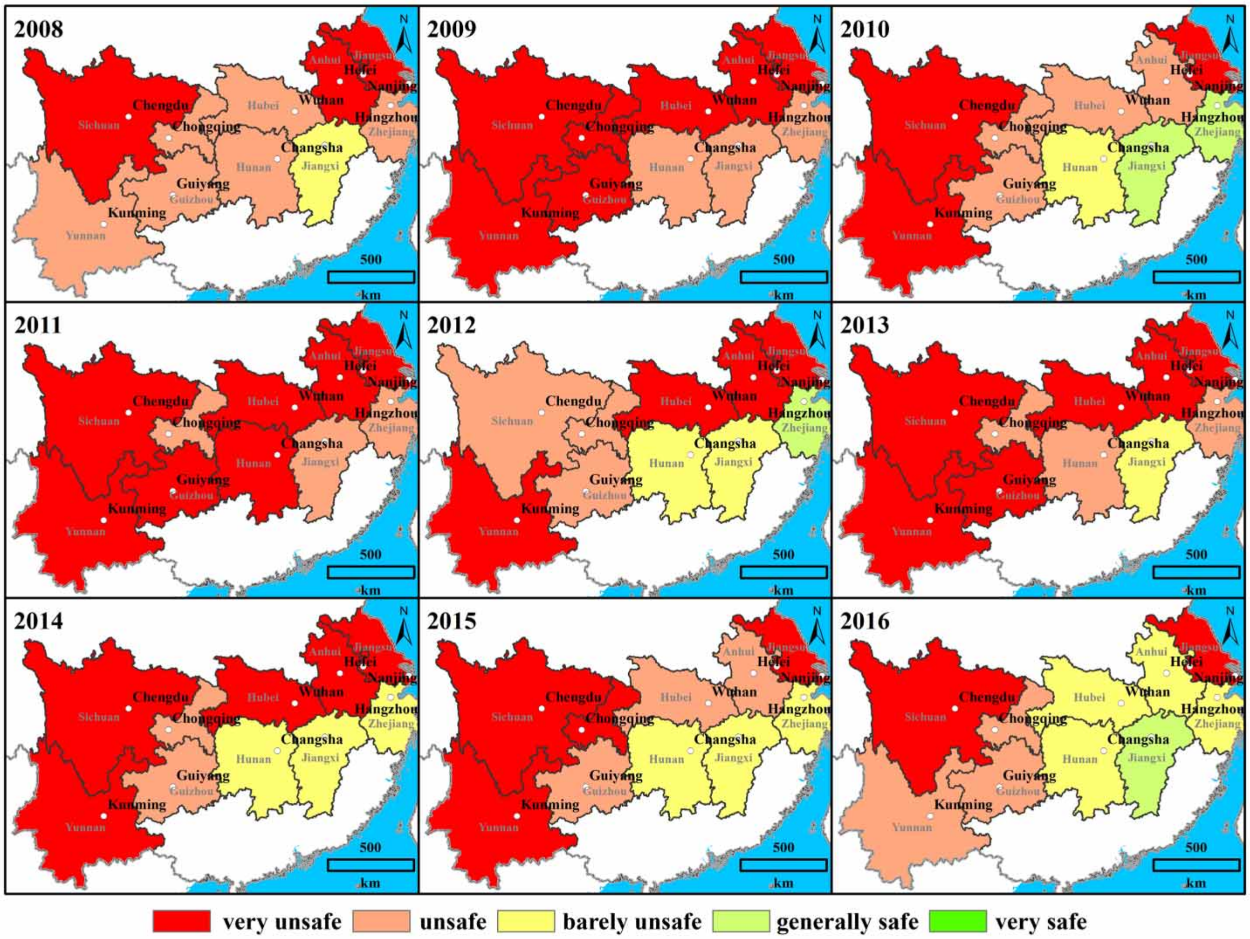

Figure 5 | Temporal and spatial variation of the water resource state security of the YREB from 2008 to 2016.

and spring and summer drought that occurred in Southwest China. Viewing the spatial distribution, the water resource impact security grade of the Yangtze River Downstream Area was higher than that of the Yangtze River Midstream Area and the Yangtze River Upstream Area. This was because the downstream coastal areas were the frontal areas of the southeast monsoon, those areas had more precipitation than the upstream and midstream areas, the urbanization level of the downstream areas was high, the water supply facilities were good, the water supply assurance rate was high, the drought-resistant capacity was strong and the chance that drought caused disasters was low.

To sum up, in the research period, the water resource driving force and the water resource state were the important factors affecting the water resource security of the YREB.

CONCLUSIONS

This paper has evaluated the water resource security states of the YREB from 2008 to 2016 and the evaluation results have intuitively reflected the water resource security situations of its areas.

The research has come to the following main conclusions. (1) Viewing the overall evaluation results of water resource security, on the whole, the water resource security of the YREB underwent a process from getting worse to getting better in the period from 2008 to 2016. In the period from 2008 to 2013, overall water resource security as a whole gradually became worse and worse. In the period from 2010 to 2013, the decreasing trend in the upstream and midstream areas was most remarkable, most areas were very unsafe and unsafe, and only a few

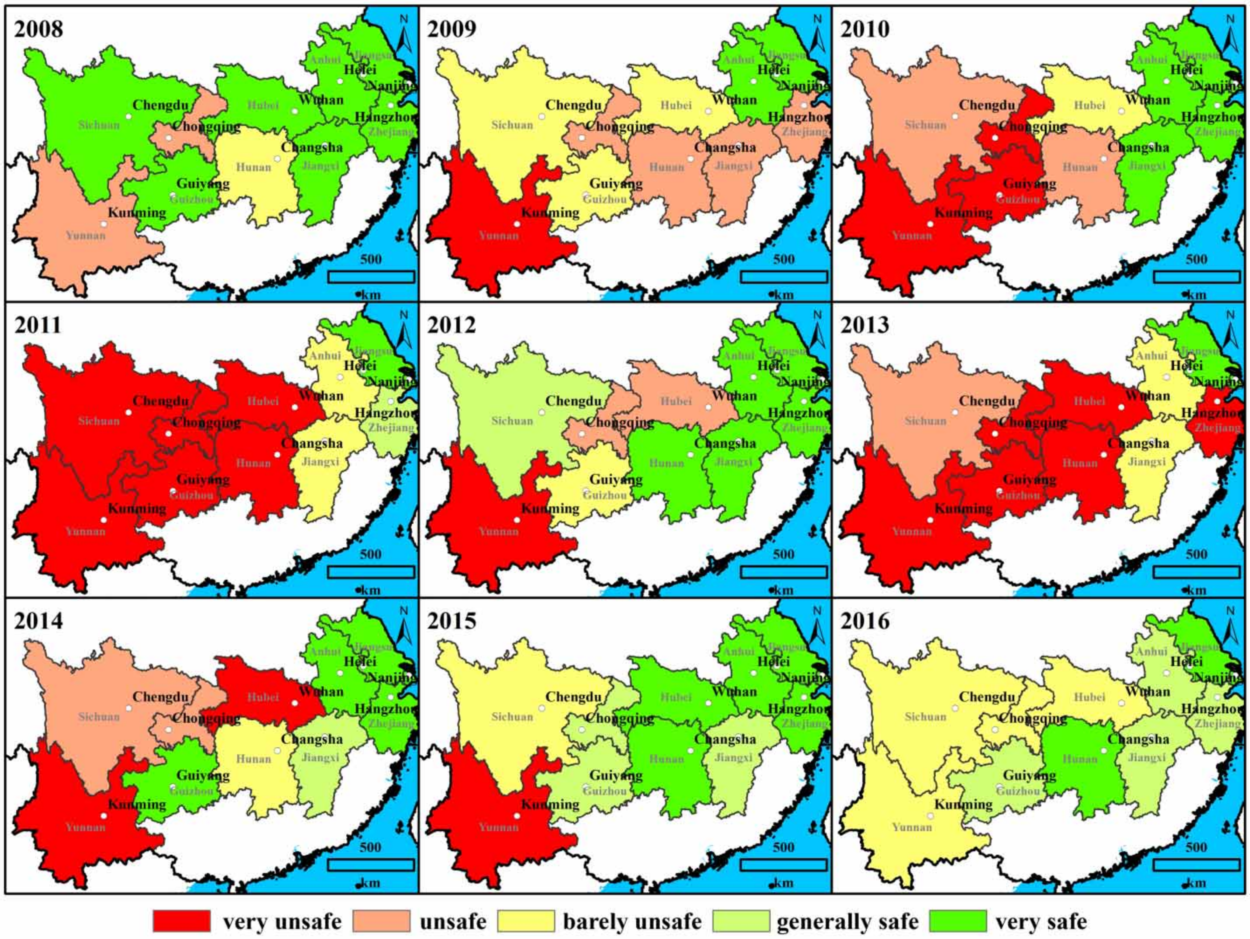

Figure 6 | Temporal and spatial variation of the water resource impact security of the YREB from 2008 to 2016.

areas were barely safe. In the period from 2014 to 2016, water resource security gradually improved as a whole, and most areas changed their security state from an unsafe state to a barely safe state. (2) Viewing the water resource security grade ranges of the three major areas in those nearly nine years, spatial variation existed in the water resource security of the YREB, that is, the water resource security grade of the downstream area was the highest, that of the midstream area was the second highest and that of the upstream area was the lowest. (3) It can be found from the water resource DPSI security evaluation results that the water resource driving force and the water resource state were important factors affecting the water resource security of the YREB in the research period from 2008 to 2016.

Because the water resource security problem is related to many aspects such as resources and environment, and the actual water resource situations of different regions are different, at present, no consensus on water resource security evaluation has been reached at home and abroad. Based on the comprehensive consideration of the water resource characteristics of all the regions of the YREB, the research has attempted to build a water resource security evaluation index system for the YREB based on the DPSI concept model, used 13 specific indexes to evaluate the water resource security state of the YREB, and made necessary preparations for following further research on the water resource security of the YREB. However, there are still shortcomings in the research. Limited by data accessibility, the research has selected the evaluation indexes from the aspect of water quantity security and it has not included water quality security in the water resource security evaluation system for the time being. Secondly, the nearly-nine-year data have been used to analyze the water resource security variation, and this time-scale is relatively short and the detailed variation of water resource security cannot be well reflected. Therefore, more comprehensive data covering a longer time-span should be collected in follow-up research to further improve the water resource security evaluation system of the YREB. In addition, the fuzzy set pair evaluation method based on the DPSI model fully considers the ambiguity of the grade standard boundary and the different weights of the evaluation indicators, can objectively reflect the status of regional water resource security, and has certain application prospects for regional water resource security evaluation. However, the model is subjective in determining the safety level of water resources, and it should be improved adaptively in the application of different natural environments and socio-economic regions. Therefore, how to reasonably and effectively classify the water resource security level is the focus of further research.

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