

Article

Evaluation and Simulation of Water Security in the Circum-Bohai Sea Region of China

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Abstract: The function and necessity of water resources make them an important factor affecting economic and social development. To explore various water security issues impacting water use, the pressure-state-response model was applied in this study to construct a water security evaluation indexing system for the Circum-Bohai Sea Region (CBSR) in China. In this study, the game method was used to balance the two weighting methods, and the water security grades were calculated by the forward cloud model. Compared with the previous work, this study tried to analyze the simulated scenarios using the ELECTRE III method, determined the optimal development scenario mode based on the water security grade, and put forward water security measures and suggestions based on the results. This study put forward three scenarios of development models. Under the scenario of “pressure reduction”, it can be proposed to build suburbs and transfer urban functional areas to relieve the pressure of urban population. Under the “ideal state” scenario, water diversion projects and water storage projects can be proposed to relieve the regional water shortage. Under the scenario of “efficient response”, strengthening ecological environment construction and improving sewage treatment capacity can be proposed.



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Keywords: Circum-Bohai Sea Region; ELECTRE III; game theory; simulated scenario; water security

1. Introduction

Water itself is a crucial natural resource, but its connection to human society requires consideration of the concept of water security. The most common international definition of water security was proposed at the Second World Water Forum and the Ministerial Conference [1] and contains the following points: (i) ensure that the freshwater, coastal, and related ecological systems can be protected and improved; (ii) ensure that the sustainable development and political stability can be promoted; (iii) ensure that everyone has access and the ability to pay for safe water in order to lead a healthy and happy life; and (iv) ensure that vulnerable people can be protected against the suffering associated with a water crisis. The United Nations defined water security as “the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability” [2]. It reflected the centrality of water to achieving a larger sense of security, sustainability, development, and human well-being. Therefore, based on the above description, water security refers to the state or ability of water resources, water environments, and water supply systems to support and guarantee (i) the sustainable development of the economy and society, (ii) the benign cycle of the ecosystem, and (iii) flood control and drought resistance throughout the social and economic development within a region, all according to the principle of coordinated development of human society, economy, and the ecological environment. In general, water security problems are caused by water problem events, which threaten human society and economic development [3]. In order to implement effective measures to

guarantee water security, researchers have studied water security issues and the associated serious consequences.

Investigations regarding water security began in the 1970s. Because of the frequency of water security problems, the relevant body of work has continuously expanded, thus gradually creating an academic and social hotspot [4]. In recent years, water security-related studies have primarily been carried out in two aspects.

First, in some cases, the study content is related to the actual situation, combined with relevant departments and innovative theories regarding water security. For example, from the perspective of sustainable development, some studies have explored water security problems associated with urban development [5,6]. The impact of irrigation water on food security and income [7] has also been evaluated in the context of water shortages. An analytical framework has been built for assessing the vulnerability of a given system in terms of water scarcity [8].

Second, some studies have focused on the innovation and improvement of conventional methods. For example, scholars have conducted quantitative studies on water security based on the principle of a water footprint combined with a fuzzy evaluation method [9]. The optimal water resource allocation model has been applied to determine reasonable levels of water allocation and improve the productivity of limited water resources [10].

The Circum-Bohai Sea Region (CBSR) of China is an economic development area which has been of concern in recent years. In order to explore whether the water security situation of the region can meet the social and economic development demands, this study analyzes the water security capacity by calculating the water security grade and puts forward scientific and reasonable suggestions based on the evaluation results to improve the water security capacity. This is the research goal of this study.

This study presents a comprehensive index system for evaluating water security based on the pressure-state-response (PSR) model. The index weights were calculated using the combination method of game theory (GT), which combines an entropic method with a criteria importance through the inter-criteria correlation (CRITIC) method. The grades of water security in the CBSR between 2014 and 2019 were calculated based on the forward cloud model (FCM). Then, the average values of the indices were used as the sample scenario. Finally, the ELECTRE III model was used to rank the simulated scenarios to obtain the optimal simulated scenario. The research framework is shown in Figure 1.

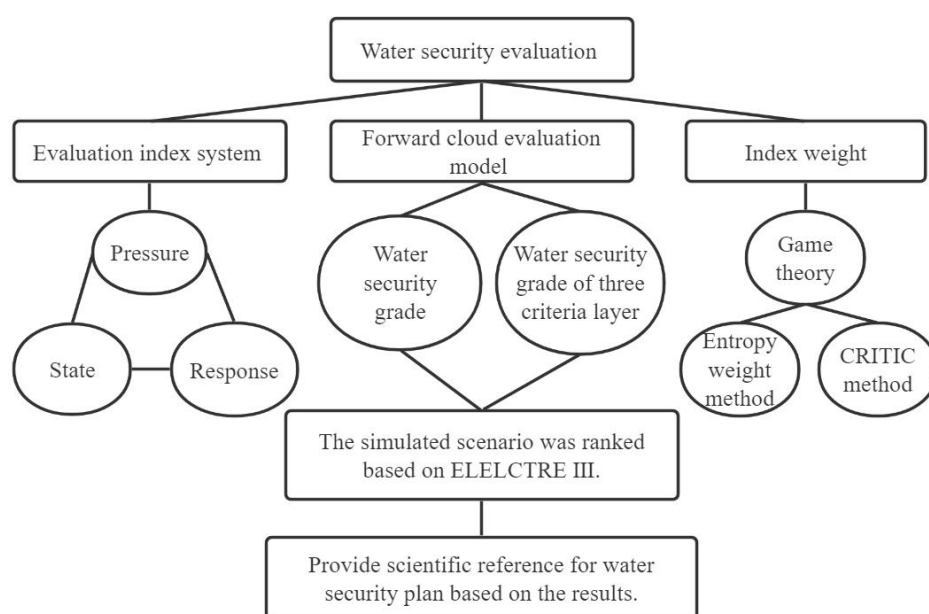


Figure 1. Research framework.

2. Materials and Methods

2.1. Study Region

The Circum-Bohai Sea Region (Figure 2) refers broadly to the three provinces and two cities around the Bohai Bay, including Beijing, Tianjin, Hebei, Shandong, and Liaoning. This region is located in the center of the Northeast Asian economic circle and is known as the third growth pole of China's economy [11]. It is an important agricultural base and represents the largest industry-intensive area in China. However, while implementing economic development plans in the CBSR, water security problems, including the shortage of surface water resources and the uneven distribution of time and space on water, have become increasingly prominent. Excessive exploitation of groundwater also causes frequent secondary disasters. Simultaneously, the water environment is seriously polluted and the water ecology is degraded. At the governmental level, water resource management functions are divided into several branches, making it difficult to solve the relevant problems effectively [12]. Therefore, water security has become a critical factor to consider in the process of planning projects concerning water resource management and protection in the CBSR.

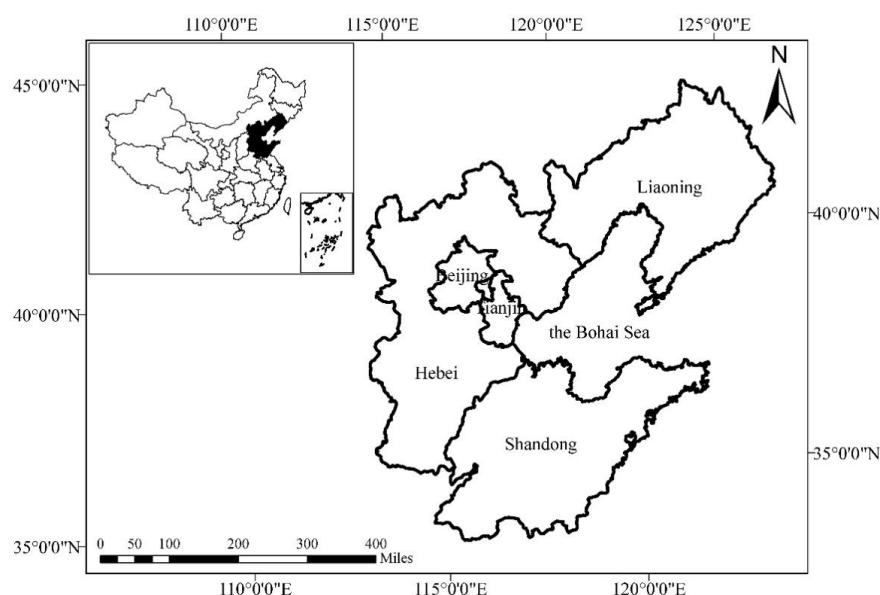


Figure 2. Geographical map of the CBSR.

2.2. Evaluation Indexing System and Standards

A water security system is a comprehensive system integrating natural, social, economic, and ecological factors. It is necessary to establish a multi-level systematic indexing system to quantitatively evaluate the degree of water security. The pressure-state-response model was originally proposed by the Organization for Economic Co-operation and Development (OECD) and aimed to establish a conceptual framework for an indexing system that was applicable to sustainable development [13,14]. The governing principle is that human activities exert pressure on the environment; under the influence of this pressure, the state of the environment is affected, and the society responds by implementing policies or measures to restore the environment. The PSR model can also reflect the internal relationships of the water security system. Specifically, domestic and economic water production generate the pressure, natural conditions, water supply systems, social development, and the water environment comprises the state under the pressure, and the relevant response involves measures that are proposed to decrease the pressure and improve the environmental state. The evaluation indices were selected based on the characteristics of the water security system and the actual situation in the study region, while referring to indexing systems reported previously [15]. The specific index system framework is shown in Table 1.

Table 1. Water security evaluation indexing system.

Criterion layer		Index layer	Design formula	Type
Pressure	Domestic water pressure	Domestic water consumption per capita, L/d (C ₁)	Domestic water consumption/total population	— ¹
		Population density, per/km ² (C ₂)	Total population/study area	—
		Natural population growth rate, ‰ (C ₃)	Birth rate-death rate	—
	Economic production water pressure	Water consumption per unit of industrial output growth, m ³ /10 ⁴ yuan (C ₄)	Industrial water consumption/industrial output growth	—
		Proportion of agricultural water consumption, % (C ₅)	Agricultural water consumption/total water consumption	—
State	Natural system state	Annual rainfall, mm (C ₆)	Statistics	+ ²
		Modulus of water production, 10 ⁴ m ³ /km ² (C ₇)	Total water resources/study area	+
		Water resources per capita, m ³ /per (C ₈)	Total water resources/total population	+
	Water supply system state	Modulus of water supply, 10 ⁴ m ³ /km ² (C ₉)	Total water supply/study area	—
		Proportion of groundwater supply, % (C ₁₀)	Groundwater supply/total water supply	—
		Utilization rate of water resources, % (C ₁₁)	Total water resources/total water supply	—
	Social development state	GDP ³ per capita, yuan (C ₁₂)	GDP/total population	+
		Urbanization rate, % (C ₁₃)	Urban population/total population	+
		Proportion of Tertiary Industry, % (C ₁₄)	Tertiary industry output growth/GDP	+
	Water environmental state	Water qualification rate of river, % (C ₁₅)	The length of the river up to standard/the length of the river monitored	+
	Response	Environmental governance response	Water consumption rate of ecological environment, % (C ₁₆)	Ecological water consumption/total water consumption
Urban sewage treatment rate, % (C ₁₇)			Sewage treatment discharge/total sewage discharge	+
Public green areas per capita, m ² /per (C ₁₈)			Public green areas/total population	+
Water supply response		Effective irrigated area rate, % (C ₁₉)	Effective irrigated area/total sown area	+
		Density of water supply network in built-up area, km/km ² (C ₂₀)	Length of water supply pipe/built-up area	+
Drainage response		Density of drainage pipe network in built-up area, km/km ² (C ₂₁)	Length of drainage pipe/built-up area	+

¹ ‘+’ refers to a positive index (the bigger, the better); ² ‘—’ refers to a negative index (the smaller, the better); ³ GDP = gross domestic product.

The evaluation standard provides the basis for a meaningful water security evaluation. In this report, the degree of water security was divided into five grades, and the specific features of each grade are described in Table 2. These classifications were established based on the following standards: (1) consideration of the national and local standards; (2) reference to water conservancy development plans, ecological environmental protection plans, and economic development plans; (3) statistical analysis of the index data from each province between 2014 and 2019 and classification according to the value range of each index; and (4) relevant research literature [16,17]. The specific standards are presented in Table 3.

Table 2. Features of water security evaluation grades.

Grade	Security Situation	Grade Feature
I	Very safe	The regional water security is safe. Water resources, water environment, and the social and economic system can coordinate healthily and develop sustainably.
II	Safe	The regional water security is rarely threatened. Water resources, water environment, and the social and economic system can develop sustainably.
III	Generally safe	The regional water security is vulnerable to threats; it can basically meet the needs of social and economic development. The water resource system, water environment and the social and economic system can't develop sustainably.
IV	Unsafe	The regional water security is faces significant threats, making it difficult to meet the needs of regional development. The sustainable development is threatened.
V	Extremely unsafe	The regional water security is seriously threatened and cannot meet the needs of social and economic development, which seriously hinders sustainable social and economic development.

Table 3. Evaluation index standards.

Index	I (Very Safe)	II (Safe)	III (Generally Safe)	IV (Unsafe)	V (Extremely Unsafe)
C ₁	60–120	120–140	140–160	160–180	180–240
C ₂	150–300	300–500	500–700	700–900	900–1400
C ₃	–1–1	1–3	3–5	5–7	7–12
C ₄	6–12	12–18	18–24	24–30	30–40
C ₅	0–35	35–45	45–55	55–65	65–75
C ₆	850–1200	700–850	550–700	400–550	250–400
C ₇	30–50	20–30	15–20	10–15	5–10
C ₈	3000–5000	2300–3000	1700–2300	1000–1700	0–1000
C ₉	5–8	8–12	12–16	16–20	20–30
C ₁₀	0–10	10–25	25–40	40–55	55–75
C ₁₁	40–60	60–80	80–1000	100–200	200–400
C ₁₂	100,000–165,000	70,000–100,000	40,000–70,000	10,000–40,000	6600–10,000
C ₁₃	70–90	60–70	50–60	40–50	30–40
C ₁₄	70–85	60–70	50–60	40–50	30–40
C ₁₅	70–90	60–70	50–60	40–50	0–40
C ₁₆	20–40	15–20	10–15	5–10	0–5
C ₁₇	96–100	92–96	88–92	84–88	80–84
C ₁₈	25–30	20–25	15–20	10–15	5–10
C ₁₉	70–100	60–70	50–60	40–50	20–40
C ₂₀	25–30	20–25	15–20	10–15	5–10
C ₂₁	25–30	20–25	15–20	10–15	5–10

2.3. Weighting Methods

2.3.1. CRITIC Method

The CRITIC method is an objective weighting approach proposed by Diakoulaki et al. in 1995 [18], which aims to determine the relative importance of elements in multiple criteria decisions making (MCDM) problems. The derived weights incorporate both the contrast intensity and the conflict. The contrast intensity is quantified by the standard deviation, whereas the conflict between indices is measured by the linear correlation coefficient. The detailed steps of the CRITIC method are presented below [19]:

1. Define a finite set A of n alternatives and a finite set C of m evaluation indices f_j , such that the evaluation schemes of the MCDM problems can be defined as shown in Equation (1).

$$\{f_1(a), f_2(a), \dots, f_m(a) \mid a = 1, 2, \dots, n\} \quad (1)$$

2. Normalization: Define a membership function x_{aj} mapping the values of $f_j(a)$ to the interval $[0,1]$. This transformation is based on the concept of the ideal point. The value x_{aj} expresses the degree to which the alternative a is close to the ideal value and far from the anti-ideal value. The detailed formula of normalization is shown in Equation (2);

$$x_{aj} = \begin{cases} \frac{f_j(a) - f_{jmin}}{f_{jmax} - f_{jmin}}, & f_j \text{ is the positive index} \\ \frac{f_{jmax} - f_j(a)}{f_{jmax} - f_{jmin}}, & f_j \text{ is the negative index} \end{cases} \quad (2)$$

where $f_j(a)$ is the value of the j -th index of the a -th alternative, f_{jmax} is the maximum of the j -th index and f_{jmin} is the minimum of the j -th index.

3. Calculate the standard deviation σ_j (Equation (3)) to evaluate the contrast intensity for J indices.

$$\sigma_j = \sqrt{\frac{1}{n-1} \sum_{a=1}^n (x_{aj} - \bar{x}_j)^2} \quad (3)$$

where σ_j is the standard deviation of the j -th index, $\bar{x}_j$ is the average of the j -th index.

4. Calculate the correlation coefficient r_{jk} between the j -th and k -th indices using Equation (4),

$$r_{jk} = \frac{\text{Cov}(x_j, x_k)}{\sqrt{\text{Var}[x_j] \text{Var}[x_k]}} \quad (4)$$

where $\text{Cov}(x_j, x_k)$ is the covariance between the j -th and k -th indices, $\text{Var}[x_j]$ is the variance of the j -th index, and $\text{Var}[x_k]$ is the variance of the k -th index.

5. Calculate the amount of information C_j contained in the j -th index using Equation (5):

$$C_j = \sigma_j \sum_{k=1}^m (1 - r_{jk}) \quad (5)$$

6. Calculate the weight W_j of each index using Equation (6):

$$W_j = \frac{C_j}{\sum_{j=1}^m C_j} \quad (6)$$

2.3.2. Entropy Weight Method

The entropy weight method is an objective weighting method wherein the uncertainty associated with signals in a communication process is called “information entropy”. This approach can reveal useful information provided by the index, although it excessively relies on objective data. The detailed steps involved in this method are presented below [20]:

Steps 1 and 2 are identical to steps 1 and 2 in the CRITIC method.

1. Calculate the entropy e_j of the j -th index using Equation (7):

$$e_j = \frac{-\sum_{a=1}^n p_{aj} \ln p_{aj}}{\ln n} \quad (7)$$

$$p_{aj} = \frac{x_{aj}}{\sum_{a=1}^n x_{aj}}, \quad a = 1, 2, \dots, n; j = 1, 2, \dots, m \quad (8)$$

2. The weight obtained based on the information entropy is expressed as shown in Equation (9),

$$W_j = (1 - e_j) / \left(m - \sum_{j=1}^m e_j \right) \quad (9)$$

where $0 \leq w_j \leq 1$, and $\sum_{j=1}^m w_j = 1$.

Comparing these two methods reveals that the CRITIC method does not consider the discretization among the data, and the entropy weight method can make up for the lack of discrete analysis; therefore, the two methods were combined.

2.3.3. Game Theory Method

The GT method can achieve a balance or compromise between various weights by minimizing the deviation between the optimal combination weight and the weights determined by various methods; this approach reduces the subjective arbitrariness and improves the objectivity of the results. The detailed steps are presented below [21]:

1. Suppose L methods are used to separately weight the indices, and obtain L index weight vectors, according to Equation (10),

$$w(k) = [w_{k1}, w_{k2}, \dots, w_{km}], \quad k = 1, 2, \dots, L \quad (10)$$

where $w_{ki} = (i = 1, 2, \dots, m)$ is the weight of the i -th index obtained using the L -th weighting method.

2. Let the arbitrary linear combination of L weight vectors be defined as shown in Equation (11),

$$w = \sum_{k=1}^L \alpha_k w_k^T, \left(\alpha_k > 0, \sum_{k=1}^n \alpha_k = 1 \right) \quad (11)$$

where α_k is the linear combination coefficient, and w represents the set of the possible combined weight vectors.

3. According to GT, the optimal weight vector will minimize the deviation between w and each $w(k)$. The calculation model is shown in Equation (12):

$$\min \left\| \sum_{k=1}^L \alpha_k w_k^T - w(k)^T \right\|, (k = 1, 2, \dots, L) \quad (12)$$

4. According to the properties of the matrix, the optimal first-order derivative condition of the formula can be represented by Equation (13),

$$\sum_{k=1}^L \alpha_k w_i w_j^T = w_i w_i^T, (k = 1, 2, \dots, L) \quad (13)$$

where i and j indicate i rows and j columns in the matrix.

5. The coefficients α_k^* of the most satisfactory weight w^* are calculated via normalization, as shown in Equation (14):

$$\alpha_k^* = \alpha_k / \sum_{k=1}^L \alpha_k \quad (14)$$

6. The most satisfactory combined weights are calculated using Equation (15):

$$w^* = \sum_{k=1}^L \alpha_k^* w_k^T \quad (15)$$

2.4. Evaluation Methods

2.4.1. Forward Cloud Method

The FCM is based on traditional fuzziness and probability statistics, and it uses natural language representation to achieve quantitative and qualitative transformations of the model. It involves the combination of the fuzziness and randomness of the uncertain concept, and it can satisfy the natural transformation between the uncertain linguistic value and the quantitative value.

The characteristics of the cloud model include expectation (E_X), entropy (E_N), and hyper entropy (H_E), where E_X represents the cloud droplet as a qualitative concept in the domain space, E_N represents the acceptable degree of the cloud droplets in the domain space, and H_E is the entropy of entropy, which represents the uncertainty of entropy and the degree of cloud droplet condensation in the domain space. These parameters (Table 4) can be calculated using the expressions in Equation (16) [22],

$$\begin{cases} E_X = (a + b)/2 \\ E_N = |a - b|/6 \\ H_E = k \end{cases} \quad (16)$$

where a and b represent the upper and lower boundary values of the qualitative concept evaluation grades, respectively, and k is a constant, which can be adjusted according to the threshold value of the fuzzy index.

Table 4. Numerical characteristics of the water security evaluation model (E_X , E_N) when $H_E = 0.1$.

Index	I (Very Safe)	II (Safe)	III (Generally Safe)	IV (Unsafe)	V (Extremely Unsafe)
C ₁	(90 ¹ , 10 ¹)	(130, 3.3)	(150, 3.3)	(170, 3.3)	(210, 10)
C ₂	(225, 25)	(400, 33.3)	(600, 33.3)	(800, 33.3)	(1150, 83)
C ₃	(0, 0.3)	(2, 0.3)	(4, 0.3)	(6, 0.3)	(9.5, 0.8)
C ₄	(9, 1)	(15, 1)	(21, 1)	(27, 1)	(35, 1.7)
C ₅	(17.5, 5.8)	(40, 1.7)	(50, 1.7)	(60, 1.7)	(70, 1.7)
C ₆	(1025, 58.3)	(775, 25)	(625, 25)	(475, 25)	(325, 25)
C ₇	(40, 3.3)	(25, 1.7)	(17.5, 0.8)	(12.5, 0.8)	(7.5, 0.8)
C ₈	(4000, 333.3)	(2650, 116.7)	(2000, 100)	(1350, 116.7)	(500, 166.7)
C ₉	(6.5, 0.5)	(10, 0.7)	(14, 0.7)	(18, 0.7)	(25, 1.7)
C ₁₀	(5, 1.7)	(17.5, 2.5)	(32.5, 2.5)	(47.5, 2.5)	(65, 3.3)
C ₁₁	(50, 3.3)	(70, 3.3)	(90, 3.3)	(150, 16.7)	(300, 33.3)
C ₁₂	(132,500, 10,833.3)	(85,000, 5000)	(55,000, 5000)	(25,000, 5000)	(8300, 566.7)
C ₁₃	(80, 3.3)	(65, 1.7)	(55, 1.7)	(45, 1.7)	(35, 1.7)
C ₁₄	(77.5, 2.5)	(65, 1.7)	(55, 1.7)	(45, 1.7)	(35, 1.7)
C ₁₅	(80, 3.3)	(65, 1.7)	(55, 1.7)	(45, 1.7)	(20, 6.7)
C ₁₆	(30, 3.3)	(17.5, 0.8)	(12.5, 0.8)	(7.5, 0.8)	(2.5, 0.8)
C ₁₇	(98, 0.7)	(94, 0.7)	(90, 0.7)	(86, 0.7)	(82, 0.7)
C ₁₈	(27.5, 0.8)	(22.5, 0.8)	(17.5, 0.8)	(12.5, 0.8)	(7.5, 0.8)
C ₁₉	(85, 5)	(65, 1.7)	(55, 1.7)	(45, 1.7)	(30, 3.3)
C ₂₀	(27.5, 0.8)	(22.5, 0.8)	(17.5, 0.8)	(12.5, 0.8)	(7.5, 0.8)
C ₂₁	(27.5, 0.8)	(22.5, 0.8)	(17.5, 0.8)	(12.5, 0.8)	(7.5, 0.8)

¹ The E_X and E_N values were calculated using Equation (16).

The forward cloud generator specifically converts qualitative concepts to quantitative data. By inputting the numerical characteristics of the cloud (i.e., E_X , E_N , and H_E) and the number of cloud drops, the cloud drops values, and the cloud drops distribution can be obtained (Figure 3). The specific algorithm involves the following steps:

1. Generate a normal random number E'_{Ni} with E_N as the expectation and H_E^2 as the variance using Equation (17):

$$E'_{Ni} = \text{NORM}(E_N, H_E^2) \quad (17)$$

2. Generate a normal random number x_i with E_X as the expectation and $E'_{Ni}{}^2$ as the variance using Equation (18):

$$x_i = \text{NORM}(E_X, E'_{Ni}) \quad (18)$$

3. Calculate the membership degree (μ) of the index for different grades using Equation (19):

$$\mu = e^{-\frac{(x-E_X)^2}{2E'_{Ni}}} \quad (19)$$

Following these steps, the membership degree of other indices in the evaluation scheme can be calculated sequentially to obtain a membership matrix based on the FCM.

Now, define the index set as $U = \{u_1, u_2, \dots, u_n\}$, the evaluation standard set as $V = \{v_1, v_2, \dots, v_n\}$, and the weight set as $W = \{w, w_2, \dots, w_n\}$. Then, the membership matrix R can be calculated by the forward cloud generator. The resulting matrix is a random matrix that reflects the correlation between the U and V sets. The fuzzy subset B can be obtained through the transformation of the weight set and the membership matrix, as shown in Equation (20),

$$B = W \times R, B = (b_1, b_2, \dots, b_m) \quad (20)$$

where b_m is a vector that contains n indices, indicating the degree of the scheme belonging to the m -th grade.

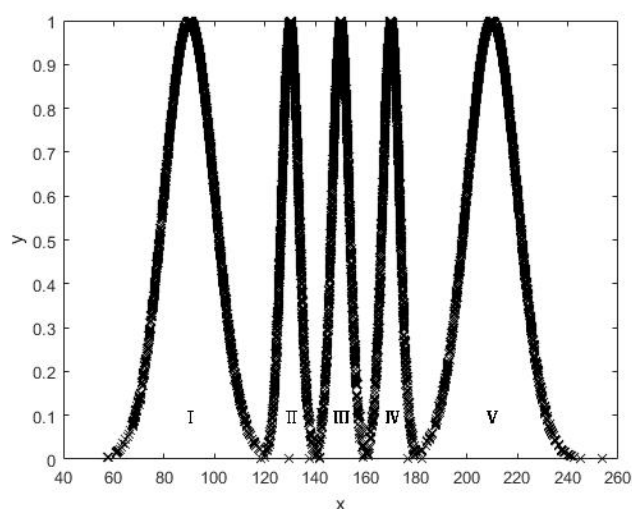


Figure 3. Evaluation index cloud droplets distribution map (In the case of C1). Notes: The map was calculated using Equations (17) and (18).

Because the traditional fuzzy mathematics method can easily provide inaccurate results and cannot reflect the ambiguity of the boundaries, some crucial information may be lost, thus providing results with relatively low effectiveness. Particularly for cases of the same membership degree, the principle of maximum membership degree will be invalid. Therefore, the membership degree is used as the weight to recalculate the grade using Equation (21),

$$j^* = \sum_{j=1}^m \left(j \cdot \frac{b_j}{\sum_{j=1}^m b_j} \right) \quad (21)$$

where j^* is the final evaluation grade of the scheme, and j represents the grade of the standard.

2.4.2. ELECTRE III

ELECTRE III is a multi-objective evaluation method, which is widely used for the scheme ranking of complex systems. The defining principle is the concept of valued outranking relation (VOR) based on the risk load of the decision-maker, which generates a preference order and decision data from the decision-maker. The threshold function compares the two schemes to form concordant and discordant matrices, which allow construction of a credibility matrix. The decision scheme is determined by comparing these matrices in order. ELECTRE III is a type of incomplete compensatory method, meaning that the high score of the scheme in some evaluation indices cannot compensate for the low score in others. This method can overcome the substitutions among indices. The steps of the ELECTRE III model are presented below [23,24]:

1. Suppose that the evaluation scheme is set as $A = \{a_i \mid i = 1, 2, \dots, n\}$, the evaluation index is set as $G = \{g_j \mid j = 1, 2, \dots, r\}$, and the evaluation scheme index value is set as $X = \{x_{ij} \mid i = 1, 2, \dots, n; j = 1, 2, \dots, r\}$. To avoid losing the generality of the index, the evaluation index values were set as positive indices. For a negative index, a negative sign was added to convert it into a positive index.
2. Define the thresholds (Table 5).

Table 5. Thresholds of the evaluation indices.

Index	q	p	v	Index	q	p	v	Index	q	p	v
C ₁	3	10	60	C ₈	100	333.33	2000	C ₁₅	1.5	5	30
C ₂	30	100	600	C ₉	0.6	2	12	C ₁₆	0.75	2.5	15
C ₃	0.3	1	6	C ₁₀	2.25	7.5	45	C ₁₇	0.6	2	12
C ₄	0.9	3	18	C ₁₁	7	23.33	140	C ₁₈	0.75	2.5	15
C ₅	1.5	5	30	C ₁₂	4500	15,000	90,000	C ₁₉	1.5	5	30
C ₆	22.5	75	450	C ₁₃	1.5	5	30	C ₂₀	0.75	2.5	15
C ₇	1	3.33	20	C ₁₄	1.5	5	30	C ₂₁	0.75	2.5	15

For the scheme (a_l, a_k) , (l and k represent the sequence number of the scheme, and the meanings shown below are the same.) three thresholds were defined as follows:

Indifference threshold q_j —When the difference between the attribute values of schemes a_l and a_k on index g_j was $\leq q_j$, the two schemes were considered to have no difference on index g_j .

Preference threshold p_j —When the difference between the attribute values of schemes a_l and a_k on index g_j was $> p_j$, scheme a_l was considered to be strictly superior to scheme a_k on index g_j .

Veto threshold v_j —When the attribute value of scheme a_l was lower than that of a_k and the difference between these values reached or exceeded v_j , the overall level of scheme a_l was no longer considered higher than that of scheme a_k .

In general, $0 \leq q_j \leq p_j \leq v_j$.

The indifference threshold q_j , preference threshold p_j , and veto threshold v_j of the evaluation indices in this report were determined using the relationships in Equation (22),

$$\begin{cases} p_j = \frac{1}{n} [g_j(a)_{\max} - g_j(b)_{\min}] \\ q_j = 0.3p_j \\ v_j = np_j \end{cases} \quad (22)$$

where $g_j(a)_{\max}$ and $g_j(b)_{\min}$ are the boundary values of a certain grade, in this study, $g_j(a)_{\max}$ is the maximum value of the evaluation standard grade II, and $g_j(b)_{\min}$ is the minimum value of the evaluation standard grade IV according to the actual situation of the study region.

1. Define the concordance index and the discordance index considering the relationships in Equation (23):

$$\begin{cases} g(a) - g(b) > p & a \text{ is superior to } b \\ q < g(a) - g(b) \leq p & a \text{ is better than } b \\ |g(a) - g(b)| \leq q & \text{there is no difference between } a \text{ and } b \end{cases} \quad (23)$$

The concordance index $C(l, k)$ (Equations (24) and (25) represents the degree to which scheme a_l is superior to scheme a_k on index j .

$$C(l, k) = \sum_{j=1}^r w_j C_j(l, k) / \sum_{j=1}^r w_j \quad (24)$$

$$C_j(l, k) = \begin{cases} 1 & \text{if } a_{lj} + q_j \geq a_{kj} \\ 0 & \text{if } a_{lj} + p_j \leq a_{kj} \\ \frac{a_{lj} + p_j - a_{kj}}{p_j - q_j} & \text{otherwise} \end{cases} \quad (25)$$

where a_{lj} and a_{kj} are the values of the l -th scheme and k -th scheme on the j -th index.

The discordance index $d_j(l, k)$ (Equation (26)) represents the degree to which scheme a_l is inferior to scheme a_k on index j .

$$d_j(l, k) = \begin{cases} 1 & \text{if } a_{lj} + v_j \leq a_{kj} \\ 0 & \text{if } a_{lj} + p \geq a_{kj} \\ \frac{a_{kj} - p_j - a_{lj}}{v_j - p_j} & \text{otherwise} \end{cases} \quad (26)$$

2. Define the VOR.

The VOR is expressed as the credibility $S(l, k)$, which represents the degree of credibility that " a_l is better than a_k ", and can be expressed as shown in Equation (27),

$$S(l, k) = \begin{cases} C(l, k) & \forall j, d_j(l, k) \leq c(l, k) \\ C(l, k) \prod_{j \in J(l, k)} \frac{1 - d_j(l, k)}{1 - c(l, k)} & \text{otherwise} \end{cases} \quad (27)$$

where $J(l, k)$ is the set of all of the properties of $d_j(l, k) > c(l, k)$.

3. Ranking.

In this work, the concordance credibility degree, the discordance credibility degree, and the net credibility degree were introduced to simplify the calculation, thereby also improving the credibility and achieving index ranking.

The concordance credibility index ($\Phi^+(a_j)$) refers to the degree of credibility that scheme a_j is superior to other schemes, and it can be calculated using Equation (28):

$$\Phi^+(a_j) = \sum_{a_k \in K} S(a_j, a_k), \forall a_j \in K \quad (28)$$

The discordance credibility index ($\Phi^-(a_j)$) (Equation (29)) indicates the degree of credibility that scheme a_j is inferior to other schemes:

$$\Phi^-(a_j) = \sum_{a_k \in K} S(a_k, a_j), \forall a_j \in K \quad (29)$$

Finally, the net credibility index ($\Phi(a_j)$), which refers to the degree to which scheme a_j is superior to other schemes, can be calculated using Equation (30):

$$\Phi(a_j) = \Phi^+(a_j) - \Phi^-(a_j) \quad (30)$$

Ultimately, all schemes can be ranked according to their net credibility.

2.5. Data Sources

The data evaluated in this report came primarily from water conservancy yearbooks and statistical yearbooks from various provinces and cities, as well as from the website of the National Bureau of Statistics, which included relevant data regarding 21 indices from 2014 to 2019. For clarity and consistency, only the index data for Beijing from 2014 to 2019 are listed herein (Table 6). The data of other regions were shown in the (Supplementary Materials Tables S1–S5).

Table 6. Index data for Beijing from 2014 to 2019.

Index	2014	2015	2016	2017	2018	2019
C ₁	187.52	183.81	173.10	188.01	198.70	168.52
C ₂	1311	1323	1324	1323	1313	1313
C ₃	4.83	3.01	4.12	3.76	2.66	2.63
C ₄	13.59	10.24	9.44	8.19	7.97	7.78
C ₅	21.82	16.75	15.46	12.91	10.69	8.87
C ₆	438.8	583.0	660.0	592.0	590.4	509.0
C ₇	12.37	16.33	21.39	18.16	21.63	15.60
C ₈	95.15	124.01	161.60	137.21	164.17	114.20
C ₉	22.85	23.28	23.64	24.07	23.95	25.41
C ₁₀	52.28	47.64	45.09	42.03	41.48	36.21
C ₁₁	184.70	142.50	110.60	132.60	110.70	162.89
C ₁₂	107,472	114,662	124,516	137,596	153,095	164,563
C ₁₃	86.35	86.50	86.50	86.50	86.50	86.58
C ₁₄	79.97	81.60	82.27	82.69	83.09	83.69
C ₁₅	47.00	53.40	52.80	62.38	71.60	87.10
C ₁₆	19.34	27.23	28.61	32.15	34.10	38.37
C ₁₇	86.10	88.40	90.60	97.50	93.40	94.50
C ₁₈	15.94	16.00	16.01	16.20	16.30	16.40
C ₁₉	72.98	79.06	84.88	95.49	100.00	100.00
C ₂₀	19.69	19.72	19.67	19.01	19.23	13.88
C ₂₁	10.32	11.06	11.90	11.62	11.98	12.33

3. Results

3.1. Weight of Evaluation Indices

The weights reported herein were calculated based on data from five provinces and cities between 2014 and 2019. Each index contained 30 values, which together formed an initial 21×30 data matrix. The weight results are presented in Table 7. The sorting of the index weights indicates that C₁₆ was the biggest and C₁₁ was the smallest. Therefore, it could be preliminarily understood that the index with the greatest influence was the water consumption rate of the ecological environment, and the index with the least influence was the utilization rate of water resources.

Table 7. Weight of evaluation indices.

Index	W ₁ ¹	W ₂ ²	W ₃ ³	Index	W ₁	W ₂	W ₃	Index	W ₁	W ₂	W ₃
C ₁	0.055	0.022	0.029	C ₈	0.043	0.067	0.062	C ₁₅	0.039	0.042	0.042
C ₂	0.092	0.085	0.086	C ₉	0.083	0.048	0.055	C ₁₆	0.042	0.106	0.093
C ₃	0.044	0.021	0.025	C ₁₀	0.041	0.026	0.029	C ₁₇	0.044	0.015	0.021
C ₄	0.038	0.017	0.021	C ₁₁	0.034	0.011	0.016	C ₁₈	0.054	0.037	0.040
C ₅	0.045	0.079	0.072	C ₁₂	0.036	0.069	0.062	C ₁₉	0.041	0.060	0.056
C ₆	0.037	0.039	0.038	C ₁₃	0.049	0.041	0.043	C ₂₀	0.052	0.054	0.054
C ₇	0.038	0.041	0.040	C ₁₄	0.043	0.060	0.057	C ₂₁	0.047	0.062	0.059

¹ W₁ values were calculated via the CRITIC method; ² W₂ values were calculated by the entropy weight method, and ³ W₃ values were calculated by the GT.

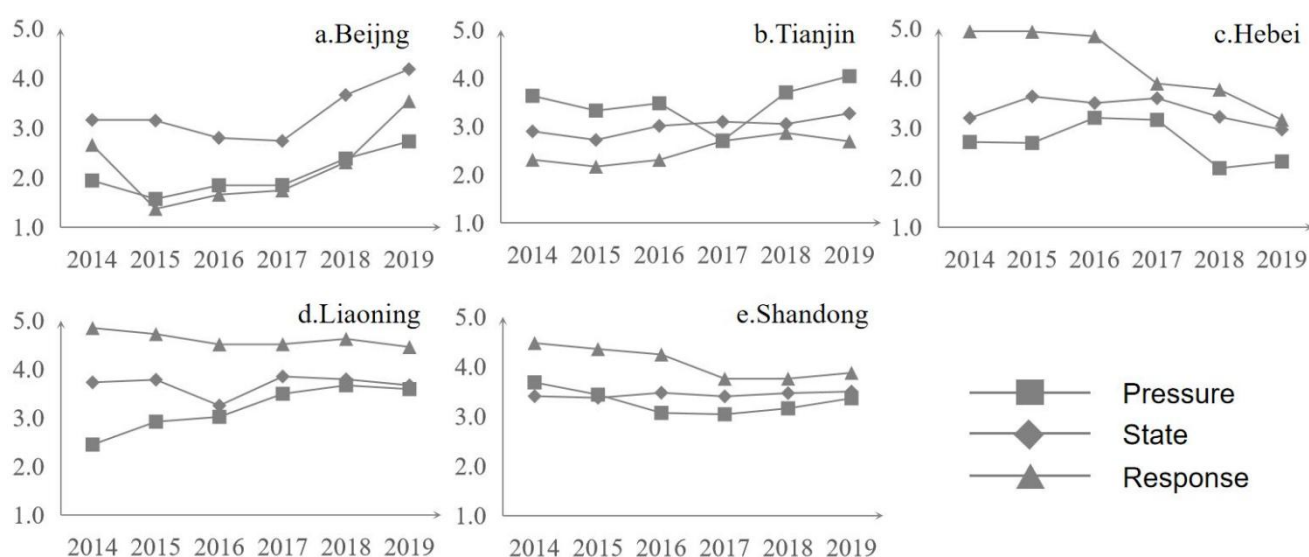
3.2. Evaluation Grades of Water Security

The FCM was used to evaluate the grade of water security. The main calculation process involved Equations (19)–(21). The results of the water security grade computations are shown in Table 8. The membership matrix *R* composed of cloud droplets provided the basis for calculating the security grades of the three criteria layers. Specifically, *R* was a 21×5 matrix, and each column contained the membership degree of each index data based on the five grades discussed above. By multiplying the membership degree of each grade with the corresponding weight, and adding the membership degrees of indices from the respective criteria layers, the security grade of each criterion could be calculated through Equation (21). The security grades of each criteria layer are shown in Figure 4.

Table 8. Evaluated water security grades in the CBSR from 2014 to 2019.

Study Area	2014	2015	2016	2017	2018	2019
Beijing	2.869	2.287	2.247	2.314	2.865	3.472
Tianjin	2.774	2.526	2.671	2.899	3.015	3.190
Hebei	3.740	3.844	3.550	3.494	3.184	2.938
Liaoning	3.823	3.867	3.346	3.895	3.917	3.718
Shandong	3.788	3.700	3.570	3.343	3.332	3.528

Notes: 0 to 1 belongs to grade I; 1 to 2 belongs to grade II; 2 to 3 belongs to grade III; 3 to 4 belongs to grade IV; 4 to 5 belongs to grade V.

**Figure 4.** Security evaluation grade charts showing each criteria layer (PSR) in the CBSR.

3.3. Water Security Scenario Simulation

To analyze the influence of the pressure, state, and response on water security evaluations, the water security evaluation scenarios were simulated using various conditions by changing the evaluation index values of the three criteria layers. The multi-objective ELECTRE III evaluation method was used to rank the simulated scenarios. First, the data for each region over six years were averaged and used as the sample scenario. The simulated scenarios were mainly divided into three types. The first scenario was the “pressure reduction”, that is, the population decreases, the domestic water pressure decreases, the water efficiency increases, and the economic production pressure decreases. The second scenario was the “ideal state”, in which water resources are abundant, water supply system is in good condition, social development is steadily improving, and water environment quality is good. The third scenario was “efficient response”, that is, high level of environmental construction, water supply and drainage construction level. The three scenarios were realized by changing the index values of pressure, state and response criteria layer respectively. The setting of 5% and 15% was mainly used to reflect the influence of the range of change on the merits of the three scenarios. The net credibility (Φ) and grades of the scenarios for the studied regions are shown in Table 9.

Table 9. The net credibility (Φ) and grades of the scenarios for five regions.

Scenario	Beijing		Tianjin		Hebei		Liaoning		Shandong	
	Φ	Grade	Φ	Grade	Φ	Grade	Φ	Grade	Φ	Grade
S_1	−0.663	2.363	−0.638	2.920	−0.421	3.476	−0.380	3.807	−0.513	3.449
S_2	−0.137	2.557	0.237	3.142	0.327	3.632	0.197	3.522	0.448	3.457
S_3	−0.407	2.034	−0.496	2.705	−0.434	3.599	−0.361	3.873	−0.499	3.350
S_4	0.819	1.922	0.631	2.897	0.840	3.433	0.786	3.642	0.955	3.257
S_5	−0.404	2.338	−0.539	2.728	−0.461	3.544	−0.461	3.790	−0.576	3.378
S_6	0.792	2.432	0.804	2.790	0.150	3.583	0.219	3.779	−0.513	3.350

4. Discussion

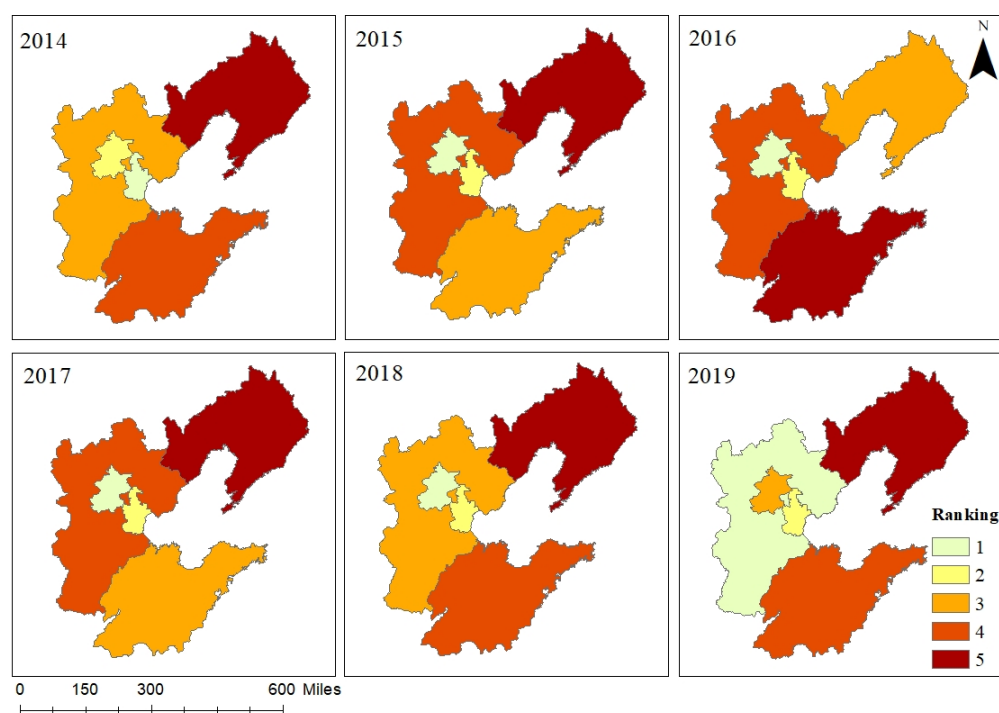
4.1. Combined Weights Analysis

The GT method achieved the balance between the two methods by minimizing the deviation. Compared with the results of the two methods, the combined weight was closer to the entropy weight method. The entropy weight method mainly reflected the degree of dispersion between data, while the critic method mainly reflects the correlation between data. Therefore, in the research field of water security, the dispersion of basic data was strong, which is basically consistent with the actual cognition.

4.2. Water Security Grades Analysis

4.2.1. Comprehensive Security Grades Analysis

Table 8 reflects the time variation trend of water security grades of the study area, and the spatial distribution analysis can be shown in Figure 5.

**Figure 5.** Changes to the water security rankings in the CBSR from 2014 to 2019.

Based on the results presented in Table 8 and Figure 4, each province in the CBSR fluctuated between generally safe and unsafe situations over the tested period. Liaoning had the highest water security grade value and the worst water security capacity, which approached an extremely unsafe situation. The water security grade values in the remaining areas were in the following order: Shandong > Hebei > Tianjin. The region with the best water security capacity was Beijing, whose average water security grade was between

2 and 3; however, the water security capacity there has significantly deteriorated, reaching 3.472 in 2019.

Different indices were in different grades before evaluation, which is a qualitative division. The FCM method realizes qualitative and quantitative transformation. After the cloud model algorithm, each index grade was comprehensively calculated to obtain an actual value, which is the quantitative comprehensive evaluation level of water security. According to the quantitative results, the comprehensive capacity of water security and the overall situation of regional water security can be understood and analyzed more directly and objectively.

4.2.2. Security Grades Analysis of the Criteria Layer

It is clear from Figure 5 that the security capacity of the state-layer (SL) in Beijing was the worst, and its grade fell between generally safe and unsafe. In contrast, that of the pressure-layer (PL) and response-layer (RL) were relatively safer, i.e., between the very safe and generally safe grades. As the capital city, Beijing is relatively more advanced and more developed in all aspects, so it has also attracted a large number of people. However, the small amount of total water resources exacerbates the water shortage problem in the case of a dense population. Therefore, water conservancy projects and water diversion projects must be implemented in order to increase the water supply to meet the water demand; however, this exerts a significant amount of pressure on the water supply security. Simultaneously, Beijing's groundwater resources are exploited, thus seriously affecting the water ecology. Although there are issues regarding the use and supply of water resources, the cost of water has decreased thanks to economic and technological support and development, and the efficiency of water use has also improved significantly. In addition, urbanization developments and adjustments of the industrial structure have helped to enhance the city's water security capacity. However, the construction of drainage networks still presents a problem because they are prone to waterlogging during the rainy season.

The security capacity of the PL in Tianjin was the worst and was characterized between the generally safe and the unsafe grades. Although its economic development was no better than that of Beijing, Tianjin still represents a relatively developed region in China. The water resource situation there is basically the same as that in Beijing, and the population is relatively dense; however, the amount of water resources per capita has always been at the lowest level in China. The water use technology and efficiency are close to those in Beijing. The most serious problem is water ecological pollution, especially considering the low water quality of the river. Tianjin is located at the intersection of the Haihe River tributaries, so the sewage and dirty water from upstream gather in the downstream area, thus significantly reducing the water quality of the river. Even if treatments are carried out, it is difficult to completely solve this issue.

The security capacity of the RL in Hebei was the worst (followed by SL and PL) and fell between the generally safe and the extremely unsafe grades. Liaoning and Shandong had similar security capacities, and the RL had the worst conditions, whereas the PL and the SL basically experienced the same grade. The overall water security capacities of Hebei, Shandong, and Liaoning were similar; all were between the generally safe and unsafe grades. Hebei is closely linked to the economic development of Beijing and Tianjin. It has a large population with a relatively sparse population density. The water resource shortage problem is serious there; over the six years considered in this study, the average water resource per capita did not exceed $200 \text{ m}^3/\text{person}$, and the groundwater supply rate was greater than 50%. Therefore, water supply security faces a huge challenge. There is still a certain gap in terms of economic technology within the developed regions, so the cost of water and water efficiency have a lot of room to improve. Urban development and the industrial structure must be further adjusted and enhanced. In addition, the most serious problem involves ecological environmental construction, as well as drainage and water supply network construction. Liaoning has a relatively developed marine economy,

sparse population density, and negative population growth. Its water resources per capita ranks first in the studied region, but it still endures water shortages. The groundwater supply rate has reached 40%, so the water supply security also introduces risks. Water ecological management and pipeline network construction are analogous to those in Hebei. In addition, the river water quality is serious, so the water supply efficiency should also be improved. Shandong has a relatively developed economic level. The proportion of water supply by groundwater is also high, so water use efficiency and technology should be further optimized. The urban development and industrial structure are similar to those in Hebei, and the water ecological management and environmental construction are poor, so these aspects must be further strengthened.

4.3. Water Security Simulated Scenarios Analysis

Table 9 shows the net credibility value and water security grade value of each region under different scenarios. The net credibility value was determined based on the threshold and the VOR of the ELECTRE III method, and the water security grade value was based on the comprehensive evaluation results of the FCM. In this study, the optimal scenario was selected by combining the optimal results of the two scenarios, and based on the optimal scenario, suggestions for future water security and the direction of social and economic development were proposed.

The net credibility value and water security grade value of S_4 in Beijing were the optimal results. From the variation range of 5% and 15%, the water security grade value in the “pressure reduction” scenario changed the most, that is, the difference between the water security grade value in S_1 and S_2 was about 0.2. Comprehensively, the “ideal state” scenario can be identified as the optimal scenario. The key issues are the lack of water resources and the large population. Therefore, measures and suggestions can be put forward from two aspects of “pressure reduction” and “ideal state”. The population can be accommodated appropriately by expanding the development of surrounding cities and building satellite cities to relieve the population pressure of the urban center. Additionally, water diversion projects and water storage projects can be promoted to achieve inter-provincial water resource mobilization.

The net credibility value of S_6 and water security grade value of S_3 in Tianjin were the optimal results. From the variation range of 5% and 15%, the water security grade value in the “pressure reduction” scenario had the largest change, that is, the difference between the water security grade value in S_1 and S_2 was about 0.22. Overall, there was no obvious optimal scenario. Therefore, measures and suggestions can be put forward from three aspects. The development of neighboring counties could reduce the population pressure of the main urban region. In addition, it is necessary to strengthen the management of water ecology, restore the water environment, strengthen the management of sewage discharge, and improve the capacity of sewage treatments.

The net credibility value and water security grade value of S_4 in Hebei province were the optimal results. From the variation range of 5% and 15%, the water security grade value in the “ideal state” scenario changed the most, that is, the difference between the water security grade value in S_3 and S_4 was about 0.22. Comprehensively, the “ideal state” scenario can be identified as the optimal scenario. Therefore, measures and suggestions can be made from the “ideal state” aspect. Water use technology should therefore be optimized by applying irrigation techniques and reducing groundwater extraction. The government should also accelerate urbanization, increase the proportion of tertiary industries, and adjust the economic structure. Meanwhile, the construction of municipal pipelines and the capacity of the urban water supply and drainage should be enhanced.

The net credibility value of S_4 and water security grade of S_2 in Liaoning province were the optimal results. From the variation range of 5% and 15%, the water security grade value in the “pressure reduction” scenario had the biggest change, that is, the difference between the water security grade value in S_1 and S_2 is about 0.285. Comprehensively, the “pressure reduction” scenario can be identified as the optimal scenario. Therefore,

measures and suggestions can be put forward from the two aspects of “pressure reduction” and “ideal state”. In addition to the aforementioned measures, the government should strengthen their protection of the ecological environment and increase investments in ecological construction projects.

The net credibility value and water security grade of S_4 in Shandong province were the optimal results. From the variation range of 5% and 15%, the water security grade value in the “ideal state” scenario changed the most, that is, the difference between the water security grade value in S_3 and S_4 is about 0.1. Comprehensively, the “ideal state” scenario can be identified as the optimal scenario. Therefore, measures and suggestions can be put forward mainly from the “ideal state” aspect. The relevant measures and suggestions were similar to the Hebei and Liaoning, and mainly focused on improving water use technology, water use efficiency, ecological construction, industrial structure adjustments, and urban pipeline network construction.

5. Conclusions

For this work, a PSR model was employed to construct a water security evaluation indexing system. Additionally, a GT method based on the entropy weight approach and the CRITIC method were used to calculate the weights of the indices, and the FCM was used to evaluate the water security grades throughout the CBSR from 2014 to 2019. Ultimately, the ELECTRE III model was applied to rank the simulated water security scenarios. The main conclusions of this study are as follows:

1. The application of the PSR model revealed the water security capacity from the three crucial aspects (i.e., pressure, state, and response) to comprehensively evaluate the influence of various subsystems (e.g., natural, social, economic, and ecological subsystems) on water security. The GT method effectively weighed the relationship between the entropy weight method and the CRITIC method, minimizing the disadvantages of each approach in order to obtain accurate results. The FCM could be used to achieve qualitative-to-quantitative conversions.
2. The cloud model can be applied to water security evaluations as well as other water resource-related evaluations. For example, the application of the cloud model to evaluate water resource carrying capacities highlighted the rationality and reliability of this method [22]. The distinctive characteristic of ELECTRE III is its ability to handle a data set with a high degree of uncertainty [24]. Therefore, it can be applied to various types of decision-related problems. The most important point is the definition of the thresholds, which allow the user to select the optimal parameters based on predefined preference criteria. Different preference thresholds will lead to different results, so this method is more flexible and can clearly reflect the changes in a decision-maker’s preferences.
3. In addition to the conventional methods and measures known to improve water security capacity, novel methods and technologies involved in water resource monitoring and management are also gaining attention in water security research [25]; examples include drinking water management, water pollution monitoring, water supply system optimization, and pipeline network construction. Legislation can also play a major role in guaranteeing water security. Developed nations worldwide have relatively complete systems regarding water laws, but China is still somewhat weak in this aspect, so legislation is another key area of focus for ongoing research.

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