Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 14 No 12, 4617 doi: 10.2166/wcc.2023.343

Integrated safety assessment of water–energy–food systems based on improved substance element extensions

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ABSTRACT

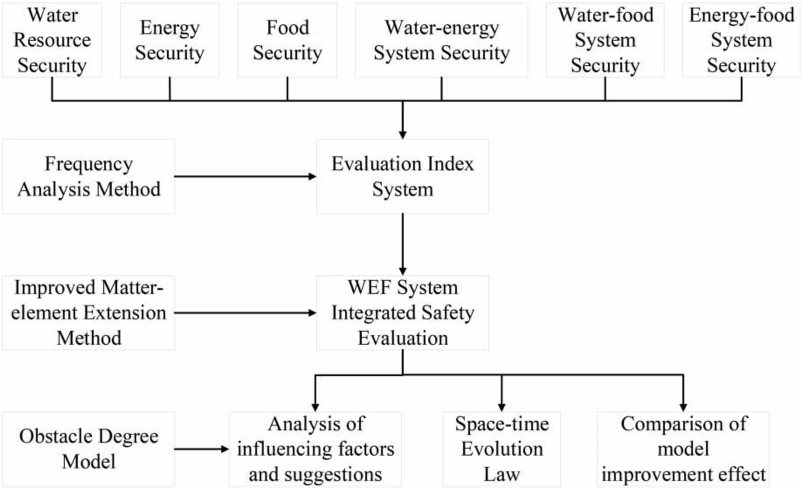
To explore the integrated security of water-energy-food system, 26 indicators were selected from six aspects: water security, energy security, food security, water-energy system security, water-energy system security, energy-food system security; the frequency analysis method was used to construct the integrated security evaluation index system for water-energy-food systems. Then, the matter-element expansion model was refined and used to assess the overall security of the water, energy and food system in the Beijing-Tianjin-Hebei region. The evaluation metrics used to assess the overall security of water, energy, and food system were examined and researched from two dimensions: time and space. This model adequately represents the overall security of the water-energy-food system, as demonstrated by empirical studies. Comparisons are made between the evaluation results of the modified model and those of the conventional matter-element inflationary model, confirming the feasibility and validity of the modified model. Finally, the main factors affecting the security of the water-energy-food system in the Beijing-Tianjin-Hebei region are discussed using the index weight and obstacle degree model. Relevant suggestions are also provided to enhance the security of the water-energy-food system.

Key words: Beijing–Tianjin–Hebei region, collaborative security, improved material-element extensibility method, space–time evolution, water–energy–food systems

HIGHLIGHTS

- This study provides a broad evaluation index system for water–energy–food (WEF) system security evaluation.
- The matter-element extension model has been enhanced and applied to assess the WEF system in the Beijing–Tianjin–Hebei region, thereby enhancing the accuracy of the evaluation outcomes.
- The security of water resources system, energy system, and energy system is the key to the security of the whole system.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water resources, food, and energy are essential for human life and development, as well as crucial for social prosperity and stable economic growth. As the world population continues to grow and modernization continues to be promoted, society's demand for water, food, and energy is growing day by day. According to some data, in the next 20 years, human demand for water, energy, and food will rise by 30%–50% (Kaddoura & Khatib 2017). With the increasing pressure on the natural environment and resources, the water–energy–food (WEF) system has attracted the attention of various countries, and has quickly become a research hotspot in academia. The concept of the WEF system first appeared in the Global Risk Report released by the World Economic Forum in Davos in 2011, which was listed as a resource security risk and became one of the core risk groups in the future (Hoff 2011). In recent years, the climate has continued to deteriorate, the process of urbanization has accelerated, and there have been repeated water shortages, energy crises, and food crises that have had a serious impact on human society. Therefore, conducting comprehensive security research on the WEF system is of great significance in ensuring water resource security, energy security, food security, and the stable development of human society.

Since the WEF system was formally proposed, both domestic and foreign scholars have conducted extensive research on it. The relevant results can be divided into two parts: (1) qualitative explanation of the concept and connotation of the WEF system, and construction of a relevant framework. Among them, some scholars focused on the concept and framework of the WEF system, focusing on water, energy, and food. Zhan *et al.* (2014), for example, believed that water is at the core of the chain of WEF-related relationships because we cannot easily create freshwater resources. Zhang *et al.* (2018) reviewed the concepts and research issues of the WEF system. After comparing and discussing the definitions of the two systems, Zhang *et al.* concluded that future research challenges lie in defining the system boundary and conducting system performance evaluations. Wang *et al.* (2022) further clarified the conceptual framework of WEF in a changing environment, pointing out that data integration, risk assessment, and dynamic regulation are key areas of concern for the development of WEF linkages. Chang *et al.* (2016) believed that the essence of the WEF bond was to comprehensively consider the interrelationship among water resources, energy resources, and food resources. Some scholars have examined the relationship between the WEF component and the external environment and have incorporated additional subsystems into the WEF system to create multicomponent systems for research. These subsystems include ecosystems (Wang *et al.* 2019; Qin *et al.* 2022), sustainable livelihoods (Biggs *et al.* 2015), cities (Liu *et al.* 2018), social economy (Gai & Zhai 2021), land (Gu *et al.* 2023; He *et al.* 2023), and climate (Laspidou *et al.* 2019), among others. (2) Quantitatively analyze the relationship between different resources such as water, energy, and food, and evaluate the development level and future development trend of the WEF system, such as exploring the interrelationship between water resources, energy, and food (Wang & Fang 2019), the bonding relationship (Hao *et al.* 2023), and the correlation relationship (Xu *et al.* 2023). While exploring these relationships, many scholars have also evaluated the development of these connections. For example, Deng & Liu (2023) and Dang *et al.* (2020) evaluated the coupling and coordination of the WEF system in Jilin and Gansu provinces, respectively, providing a reference for the development of coupling and coordination in the WEF system in the studied regions. Zhang *et al.* (2020) developed a model to evaluate the synergistic effect of the ecosystem and study the steady state of China's WEF system. The findings indicate that water resources play a crucial role in determining the stability of the entire system. Ibrahim *et al.* (2019) analyzed the efficiency of the WEF system in OECD countries, and the results showed variations in efficiency among member countries. The WEF system has been studied at various scales, including the small scale of farmland (Fabiani *et al.* 2020) and household level (Hussien *et al.* 2017), the large scale of national level (Bai & Zhang 2018; Sun & Yan 2018), and the global scale (Karnib 2018; Wicaksono & Kang 2019). However, the study of catacombs has primarily focused on the large mesoscale level.

In the study of WEF system evaluation, a wealth of research results have also been achieved, mainly including system coupling coordination degree (He & Yuan 2021; Feng *et al.* 2022), system cooperative security (Li *et al.* 2021; Ren *et al.* 2021), system efficiency (Li *et al.* 2017; Hao & Sun 2022), etc., while the evaluation of the WEF system comprehensive security is less. Currently, comprehensive security assessments of the WEF system mainly focus on national, provincial, or large-scale river basin levels, with little research on regional economies. Moreover, most of the current research focuses on evaluating individual resources, disregarding the interconnections and interactions among water, energy, and food. Therefore, this article comprehensively considers water resource security, energy security, food security, water–energy system security, water-–food system security, and energy–food system security and takes the Beijing–Tianjin–Hebei region as an example to build a model to conduct comprehensive security evaluation of its WEF system in the past 10 years, revealing the changes of WEF system comprehensive security from two dimensions of time and space. It enhances the scope and depth of research in this field.

2. STUDY AREA AND METHODS

2.1. Overview of the study area

The Beijing–Tianjin–Hebei Region, which includes Beijing, Tianjin, and Hebei Province, spans a total area of 218,000 km^2. It is situated in the northern part of the North China Plain (Figure 1). It has a warm temperate continental monsoon climate. In 2021, the GDP of the Beijing–Tianjin–Hebei region was 9.6 trillion-yuan, representing 8.39% of the national total. The region had a permanent population of 110.369 million and possessed a total water resource of 47.768 billion m^3. The total water consumption was 25.531 billion m^3, accounting for 1.6% and 4.39% of the national total water resources and water use, respectively. Total energy consumption was 478.872 million tons, while total primary energy production was 18.814 million tons. These figures represent 9.13% and 2.97% of the country's total energy consumption and production, respectively. Total grain production was 41.127 million tons, which accounted for 6.02% of the country's overall grain production. The rapid development of the Beijing–Tianjin–Hebei region has resulted in a growing disparity between the supply and demand of water, energy, and grain. This contradiction has significant implications for the efficient allocation of resources and the sustainable development of society. Evaluating the security of the WEF system and analyzing the impact factors are important for optimizing resource allocation, improving resource utilization efficiency, and ensuring social sustainability.

2.2. Data sources

Data for the study was obtained from various sources, including the 2011–2020 China Statistical Yearbook, the China Energy Statistical Yearbook, the Hebei Statistical Yearbook, the Tianjin Statistical Yearbook, the Beijing Statistical Yearbook, the China Environmental Statistical Yearbook, and the water resources bulletins for each region. Some missing data were replaced by fitted values.

2.3. Construction of WEF system safety evaluation index system

2.3.1. WEF system conceptual framework

Water, energy, and food are essential resources for human survival and social development. The current balance between the three resources will be broken if there are any security problems in any of them, which will have a serious impact on regional development. It is important to study the relationship and interaction of the three resources, and explore the modes of cooperative development of the three resources – water, energy, and food – for regional sustainable development. This study also explores modes of cooperative development among these resources and assesses the current situation of water, energy, and food system security. At present, the concept of a WEF system has not been unified, but generally speaking, scholars believe that water, energy, and food have a relationship of mutual influence and mutual limitation, known as a bond relationship, such that water, energy, and food constitute an inseparable whole. To better address the issues of water, energy, and food

Figure 1 | Regional overview of the Beijing–Tianjin–Hebei region.

security, it has become inevitable to consider the linkages of the WEF system. Based on the interpretation and framework established by domestic and international scholars on the concept of the WEF system, this article presents a framework diagram illustrating the WEF system relationship, as depicted in Figure 2.

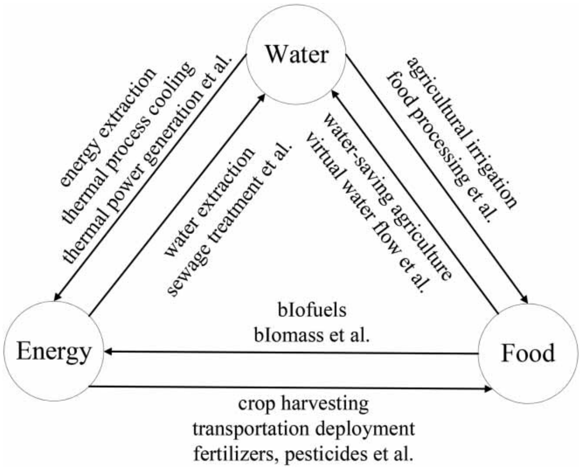


Figure 2 | Conceptual framework of the water–energy–food system.

2.3.2. Index screening

In literature studies, it has been found that various domestic and foreign scholars employ different metrics to assess the WEF system. However, certain metrics are more commonly used in these studies. In this article, the frequency analysis method is adopted to statistically analyze various indicators from numerous literatures involving the WEF system. Targeted metrics are selected comprehensively based on importance and occurrence frequency.

The formula for the calculation is as follows:

$$I = \frac{d + f + s}{3} \tag{1}$$

In Equation (1), I represents the important value, d represents the relative density, f represents the relative frequency, and s represents the relative dominance.

$$d = \frac{\sum_{1}^{n} Q_{ij}}{\sum_{1}^{m} \sum_{1}^{n} Q_{ij}} \tag{2}$$

In Equation (2), i represents the number of indicators, j represents the number of references, and Q_{ij} represents the density of the ith indicator in the jth case.

$$f = \frac{n_i}{N \sum_{1}^{m} \frac{n_i}{N}} \tag{3}$$

In Equation (3), i represents the number of indicators, n_i represents the number of the ith indicator appearing in all literature, and N represents the total number of literature.

$$s = \frac{\sum_{1}^{n} w_{ij}}{\sum_{1}^{m} \sum_{1}^{n} w_{ij}} \tag{4}$$

In Equation (4), w_{ij} represents the weight of the ith index in the jth document.

2.3.3. Determine evaluation index

First, a frequency analysis was conducted to search for literature related to the topic of the WEF system. A total of 465 domestic and foreign papers related to the topic were searched from the China National Knowledge Web site with WEF systems as keywords. From these, 81 relevant articles were selected for the WEF system evaluation. Among them, 65 doctoral and master's theses and core journals were selected to count WEF system evaluation indicators. Equations (1)–(4) were used to determine the ranking of important values for all indicators using the frequency analysis method. Based on previous studies by Liu *et al.* (2020) and Yu *et al.* (2021), and considering the characteristics of the research region, this article identified a total of 26 indicators at two levels from six categories: water resource security, energy security, food security, water–energy system security, water–food system security, and energy–food system security. These indicators are presented in Table 1. Most of the indicators selected in this article are based on frequency analysis. Some indicators such as water consumption per 10,000 yuan of GDP and energy consumption elasticity coefficient were selected based on the characteristics of the Beijing–Tianjin–Hebei region. Therefore, this evaluation index system can also serve as a reference for evaluating the safety of the WEF system in other regions.

2.4. Weight fixing

The entropy weighting method computes the entropy value based on the size of the information entropy and uses this value to reflect the impact of each metric on the synthesis evaluation. This results in the computation of an objective weight for each

Table 1 | WEF system comprehensive security evaluation index

Indicator	Evaluation indicator	Calculation method	Indicator type	Final weight
Water security (A_1)	Water resources per capita (C_1)/m^3	Direct access to statistics	+	0.0456
	Water consumption per capita (C_2)/m^3	Direct access to statistics	−	0.0029
	Wastewater discharge per capita (C_3)/t	Direct access to statistics	−	0.0287
	Water consumption per 10,000 Yuan GDP (C_4)/t. 10,000 Yuan $^{-1}$	Total water consumption per 10,000 Yuan GDP	−	0.0428
	Water production modulus (C_5)/10^4 m^3.km^2	Total water resources/total area of the region	+	0.0439
Energy security (A_2)	Energy consumption per capita (C_6)/t	Direct access to statistics	−	0.0017
	Energy production per capita (C_7)/t	Direct access to statistics	+	0.0064
	Energy self-sufficiency rate (C_8)/%	Energy production/energy consumption	+	0.0053
	Energy consumption per 10,000 Yuan GDP (C_9)/t. 10,000 Yuan $^{-1}$	Energy consumption/GDP	−	0.0248
	Share of clean energy generation (C_{10})/%	Clean energy generation/total generation	+	0.1835
	Energy consumption elasticity coefficient (C_{11})	Direct access to statistics	−	0.2295
	Share of energy industry investment (C_{12})/%	Energy industry investment/regional GDP	+	0.0055
Food security (A_3)	Food production per capita (C_{13})/kg	Direct access to statistics	+	0.0011
	Food consumption per capita (C_{14})/kg	Direct access to statistics	−	0.0123
	Grain sown area per capita (C_{15})/ hm^2.person^{-1}	Grain sown area/total population	+	0.0006
	Crop damage rate (C_{16})/%	Crop damage area/sown area	−	0.1885
	Engel's coefficient for urban residents (C_{17})/%	Direct access to statistics	−	0.0155
	Engel's coefficient for rural residents (C_{18})/%	Direct access to statistics	−	0.0772
	Fertilizer load (C_{19})/kg.hm^{-2}	Fertilizer use/crop sown area	−	0.0018
Water–energy system security (A_4)	Industrial water use share (C_{20}/%	Industrial water use/total water use	−	0.0004
	Percentage of urban industrial water reuse (C_{21})/%	Water reuse/total industrial water use	+	0.0149
Water–food system security (A_5)	Effective irrigation index (C_{22})/%	Effective irrigated area/area arable land	+	0.0003
	Precipitation (C_{23})/mm	Direct access to statistics	+	0.0127
	Share of water used in agricultural production (C_{24})/%	Agricultural water use/total water use	−	0.0174
Energy–food system security (A_6)	Power input per unit sown area (C_{25})/ (KW.hm^{-2})	Total power of agricultural machinery/total crop sown area	+	0.0193
	Energy consumption share of primary production (C_{26})/%	Energy consumption of primary industry/total energy consumption	−	0.0174

indicator, making it an objective weighting method. To perform this calculation, it is necessary to standardize the data and unify the ranges of variation.

Positive indicators:

$$y_{ij} = \frac{x_{ij} - x_{j\min}}{x_{j\max} - x_{j\min}} \tag{5}$$

Contrary indicators:

$$y_{ij} = \frac{x_{j\max} - x_{ij}}{x_{j\max} - x_{j\min}} \tag{6}$$

In Equations (5) and (6), y_{ij} represents the normalized value, x_{ij} represents the initial value, and $x_{j\max}$ and $x_{j\min}$ represent the maximum and minimum values, respectively, of the j index. A positive indicator indicates that a larger value is preferable for the system, while a negative indicator indicates that a smaller value is preferable for the system. To calculate the information entropy, the information entropy E_j of the evaluation index can be expressed as follows:

$$E_j = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ij}\ln p_{ij}(i = 1, 2, \ldots, n; 0 \leq E_j \leq 1) \tag{7}$$

$$p_{ij} = \frac{y_{ij}}{\sum\limits_{i=1}^{n} y_{ij}} \tag{8}$$

Then, the weight W_j of the jth index is computed as follows:

$$W_{j1} = \frac{1 - E_j}{\sum\limits_{i=1}^{n} (1 - E_j)} \tag{9}$$

Applying these equations, the weight calculation results for each evaluation index of the WEF system are shown in Table 1. According to the weighting results, the three indexes of water security, energy security, and food security have higher weights. This indicates that the security situation of these three subsystems has a greater impact on the overall system security. Moreover, the weight of the inverse index is higher than that of the positive index, indicating that the inverse index has a greater impact on the system security.

2.5. Research methods

Matter-element analysis is a technical method developed by Chinese scholar Cai Wen to resolve contradictions and incompatibilities. It is primarily used to deal with uncertainty and ambiguity. The main idea is to represent the object to be evaluated using things, features, and values, and form triples $R = (N, C, V)$, to convert practical problems into formal problems for resolution. Matter-element extended models can enhance the efficiency and accuracy of data analysis, enabling individuals to make more informed decisions. However, practical applications of these models may encounter the following issues: first, when an index value exceeds a finite range, it becomes impossible to obtain the value of the correlation function. Second, the value of the correlation function is influenced by the central value of the segment range. When the value of the data being evaluated changes, the degree of correlation also changes, introducing a bias in determining the level of safety. Therefore, this article improves the matter-element expansion method by normalizing the values of the quantities to ensure that they all fall within a finite range. The second approach is to replace the maximum membership principle with a threshold eigenvalue to determine the safety level. This approach takes into account the influence of other evaluation metrics on the system's safety level, in addition to the one associated with the maximum membership.

2.5.1. WEF system comprehensive security evaluation index

The overall development status of the system is determined by analyzing the interrelationships and characteristics of the WEF system. The comprehensive security evaluation index of the system is calculated using the following formula:

$$T = \sum_{j=1}^{n} W_j X_j^{\cdot} \tag{10}$$

In Equation (10), T represents the integrated security assessment metric of the WEF system, W_j represents the corresponding weight of the system metric, and $X_j^{\cdot}$ represents the value of the system evaluation index after standardized processing.

2.5.2. Improving the object element topology method

(1) Construction of classical domains, nodal domains, and object elements

After reviewing relevant information and existing studies (Li 2020; He & Yuan 2021), this article combines the characteristics of the collected data and divides some indicators into categories based on data quantile points to determine collaborative security evaluation criteria. The security status is then divided into five categories: low security, lower security, critical security, higher security, and high security. An overview of the partitioning criteria for each indicator is provided in Table 2.

To evaluate the collected data according to the classification criteria, the classical, nodal, and matter elements are constructed for the comprehensive security assessment of the Beijing–Tianjin–Hebei region conducted by the WEF. The

Table 2 | Evaluation criteria for the security level of each indicator

Indicator	Low security N5	Lower security N4	Critical security N3	Higher security N2	High security N1
C_1	0–500	500–1,000	1,000–2,000	2,000–3,000	3,000–4,000
C_2	200–300	160–200	120–160	80–120	0–80
C_3	40–100	30–40	20–30	10–20	0–10
C_4	280–340	180–280	80–180	40–80	0–40
C_5	5–10	10–20	20–30	30–40	40–60
C_6	4.2–5.5	3.4–4.2	2.6–3.4	1.8–2.6	1–1.8
C_7	0–0.4	0.4–1.3	1.3–3.2	3.2–7.4	7.4–12
C_8	0–60	60–70	70–80	80–90	90–100
C_9	1.39–2.24	1.07–1.39	0.75–1.07	0.43–0.75	0–0.43
C_{10}	0–10	10–20	20–40	40–60	60–80
C_{11}	1.0–1.5	0.5–1.0	0–0.5	−0.5–0	−1.5–0.5
C_{12}	0–2	2–4	4–7	7–10	10–13
C_{13}	0–200	200–300	300–400	400–500	500–700
C_{14}	190–220	165–190	140–165	120–140	90–120
C_{15}	0–0.04	0.04–0.07	0.07–0.1	0.1–0.13	0.13–0.16
C_{16}	32–60	24–32	16–24	8–16	0–8
C_{17}	60–100	50–60	40–50	20–40	0–20
C_{18}	60–100	50–60	40–50	20–40	0–20
C_{19}	0.7–0.9	0.55–0.7	0.4–0.55	0.25–0.4	0.2–0.25
C_{20}	90–100	80–90	70–80	60–70	10–60
C_{21}	0–70	70–75	75–80	80–85	85–100
C_{22}	0–20	20–40	40–55	55–75	75–100
C_{23}	0–400	400–800	800–1,200	1,200–1,600	1,600–2,600
C_{24}	90–100	80–90	70–80	60–70	10–60
C_{25}	0–3	3–6	6–9	9–12	12–15
C_{26}	4.53–6	3.33–4.53	2.13–3.33	0.93–2.13	0.2–0.93

classical matter-element R_j is shown as follows:

$$
\begin{aligned}
R_j(N_j, C_n, V_j)\begin{bmatrix} & C_1 & v_{1j} \\ & C_2 & v_{2j} \\ N & \vdots & \vdots \\ & C_n & v_{nj} \end{bmatrix} &= \begin{bmatrix} & C_1 & (a_{1j}, b_{1j}) \\ & C_2 & (a_{2j}, b_{2j}) \\ N_j & \vdots & \vdots \\ & C_n & (a_{nj}, b_{nj}) \end{bmatrix} \\
&= \begin{bmatrix} N & N_1 & N_2 & N_3 & N_4 & N_5 \\ C_1 & (0, 500) & (500, 1000) & (1000, 2000) & (2000, 3000) & (3000, 4000) \\ C_2 & (200, 300) & (160, 200) & (120, 160) & (80, 120) & (0, 80) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ C_{26} & (0, 20) & (20, 40) & (40, 55) & (55, 75) & (75, 100) \end{bmatrix}
\end{aligned}
\tag{11}
$$

In Equation (11), N_j represents the jth evaluation level. $C_1, C_2 \dots C_n$ are the evaluation indices, and (a_{nj}, b_{nj}) represents the magnitude range corresponding to the evaluation grade j, which is known as the classical domain.

The R_P profile domain is constructed based on the hierarchy of the Beijing–Tianjin–Hebei WEF comprehensive security evaluation index.

$$R_p(N_p, C_p, V_p) = \begin{bmatrix} N & C_1 & v_{p1} \\ & C_2 & v_{p2} \\ & \vdots & \vdots \\ & C_n & v_{pn} \end{bmatrix} = \begin{bmatrix} N_p & C_1 & (a_{p1}, b_{p1}) \\ & C_2 & (a_{p2}, b_{p2}) \\ & \vdots & \vdots \\ & C_n & (a_{pn}, b_{pn}) \end{bmatrix} = \begin{bmatrix} & C & V \\ & C_1 & (0, 4000) \\ N_p & C_2 & (0, 300) \\ & \vdots & \vdots \\ & C_{26} & (0, 100) \end{bmatrix} \tag{12}$$

In Equation (12), p represents the overall evaluation level, v_{p1}, $v_{p2}\ldots$ v_{pn} represent the value range of features C_1, $C_2\ldots$ C_n, which correspond to the section domain.

Construct the element to be evaluated by assigning values to indicators R.

$$R(N, C, V) = \begin{bmatrix} N & C_1 & v_1 \\ & C_2 & v_2 \\ & \vdots & \vdots \\ & C_n & v_n \end{bmatrix} = \begin{bmatrix} N & C_1 & 162.71 & 187.94 & \ldots & 172.51 \\ & C_2 & 239.73 & 186.70 & \ldots & 233.19 \\ & \vdots & & \vdots\ \vdots & \vdots\ \vdots & \\ & C_{26} & 69.99 & 70.48 & \ldots & 66.35 \end{bmatrix} \tag{13}$$

In Equation (13), R represents the matter element to be evaluated, and v_1, $v_2\ldots$ v_n represent the measured data of features C_1, $C_2\ldots$ C_n.

(2) Normalization

Data normalization is necessary to ensure that partial data does not exceed the profile's domain and impact the evaluation results. This involves dividing the numerical value of the classical domain and the object element to be evaluated by the endpoint value of the profile domain. Specifically, the forward index value is divided by the right endpoint value of the profile domain, while the backward index value is divided by the nonzero left endpoint value of the profile domain. After normalization, the classical domain can be represented as follows:

$$R^{,}\ (N, C, V) = \begin{bmatrix} R & c_1 & \dfrac{v_1}{b_{p1}} \\ & c_2 & \dfrac{v_2}{a_{p2}} \\ & \vdots & \vdots \\ & c_n & \dfrac{v_n}{b_{pn}} \end{bmatrix} \tag{14}$$

The classical domain is normalized.

$$R_j^{,}\ (N_j, C_n, V_j^{,}\ ) = \begin{bmatrix} N & N_1 & N_2 & N_3 & N_4 & N_5 \\ C_1 & (0, 0.125) & (0.125, 0.25) & (0.25, 0.5) & (0.5, 0.75) & (0.75, 1) \\ C_2 & (0.667, 1) & (0.533, 0.667) & (0.4, 0.533) & (0.267, 0.4) & (0, 0.267) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ C_{26} & (0, 20) & (20, 40) & (40, 55) & (55, 0.75) & (75, 100) \end{bmatrix}$$

Normalize the evaluation matter-element R.

$$R^{,}\ (N, C, V) = \begin{bmatrix} N & C_1 & 0.041 & 0.047 & \ldots & 0.043 \\ & C_2 & 0.799 & 0.622 & \ldots & 0.777 \\ & \vdots & & \vdots\ \vdots & \vdots\ \vdots & \\ & C_{26} & 69.99 & 70.48 & \ldots & 66.35 \end{bmatrix}$$

(3) Determined membership

The membership degree is used to replace the correlation degree, and the expression is as follows.

$$P = \sum_{j=1}^{n} D_{ij} W_j \tag{15}$$

$$D_{ij} = \left| v_j - \frac{(a_{pi} + b_{pi})}{2} \right| - \frac{(b_{pi} - a_{pi})}{2} \tag{16}$$

In the aforementioned formula, P represents membership, D_{ij} represents distance, and W_j represents integrated weight.

(4) Determine the evaluation level

Since the principle of maximum membership neglects the effects of other indicators besides the maximum membership and deviates from the principle of comprehensive evaluation and comprehensive consideration, this article adopts graded feature values to determine the level of the evaluated object. The level eigenvalues are computed as follows.

$$H = \sum_{i=1}^{m} iP \tag{17}$$

In Equation (17), H represents the level characteristic value, and P represents the degree of membership of index j relative to level i. The criteria for judging the safety level are as follows:

$1 \leq H \leq 1.5$, the evaluation level is 1.
i–$0.5 \leq H \leq i$, the evaluation grade is i, biased toward i–1; ($i = 2,3,\ldots m$–1)
$i \leq H \leq i + 0.5$, the evaluation level is i, biased toward $i + 1$; ($i = 2,3,\ldots m$–1)
m–$0.5 \leq H \leq m$, the evaluation grade is m.

2.6. Obstacle degree model

The weights reflect to some extent the effect of each metric on the security of the system. The larger the value, the higher the degree of influence, and the main factors affecting the security of the system can be tentatively identified. To further explore the main factors affecting the security of the water, energy, and food systems, and to analyze the variability of the factors, the obstacle degree model is introduced to identify the major factors. The obstacle degree model is built on top of the integrated evaluation model, and the impact of each index on system security is determined by three variables: factor contribution, index bias, and obstacle degree. Here, the factor contribution Fi refers to the weight of the factor on the overall objective, which is generally expressed in terms of the weights of the indicators. The deviation I_i represents the difference in security within the WEF system for a single index. It can be obtained from standard data after applying a dimensionless treatment to each index. The obstacle degree O_i represents the level of obstruction that each index poses to the security level of the WEF system. The higher the value, the greater the obstacle degree of this index to the system's security level. The formula for the calculation is as follows:

$$O_{ij} = \frac{W_j(1 - x_{ij})}{\sum_{j=1}^{n} W_j(1 - x_{ij})} \tag{18}$$

In Equation (18), O_{ij} represents the degree of obstacle for the jth index in year i to the security of the WEF system in that year. W_j represents the index weight, and x_{ij} is the standardized value after dimensionless processing.

3. RESULTS AND DISCUSSION

3.1. Analysis of WEF system comprehensive safety evaluation index

According to Formula (6), the overall comprehensive safety evaluation index of the WEF system in the Beijing–Tianjin–Hebei region is calculated as depicted in Figure 3.

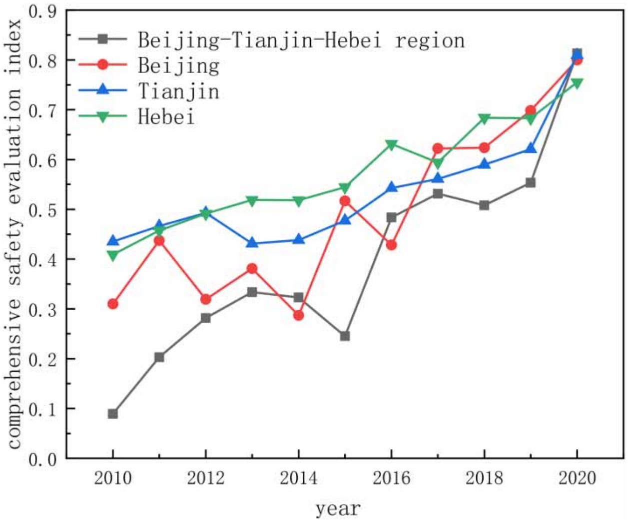


Figure 3 | Changes in the comprehensive safety evaluation index of WEF system in the Beijing–Tianjin–Hebei region.

3.1.1. Changes in the comprehensive safety evaluation index of Beijing–Tianjin–Hebei region WEF system

This is shown in Figure 3: the integrated evaluation index of the WEF system for the Beijing–Tianjin–Hebei region from 2010 to 2020 shows an overall upward trend, with a particularly strong upward trend in 2015–2016. The comprehensive security assessment index for the region was split into two segments during this period, with the 2010–2015 period showing generally lower indices. This is because there are still many loopholes in the management of water, energy, and food during this period, and development is focused on industry and the economy, resulting in a large amount of resources being consumed, which puts greater pressure on the ecological environment and natural resources. As the integrated and coordinated development strategy of the Beijing–Tianjin–Hebei region progresses from 2016 to 2020, green development and high-quality development have emerged as the primary objectives for social progress. Pursuing economic development, local departments have also emphasized the importance of ecological and environmental protection. As a result, the comprehensive security assessment index for this period is significantly higher than the previous one.

Figure 3 shows the comprehensive security assessment metrics for various regions within the Beijing–Tianjin–Hebei region.

3.1.2. Changes in the comprehensive safety evaluation index of the Beijing WEF system

As shown in Figure 3, the integrated safety assessment index of the Beijing WEF system fluctuates between 0.29 and 0.73 during the 2010–2020 period, showing a slow upward trend overall, which can be divided into two phases based on the growth trend. The first phase was from 2010 to 2015, during which the index fluctuated. One reason for this is that the significant fluctuations in precipitation during this period, coupled with population growth and the prolonged overexploitation of groundwater, result in water scarcity. This scarcity becomes a bottleneck that restricts the overall security of the WEF system. In particular, the average annual precipitation in 2014 was the lowest between 2010 and 2020. This led to water shortages that not only impacted the daily lives of residents but also had significant effects on industry and agriculture. As a result, the overall security assessment index for that year was low. The average number of days without rain during this period was 307, and natural disasters such as droughts, floods, and high winds occurred frequently, resulting in widespread crop disasters and large yield reductions. However, total water resources fluctuated, while energy supplies remained mostly stable. The change in the integrated security assessment index is consistent with the actual situation of the WEF system during this period.

The second phase is from 2016 to 2020, with the index slowly rising. During this period, Beijing has intensified its efforts in environmental protection by implementing measures such as water protection, water environment consolidation, energy conservation, and emission reduction. As a result, Beijing has made significant improvements to its ecological environment. However, as Beijing is a typical resource-importing city, it relies heavily on other provinces for water, energy, food, and other resources. The trend of the comprehensive security assessment index in this period is roughly in line with the actual situation in Beijing.

3.1.3. Changes in the comprehensive safety evaluation index of the Tianjin WEF system

The trend of the WEF Comprehensive Security Assessment Index in Tianjin, as measured by the WEF, can be divided into two stages. The first phase, spanning from 2010 to 2014, exhibits a fluctuating upward trend, with values ranging from 0.29 to 0.38. This trend of change is primarily associated with significant fluctuations in precipitation and energy consumption, both of which have a direct impact on the overall water supply. Water resources are closely related to the development of industrial and agricultural production. Therefore, significant changes in precipitation and energy consumption directly impact the fluctuations in the integrated safety assessment index. In 2013, the evaluation index was the lowest in recent years. Tianjin was hit by a severe flood disaster this year, which affected a larger area of crops than the combined area of disasters from 2010 to 2020, resulting in significant losses in grain production. The trend of the evaluation index closely corresponds to the actual situation in Tianjin.

The second phase is from 2015 to 2020, during which the index rises gradually from 0.44 to 0.68. To better promote the integrated and coordinated development of the Beijing–Tianjin–Hebei region, Tianjin has implemented several measures to facilitate a comprehensive green transformation of its economic and social development. These measures aim to enhance the ecological environment and strengthen ecological restoration efforts. As a result, resource utilization and reuse rates improved, resulting in a year-on-year increase in the integrated security assessment index. As an important industrial city, the energy consumption of secondary industries is relatively high. In 2007, secondary industries in Tianjin accounted for 70.44% of energy terminal consumption, while in 2016, the figure was 69.17%. While this figure did not change significantly, the energy utilization rate improved significantly. Tianjin's energy consumption per unit of GDP in 2020 was 0.38 tons of standard coal, 24% lower than in 2015. A change in the integrated security assessment metric can correspond to such a realistic situation.

3.1.4. Changes in the comprehensive safety evaluation index of the Hebei WEF system

The integrated security assessment index of the WEF system in Hebei showed an overall upward trend from 2010 to 2020, with the evaluation index below 0.4. The rate of increase accelerated after 2014. Groundwater, which accounted for more than 50% of the water supply from 2010 to 2014, is severely overdepleted, with agricultural water consumption remaining above 60%. In addition, the total energy consumption continues to grow, with coal consumption accounting for more than 80%. This has a significant impact on the safety level of the WEF system. The low state of the evaluation index basically indicated that there are many inefficiencies in the water and energy systems in Hebei during this period.

After 2014, the coordinated development of Beijing, Tianjin, and Hebei has become a national strategy. Hebei has implemented several measures to promote energy conservation and reduce emission, facilitate industrial restructuring, and restore ecological balance. While total agricultural water consumption still accounts for the largest proportion, both the total and proportion are declining year-on-year, and water utilization has improved. The water consumption per ten thousand yuan of GDP has decreased from 108 m^3 in 2010 to 50 m^3 in 2020, representing a decrease of 53.7%. The growth rate of energy consumption has gradually slowed to an annual average of 1.19%, and the intensity of carbon emissions intensity has gradually decreased. In addition, as a major agricultural province, Hebei has achieved 9 consecutive years of stable grain output exceeding 35 billion kilograms. The gradual improvement of the evaluation index during the period corresponds to the improvement of Hebei's water, energy, and grain resources.

3.2. Characteristics of comprehensive security time variation of Beijing–Tianjin–Hebei WEF system

The characteristic values and safety levels of the WEF system in the Beijing–Tianjin–Hebei region from 2010 to 2020 were calculated using Equation (11), as shown in Table 3. The integrated security level is gradually increased from low security as the system progresses. The security level of the WEF system in the Beijing–Tianjin–Hebei region can be divided into two phases: the first phase, from 2010 to 2015, had a lower security level and a more severe security situation. The second phase, from 2016 to 2020, was characterized by a critical state of security. Since 2018, the security level has gradually increased, indicating that the security situation of the Beijing–Tianjin–Hebei WEF system is improving. Compared to the first phase, the security situation has improved significantly. In the initial phase, there are still numerous deficiencies in the management of water, energy, and food resources in the Beijing–Tianjin–Hebei region. Rapid industrial and agricultural development consumes significant quantities of water and energy, yet the utilization rate is relatively low, leading to a level of integrated security in the WEF system. With the proposal of the Beijing–Tianjin–Hebei integration strategy and the gradual advancement of sustainable development and high-quality development, various departments have also

Table 3 | The characteristic values and security levels of the comprehensive security level of the Beijing–Tianjin–Hebei WEF system

Year	Level characteristic value	Comprehensive safety evaluation level
2010	3.87	N4 is biased to N3
2011	3.62	N4 is biased to N3
2012	3.41	N3 is biased to N4
2013	3.42	N3 is biased to N4
2014	3.18	N3 is biased to N4
2015	3.53	N4 is biased to N3
2016	3.16	N3 is biased to N4
2017	2.90	N3 is biased to N2
2018	3.15	N3 is biased to N4
2019	3.18	N3 is biased to N4
2020	2.70	N3 is biased to N2

strengthened their management efforts, paying increasing attention to green development and sustainability. They have adopted a series of relevant measures, making full and reasonable use of relevant resources, continuously transforming and upgrading the industrial structure, and improving the comprehensive security level of the WEF system.

3.3. Changes in the comprehensive security space of the Beijing–Tianjin–Hebei WEF system

To analyze the spatial distribution characteristics of WEF collaborative security in the Beijing–Tianjin–Hebei region, 3 representative years were selected at equal intervals (Figure 4). The security measures implemented in the WEF system in Beijing, Tianjin, and Hebei from 2010 to 2020 can be categorized into three levels: low security, lower security, and critical security. In 2010, Beijing had the lowest overall security level at N5, while both Tianjin and Hebei had an overall security level of N4 and were trending toward N3, indicating an improving trend in the security situation. The integrated security of WEF systems in Beijing, Tianjin, and Hebei Province was improved in 2015. Beijing's overall security level was raised to N4, while Tianjin and Hebei, which had been in a critical-security situation, were raised to N3. Tianjin's security level, however, is skewed toward N4, while Hebei's is skewed toward N2. Security levels in Beijing and Hebei were raised again in 2020. Beijing was raised from N4 to N3 and entered a critical-security state, while Hebei entered a relatively high security state with a good system security situation. The level of security in Tianjin has not changed, but there has been a shift in the trend of development from N4 to N2, resulting in an improved security situation.

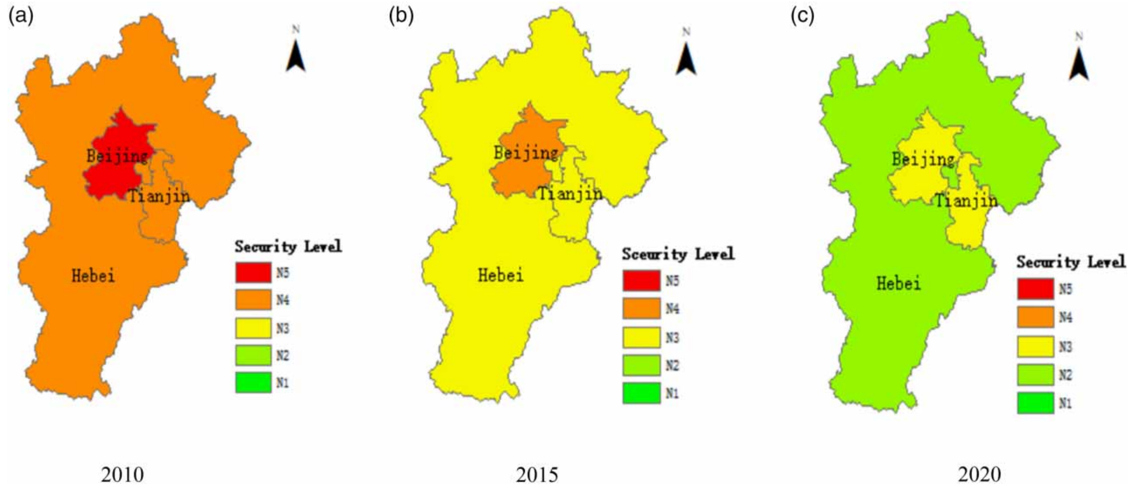


Figure 4 | Comprehensive security level of WEF system in Beijing–Tianjin–Hebei: (a) 2010, (b) 2015, and (c) 2020.

Overall, the integrated security of the WEF system in Hebei remained at the top of the list, while the security level in Tianjin was higher than that of Beijing most of the time. However, after 2018, the security level in Tianjin was placed on the same level as Beijing. The high level of integrated security in the WEF system in Hebei is primarily due to the province's abundant fossil energy and food resources, particularly the food resources that contribute to the overall security of the WEF system. Due to the scarcity of resources, Beijing has a low per capita resource ownership, but high consumption and a high dependence on resource imports of resources from other provinces, resulting in a low level of security. Despite its limited resources, Tianjin has a high self-sufficiency rate, deployment capacity, and utilization rate. In addition, its security level falls between that of Hebei and Beijing.

3.4. Improvement effect analysis

To test the effectiveness of the modified matter-element expansion model, we evaluate the security of the WEF system in the Beijing–Tianjin–Hebei region using the conventional matter-element expansion model. The evaluation results of the two models are shown in Table 4. It can be observed that the evaluation results of the two models are generally consistent, which confirms the viability of the modified model. Using 2020 as an example, the proximity degree of N5-N1 can be divided into -0.6777, -0.6065, -0.6914, -0.2534, and -0.5796 using the traditional model of matrix-element expansion. According to the principle of maximum membership, the WEF system has a security level of N2. However, the safety level of the system should be between N3 'critical safety' and N2 'high safety.' According to the evaluation results obtained by the traditional mature-element extension model, only the evaluation vector corresponding to the maximum membership degree is considered. This approach ignores the fuzziness of the object being evaluated, which goes against the principle of comprehensive evaluation and can lead to the loss of evaluation information. The results obtained by using the modified matter-element extended model are that N3 is biased toward N2, which directly reflects the trend of safety level development, and the evaluation accuracy is higher. The relevant departments can take timely measures in accordance with the development trends, which will contribute to enhancing the security level of the WEF system. The modified matter-element expansion model is more efficient compared to the conventional one.

3.5. Influencing factors analysis and suggestions

Based on the index weights, the main factors affecting the security of the WEF system can be tentatively identified as the elasticity coefficient of energy consumption, the proportion of clean energy generation, the crop disaster rate, and the Engel coefficient of rural residents. To further analyze the specific changes in the influencing factors, this article calculates the degree of influence of each indicator that affects the security of the system based on the weights of the indices and the obstacle degree model. Due to the large number of indicators, this article considers the top five indicators of obstacle degree as the main influences. The major influencing factors for the Beijing–Tianjin–Hebei region from 2010 to 2020 are listed in Table 5. As can be seen from the table, the elasticity coefficient of energy consumption, the proportion of clean energy in

Table 4 | Comparison of evaluation results between traditional model and improved model

	Safety evaluation level	
Year	**Traditional matter-element extension model**	**Improved matter-element extension model**
2010	N4	N4 is biased to N3
2011	N3	N4 is biased to N3
2012	N3	N3 is biased to N4
2013	N3	N3 is biased to N4
2014	N4	N3 is biased to N4
2015	N4	N4 is biased to N3
2016	N3	N3 is biased to N4
2017	N3	N3 is biased to N2
2018	N3	N3 is biased to N4
2019	N3	N3 is biased to N4
2020	N2	N3 is biased to N2

Table 5 | Ranking of major influencing factors in the Beijing–Tianjin–Hebei region

		Index ranking				
Year	**Item**	**No. 1**	**No. 2**	**No. 3**	**No. 4**	**No. 5**
2010	Obstacle factor	C11	C16	C10	C18	C4
2011	Obstacle factor	C11	C10	C16	C18	C5
2012	Obstacle factor	C11	C10	C16	C18	C3
2013	Obstacle factor	C11	C10	C18	C16	C5
2014	Obstacle factor	C10	C16	C11	C18	C1
2015	Obstacle factor	C16	C11	C10	C18	C1
2016	Obstacle factor	C16	C11	C10	C3	C25
2017	Obstacle factor	C10	C16	C11	C18	C1
2018	Obstacle factor	C11	C10	C18	C16	C1
2019	Obstacle factor	C11	C10	C18	C1	C5
2020	Obstacle factor	C18	C5	C1	C25	C14

electricity generation, the crop disaster rate, the Engel coefficient of rural residents, and the per capita water resources are the main factors affecting system security from 2010 to 2019. In 2020, the main influencing factors will include the Engel coefficient of rural residents, water yield modulus, per capita water resources, power input per unit of sown area, and per capita grain consumption.

To enhance the security of the Beijing–Tianjin–Hebei WEF system, the following recommendations have been proposed:

(1) Strengthening water resources management and raising awareness of water resources protection: Relevant departments should establish a joint prevention and control mechanism, and implementing a legal management system for water resources protection is essential. It is crucial to build an efficient joint prevention and control mechanism for water resources protection and water pollution treatment. In addition, coordinating the promotion of water resources protection, water pollution treatment and monitoring, and water ecological restoration in various river basins in the region is necessary.

(2) Promoting the restructuring of the energy industry: Local governments should impose strict limitations on the development of energy-intensive and high-polluting industries, vigorously promote the development of clean energy, increase investment in clean energy, effectively harness and utilize clean energy, and encourage its greater substitution for fossil fuels. In addition, local governments should increase investment in scientific research and enhance energy efficiency.

(3) Promoting the development of water-saving agriculture and enhancing the efficiency of agricultural water usage: Relevant departments should ensure grain production and supply, control the limit of arable land, and restrict the area of arable land and farmers' income. In addition, they should enhance our capacity to respond to natural disasters promptly, reduce the extent of poor or failed harvests caused by natural disasters, and increase grain production and disaster subsidies for farmers.

4. CONCLUSIONS

(1) Considering the complexity of the WEF system and the interdependence and correlation of each subsystem, this article constructed a comprehensive security evaluation index system for the WEF system from six aspects: water resource security, energy security, food security, water–energy system security, water–food system security, and energy–food system security. This approach made the evaluation results more comprehensive and objective.

(2) The WEF's systemic comprehensive security assessment index for the Beijing–Tianjin–Hebei region showed an overall upward trend, with the largest change observed in Beijing, which showed a fluctuating upward trend, while Tianjin and Hebei showed a slower upward trend. Prior to 2014, the WEF systemic integrated security assessment index was low, and after 2014, the assessment index was generally above 0.5.

(3) In terms of temporal variation, the security of the Beijing–Tianjin–Hebei region showed overall improvement from 2010 to 2020. The security increased from low to critical. The security of the Beijing–Tianjin–Hebei WEF system has undergone significant changes since 2015. The security situation has improved, and the security level has gradually risen.
(4) In terms of spatial change, from 2010 to 2020, the Beijing–Tianjin–Hebei region mainly experienced low-security, and critical-security levels. From 2010 to 2015, Beijing and Tianjin maintained low-security levels for an extended period, while Hebei remained at a critical level. From 2015 to 2020, security levels in Beijing and Tianjin were raised to critical levels, while Hebei remained mostly unchanged but increased to a higher level in 2020. Overall, the integrated security rating of the WEF system in Hebei remained in first place, with Tianjin consistently ranking higher than Beijing. This trend continued for several years after 2018.
(5) By comparing the improved model with the traditional matter-element extension model, readers can verify the feasibility and effectiveness of the improved model. This comparison helps to avoid the problem of the traditional material-element extension model, which may ignore the fuzziness of the material element itself during evaluation. As a result, the evaluation results become more accurate and precise.
(6) The main factors influencing the security of the WEF system in 2010–2019 are the elasticity coefficient of energy consumption, the proportion of clean energy power generation, the crop disaster rate, the Engel coefficient of rural residents, and the per capita water resources. In 2020, the main factors that will influence the security level of the WEF system in the Beijing–Tianjin–Hebei region are the Engel coefficient of rural residents, water yield modulus, per capita water resources, power input per unit of sown area, and per capita grain consumption. These factors can be considered key factors in improving the security level of the WEF system.

In this article, the WEF system is evaluated in six aspects, including water security and energy security. Although the interaction of resources themselves is considered, the WEF system is complex and is affected not only by its own factors but also by external economic, social, environmental, and other factors. Therefore, the established system of evaluation metrics needs further discussion. Second, the weights of the metrics will influence the evaluation results, which may vary between subjective and objective weighting methods. When sample data are added or removed, the weights need to be recalculated. As a result, the weights of the metrics may change, and the evaluation results may differ from the previous results. Moreover, research on the security of WEF systems is still in its infancy. Evaluation methods that have been used so far are based on approaches from other disciplines, and there is no universally accepted evaluation method. Therefore, to evaluate the security methods of the WEF system, further exploration is necessary.

FUNDING

This research was funded by the research project of Hebei Province's social development from the Hebei Federation of Social Science Associations (Grant No. 20220202459), the 2022 Funding Project from the key Research Bases of Humanities and Social Sciences of Higher Education Institutions in Hebei Province (Grant No. JJ2211), the Soft Science Research Special Project of Hebei Science and Technology Innovation Capacity Improvement Program from Hebei Provincial Department of Science and Technology (Grant No. 22557634D), and the Humanities and Social Science Research Major Project of the Hebei Education Department (Grant No. ZD202114).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 13 June 2023; accepted in revised form 2 November 2023. Available online 15 November 2023