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Comprehensive evaluation and obstacle factors of coordinated development of regional water–ecology–energy–food nexus

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Abstract
Water, ecology, energy and food are indispensable resources for human survival and social progress, as well as the core of the regional sustainable development. They are interdependent and closely related. The importance of ecology support and feedback capability has been overlooked in traditional studies of the water–energy–food nexus. In this paper, the concept of water–ecology–energy–food (WEEF) nexus was proposed. Then, a comprehensive evaluation indicator system of WEEF nexus was established from three criteria of stability, coordination and sustainability based on synergy theory. A comprehensive variable fuzzy evaluation model was constructed to evaluate the coordinated development level of WEEF nexus in Tianjin, China. And the main obstacle factors that constrained the coordinated development of WEEF nexus were analyzed through the obstacle degree model. The results showed that: from 2010 to 2021, the comprehensive coordinated development level of the WEEF nexus showed an upward trend, with an average growth rate of 4.0%. The stability, coordination and sustainability all significantly affected the comprehensive coordinated development of regional WEEF nexus. The coordination of water–ecology, energy–ecology and food–ecology subsystems was relatively low. Food self-sufficiency rate, average water consumption for energy production, annual rainfall and ecological environment index were the main obstacle factors of WEEF nexus. In summary, the nexus framework and evaluation method proposed in this paper can provide a new perspective on the basic theory and application of regional WEEF nexus.

Keywords Water–ecology–energy–food nexus · Synergy theory · AHP-entropy weight · Variable fuzzy evaluation method · Tianjin

1 Introduction

Water, energy and food are the resources that human beings depend on for survival (Abulibdeh & Zaidan, 2020). With the increase in population and continuous socioeconomic development, each country is facing different degrees of resource shortage crisis (Hoolohan et al., 2018; Young et al., 2015). At the same time, the significant increase in the demand for water, energy and food aggravated the vulnerability of the ecology, reduced the

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Extended author information available on the last page of the article self-regulation and repair ability of the natural environment and in turn hindered the coordinated development of water–energy–food (WEF) nexus (Flörke et al., 2018; Covarrubias, 2019, Ma & Li, 2020). However, the traditional comprehensive evaluation of WEF nexus was limited in scope and often did not consider the impact of feedback effects of eco-environmental degradation system on the imbalance of water, food and energy demand and supply. Therefore, it has become a study of great significance to carry out a comprehensive evaluation of water–ecology–energy–food (WEEF) nexus coordinated development to promote sustainable regional economic and social development (Karabulut et al., 2016; Momblanch et al., 2019).

Although there are not many studies on WEEF nexus, and there is no clear concept of WEEF nexus, many scholars have studied the connection between water, energy, food and a certain ecosystem (Arthur et al., 2019; Molefe & Inglesi-Lotz, 2022; Vanham, 2016). China Water Net (2018) pointed out that water exploitation, energy and food production all have a direct impact on ecology and the environment. So, the basic requirements of ecological environmental protection should be taken into account in WEF nexus research, in other words, from WEF nexus to (water–energy–food–ecology) WEFE nexus. According to Zhao et al. (2016), the coupled system of water–land–energy–carbon (WLEC) system constituted the core of regional natural–economic–social system, and they were interlinked and serve as resources for each other in different ways. Melo et al. (2020) proposed a hybrid framework, called WEEF nexus (the nexus among water, energy, food and forest security), which adds “forests” as an interrelated dimension to the water–energy–food nexus, emphasizing the fundamental role of forests in achieving water, energy and food security. Ringler et al. (2013) explored the potential of the connection between water, energy, land and food (WELF) to improve resource utilization efficiency, and they concluded that the use of the WELF nexus in the analysis of scientific studies allows the recognition of the interdependent nature of water, energy, land and food systems. Associating the WEF nexus with a single ecosystem often fails to reflect the complex correlations between water, energy, food and ecology. Moreover, there is a lack of research on the connotation and mechanism of WEEF nexus coordinated development.

With the gradual advancement of relevant research, more and more scholars realize the importance of collaborative resource management. The subsystems within the nexus relationship are regarded as equally important and focus on a comprehensive evaluation of the system as a whole (Molajou et al., 2021; Zhi et al., 2020). At present, most of the methods used to comprehensively evaluate WEF nexus and other certain ecosystems as a whole system are borrowed from other fields, mainly including coupling coordination degree model, multi-objective decision making, indicator system method, etc. (Li et al., 2018). Wang et al. (2021a) analyzed the dynamic trends of the WEFE nexus and the convergence or divergence characteristics of the WEFE nexus between different cities in Northwest China utilizing the coupling coordination degree (CCD) model and the spatial convergence model. Yue et al. (2020) developed a multi-objective nonlinear optimization model to evaluate the interactions among water, food, energy, climate change and land subsystems and optimize them. Dang (2021a) constructed a water, land, energy and food (WLEF) nexus security evaluation indicator system and selected 28 indicators for the comprehensive evaluation of water, land, energy and food systems. Wolde et al. (2021) selected 25 sub-driver indicators to quantitatively estimate the impact of driver indicators on land, water, energy and food (LWEF) nexus from five main driving drivers: social, economic, institutional and policy changes, environment and technology. Most previous studies, no matter in the comprehensive evaluation method or index selection, rarely focus on the synergistic effects generated by the internal and external environment of the system. It is difficult to establish a unified evaluation framework, which affects the accuracy of the comprehensive evaluation results of the system.

Thus, this paper took water, ecology, energy and food as a whole to study the coordinated relationship among the four subsystems. First, the ecology was added to the traditional WEF nexus and a complete WEEF nexus was constructed for the first time. The concept and coordinated development mechanism of WEEF nexus were given to solve the defects of imperfect construction and unclear mechanism of WEEF nexus in current research. Second, a comprehensive evaluation indicator system for the coordinated development of WEEF nexus was constructed from stability (S), coordination (C) and sustainability (T). Stability reflected the internal resources supply and demand level of each subsystem. Coordination reflected the conversion efficiency and influence degree between two subsystems. Sustainability reflected the resistance of WEEF nexus to external disturbances. The quantitative calculation of comprehensive coordinated development level characteristics of WEEF nexus was realized. Third, previous studies have mostly focused on the discussion of the results, and provided corresponding countermeasures and suggestions based on the evaluation results of WEF nexus. In this paper, the obstacle degree model was introduced to analyze the main obstacle factors affecting the coordinated development of WEEF nexus. It is conducive to put forward targeted measures to enhance the coordinated development of WEEF nexus and reduce the negative impact of obstacle factors from the root.

2 Materials and methods

2.1 Study area

Tianjin is located at 116°43′ ~ 118°′E, 38°34′ ~ 40°15′N, at the lower reaches of the Haihe River and straddles both sides of the river. It is a warm temperate semi-humid monsoonal climate, mainly governed by the monsoon circulation. Spring and winter are dry with little rain, and summer is hot with concentrated rainfall. Over the years, the socio-economy has maintained a generally stable and sustained positive trend. By the end of 2021, the city's permanent resident population was 13.73 million. Tianjin has a serious shortage of water resources, and the contradiction between urban and rural water supply is acute. The average annual total water resources is about 1 billion m^3. The per capita water resources possession in 2021 was only 289.68 m^3, far below the world's recognized per capita possession of 1,000 m^3 water shortage alert line. Relatively rich in energy and minerals, the development of oil and natural gas occupies an important position in China, with proven oil reserves of 4 billion tons and an oil field area of about 100 km^2. Modern urban agriculture is developing rapidly, and the terrain is dominated by plains and depressions, with relatively abundant land resources. The arable land area in 2021 was 347,100 hectares, accounting for 29% of the total land area of the city. Grain production remained stable, reaching more than 2 million tons for five consecutive years. However, with the rapid economic development and continuous advancement of urbanization in Tianjin, the contradiction between supply and demand of water, energy and food has intensified, causing serious damage to the ecological environment. In recent years, with the gradual improvement of people's requirements for ecological environment, the ecological environment condition of the city has been greatly improved. In 2021, the overall quality of the city's surface water reached Class IV, and the proportion of days with good air quality reached 72.3%. Meanwhile, the Ecological Environment Index (EI) was 73.48, and the ecological environment level was good. Due to ecological and environmental problems, resource management in Tianjin is in a dilemma, which brings severe challenges to the current and future development. Therefore, it is a typical field to explore coordinated development of the WEEF nexus, as shown in Fig. 1 (GIM Cloud, 2021).

2.2 Data sources

Data used in this paper were obtained from various sources and the time span was 2010–2021. Data of the water resources subsystem were obtained from the Tianjin Water Resources Bulletin, and data of the ecology subsystem were obtained from the Tianjin Ecological Environment Status Bulletin. Data of energy, food, and economic, social and natural subsystems were obtained from China Statistical Yearbook, Tianjin Statistical Yearbook and Tianjin Statistical Bulletin of National Economic and Social Development. The missing data in some years were uniformly estimated by the linear comparison method.

2.3 Theoretical framework for coordinated development of regional WEEF nexus

2.3.1 Concept of regional WEEF nexus

The Nexus concept was widely noticed and popularized mainly in the 2011 Nexus Conference in Bonn (Hoff, 2011) and the Global Risk Report of the World Economic Forum (2011). Nexus thinking argues that natural resources have begun to hinder economic and social progress and sustainable development to a large extent. The nexus approach is used to study the connections between the various sectors of natural resources and work together to improve the efficiency. It is not only beneficial to the present generation but also to the sustainable development of humanity (Liu et al., 2018). The Nexus concept has received

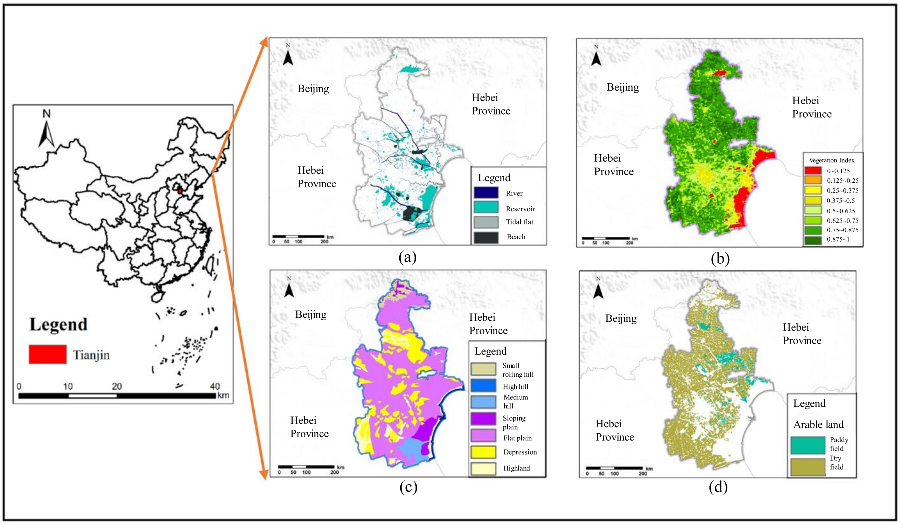


Fig. 1 Overview map of WEEF nexus in Tianjin, China. **a** Water spatial distribution map; **b** Vegetation index map; **c** Geomorphic type distribution map; **d** Spatial distribution of arable land resources

a lot of attention due to the adverse effects of managing resources in a single department and the fragmentation of management in different departments. While the traditional WEF nexus focuses on the interactions between water, energy and food, system frameworks such as WEFF and WLEF consider that water, energy and food are also closely linked to resources such as forests and land (Benites-Lazaro et al., 2020; Elagib & Al-Saidi, 2020; Singh & Tayal, 2022).

Although most current nexus conceptual frameworks do not include the ecological dimension, the support and feedback capacity of ecology is not only vital for water supply, but also affects energy and food production (El-Gafy, 2017; Ma et al., 2020). The interaction mechanism between water, ecology, energy and food is shown in Fig. 2. Specifically, the judicious use of water resources and waste disposal are beneficial to the sustainable development of ecological environment. On the contrary, the over-exploitation of water resources and the casual discharge of sewage may cause significant ecological harm. Water resources play an irreplaceable role in the exploitation and transformation of energy. Energy contributes significantly to both the exploitation and purification of water resources and to the rational allocation and dispatch of water resources. Water resources can be used to irrigate food, which directly influences the quality and production of food crops. However, chemical compounds such as pesticides and fertilizers applied during food cultivation can pollute water resources, while inefficient agricultural water use also results in a large amount of wasted water resources. Natural ecology can generate some clean energy such as solar energy, hydro energy, wind energy and tidal energy. However, excessive energy extraction and waste discharge can cause serious environmental pollution. A good ecological environment can increase the production of food. But uncontrolled development of arable land and extensive use of pesticides and fertilizers can cause indelible damage to the ecological environment. Rational use of energy can not only help harvest and transport

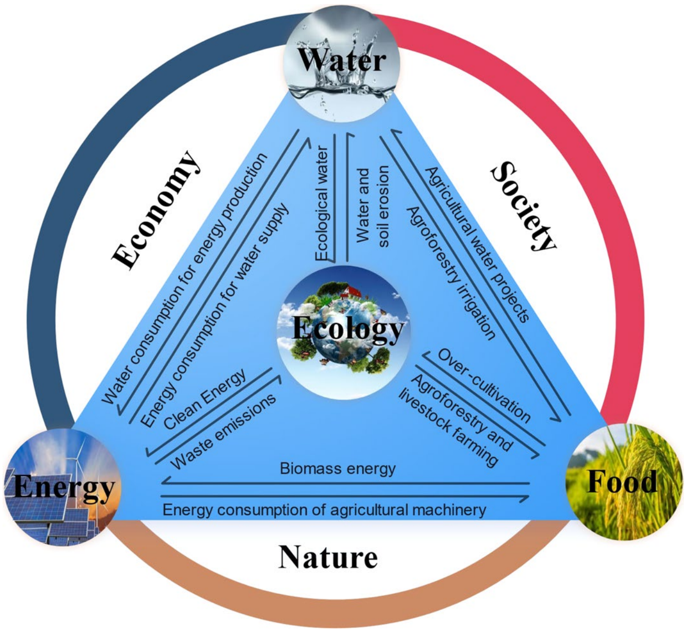


Fig. 2 Interaction mechanism of WEEF nexus

food, but also promote the production and utilization of food. Water, ecology, energy and food are intertwined, interdependent and mutually influential. Studying WEEF nexus as a whole and considering the interaction and relationship among the four resources with systematic thinking will facilitate in the scientific and effective formulation of sustainable development strategies and policies, as well as the reduction of resource security risks (Howells et al., 2013; Fasel et al., 2016; Golfam et al., 2021).

Therefore, an extended nexus framework was proposed to assess the connections between water, ecology, energy and food based on a synthesis of WEEF nexus interaction mechanisms and related conceptual definitions by many domestic and international experts and scholars. In this paper, the WEEF nexus was generally defined as a systemic approach that considers water, ecology, energy and food as interdependent and interlocking in a complex natural environment of population growth-social development-climate change interdependence, and the existence of multiple complex causal links that make these four components an inseparable whole (Lee et al., 2020; Wang et al., 2021b).

2.3.2 Connotation analysis of regional WEEF nexus coordinated development

The WEEF nexus issue is complicated by the fact that the interaction between water, ecology, energy and food should be considered in an integrated manner, rather than narrowly focused on a specific issue. Exploring the role relationship of WEEF nexus based on a coordinated perspective not only provides a good analysis of the interrelationship between the internal subsystems, but also facilitates the efficient use of WEEF nexus resources and sustainable development. “Coordinated development,” according to the synergy foundation theory, is a collaborative interaction in the development process between different development subjects or regions, as well as their internal subsystems and elements, to achieve mutual benefits and win–win results and common development (Giupponi & Gain, 2017; Qi et al., 2022). The coordinated development of the WEEF nexus is primarily manifested in the stability, coordination and sustainability of the system. The stability criterion evaluates the supply and demand of four resources: water, ecology, energy and food. The coordination criterion evaluates the interdependence and mutual consumption of water and each other element. The sustainability criterion evaluates the degree of adaptation of the WEEF nexus to the external environment (Afshar et al., 2022).

In this paper, WEEF nexus coordinated development was defined as a system in which the resources will be fully and rationally developed and utilized under certain external conditions of economic, social development and geographical environment. The regional WEEF nexus operates harmoniously within the carrying capacity of water, ecology, energy and food subsystems. It contributes to sustainable socioeconomic development and maintains an excellent ecological and geographical environment. Through the coordinated development of regional WEEF nexus, the coordinated development of regional nature-society-economy-environment can be realized, and the effect of internal optimization and external coordination can be achieved. Then, a virtuous circle of synergistic interaction of four resources is formed, and the coordinated development plan of the region is completed (Afkhami & Zarrinpoor, 2022). It is a composite system composed of water resources, ecology, energy, food, economy and society. Each subsystem influences and interacts with each other, and promotes the development of the comprehensive system through synergy. The key lies in solving the coordinated problem of stability, coordination and sustainability among the economy, society and resources that constitute the regional complex composite system. This provides a basis for the establishment of a comprehensive evaluation indicator system for the coordinated development of regional WEEF nexus.

2.4 Construction of a comprehensive evaluation indicator system for regional WEEF nexus

The construction of WEEF nexus coordinated development comprehensive evaluation indicator system is an important element in conducting the comprehensive evaluation of WEEF nexus coordinated development. In this paper, based on the reference of system evaluation indicators such as WEF and WLEF nexus, the interactions among water, ecology, energy and food were considered and the principles of indicator construction were strictly followed. The stability (S), coordination (C) and sustainability (T) of the coordinated development system were used as criteria to finally create a comprehensive evaluation indicator system for the coordinated development of the WEEF nexus (Table 1).

Stability (S) evaluation indicators primarily considered the storage and demand of individual resources, the ability to resist external disturbance or the degree of dependence on the outside world, etc. If water resources, ecology, energy and food were in short supply in the region, the foundation of regional coordinated development will be unstable.

Coordination (C) evaluation indicators primarily considered the interaction among the four resources of water, ecology, energy and food, and was the key to the coordinated development of the regional WEEF nexus. In the process of frequent material and energy exchange of each subsystem, different resources were interdependent and mutually constrained, resulting in synergy and contradiction.

Sustainability (T) evaluation indicators mainly considered whether the consumption of water, ecology, energy and food resources and the impact on the environment exceeded the carrying capacity limit under the current development mode. At the same time, the reaction forces of water, ecology, energy and food resources to the economy, society and environment were considered.

2.5 Comprehensive evaluation methods

2.5.1 Variable fuzzy evaluation method

The variable fuzzy evaluation model and method were proposed based on variable fuzzy set theory, which can scientifically and reasonably determine the relative membership degree of sample indicators to standard intervals of indicators at all levels and reasonably determine the evaluation levels of the samples (Chen & Hu, 2006; Fang et al., 2019). The coordinated development of WEEF nexus is a dynamic and variable fuzzy concept, so this paper used the level eigenvalue calculation method based on the variable fuzzy evaluation method for evaluation.

(1) Grading of indicator evaluation

Let the characteristic value of WEEF nexus coordinated development indicator x_{ij} denote the characteristic value of the i th indicator of sample j; i=1, 2, ···, m; j=1, 2, ···, n, and the evaluation level is noted as h, h=1, 2, ···, c.

The attraction (dominant) domain matrix $I_{ab} = \left(\left[a_{ih}, b_{ih}\right]\right)$, the range matrix $I_{cd} = \left(\left[c_{ih}, d_{ih}\right]\right)$ and the point value matrix $M = \left(\left[M_{ih}\right]\right)$ with the relative membership degree equal to 1 are determined with reference to the standard value matrix of indicators and the actual situation.

Table 1 WEEF nexus coordinated development comprehensive evaluation indicator system

Target	Criterion	Subsystem	Indicators	Indicator calculation methodology	Unit
Water–ecology–energy–food nexus coordinated development	Stability, S	Water system, W_S	Per capita water resources, W_{S1}	Total water resources/total population	m^3/person
			Groundwater resources utilization rate, W_{S2}	Groundwater resources supply/total groundwater resources	%
			Water resources development and utilization ratio, W_{S3}	Total water consumption/total water resources	%
		Ecology system, G_S	Forest coverage, G_{S1}	Total forest area/total land area	%
			Greening coverage of built-up areas, G_{S2}	Green area of built-up area/total area of built-up area	%
			Greenhouse gas emissions per unit of GDP, G_{S3}	Greenhouse gas emissions/GDP	kg/10^4 yuan
		Energy system, Es	Per capita energy production, E_{S1}	Total energy production/total population	tons of standard coal/person
			Energy self-sufficiency rate, E_{S2}	Total energy production/total energy consumption	%
			Energy processing conversion efficiency, E_{S3}	Energy processing and conversion output/energy processing and conversion input	%
		Food system, Fs	Per capita arable land area, F_{S1}	Arable land area/total population	m^2/person
			Per capita food production, F_{S2}	Total food production/total population	kg/person
			Food self-sufficiency rate, F_{S3}	Total food production/total food consumption	%
		Water–ecology system, WG_C	Proportion of ecological water consumption, WG_{C1}	Ecological water consumption/total water consumption	%
			Wastewater treatment rate, WG_{C2}	–	%
			Non-conventional water resources ratio, WG_{C3}	Non-conventional water resources supply/total water resources supply	%

Table 1 (continued)

Target	Criterion	Subsystem	Indicators	Indicator calculation methodology	Unit
		Water-energy system, WE_C	Average water consumption for energy production, WE_{C1}	∑ (Each energy production*water quota)/total energy production	m^3/ tons of standard coal
	Coordination, C		Energy production water use ratio, WE_{C2}	∑ (Each energy production * water quota)/ total water consumption	%
			Industrial wastewater discharge, WE_{C3}	–	t
		Water-food system, WF_C	Proportion of agricultural water consumption, WF_{C1}	Agricultural water consumption/total water consumption	%
			Proportion of effective irrigation area, WF_{C2}	Effective irrigation area/ total sown area	%
			Annual rainfall, WF_{C3}	–	mm
		Energy–food system, EF_C	Agricultural machinery power of per unit cultivated land area, EF_{C1}	Total power of agricultural machinery/total cultivated land area	kW/ha
			Rural electricity consumption, EF_{C2}	–	kW·h
			Proportion of the energy consumption in primary production, EF_{C3}	Primary production energy consumption/ total energy consumption	%
		Energy–ecology system, EG_C	Proportion of clean energy power generation, EG_{C1}	Clean energy generation/total electricity generation	%
			Industrial sulfur dioxide emissions, EG_{C2}	–	t
			Rate of comprehensive utilization of industrial waste residue, EG_{C3}	Comprehensive utilization of industrial waste residue /(Industrial waste residue generation)	%
		Food–ecology system, FG_C	Fertilizer application amount per unit cultivated area, FG_{C1}	Fertilizer application amount/total cultivated land area	t/ha
			Water and soil erosion control area, FG_{C2}	–	km^2
			Area of returned farmland to forest, FG_{C3}	–	10^4 ha

Table 1 (continued)

Target	Criterion	Subsystem	Indicators	Indicator calculation methodology	Unit
	Sustainability, T	Economic system, J_T	Per capita GDP, J_{T1}	GDP/total population	10^4yuan/person
			Water consumption per unit of GDP, J_{T2}	Total water consumption/GDP	$m^3/10^4$ yuan
			Proportion of environmental protection expenditure to GDP, J_{T3}	Environmental protection expenditure/GDP	%
			Energy consumption per unit of GDP, J_{T4}	Energy consumption/GDP	tons of standard coal/10^4 yuan
			Proportion of primary production added value in the GDP, J_{T5}	Primary production value added/GDP	%
		Social system, H_T	Population density, H_{T1}	Total population/total area	person/km^2
			Per capita water consumption, H_{T2}	Total water consumption/total population	m^3/person
			Per capita area of parks, H_{T3}	Total park area/total population	m^2
			Per capita domestic energy consumption, H_{T4}	Total domestic energy consumption/total population	tons of standard coal
			Per capita food consumption, H_{T5}	Total food consumption/total population	kg
		Natural system, Z_T	Ecological environment index, Z_{T1}	–	–
			Proportion of poor V water quality, Z_{T2}	–	%
			Annual average concentration of PM2.5, Z_{T3}	–	μg/m^3
			Annual average concentration of nitrogen dioxide, Z_{T4}	–	μg/m^3
			Volume of living garbage disposal, Z_{T5}	–	10^4t

(2) Determination of evaluation indicator weights

The determination of indicator weights is an important link in the comprehensive evaluation study of the coordinated development of WEEF nexus, and the choice of weight calculation method can directly affect the scientificity of the evaluation results. Since the units of each indicator in Table 1 are different, the max–min normalization method is used to perform dimensionless processing on the raw data. In order to avoid the limitations of single assignment method, adopts analytic hierarchy process (AHP)-entropy weight combination assignment method to determine the final weights ω_i (Zhong et al., 2022):

$$\omega_i = \alpha_i\beta_i \Big/ \sum_{\mathrm{i=1}}^{\mathrm{m}} \alpha_i\beta_i \tag{1}$$

where α_i is the AHP indicator weight, and β_i is the entropy method indicator weight.

(3) Calculate the comprehensive relative membership degree

Compare the integrated evaluation indicator characteristic value x_{ij} with M_{ih} of level h (Chen & Hu, 2006).

If x_{ij} falls to the left of M_{ih},

$$\begin{cases} D_A(u) = \left[\frac{x-a}{M-a}\right]^\beta ;x \in [a, M] \\ D_A(u) = -\left[\frac{x-a}{c-a}\right]^\beta ;x \in [c, a] \end{cases} \tag{2}$$

If x_{ij} falls to the right of M_{ih},

$$\begin{cases} D_A(u) = \left[\frac{x-b}{M-b}\right]^\beta ;x \in [M, b] \\ D_A(u) = -\left[\frac{x-b}{d-b}\right]^\beta ;x \in [b, d] \end{cases} \tag{3}$$

Equations (2) and (3) β in a nonnegative exponential function, which is usually taken as $\beta = 1$.

Then, the comprehensive relative membership degree variable fuzzy evaluation model of sample j to level h can be calculated in Eq. (4):

$$u'_h = 1 \Bigg/ \left(1 + \left\{ \frac{\sum_{i=1}^{m} \left\{\omega_i\left[1 - \mu_A\left(x_{ij}\right)_h\right]\right\}^p}{\sum_{i=1}^{m} \left[\omega_i\mu_A\left(x_{ij}\right)_h\right]^p} \right\}^{\alpha/p}\right) \tag{4}$$

where u'_h is the non-normalized integrated relative membership degree; α is the model optimization criterion parameter; ω_i is the indicator weight; m is the number of identified indicators; p is the distance parameter, $p = 1$ is the Hemming distance, $p = 2$ is the Euclidean distance.

The obtained coordinated development level integrated relative membership degree matrix can be normalized in Eq. (5) and (6):

$$U = \left(u_h\right) \tag{5}$$

$$u_h = u'_h / \sum_{h=1}^{c} u'_h \tag{6}$$

According to the inapplicability of the maximum membership degree principle for fuzzy concepts under hierarchical conditions, the level eigenvalues are applied in Eq. (7):

$$H = (1, 2, \cdots, c) \cdot U \tag{7}$$

2.5.2 WEEF nexus coordinated development evaluation level standard

Based on the reference of WEFF, WLEF and other related studies, and by analogy Li et al. (2021) and Wang et al. (2022), the characteristic values of the levels of WEEF stability, coordination, sustainability and comprehensive coordinated development were divided into five levels from low to high. The five levels corresponded to lower, low, middle, high and higher degrees of system coordinated development, respectively, as shown in Table 2.

2.6 Obstacle factor model of regional WEEF nexus

In order to identify the negative effect intensity of each evaluation indicator on the coordinated development of WEEF nexus in Tianjin, the obstacle degree model is used to calculate and diagnose the obstacle factors. The calculation process is shown in Eq. (8) (Fan & Fang, 2020):

$$M_{ij} = \frac{\left(1 - r_{ij}^*\right) w_i}{\sum_{i=1}^{m} \left(1 - r_{ij}^*\right) w_i} \times 100\% \tag{8}$$

where M_{ij} is the obstacle degree; r_{ij}^* is the standardized value of the ith indicator of the jth year; $\mathrm{T}_{ij} = 1 - r_{ij}^*$ represents deviation between indicators and coordinated development goals; w_i is the weight of the indicator. The higher M_{ij} is, the greater the constraint effect.

3 Results and discussion

3.1 Evaluation level of coordinated development in Tianjin

According to the combined weighting method formula of AHP-entropy weight method, the indicator weights of the stability, coordination and sustainability criteria layers of Tianjin City from 2010 to 2021 were calculated, and the indicator weight radar chart was drawn, as shown in Fig. 3. Then, based on the indicator weights of each criterion layer, the comprehensive evaluation indicator weights of the coordinated development of WEEF nexus were calculated.

Table 2 Classification of system coordinated development levels

Coordinated development levels	Lower	Low	Middle	High	Higher
Stability	< 2.30	2.30–2.70	2.70–3.10	3.10–3.45	> 3.45
Coordination	< 2.80	2.80–3.20	3.20–3.60	3.60–4.00	> 4.00
Sustainability	< 2.80	2.80–3.10	3.10–3.40	3.40–3.60	> 3.60
Comprehensive coordinated development	< 2.70	2.70–2.90	2.90–3.20	3.20–3.45	> 3.45

From 2010 to 2021, the S, C, T and comprehensive coordinated development level characteristics of the WEEF nexus in Tianjin were calculated by using variable fuzzy evaluation method described in Sect. 2.5.1. The calculation results of the level characteristic values were summarized and are compared with Table 2 to obtain the annual evaluation level of coordinated development, as shown in Table 3.

The derived values of system S, C, T and integrated coordinated development characteristics were plotted as line graphs (Fig. 3).

3.2 Analysis of evaluation results of WEEF nexus in Tianjin

(1) Stability analysis: from Fig. 4, the stability of the WEEF nexus in Tianjin increased gradually from 2010 to 2021 but slightly decreased from 2017 to 2019. The stability evaluation results gradually increased from low level to middle level. Furthermore, calculated the water, ecology, energy and food system stability level characteristic values (Fig. 5). The results showed that the stability of the regional system varies in sensitivity to different influencing factors. The per capita water resources, greenhouse gas emissions per unit of GDP, energy self-sufficiency rate and food self-sufficiency rate were the key factors on regional system stability. Tianjin, as a municipality directly under the central government of China and the first coastal open city, had a high demand for various resources. Groundwater utilization rate and water resources utilization rate were far beyond the reasonable limit, and the conflict between water resources supply and demand was outstanding. But the per capita water resources had been maintained at 100 m^3/person, far below the normal standard. At the same time, as a province with a large demand for energy and food, per capita energy production had just reached normal standards, and per capita arable land area had been maintained at only about 230 m^2/person. At the same time, as a province with a large demand for energy and food, the energy self-sufficiency rate had been lower than 65% for a long time and food production was basically self-sufficient. The stability evaluation results of WEEF nexus are shown in Fig. 6a. Sun et al. (2022) evaluated the sustainable relationship of WEF nexus in Tianjin from 2010 to 2019 by using GRD-ITOPSIS, an improved TOPSIS method of gray correlation, as shown in Fig. 6b. The comparison results showed that the characteristic values of the stability level and the sustainable relationship index of water, energy and food subsystems all showed a trend of fluctuation growth, and they all were at a low level. As a result, with limited water, energy and food, as well as an unfavorable ecological state, system stability was slow to improve or even regress. Therefore, Tianjin should improve the utilization rate of resources and increase the supply of external resources when necessary to meet its own demand.

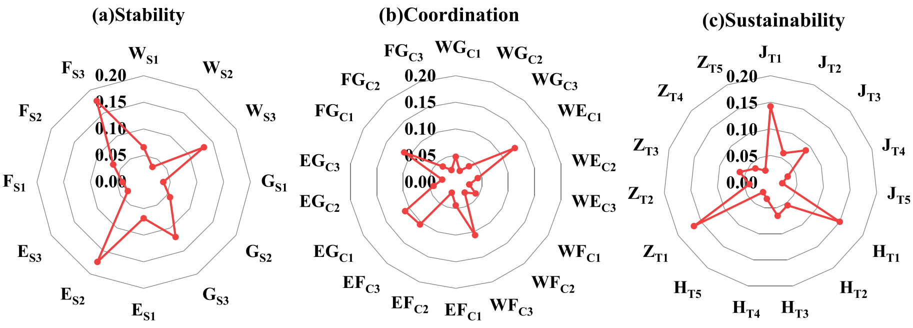


Fig. 3 WEEF nexus stability, coordination and sustainability indicator weights

Table 3 Summary of coordinated development evaluation levels

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Stability	2.587 (low)	2.517 (low)	2.582 (low)	2.487 (low)	2.497 (low)	2.646 (low)	2.757 (middle)	2.482 (low)	2.639 (low)	2.538 (low)	2.771 (middle)	3.018 (middle)
Coordination	1.916 (lower)	1.904 (lower)	1.918 (lower)	2.017 (lower)	2.219 (lower)	2.434 (lower)	2.560 (lower)	2.725 (lower)	3.014 (low)	3.102 (low)	3.299 (middle)	3.314 (middle)
Sustainability	2.281 (lower)	2.110 (lower)	2.270 (lower)	2.227 (lower)	2.067 (lower)	2.071 (lower)	2.059 (lower)	2.345 (lower)	2.894 (low)	3.392 (middle)	3.354 (middle)	3.598 (high)
Comprehensive coordinated development	2.191 (lower)	2.103 (lower)	2.184 (lower)	2.159 (lower)	2.255 (lower)	2.411 (lower)	2.493 (lower)	2.570 (lower)	2.926 (middle)	3.085 (middle)	3.200 (middle)	3.357 (high)

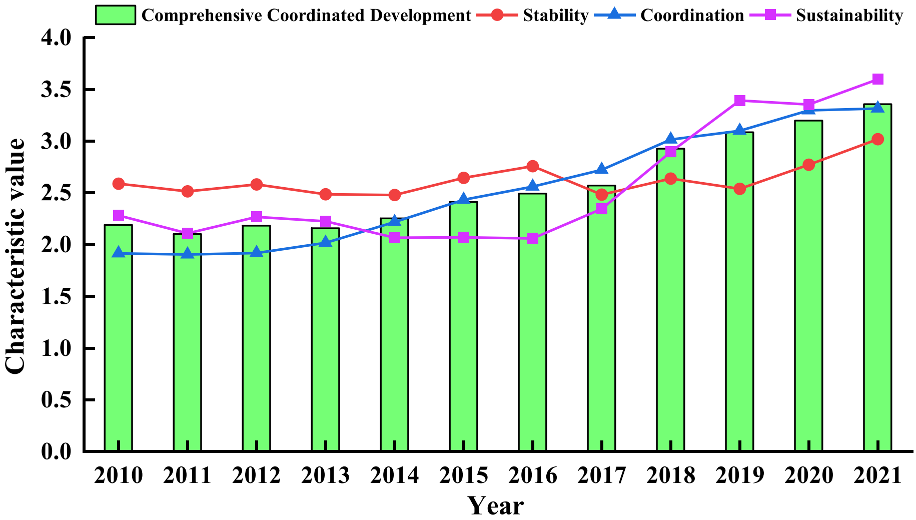


Fig. 4 Trend of the change of the characteristic value of WEEF nexus

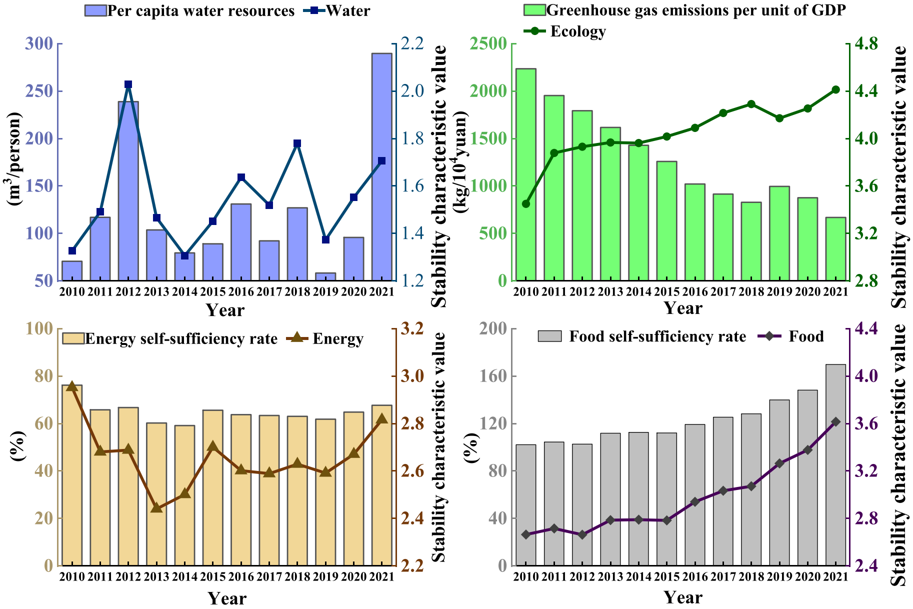
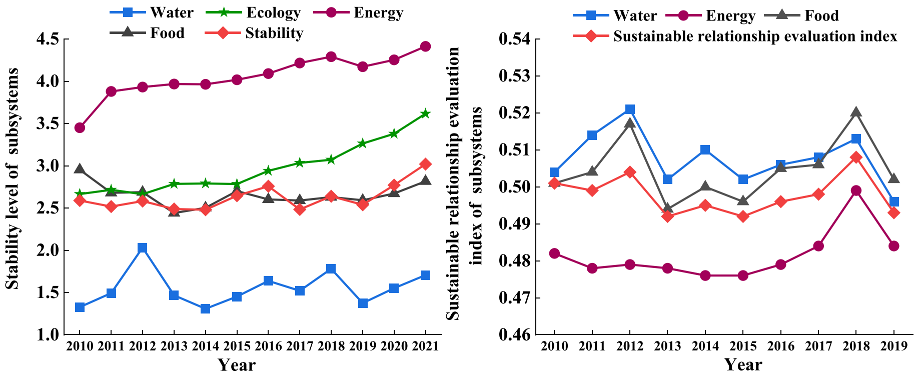


Fig. 5 The stability level characteristic values of water, ecology, energy and food subsystems

(2) Coordination analysis: from Fig. 4, it could be seen that the coordination of WEEF nexus in Tianjin gradually increased. However, the coordination level had been lower or low for many years, which was poorly coordinated. The coordination of the nexus was mainly expressed as the mutual coordination and cooperation between the two subsystems, so as to achieve better results. This paper focused on the coordinated relationship between the ecology and other subsystems in Tianjin, so the characteristic



(a)

(b)

Fig. 6 Comparison of the stability level characteristic values and sustainable relationship evaluation index of each subsystem in Tianjin. **a** Research results of this paper; **b** Control group results (modified by Sun et al., 2022)

values of coordination levels of ecology–water, energy and food were calculated (Fig. 7). The results showed that the coordination between ecology and water, energy, food in Tianjin was low and improved slowly from 2010 to 2017. After 2017, with the improvement of the ecology system in Tianjin, proportion of ecological water consumption, proportion of clean energy power generation increased significantly and fertilizer application amount per unit cultivated area decreased significantly. The coordination between Tianjin's ecology system and other resource systems improved significantly.

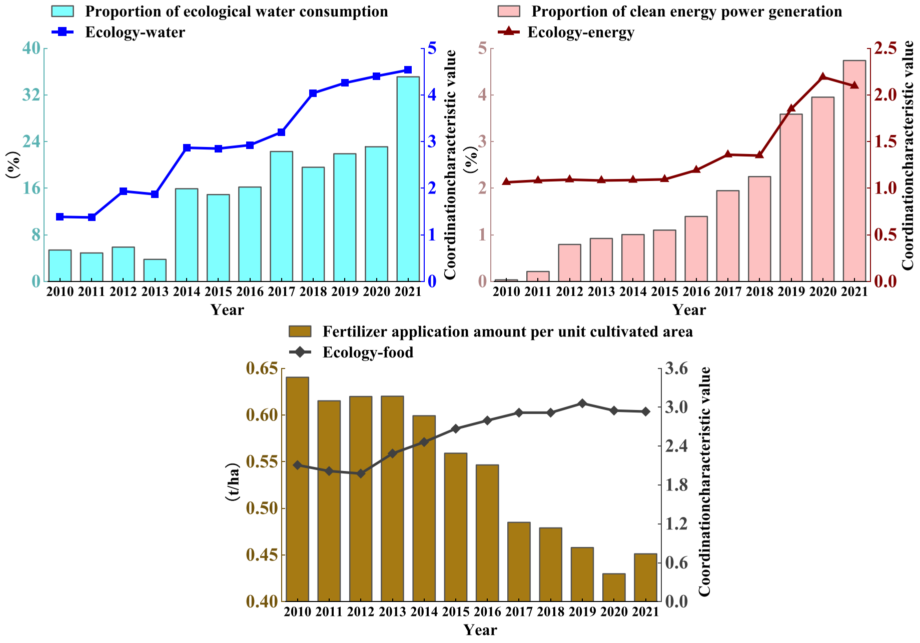
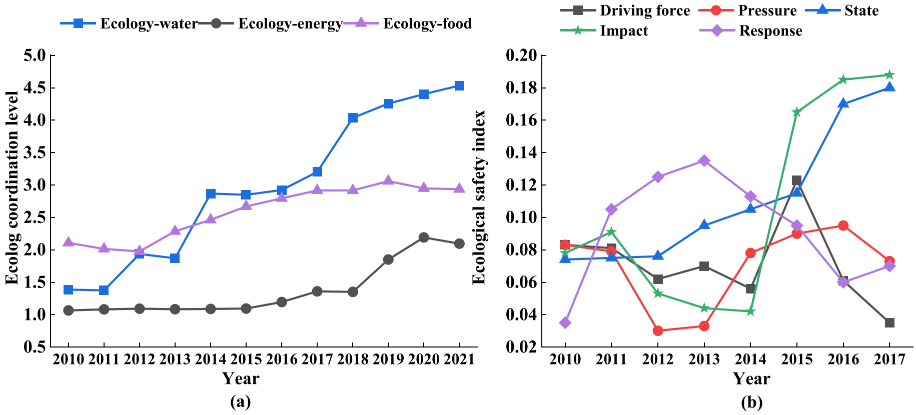


Fig. 7 Coordination characteristic values of ecology–water, ecology–energy and ecology–food subsystems

But the proportion of clean energy generation was less than 5%, and the area of water and soil erosion control and reforestation was relatively small. These resulted in relatively prominent ecology–energy as well as ecology–food conflicts and low coordination. The results of ecology subsystem coordination evaluation are shown in Fig. 8a. Hu et al. (2021) evaluated the ecological security of Tianjin from 2010 to 2017 based on DPSIR model, as shown in Fig. 8b. The comparison results showed that the ecological security index of Tianjin had been in a medium warning state for a long time, and reached a critical safety state in 2016 and 2017. Both indicated that the ecology structure of Tianjin was disordered before 2017, and the problems of resource consumption and environmental pollution were serious. Therefore, the contradiction between the two subsystems of ecology and water, energy and food should be alleviated. The cooperative of each department should be strengthened to improve the efficiency of resource management and promote the overall coordinated development.

(3) Sustainability analysis: from Fig. 4, sustainability of the WEEF nexus in Tianjin gradually remained stable from 2015 to 2019, slightly decreased from 2014 to 2016 and significantly increased from 2017 to 2021. The sustainability evaluation results also increased from lower level in 2010 to middle level in 2019–2020, and even reached high level in 2021. The results of the calculation of the characteristic values of the sustainability levels of the economic, social and natural systems in Tianjin are plotted in Fig. 9. The values of the main indicators affecting each subsystem were analyzed. Tianjin's per capita GDP was in the middle to upper level in China, indicators such as water consumption, energy consumption per unit of GDP and proportion of primary production added value in the GDP were at a low level. This indicated that the sustainability of the economy was stabilized at a high level. Meanwhile, the population density had been maintained at around 1,150 person/km^2, and indicators such as per capita water consumption, per capita domestic energy consumption were at a high level. This indicated that the sustainability of society stabilized at a lower level. Before 2014, the economic development of Tianjin was relatively slow, and the ecological environment quality also maintained a good state. However, with the unreasonable economic development, the ecological environment of Tianjin was destroyed from 2015 to 2017, and the environmental sustainability was reduced. Finally, Tianjin started the battle of pollution prevention and control, increased the proportion of environmental protection expenditure to GDP and so on. Natural indicators such as



(a) (b)

Fig. 8 Comparison of coordination characteristic values of ecology and ecological safety index in Tianjin. **a** Research results of this paper; **b** Control group results (modified by Hu et al., 2021)

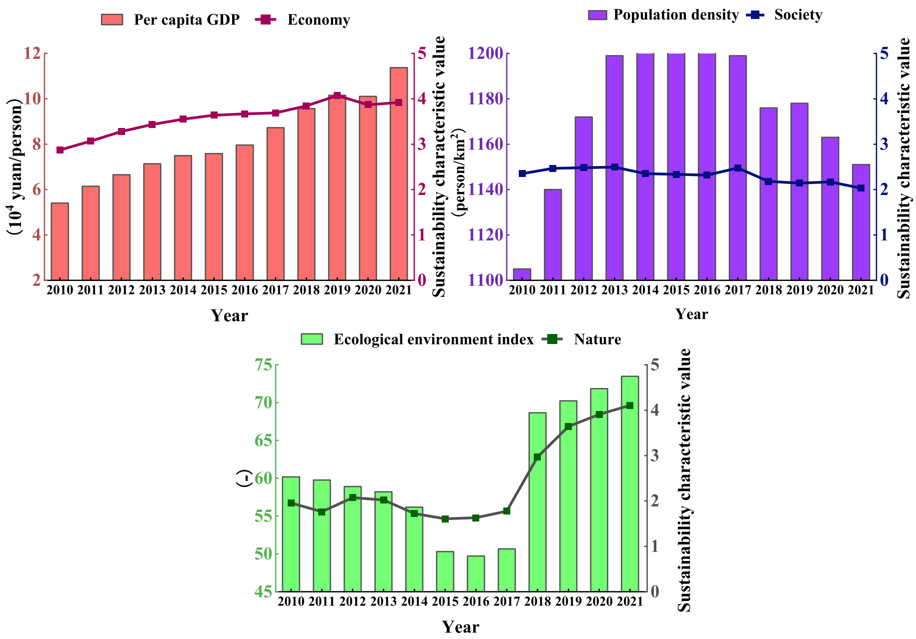


Fig. 9 Sustainability level characteristic values of economic, social and natural subsystems

the annual average concentration of PM2.5 and the proportion of poor V water quality in Tianjin decreased to varying degrees. The ecological environment index increased from a relatively poor 50.3 to 73.48, and the sustainability level of the environment increased from low level to high level. It indicated that the ecological improvement work in Tianjin was effective, which led to a significant increase in sustainability. The sustainability evaluation results are shown in Fig. 10a. Xuan (2021) evaluated the order degree of economy, society and ecology subsystems of Tianjin from 2010 to 2018 based on the composite system cooperation degree model, as shown in Fig. 10b. The comparison results showed that the critical limiting factors for the sustainability of the WEEF nexus and the coordination degree of the economy–society–ecology composite system in Tianjin were both in the ecology subsystem. To achieve the healthy and stable development of the ecological environment while ensuring economic and social development is an issue that Tianjin needs to consider in the future.

(4) Analysis of the level of comprehensive coordinated development: from Fig. 4, the evaluation results of comprehensive coordinated development of WEEF nexus in Tianjin had been on the rise. The evaluation level of comprehensive and coordinated development had gradually improved from lower level in 2010–2017 and jumped up to middle level in 2018–2020, but had not yet stabilized at a high level. The coordination and sustainability of the nexus were at low level or lower level from 2010 to 2016. However, as the stability of the nexus gradually increased, the level of promoting comprehensive and coordinated development also gradually improved. It could be concluded that the level of comprehensive coordinated development of the WEEF nexus in Tianjin could only steadily increase if the level of water, ecology, energy and food supply was improved. Meanwhile, the WEEF nexus sustainability in Tianjin had reached a high standard in 2021. Although stability and coordination were still relatively lagging behind, the level of comprehensive

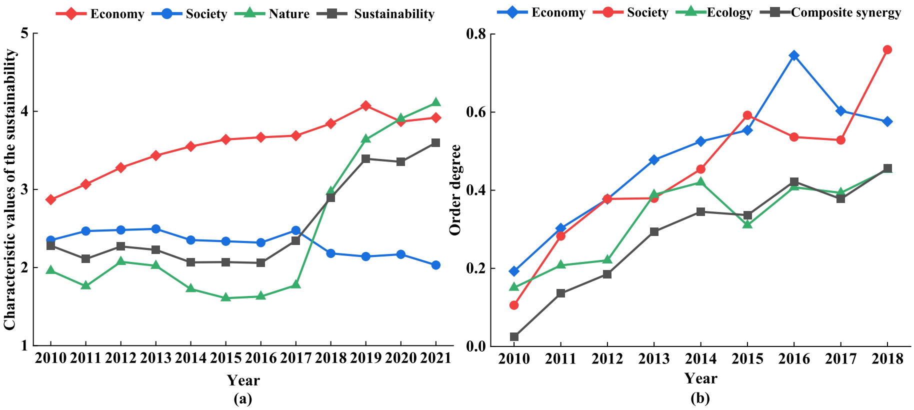


Fig. 10 Comparison of sustainability level characteristic values and order degree of economy–society–ecology composite system in Tianjin. **a** Research results of this paper; **b** Control group results (modified by Xuan, 2021)

coordination was driven to the high level. As a result, the sustainability of the WEEF nexus in Tianjin had improved. Especially the positive impact of the ecology on the economy, society and nature contributed significantly to the level of comprehensive and coordinated development. The evaluation results of comprehensive coordinated development level of WEEF nexus are shown in Fig. 11 a. Sun et al. (2022) evaluated the coupling coordination degree (CCD) of Tianjin WEF nexus from 2010 to 2019 based on the coupling coordination model, as shown in Fig. 11b. The comparison results showed that the comprehensive coordinated development level of WEEF nexus and the coordinated development level of WEF nexus both were on the upward trend year by year. The coupling coordination degree of Tianjin transitioned from primary coordination to intermediate coordination, but it has not yet reached a good state of coordinated development. Consequently, the high level of economic and social development in Tianjin should be continued. The investment in water

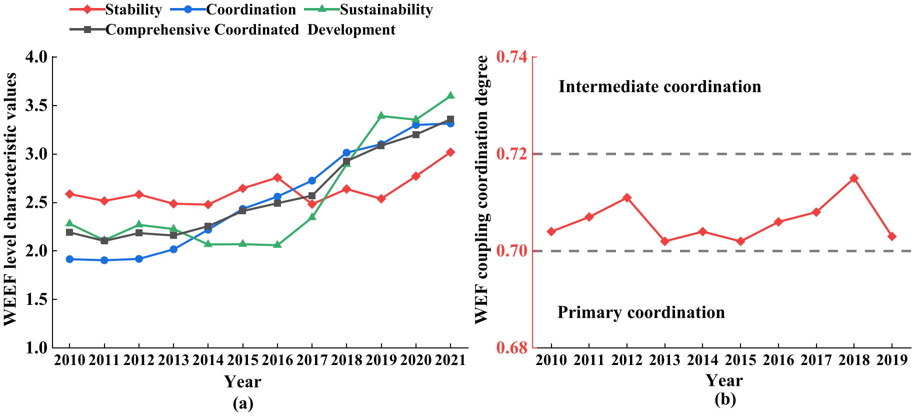


Fig. 11 Comparison of WEEF nexus level characteristic values and WEF nexus coupling coordination degree in Tianjin. **a** Research results of this paper; **b** Control group results (modified by Sun et al., 2022)

conservancy projects, energy development, food production and ecological restoration should be increased. Meanwhile, the two-way flow of socioeconomic resources and natural resources should be encouraged, which could alleviate the contradiction between supply and demand of resources and promote regional coordinated development.

3.3 Analysis of obstacle factors in Tianjin

The obstacle degree of each criterion layer was analyzed through the obstacle degree model, as shown in Fig. 12. According to the calculation results, the obstacle degree of WEEF nexus coordinated development in Tianjin was different among the three criterion layers. The obstacle degree of stability was relatively minor and showed a fluctuating trend. The obstacle degree of coordination decreased significantly from 46.03 to 20.67%, indicating that the efficiency of resource allocation and utilization between the two subsystems had been improved. The obstacle degree of sustainability decreased slightly in 2019, but showed an overall upward trend and reached 59.10% in 2021.The main obstacle factors of the indicator layer changed significantly in the time series, as shown in Fig. 13. From 2010 to 2014, the coordinated development of WEEF nexus in Tianjin was mainly constrained by food, energy–ecology and food–ecology subsystems. The top obstacle factors were food self-sufficiency rate (F_{S3}), proportion of clean energy power generation (EG_{C1}) and fertilizer application amount per unit cultivated area (FG_{C1}). Meanwhile, annual rainfall (WF_{C3}) and average water consumption for energy production (WE_{C1}) reflected the constraints of water-food and water-energy subsystems to a certain extent. From 2015 to 2017, the coordinated development of WEEF nexus in Tianjin was mainly constrained by natural and social subsystems. The top obstacle factors were ecological environment index (Z_{T1}) and population density (H_{T1}). Although the obstacle degree of food self-sufficiency rate (F_{S3}) and annual rainfall (WF_{C3}) gradually decreased, they still occupied an important position. The obstacle degree of average water consumption for energy production (WE_{C1}) increased year by year. From 2018 to 2021, the coordinated development of WEEF nexus in Tianjin was mainly constrained by energy, water-energy and water-food subsystems. The top obstacle factors were

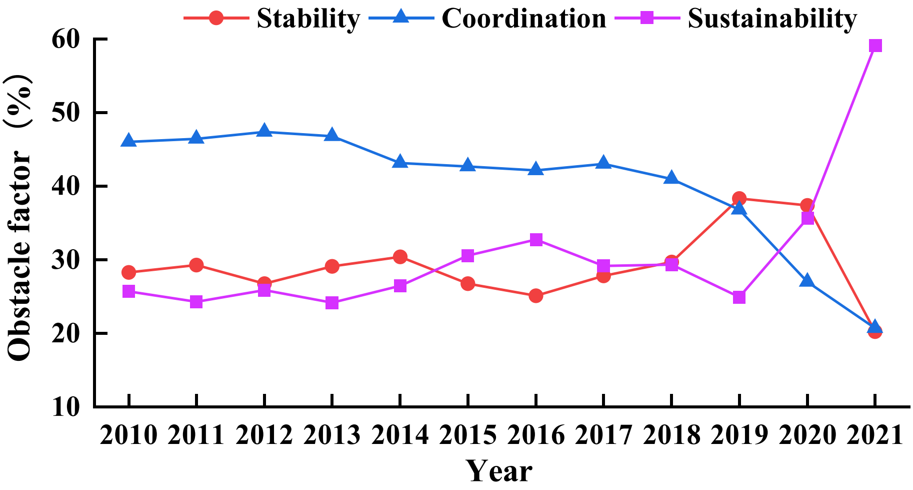


Fig. 12 The obstacle degree of criterion layer of WEEF nexus

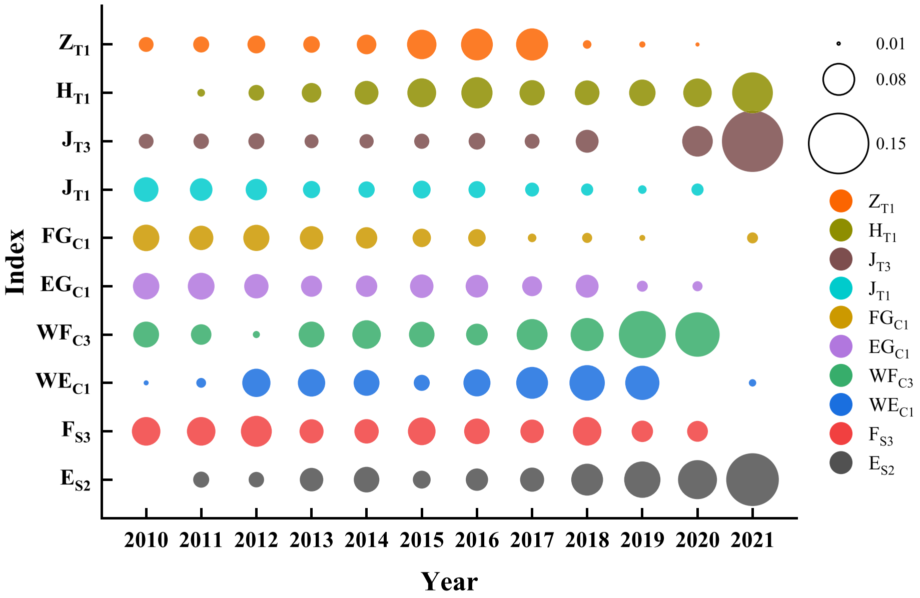


Fig. 13 Analysis of main obstacle factors of WEEF nexus from 2010 to 2021

energy self-sufficiency rate (E_{S2}), average water consumption for energy production (WE_{C1}) and annual rainfall (WF_{C3}). The obstacle degree of proportion of environmental protection expenditure to GDP (J_{T3}) increased significantly in 2021. In summary, the coordination between the two subsystems of water, ecology, energy and food is still a prominent obstacle factor in Tianjin and the ecological problems cannot be ignored.

4 Conclusions

In this paper, the mechanism and concept of coordinated development of water–ecology–energy–food (WEEF) nexus were clarified based on the synergy theory. A comprehensive evaluation indicator system for the coordinated development of WEEF nexus was constructed from stability (S), coordination (C) and sustainability (T). The coordinated development of WEEF nexus in Tianjin from 2010 to 2021 was evaluated by using variable fuzzy method, and the main obstacle factors were calculated. The empirical results were as follows: from 2010 to 2021, the comprehensive coordinated development level of the WEEF nexus showed an upward trend, with a slow at first and then fast growth rate. The evaluation levels of stability and coordination increased from low level and lower level to middle level, with a relatively slow upward trend. The evaluation levels of sustainability increased from low level to high level, with the most obvious improvement trend. The obstacle factors were mainly distributed in the coordination criterion layer, accounting for 40.25%, while the stability and sustainability were basically equal, accounting for 29.09 and 30.66%. Obstacle factors such as food self-sufficiency rate (F_{S3}), average water consumption for energy production (WE_{C1}), annual rainfall (WF_{C3}) and ecological environment index (Z_{T1}) constrained the coordinated development of WEEF nexus. In the future, Tianjin should enhance the ability of resources security and strengthen the comprehensive and efficient management of water, energy, food and ecology.

Although the above results were achieved, the water, ecology, energy and food systems are complex “nexus.” Moreover, the related research was incomplete and there were some flaws: some data were not easily accessible, and the indicator selection was not comprehensive when evaluating the comprehensive coordinated development level of the WEEF nexus in Tianjin. At the same time, the evaluation level of WEEF nexus coordinated development was divided into 5 levels from lower to higher. Due to the narrow reference range values, the division of system evaluation levels needed to be improved, which may lead to the lack of accuracy of the evaluation results of coordinated development levels. In future studies, efforts will be made to overcome the flaws and obtain more realistic research outcomes.

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Data availability All data are openly available and sources of data are dully cited in the data section.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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