Environmental Science and Pollution Research (2023) 30:34978–34995
https://doi.org/10.1007/s11356-022-24659-1

RESEARCH ARTICLE

Coupling coordination and spatiotemporal dynamic evolution of the water-energy-food-land (WEFL) nexus in the Yangtze River Economic Belt, China

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Received: 20 July 2022 / Accepted: 5 December 2022 / Published online: 16 December 2022

Abstract
The interrelationship between regional water, energy, food, and land systems is extremely complex. Hence, accurately assessing the coupling coordination relationship and identifying the influential factors of the water-energy-food-land nexus (WEFL nexus) are of utmost importance. This study proposes a novel analytical framework and evaluation index system for exploring interactions across the WEFL nexus. The comprehensive benefit evaluation index (CBEI), coupling coordination degree (CCD) model, and obstacle factor diagnosis model are integrated to assess and analyze the coupling coordination relationship and spatiotemporal dynamic evolution of the WEFL nexus in the Yangtze River Economic Belt (YREB) from 2006 to 2020. The results indicated that (1) the CBEI and CCD generally increased from 0.23 to 0.79 and 0.45 to 0.88, respectively, revealing the upward trend of the coordination development levels of the WEFL nexus in the YREB. (2) The lower reaches achieved a relatively higher coordination development degree than the upper and middle reaches of the YREB. (3) The findings of obstacle factors reveal that agricultural non-point source pollution control, waterlogging disaster prevention, industrial solid waste efficient treatment, and urban water-saving are the essential fields that need to be improved in YREB's future development. This study helps to understand the complex interrelation of the WEFL nexus at different spatial–temporal scales and provides a novel framework that can be used as an evaluation system and policy insights for a region's integrated resources, environmental management, and green sustainable development.

Keywords Water-energy-food-land nexus · Coupling coordination relationship · Spatiotemporal dynamic evolution · Obstacle factors · Yangtze River Economic Belt · Sustainable development

Abbreviations

CBEI	Comprehensive benefit evaluation index
CCDM	Coupling coordination degree model
OFDM	Obstacle factor diagnosis model
WEFL	Water-energy-food-land
YREB	Yangtze River Economic Belt
AFP	Application of fertilizer and pesticide
CVM	Coefficient of variation method
EWM	Entropy weight method
GDP	Gross domestic product
NPS	Non-point source
PSR	Pressure-state-response
NA	Natural-artificial
OF	Obstacle factor
OD	Obstacle degree
NO	Number of occurrences

Responsible Editor: Philippe Garrigues

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Introduction

The contradiction between uncertain supply and relentless demand for energy, water, and food is becoming severe due to extreme climate events and aggravated human activities, which threaten regional resources security and green sustainable development (AghaKouchak et al. 2020; Bazilian et al. 2011). It is predicted that the global human consumption of food, water resources, and energy will increase by 35%, 40%, and 50% by 2030, respectively (USNIC 2012). Meanwhile, due to climate change, freshwater availability is predicted to drop by 50% (Gupta et al. 2020). In this sense, research on the interaction relationship between water resources, energy, and food systems has become essential in regional sustainable development (Pereira 2017; Cai et al. 2018).

The water-energy-food nexus (WEF nexus) was first proposed at the Bonn 2011 Conference (Hoff 2011). WEF nexus provides a novel idea to deal with resource scarcity, in which through cross-sectoral management and cooperation, the security of water, energy, and food, as well as the improvement of the production and utilization efficiency of the three resources (i.e., water-energy-food), is ensured in several fields such as social, economic, environmental, and health. There are some differences in understanding the basic concept of the WEF nexus. Some scholars interpret the nexus system's interactions among different subsystems (or sectors). They focus on the close and complicated relationship between water, energy, and food based on one foundation of taking any of the three resources as the core of the WEF nexus (Lawford et al. 2013; Cai et al. 2018; Mercure et al. 2019). Others preferred to define the WEF nexus from a methodological perspective and employed research on the assessment tools, analysis framework, and management approach (Scott et al. 2014; Biggs et al. 2015; Guerra et al. 2021).

Scholars have employed theoretical research and empirical analysis on the WEF nexus at different scales; discriminated the conceptual framework of the nexus from multiple perspectives; and developed various methods for quantitative evaluation, simulation prediction, and tool integration. Daher and Mohtar (2015), An et al. (2021) , Chen and Xu (2021), Ma et al. (2021) , and Sun et al. (2021) combine multiple methods, such as the WEF nexus Tool 2.0, Bayesian network, RF-Haken model, super-efficiency network DEA model, and bi-level decentralized chance-constrained programming (BDCP), to reveal the internal correlation mechanism, explore the synergy evolution, and assess the resources security of the WEF nexus. Since the external conditions also impact the internal production and consumption of resources in the WEF nexus, some researchers investigated external impacts and simulated the WEF nexus relationship's dynamic variations and response strategies under different natural, socio-economic, and ecological environmental conditions, such as policy dynamics, deforestation, hydroelectricity, and climate change (Lazaro et al. 2021; Molajou et al. 2021; Mercure et al. 2019; Susnik et al. 2022; Shi et al. 2020).

Considering land is essential for grain planting, water supply (e.g., reservoirs, underground water storage), and energy construction and production (e.g., biofuels or fossil fuel), many existing studies incorporated land as one of the core elements into the WEF nexus to form the water-energy-food-land nexus (WEFL nexus) (Ringler et al. 2013; Sargentis et al. 2022; Lazaro et al. 2021; You et al. 2021; Laspidou et al. 2019). van den Heuvel et al. (2020) and Susnik et al. (2022) integrated the land and climate into the WEF nexus to explore the impacts of policies on the nexus system and the anthropogenic pressures within the nexus from the perspective of ecosystem services. You et al. (2021) and Abdali et al. (2021) proposed the optimization model for the bioethanol and sugarcane-to-bioenergy supply chain network under the WEFL nexus framework.

Although valuable improvements in theory and application for exploring the WEF nexus have been made, it could state that the previous studies on the interaction relationship of the WEF nexus still have several gaps. Considering land is vital for the WEF (Ringler et al. 2013; Laspidou et al. 2019), the coupling coordination relationship and spatiotemporal dynamic evolution of the regional WEFL nexus have not been explored. Furthermore, previous studies less established a comprehensive analytical framework and evaluation index system for exploring the complex interrelation of the WEFL nexus (You et al. 2021; Sargentis et al. 2022). However, such a framework and evaluation index system is essential in understanding the interactions of the WEFL nexus and quantitatively assessing the regional sustainable development levels. Finally, concerning the fact that WEFL nexus research mainly focused on specific regions (van den Heuvel et al. 2020; Susnik et al. 2022; Abdali et al. 2021), the spatiotemporal differences and evolution characteristics of the holistic and internal WEFL nexus in the Yangtze River Economic Belt (YREB) have not been presented. Since the YREB occupies a dominant position in China's development strategy (Jing et al. 2022), conducting more extensive WEFL nexus research on this region is essential in promoting the effective coordinated development of water, energy, food, and land; ensuring the YREB's resource supply security; and understanding the internal coupling mechanism of WEFL system.

In order to narrow these research gaps, the primary objectives of this study could be listed as follows: (1) Considering the natural and socio-economic attributes of the water, energy, food, and land resources, this study proposed a novel analytical framework and evaluation index system to explore the WEFL nexus's interaction relationship. (2) The comprehensive benefit evaluation index (CBEI) and coupling coordination degree model (CCDM) are integrated to evaluate and analyze the coupling coordination relationship and spatiotemporal dynamic of the WEFL nexus in the YREB. (3) The main obstacle factors (OFs) affecting the WEFL nexus's coupling coordination relationship in the YREB are identified and analyzed, and policy recommendations for future development are proposed. Hence, the significance of this study is to expand the theoretical basis and applied scope of sustainable development research from the perspective of the WEFL nexus and provide valuable guidelines for integrated resources and environmental management among the YREB's high-quality development, which helps to understand the complex interrelation of the WEFL nexus at different spatial–temporal scales.

Methodology and materials

Analytical frameworks and evaluation index system for the WEFL nexus

The PSR (pressure-state-response) framework is a conceptual approach to analyzing and solving problems related to resources, environment, and sustainability (Wang et al. 2021b). The mechanism of the PSR framework is to establish cause-effect relations between anthropogenic activities and their environmental and socio-economic consequence (Mosaffaie et al. 2021). The previous studies employing the PSR framework hold that "pressure" and "response" are the exclusive attributes of the human socio-economic system, while the "state" is specifically used to characterize the natural ecosystem (Hazbavi et al. 2020; Liu et al. 2021; Chen and Xu 2021). As it is illustrated in Fig. 1, this study proposes a PSR framework based on natural-artificial (PSR-NA) to explore the internal mechanism of the WEFL nexus and its mutual effects with the external socio-economic and natural system. The core idea of the PSR-NA framework is that pressure, state, and response are not unique characteristics of the human socio-economic system or natural ecosystem. The three interlinked characteristics interact and influence each other and are reflected in the four subsystems within the whole system. Specifically, pressure represents the effects of socio-economic systems and the natural ecosystem on the regional WEFL nexus. State refers to regional socio-economic development and ecological environment conditions during a specific period after influencing each other. Response expresses how human beings take measures (e.g., environmental protection, investment, conservation) to reduce (or enhance) the negative (or positive) impacts of human activities on resources and ecological environments. It should be mentioned that the natural ecosystem also responds to human measures (e.g., the service function of self-purification or assimilating waste), and the response attributes (support or restraint) depend on the extent of human beings' ecological pressure and improved measures.

The WEFL nexus is an open system with complexity, uncertainty, and hierarchy. There are complex relations of interdependence and interaction among many elements constituting the nexus system, which promote and restrict each other, having positive and negative effects. The WEFL nexus can be divided into internal relevance and external relevance. The internal relevance refers to the relationship between core resource elements within the WEFL nexus, such as the water consumption and land occupation in the whole process of the production-processing-transportation-sale of energy and food; grain supplies biomass energy for supporting the production and living activities and survival of human beings; the extraction, purification, consumption, delivery, and drainage of water resources need the energy guarantee; substantial water, energy, and land inputs are required for irrigation systems (e.g., groundwater pumping) and food production. External relevance correlates socio-economy, natural ecosystem, or climate change with the WEFL nexus, such as changes in water availability and food-energy production arising from government policies and global economic conditions (Pahl-Wostl et al. 2012); variations in temperature, hydrological regime, and atmospheric carbon dioxide concentrations may result in the fluctuation of agricultural production, energy consumption, and the terrestrial water cycle in a basin (Lawford et al. 2013).

Based on the PSR-NA framework and the actual situation of the YREB, this study developed a novel analytical framework to explore the coupling coordination and interaction relationship of the WEFL nexus (Fig. 2). We take the

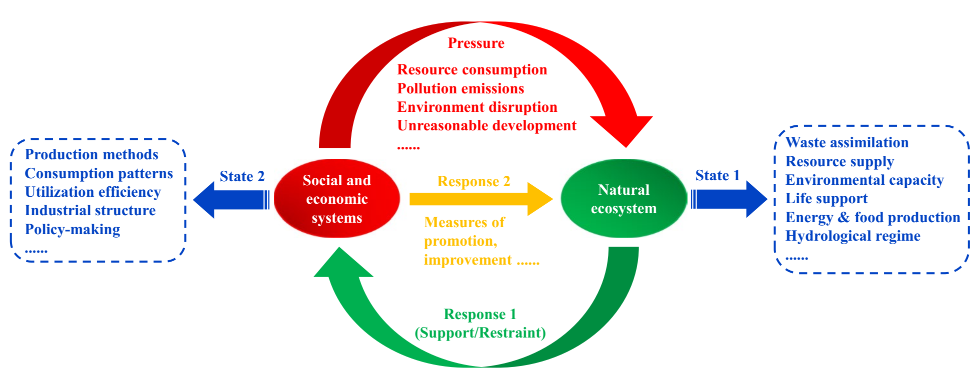

Fig. 1 Conceptual framework of the PSR-NA for exploring interactions across the WEFL nexus

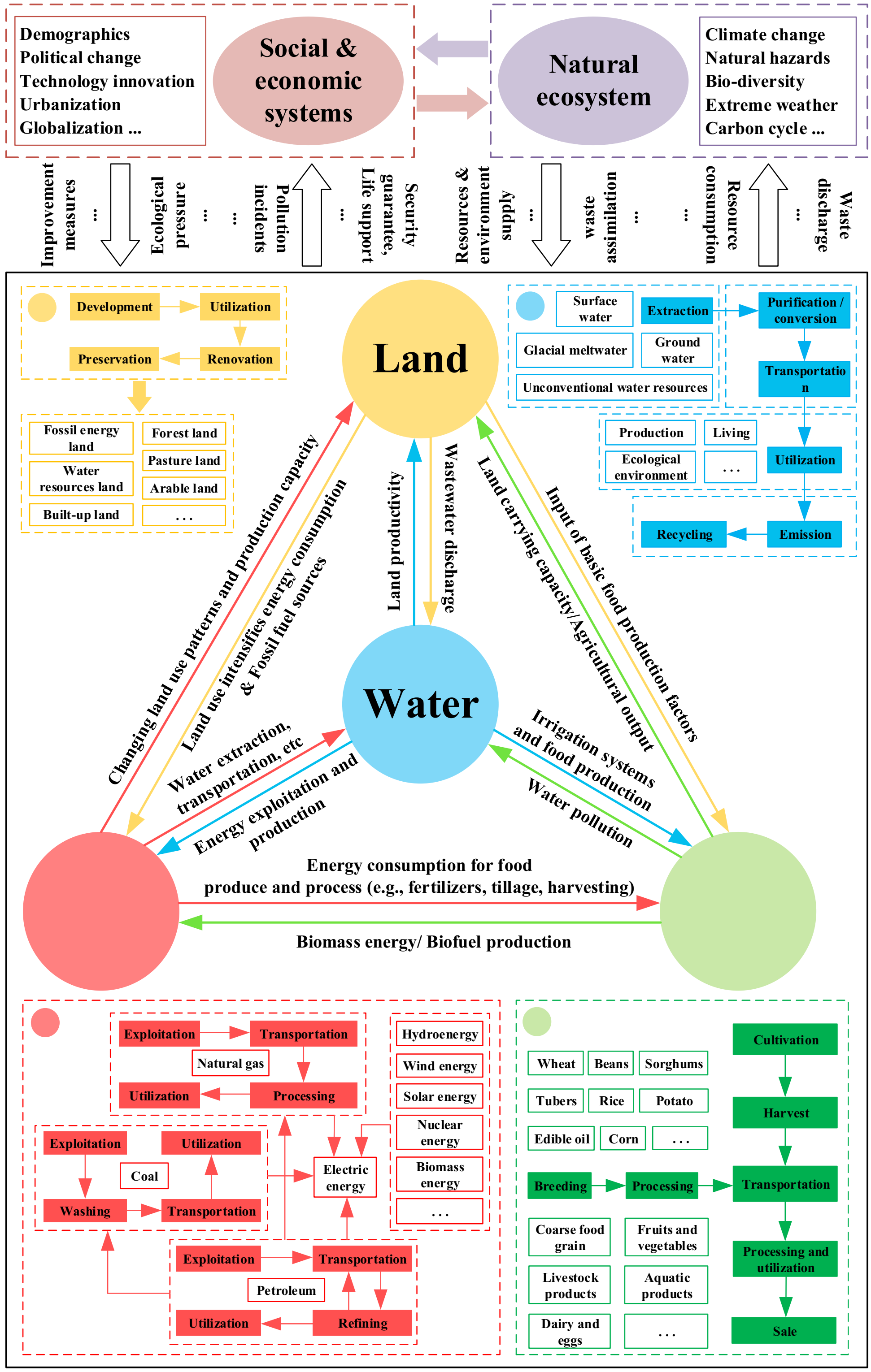

Fig. 2 The analytical framework of the coupling coordination and interactions of the WEFL nexus

water, food, energy, and land resources as the core internal elements, appropriately considering the influence and interaction of comprehensive factors such as social, economic, environmental, and ecological factors in the internal and external correlation. In this study, we held that the coupling coordination of the WEFL nexus means realizing green sustainable development in a region.

Based on the analysis of the PSR-NA and analytical frameworks of the interactions across the WEFL nexus, which is shown in Figs. 1 and 2, the actual situation of the study area, and previous studies (Sun et al. 2021; Kong et al. 2022; Xing et al. 2019; Li et al. 2021), the evaluation index system composed four subsystems: water subsystem (W), energy subsystem (E), food subsystem (F), land subsystem (L); and there were 55 evaluation indexes. As it is tabulated in Table 1, pressure, state, and response are present as the sub-criteria layer by following the principles of scientificity, availability, integrity, and dynamics. In addition, the purpose of selecting indicators for each subsystem is to effectively reflect the original characteristics of water, energy, food, and land and the interaction between the four subsystems. For example, the C1–C10 in Table 1 are the indicators reflecting water resource consumption or water environment pollution, representing human activities' pressure on natural ecosystems. Therefore, C1–C10 belongs to the water subsystem's indicators of the pressure sub-criteria layer. The evaluation index system aims to provide a more comprehensive and accurate description of the WEFL nexus's coupling coordination development degree.

Weight determination method

Due to the different dimensions and effects of the original data, this study takes dimensionless processing for original data to make them consistent and comparable. Since the logarithm of the standardized index value is required to calculate the weight, referring to previous studies (Li et al. 2021; Liu et al. 2022a; Kong et al. 2022), the index standardization of non-zero transformation is adopted to keep the range of variation in the standardized data between 0.01 and 1.

If x_{ij} is a positive indicator:

$$X_{ij} = \frac{x_{ij} - \min\left\{x_{1j}, x_{2j}, \cdots, x_{ij}\right\}}{\max\left\{x_{1j}, x_{2j}, \cdots, x_{ij}\right\} - \min\left\{x_{1j}, x_{2j}, \cdots, x_{ij}\right\}} \times 0.99 + 0.01 \tag{1}$$

If x_{ij} is a negative indicator:

$$X_{ij} = \frac{\max\left\{x_{1j}, x_{2j}, \cdots, x_{ij}\right\} - x_{ij}}{\max\left\{x_{1j}, x_{2j}, \cdots, x_{ij}\right\} - \min\left\{x_{1j}, x_{2j}, \cdots, x_{ij}\right\}} \times 0.99 + 0.01 \tag{2}$$

where X_{ij}, x_{ij}, $\max\{x_{ij}\}$, and $\min\{x_{ij}\}$ are the standardized value, original value, maximum value, and minimum value of the j_{th} evaluation index ($j = 1, 2, \ldots, n$) in the year i ($i = 1, 2, \ldots, m$), respectively.

The weights of each index in Table 1 are determined by the entropy weight method (EWM) and coefficient of variation method (CVM). The EWM can judge the index weight by calculating the dispersion degree of the index, objectively reflecting the amount of information in the data, and avoiding the error caused by subjective factors in the weight calculation (Han et al. 2020; Xing et al. 2019). The calculation steps to get the index weight by EWM are as Formulas (3)—(6) (Kong et al. 2022; Li et al. 2021; Liu et al. 2022b).

Step 1: Calculating the proportion of the sample index weight:

$$p_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}} \tag{3}$$

where p_{ij} $(0 \leq p_{ij} \leq 1)$ is the proportion of the j_{th} evaluation index in year i.

Step 2: The information entropy of the evaluation index is calculated as follows:

$$e_j = -\frac{1}{\ln\ m} \sum_{i=1}^{m} \left[p_{ij} \times \left(\ln p_{ij}\right)\right] \tag{4}$$

where e_j $(0 \leq e_j \leq 1)$ is the information entropy of the j_{th} evaluation index and $1/\ln m$ $(1/\ln m > 0)$ is the coefficient of the information entropy.

Step 3: The weight calculated by the EWM is as follows:

$$p_{j=} \frac{1 - e_j}{\sum_{j=1}^{n} \left(1 - e_j\right)} \tag{5}$$

where ρ_j $(\sum_{j=1}^{n} \rho_j = 1,\ 0 \leq \rho_j \leq 1)$ is the weight of the j_{th} evaluation index calculated by the EWM.

The CVM is another objective weight determination method, which directly uses the information on the importance of the original data contained in each system to calculate the index's weight. It has the advantages of simple operation, convenient calculation, objectivity, and impartiality (Wu et al. 2020) and is calculated as follows:

$$v_j = \frac{\sigma_j}{\overline{X}_j} \tag{6}$$

$$\theta_j = \frac{v_j}{\sum_{j=1}^{n} v_j} \tag{7}$$

where v_j is the coefficient of variation of the j_{th} evaluation index, σ_j ($\sigma_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(X_{ij} - \overline{X}_j\right)^2}$) is the standard deviation, and $\overline{X}_j$ ($\overline{X}_j = \frac{1}{m}\sum_{i=1}^{m} X_{ij}$) is the mean standardized value of the j_{th} evaluation index. θ_j ($\sum_{j=1}^{n} \theta_j = 1, 0 \leq \theta_j \leq 1$) represents the weight of the j_{th} evaluation index calculated by the CVM.

The weight measurement method of each indicator within the evaluation system usually employs a single weight determination method (Liu et al. 2022a; Li et al. 2012), while it is

Table 1 Evaluation index system for coupling coordination development of the WEFL nexus

Criterion layer	Sub-criteria layer	Evaluation index	Index interpretation and source (unit)
Water subsystem (W)	Pressure	C1: Per capita water consumption *	Total water use/total population (m^3/cap)
		C2: Comprehensive water consumption rate *	Statistical data (%)
		C3: Proportion of productive water consumption *	Productive water use/total water use (%)
		C4: Proportion of domestic water consumption *	Domestic water use/total water use (%)
		C5: Water consumption per 10,000 CNY of GDP *	Total water use/GDP (m^3/10,000 CNY)
		C6: Farmland irrigation water consumption *	Statistical data (m^3/ha)
		C7: Water consumption per 10,000 CNY of value-added by industry *	Statistical data (m^3/10,000 CNY)
		C8: Wastewater discharge *	Statistical data (t)
		C9: Chemical oxygen demand (COD) discharge in wastewater *	Statistical data (t)
		C10: Ammonia nitrogen emission (NH_3^-N) discharge in wastewater *	Statistical data (t)
	State	C11: Mean annual precipitation	Statistical data (mm)
		C12: Per capita water resources	Statistical data (m^3/cap)
		C13: Water production modulus	Total water resources/total area (10,000 m^3/km^2)
		C14: Water production coefficient	Total water resources/total precipitation
	Response	C15: Proportion of ecological environment water consumption	Ecological environment water use/total water use (%)
		C16: Treatment rate of urban sewage	Statistical data (%)
		C17: Reuse rate of urban industrial water	Statistical data (%)
		C18: Urban water-saving	Statistical data (10,000 m^3)
		C19: Investment in industrial wastewater treatment	Statistical data (10,000 CNY)
Energy subsystem (E)	Pressure	C20: Per capita energy consumption *	Total energy consumption/total population (tons of SC/cap)
		C21: Proportion of electricity consumption of primary industry *	Primary industry electricity use/total electricity use (%)
		C22: Proportion of electricity consumption of secondary industry *	Secondary industry electricity use/total electricity use (%)
		C23: Proportion of electricity consumption of third industry	Third industry electricity use/total electricity use (%)
		C24: Industrial SO_2 emissions *	Statistical data (t)
	State	C25: Elasticity ratio of energy consumption *	Annual average growth rate of energy consumption/annual average growth rate of GDP
		C26: Elasticity ratio of electricity consumption *	Annual average growth rate of electricity consumption/annual average growth rate of GDP
		C27: Primary energy production	Statistical data (10,000 tons of SC)
	Response	C28: Energy moving in from other provinces *	Statistical data (10,000 tons of SC)
		C29: Recovery of energy	Statistical data (10 billion kJ)
		C30: Ratio of industrial solid wastes treated and utilized	Statistical data (%)
		C31: Investment in industrial gas waste treatment	Statistical data (10,000 CNY)
		C32: Investment in industrial solid waste treatment	Statistical data (10,000 CNY)

Table 1 (continued)

Criterion layer	Sub-criteria layer	Evaluation index	Index interpretation and source (unit)
Food subsystem (F)	Pressure	C33: Disaster area of crops *	Statistical data (ha)
		C34: Intensity of fertilizer application *	Application amount of agricultural chemical fertilizer/sowing area of main crops (t/ha)
		C35: Intensity of pesticide use *	Pesticide usage/sowing area of main crops (t/ha)
	State	C36: Total agricultural output value	Statistical data (billion CNY)
		C37: Per capita grain yield	Food production/total population (kg/cap)
		C38: Total output of livestock meat products	Statistical data (10,000 t)
		C39: Total output of aquatic products	Statistical data (10,000 t)
		C40: Per capita disposable income of residents	Statistical data (CNY)
	Response	C41: Total power of agricultural machinery	Statistical data (10,000 KW)
		C42: Effective irrigation area	Statistical data (ha)
		C43: Waterlogging control area	Statistical data (ha)
Land subsystem (L)	Pressure	C44: Urban population density *	Urban population/urban area (cap/ha)
		C45: Urban wastewater discharge per unit area *	Urban wastewater discharge/urban area (t/ha)
		C46: Proportion of urban construction land *	Urban construction land/urban area (%)
		C47: Urbanization rate	Urban population/total population (%)
	State	C48: GDP per unit area	GDP/Total area (10,000 CNY/ha)
		C49: Forest coverage	Statistical data (%)
		C50: Urban green space area	Statistical data (ha)
		C51: Urban park area	Statistical data (ha)
		C52: Population carrying capacity of land resources	Land productivity/per capita grain consumption standard (person)
	Response	C53: Total area of artificial afforestation	Statistical data (ha)
		C54: Water and soil erosion control area	Statistical data (ha)
		C55: Greening coverage rate of built-up area	Statistical data (%)

(1) The evaluation indexes plus the "*" represent the negative indicator; otherwise, they are positive. The larger the positive (negative) indicators' value, the better (worse) the WEFL nexus's development. (2) The abbreviation of SC represents the standard coal

challenging to measure the weight accurately. In order to avoid the limitation of the single weighting method and increase the calculation accuracy of index weight, this study integrates the EWM and the CVM to determine the final weight of the evaluation indexes as follows:

$$\omega_j = \frac{\left(\rho_{j \cdot \theta_j}\right)^{1/2}}{\sum_{j=1}^{n}\left(\rho_{j \cdot \theta_j}\right)^{1/2}} \quad (8)$$

where ω_j ($\sum_{j=1}^{n}\omega_j = 1, \omega_j > 0$) is the final weight of the j_{th} index.

Coupling coordination evaluation model

Comprehensive benefit evaluation index model

Based on the standardized value and the corresponding weight for each indicator, the comprehensive development level of the WEFL nexus can evaluate by the CBEI model as follows:

$$CBEI = \sum_{j=1}^{n} \omega_j X_{ij} \quad (9)$$

$$CBEI_k = \begin{cases} WA(x) = \sum_{a=1}^{19} \omega_a X_{ij\_a} \\ EN(y) = \sum_{b=1}^{13} \omega_b Y_{ij\_b} \\ FO(z) = \sum_{c=1}^{11} \omega_c Z_{ij\_c} \\ LA(p) = \sum_{d=1}^{12} \omega_d P_{ij\_d} \end{cases} \quad (10)$$

where $CBEI_k$ is the CBEI of each subsystem in the WEFL nexus (k = 1, 2, 3, 4), ranging from 0 to 1. Correspondingly, $WA(x)$, $EN(y)$, $FO(z)$, and $LA(p)$ present the comprehensive development level of the subsystem of water, energy, food, and land, respectively.

Coupling coordination degree model

Coupling originates from physics and describes the phenomenon that two or more systems (elements) are interrelated and influence each other through interaction to unite (Li et al. 2012). Based on the sustainable development theory, coupling coordination theory, the CBEI model, and previous studies (Xing et al. 2019), the coupling degree model of the WEFL nexus is presented as follows:

$$C = \frac{\left[WA(x) \cdot EN(y) \cdot FO(z) \cdot LA(p)^{1/4}\right]}{\left[WA(x) + EN(y) + FO(z) + LA(p)\right]/4} \tag{11}$$

where C ($0 \le C \le 1$) indicates the coupling degree of the regional WEFL nexus, and C approaches 0 (or 1), demonstrating that the subsystems in the WEFL nexus tend to disorder (or ordered coupling).

The coupling coordination degree (CCD) is used to measure the overall function of the system and the synergistic development effect between the subsystems (Xing et al. 2019). Based on the literature on coupling coordination (Li et al. 2012; Han et al. 2020) and the coupling degree model, we constructed a coupling CCDM for the WEFL nexus as follows:

$$T = \alpha \cdot WA(x) + \beta \cdot EN(y) + \gamma \cdot FO(z) + \eta \cdot LA(p) \tag{12}$$

$$D = \sqrt{C \times T} \tag{13}$$

where T is the weighted CBEI, and α, β, γ, and η denote subsystems' weight coefficients ($\alpha+\beta+\gamma+\eta=1$), indicating the importance of each subsystem in the WEFL nexus system. As mentioned above, this study considered that water, energy, food, and land are essential resources for maintaining sustainable development of the regional socio-economic system and stable health operation of the natural ecosystem. The four subsystems were equally crucial for the WEFL nexus; thus, $\alpha=\beta=\gamma=\eta=0.25$ was set. D is the coupling coordination degree (CCD) of the regional WEFL nexus, ranging from 0 to 1. According to the relevant studies (Liu et al. 2021) and the actual conditions of the study area, the coupling coordination types of the WEFL system can be divided into three categories and ten subcategories (Table S1).

Obstacle factor diagnosis model

Based on the dynamic evaluation of the coupling coordination level of the WEFL nexus in the study area, the obstacle degree (OD) is introduced to explore and analyze the main OFs that affected the coupling coordination development of the WEFL nexus in the YREB (Ding and Chen 2021; Lv et al. 2022; Kong et al. 2022). The OFDM is as follows:

$$O_{ij} = \frac{R_{ij} \cdot \omega_j}{\sum_{j=1}^{n} R_{ij} \cdot \omega_j} \tag{14}$$

where O_{ij} represents the OD of the j_{th} evaluation index in the i_{th} year, and R_{ij} ($R_{ij} = 1 - X_{ij}$) is the deviation degree of the j_{th} index in the WEFL nexus. The higher the index's OD value, the greater degree of obstruction of the index to the coupling coordination development of the WEFL nexus system.

Study area and data sources

The YREB is the giant inland economic belt of the world and vital grain production and ecological conservation area in China (Fig. 3), which carries more than 40% of China's total population, water resources, and GDP (Jing et al. 2022). The YREB covers 11 municipalities and provinces, which span the upper reaches (Chongqing, Sichuan, Guizhou, and Yunnan), middle reaches (Jiangxi, Hubei, and Hunan), and lower reaches (Shanghai, Jiangsu, Zhejiang, and Anhui). The YREB produces about 1/3 of China's total grain output and occupies 20% of China's land area. Meanwhile, spatial distribution differences significantly differ in the economic development model and strategic resources. For example, Shanghai and Jiangsu are the core area of the YREB with active economic development, a high degree of openness, and significant dependence on water resources. Conversely, the contradiction between the supply and demand of water resources in these two provinces is prominent (Fig. 3). Consequently, with accelerated urbanization and population agglomeration (Ding and Chen 2021), the YREB needs to plan the water, energy, food, and land to promote its provinces' effective coupling and coordinated development to ensure the security of resources, ecology, and environment.

Data on the production, consumption, and pollution discharge of water, energy, and food; precipitation; water-saving; and the land type and utilization were obtained from the Water Resources Bulletins, Climate Bulletins, Ecological Environment Statistical Yearbook, Energy Statistical Yearbook, and Urban and Rural Construction Statistical Yearbook of China and the YREB's provinces (2006–2020). Especially, GDP, the permanent resident population, urbanization rate, and other indicators are obtained from the National Bureau of Statistics of China and Provincial Statistical Yearbooks along with the YREB (2007–2021).

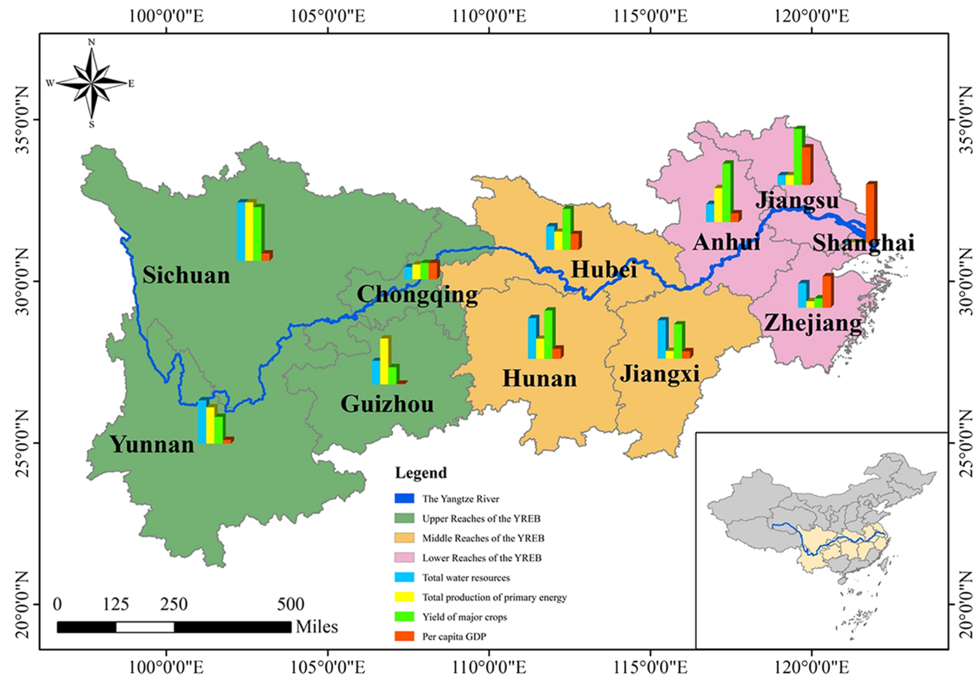

Fig. 3 The geographical location of the YREB in China. In order to reflect and compare the spatial differences of the essential resources' distribution in the YREB, the values of the histogram in Fig. 3 are normalized

Results and analysis

Spatiotemporal variation of comprehensive development levels

The CBEI of the WEFL nexus and subsystems of water ($CBEI_w$), energy ($CBEI_e$), food ($CBEI_f$), and land ($CBEI_l$) in the YREB from 2006 to 2020 are shown in Fig. 4. During the study period, the CBEI of the YREB's WEFL nexus presented a fluctuating upward trend and revealed a "W" shape, while the spatiotemporal differentiation was evident. The time development stage of the YREB could be divided into three stages: the slowly rising stage (2006–2010), fluctuating rising stage (2011–2016), and the rapid development stage (2017–2020).

In terms of the subsystem, the $CBEI_w$ change fluctuates significantly, and the highest and lowest $CBEI_w$ values appeared in 2020 (0.7463) and 2011 (0.2688), showing uneven distribution in other years (Table S2). It should be renowned that (1) from 2010 to 2011, the $CBEI_w$ reduced sharply, while the $CBEI_e$, $CBEI_f$, and $CBEI_l$ increased relatively steadily, ensuring that the CBEI of the WEFL nexus maintained a slight decrease trend. Except for the extreme weather events in the Yangtze River basin in 2011 (Wang et al. 2020a), the wastewater discharge and the COD and NH_3^-N emissions in wastewater are 1.1, 1.8, and 2.4 times that of 2010, respectively. (2) The development trends of the $CBEI_f$ and $CBEI_l$ were relatively stable, while the $CBEI_w$ and $CBEI_e$ showed similar sudden increasing in 2016. Compared with 2015, the effects of water-saving and pollution control and treatment of the YREB in 2016 were significant. The water consumption per 10,000 CNY of GDP decreased by 9.71%, and the urban water-saving was 2.3 times that of 2015. Furthermore, the COD and NH_3-N in wastewater and industrial SO_2 emissions decreased by 63.03%, 73.27%, and 48.4%, respectively. Conversely, investments in industrial wastewater and solid waste increased by 12.73% and 11.34%. These measures systematically solved various pollution-related problems to a certain extent and improved the comprehensive development levels of the water and energy subsystems in the YREB.

The inhomogeneity of spatiotemporal distribution exists in the CBEI of the YREB's WEFL nexus (Fig. 4). The lower reaches have relatively higher comprehensive benefit development levels. Jiangsu performs a relatively fast development trend, and the CBEI increased from 0.219 to 0.745 during the study period (Table 2). The comprehensive development levels of Hubei and Sichuan in the middle and upper reaches increased relatively rapidly, respectively.

Analysis of the spatiotemporal distribution of coordination development levels

The coupling coordination degree (CCD) values of the WEFL nexus in the YREB from 2006 to 2020 increased from 0.4536 to 0.8831 (Fig. S1). According to Table S1, the coupling coordination development stages of the WEFL nexus in the YREB experienced from the "on the verge of decoupling (V)" to "senior coupling coordination (IX)," which spans three categories of primary stage, intermediate stage, and advanced stage. Combined with Table 3 and Table S1, the coupling coordination relationship of the

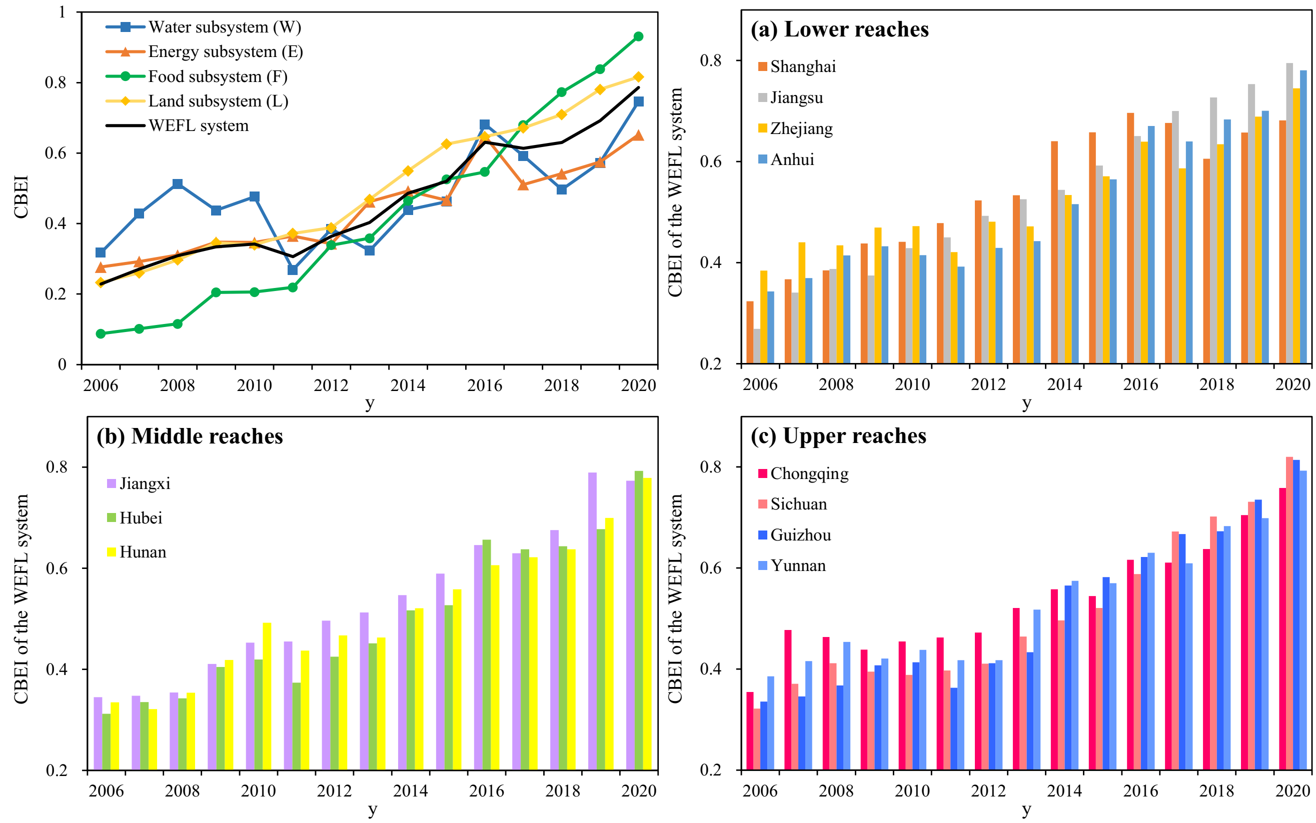

Fig. 4 Temporal and spatial variation of the CBEI of the WEFL nexus and subsystems in the YREB from 2006 to 2020

WEFL nexus in the YREB from 2006 to 2020 can be divided into three periods:

(1) During 2006–2010, the CCD is relatively low, showing a slow upward trend, rising from 0.4536 to 0.5725

Table 2 The comprehensive development levels of the WEFL nexus in the YREB from 2006 to 2020

y	SH	JS	AH	ZJ	JX	HB	HN	CQ	SC	GZ	YN
2006	0.273	0.219	0.334	0.293	0.295	0.262	0.285	0.305	0.272	0.286	0.336
2007	0.317	0.291	0.390	0.320	0.297	0.285	0.271	0.427	0.321	0.296	0.366
2008	0.335	0.338	0.384	0.365	0.304	0.292	0.304	0.413	0.362	0.317	0.404
2009	0.388	0.324	0.419	0.382	0.360	0.354	0.369	0.389	0.345	0.357	0.371
2010	0.391	0.378	0.422	0.365	0.403	0.369	0.442	0.405	0.339	0.363	0.388
2011	0.428	0.400	0.371	0.342	0.405	0.324	0.387	0.413	0.347	0.313	0.368
2012	0.473	0.442	0.431	0.379	0.446	0.375	0.417	0.422	0.361	0.362	0.368
2013	0.483	0.475	0.422	0.392	0.462	0.401	0.413	0.471	0.414	0.383	0.468
2014	0.590	0.494	0.484	0.466	0.497	0.467	0.471	0.508	0.447	0.515	0.525
2015	0.608	0.542	0.521	0.515	0.540	0.477	0.508	0.495	0.471	0.532	0.520
2016	0.646	0.601	0.590	0.620	0.596	0.607	0.556	0.566	0.538	0.572	0.580
2017	0.626	0.650	0.537	0.590	0.580	0.587	0.572	0.561	0.623	0.617	0.560
2018	0.555	0.677	0.584	0.634	0.626	0.594	0.587	0.587	0.652	0.623	0.633
2019	0.607	0.703	0.639	0.651	0.739	0.628	0.650	0.655	0.681	0.685	0.649
2020	0.631	0.745	0.695	0.730	0.723	0.743	0.729	0.709	0.770	0.764	0.743

Abbreviation of provinces and municipalities in the YREB: Shanghai (*SH*), Jiangsu (*JS*), Zhejiang (*ZJ*), Anhui (*AH*), Jiangxi (*JX*), Hubei (*HB*), Hunan (*HN*), Chongqing (*CQ*), Sichuan (*SC*), Guizhou (*GZ*), and Yunnan (*YN*) (increasing rate of 26.21%). The coupling coordination stage has developed from V to basic coupling coordination (VI). The coupling coordination relationship of the WEFL nexus in the YREB is slowly improving. (2) During 2011–2016, the CCD increased from 0.5468 to 0.7929 (increasing rate of 45.01%). The coupling coordination relationship showed a fluctuating trend of rising. Nevertheless, this upward trend followed a decline. From 2010 to 2011, the CCD dropped from 0.5725 to 0.5468. The $CBEI_w$ reduced sharply from 0.4764 to 0.2688, affecting the WEFL nexus's overall coupling. (3) During 2017–2020, the CCD increased from 0.7808 to 0.8831, the coupling coordination relationship developed from intermediate coupling coordination (VIII) to senior coupling coordination (IX), and the CCD reached senior coupling coordination in 2019, which is in the advanced stage of coordinated development.

In terms of the spatial distribution characteristics, it can be seen that the mean CCD values of the WEFL nexus in all provinces were higher than 0.6 during the study period (Table S3). The spatiotemporal pattern of the CCD has mainly been reflected in the lower reaches > upper reaches > middle reaches. The CCD in 2008, 2012, 2016, and 2020 shows an overall upward trend (Fig. 5), which indicates that the coordinated development level of the WEFL nexus in the YREB is constantly improving, but spatial differences are apparent. The highest mean CCD values in 2008, 2012, 2016, and 2020 appear in the upper, lower, lower, and upper reaches, respectively. Jiangsu's increased speed of coupling coordination of the WEFL nexus is faster than other provinces (from 0.422 to 0.861). As one of the most economically developed provinces in China, Jiangsu has been continuously implementing industrial transformation and upgrading with high-quality economic development in recent years, actively adjusting the proportion of various industries in the economic structure and paying attention to the efficient utilization of resources and the protection of the ecological environment (Peng et al. 2022; Liu et al. 2022b). Moreover, Shanghai was the first province to achieve the advanced stage development of senior coupling coordination in 2016 (CCD = 0.8023).

Table 3 Coupling coordination degree of the WEFL nexus in the YREB from 2006 to 2020

y	C	T	CCD	Subcategories
2006	0.8995	0.2287	0.4536	V
2007	0.8865	0.2707	0.4899	V
2008	0.8797	0.3091	0.5214	VI
2009	0.9647	0.3338	0.5674	VI
2010	0.9581	0.3421	0.5725	VI
2011	0.9766	0.3061	0.5468	VI
2012	0.9980	0.3636	0.6024	VII
2013	0.9873	0.4031	0.6309	VII
2014	0.9965	0.4864	0.6962	VII
2015	0.9924	0.5199	0.7183	VIII
2016	0.9966	0.6308	0.7929	VIII
2017	0.9935	0.6136	0.7808	VIII
2018	0.9834	0.6303	0.7873	VIII
2019	0.9851	0.6917	0.8255	IX
2020	0.9916	0.7864	0.8831	IX

Dynamic changes of the obstacle factors and their obstacle degrees

The top ten OFs and OD of the WEFL nexus in the YREB from 2006 to 2020 are calculated in Table 4. The results showed that in terms of the number of occurrences (NO), the intensity of fertilizer application (C34), investment in industrial solid waste treatment (C32), the intensity of pesticide use (C35), waterlogging control area (C43), urban water-saving (C18), and the urban park area (C51) were the significant OFs for the YREB's coordinated development. The ODs were 26.23%, 22.24%, 16.36%, 20.24%, 14.77%, and 14.42%, respectively. Furthermore, urban population density (C44) and the proportion of urban construction land (C46) are relatively less apparent factors, whereas the ODs achieved 30.65% and 26.03%, respectively. It should be mentioned that the proportion of domestic water consumption (C4), COD discharge in wastewater (C9), disaster area of crops (C33), and the total output of livestock meat products (C38) are gradually beginning to appear since 2019, which represents the new OFs for restricting the WEFL nexus's sustainable development. The above indicators had an immense comprehensive impact on the coordination development of the WEFL nexus in the YREB.

Figure 6 shows the spatial distributions of the main OFs affecting the coupling coordination development of the WEFL nexus in the YREB. In terms of the NO, the significant OFs of the three reaches in the YREB are C34, C32, C43, C35, and C18 (Fig. 6a–c). In terms of the OD, C38, C46, C20 (per capita energy consumption), and C44 in the lower reaches of the YREB are relatively high, achieving 33.65%, 25.47%, 24.49%, and 24.07%, respectively (Fig. 6a). The C41 (total power of agricultural machinery, OD = 32.57%), C37 (per capita grain yield, OD = 28.96%), and C33 (OD = 62.8%) are newly appeared OFs in 2020 (Table S4.1–4.4). The C38 (OD = 33.24%), C46 (OD = 32.4%), and C44 (OD = 28.41%) are the main OFs in

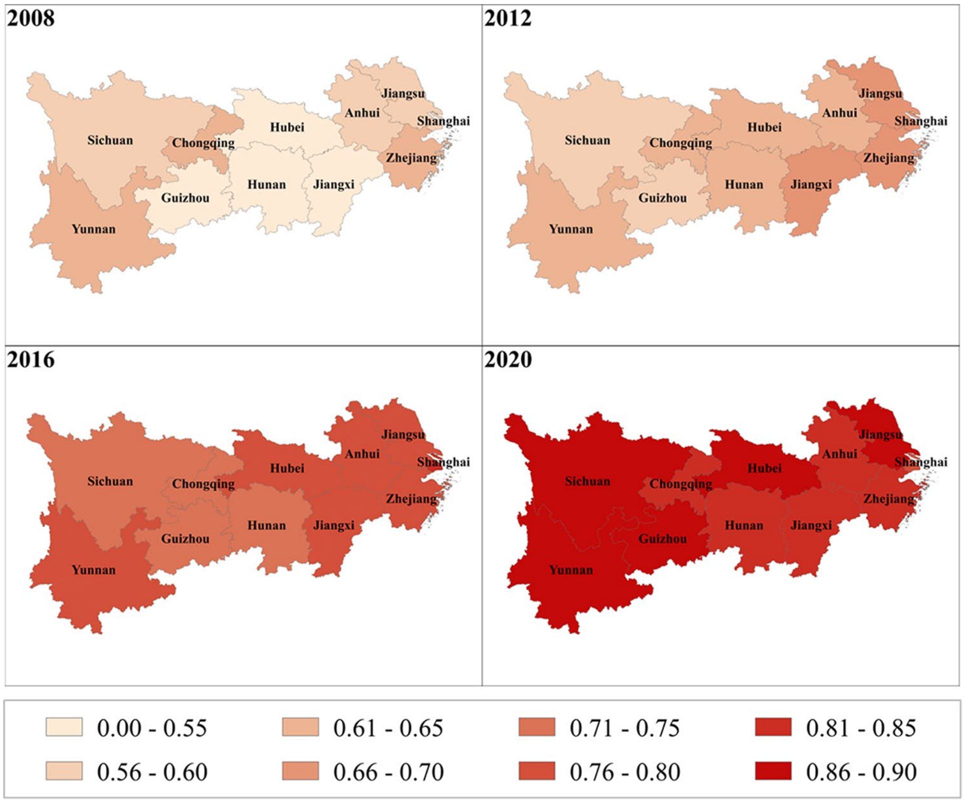

Fig. 5 Spatial patterns of CCD for the WEFL nexus of the YREB in 2008, 2012, 2016, and 2020. The darker the color, the higher the coupling coordination development level of the WEFL nexus

the middle reaches of the YREB (Fig. 6b; Table S4.5–4.7). The C38 (OD = 41.01%), C44 (OD = 30.06%), and C46 (OD = 29.17%) are the main OFs in the upper reaches of the YREB (Fig. 6c; Table S4.8–4.11). The C37 (OD = 45.16%) also negatively impacts the WEFL nexus's development in the upper reaches. Furthermore, the C33, C37, C38, C41, C44, and C46 are the common OFs of the YREB, which mainly related to the food and land subsystems.

Discussions

Effects of the comprehensive development levels in the YREB

The $CBEI_w$ showed a fluctuating trend during the study period (Fig. 4), which is mainly due to the influences on the YREB's water subsystem development, such as the

Table 4 The main OFs and ODs in the YREB from 2006 to 2020.

y	1 th		2 th		3 th		4 th		5 th		6 th		7 th		8 th		9 th		10 th	
	OF	OD (%)	OF	OD (%)	OF	OD (%)	OF	OD (%)	OF	OD (%)	OF	OD (%)	OF	OD (%)	OF	OD (%)	OF	OD (%)	OF	OD (%)
2006	C43	17.71	C32	16.16	C51	14.49	C29	14.41	C34	14.08	C54	13.23	C15	12.98	C22	12.73	C23	12.54	C18	12.43
2007	C32	18.23	C43	17.79	C34	15.38	C51	14.58	C29	14.50	C15	14.38	C22	13.56	C54	13.21	C18	13.20	C35	12.58
2008	C43	17.96	C34	17.20	C15	16.44	C32	16.21	C51	14.64	C29	14.58	C35	13.95	C54	13.35	C22	12.21	C3	12.15
2009	C43	19.32	C34	18.15	C32	16.01	C51	15.78	C29	15.00	C35	14.38	C15	13.85	C54	13.48	C23	12.97	C31	12.18
2010	C32	20.02	C34	19.34	C43	19.11	C18	17.76	C35	15.20	C51	15.02	C29	14.17	C15	13.81	C31	13.47	C54	12.66
2011	C34	21.55	C43	19.72	C32	14.44	C31	14.40	C35	14.27	C29	14.23	C51	13.65	C22	13.49	C18	13.08	C54	12.60
2012	C34	25.59	C43	22.82	C32	20.94	C35	17.00	C18	15.80	C15	13.90	C20	12.89	C51	12.78	C45	12.77	C29	12.47
2013	C34	25.98	C32	25.69	C43	22.85	C35	15.84	C18	13.99	C51	13.75	C20	13.33	C22	13.20	C45	12.15	C23	11.52
2014	C34	31.32	C32	25.54	C43	24.54	C35	17.85	C18	16.08	C20	15.15	C51	14.65	C45	14.54	C22	13.06	C46	12.90
2015	C34	33.12	C32	26.70	C43	25.66	C35	18.55	C18	17.91	C45	17.69	C46	15.80	C51	14.85	C8	14.12	C20	13.18
2016	C34	35.50	C8	23.78	C43	23.46	C20	21.63	C15	18.87	C46	18.08	C35	17.47	C44	15.76	C45	15.47	C24	14.80
2017	C34	42.83	C44	26.85	C46	22.55	C35	20.25	C32	20.18	C20	16.65	C8	15.43	C15	14.17	C24	12.04	C43	11.92
2018	C34	40.60	C32	30.31	C44	28.97	C46	28.32	C35	20.98	C20	18.84	C8	13.83	C24	13.55	C18	13.50	C45	12.56
2019	C46	36.45	C32	31.88	C44	31.48	C34	26.61	C38	23.59	C20	22.22	C8	15.49	C24	15.08	C35	14.42	C18	13.93
2020	C38	58.43	C44	50.19	C46	48.14	C32	29.08	C20	28.04	C24	19.85	C8	19.52	C9	18.74	C4	18.32	C33	18.02

The color from red to blue in the cell represents that the OD is decreasing. The darker the red (blue) color, the higher (lower) degree of the OF hinders the coupling coordination development of the WEFL nexus in the YREB

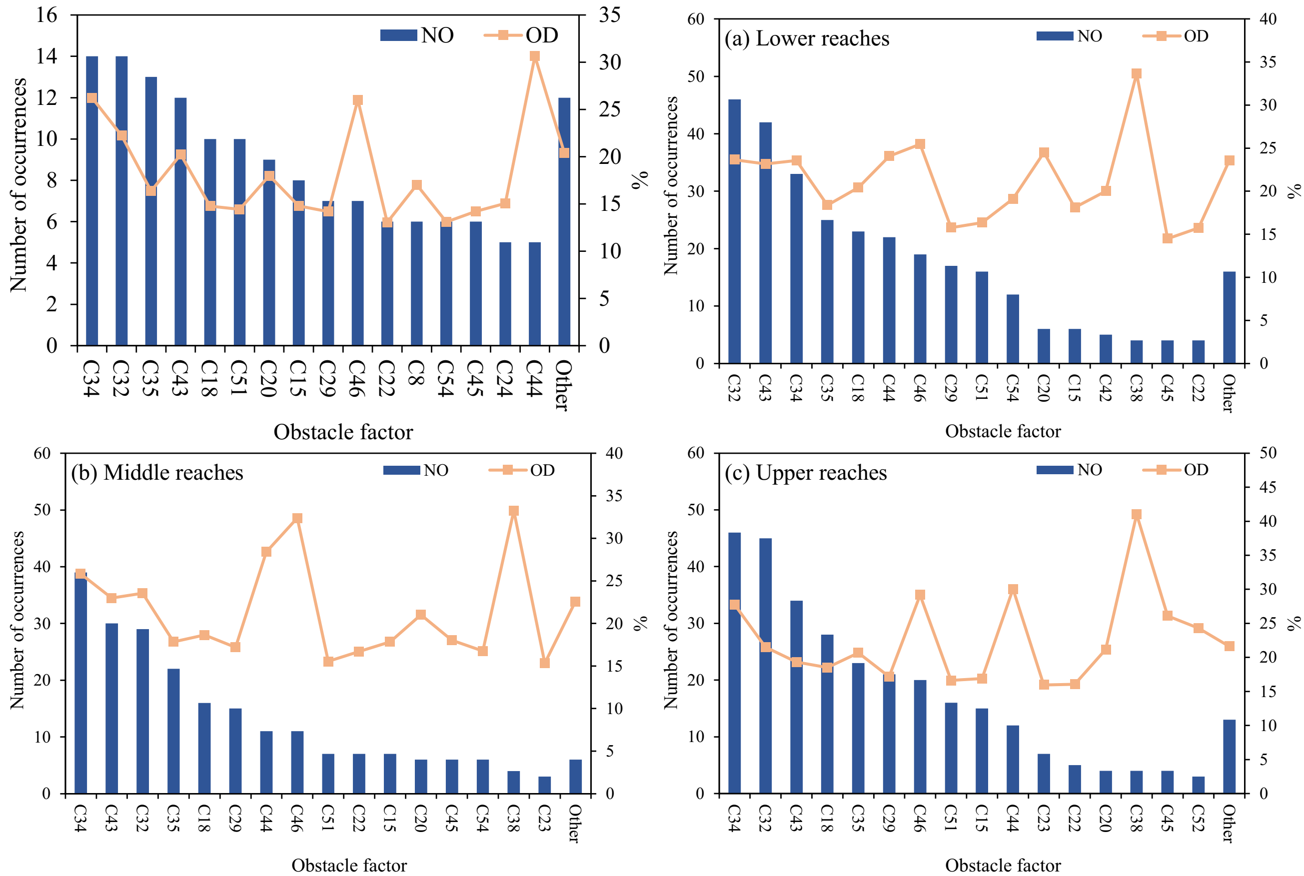

Fig. 6 Spatial patterns of OF and the OD for the WEFL nexus in the YREB from 2006 to 2020

water-using structure changing extensively under the rapid economic development, explosive population growth, uneven distribution of precipitation, frequently occurred environmental disasters, and the acceleration of industrialization and urbanization (Jing et al. 2022). Additionally, the extremely dry weather and drought-flood abrupt alternation events occurred in the middle and lower reaches of the Yangtze River in early 2011 (Wang et al. 2021a). When spring turns to summer in 2011, the precipitation in the middle and lower reaches of the Yangtze River basin reduced resulting in the most severe continuous meteorological drought in recent 60 years. However, in June 2011, the middle and lower reaches of the Yangtze River were successively attacked by five rounds of the heavy precipitation process, and the mean precipitation reached 200–400 mm (maximum value in the local area exceeded 800 mm). Among them, the rainfall of the first four rounds of heavy precipitation is the highest in the same period of nearly 60 years (Wang et al. 2020a). Consequently, climate change and human activities will bring about overall, multi-scale, multi-level, and sustained impacts on the development of water resources and watershed ecosystems in the YREB.

The $CBEI_e$ represents a relatively slow growth trend except in 2016, mainly due to the excessive speed of economic development and the rapid growth of high energy-consuming industries, resulting in the swift rise in energy consumption per unit GDP, the energy consumption of industrial added value, and consumption elasticity coefficient, thus affecting the development of energy subsystem (Ding and Chen 2021). The $CBEI_f$ value was the lowest in the WEFL nexus from 2006 to 2012 (Fig. 4), which is mainly due to the impact of the backward agricultural mechanization level, extensive use of agricultural irrigation water, and severe meteorological disasters such as large-scale and prolonged drought; low temperature and frost; extreme precipitation and snowfall (AghaKouchak et al. 2020); concealment and abruptness of the decline of grain output; and the long time-consuming recovery healthy growth. With the continuous improvement of the agricultural disaster prevention and reduction ability and the level of agricultural production modernization in the YREB (Pan et al. 2022), the grain sowing area, agricultural mechanization level, grain output per unit area, and per capita grain output significantly increase, which are advantageous to the food subsystem's healthy and sustainable development from 2012 to 2020.

The $CBEI_l$ showed a steady upward trend, mainly due to the optimization of spatial land layout and the efficient utilization of land resources in the YREB, such as the strict control of the disorderly occupation of cultivated and forest land by construction land, growth of urban greening and park area, reduction of pollutant discharge per unit area, and standardization of the planning and approval procedures of construction land. The changing trend of the CBEI of the YREB is most affected by the $CBEI_w$ fluctuation. Therefore, it is necessary to pay attention to the respective development and coordinated development trends of the four subsystems to maintain the WEFL nexus system's synergy.

Identification of main obstacles to the coordination development of the YREB

Since the CCD is one of the important indexes to measure the coordination development of the YREB's WEFL nexus, identifying and profoundly analyzing its main OFs is of great significance. Among these OFs (Fig. 6, Table 4), the C34, C35, and C43 belong to the food subsystem; C18, C32, and C51 belong to the water, energy, and land subsystem, respectively. These findings are synchronously related to the spatiotemporal evolution of subsystems' CCD and the actual situation of the YREB.

The widespread application of fertilizers and pesticides (AFP) is one of the main driving forces of agricultural economic growth. At the same time, the unreasonable AFP will result in agricultural non-point source (NPS) pollution and aggravate the eutrophication of surface water bodies, causing nitrate (NO_3^-) pollution of underground water (Xu et al. 2022). Some studies found less prevention and treatment of agricultural NPS pollution in the YREB (Lv et al. 2022). The concentration of NO_3^- caused by agricultural production in the lower reaches is approximately double that in the upper reaches of the Yangtze River (Muller et al. 2008). These hazards will threaten the quality and safety of agricultural products and cause variation in comprehensive development levels of the food subsystem ($CBEI_f$), eventually affecting the CCD of the YREB's WEFL nexus.

Affected by climate change and human activities, waterlogging disasters frequently occur in the middle and lower reaches of the Yangtze River (Wang et al. 2020a). The upper reaches remain the problem of soil erosion caused by severe destruction of vegetation, thinning of the soil layer, and declining water conservation capacity (Fan et al. 2004; Ge et al. 2022). A large amount of sediment is discharged and deposited in the critical lakes and reservoirs, reducing the basin's capacity for regulation, storage, and flood discharge when the flood peak comes, raising the contradiction between the objective of flood control and the other multiple purposes of reservoirs (Zeng et al. 2021). These events further increased the pressure of urban waterlogging control in the middle and lower reaches of the YREB and effect the CCD among the subsystems of the WEFL nexus.

During the study period, the amount of urban water-saving in the lower reaches of the YREB is twice than that in the middle reaches and 5.7 times than that in the upper reaches (Table S5). The urban water-saving in the middle reaches achieved remarkable results during China's "13th Five-Year Plan (2016–2020)," but there is much room for improvement compared with the lower reaches. The urban public water supply pipe network's leakage volume and total leakage rate in the upper reaches are relatively high. The urban water-saving volume and investment, urban reclaimed water consumption, and utilization rate are relatively low (Peng et al. 2022). Some research found that developing water-saving technology is the fundamental way to achieve sustainable development in the YREB (Kong et al. 2021; Wang and Wang 2020; Lv et al. 2022). Therefore, developing key technologies for urban water-saving reduces water consumption, improves water utilization efficiency, and promotes the CCD between the water subsystem and other subsystems in the WEFL nexus.

With the urbanization acceleration and the population explosion, the increase of urban construction land provides security for supporting regional economic development and meeting the urban residents' social needs. Nevertheless, it also highlights the problem of the disorderly expansion of urban construction land under extensive economic growth and population surge (Deng et al. 2008). As land is the fundamental source for supporting the WEF (Ringler et al. 2013; Sargentis et al. 2022), improving the WEFL nexus's CCD should pay great attention to the land subsystem's sustainable development and the prominent OFs simultaneously.

Comparison with the previous literature

Many previous studies have focused on the internal interaction and external influencing conditions of the WEF nexus on the multi-spatiotemporal scales by using various analysis frameworks and approaches, which achieved many valuable results (An et al. 2021; Cai et al. 2018; Ding and Chen 2021; Ma et al. 2021; Molajou et al. 2021; Mercure et al. 2019; Shi et al. 2020; Ge et al. 2022). Compared with the existing research findings, this study contributes to the body of knowledge by extending the theoretical basis and research scope and improving the cross-application methods in sustainable development from the perspective of the WEFL nexus.

Ding and Chen (2021) found that the provinces in the upper reaches achieved a relatively higher development level of the water subsystem, and the food subsystem in

Shanghai was better than in other regions from 2008 to 2019. Peng et al. (2020) claimed that the water-related disaster risk in the middle and lower reaches of the YREB was higher than in the upper reaches from 2000 to 2015. These findings agree with the proposed results in Table S6.1–S6.4 and Fig. S2, and this study also indicates that the mean $CBEI_f$ value of Shanghai is the highest ($CBEI_f = 0.565$). Note that some slight differences between Ding and Chen (2021), Peng et al. (2020), and the results proposed in this study are mainly due to the selection of differentiated evaluation indicators. An et al. (2021) found that the AFP during agricultural production brought severe environmental pollution in the YREB from 2004 to 2018, similar to the presented findings of the main OFs affecting the food subsystem in this study (Table 4; Fig. 6). Liu et al. (2021) found that the CCD of the energy-economy-ecology nexus in the YREB presents an upward trend from 2008 to 2017. The CCD in the east (i.e., lower reaches) is higher than in the west (i.e., upper reaches), which agrees with the research findings in the "Analysis of the spatiotemporal distribution of coordination development levels" section, Fig. S1, and Table S3. Chen and Xu (2021) conclude that the water resource security in the upper reaches is better in the YREB from 2008 to 2017, while the lower reaches achieve better food security. The results proposed in this study also indicate similar conditions (Fig. S2). Lv et al. (2022) found that agricultural NPS pollution control and wastewater treatment are the main obstacles affecting the CCD in the YREB at present and in the future, which agrees with the research findings in the "Dynamic changes of the obstacle factors and their obstacle degrees" section and Table 4. Accordingly, the analysis results of the WEFL nexus in the YREB reasonably agree with the previous literature and the actual situation of the study area and fill the existing research gaps in the WEF nexus.

Conclusions and policy implications

Conclusions

This study proposed a novel analytical framework and the evaluation index system based on the PSR-NA for exploring the WEFL nexus's coupling coordination and interaction relationship. Taking the YREB as a case study, the CBEI, CCDM, and OFDM are incorporated to analyze the coupling coordination relationship and spatiotemporal evolution characteristics of the WEFL nexus and its main influential factors from 2006 to 2020. The findings of comparative analysis verified this study's rationality and scientific value in theoretical research and method application in exploring the interaction relationship, assessing the coupling coordination, and identifying the OFs of the WEFL nexus.

Overall, the comprehensive development level of the WEFL nexus system in the YREB has been constantly promoted from 2006 to 2020. The $CBEI_w$ fluctuates significantly because of the extreme meteorological events and excessive wastewater discharge in the Yangtze River basin. The variation trends of $CBEI_e$, $CBEI_f$, and $CBEI_l$ are relatively stable. The CCD developed well during the study period, while there is still room for improvement for high-quality coupling coordination development in the future. Significant differences exist in the spatiotemporal distribution in the coupling coordinated development of YREB's WEFL nexus. The lower reaches have higher comprehensive and coordinated development levels than the upper and middle reaches relatively. The pollution derived from the fertilizer and pesticide application, investment in industrial solid waste treatment, waterlogging control area, and urban water-saving were significant OFs of WEFL's coupling coordinated development in the YREB. Moreover, the results of common OFs represent that food security guarantee capacity, urban construction land management, and the balanced development between population and land resources are also essential fields to be promoted in the future of the YREB.

This study sheds light on the coupling coordination relationship, spatiotemporal dynamic evolution, and its significant influence factors of the WEFL nexus in the YREB, which helps understand the complex interrelation of the WEFL nexus at different spatial–temporal scales.

Policy implications

In short, based on the above results of the coupling coordination, spatiotemporal dynamic evolution, and main obstacle factors of the WEFL nexus, this study puts forward the following four suggestions for integrated resources and environmental management among the YREB's high-quality development:

(1) Given the characteristics of flood disasters in the Yangtze River basin, it is necessary to vigorously promote the control of water and soil erosion control in the middle and upper reaches. At the same time, relevant basin management agencies should give full play to the function of the joint flood control operation of the Yangtze River cascade reservoirs. In terms of urban water-saving, continuous speed up sewage recycling is conducive to the resource utilization of sewage treatment and the ecological water replenishment of urban.

(2) With the in-depth implementation of China's national strategy of "Great Protection of the Yangtze River," the

investment in the industrial solid waste treatment of the YREB is a pivotal link in protecting and restoring the ecological environment of the Yangtze River. From the perspective of integrated management, on the one hand, more exceptional fund support is needed for relevant enterprises and demonstration projects related to the protection and restoration of the ecological environment in the YREB to reduce the financial pressure on these enterprises, and on the other hand, the implementation of tax relief, tax rebates, and other incentive policies to give tax regulation to circular economy projects.

(3) Agricultural mechanization is directly related to the rate of progress, quality, and benefit during agricultural production. Therefore, enhancing the crop planting mechanization level, meat supply guarantee capacity, and agricultural disaster prevention and resilience are critical to reducing grain production costs, promoting price comparison benefits, and guaranteeing food security. Additionally, improving grain production efficiency and land resource carrying capacity is an important measure to promote the coupling coordination of the WEFL nexus and realize the healthy and balanced development between population and land resources.

(4) Compared with the accelerated expansion of construction land, urban green space and parks are relatively insufficient. Therefore, the core task of urban construction land regulation and management in the YREB is to curb the chaotic spread of cities, properly increase the proportion of urban green space and park area, rationally plan the land resources, and eventually realize the efficient utilization of urban construction land.

Due to data limitations, less analysis and assessment were conducted on the urban scale, WEFL nexus-related sectoral scale, and household scale. Scholars can collect detailed information and conduct in-depth research on the multi-scale influence of the external conditions on the WEFL nexus. The external conditions could include but are not limited to the impacts of climate change, hydroelectric dam reservoirs, significant public health, natural hazards and their secondary hazards events, and other global/local risks. Although this study investigated the coupling coordination relationship of the WEFL nexus in the YREB, the novel analytical framework, evaluation index system, and coupling coordination evaluation model can extend to more regions of China and other countries for theoretical basis and practical reference of the WEF nexus and sustainable development.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-24659-1.

Author contribution The original draft of the manuscript was written by Jing P.R., and all authors commented on previous versions of the manuscript. Writing—original draft preparation: Jing P.R.; conceptualization: Jing P.R., Hu T.S., Sheng J.B.; methodology: Jing P.R., Hu T.S.; writing—review and editing and supervision: Hu T.S., Sheng J.B., Mahmoud A.; formal analysis and investigation: Jing P.R., Yang D.W., Guo L.D., Li M.X.; data curation and software: Jing P.R., Liu Y., Wu Y.T.; funding acquisition: Hu T.S., Sheng J.B., Yang D.W., Guo L.D. All authors read and approved the final manuscript.

Funding This work is supported by the National Natural Science Foundation of China (no. 52179022, 51909174, and 71974053) and the Fundamental Research Funds for Central Public Welfare Research Institutes (no. Y722003 and Y722007).

Data availability The data sets used in the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval No ethical approval was necessary for this study.

Consent to participate All participants in this study consent to participate.

Consent for publication All authors consent to this publication.

Competing interests The authors declare no competing interests.

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