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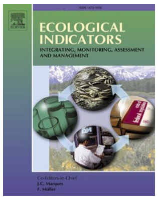

Coordinated analysis and evaluation of water–energy–food coupling: A case study of the Yellow River basin in Shandong Province, China

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ABSTRACT

Water resources, energy, and food are important basic resources for high-quality regional development. In the process of rapid development of regional economy, how to coordinate the development of basic resources has become one of the most serious challenges to the high-quality development of the Yellow River basin and even the whole Yellow River basin in Shandong province. Previous studies have produced few such analyses and evaluations for cities in the Yellow River basin, and there is a lack of research on multi-scale analysis, evaluation and prediction of urban coupling and coordinated development level. Hence, in this study, we propose an indicator system consisting of 24 indicators for the water resources, energy, and food system based on panel data for 9 cities in the Yellow River basin in Shandong Province for 2011–2020. Spatial autocorrelation analysis and temporal and spatial distribution analysis were used to determine the current state of water resources, energy, and food systems at multiple scales; combined weighting, comprehensive evaluation, and coupling coordination quantification were used to formulate the coupling coordination relationships of water resources–energy–food and identify the spatiotemporal formation and development of the water resources–energy–food system. A particle swarm optimization–back propagation model (PSO-BP) was used to predict the coupled and coordinated changes in the water resources–energy–food system for the next five years. The study results show that: (1) The composite index of the water resources–energy–food system showed an increasing trend, and the composite index of the food subsystem increased relatively quickly. (2) In 2020, the coupling coordination degree for eight of the nine cities in the Yellow River basin in Shandong Province was 0.70. Jinan, the exception, was at a critical stage of transitioning from low to moderate coupling, and the other eight cities were at the moderate stage of coupling coordination. (3) The coupling coordination of the water resources–energy–food system is increasing; it has transitioned from low to moderate and is about to transition to the stage of good coupling coordination. (4) The PSO-BP model predicted that the coupling coordination of water resources–energy–food systems in the Yellow River basin in Shandong Province will reach the stage of good coupling coordination in 2023. The research results presented in this paper can provide a theoretical basis for formulating policy recommendations in the Yellow River basin in Shandong Province.

1. Introduction

The concept of sustainable development is becoming increasingly important in real life (Li et al., 2022), which is reflected in fields such as urban land use change, landscape planning, and campus transportation planning. The premise of regional sustainable development is the coordinated development of basic resources (Onac et al., 2021; Aksoy et al., 2022; Cetin, 2020). Water, energy, and food are three basic resources for human survival. There is a fragile balance between the three, and interference with any one of them may disrupt this balance. Water resources support energy development and food production (Wang et al., 2021a). The development of energy depends on the supply of water resources and food, and food production is strongly influenced by water resources and energy. The concurrent development of the three resources directly affects the regional economy. The eastern section of the Yellow River is 11.5% of the total length of the river, and it is strategically positioned for the construction of a green ecological corridor in the Yellow River basin: a long-term calm demonstration area

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that will be a new force for scientific and educational innovation, a growth pole for high-quality development, a pilot zone for reform and opening up and a large platform for the cultural “two innovations”. In order to ensure the high quality of economic development in the Yellow River basin in Shandong Province, the concurrent development of water resources, energy, and food in the region has become a top priority (Peng et al., 2017).

The water–energy–food (WEF) nexus was first recognized at the Bonn Conference in 2011 (Koehler, 1974). In 2013, the United Nations Economic and Social Council for Asia and the Pacific released the *Asia–Pacific Water–Energy–Food Nexus Report*, which elaborated on the temporal and spatial links within WEF and argued that climate, environment, urban development, and overconsumption all affect the nexus (Unescap, 2013). In 2014, the Food and Agriculture Organization of the United Nations examined WEF from the perspective of food security to determine how to interpret WEF in food security decision making (Fao, 2014).

In recent years, research into the relationships between water resources, energy, and food ties and policy has intensified. Janez developed a nationwide quantitative WEF model for Latvia. The model was validated in qualitative and quantitative terms by local stakeholders, and it amalgamated Latvia’s policy objectives as potential policies for future implementation and provided recommendations for narrowing the science-policy divide (Sušnik et al., 2021). Liu et al. developed a stochastic interval fuzzy policy analysis model to create optimal safe management strategies for WEF systems in urban agglomerations with several uncertainties. They produced several planning strategies that varied according to surface and groundwater conditions over random intervals that were scored and ranked, and the strategy with the highest score was considered to be the best choice (Liu et al., 2020). Wu et al. predicted the state of the WEF nexus for Saskatchewan, Canada, for various combinations of climate change, transboundary inflows, and policy choices. They assessed model performance using a previously developed WEF system dynamic relationship model and showed that increasing the use of renewable energy would optimize the WEF nexus between 2021 and 2050 (Wu et al., 2022).

Wang and Sun introduced land factors into WEF and used a coupled coordination model to represent temporal and spatial variation in WEF for the Beijing–Tianjin–Hebei urban agglomeration for 2005–2018. They found that, in the context of WEF, land in the Beijing–Tianjin–Hebei urban agglomeration will affect the overall WEF system and its internal subsystems and that there is a need to rationally allocate resources and optimize the location of the industry to achieve sustainable development (Wang and Sun, 2022). Ren et al. developed a comprehensive and collaborative development model using a co-evolution algorithm and gray correlation. They used Heilongjiang Province as an example to model the development of WEF for 2009–2018 and found that the use of energy in agricultural production promoted coordinated development of the subsystems (Ren et al., 2021).

As one of the most important grain-producing areas in China, the Yellow River basin is severely restricted by the shortage of water resources in development. According to the existing literature, there are few studies on the WEF nexus in the Yellow River basin as a coupling system, which mainly simulate the interactive relationship to study the coordinated development of the Yellow River basin.

Zhao et al. took the Yellow River basin as the research object and constructed a coupling and coordinated model of new urbanization and ecological environment. The spatial–temporal pattern of coupling and coordination between new urbanization and eco-environment in the Yellow River basin from 2005 to 2016 was quantitatively measured, and the state of simultaneous development of the two was determined. Moreover, they investigated the related influencing factors (Zhao et al., 2020). Wang et al. analyzed the spatial–temporal fit and correlation of WEF in the Yellow River basin during the last 20 years, aiming to analyze the distribution and transfer direction of single resource elements, the matching and evolution of energy and food linked by water resources, and finally the nexus based on the Copula function. The results show that water resources, farmland, and energy production are concentrated in different areas, while the gravity center shifted to the northwest, northeast, and west of the basin, respectively (Wang et al., 2022d). Peng analyzed the WEF interaction and its optimization path in the Yellow River basin. The coordinated development of WEF in the Yellow River basin is faced with multiple difficulties, such as mismatched spatial distribution of resource elements, shortage of water resources, complex urban linkages, and uncoordinated departmental management (Peng, 2021).

Forecasting is an essential part of the research. Some researchers have created models to predict the coordinated development of WEF. Most models that predict the coupled coordination of WEF have been based on Grey Model (1,1) (GM (1,1)) prediction models (Chen et al., 2022; Zhou et al., 2016; Xu et al., 2021b). Other models have used system dynamics, Autoregressive integrated moving average (ARIMA) model, and back propagation (BP) neural networks for coupled coordination predictions. Li et al. used system dynamics to model a WEF-related system in Beijing and predict change trends in WEF. Their conclusions were that the primary energy supply structure should be optimized, coal consumption should be effectively controlled, and government departments should adopt social policy measures (Li et al., 2016). Luo et al. empirically analyzed the co-evolution of WEF components in the Yellow River basin from 2010 to 2019 and predicted ARIMA to show that there were mismatches in the development of the three subsystems and that energy production and distribution in the lower reaches of the Yellow River and food production in the middle reaches must become the focus of regional optimization and future adjustment (Luo et al., 2022).

Although there has been a great deal of research into coordinated regional water, energy, and food system assessments, some shortcomings persist. (1) There have been very few studies of the Yellow River basin that identify cities as the basic units. Shandong Province is in the lower reaches of the Yellow River, and the coordinated development of WEF affects development along the entire Yellow River basin. Current research does not pay enough attention to the basin, and most studies have taken the country or the province to be research object. (2) In terms of the analysis of composite systems, current analyses are incomplete and lack depth. Multiscale analysis of the current situation of the subsystems will provide an important reference basis for subsequent research.

Shandong province is located in the lower reaches of the Yellow River. The coordinated development of water resources-energy-food affects the high-quality development of the whole Yellow River basin. Although the research at the level of administrative units is more useful in guiding management and government decision-making, the current research has not paid enough attention to it, and most of the research is carried out on countries or river basins. In addition, regional high-quality development is a process of interaction between different dimensions, and the coordinated development of water, energy and food should also consider the interaction between internal regions and different dimensions.

In order to fill this gap, we put forward a new evaluation index system of WEF system, which takes city as the basic unit, the spatio-temporal distribution of the three subsystems is analyzed in terms of these indicators, and the weight of each indicator is determined using a combined weighting method. We then create the coupling coordination model of the WEF nexus in the Yellow River basin in Shandong Province and examine the level or state of development of each subsystem. For the first time, the PSO-BP combined forecasting model is employed to the coupling coordination degree model. The development trend of coupling coordination for the next 5 years is predicted by a combined PSO-BP model, and the predictions are incorporated into development plans. In conclusion, we suggest environmental protection measures and high-quality development in the Yellow River basin in Shandong Province.

2. Research region and research methods

2.1. Profile of the research region

Shandong Province is an important grain-producing region in China. It is situated in the lower reaches of the Yellow River, between 34°22.9′–38°24.01′ N and 114°47.5′–122°42.3′ E longitude. The Yellow River flows through the nine cities of Heze, Jining, Tai'an, Liaocheng, Jinan, Dezhou, Binzhou, Zibo, and Dongying in Shandong Province and finally flows into the Bohai Sea. It covers an area of 13,600 km^2 in Shandong province (Liu et al., 2021; Luan et al., 2021). The Yellow River estuary begins below Lijin, in Dongying, where the land area is continuously being extended due to siltation creating an average of 25–30 km^2 of land each year. Continuous siltation and increasing elevation of the flood channel have resulted in the formation of a "river on the ground" above the river banks, which floods or diverts to new channels in certain conditions. Shandong Province is one of China's largest energy consumption provinces. From 2015 to 2020, the average annual per person domestic energy use increased each year; in 2020, in Shandong Province, the average annual per person domestic energy consumption was 436.7 kgce, an increase of 4.8% over 2019 (Shandong Provincial Bureau of Statistics, 2021). Increasing energy demand threatens environmental damage and constrains economic development. The Yellow River basin in Shandong Province and the nine cities that form the study area are shown in Fig. 1.

2.2. Research methods

2.2.1. WEF indicator system construction

No complete indicator–index system has yet been developed for the analysis of WEF. We used the principles and methods of indicator construction (Held et al., 2018; Qaiser et al., 2017; Michael et al., 2014) to create indicators of the interactions between WEF components in the Yellow River basin in Shandong Province and the effects of interaction between indicators that can be caused by changes in a single factor. The individual factors that form the indicators are shown in Table 1.

2.2.2. Combined weighting method

We combined entropy weighting and hierarchical analysis weighting to create indicators that accurately represented the real world situation (Wang et al., 2022a; b; Wei et al., 2022; Zhou, 2022).

The combined weighting was calculated by:

$$Q_i = \alpha w_i + (1-\alpha)c_i \tag{1}$$

where Q_i is the combined weight, w_i is the objective weight, c_i is the subjective weight and α is the weight compromise factor; we set $\alpha = 0.4$. The indicator weights calculated are shown in Fig. 2.

2.2.3. Spatial autocorrelation analysis model

1. Global autocorrelation analysis

Global spatial autocorrelation is a macroscopic measure of the degree of aggregation or dispersion of factor values across a region; it is expressed as the global Moran's index I_G, which takes values in the range [−1,1] (Tian et al., 2021). When $I_G > 0$, there is a positive correlation between the multiyear averages of this index in the nine cities in the Yellow River basin in Shandong Province; when $I_G < 0$, there is a negative correlation between the multiyear averages; when $I_G = 0$, there is no correlation. We used an ArcMap 10.6 univariate global spatial autocorrelation model to create a Queen neighborhood spatial weight matrix to calculate I_G for 24 indicators for each of 9 cities in the Yellow

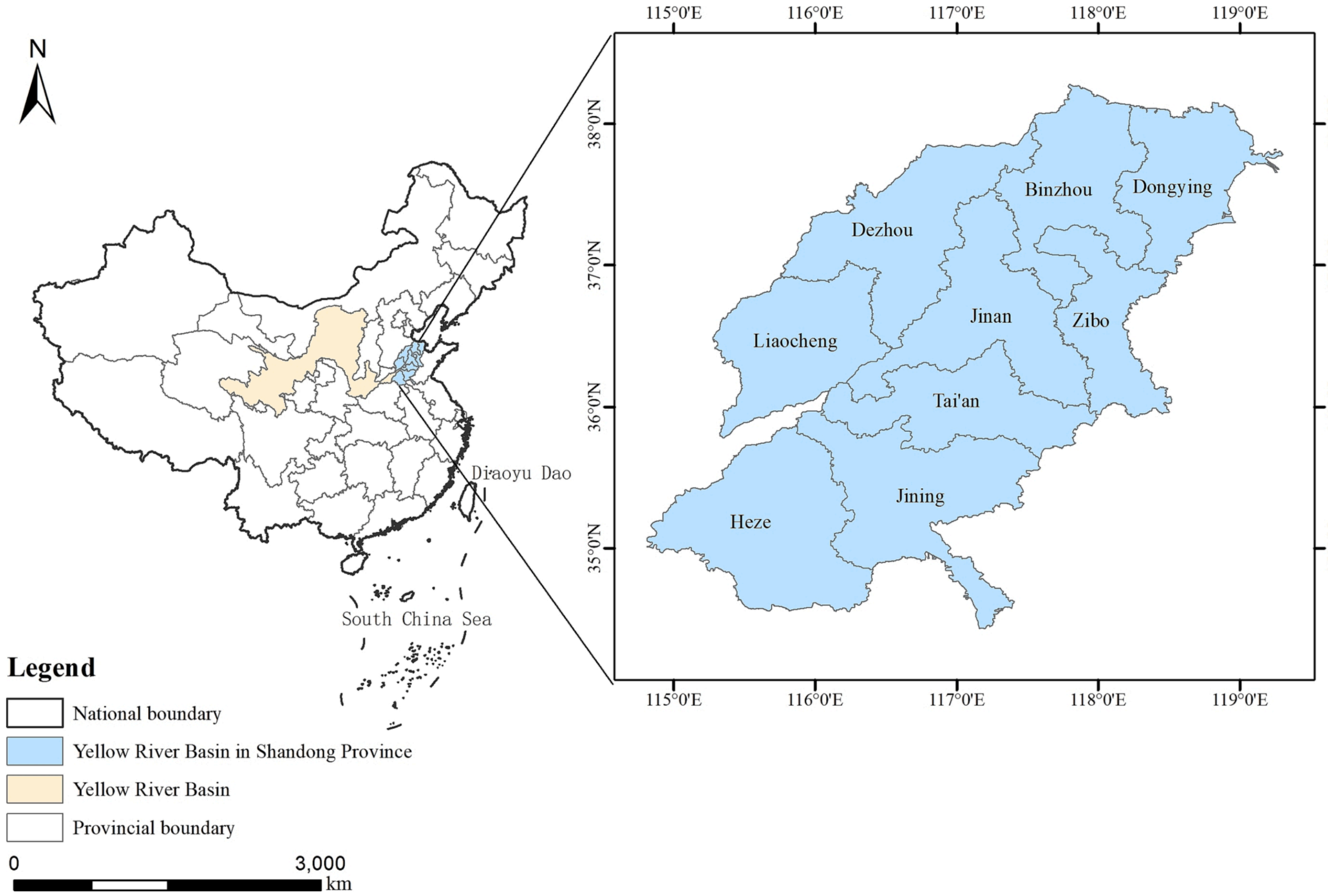

Fig. 1. Study area map.

Table 1
Comprehensive indicator system for WEF in the Yellow River basin in Shandong Province.

Indicator No	System	Indicator layer	Data source and calculation	Unit	Attribute
1	Water	Per capita water resources	Total water resources/ population	m^3/ person	+
2		Water yield modulus	Total water resources/ land area	m^3/km^2	+
3		Average water consumption	Total water consumption/ population	m^3/ person	−
4		Unit Gross Domestic Product (GDP) water consumption	Total water consumption /GDP	m^3/yuan	−
5		Water resources development and utilization rate	Water consumption/ total water resources	%	+
6		Proportion of domestic water	Domestic water consumption/ total water consumption	%	−
7		Ecological water use ratio	Ecological water consumption/ total water consumption	%	+
8		Wastewater discharge	Statistical data	Ten thousand m^3	−
9	Energy	Per capita primary energy production	Total primary energy production/ total population	Tons/ person	+
10		Total electricity consumption	Statistical data	Billion kWh	−
11		Total energy consumption	Statistical data	Ten thousand tons of standard coal	−
12		Coal consumption	Statistical data	Ten thousand tons	−
13		Agricultural diesel oil consumption	Statistical data	Ton	−
14		Proportion of industrial water use	Total industrial water consumption/ total water consumption	%	−
15		Ten thousand yuan GDP energy consumption	Statistical data	%	−
16		Industrial waste gas emission	Statistical data	Billion cubic meters	−
17	Food	Per capita grain production	Total grain output/ population	kg/ person	+
18		Grain sown area ratio	Grain sown area/land area	%	+
19		Effective irrigated area ratio	Effective irrigated area/ total cultivated land area	%	+
20		Fertilizer load	Fertilizer quantity/ sown area of crops	t/km^2	+
21		Agricultural water use ratio	Total agricultural water consumption/ total water consumption	%	+
22		Engel coefficient of urban households	Statistical data	–	–
23		Engel coefficient of rural households	Statistical data	–	–
24		Natural population growth rate	Statistical data	‰	–

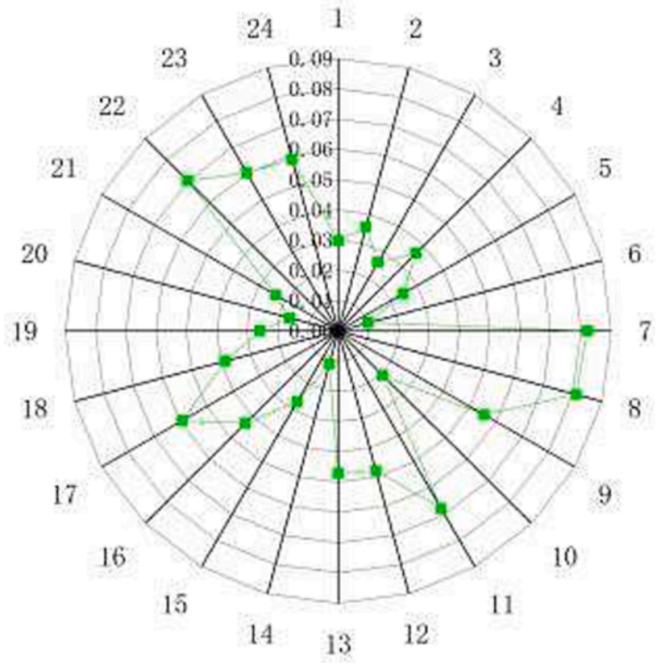

Fig. 2. Indicator weights calculated for the Yellow River basin in Shandong Province. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

River basin in Shandong Province based on multiyear averages. The calculation was:

$$I_G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\omega_{ij}\left(x_i-\overline{x}\right)\left(x_j-\overline{x}\right)}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n}\omega_{ij}} \tag{2}$$

where I_G is the global Moran's index, x_i and x_j are the respective index values for city i and city j, $\overline{x}$ is the average of the indexes, $n = 9$, ω_{ij} is the spatial weight matrix, and s is the variance of the sample.

2. Partial autocorrelation analysis

Local Moran's index I_L identifies the locations of spatial aggregations of factor values within the region and enables the analysis of spatially aggregated, heterogeneous or random distributions of indicators for municipalities in the Yellow River basin in Shandong Province (Zuo et al., 2022; Kong et al., 2022). Local autocorrelation was identified using ArcMap 10.6 analysis that was carried out by combining global autocorrelation analysis and selecting multiyear averages of indicators with large Moran indexes to analyze the spatial aggregation characteristics of some indicators from nine cities in the Yellow River basin in Shandong Province from a local perspective. I_L is calculated by:

$$I_L = \frac{n(x_i - \bar{x})\sum_{j=1}^{n}\omega_{ij}\left(x_j - \bar{x}\right)}{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \tag{3}$$

where I_L is the local Moran's index, x_i and x_j are the respective indexes for city i and city j, x^{-} is the average value of the indexes, $n = 9$, and ω_{ij} is the spatial weight matrix.

2.2.4. Integrated evaluation model

The composite indexes are given by:

$$\begin{cases} w(x) = \sum_{i=1}^{m}\alpha_i x_i \\ e(y) = \sum_{i=1}^{n}\beta_i y_i \\ f(z) = \sum_{i=1}^{k}\gamma_i z_i \end{cases} \tag{4}$$

where $w(x)$, $e(y)$ and $f(z)$ are respectively the composite indexes of each subsystem; α_i, β_i and γ_i are respective the weights of each indicator for each subsystem; and x_i, y_i and z_i are dimensionless values that respectively weight each indicator.

2.2.5. Coupling coordination degree model (CCD)

Coupled systems are two or more systems that interact with and influence each other through intrinsic mechanisms that are interlinked to form a complex system. Coupling coordination degree models are now widely used to determine the interactions between systems and to quantify how well they are coordinated (Xu et al., 2021c). We drew on existing research results (Zuo et al., 2021; Deng et al., 2017) to combine the models given in Eq. (4) for use as a baseline reference (Jiang et al., 2017) as follows:

$$C = \frac{3\sqrt[3]{w_{(x)}e_{(y)}f_{(z)}}}{w_{(x)} + e_{(y)} + f_{(z)}} \tag{5}$$

where the degree of coupling C indicates the strength of the interaction and mutual influence between subsystems. When $0 \leq C \leq 1$, a greater value of C indicates a more coordinated system; when C is in the range 0–0.3, coupling is *low*; when C is in the range 0.3–0.5, coupling is *moderate*; when C is in the range 0.5–0.8, coupling is *good*; and when C is in the range 0.8–1.0, coupling is *high*.

WEF is complex and dynamic. In some cases, the degree of coupling does not adequately express the overall relationship between the three components or its intensity. We used the following coupling coordination degree model to better indicate the high degree of local system coupling:

$$D = \sqrt{C \times T} \tag{6}$$

and:

$$T = \alpha w_{(x)} + \beta e_{(y)} + \gamma f_{(z)} \tag{7}$$

where D is the degree of coupling coordination; T is the composite index of the system; and α, β and γ are the weights of the subsystems. We used a weighted combination of entropy weighting and expert opinion to determine the weight of each subsystem, considering that the degree of influence of water, energy and food on social development varies according to the city.

In order to better study the degree of coordinated development and the stage of the coupled WEF in the lower Yellow River, the coupling coordination degree is qualitatively graded, with reference to existing research results, as shown in Table 2.

2.2.6. PSO-BP combined predictive models

BP neural network prediction models have been widely used in many fields, such as industry, electricity, agriculture, and medicine (Cheng et al., 2022; Syaiful et al., 2021; Xu et al., 2021a; Wang et al.). However, the widespread use of BP neural network models has highlighted their poor data search capabilities and tendencies to output minimal values, among other shortcomings (Guo and Yu, 2022). PSO has a powerful search capability that converges rapidly (Shi et al, 2022; Wang et al., 2022c; Zhou et al., 2021). We used PSO to optimize the BP neural network. PSO performed a global search on the sample data, and the fitness values that met the accuracy requirements were recorded. The BP neural network derived weights and threshold values from the recorded fitness values, and the prediction parameters were optimized after several network training operations. The PSO optimization–BP neural network process is shown in Fig. 3.

2.3. Data sources

We mainly used data from the 2011–2020 China Statistical Yearbook, Shandong Statistical Yearbook, Shandong Water Resources Bulletin, 2011–2020 Shandong Municipal Statistical Yearbooks and Water Resources Bulletin, 2011–2020 Yellow River Water Resources Bulletin to determine the degree of coordination of WEF.

3. Analysis of WEF

3.1. Spatial autocorrelation analysis

3.1.1. Global autocorrelation analysis

The spatial autocorrelation analysis of the multiyear averages of 24 indicators in the Yellow River basin in Shandong Province showed that 50% of the indicators had a Moran index $I > 0$; only 5 of this group had a p-value < 0.1 and a z-value > 1.65, the critical value, and these 5 indicators were spatially positively correlated, as shown in Table 3. The Moran indexes for water resources, energy, and food were greatest, which shows that the spatial aggregation of the multiyear averages of these three indicators is strong.

3.1.2. Partial autocorrelation analysis

Fig. 4 shows a high–high clustering pattern for the multiyear averages of water resources per capita and a low–low clustering pattern for the multiyear averages of agricultural diesel use and the Engel coefficients of rural residents. The multiyear averages of the indicators

Table 2
Degree of coupling coordination and evaluation criteria.

The range of coupling coordination degree D	Qualitative descriptor
[0.0–0.1]	Extreme disorder
(0.1–0.2]	Serious disorder
(0.2–0.3]	Moderate disorder
(0.3–0.4]	Low disorder
(0.4–0.5]	Marginal disorder
(0.5–0.6]	Marginal coordination
(0.6–0.7]	Low coordination
(0.7–0.8]	Moderate coordination
(0.8–0.9]	Good coordination
(0.9–1.0]	High coordination

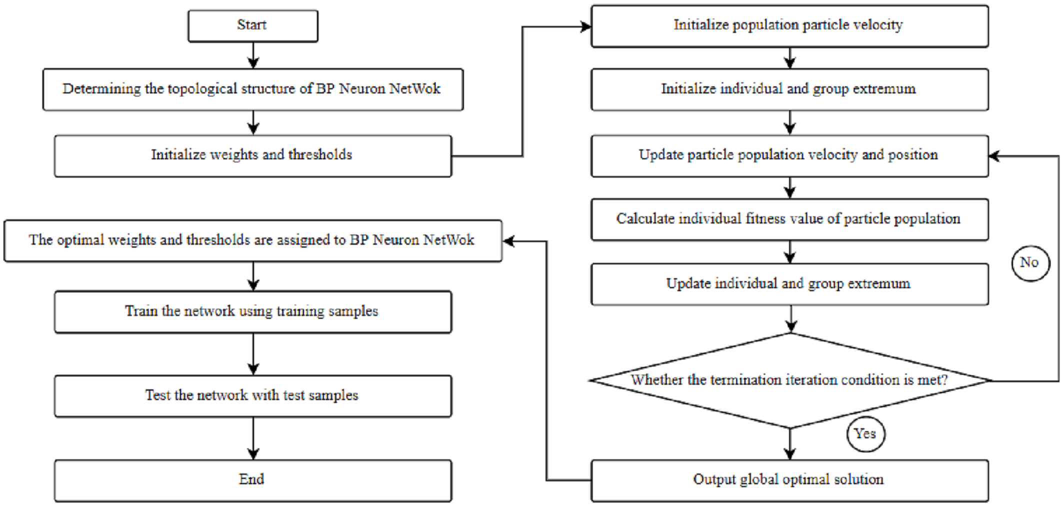

Fig. 3. PSO optimization–BP network flow chart.

Table 3
Values of positive spatial correlation indexes.

Indicator	Moran's *I*	*p*-value	z-value
Per capita water resources	0.522	0.006	2.534
Per capita primary energy production	0.192	0.035	2.029
Agricultural diesel oil consumption	0.607	0.001	2.904
Engel coefficient of urban households	0.370	0.028	1.922
Engel coefficient of rural households	0.423	0.012	2.491

show the general characteristics of the distribution of the indicator. The high–high clustering pattern of the multiyear average of water resources per capita in Dongying and Binzhou is related to the relatively low population of these two cities over the years. The low–low clustering pattern of the multiyear average of agricultural diesel use in Dongying, Binzhou, and Zibo is related to the proximity of these three cities to the mouth of the Yellow River, the severe salinization of the soil, and the low proportion of the area sown to grain. The low multiyear average of the Engel coefficient for rural residents in Dongying and Binzhou shows a low–low clustering, which implies that rural residents in these two cities were relatively well-off and spent relatively little on food as a proportion of total household consumption expenditure.

3.2. Spatial and temporal distribution patterns

3.2.1. Spatial and temporal distribution patterns of water resource subsystems

The water resources subsystem uses water yield modulus, water resources development and utilization rate, and unit GDP water consumption as indicators of the water resources situation in the Yellow River basin. The water yield modulus is the ratio of the total regional water resources to the total area of the region, which spatially indicates the scarcity of water resources. The water resources development and utilization rate is the ratio of total water use to total regional water resources, which indicates the degree of development and utilization of regional water resources as a whole. Unit GDP water consumption is the ratio of total water use to GDP, indicating the use of water resources in regional economic activities. These three indicators are useful because they give spatial, overall and local indication of the water resources situation in the Yellow River basin in Shandong Province. Interannual variation in the water resources subsystem is shown in Fig. 5.

The indicators of water production in the Yellow River basin in Shandong Province show that Zibo had the largest water production of 330 912 m^3/km^2 in 2011 followed by Jinan; these values are related to the small land area and abundant total water resources of these two cities. Average water yield modulus 2011–2020 was greater than other indicator values for all nine cities. The water resources development and utilization rate in Dongying was 674% in 2014, which is due in part to Dongying being in the Yellow River delta, where shallow fresh water is scarce and water use is mainly dependent on water being transferred from elsewhere in the river basin. The water consumption per unit of GDP was relatively large in Heze for 2011–2020, with an overall downward trend from 0.013 m^3/yuan in 2011 to 0.006 m^3/yuan in 2020 due to several initiatives being implemented to save water in Heze.

3.2.2. Spatial and temporal distribution patterns of energy subsystems

Water and energy subsystems complement each other, as do energy and food. Water is consumed in the production of energy, and energy is

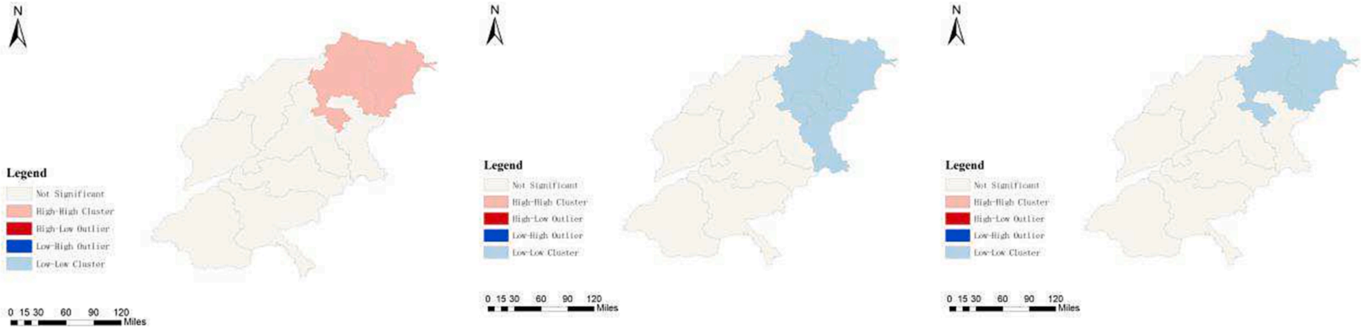

Fig. 4. LISA cluster diagram of per capita water resources, agricultural diesel consumption and Engel coefficients for rural residents in the Yellow River basin in Shandong Province. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

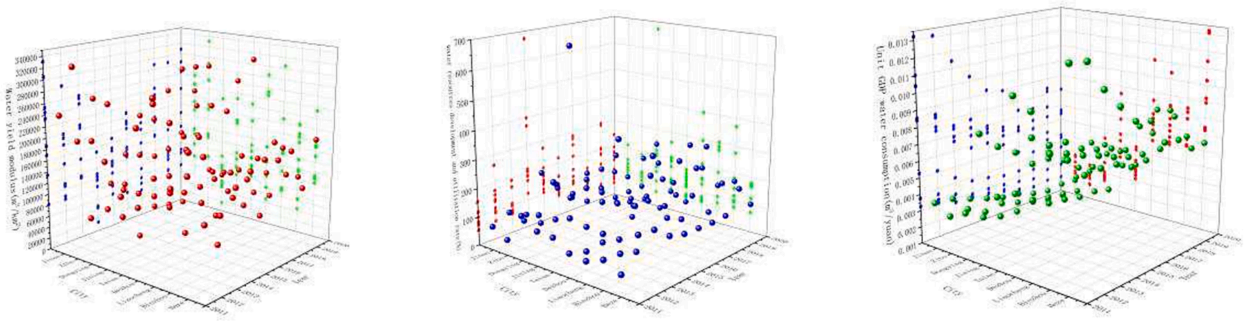

Fig. 5. Interannual changes in water yield modulus, water resources development and utilization rate and unit GDP water consumption in the Yellow River basin in Shandong Province for 2011–2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

constantly consumed in the utilization of water; energy is produced by the production of food, which also consumes energy. The energy subsystem, therefore, used total electricity consumption, agricultural diesel oil use, and the proportion of industrial water use as indicators. Total electricity consumption indicates regional electricity use; agricultural diesel oil use indicates regional diesel use; the industry is the main energy-using sector, and the proportion of industrial water use indirectly indicates regional energy use. These three indicators are relevant to the analysis of the energy situation in the Yellow River basin in Shandong Province, and interannual variation in these indicators shows the activity of the energy subsystem in the Yellow River Basin in Shandong Province (Fig. 6).

Total electricity consumption in the Yellow River basin in Shandong Province for all nine cities showed an increasing trend. Total electricity consumption in Binzhou increased rapidly after 2015, and total electricity consumption in 2015 was 4.2 times that of 2014 due to the vigorous development of secondary industry in Binzhou, which was responsible for 95.48% of the total electricity consumption of the city in 2020. Interannual variation in the use of agricultural diesel oil can be seen in the nine cities, although the use of agricultural diesel oil has been decreasing year over year. Zibo, Dongying, and Binzhou had relatively small multiyear averages for this indicator. The proportion of industrial water use in Zibo was relatively large from 2011 to 2020, reaching 34.07% in 2020, but the proportion of industrial water use in both Dezhou and Heze was relatively small, with respective averages over the period of 7.26% and 8.12%.

3.2.3. *Spatial and temporal distributions of food subsystems*

Indicators used for the food subsystem were per capita grain production, effective irrigated area ratio, and natural population growth rate. Per capita food production, like per capita water resources, indicates the average food production per person in a region. The effective irrigated area ratio is the ratio of effective irrigated area to total arable land area, which indicates the degree of effective irrigation of regional arable land and indirectly indicates regional agricultural water use. The natural population growth rate indicates population growth in the region and is a measure of regional food security. These three indicators are significant for analyzing the food situation in the Yellow River basin in Shandong Province. Interannual variation in the food subsystem indicators is shown in Fig. 7.

The interannual variation in per capita grain production from 2011 to 2020 shows that Dongying, Dezhou, Binzhou, and Heze had an increasing trend, Jining and Liaocheng fluctuated respectively between 500 and 600 kg/person and 800–900 kg/person, and Jinan, Zibo, and Tai’an had a decreasing trend. The proportion of effective irrigated area showed a gradual increase in this indicator in all nine cities, with Zibo city having the lowest indicator at 61.58% by 2020. The per capita grain production of nine cities was on an upward trend from 2011 to 2018, which is reflected by the natural population growth rate, but it begun to decline after that, of which Zibo, Jining, Tai’an, and Dezhou all had a negative natural population growth rate in 2019. Multiple factors result in the slowdown in the natural population growth rate.

3.3. *Comprehensive evaluation time-series analysis*

The composite indexes were calculated, as shown in Fig. 8. The WEF composite index showed a fluctuating growth trend, increasing from 0.42 in 2011 to 0.60 in 2020. The composite indexes for the water, energy and food subsystems vary considerably between individual years, with the water index showing a very clear initial downward trend, but the food subsystem as a whole shows an upward trend.

Although the average per capita water resources of Dongying and Binzhou were high in terms of area covered, it cannot be inferred that the total water resources of these two cities were abundant. The per capita water consumption of these two cities has increased annually since 2013. The per capita water consumption of Dongying increased

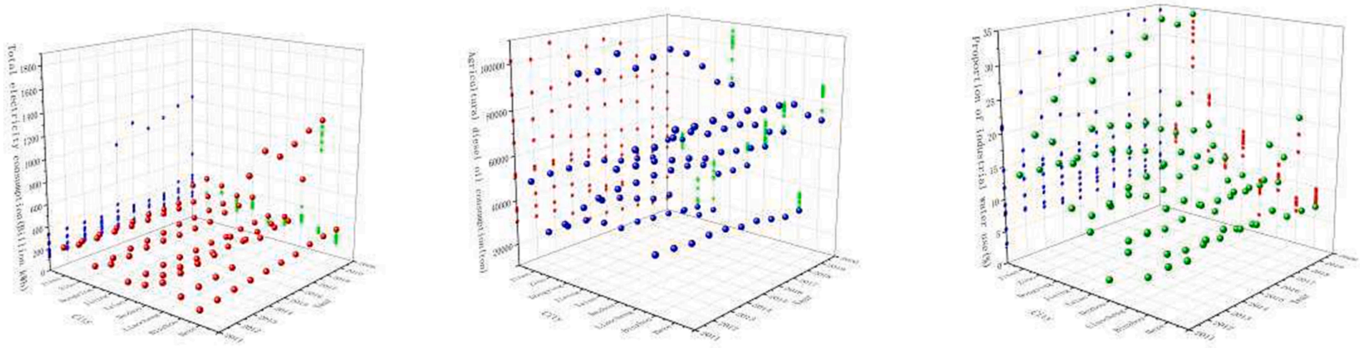

Fig. 6. Interannual changes in total electricity consumption, agricultural diesel oil consumption and proportion of industrial water use in the Yellow River basin in Shandong Province for 2011–2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

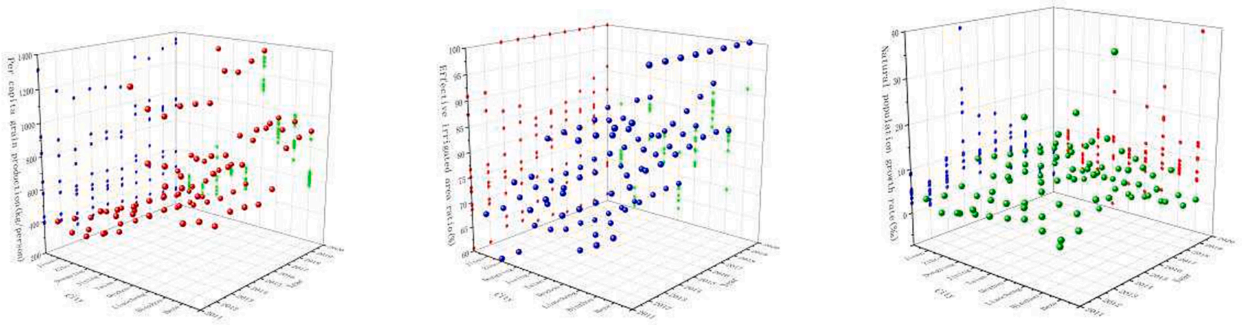

Fig. 7. Interannual variation in per capita grain production, effective irrigated area ratio and natural population growth rate in the Yellow River basin in Shandong Province for 2011–2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

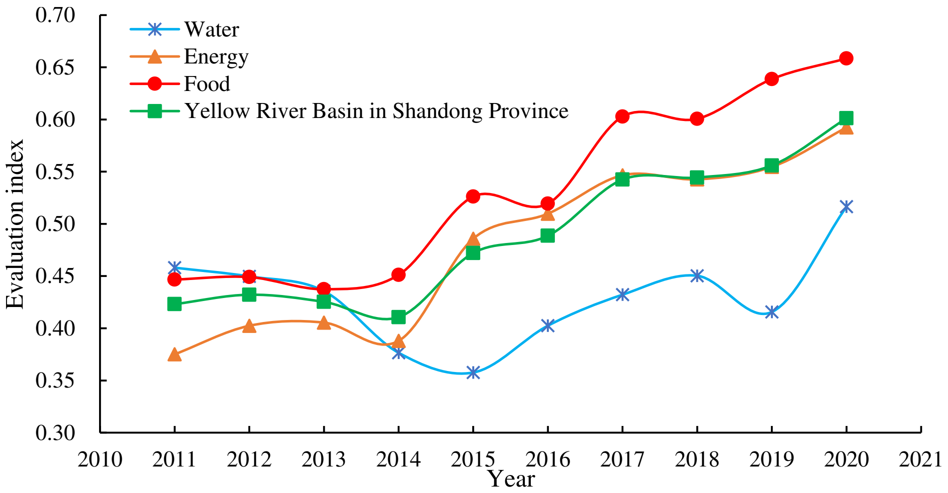

Fig. 8. Composite indexes of WEF in the Yellow River basin in Shandong Province for 2011–2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from 432.98 m^3/person in 2013 to 477.23 m^3/person in 2015, and the per capita water consumption of Binzhou increased from 373.43 m^3/person in 2013 to 399.33 m^3/person in 2015, respective increases of 10.23% and 6.94%. The year 2016 was the first year of the *13th Five-Year Plan*, and Shandong Province promulgated the *Shandong Province Urban Water Conservation Development Plan*, which clarified the development goals and tasks for urban water conservation during the *13th Five-Year Plan* period, strengthened the management of planned water use and quotas, implemented the “three simultaneous” initiatives for management of water conservation, and increased the utilization of reclaimed water and rainwater. By 2020, the water-saving measures implemented in Shandong Province had shown results, and the water resources development and utilization rate in most cities has dropped significantly; for example, the utilization rate of water resources development in Liaocheng in 2020 decreased by 53.31% from 2019. For the reasons already given, the composite index of the water resources subsystem decreased around 2013 and began to rise in 2016.

The composite index of the energy subsystem fluctuated greatly from 2011 to 2020. It was relatively stable from 2011 to 2014, then showed a rapidly increasing trend from 2014 to 2015, and continued to increase from 2015 to 2020. In 2015, the final year of the *12th Five-Year Plan*, total energy consumption and total coal consumption in the Yellow River basin in Shandong Province decreased significantly, and the use of agricultural diesel oil in many cities showed spatial low–low clustering. In 2016, into the *13th Five-Year Plan* period, the composite index of the energy subsystem continued to increase slightly due to Shandong Province’s vigorous promotion of the conversion of old and new forms of kinetic energy in the energy industry, promotion of energy supply-side structural reform, and improvement of energy development quality and efficiency.

The composite index of the food subsystem decreased in 2013. Per capita food production decreased in all cities in 2013 from 2012, with Zibo, Liaocheng, Binzhou, and Heze experiencing larger decreases of 16.17%, 9.94%, 10.23%, and 9.99%, respectively.

The overall increasing trend of the composite index of the grain subsystem from 2014 to 2020 was stepwise due to Shandong Province being a large agricultural province; total grain production in the Yellow River basin increased annually during this period until 1920 when per capita grain production was 792.86 kg.

3.4. *The evolution of coupling coordination*

3.4.1. *The evolution of coupling coordination in nine municipalities*

The coupled WEF system is a complex dynamic system that changes over time. We used the coupling coordination degree model to indicate the overall coupling coordination degree of the coupled WEF system in nine cities in the Yellow River basin in Shandong Province in order to fully understand the current status of the coupled coordination of WEF.

Fig. 9 shows that the number of cities in a low state of coordination decreased from 2011 to 2020, and the number of cities in a moderate state of coordination increased. In 2013, nine cities were marginally coordinated, and by 2017 they were almost all in a moderate state of coordination, and only Jinan and Binzhou were in a state of low coordination due to the relative lack of resources and large consumption of these two cities. In 2020, Jinan was still in a state of low coordination, and the other 8 cities (Zibo, Dezhou, Dongying, Jining, Tai’an, Dezhou,

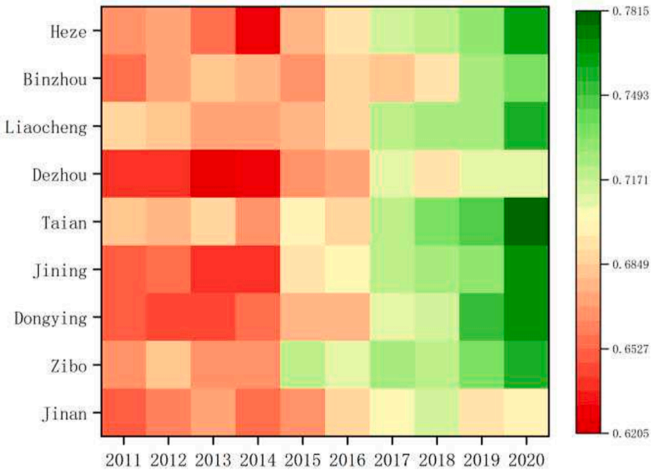

Fig. 9. Changes in the coupling coordination degree of 9 cities in the Yellow River basin in Shandong Province from 2011 to 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Heze, and Liaocheng) were in a moderate state of coordination. When we consider the changes in the composite index of the coupled system and the spatiotemporal distributions of each indicator, we find that the coupling and coordination of WEF systems are not acceptably stable due to pressure for water resources and food resources in the region. There is still much room for improvement in the coupling and coordinated development of the system and in leveling the uneven spatial and temporal distribution of resources. Measures must be taken to avoid inefficient and insecure development of water and food resources over the long term in order to avoid serious adverse effects and other constraints on the energy system that will affect the security, coupling, and coordinated development of the entire system.

3.4.2. Analysis of the coupling and coordinated development of the Yellow River basin in Shandong Province

Fig. 10 shows that WEF in the Yellow River basin in Shandong Province was coupled at a high level during the period 2011–2020. This coupling is inextricably linked to the interdependence and mutual influencing of water, energy, and food. Fig. 11 shows that the coupling coordination degree of WEF for 2011–2020 was transitioning from low to moderate coordination, showing a gradual increase with a relatively slow growth rate due to the influence of fluctuations in the composite index of the subsystem. The coupling coordination degree of the Yellow River basin in Shandong Province from 2011 to 2020 increased from 0.6492 to 0.7735, with an overall increasing trend, and decreased only in 2014.

3.5. Predictions of coupling coordination

We created a PSO-BP neural network prediction model in MATLAB 2018b, with PSO-related parameters set as follows: learning factor C1 = C2 = 1.5; inertia weight w = 0.8; number of particles n = 20; maximum number of iterations 100; and maximum particle velocity 1. In order to verify the optimization of the PSO-BP neural network model, a BP neural network model was created using the same modeling approach and parameter settings. The average relative error, average absolute error and mean square error for both models are shown in Fig. 12. In general, the model simulation is considered good when the absolute value of the relative error is in the range 0%–10%.

It is clear from Fig. 12 that the PSO-BP neural network model was more accurate than the BP neural network model, with the absolute value of the relative error <10%. The PSO-BP neural network model has lower values of average relative error than the BP neural network model by 18.97%, average absolute error by 14.41%, and mean square error by 2.68%. The PSO-BP neural network model was used to predict the coupling coordination of WEF in the Yellow River basin in Shandong Province for the next five years, and the results are shown in Fig. 13. Good coordination will be reached in 2023 and maintained for three years afterward.

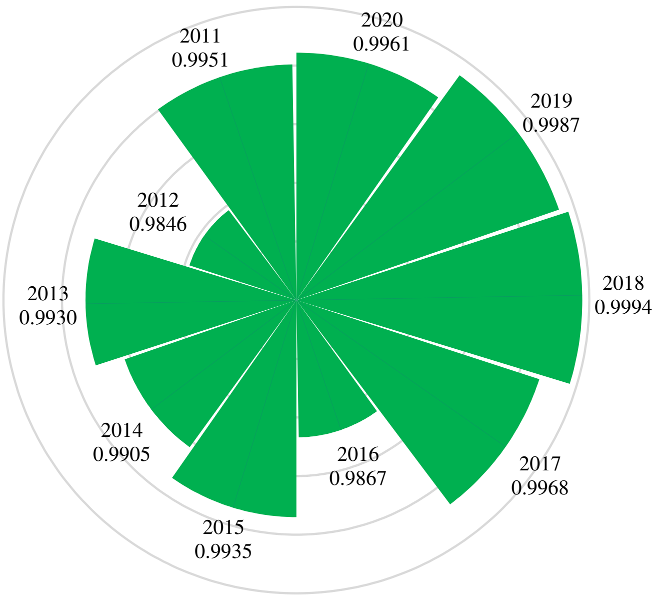

Fig. 10. Development of the coupling coordination degree of WEF in the Yellow River basin in Shandong Province for 2011–2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

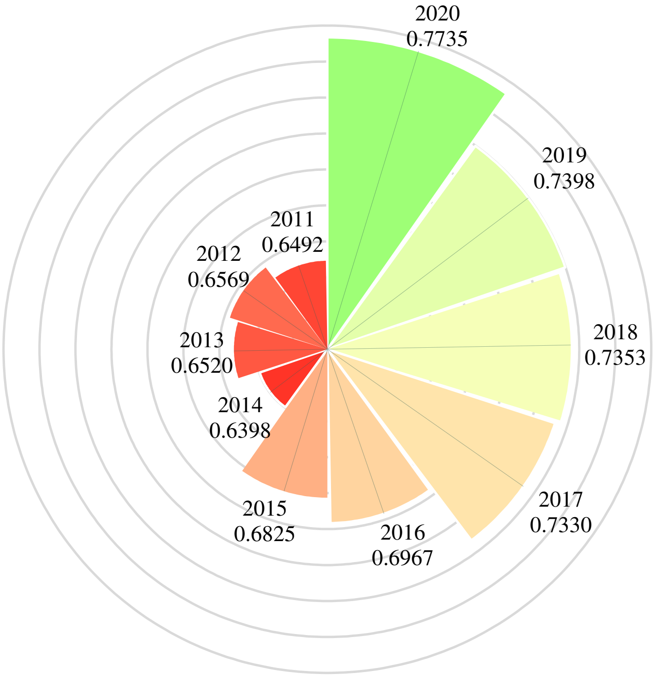

Fig. 11. Development of the coupling coordination degree of WEF in the Yellow River basin in Shandong Province for 2011–2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

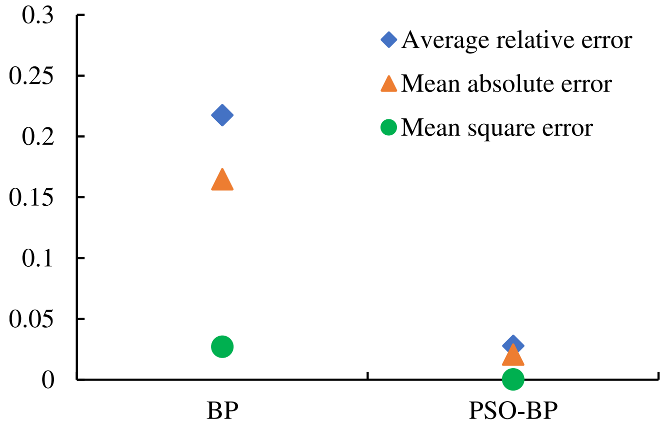

Fig. 12. Prediction error plot.

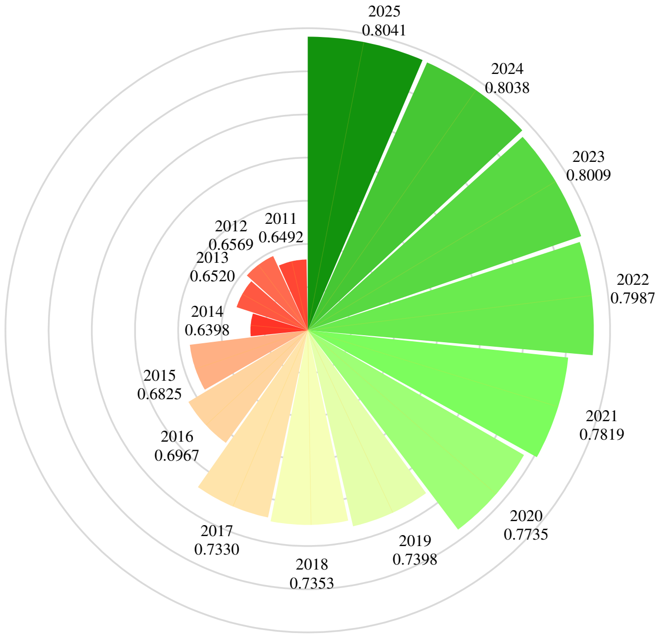

Fig. 13. Prediction of the coupling coordination degree of WEF.

4. Discussion

Ecological protection and high-quality development of the Yellow River basin is one of the major national strategies, and regional high-quality development necessitates coordinated development of basic resources. In this paper, the overall evaluation and coupling analysis and simulation forecast for the Yellow River basin in Shandong Province can provide novel ideas for research and development. In terms of research methods, comprehensive evaluation method and coupling and coordination analysis method are adopted to make an objective and thorough evaluation on the water resources–energy–food coupling system of the Yellow River basin in Shandong Province. The PSO-BP combined forecasting model is used to make the simulation forecast for the following 5 years, and the developing state of the coupling coordination degree is obtained. It is expected to provide theoretical and practical reference for the high-quality development and ecological civilization construction of the Yellow River basin in Shandong Province.

The *14th Five-Year Plan* is the first and key stage in the ecological protection and high-quality development of the Yellow River basin in Shandong Province. In recent years, the economic growth in Shandong Province has increased the demand of various economic sectors for energy sources such as electricity and oil, and using fossil energy sources such as petroleum and natural gas generates large amounts of carbon emissions. An in-depth analysis of the logical relationships between water, energy and food systems shows that informed use of water resources can reduce carbon emissions. Examples are the informed development of hydropower and the promotion of new forms of energy storage; in carbon and economic linkage, carbon trading promotes economic development; economic development consumes energy while forcing energy transformation; energy development utilizes food crops as biofuels to replace traditional fuels; food production uses water resources as crop irrigation and livestock production cannot be separated from water resources. These five examples form a cycle, as shown in Fig. 14. Water resources, energy and food are indispensable basic resources for social development, so it is of great significance to coordinate their development.

Subsystem weights play a very important role in coupled coordination calculations, and so far, there is no standard weight allocation method for composite systems. Based on the Chinese National Knowledge Infrastructure (CNKI) website, we searched the keyword “Water-energy-food coupling”, covering the period from January 2017 to January 2023. Six invalid articles were excluded from a total of 40 articles. Examination of the literature showed that there are three general methods of system weight assignment: (1) Consider each subsystem equally important and give them all the same weight (Fang and Huang, 2020). (2) Consider each system weight as a summation of the indicators of that system (Wang and Sun, 2022). (3) Determine system weights according to the development status of each region (Wang et al., 2021b). There is another case when the system weights are not specified. The abovementioned four scenarios are shown in Fig. 15. We used both subjective and objective methods to allocate subsystem weights, using a combination of entropy weighting and expert consultation to determine the subsystem weights so that the calculated coupling coordination degree results are close to the actual situation. To verify the rationality of the weight distribution method in this paper, we compare the coupling coordination degree of WEF in the Yellow River basin in Shandong Province with that of others. Since the WEF coupling coordination in the Yellow River basin in Shandong Province has not yet been studied by scholars alone, the Shandong section of the Yellow River basin is compared with other scholars in the study of WEF coupling coordination in the whole Yellow River basin. Zhao et al. studied the coupling coordination degree of the WEF system in the eight main provinces (regions) of the Yellow River basin from 2007 to 2017. The coupling coordination degree of the basin is in the transition stage from primary coupling to intermediate coupling, and the coupling

Fig. 14. The system cycles.

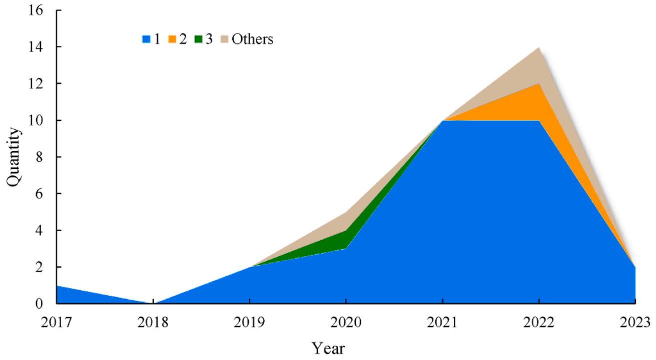

Fig. 15. Literature chart.

coordination degree of the Yellow River basin in Shandong province reached the intermediate coordination stage in 2017 (Zhao et al., 2021). Bai explored the coupling coordination degree of WEF in provinces along the Yellow River basin from 2010 to 2019. The coupling coordination degree of WEF in the Yellow River basin in Shandong Province showed a fluctuating increasing trend, from 0.6416 in 2010 to 0.7113 in 2019 (Bai, 2022). Although the research period of this paper is different from that of the above studies, the obtained results of water resources-energy-grain coupling coordination degree in the Yellow River basin in Shandong Province tend to be consistent in the common research period.

After our in-depth analysis of the coupling coordination degree of WEF in the Yellow River basin in Shandong Province from 2011 to 2020, we forecast the coupling coordination degree of WEF in the Yellow River basin in Shandong Province during the *14th Five-Year Plan* period. The cities along the Yellow River in Shandong Province should, on the basis of existing development, promote the economical and intensive use of water resources. Actions include strict water use control, domestic water use reduction, wastewater emission reduction, water resource recycling improvement, increasing the use of ecological water, increase in the conversion of old to new energy sources, coal consumption reduction, agricultural diesel use reduction, and industrial emissions reduction thereby reducing carbon dioxide emissions and making the most of the advantages of being a large agricultural province by increasing the area of irrigated agricultural land, develop and use saline land, increasing the grain growing area, and increasing grain production by reducing the use of chemical fertilizers.

Forecasting is an activity in which people use the known to predict the unknown. Forecasting is essential in the study of coupled and coordinated development, and accurate and effective forecasting can provide sound policy recommendations for coordinated regional development, thus making high-quality regional development more optimal. However, most forecasting models basically require long time series. In the study of coupling coordinated development, data is limited, and it is difficult to find a complete long time series for each indicator. The only way to ensure accurate forecasts is, therefore, to correct model error. Recently, combinatorial forecasting models have been widely used by researchers in various fields because such models can handle the problem of insufficient accuracy faced by single forecasting models. The combined PSO-BP model is based on a BP neural network model and uses PSO to find the optimal weights and thresholds to assign to the BP neural network in order to maximize the accuracy. Wang et al. used the PSO algorithm to optimize the training parameters of the BP neural network, and established a prediction model for validation through the displacement monitoring data of a tailings dam. The GM (1,1) model, BP neural network model, PSO model and PSO-BP combined model under different conditions were used to compare and analyze the results. The PSO-BP combined model had the highest prediction accuracy, with an average absolute percentage error of 8.5326 (Wang et al., 2022e). Gao et al. provided a scientific basis for predicting the date of glacier breakup and preventing and controlling glacier movement, where the fracture toughness under different types of ice and strain rate was measured by the three-point bending test. And the fracture toughness of the Yellow River ice was predicted and analyzed by the BP model and PSO-BP model. The probability of predicted values of the training set and test set for the BP model and PSO-BP model within 20% error was 78.57% and 85.71%, respectively. Wang et al. developed a model based on the PSO-BP neural network algorithm to predict the driver reaction time. A wavelet transform algorithm was used to denoise the signal first in order to improve the convergence speed and prediction accuracy of the model. Meanwhile, the BP neural network prediction model based on the PSO was established to optimize the weights and thresholds of the BP neural network, so that the prediction of the driver reaction time was achieved. The prediction results obtained from the PSO-BP neural network model were compared with that of the BP neural network model. It demonstrated that the prediction results obtained in this paper have smaller error values, verifying the reasonableness and validity of the model (Wang et al., 2022f). We used the PSO-BP model to predict coupling coordination, and the average relative error and absolute error were maintained at around 2%; the prediction results were more accurate than those given by the BP model before optimization. The next step will be to increase the length of the time series and continue to correct the model error to ensure more accurate predictions.

5. Conclusions and suggestions

(1) The composite index of WEF in the Yellow River basin in Shandong Province has increased over the study period. The composite index of the water resources subsystem showed large variation with the change in per capita water consumption in 2013 and the change in water use policy in Shandong Province in 2016. The composite index of the energy system had the greatest average increase and is the subsystem that contributed most to the rise in coupling coordination. The composite index of the energy subsystem has risen continuously since 2014 as the result of a significant reduction in traditional energy use, a booming new energy sector, and a significant increase in the quality and efficiency of energy development. The composite index of the food subsystem showed an overall increasing trend, but in 2013 and 2016, the composite index showed a short-term decrease due to a significant decrease in per capita food production.

(2) The coupling coordination degree of WEF in the cities of the Yellow River basin in Shandong Province is increasing. In terms of the speed and magnitude of change, there is greater obvious spatial heterogeneity between cities. The overall degree of coordination is at the stage of transitioning from low coordination to moderate coordination, with more room for increase. Shandong Province must address the increased pressure brought to bear by water and food resources on the coupled and coordinated development of the system and take active measures to address the unstable state of the development of water and food resources and promote the controlled and coordinated development of the entire basin system.

(3) The overall trend of WEF coupling coordination in the Yellow River basin of Shandong Province is increasing. WEF coupling reached a moderate level of coordination in 2020, with a high degree of coupling between the three subsystems. In 2014, the degree of WEF coupling decreased due to a significant decrease in water resources per capita in the water resources subsystem.

(4) The PSO-BP network model predictions show that the coupling coordination degree of WEF in the Yellow River basin in Shandong Province will become good in 2023, and that level will be maintained in 2024–2025 with a reduced increase.

Most researchers investigating coupling coordination have selected the province as the basic unit to study WEF in the Yellow River basin and have ignored interactions between cities. We analyzed spatial and temporal distributions of indicators, spatial autocorrelation, and coupling coordinated development on a city basis. However, we only considered spatial and temporal interactions of the indicators we developed, and the follow-up study should analyze internal relationships between the indicators in depth. Due to the restricted study period, data from 10 years only were collected, making the coupling coordination evaluation in this paper lack a certain degree of completeness. It thus limited the prediction of coupling coordination. Future research should combine the current situation of the Yellow River basin and fully consider other influencing factors to broaden the scope and increase the depth of research. Thus, not only the coordination of the WEF coupling system of the entire Yellow River basin but also the sustainable, high-quality, and stable development of the Yellow River basin can be achieved.

CRediT authorship contribution statement

Shunsheng Wang: Conceptualization, Methodology, Writing – original draft. **Jinyue Yang:** Software, Data curation. **Aili Wang:** Supervision, Writing – review & editing. **Tengfei Liu:** Visualization. **Shuaibing Du:** Methodology. **Shuaitao Liang:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Aksoy, H., Kaptan, S., Varol, T., Cetin, M., Ozel, H.B., 2022. Exploring land use/land cover change by using density analysis method in yenice. Int. J. Environ. Sci. 19 (10), 10257–10274. https://doi.org/10.1007/s13762-021-03847-5.

Bai, S.M., 2022. Study on coupling coordination evaluation of Water-Energy-Foodsystem in the Yellow River Basin. North China Univ. Water Resour. Electric Power. https://doi.org/10.27144/d.cnki.ghbsc. 2022.000626.

Cetin M., 2020. The Changing of Important Factors in The Landscape Planning Occur Due to Global Climate Change in Temperature, Rain and Climate Types: A Case Study of Mersin City. Turkish Sci Te Publishing. 8(12): 2695-2701. https://doi.org/10.24925/turjaf.v8i12.2695-2701.3891.

Chen, K., He, Y., Xie, H., Li, Y., Zhao, Y., 2022. Evaluation and prediction of coupling coordinated development of compound system of key state-owned forest region in Daxing'anling, Heilongjiang Province. J. Ecol. Rural. Environ. 38 (0–5), 578–586. https://doi.org/10.19741/j.issn.1673-4831.2021.0475.

Cheng, J., Wang, S., Luo, Y., Zhang, C., 2022. Aboveground biomass model of *Salix psammophila* based on BP neural network. For. Res. 35 (03), 193–198. https://doi.org/10.13275/j.cnki.lykxyj.2022.03.022.

Deng, P., Chen, J., Chen, D., Shi, H., Bi, B., Liu, Z., Yin, Y., Cao, X., 2017. The evolutionary characteristics analysis of the coupling and coordination among water, energy and food:take Jiangsu Province as an example. J. Water Resour. Water Eng. 28(6), 232-238. DOI: 10. 11705 /j. issn. 1672 – 643X. 2017. 06. 41.

Fang, S., Huang, Y., 2020. Spatio-temporal evolutions and coordination of tourism efficiency and scale in the Yangtze River Economic Belt. Acta Geograph. Sin. 75 (08), 1757–1772. https://doi.org/10.11821/dlxb202008014.

FAO, 2014. The water-energy-food nexus: a new approach in support of food security and sustainable arriculture. http://www. fao. org/ nr/ water/ docs/ FAO-nexus-concept. Pdf/ (accessed 27 February 2020).

Guo, L., Yu, J., 2022. Application of PSO-BP neural network in forecasting oil material production. Cereals Oils 35 (04), 107–110.

Held, B., Rodenhaeuser, D., Diefenbacher, H., Zieschank, R., 2018. The National and regional welfare index (nwi/rwi): redefining progress in germany. Ecol. Econ. 145, 391–400. https://doi.org/10.1016/j.ecoleco-n.2017.11.026.

Jiang, L., Bai, L., Wu, Y., 2017. Coupling and coordinating degrees of provincial economy, resources and environment in China. J. Nat. Resour. 32 (5), 788–799. https://doi.org/10.11849/zrzyxb.20160512.

Koehler, J.E., 1974. The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind. by Donella H. Meadows; Dennis L. Meadows; Jørgen Randers; William W. Behrens. 126, 102-104. DOI: 10.2307/2129091.

Kong, F., Yuan, R., Xu, C., 2022. Temporal and spatial characteristics and correlation of the coordinated development of economy, society and ecological environment in the Yangtze River Delta, China. Chin. J. Appli. Ecol. 33 (7), 2009–2016. https://doi.org/10.13287/j.1001-9332.202207.026.

Li, G., Li, Y., Jia, X., Du, L., Huang, D., 2016. Establishment and simulation study of system dynamic model on sustainable development of water-energy-food nexus in Beijing. Manag. Rev. 28 (10), 11–26. https://doi.org/10.14120/j.cnki.cn11-5057/f.2016.10.002.

Li, X., Lu, Z., Hou, Y., Zhao, G., Zhang, L., 2022. The coupling coordination degree between urbanization and air environment in the Beijing(Jing)-Tianjin(Jin)-Hebei (Ji) urban agglomeration. Ecol. Ind. 137, 108787 https://doi.org/10.1016/J.ECOLIND.2022.108787.

Liu, J., Li, Y., Li, X., 2020. Identifying optimal security management policy for water–energy–food nexus system under stochastic and fuzzy conditions. Water 12 (11), 3268. https://doi.org/10.3390/w12113268.

Liu, Y., Zong, R., Zhuang, H., 2021. Analysis on hydrology monitoring station grid in the Yellow River Watershed in Shandong. Shandong Water Resour. 9 https://doi.org/10.16114/j.cnki.sdsl.2021.09.014, 30-31+33.

Luan, J., Wang, R., Zhu, Z., Li, T., 2021. Study on agricultural production pattern under the change of grain supply and demand in Shandong province. Chin. J. Agric. Resour. Reg. Plan. 42 (08), 201–209. https://doi.org/10.7621/cjarrp. 1005-9121.20210823.

Luo, W., Yang, X., Yang, Y., Cheng, S., 2022. Co-evolution of water-energy-food nexus in the Yellow River Basin and forecast of future development. Resour. Sci. 44 (03), 608–619. https://doi.org/10.18402/resci.2022.03.14.

Michael, F.L., Noor, Z.Z., Figueroa, M.J., 2014. Review of urban sustainability indicators assessment – Case study between Asian countries. Habitat Int. 44, 491–500. https://doi.org/10.1016/j.habitatint.2014.09.006.

Onac, A.K., Cetin, M., Sevik, H., Orman, P., Sutcuoglu, G.G., 2021. Rethinking the campus transportation network in the scope of ecological design principles: case study of Izmir Katip elebi University ili Campus. Environ. Sci. Pollut. Res. 18 https://doi.org/10.1007/s11356-021-14299-2.

Peng, S., Zheng, X., Wang, Y., Jiang, G., 2017. Study on water-energy-food collaborative optimization for Yellow River basin. Adv. Water Sci. 28 (5), 681–690. https://doi.org/10.14042/j.cnki.32.1309.2017.05.005.

Peng J.J. 2021."Water–energy–food" interaction relationship and its optimization path in the Yellow River Basin. Academic J Zhongzhou. 296(08):48-54.

Qaiser, B., Nadeem, S., Siddiqi, M.U., Siddiqui, A.F., 2017. Relationship of Social Progress Index (SPI) with Gross Domestic Product (GDP PPP per capita): The moderating role of Corruption Perception Index (CPI). Pak. J. Eng. Technol. Sci. 7 (1), 61–76. https://doi.org/10.22555/pjets.v7i1.2083.

Ren, X., Ren, Y., Wu, F., Si, T., Wang, Z., 2021. Collaborative development model of regional water-energy-food nexus. Bull. Soil Water Conservation 4–1 (05), 218–225. https://doi.org/10.13961/j.cnki.stbctb.2021.05.029.

Shandong Provincial Bureau of Statistics, 2021. 2021 Shandong Statistical Yearbook. http://tjj.shan-dong.go-v.cn/tjnj/nj2021/zk/indexc-h.htm/ (accessed 27 February 2022).

Shi, C., Tian, L., Xu, Z., Zhi, R., Chen, J., 2022. Effectiveness evaluation method of emergency communication and sensing equipment based on PSO-BP. Syst. Eng. Electron. 44 (11), 3455–3462. https://doi.org/10.12305/j.issn.1001-506X.2022.11.20.

Sušnik, J., Masia, S., Indriksone, D., Brēmere, I., Vamvakeridou-Lydroudia, L., 2021. System dynamics modelling to explore the impacts of policies on the water-energy-food-land-climate nexus in Latvia. Sci. Total Environ. 775, 145827. https://doi.org/10.1016/J.SCITOTENV.2021.145827.

Syaiful, A., Assidiq, M.M.H.A., Noor, H., Indah, Y., Zuraidah, F., Mifta, M.D., 2021. Predicting the number of COVID-19 sufferers in Malang city using the backpropagation neural network with the Fletcher-Reeves method. Appl. Comput. Intell. Soft Comput. 2021, 1–9. https://doi.org/10.1155/2021/6658552.

Tian, P., Wang, J., Hua, W., Hao, F., Huang, J., Gong, Y., 2021. Temporal-spatial patterns and coupling coordination degree of water resources carrying capacity of urban agglomeration in the middle reaches of the Yangtze River. J. Lake. Sci. 33 (6), 1871–1884. https://doi.org/10.18307/2021.0621.

UNESCAP, 2013.The Status of the Water-Food-Energy Security Nexus in Asia and the Pacific Rejion. http://www. unescap. org/ sites/ default/ files/ Status-of-the-Water-Energy-Food-Nexus-15%2520 March. Pdf/ (accessed 27 February 2020).

Wang, J., Bao, Z.X., Zhang, J.Y., Wang, G.Q., Liu, C.S., Wu, H.F., Yang, Y.Q., 2022d. Spatio-temporal matching and nexus of water–energy–food in the yellow river basin over the last two decades. Water 14 (12), 1859. https://doi.org/10.3390/W14121859.

Wang, Y., Sun, R., 2022. Impact of land use change on coupling coordination degree of regional water-energy-food system: a case study of Beijing-Tianjin-Hebei Urban Agglomeration. J. Nat. Resour. 37 (3), 582–599. https://doi.org/10.31497/zrzyxb.20220303.

Wang, Y., Chen, X., Sun, P., Liu, H., He, J., 2021b. Spatial-temporal evolution of the urban-rural coordination relationship in northeast China in 1990–2018. Chin. Geogr. Sci. 31 (3), 429–443. https://doi.org/10.1007/s11769-021-1202-z.

Wang, B., Chen, M., Zheng, S., 2022a. Comprehensive evaluation of inter-regional scientific and technological innovation capability in anhui province based on AHP-EWM method. Sci. Technol. Manag. Res. 42 (02), 75–83. https://doi.org/10.3969/j.issn.1000-7695.2022.2.010.

Wang, D., Wang, L., Zhang, G.,2012. Short-term wind speed forecast model for wind farms based on genetic BP neural network. J. Zhejiang University (Eng. Sci.) 46(0-5), 837-841+904. doi:10.3785/j.issn.1008-973X. 2012. 05. 010.

Wang Q., Zhao J., Wang Y.S., 2022e. Deformation Prediction of Tailings Dam Based on PSO-BP Combined Model. Geospat Inf.20(11):119-122+128. DOI:10. 3969/j.issn. 1672-4623.2022.11.028.

Wang, D., Hong, L., Zhang, C., Bai, Y., Bi, Z.Z., Lin, Y., Khan, M.A., 2022f. Prediction model for driver reaction time based on PSO-BP neural network model. Secur. Commun. Netw. 2022, 1–13. https://doi.org/10.1155/2022/6100702.

Wang, Z., Tian, X., Huang, M., Zhang, B., 2022c. Design of thrust estimator in the solid rocket ramjet based on PSO-BP neural network. J. Aerosp. Power. 37 (7), 1487–1494. https://doi.org/10.13224/j.cnki.jasp.20210325.

Wang, S., Yang, J., Wang, A., Chen, C., Liu, T., 2022b. Evaluation and forecast of coupling coordination of water resources, economy and ecosystem in the Yellow River Basin of Henan Province. J. Lake Sci. 34 (03), 919–934. https://doi.org/10.18307/2022.0314.

Wang, J., Zhang, J., Bao, Z., Wang, G., Wu, H., Yang, Y., 2021a. Response of grain yield to climate change driving water resources change. Adv. Water Sci. 32 (6), 855–866. https://doi.org/10.14042/j.cnki.32.1309.2021.06.005.

Wei, X., Lin, L., Luo, P., Wang, S., Yang, J., Guan, J., 2022. Spatiotemporal pattern and driving force analysis of multi-functional coupling coordinated development of cultivated land. Trans. Chin. Soc. Agric. Eng. 38 (04), 260–269. https://doi.org/10.11975/j.issn.1002-6819.2022.04.030.

Wu, L., Elshorbagy, A., Alam, M.S., 2022. Dynamics of water-energy-food nexus interactions with climate change and policy options. Environ. Res. Commun. 4 (1), 015009.

Xu, L., Deng, X., Jiang, Q., Ma, F., 2021c. Identification and poverty alleviation pathways of multidimensional poverty and relative poverty at county level in China. Acta Geograph. Sin. 76 (06), 1455–1470. https://doi.org/10.11821/dlxb202106010.

Xu, B., Li, L., Wang, Z., Zhou, H., Liu, D., 2021a. Prediction of springback in local bending of hull plates using an optimized backpropagation neural network. Mech. Sci. 12 (2), 777–789. https://doi.org/10.5194/MS-12-777-2021.

Xu, H., Wang, Y., Zhang, Z., Gao, Y., Zhang, D., 2021b. Coupling mechanism of water-energy-food and spatiotemporal evolution of coordinated development in the Yellow River Basin. Resour. Sci. 43 (12), 2526–2537. https://doi.org/10.18402/resci.2021.12.14.

Zhao, L., Liu, S., Sun, C.,2021. Study on coupling and coordinated development of water-energy-food security system in the Yellow River Basin. Water Resour. Protection 37-(01):69-78. doi: 10. 3880 /j. issn. 1004-6933. 2021. 01. 010.

Zhao, J.J., Liu, Y., Zhu, Y.K., Tai, S.L., Wang, Y.H., Miao, C.H., 2020. Spatiotemporal differentiation and influencing factors of the coupling and coordinated development of new urbanization and ecological environment in the Yellow River Basin. Resour. Sci. 42 (1), 159–171. https://doi.org/10.18402/resci.2020.01.16.

Zhou, K., 2022. Comprehensive evaluation on water resources carrying capacity based on improved AGA-AHP method. Appl. Water Sci. 12 (5) https://doi.org/10.1007/S13201-022-01626-2.

Zhou, C., Feng, X., Tang, R., 2016. Analysis and forecast of coupling coordination development among the regional economy-ecological environment-tourism industry—A case study of provinces along the Yangtze Economic Zone. Econ. Geogr. 36 (03), 186–193. https://doi.org/10.15957/j.cnki.jjdl.2016.03.025.

Zhou, D., Zuo, X., Xi, W., Xiao, B., You, B., 2021. Combined SBAS-InSAR and PSO-BP algorithm for evaluating the risk of geological disasters in alpine valley regions. Trans. Chin. Soc. Agric. Eng. 37 (23), 108–116. https://doi.org/10.11975/j.issn.1002-6819.2021.23.013.

Zuo, Z., Guo, H., Cheng, J., Li, Y., 2021. How to achieve new progress in ecological civilization construction? – Based on cloud model and coupling coordination degree model. Ecol. Ind. 127, 107789 https://doi.org/10.1016/J.ECOLIND.2021.10-7789.

Zuo, Q., Yang, Z., Cao, H., Ma, J., 2022. Evaluation and analysis of water ecological security in the Yellow River basin based on SMI-P method. J. Henan Norm. University (Nat. Sci. Ed.) 50 (3). https://doi.org/10.16366/j.cnki.1000-2367.2022.03.002, 10–19+165.