Development and synergetic evolution of the water–energy–food nexus system in the Yellow River Basin

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Abstract

The water–energy–food nexus is a complex system where balancing the trade-offs across water, energy, and food sectors is especially difficult in resource-deficient areas. The Yellow River Basin is an area in which water shortages lead to conflicts among water, energy, and food resources. Thus, investigating the evolution state and spatial characteristics of the water–energy–food nexus in the Yellow River Basin is essential for the management of resources and sustainable development orientation of the region’s water–energy–food nexus system. This study proposed an integrated assessment framework by using synergy theory and the integrated index system method. The improved Lotka–Volterra symbiotic model was used to elucidate the development and synergy evolution status of the water–energy–food nexus system in prefecture-level cities in the Yellow River Basin between 2004 and 2019. The results show that the order degree of the water and energy subsystems in the Yellow River Basin increased by an average of 0.12 and 0.42, on average respectively, from 2004 to 2019, whereas that of the food subsystem only increased by an average of 0.004 compared to the initial year. Furthermore, most prefecture-level cities experienced subsystem degradation of one or two subsystems during the evolution of the water–energy–food nexus system. Based on the uniqueness and evolution process of each city, there are eight possibilities for system evolution and three types of feedback state between each pair of subsystems, which may lead to a certain spatial aggregation. Additionally, the interaction and competition states are more common than synergy states in the water–energy–food nexus system of the Yellow River Basin. This study provides an important basis and suggestions for the internal relationship and sustainable orientation of water–energy–food nexus systems in such water-deficient areas.

Keywords Water–energy–food nexus · Yellow River Basin · Synergy theory · Spatio–temporal dynamics · Lotka–Volterra model · Feedback

Introduction

The conflict between limited resources and increasing resource demand is on the rise globally (Zhang et al. 2019). The World Meteorological Organization (WMO) reported that 3.6 billion people experienced water shortages for at least 1 month per year in 2018 (WMO 2021) and this number is expected to rise to 5 billion people by 2050. Additionally, 759 million people worldwide lived without access to electricity (International Energy Agency [IEA] 2021) and nearly 690 million people worldwide faced starvation in 2019 (Food and Agriculture Organization of the United Nations [FAO] 2020). Water, energy, and food are essential resources for human survival, well-being, and development and are included in the United Nations (UN) Sustainable Development Goals (UN 2015). Water, energy, and food are intrinsically linked and any constraint on the availability of one affects that of other resources in this system (Bazilian et al. 2011). This nexus highlights that the realization of the Sustainable Development Goals can lead to diverse synergistic benefits and trade-offs (Zhang et al. 2020a). Thus, quantifying the complicated interdependencies among water, energy, and food is critical for sustainable development (Liu et al. 2018). The water–energy–food nexus (WEFN) is complex, dynamic, and also uncertain as mutual feedback among these and external influencing factors fundamentally affects the entire system (Lin et al. 2021). Due to differences
in resource endowment and economic development across regions, WEFN tends to possess distinct regional characteristics. In densely populated and ecologically fragile areas, there are often particularly severe conflicts among water consumption, energy access, and food production goals (Wang et al. 2021a). The cross-feed and cascade effect of the cross-regional water–energy–food (WEF) system (Ozturk 2015) should be investigated extensively considering the universality of the WEFN and the resource flow induced by commerce.

The Yellow River Basin (YRB) in China is extremely scarce in water resources and suffers from a fragile water environment as a result of its climate and geographical location. Since ancient times, the region has been a representative area in China with an inherently weak ecology and human-resource conflicts (Chen and Chen 2009; Wang et al. 2021b). However, it has also been known for its exceptional energy resources and large grain production capability (Xiang et al. 2016). The rapid expansion of coal-fired power generation and the increasing demand for food grains further exacerbated water scarcity in the supply chain of watershed resources (Toshiaki et al. 2019). There are complex connections and interactions among water, energy, and food, both direct and indirect. Water is purified and transported for use in agriculture, energy, and other sectors. Water resources also support the production and transportation of a great quantity of primary energy resource in the basin, such as coal production. At the same time, water treatment and transportation processes need support from the energy sector. Finally, food production consumes a large amount of water, and transportation and processing of food products require energy support. Furthermore, agriculture holds the potential for future biomass energy production. The YRB is a water resource-deficit miniature (Chen et al. 2020) and provides an example of the concentrated and prominent contradictions which can occur within a regional WEFN. The YRB is a water resource-deficit miniature in Asia and Africa (Chen et al. 2020), and is an example of concentrated and prominent contradictions within regional WEFN.

Thus far, there have been few relevant studies on the WEFN of the YRB. Most studies have focused on the macro perspective, and quantitative studies on the evolution process of the WEFN. However, studies that explore the mutual-feed state within the YRB WEFN system are lacking. Overall, water resources have been the focus of research in the YRB for a long time. Numerous studies have analyzed the YRB’s watershed water systems and management (Omer et al. 2021; Jia et al. 2015; Xiao et al. 2019) and the interaction between water and other systems (Wang et al. 2020; Yin et al. 2021a). Water resources undoubtedly play a major role in the resource system of the YRB. However, based on the complex relationship of WEFN and the reality of the water resource scarcity in this region, efforts toward sustainable development of the YRB must be based on the coordinated management of multiple sectors with a focus on water resources, especially for coordinating the agriculture and energy sectors (Rasul 2016). Sun et al. (2020) quantified the energy and food production process and the pressure on water systems based on footprint theory under the framework of the WEFN. Furthermore, Peng et al. (2017) discussed the optimal layout of the three resources by establishing a collaborative optimization model. Most studies were conducted either from a holistic perspective of the watershed or with provincial administrative regions as the study areas. According to the river system, the YRB is a natural boundary, but not an appropriate boundary for a complete provincial region (Li et al. 2021b) and simply considering the provincial administrative regions as the research object would fail to achieve a more tailored analysis of the basin. Additionally, the resource endowment and utilization degree exhibit distinct regional characteristics, which greatly affects the development of the WEFN system in micro-scale areas (Qiu and Chen 2020). Thus, at a micro-scale, the development characteristics and trends of the WEFN system in the YRB could be better interpreted (Zhang et al. 2021).

Various methods can be applied for different research purposes on the WEFN that can be classified as follows. The first type is accounting and evaluation methods, such as input–output analysis (Liu et al. 2017), index system methods (Schlor et al. 2018), and pressure-state-response models (Wang et al. 2018). The second is about demonstrate and simulate the evolution of associated systems, such as the system dynamics model (Wu et al. 2021; Zeinab et al. 2020), which is a typical method for simulating the evolution of the WEFN. The last kind is about system optimization and development decision assistance models, such as the water–energy–food nexus tool 2.0, developed by Daher and Mohtar (2015). From this context, synergy theory and associated methods have been widely used for complex systems. Synergy theory was introduced based on multi-disciplinary links, form the works of the German physicist Haken (1975). This theory examines the similarities between various systems that range from disorder to order. Synergy between the subsystems of any complex system arises due to external causes or when the aggregation state of matter reaches a critical point (Yin et al. 2021b). This effect can induce qualitative changes in the system at the critical point. Additionally, the symbiotic theory originating from biological research (Quispel 1951) has also been widely applied in social, economic, and resource studies to describe symbiotic relationships between systems (Chen and Chen 2021; Wei et al. 2018). Zhang and Huang (2021) used this theory to analyze the competitive and cooperative relationships among four systems using the Grey Lotka-Volterra model. Similar to other complex systems, the evolution of the WEFN includes material production, energy, and information exchange. Each
The complex nonlinear interaction of subsystems in the WEFN system is likely to cause the entire system to develop in an orderly manner and eventually stabilize. By applying synergy and symbiotic theory to the WEFN system, one can identify the feedback state between subsystems. Notably, Zhang et al. (2020b) used the Lotka–Volterra symbiotic model to analyze the evolution state of the WEFN system in microscopic areas.

In summary, the development level of the WEFN system and the synergetic evolution of the system in the YRB are poorly understood. Moreover, the mutual feedback of state within the system and the role of the WEFN system in micro regions of the YRB are understudied. This study explores the WEFN system evolution process of the YRB between 2004 and 2019. Based on the results and the unique characteristics of region, spatio-temporal dependencies are evaluated and relevant laws are summarized. The WEF integrated index system is based on the water, energy and food subsystems for prefecture-level cities. The objectives of this study are (1) to elucidate the development and synergy evolution process of the WEFN system in the YRB, a representative water-scarce region; (2) to quantify and reflect individual differences in YRB cities and the spatial heterogeneity of each YRB region from the perspective of cities; (3) to apply the synergy evolution model, which is an improved Lotka–Volterra symbiotic evolution model, to estimate the synergy evolution status of the YRB WEFN system; and (4) to analyze the synergy evolution and feedback state of the three subsystems and detect their spatial evolution characteristics. The study aims to provide references and specific policy guidelines for future studies and decision-makers to aid in the creation of efficient and sustainable YRB resource systems.

The remainder of this paper is organized as follows: “Methods and materials” introduces the context of the study area and proposes the formulation and solution process of the WEF synergy evolution model; “Results” describes the results of the order degree and the synergy evolution process; “Discussion” discusses the horizontal comparison of subsystem development characteristics and offers suggestions for future research directions; and “Conclusions and policy implications” presents the main conclusions and suggests policy implications.

### Methods and materials

#### Study area

The Yellow River is China’s second longest river, and an important water source for northern China. It flows through nine provinces, namely Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong. YRB comprises mostly arid and semi-arid areas with relatively scarce precipitation, with an average of only 496.9 mm in 2019 (MWR China’s water resource report in 2019, 2020). Although the basin’s per capita water supplies are far below the world average, water resources are diverted for irrigation and replenishing tributaries in the region. The Yellow River’s runoff has been declining annually since the late twentieth century, and the scarcity of water resources has increasingly worsened (Zhang et al. 2009). However, there is a pressing need for economic growth (Fu et al. 2021) despite the vulnerability of the basin’s ecology. The YRB is also known as China’s “energy basin,” as it hosts nearly half of China’s coal bases and 70% of coal-fired power stations (Zhao et al. 2021). Energy is mainly transported to developed and high-demand areas in the east in the form of coal or electricity. There are many major agricultural areas in the YRB such as Fenwei Plain and North China Plain, which are important for maintaining national food security (Xiang et al. 2017). Most of China’s water resources are distributed in the south, whereas coal and grain production areas are clustered in the north. From this perspective, spatial mismatches are the main driver of water resource shortages in the YRB. However, the dependence on the rapid development of mineral resources indicates that resource depletion and environmental pollution are likely to pose challenges to the future development of the basin (Li et al. 2020). The contradiction between the supply and demand of resources manifested by the WEFN in the YRB has become increasingly prominent, thereby greatly affecting the sustainable development of the area (Fig. 1). Water resources are the key to the security and sustainable development of the WEFN system in the YRB, both of which are currently under threat.

We selected 66 cities (including prefecture-level and leagues) in the YRB for analysis, covering nine provinces with eight provincial capital cities (Fig. 2). It should be noted that due to the challenges of acquiring data at micro-scales, the regions of Qinghai province except for Xining and Haidong were not included. Of the 66 cities, 36<sup>1</sup> are resource-based cities, and they account for nearly 30% of the total number of resource-based cities in China. (Resource-based cities are cities with the mining and processing of natural resources such as minerals in the region as the leading industry<sup>1</sup>.) These cities feature significant differences in resource endowment and economic development (Li et al. 2013). In general, there is a clear spatial pattern of high development in the east and low development in the west (Wang et al. 2020), although industrial competitiveness

<sup>1</sup>The data are obtained according to China official statistics. http://www.gov.cn/zwgk/2013-12/03/content_2540070.htm
shows variable development trends. For instance, in 2017, the GDP disparity between Jinan and Xining (the two provincial capitals in the eastern and western parts of the basin) was more than fivefold (China National Bureau of Statistics). Overall, it is necessary to elucidate the differences in resources and the socio-economic development of cities along the YRB and their potential impacts on the development of the micro-scale WEFN system.

**Data sources**

The WEFN system has multiple functions and feedback routes, necessitating the identification of the system’s core challenges and boundaries. Given the data available, this analysis assumes that city systems are independent. We investigated the resource conditions, level of regional resource development, and feedback state without considering the possibility of resource mobility between regions.
The indicator selection considered the supply, consumption, efficiency, and quality of resources in each subsystem. Given the availability and reliability of the data, 18 indicators were selected for the three subsystems to establish an integrated index of the WEFN system in cities in the YRB from 2004 to 2019 (Table 1). The data were obtained from the China National Bureau of Statistics, the China City Statistical Yearbook, the China Water Resources Bulletin, and the statistical yearbooks and water resource bulletins of provinces and cities in the basin. The data gaps of some years were filled by linear interpolation.

### Evaluation framework of WEFN system development and synergetic evolution

First, the development level and evolution process of the WEFN system in the YRB was evaluated. Here, “development level” is defined as the scale and development degree of the WEFN system over the research period. Second, the synergetic effect of the WEFN system, including synergy evolution and the synergy feedback state, was evaluated. Index selection, order degree calculation, a synergy evolution model, and a synergy optimization model were combined to provide an integrated methodology. Based on index selection, the variable weights were obtained using the entropy method, which is objective and can solve the problem of information overlap between multi-index variables. The order degree of the subsystem was obtained by multiplying the variable weight and the standardized component value. The order degree can reflect the evolution process of the system and is a reference for evaluating the system’s development level. Based on the improvement of the Lotka–Volterra model, a synergy evolution model was obtained. Based on the model, the order degree of the subsystem was used as the data sample to describe the synergetic effect of the system. The optimal coefficient solution and the optimal value of the subsystem were obtained through the synergy optimization model, which can be used to judge whether the WEFN system of each city can reach the progressive evolution state. Finally, the synergy evolution model was solved under the proved steady state criteria.

### Order degree assessment

#### Index weights

First, the WEFN system was defined as $S_i (i = 1, 2, 3)$, where $S_1$, $S_2$, and $S_3$ represent the water, energy, and food subsystems, respectively. $x_i (i = 1, 2, \ldots, I)$ represents the variable. For any subsystem, $S_i$ has $m (m = 5, 6, 7)$ variable sets, where a variable set consists of all the components in a time series of the variable.

To eliminate the dimensional impacts, the components need to be normalized and divided into positive and negative types based on their characteristics. A component with positive characteristics, such as total water resources, indicates that the larger the value of the component, the better the impact of the component on the system. In contrast, a component

### Table 1 Index institution and weights

| Subsystem | Variable                                | Data sources and explanation                                      | Weights |
|-----------|-----------------------------------------|-------------------------------------------------------------------|---------|
| Water     | Total water resources                    | Water Resources Bulletin by Region                                 | 0.1703  |
|           | Water supply                            | Water Resources Bulletin by Region                                 | 0.1399  |
|           | Water production coefficient            | Ratio of precipitation to land area                               | 0.1540  |
|           | Per capita water consumption            | Water Resources Bulletin by Region                                 | 0.1339  |
|           | Water pressure                          | Ratio of the sum of agricultural and industrial water consumption to water consumption | 0.1423  |
|           | Proportion of groundwater in water supply| Ratio of groundwater to water supply                              | 0.1343  |
|           | Industrial wastewater discharge         | Water Resources Bulletin, City and Statistical Yearbook by Region  | 0.1253  |
| Energy    | Power generation                        | Statistical Yearbook by Region                                    | 0.1960  |
|           | Main primary energy output              | Statistical Yearbook by Region (include raw coal, crude oil, and natural gas) | 0.2414  |
|           | Energy consumption per 10^4 Yuan GDP    | Statistical Yearbook by Region                                    | 0.1741  |
|           | Energy consumption                      | Statistical Yearbook by Region                                    | 0.1940  |
|           | Entire society’s power usage            | Statistical Yearbook by Region                                    | 0.1944  |
| Food      | Residents’ food consumption expenditure| Statistical Yearbook by Region                                    | 0.1765  |
|           | Effective irrigation area               | Statistical Yearbook by Region                                    | 0.1738  |
|           | Power of agricultural machinery         | Statistical Yearbook by Region                                    | 0.1724  |
|           | Proportion of sown area of crops        | Ratio of sown area of crops to total sown area                    | 0.1520  |
|           | Grain output                            | Statistical Yearbook by Region                                    | 0.1603  |
|           | Proportion of agricultural water        | Ratio of agricultural water consumption to water consumption      | 0.1651  |
with negative characteristics, such as industrial wastewater discharge, indicates that the lower the component value, the better the impacts on the system. The normalization of the two types of components can be described by Eqs. (1) and (2):

\[
x'_{ij} = \frac{x_{ij} - b_{ij}}{a_{ij} - b_{ij}} \quad \text{(positive component)} \tag{1}
\]

\[
x'_{ij} = \frac{x_{ij} - b_{ij}}{a_{ij} - b_{ij}} \quad \text{(negative component)} \tag{2}
\]

where \(x'_{ij} \in [0, 1]\) represents the normalized value, \(x_{ij}\) represents the value of each order component in the \(j\)th year of \(l\) th city, and \(a_{ij}\) and \(b_{ij}\) represent the maximum and minimum components of each variable, respectively (\(a_{ij} > x_{ij} > b_{ij}\)).

The entropy method was applied to calculate the weights to avoid the randomness and conjecture that are inherent in a subjective weighting method. Suppose there were \(L\) cities, \(x'_{ijl}\) was the normalized value of \(i\) th variable in the \(j\) th year of \(l\) th city. Here, the three subsystems were considered to be equally important. Thus, the sum of the variable weight for each subsystem was set as 1. The weight can be calculated using Eqs. (3)–(5):

\[
p_{ijl} = \frac{x'_{ijl}}{\sum_{j=1}^{J} \sum_{i=1}^{I} x'_{ijl}} \tag{3}
\]

\[
e_i = -k \sum_{j=1}^{J} \sum_{i=1}^{I} p_{ijl} \ln (p_{ijl}) \tag{4}
\]

where \(k = 1 / \ln(n)\), \(e_i \geq 0\). Non-zero processing need carried out on the \(p_{ijl}\)

\[
w_i = \frac{1 - e_i}{\sum_{i=1}^{I} 1 - e_i} \tag{5}
\]

### Order degree

After retrieving the weights, the order degree was calculated using Eq. (6):

\[
u_{ijl} = \sum_{i=1}^{I} x_{ijl} w_i \tag{6}
\]

where \(u_{ijl}\) is the order degree of the subsystem in the \(j\) th year of \(l\) th city and \(w_i\) is the weight of each variable (Table 1). The order degree levels are shown in Table 2.

### Synergy evolution model

Like other complex systems, the WEFN system evolution trajectory conforms to the logistic model, where \(X\) represents the development level of the system. The resultant equation is shown below as Eq. (7):

\[
dX/dt = \alpha X(1 - X) \tag{7}
\]

where \(\alpha\) denotes the growth coefficient of the system. \(\alpha X\) and \(1 - X\) represent the positive growth feedback and deceleration growth feedback of the system, respectively.

Based on the logistic model, the Lotka–Volterra model was extended to determine the competition among biological populations through Eq. (8):

\[
dX_1/dt = \alpha X_1(1 - \frac{X_1}{N_1} - \beta \frac{X_2}{N_2}) \tag{8}
\]

For species A and B, \(X_1\) and \(X_2\) are the population sizes of the two species, \(N_1\) and \(N_2\) are the environmental tolerance of the two species, \(\alpha\) is the population growth coefficient of \(X_1\), and \(\beta\) is the competition coefficient of species B against species A.

Given the extremely scarce water resources, the YRB suffers from water resource allocation deficit and a trade-off between energy and agricultural production sectors. For analyzing the feedback among the three subsystems, the competition for water can be represented by the competition among biological populations.

With reference to existing research (Zhang et al. 2020b), the calculation was improved based on the panel data of the cities WEFN system in the YRB from 2004 to 2019. Therefore, the Lotka–Volterra model was adapted for the WEFN system, as shown in Eqs. (9)–(11):

\[
dX_1/dt = f_1(X_1, X_2, X_3) = F'_1 = \alpha_1 X_1(1 - X_1 - \beta_{12} X_2 - \beta_{13} X_3) \tag{9}
\]

\[
dX_2/dt = f_2(X_1, X_2, X_3) = F'_2 = \alpha_2 X_2(1 - X_2 - \beta_{21} X_1 - \beta_{23} X_3) \tag{10}
\]

\[
dX_3/dt = f_3(X_1, X_2, X_3) = F'_3 = \alpha_3 X_3(1 - X_3 - \beta_{31} X_1 - \beta_{32} X_2) \tag{11}
\]

where \(X_1\), \(X_2\), and \(X_3\) represent the order degree of water, energy, and food subsystems, respectively, while \(\alpha_1\), \(\alpha_2\), and \(\alpha_3\) are the growth coefficients of the three subsystems,

| Level       | Extremely low | Relatively low | Medium | Relatively high | Extremely high |
|-------------|---------------|----------------|--------|----------------|----------------|
| Order degree| [0–0.2)       | [0.2–0.4)      | [0.4–0.6) | [0.6–0.8)     | [0.8–1.0)       |

Table 2: Levels of order degree
Table 3 Types of synergy evolution state among subsystems

| Interspecific state | $\beta_h$ | $\beta_i$ |
|---------------------|-----------|-----------|
| Synergy             | $< 0 < 0$ | $= 0 < 0$ |
|                     | $= 0 > 0$ | $> 0 < 0$ |
| Interacting         | $> 0 < 0$ | $< 0 > 0$ |
| Competitive         | $> 0 > 0$ | $> 0 = 0$ |
|                     | $= 0 > 0$ | $= 0 = 0$ |

respectively. Further, $\beta_{12}$ and $\beta_{13}$ are the competition coefficients for the energy and food subsystems to the water subsystem, respectively; $\beta_{21}$ and $\beta_{23}$ are the competition coefficients for the water and food subsystems to the energy subsystem, respectively; and $\beta_{31}$ and $\beta_{32}$ are the competition coefficients for the water and energy subsystems to the food subsystem, respectively. If both competition coefficients are negative, the two subsystems exhibit a synergistic state. If both competition coefficients are positive, the two subsystems exhibit a competitive state. With one negative and one positive coefficient, the two subsystems manifest as an interacting state with both positive and negative interactions (Table 3). The synergy evolution model of the WEFN system in cities in the YRB was established. The results of the model were retrieved by Matlab (2017), where the value spaces of $\alpha$ and $\beta$ were set at $[-1, 1]$ and $[-6, 6]$, respectively, to enable fast convergence.

**Analysis of the stable point**

$A(t)$ is stable when all solutions start in a sufficiently close surrounding and remain in this surrounding. If $B(t)$ approaches $A(t)$ over time, the distance will eventually disappear (Zhang et al. 2020b). Based on this, whether the WEFN system finally reaches the stable state can be determined. When $f_1 = 0$, $f_2 = 0$, and $f_3 = 0$, the stable points can be determined using the steady-state equation. There are five stable points: $Q_1(0, 0, 0)$, $Q_2(0, 0, 1)$, $Q_3(0, 1, 0)$, $Q_4(1, 0, 0)$, and $Q_5(X^0, X^0, X^0)$. $Q_1$, $Q_2$, $Q_3$, and $Q_4$ do not conform to a stable state of coexistence for the three subsystems. $Q_5$ indicates that the three subsystems eventually vanish. $Q_2$, $Q_3$, and $Q_4$ indicate that only one of the three subsystems will reach stability and the other two will vanish. $Q_5$ is the only stable point in the system at which the three subsystems achieve coexistence. By solving the simultaneous equations, the stable point can be concluded.

$$Q_5(X^0, X^0, X^0) = Q_5(M_1/M, M_2/M, M_3/M)$$  \(12\)

In order to solve the model coefficients and stable points, the steady-state equation was converted into a Taylor series and formulated as follows:

$$f_1 = M_{11}(X_1 - M_1/M) + M_{12}(X_2 - M_2/M) + M_{13}(X_3 - M_3/M)$$  \(13\)

$$f_2 = M_{21}(X_1 - M_1/M) + M_{22}(X_2 - M_2/M) + M_{23}(X_3 - M_3/M)$$  \(14\)

$$f_3 = M_{31}(X_1 - M_1/M) + M_{32}(X_2 - M_2/M) + M_{33}(X_3 - M_3/M)$$  \(15\)

$$M = \begin{bmatrix}
M_{11} & M_{12} & M_{13} \\
M_{21} & M_{22} & M_{23} \\
M_{31} & M_{32} & M_{33}
\end{bmatrix}$$  \(16\)

Setting the solutions of the matrix to $\lambda_1, \lambda_2, \lambda_3$, the solutions can be obtained through matrix $M$ as described in Eq. (13). When $|\lambda E - M|$ equals zero:

$$|\lambda E - M| = \lambda^3 - \lambda^2 + r \lambda - q = 0$$  \(17\)

It can be derived using Eqs. (19)–(21):

$$p = \lambda_1 + \lambda_2 + \lambda_3$$  \(18\)

$$q = \lambda_1 \lambda_2 \lambda_3$$  \(19\)

$$r = \lambda_1 \lambda_2 + \lambda_1 \lambda_3 + \lambda_2 \lambda_3$$  \(20\)

Considering the practical significance of WEFN systems, the singular point is asymptotically stable when $\lambda < 0$. Therefore, when $p < 0$, $q < 0$, and $r > 0$, point $Q_5$ is stable.

**Synergy optimization model**

The improved accelerated genetic algorithm (AGA) (Jin and Yang 2001) is used to solve the optimal values of $\alpha$ and $\beta$ under constraints. The equation of AGA can be expressed as follows:

$$\min f(c_1, c_2, \ldots, c_H) \quad a_h \leq c_h \leq b_h \quad h = 1, 2, \ldots, H$$  \(21\)

where $\{c_h\}$ denotes $H$ variables. $[a_h, b_h]$ is the initial change interval of $c_h$. $f$ is a non-negative optimization criterion.
function. The general step of genetic algorithm includes generating the next generation population estimated value by probabilistically selecting individuals from observed value to produce offsprings via genetic operators of crossover and mutation (Lakka et al. 2013). Based on the improved AGA, an optimal model was constructed to obtain the optimal order degree of the three subsystems. The formula is shown as Eq. (23):

\[ f = \min \frac{1}{3} \left[ \sum_{j=1}^{16} (F_j^1 - f_j^1)^2 + \sum_{j=1}^{16} (F_j^2 - f_j^2)^2 + \sum_{j=1}^{16} (F_j^3 - f_j^3)^2 \right] \]  

where the objective function \( f \) was set as the minimization of the mean square error, between observed and estimated values for each subsystem’s order degrees. \( F_j^1, F_j^2, \) and \( F_j^3 \) are the observed values of each subsystem’s order degrees in the \( j \)th year, respectively; \( f_j^1, f_j^2, \) and \( f_j^3 \) are the estimated values of each subsystem’s order degrees, respectively. \( a \) and \( \beta \) can be solved using the proposed model. The equation must conform to \( p < 0, q < 0, r > 0, \) and \( 0 < x < 1. \)

Results

Results of order degree

Order degree of the water subsystem

Figure 3 shows the water subsystem order degree level of 66 cities from 2004 to 2019. The order degree of the water subsystem in cities exhibits a positive trend with some fluctuations. It increased by 0.12 (or 26.08%) in 2019 on average. The inflection point of 2017, with \( \sim 1/3 \) of the cities exhibiting a high or extremely high level after 2017. Compared with the other two subsystems, the development process of the water subsystem in cities fluctuates more prominently. The substantial annual variation in precipitation driven by regional climate and the influence of flooding in some years were the main factors that affected the regional water production coefficient. Precipitation was the main source of regional water production, without considering the source of water diversion. Meanwhile, the weights of the total water resources and water production coefficient in the water subsystem were 0.170 and 0.154, respectively. They accounted for the first and second highest proportions. The interannual differences in precipitation exerted a substantial impact on the fluctuation of the water system in the study area.

During the entire study period, most cities in the lower reaches of the YRB did not experience significant improvement in the water subsystem order degree (Fig. 3). The variation suggests that water subsystem development in the entire basin was limited during the study period. The downstream urban population density was high, and regional water consumption, especially by agriculture, was also high. Water pollution due to large-scale agricultural development poses a severe challenge to the quality of the regional water environment. Therefore, the downstream water system is more vulnerable to the influence of economic and social factors compared to other parts of the basin. In contrast, the cities in the upper and middle reaches of the YRB exhibited a more positive trend after 2017. Water resources in the middle and upper basin of cities with less economic or social pressure can maintain a delicate balance with other sectors and have a comparably healthier level of development. The modest decrease in water pressure, in addition to the order degree, implicitly represents the subsystem’s demerits. Simultaneously, the proportion of groundwater supply to overall water supply
in the whole basin is generally controlled. Reconciling the conflict between water supply and agriculture will be an important task for YRB water resource management in the future.

**Order degree of the energy subsystem**

Figure 4 illustrates the order degree level of energy subsystems in 66 cities. As noted, development of the energy subsystem of cities in the YRB generally exhibited a positive trend. The order degree of the energy subsystem increased on an average by 0.42 in 2019, thereby manifesting a staggering increase of 168.20%. Notably, some cities in the YRB’s middle reaches, such as Yulin and Shuozhou, played a pivotal role in the development of the energy industry in the basin and even at the national level. Furthermore, the vast majority of the energy subsystems of cities also developed to various degrees. Energy subsystems were mainly impacted by energy supply, which included primary energy and electricity production. Primary energy production had the highest weightage in the energy subsystem. Cities in the middle reaches of Shanxi Province have superior energy resource conditions. Meanwhile, the adjustment of the industrial structure and technological innovation had improved regional energy production and utilization efficiency. Therefore, the level of the energy subsystem in these cities noticeably improved over time. In contrast, cities with weak energy resources or those with high energy consumption experienced a relatively minor increase in the development level.

In addition to resource endowment, the development of energy subsystem is also inseparable from the stimulation of external economic factors. Compared with the natural mobility of water resources, the development and transfer of energy resources rely more on human operation and intervention. Therefore, regions with weak energy endowment or high demand need to rely on external support. This will have a certain impact on the stability of regional energy system. The majority of city energy subsystems attained the medium level after 2010. Since the world began to recover from the impact of the financial crisis (Reinhart and Rogoff 2014), China’s economy also changed from the period of rapid development before the financial crisis to the period of industrial structure adjustment. In this regard, economic development and industrial structural changes also had an impact on the energy sector’s requirements. For example, the entire society’s power usage is increasing annually. The corresponding power generation and traditional energy conversion efficiency are also improving. Furthermore, environmentally friendly ideals and low-carbon development both necessitate structural reforms in the energy sector to increase the proportion of renewable and clean energy. The development of abundant hydropower, wind, and solar energy resources in the YRB, in addition to traditional energy, can revitalize this “energy basin.”

**Order degree of the food subsystem**

Figure 5 shows that the development level of the food subsystem in cities exhibited a parabolic trend (first – increase, then – decrease). The order degree of the food subsystem only improved by 0.004 (1.08%) on average from the beginning of the year. In contrast to the favorable trends observed in the water and energy subsystems, that of the food system's development was negative towards the end of the study period. In 2019, the order degree of the food subsystem declined by 0.18 (28.74%) on average compared to 2015. Simultaneously, pronounced disparities were observed in city development levels. Cities in agricultural areas, such as those in Henan and Shandong provinces, showed a steady development trend in the food subsystem. Following 2016, the food subsystem witnessed a downward trend in development. At the end
of the study period, approximately one-third of cities, including Taiyuan, Zibo, and Xi’an, witnessed a decline in development.

Grain supply and consumption mainly influenced the food subsystem. Being affected by natural factors, the main agricultural areas in the YRB, located in the middle and lower reaches, are often affected by floods. At the same time, the demand for food in the middle and lower reaches of the densely populated and surrounding areas of the river basin is high. Per capita food consumption expenditures and consumption annually increased over the study period. The agricultural sector is the largest water user. From the perspective of the YRB, it is challenging to only rely on diversion irrigation from the Yellow River to meet the demand for agricultural water because it contradicts the ecological and sustainable requirements. In turn, this has triggered a long-term severe conflict between agricultural demand and water resources. The development of water-saving and high-efficiency agriculture is essential to balance the contradiction between agriculture and the water sector, the environment, and alleviate the water pressure of other sectors in the YRB. Moreover, agricultural development hides the vast potential for future energy sector development. The participation of local measures and policies can strengthen the stability of food subsystem. Agricultural production guidance and disaster warnings are necessary. The efficient cooperation between agriculture, water, and energy departments is therefore conducive for promoting the output efficiency of the food subsystem and the coordinated and stable development of the basin’s WEFN system.

Analysis for the system evolution within the WEFN

The system evolution and spatial characteristics

The feedback state of the WEFN system was analyzed based on the results of $\alpha$ and $\beta$. The results showed that the optimal order degree of water, energy, and food subsystems improved in five cities. Thus, the synergy evolution and stability of the WEFN system can be achieved without increasing consumption in other subsystems. The optimal order degree of only two subsystems of the 30 cities improved at the cost of increasing the consumption of the third subsystem. The remaining cities improved the third subsystem at the cost of the two other subsystems.

We also revealed the variations of the subsystems and their relations. The analysis of $\alpha$ showed that the WEFN system evolution of the 66 cities could be divided into eight types (Fig. 6). Figure 6 shows that there were seven cities with $\alpha_1$, $\alpha_2$, and $\alpha_3$ greater than zero, with most of them located in the lower reaches of the basin. There were nine cities with $\alpha_1$, $\alpha_2$, and $\alpha_3$ below zero, which were scattered. Moreover, most cities featured different degrees of subsystem degradation during WEFN system evolution, with degradation in one or two subsystems. It could be seen that cities with one or two subsystems degradation are more common in YRB, and one subsystem degradation is concentrated in the middle reaches.

Feedback status among the subsystems was analyzed using the results of $\beta$ shown in Figs. 7 and 8. Compared with the decentralized distribution of cities in the energy–food subsystems, cities in the water–food subsystems are more concentrated in the first and second quadrants, which means that the food subsystem tends to have a negative effect on the water subsystem. In the water–energy subsystems, cities are more obviously concentrated in the first and fourth quadrants, which represent the tense negative relationship between water and energy subsystems. The synergy state between the energy and food subsystems was better than that for the other two couples. There were nine cities in the synergy state for the water–energy subsystems, which are scattered. The number of cities with interacting and competition states was
similar. Thirteen cities reached the state of energy–food subsystem synergy; most cities were distributed in the middle and lower reaches of the basin. Of the rest, two-thirds were in an interacting state, and one-third was in a competitive state, mainly distributed in the upper reaches of the basin. Additionally, there were four cities in the synergy state for water–food subsystems, mainly clustered in the middle and lower reaches of the river basin. The cities with competition state were mainly distributed in the lower reaches of the river basin and the cities with developed agriculture.

Overall, the synergy evolution among the subsystems in the YRB did not show the positive state. Given the limitations posed by water, the synergy state among the subsystems was weaker, and most cities had one or two subsystems in a pairs of competition state. The resource characteristics of each region indicated that the synergy evolution state of the subsystems basically followed a spatial distribution law. Compared with the decentralized spatial distribution of the synergy evolution state of water–energy subsystems, the aggregated spatial distribution of energy–food and water–food subsystems was more prominent. The water–energy subsystems exhibited distinct zoning aggregation, while the water–food subsystems exhibited extensive agglomeration characteristics. Generally, places with more intense agricultural activity or energy production require water resources more urgently, thus exacerbating the tension among the three subsystems. This spatial distribution corresponds to regions with superior energy endowment and...
agricultural production capacity. Notably, both Liaocheng and the provincial capital Xi’an experienced two synergy states and one interacting state. The $\alpha$ coefficients of the two cities were all above zero (Table 4), suggesting that the WEFN system is in the ideal process of synergy development. While the provincial capital city Xi’an is currently under the condition of balancing the distribution of water resources and adjusting the proportion of agricultural production. Xi’an relies on the superior economic strength and leading role of the capital city and stands out with a higher synergy evolution level than Liaocheng.

**Uniqueness of feedback state of research object**

The uniqueness of WEFN system in cities was well reflected in the feedback state (Fig. 7). The feedback state between subsystems can be elucidated by analyzing the actual situation of the cities. By taking the Hohhot city (Inner Mongolia) as an example, the $\beta_{12}$ and $\beta_{21}$ in the water–energy subsystems of Hohhot are less than zero. This means that water and energy development promote each other. Inner Mongolia, where Hohhot is located, is a major energy province not only in the river basin but even in China. By relying on the abundant solar energy in the region, Hohhot is vigorously developing photovoltaics and actively adjusting the energy industry structure, to indirectly reduce pressure on the water sector. Additionally, $\beta_{23} > 0$ and $\beta_{32} < 0$ in the energy–food subsystems of Hohhot, thereby exhibiting an interacting state. Besides the positive role of energy in agricultural production, water resources are the main factor, leading to competition between the energy and food sectors. The vigorous development of clean energy in the future may change this state. At $\beta_{13} > 0$ and $\beta_{31} > 0$, competition exists between the water and food subsystems. The mismatch between supply and demand of water resources induces the competitive state between the two subsystems. An increasing agricultural grain output inevitably enhances agricultural water consumption. In contrast, the management of water resources inevitably affects agricultural efficiency and expansion. Competition between the two subsystems becomes more apparent as one progresses; in comparison, the other will be limited or even regress. However, in Jiaozuo (another city downstream) the state of the three pairs of subsystems is opposite to that in Hohhot. This is related to its dependence on traditional energy and low utilization efficiency. Yangquan, with poor water resources is a coal resource-based city in the middle reaches of the YRB and presents competition state in the three pairs of subsystems. It has a weak agricultural foundation but stands out with developed industry. The regional industry is highly demanding from an energy and water resource perspective, while the agricultural sector also needs water for development. It is an emblematic example of the conflict between scarce water resources and the high demand for energy and agricultural development. It can be seen that even in large areas with general shortage of water resources, the synergy evolution and feedback state of WEFN system in internal micro areas are not the same. Overall, WEFN systems are seemingly more sustainable in the areas of the YRB where water resources are relatively abundant and the demand for

**Table 4** Comparison of $\alpha$ between Xi’an and Liaocheng

| City     | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ |
|----------|------------|------------|------------|
| Xi’an    | 0.0656     | 0.0914     | 0.2257     |
| Liaocheng| 0.0261     | 0.0679     | 0.0029     |
other sectors is low. The more finding needs to be examined by analyzing the detailed characteristics of cities.

**Discussion**

This study evaluated the development level and synergy effect of the WEFN system in prefecture cities in the YRB, and confirmed that there are three types of feedback states in the WEFN system. Compared with previous studies (e.g., Xiang et al. 2017) which reveal that there is competition among water use, energy, and food production requirements, this study attempted to go deeper into the cities of the basin, providing a reference for the study of the WEFN system from the meso perspective at a cross-regional scale. The following properties are discussed in detail from three aspects: (1) the characteristics of the WEFN system in the YRB, (2) the meaning of optimal value, and (3) resource-based city and the way forward.

**Characteristics of the WEFN system in the YRB**

By calculating the basin interannual average value of the order degree of the three subsystems, the development of the subsystems was compared horizontally (Fig. 9). It can be seen that the interannual average order degree of the three subsystems is mainly concentrated at the medium level; the upper limit values are between 0.6 and 0.7, i.e., relatively high. It could be found that the energy subsystem has the lowest initial average development level and the largest span, but the mean value is the lowest among the three subsystems, and the gap between the mean value and the median is also the largest. The upper and lower line interval of food subsystem is the smallest. Through simple comparison, we found the law of the average development level of three subsystems. Although the box diagram could not reflect the rise and fall of the food subsystem, the food subsystem is still the best in terms of the overall development level of the three subsystems. The energy subsystem has experienced an excellent and great leap forward development process. Consistent to the findings in the results, the average of interannual order of water subsystem is relatively concentrated, the development range is limited, and the overall development level is also the lowest among the three subsystems.

We think that the significance of the WEFN in reality society is reflected in the positive synergy among the three subsystems. By optimizing subsystems and the mutual synergy feedback state, the WEFN can ensure social stability and coordinated development. In other words, whether WEFN can realize the benign and sustainable cycle through interaction between the subsystems and finally achieve sustainable development? The goal is not to pursue the optimization of one or two subsystems over others, but rather to find a non-zero-sum game way to trade-off the three subsystems to obtain the maximum benefits. However, it is difficult to maintain static stability in the balance of the three subsystems. Due to the interference of social and economic factors, the balance may be better described as a dynamic balance: the interaction between the three subsystems should be flexibly and appropriately adjusted while considering external factors. However, this goal is more difficult to achieve in the YRB given its limited water resources.

**Meaning of optimal value**

The lack of water resources is the main factor, affecting the state of the WEFN system in the YRB. As seen, the shortcomings of any sector in the system affect the development status of all three subsystems and the feedback status among them. It is really difficult for some regions in the YRB to balance the water demand between industrial, agricultural, and ecological needs owing to limited water resources. This difficulty of trade-off is manifested by the fact that the stability points of some cities do not pass the stability test, with negative optimal values for some cities according to the synergy optimization model. The untested stability point indicates that even if the WEFN system of a city is in a stable equilibrium state, it may break the balance due to the interference of minor factors. At the same time, the negative optimal value does not agree with the practical significance of the WEFN system. It should be noted that it is difficult for the system to reach a satisfactory synergy development level without sacrificing any subsystem, when considering
research period and the existing development mode and level. Thus, it is urgently necessary to simulate the evolution process of the WEFN system, to find the optimal development method of the system, and to realize it in practice.

**Resource-based city and the way forward**

Coal, nonferrous metals and other resource-based cities in the middle and upper reaches are representative cities in the YRB. These resource-based cities are in different stages of the life cycle. It can be found from Fig. 7a that the tension between water and energy subsystems in resource-based cities is more common. Whether resource-based cities have a more universal relationship between the development of WEFN system and evolution feedback needs further analysis. The WEFN system for resource-based cities also needs more targeted evaluation framework and data support.

The resource flows across regions were not considered because of the scarcity of available data. In practice, regional resources move between regions in complex forms, both directly and virtually. In the future, a multi-layer flow network of the WEFN system in the YRB could be constructed by defining the flow boundary of resources and describing the flow network of water, energy, and food resources. This framework could then be used to elucidate the optimal sustainable development state of the WEFN and the implied environmental responsibility for the resource flow.

**Conclusions and policy implications**

This study, by combining the index system method and synergy assessments, proposed an integrated assessment framework for the YRB, China. An integrated index system was established to measure the WEFN system development level of cities in the YRB. The improved Lotka–Volterra model was applied to quantify the WEFN system synergy evolution state in the study region.

We found that the development level of water and energy subsystems in the YRB increased to different degrees, while the food subsystem exhibited a downward trend at the end of the study period. We observed that most of the WEFN systems of cities experienced one or two system degradation processes during evolution. We identified the synergy, interaction, and competition states in the WEFN systems of cities in the basin. The competition which expresses as one progress, the other will be limited or even regress between the water subsystem and the other two subsystems, especially for the food subsystem, was found to be substantial. The lack of water resources will have a significant adverse effect on the state between the other subsystems. It is challenging for most downstream cities to significantly advance the WEFN system toward sustainability without strong water management and conservation measures. Ultimately, we demonstrated that the development level and feedback state of the WEFN system in different regions of the YRB exhibited different characteristics and regional aggregation, and analyze the impact of detailed characteristics on WEFN system.

We suggest that the regional WEFN system can be promoted to be somewhat sustainable through agricultural, energy, and technological improvements and by proportional structure adjustments tailored by effective policy measures. On one hand, agriculture stands out with the greatest potential and contribution to water sustainability and the WEFN system feedback. Hence, improving the agricultural water use and adjusting the structure of agricultural crops can strongly reinforce regional water conservation. On the other hand, reducing the energy industry’s dependence on water will likely alleviate the regional water conflicts and will promote the stability of the development of the WEFN system. Nowadays, primary energy and thermal power generation are essential for energy production systems, thereby requiring improvements in the energy conversion efficiency and water efficiency. In this context, the proportion of clean energy could be reasonably increased in the basin. Then, regional decision-makers need to change the mode of resource development and move toward development with high added value and low emissions. For instance, the dependence on the ecological resources of the region suggests that the water resources of the upstream region could be reasonably and efficiently converted into economic value, such as through the development of ecological tourism. At the same time, pave the way toward exploring and improving the water rights system through policies and market mechanisms. It is possible to extend this approach to other resource systems in order to promote the flow of resources and improve resource utilization efficiency. Ultimately, any policy and initiative should consider the synergistic effects for all measures, which requires collaborative resource management. When considering industrial layout and resource allocation, in addition to the macro perspective, it should also be combined with the actual situation and sustainability of meso regions.

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**Data availability** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Declarations**

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Conflict of interest** The authors declare no competing interests.

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