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Identification of key brittleness factors and multi-scenario analysis of the water-energy-food-ecology nexus vulnerability based on NRS-BN

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Water, energy and food are the basic resources on which human beings depend for survival. With the intensification of human activities, the demand for resources represented by water, energy and food continues to increase, resulting in increasing pressure on the ecological environment, and the vulnerability of water, energy, food and ecosystem becomes increasingly prominent. Identifying the critical vulnerability factors of the water-energy-food-ecology nexus and formulating targeted management measures have become the key to achieving sustainable development. This paper innovatively proposes to study the water-energy-food-ecology nexus from the perspective of vulnerability for the first time, in which the vulnerability evaluation index system of the water-energy-food-ecology nexus is firstly constructed based on the VSD framework, and the attribute reduction is carried out using neighborhood rough sets. Then, a Bayesian network model is built and parameter learning is performed by combining machine learning and expert experience. Finally, different scenarios are set up to identify the key factors that hinder the vulnerability reduction of the water-energy-food-ecology nexus and obtain the vulnerability probability of the nexus under different scenarios using forward and backward inference and sensitivity analysis of Bayesian networks, overcoming the drawback that many prediction models cannot achieve diagnostic inference. The results show that: 1) from 2008 to 2019, the overall vulnerability of the water-energy-food-ecology nexus in the Yangtze River Economic Belt is low. 2) The key factors at the indicator level that hinder the vulnerability reduction of the water-energy-food-ecology nexus mainly include the storage capacity of water conservancy projects, wastewater discharge per 10,000-yuan GDP, and water consumption per 10,000-yuan GDP, and the subsystem level is water, food, energy and ecology system, in that order. 3) The reduction in vulnerability within an individual subsystem can have a beneficial impact on reducing vulnerability within the water-energy-food-ecology nexus. However, this reduction may also lead to

an increase in vulnerability within other subsystems. Therefore, in the process of developing water, energy, food, and ecology system, high priority should be given to the coordinated development of all four.

KEYWORDS

water-energy-food-ecology nexus, vulnerability, neighborhood rough set, Bayesian network, Yangtze River Economic Belt

1 Introduction

Water, energy, and food are indispensable resources for human survival and development, as well as the key to national economic development, and their stable supply is essential for the smooth operation of society (Zhang et al., 2022). The concept of the “water-energy-food” nexus was first introduced in Bonn, Germany, in 2011, which clarified the complex relationship between water, energy and food systems (Wang et al., 2021). At present, scholars at home and abroad have explored and analyzed the impact of resources on regional economic development (Xu et al., 2021) and the sustainable development paths of resources (Luxon et al., 2018) at the national (White et al., 2018), regional (Markantonis et al., 2019) and urban (Li et al., 2016) levels, focusing on the social and natural properties of the water-energy-food nexus. Water, energy and food are relatively independent and inextricably coupled feeder systems, and developing one system often requires the consumption of resources of the other two systems. For example, the transportation of water resources and the processing of food require large amounts of energy. Also, the extraction of energy and the growth of food cannot be achieved without the support of water resources (Ma et al., 2021). However, these processes are often also closely related to the ecology system. The United Nations Economic Commission for Europe (UNECE) states that the resources and services provided by ecosystems are an essential guarantee for the security of the water-energy-food nexus and a necessary basis for achieving sustainable regional development (Wang et al., 2022). Currently, ecosystems have become an important indicator for measuring sustainability (Reyers and Selig, 2020), adaptability (Zhi et al., 2020), security (Ravar et al., 2020; Cansino-Loeza et al., 2022), and coupling coordination (Luo et al., 2022) of water-energy-food nexus (Ji et al., 2023). Urbanization and industrialization, as driving factors, not only increase the continuous consumption of resources, but also put tremendous pressure on the ecological environment, reducing the self-regulation and self-repair capacity of the ecosystem, which in turn hinders water, energy, food, and ecosystem security (Wang et al., 2021), making water, energy, food and ecology inextricably intertwined. As a result, a complex and dynamic water-energy-food-ecosystem is formed. Therefore, based on the importance of ecology to the water-energy-food system, the ecology system should be included in the water-energy-food nexus to understand the linkages among water, energy, food, and ecosystems from a more comprehensive perspective, and the concept of water-energy-food-ecology nexus is proposed on this basis. At this stage, studies on the water-energy-food-ecology nexus have mainly focused on developing countries with unstable social development, scarce natural resources, weak concepts of sustainable development, and poor ecological environments (Shi et al., 2020a). They have mainly

focused on exploring resource sector management strategies (Howells et al., 2013) and addressing the resilience of social-ecological systems to external shocks (Schlör et al., 2018), and other frontier issues such as the value of services in the water-energy-food nexus (Sun and Xie, 2020). The research methods include life cycle assessment (Armengot et al., 2021), computable general equilibrium models (Chen et al., 2020), Bayesian network models (Shi et al., 2020b). For example, Sun and Xie (2020) established the “water-energy-food” service value accounting system based on the concept of the value of ecosystem services, and calculated the service value of “water-energy-food” on social economy and natural ecology and its linkage relationship in Guizhou Province during 2013–2017. The water-energy-food-ecology nexus has become a theory and tool to alleviate regional water, energy, food, and ecological tensions, as well as an effective method to achieve more efficient resource use (Vanham, 2016).

Water-energy-food-ecology nexus systems are enormous and complex. Vulnerability is the inherent attribute (Wang and Fu, 2019). In recent years, with the massive gathering of population and industries, the increasing shortage of water resources, fluctuations in food supply, dramatic increase in energy demand, and damage to ecological functions have become increasingly severe, and the water, energy, food, and ecological nexus systems have emerged with prominent vulnerability characteristics. Vulnerability is a comprehensive concept that includes risk, sensitivity, adaptability, resilience, and other related elements, and there is no clear boundary between the components (Yang et al., 2019). The widely accepted elements of vulnerability are exposure, sensitivity, and adaptive capacity, as indicated in the IPCC report (IPCC, 2001). Based on the existing studies on the concept of vulnerability, this paper considers that the vulnerability of the water-energy-food-ecology nexus means that the structure, state and function of the system change toward the trend of dysfunction and subsequently present an unstable state under the influence of the disturbance of external environment such as human activities and natural conditions and the unbalanced development of the internal system. At this stage, most studies on the vulnerability of the water-energy-food-ecology nexus have explored the impact of changes in internal and external conditions on the vulnerability of individual subsystems such as water resources and ecology from the perspectives of climate, production and supply of resources (Yao et al., 2019), and optimal regulation of resources (Zhou et al., 2019). For example, Zhou et al. (2019) proposed a specific plan to control the vulnerability of groundwater resources under climate change through the assessment and scenario simulation of water resources vulnerability in Chongqing. Wang (2017) built a vulnerability assessment model of the food supply chain network and explored the vulnerable links in the food supply chain network. Song et al. (2021) analyzed the vulnerability of the energy system in the process

of coping with climate change from different aspects, and put forward corresponding development suggestions for the development of China's energy system in coping with climate change. These studies are conducive to the sustainable use of individual resources. However, to a certain extent, they ignore the interrelationships between the four, which is not conducive to the integrated management and regulation of the water-energy-food-ecology nexus, and only a few scholars have paid attention to this issue and evaluated the vulnerability of it from the perspective of complex systems (Chen et al., 2018). In addition, in the construction of the evaluation index system, due to the influence factors of the water-energy-food-ecology nexus exist not only within the nexus, but also in the external systems such as social and economic, the evaluation index system involves a vast range and content. Therefore, building an objective and comprehensive evaluation index system is challenging, and it is easy to ignore the dynamic linkage and degree of mutual influence between the indicators, which to a certain extent will increase the complexity of the prediction model. Forecasting research is still mainly focused on exploring the consumption of resources such as water, energy and food, as well as the impact on ecology and social environment. Fewer studies have been conducted to forecast vulnerability in the form of probability from the perspective of scenario analysis.

Therefore, this paper firstly constructs a vulnerability evaluation index system of the water-energy-food-ecology nexus based on the VSD framework which decomposes system vulnerability into three elements of system exposure, sensitivity and adaptive capacity, and uses neighborhood rough sets for attribute reduction to eliminate redundant indicators. Then, a Bayesian network is constructed based on machine learning and expert experience training, and its parameters are learned. Finally, the key vulnerability factors are identified, and different scenarios are set to perform Bayesian network inference. This paper introduces the Bayesian network into the vulnerability study of the water-energy-food-ecology nexus in the Yangtze River Economic Belt from the perspective of vulnerability. By using Bayesian networks with the features of sensitivity analysis, forward inference and backward inference to carry out prediction research, the vulnerability probability of the nexus under different scenarios can be obtained, overcoming the drawback that many prediction models cannot achieve diagnostic inference, and providing a reference for relevant departments to formulate strategic development plans for water, energy, food and ecology systems.

2 Methods and materials

2.1 Overview of the study area

The Yangtze River Economic Belt covers 11 provinces and cities, as is shown in Figure 1, including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Guizhou, and Yunnan, with an area of about 2.05 million km² and a GDP share of more than 40% of the country, making it one of the regions with the strongest comprehensive strength in China (He et al., 2019). With the constant advancement of industrialization and urbanization, the social economy has developed rapidly and people's living standards have been greatly improved, but at the same time, problems such as

resource shortage and ecological environment degradation have emerged. In terms of water resources, the regional distribution of water resources is uneven, the local water supply contradictions are prominent, and there are water quality and resource water shortages (Kong et al., 2021); in terms of energy supply and consumption, the total energy consumption in the Yangtze River Economic Belt accounts for about 36.8% of the country, but the primary energy production is low, mainly relying on the transfer and import from outside the province. What's more, there are problems in ensuring energy security and promoting green and low-carbon energy transformation. In food, it is more difficult to balance food supply and demand, structural contradictions are increasingly prominent, and food production capacity is lower than the national average (Hu et al., 2019); in ecology, ecological land is occupied, air pollution is obvious, and ecological and environmental risks are prominent. Overall, the water-energy-food-ecology nexus and its subsystem security problems in the Yangtze River Economic Belt are becoming increasingly prominent and have emerged with obvious vulnerability characteristics which restrict the sustainable development. Therefore, it is crucial to investigate the vulnerability of the water-energy-food-ecology nexus in the Yangtze River Economic Belt to promote sustainable development in the region.

2.2 Data resources

The data involved in this study are derived from the 2009–2020 China Statistical Yearbook, China Energy Statistical Yearbook, China Environmental Statistical Yearbook, China Soil and Water Conservation Bulletin, and provincial and municipal statistical yearbooks, and some missing data are obtained by interpolation of adjacent years.

2.3 Research methods

The research in this paper is broadly divided into the following steps: the first step is to construct a vulnerability evaluation index system of the water-energy-food-ecology nexus based on the VSD framework and use the neighborhood rough set theory to approximate the attributes of the original index system; the second step is to train the Bayesian network structure and perform parameter learning based on machine learning and expert experience, and use Netica 5.18 to visualize the Bayesian network; In the third step, the key influencing factors are identified using sensitivity analysis and Bayesian network inference is performed. The specific process is shown in Figure 2.

2.3.1 Construction of vulnerability evaluation index system of the water-energy-food-ecology nexus

The VSD framework decomposes system vulnerability into three dimensions, which are exposure, sensitivity and adaptive capacity (Wang and Zhang, 2021). Among them, exposure refers to the extent to which the system is affected by uneven internal development and disturbed by external conditions such as human activities (Chen et al., 2018); sensitivity refers to the extent to which the structure, state and function of the system are affected; and adaptive capacity refers to the system's ability to



FIGURE 1
Geographic location map of the Yangtze River Economic Belt.

recover itself. On this basis, this paper combined the current situation of water, energy, food and ecology resources in the Yangtze River Economic Belt and the acquisition of data and information to construct a vulnerability evaluation index system for the water-energy-food-ecology nexus, which is shown in Table 1. Among them, the larger the value of the positive index and the smaller the value of the negative index, the more vulnerable the water-energy-food-ecology nexus is.

2.3.2 Neighborhood rough set

Rough set theory was initially proposed by Z. Pawlak (1997), which is centered on knowledge simplification and can effectively

eliminate unimportant and redundant information in evaluation object indicators, and has been widely used in water resources, ecology and other fields in recent years. However, the classical rough set is limited to discrete data, which may lead to inaccurate final results. In response, Hu et al. (2008) introduced the neighborhood model into rough sets based on the existing research. Neighborhood rough sets can handle discrete and continuous data and attribute reduction for symbolic data and their mixed data. The following are some basic definitions of neighborhood rough sets:

Definition 1. For any set $U = \{x_1, x_2, \dots, x_n\}$ on a given real space Ω , the neighbor δ of $\forall x_i$ is defined as:

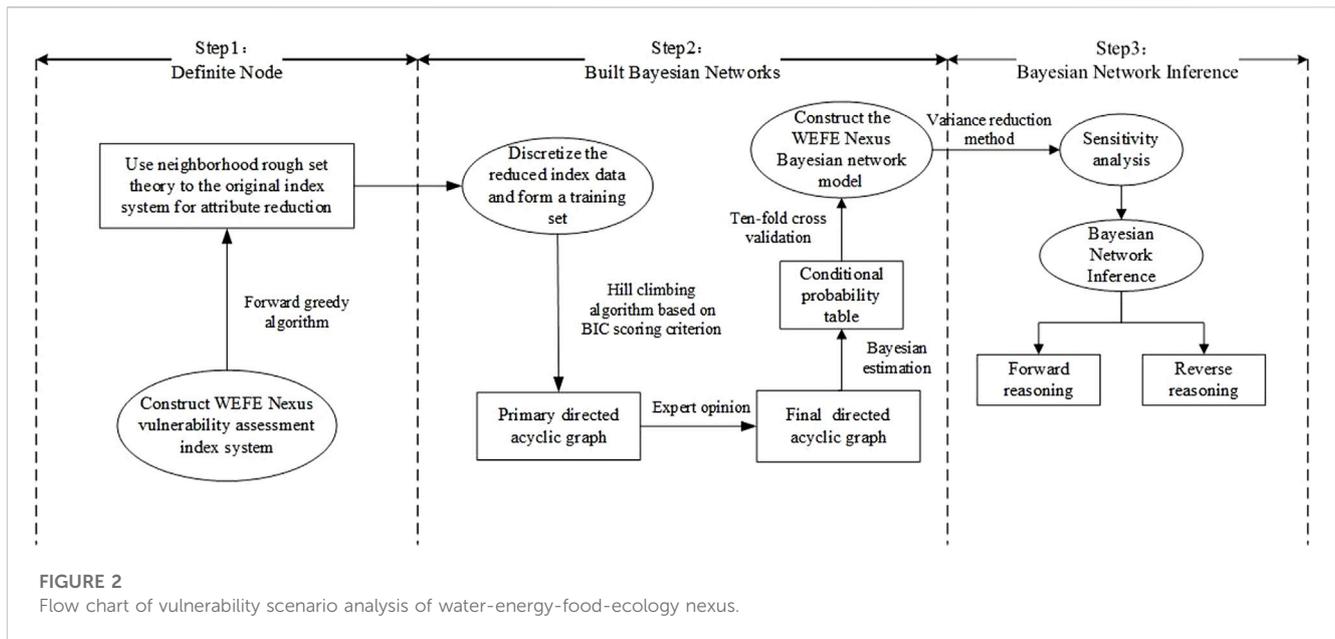


FIGURE 2
Flow chart of vulnerability scenario analysis of water-energy-food-ecology nexus.

$$\delta(x_i) = \{x | x \in U, \Delta(x, x_i) \leq \delta\}, \delta \geq 0 \tag{1}$$

In the formula, Δ is the distance function.

Definition 2. U is the universe, N is the neighborhood relationship on U , and $\{\delta(x_i) | x_i \in U\}$ is the set of neighborhood granularities, then (U, N) is called as an approximate neighborhood space.

Definition 3. A non-empty finite set $U = \{x_1, x_2, \dots, x_n\}$ on the real space Ω and its neighborhood relation N . That is the two-tuple $NS = (U, N), \forall X \subseteq U$. Then the upper approximation and the lower approximation of X in the neighborhood approximation space $NS = (U, N)$ are:

$$\bar{N}X = \{x_i | \delta(x_i) \cap X \neq \emptyset, x_i \in U\} \tag{2}$$

$$\underline{N}X = \{x_i | \delta(x_i) \subseteq X, x_i \in U\} \tag{3}$$

Definition 4. The neighborhood decision table is mainly described by the basic attributes of objects and their attribute values. A neighborhood decision table can be expressed as: $S = \langle U, C, D, V, F \rangle$.

Definition 5. In the neighborhood decision table, let B and D be the attribute sets in U , the positive region of B and D are denoted as $Pos_B(D)$, and the negative region are denoted as $Neg_B(D)$. The formulas are:

$$Pos_B(D) = \underline{N}_B D \tag{4}$$

$$Neg_B(D) = U - \bar{N}_B D \tag{5}$$

Definition 6. The dependence of decision attribute D on condition attribute B is defined as:

$$\gamma_B(D) = \frac{|Pos_B(D)|}{U} \tag{6}$$

Definition 7. Given the neighborhood decision table $S = \langle U, C, D, V, F \rangle$, $B \subseteq C$, $\forall a \in B$, the importance of the attribute a is:

$$SIG(a, B, D) = \gamma_B(D) - \gamma_{B-a}(D) \tag{7}$$

When $\gamma_{B-a}(D) < \gamma_B(D)$ and $\gamma_B(D) = \gamma_C(D)$ are satisfied, then B is said to be a reduction of C .

2.3.3 Bayesian network

2.3.3.1 The basic principle of Bayesian network

Bayesian network is a probabilistic network model based on Bayesian causal inference, first proposed by American scholar Pearl. It can effectively combine priori knowledge and sample data, synthesize the practical expertise of domain experts, and organically unify subjectivity and objectivity, facilitating qualitative and quantitative analysis and avoiding the overfitting of data. Bayesian network is a directed acyclic graph model, the nodes represent the probability distribution of variables, the directed edges between nodes represent the “causality” represented by the conditional probability table, and the nodes are connected into a network by Bayesian conditional probability formula. The conditional probability distribution of network nodes is obtained by prior knowledge and observation data. When adjusting the probability distribution of some nodes, combined with Bayesian formula, Bayesian network can calculate the posterior conditional probability distribution of other nodes to achieve prediction or diagnostic analysis. Therefore, this paper introduces Bayesian network into the vulnerability study of water-energy-food-ecology system in the Yangtze River Economic Belt, carries out prediction research in the form of probability, and uses the characteristics of Bayesian network such as sensitivity analysis, forward reasoning and backward reasoning to screen key impact factors and explore the potential relationship between key impact factors and target nodes, which overcomes the drawback that many prediction models cannot achieve diagnostic inference.

TABLE 1 Vulnerability evaluation index system of WEFE nexus.

Evaluation index system				Impact	
Vulnerability of the WEFE nexus	Vulnerability of water subsystem	Exposure	Domestic water consumption <i>per capita</i> W_1	+	
			Water consumption per 10,000-yuan GDP W_2	+	
			Wastewater discharge per 10,000-yuan GDP W_3	+	
		Sensitivity	Per capita water resource W_4	-	
			Utilization rate of water resources W_5	-	
			Water production module W_6	-	
		Adaptability	Storage capacity of water conservancy project W_7	-	
			Complete investment in wastewater treatment W_8	-	
			Afforestation area W_9	-	
		Vulnerability of energy subsystem	Exposure	Per capita energy consumption E_1	+
				Proportion of energy consumption in primary industry E_2	+
				Intensity of energy consumption E_3	+
	Sensitivity		Primary energy production E_4	-	
			Rate of energy self-sufficiency E_5	-	
			Energy market liquidity E_6	-	
	Adaptability		Investment intensity of resource exploration E_7	-	
			Investment intensity of energy industry E_8	-	
			Comprehensive utilization rate of industrial solid waste E_9	-	
	Vulnerability of food subsystem	Exposure	Per capita food consumption F_1	+	
			Per capita grain sown area F_2	+	
			Fertilizer application per unit grain sowing area F_3	+	
		Sensitivity	Per capita grain possession F_4	+	
			Proportion of grain sown area F_5	+	
			Engel's coefficient F_6	+	
		Adaptability	Area of arable land protected by embankments F_7	-	
			Investment intensity of grain and material reserves F_8	-	
			Investment proportion of agriculture, forestry and water conservancy F_9	-	
	Vulnerability of ecology subsystem	Exposure	Proportion of forest disaster area C_1	+	
			Industrial smoke and dust emissions C_2	+	
			Sulfur dioxide emissions C_3	+	
Sensitivity		Annual precipitation C_4	-		
		Crop disaster rate C_5	-		
		Forest coverage rate C_6	-		
Adaptability		Urban sewage treatment rate C_7	-		
		Intensity of investment in energy conservation and environmental protection C_8	-		
		Soil erosion control area C_9	-		

Note: “+” means positive action; the larger the value, the more vulnerable the water-energy-food-ecology nexus; “-” means negative action.

2.3.3.2 Construction of Bayesian network model and parameter learning

Bayesian network structure learning mainly includes structure learning methods based on independence tests, scoring, and search. Among them, the structure learning method based on the independence test is more intuitive and has the advantages of small computational effort and fast convergence, but the accuracy of the learned network structure is lower. The scoring and search-based structure learning method constructs the network according to specific search strategies and scoring criteria in the structure space of all nodes (Zhang et al., 2014), and its learning goal is to search for network structures with high scores, so the accuracy is better than the independence-based structure learning method. The method mainly consists of selecting the network structure scoring function and the network structure learning algorithm. This paper proposes to construct a Bayesian network using the BIC scoring criterion and Hillclimb algorithm to process the sample data better. BIC (Bayes information criterion) approximates the marginal likelihood function, which is easy to use and helps avoid overfitting, and is the most commonly used scoring function in practice. Hillclimb algorithm starts the search from the initial model, and during the search process, the current model is first modified locally with the search operator to obtain a series of candidate models; then the score of each candidate model is calculated and the best candidate model is compared with the current model. If the best candidate model scores higher, it is used as the next current model, and the search continues; otherwise, stop searching and return to the current model (Li et al., 2019).

Parameter learning of Bayesian network models mainly refers to analyzing sample data to find the conditional probability distribution among the nodes with known network structure. Parameter learning in Bayesian networks can be divided into two cases: data-complete and data-incomplete, when data-complete is usually learned by Bayesian estimation and maximum likelihood method, and when data-incomplete can be learned by EM algorithm (Guan and He, 2016). Compared to the maximum likelihood method, Bayesian estimation treats the parameters to be estimated as random variables that conform to some prior probability distribution. The process of observation of the sample is to transform the previous probability density into the posterior probability density, which corrects the initial estimates of the parameters using the information from the sample and applies to the case of a small sample size. Therefore, this paper proposes to use Bayesian estimation for parameter learning and is implemented by the R language `bnlearn` program package.

2.3.3.3 Bayesian network model sensitivity analysis

Sensitivity analysis has been widely used in various fields of society, such as medical diagnosis and machine fault diagnosis. In Bayesian networks, Sensitivity Analysis (SA) is mainly used to quantify the impact of parameter changes on the target nodes by changing the parameter values of the input nodes. In Netica 5.18, sensitivity analysis is often performed using Mutual Information (MI) based on entropy reduction and Variance of Belief (VB) based on variance reduction (Shi et al., 2022) with the following equations:

$$MI = H(M) - H(M|N) = \sum_m \sum_n P(m, n) \log_2 \left(\frac{P(m, n)}{P(m)P(n)} \right) \quad (8)$$

$$\begin{aligned} VB &= V(M) - V(M|N) \\ &= \sum_m P(m) [X_m - \sum_m P(m)X_m]^2 \\ &\quad - \sum_m P(m|n) [X_m - \sum_m P(m|n)X_m]^2 \end{aligned} \quad (9)$$

Where, V denotes the variance; H denotes the entropy; M denotes the target node; N denotes the other nodes; m and n denotes the state of M and N , respectively; X_m is the real value corresponding to the state m .

2.3.4 Attribute reduction of evaluation indexes and data pre-processing

From the index system constructed above, it can be seen that the water-energy-food-ecology nexus is vulnerable to the joint influence of many internal and external factors, and the possible duplication and redundancy of information among the indexes will have an impact on the research results of the vulnerability of the water-energy-food-ecology nexus. In this paper, without changing the structure and classification ability of the indexes, we apply the neighborhood rough set theory to simplify the attributes of the original index system, which reduces information duplication, improves the accuracy of the evaluation work, and at the same time reduces the complexity of the prediction work. Both conditional and decision attributes are required when using neighborhood rough sets to approximate the evaluation index system. Among them, the decision attributes also need to be discretized data. Therefore, in this paper, the water-energy-food-ecology nexus vulnerability values are calculated using the TOPSIS model (Yue et al., 2019), and the discretization results are used as decision attributes using K-means clustering for discretization.

3 Results and analysis

3.1 Attribute reduction of the indexes

According to the results of discretization, the minimum approximate set is obtained after several times of parameter debugging. Among them, the approximate set of water subsystem is $W = \{W_2, W_3, W_6, W_8\}$, the approximate set of energy subsystem is $E = \{E_1, E_2, E_4, E_7, E_9\}$, the approximate set of food subsystem is $F = \{F_5, F_6, F_8\}$, and the approximate set of ecological subsystem is $C = \{C_3, C_4, C_5\}$. However, due to the limitation of sample data volume, the situation that the more important indicators may be mistakenly deleted during the simplification process may occur. Based on the existing approximate set, indicator W_7 is added to the water resources subsystem, indicators F_2 and F_3 to the food subsystem, and indicators C_6 and C_9 to the ecological subsystem, respectively, to obtain the final index system, as shown in Table 2 below (Chen et al., 2021).

3.2 Construction of Bayesian network

3.2.1 Structure of Bayesian network and parameter learning

First, the initial Bayesian network was constructed and parameters were learned using the R studio `bnlearn` package to

TABLE 2 The index system after the reduction.

Evaluation index system				Impact
Vulnerability of the WEFE nexus	Vulnerability of water subsystem	Exposure	Water consumption per 10,000-yuan GDP W_2	+
			Wastewater discharge per 10,000-yuan GDP W_3	+
		Sensitivity	Water production module W_6	-
		Adaptability	Storage capacity of water conservancy project W_7	-
			Complete investment in wastewater treatment W_8	-
	Vulnerability of energy subsystem	Exposure	Per capita energy consumption E_1	+
			Proportion of energy consumption in primary industry E_2	+
		Sensitivity	Primary energy production E_4	-
		Adaptability	Investment intensity of resource exploration E_7	-
			Comprehensive utilization rate of industrial solid waste E_9	-
	Vulnerability of food subsystem	Exposure	Per capita grain sown area F_2	-
			Fertilizer application per unit grain sowing area F_3	+
		Sensitivity	Proportion of grain sown area F_5	-
			Engel's coefficient F_6	+
		Adaptability	Investment intensity of grain and material reserves F_8	-
	Vulnerability of ecology subsystem	Exposure	Sulfur dioxide emissions C_3	+
		Sensitivity	Annual precipitation C_4	-
			Crop disaster rate C_5	+
			Forest coverage rate C_6	-
Adaptability		Soil erosion control area C_9	-	

Note: "+" means positive action; the larger the value, the more vulnerable the water-energy-food-ecology nexus; "-" means negative action.

obtain the initial conditional probabilities (Table 3). Then, the trained Bayesian network was visualized in Netica 5.18 (Figure 3), and it can be seen that the vulnerability of the water-energy-food-ecology nexus in the Yangtze River Economic Belt is at a low level overall and has a good development trend from 2008 to 2019. However, the probability of a vulnerability being at a high level is still 41.1%, which means there is still more room for improvement in future water, energy, food and ecological resource management. From the subsystem level, the probability that the vulnerability of the water resources subsystem is in a low state is 51.9% at this stage, which is slightly higher than 50%, indicating that the development situation of the water resources subsystem has been more complicated in recent years and the vulnerability status is not optimistic. The probability that the vulnerability of the energy subsystem is in a high state is 54.2%, which is about 10% higher than the low state of vulnerability, and the overall development situation is not good. The food and ecology subsystems perform better, with probabilities of low vulnerability of 80.4% and 74.0%, respectively, indicating that these two systems have better adaptive capacity and higher system security, and are less vulnerable to uneven internal development and external environmental changes. In addition, the complex relationship between the indicators interacting and constraining each other can be seen in Figure 3, and the subsystems are not entirely independent. The indicators can influence the vulnerability state of the subsystem and,

thus, the overall vulnerability of the water-energy-food-ecology nexus.

3.2.2 Validation of Bayesian network

After the structure and parameters of the Bayesian network are learned, the validity of the model needs to be tested (Zhang and Sheng, 2019; Wang et al., 2021). In this paper, we use "water-energy-food-ecology nexus vulnerability" as the target variable and use ten-fold cross-validation to verify the validity of the model and obtain the confusion matrix shown in Table 4. It can be seen that the overall accuracy of the Bayesian network constructed in this paper is 77.2% in predicting the vulnerability of the water-energy-food-ecology nexus, which indicates its high accuracy and reliability.

3.3 Bayesian network inference

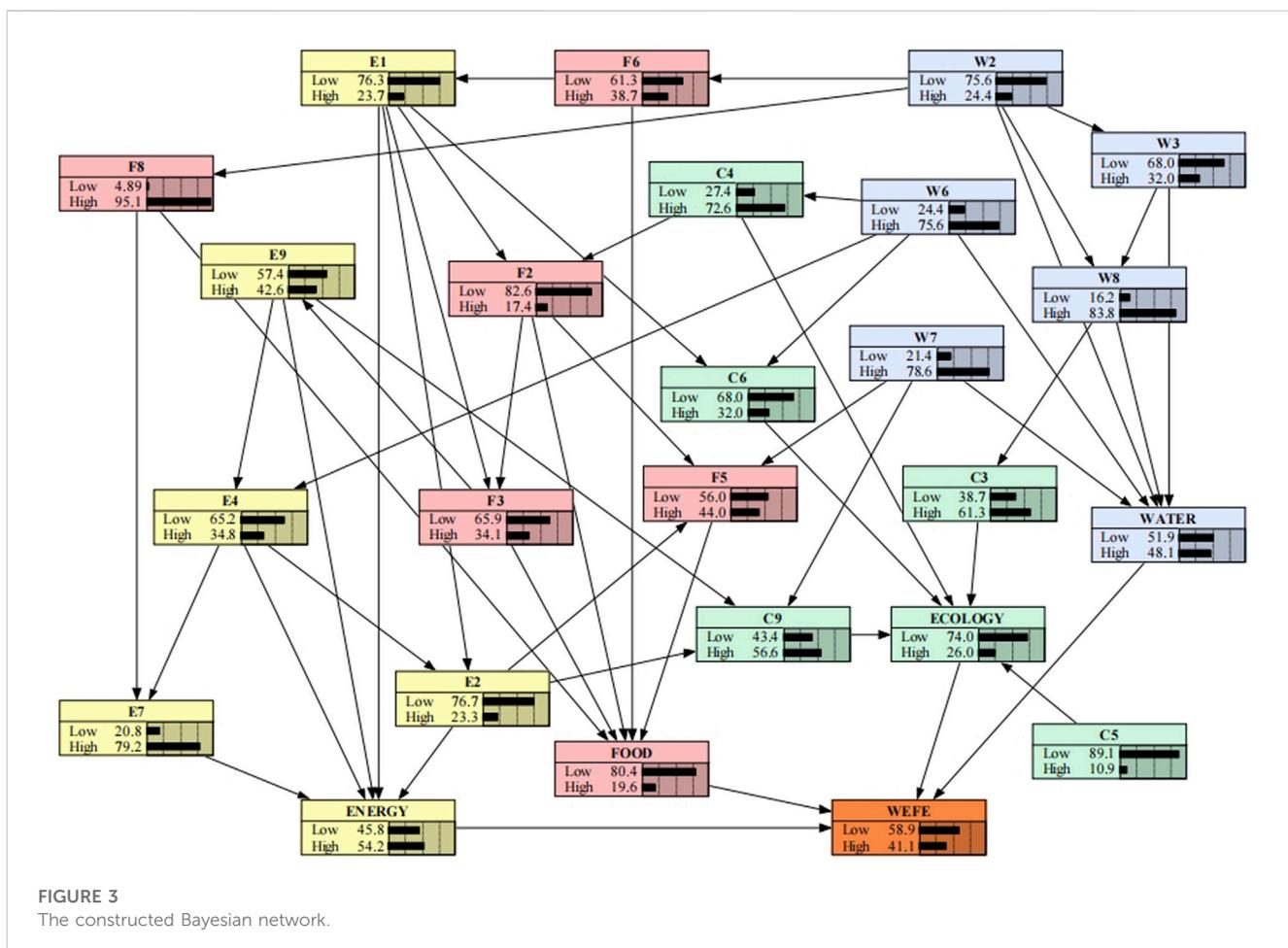
3.3.1 Sensitivity analysis

In Bayesian networks, the essence of sensitivity analysis is also probabilistic inference, which can infer the relationship between one variable and other variables, whereby the degree of influence of certain probabilistic parameters on the outcome is analyzed, and the cause that is most sensitive to the outcome is identified. In this paper, it is mainly used to explore the factors that have a greater influence on the vulnerability of the water-energy-food-ecology nexus at other

TABLE 3 Initial probabilities of Bayesian network nodes.

Nodes	Probability (%)		Nodes	Probability (%)		Nodes	Probability (%)	
	Low	High		Low	High		Low	High
W ₂	75.6	24.4	E ₁	76.3	23.7	F ₂	82.6	17.4
W ₃	68.0	32.0	E ₂	76.7	23.3	F ₃	65.9	34.1
W ₆	24.4	75.6	E ₄	65.2	34.8	F ₅	56.0	44.0
W ₇	21.4	78.6	E ₇	20.8	79.2	F ₆	61.3	38.7
W ₈	16.2	83.8	E ₉	57.4	42.6	F ₈	4.9	95.1
C ₃	38.7	61.3	C ₄	27.4	72.6	C ₅	89.1	19.6
C ₆	68.0	32.0	C ₉	43.4	56.6	Ecology	74.0	26.0
Water	51.9	48.1	Energy	45.8	54.2	Food	80.4	19.6
WEFE	58.9	41.1						

Note: Nodes represent each random variable.



linkage nodes to target the problems in the development of the water-energy-food-ecology nexus. To reflect the influence of each variable on the target variable, the target node “water-energy-food-ecology nexus vulnerability” was used as the analysis variable, and the sensitivity analysis of other variables was conducted using Netica

software. As seen from Figure 4, the sensitivity analysis results based on mutual information and belief variance show the same trend, the larger the mutual information and belief variance, the higher the sensitivity of the target variables to them. From the subsystem level, the water resources subsystem is the key factor affecting the

TABLE 4 Confusion matrix of the trained Bayesian network.

Prediction	Low	High	Row total
Low	60	13	73
High	17	42	59
Column	77	55	132

vulnerability of the water-energy-food-ecology nexus, which is also consistent with the existing findings (Scott et al., 2015; Shi et al., 2022), followed by the food and energy subsystems with mutual information of 0.15995 and 0.01981 and belief variances of 0.05161 and 0.00675, respectively, which means that the food and energy subsystems are the second and third influencing factor of the water-energy-food-ecology nexus, respectively. The ecology subsystem has the least influence, whose mutual information is 0.00423 and belief variance is 0.00141. From the indicator level, the storage capacity of water conservancy project, wastewater discharge per 10,000-yuan GDP and water consumption per 10,000-yuan GDP have a greater impact on the vulnerability of the water-energy-food-ecology nexus.

3.3.2 Forward reasoning analysis

The forward reasoning is mainly used to infer the probability values of the water-energy-food-ecology nexus in different vulnerability states for situations already existing, such as large industrial wastewater effluent discharge and increased water consumption. Based on the results of sensitivity analysis, this paper selects the top three indicators from the subsystem level and the indicator level, sets different scenarios, and uses forward reasoning to examine the degree of impact on the vulnerability of the water-energy-food-ecology nexus when some indicators are optimized. Scenario 1 sets the probability that the water resources subsystem is in a low vulnerability state to 100%; Scenario 2 sets the probability that the food subsystem is in a low vulnerability state to 100%; Scenario 3 sets the probability that the energy subsystem is in a low vulnerability state to 100%; Scenario 4 sets the probability that the storage capacity of water conservancy project is in a low vulnerability state to 100%; Scenario

5 is set as the probability that Wastewater discharge per 10,000-yuan GDP is in a lower vulnerable state is 100%; Scenario 6 is set as the probability that the water consumption per 10,000-yuan GDP is in a lower vulnerable state is 100%. When setting the relevant scenarios, the socio-economic development level of the Yangtze River Economic Belt, scientific and technological innovation capacity, and the target planning of policy documents such as the “14th Five-Year Plan” and “14th Five-Year Plan” for water security were all taken into consideration.

The changes of the probability values of the water-energy-food-ecology nexus system being in different vulnerable states under these six different scenarios are shown in Table 5. As can be seen from the table, when the probability of the water resources subsystem being in a lower vulnerability state is 100%, the probability of the water-energy-food-ecology nexus system being in a lower vulnerability state has the largest rate of change, increasing by 21.9%. Therefore, the stable development of the water resources subsystem will rapidly decrease the vulnerability of the nexus and, *vice versa*, constrain the coordinated development of water, energy, food, and ecosystems. The decrease in the vulnerability of food and energy subsystems leads to a 4.1 percentage point increase in the probability that the water-energy-food-ecology nexus is in a lower vulnerability state, indicating that the decrease in the vulnerability of the food and energy subsystems also has a role in the decrease in the vulnerability of the water-energy-food-ecology nexus. In addition, increasing the storage capacity of water conservancy projects increases the probability of reducing the vulnerability of the water-energy-food-ecology nexus by 16%, indicating the importance of promoting water construction and optimizing water allocation. Moreover, reducing wastewater discharge per 10,000-yuan GDP and water consumption per 10,000-yuan GDP can increase the probability of vulnerability reduction of the water-energy-food-ecology nexus system by 5.9% and 4.5%, respectively. It shows that strict water resources regulation, increased treatment of urban sewage and industrial wastewater, and resource utilization of wastewater can improve water resources utilization efficiency and reduce water resources consumption, which can effectively promote the stable development of the water-energy-food-ecology nexus.

In addition, as shown in Table 6, the probability of a subsystem being in a lower vulnerability state changes with the probability of

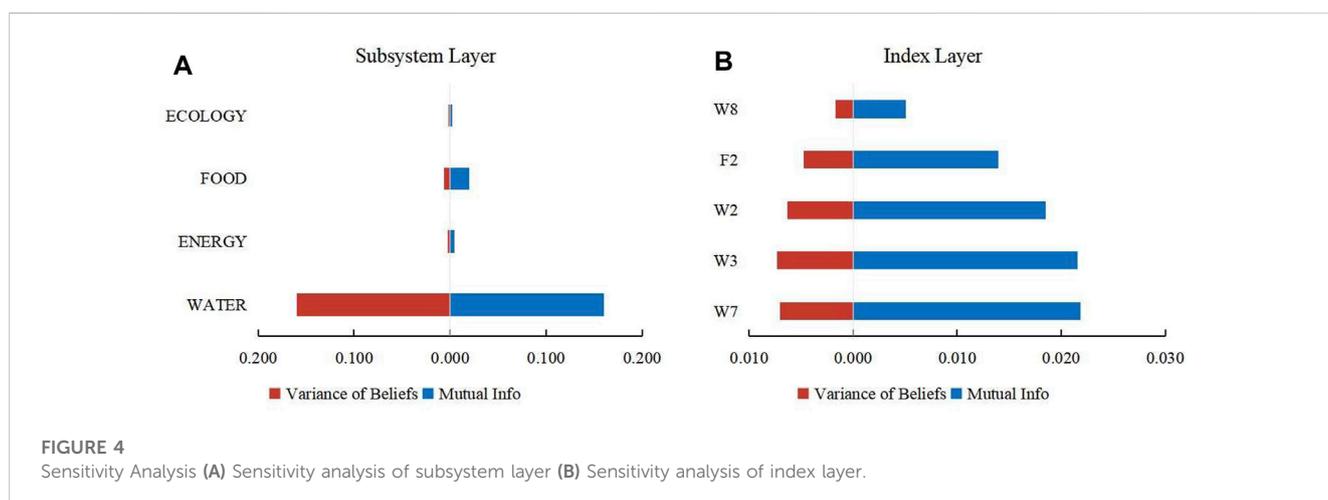


FIGURE 4 Sensitivity Analysis (A) Sensitivity analysis of subsystem layer (B) Sensitivity analysis of index layer.

TABLE 5 Changes in the probability values of vulnerability of the water-energy-food-ecology nexus under different scenarios.

Scenarios	Posterior probability of WEFE (%)		Change rate (%)
	Low	High	
Initial status	58.90	41.10	—
Scenario 1	80.80	19.20	+21.9
Scenario 2	63.00	37.00	+4.1
Scenario 3	63.00	37.00	+4.1
Scenario 4	74.90	25.10	+16
Scenario 5	64.80	35.20	+5.9
Scenario 6	63.40	36.60	+4.5

TABLE 6 Probability of water, energy, food, and ecosystem being in a less vulnerable state under different scenarios and their changes (%).

	Initial	Scenario 1	Change rate	Scenario 2	Change rate	Scenario 3	Change rate
Water	51.9	100	48.1	48.8	-3.1	52.7	0.8
Energy	45.8	46.5	0.7	40.8	-5	100	54.2
Food	80.4	75.6	-4.8	100	19.6	71.6	-8.8
Ecology	74	70.7	-3.3	77.1	3.1	71.6	-2.4

other subsystems. For example, when scenario 1 occurs, the probability of the energy, food, and ecosystem subsystem vulnerability being in a lower vulnerability state change to 46.5%, 75.6%, and 70.7%. The energy subsystem improves by 0.7%, while the food and ecology subsystem decrease by 4.8% and 3.3%, respectively. This also occurs in scenario 3. The probability of the food and ecology subsystems being in a lower state of vulnerability also increase to varying degrees when scenario 2 occurred. This suggests that although the decrease in the vulnerability of individual subsystems can contribute positively to the decrease in the vulnerability of the water-energy-food-ecology nexus, promoting the sustainability of the system, it may also cause an increase in the vulnerability of other subsystems. Therefore, it is necessary to pay attention to the coordinated development of the four. For example, while optimizing water resource allocation, improving water resource utilization efficiency, adjusting energy structure, and reducing energy consumption intensity, we also need to pay attention to the use of pesticides and chemical fertilizers and strengthen ecological protection.

3.3.3 Backward reasoning analysis

In 2020, President Xi pointed out at the symposium on comprehensively promoting the development of the Yangtze River Economic Belt that promoting the development of the Yangtze River Economic Belt requires the integrated consideration of the organic linkage of various aspects such as water ecology and water culture, and it is necessary to optimize the industrial layout, strengthen the protection and restoration work of the ecological and environmental systems, and pay great attention to the issue of food security at the same time. In this regard, this paper takes the vulnerability of the water-energy-food-ecology

nexus as the target node and sets scenario 7, that is, the probability that the water-energy-food-ecology nexus is in a lower vulnerability state is 100%, so as to obtain the probability of each node, as shown in Figure 5.

As can be seen from Figure 5, the probabilities of vulnerability states of water resources, energy, food, and ecological subsystems all change accordingly, and the probabilities of being in lower vulnerability states are 71.1%, 49%, 85.9, and 75.4%, respectively. When the target node is in the ideal state, that is, the probability of the water-energy-food-ecology nexus being in a lower vulnerability state is 100%, the water resources subsystem changes the most, the food and energy subsystems follow, and the ecology subsystem changes the least, with change rates of 19.2%, 5.5%, 3.2%, and 1.4%, respectively. In other words, the water resources subsystem is the most prominent factor affecting the vulnerability of the water-energy-food-ecology nexus at the subsystem level. Therefore, to reduce the vulnerability of the water-energy-food-ecology nexus in the Yangtze River Economic Belt, the primary focus must be on how to reduce the vulnerability of the water resources subsystem. Since the food, energy and ecology subsystems also have an impact on the whole vulnerability, the role of these three cannot be ignored either. In addition, changes in the vulnerability state of the water-energy-food-ecology nexus have somewhat different effects on different indicators. Compared with the initial state, the most obvious change is the wastewater discharge per 10,000-yuan GDP, followed by the storage capacity of water conservancy projects, water consumption of 10,000 Yuan GDP, and then the *per capita* grain sown area. The probability of being in a lower vulnerability state increases by 6.8%, 5.9%, 5.7% and 4.5%, respectively. From this, the vulnerability of the water-energy-food-ecology nexus is mainly influenced by the increase in water consumption, large discharge of wastewater, and decrease in *per capita* grain sown area during the economic development process. It is

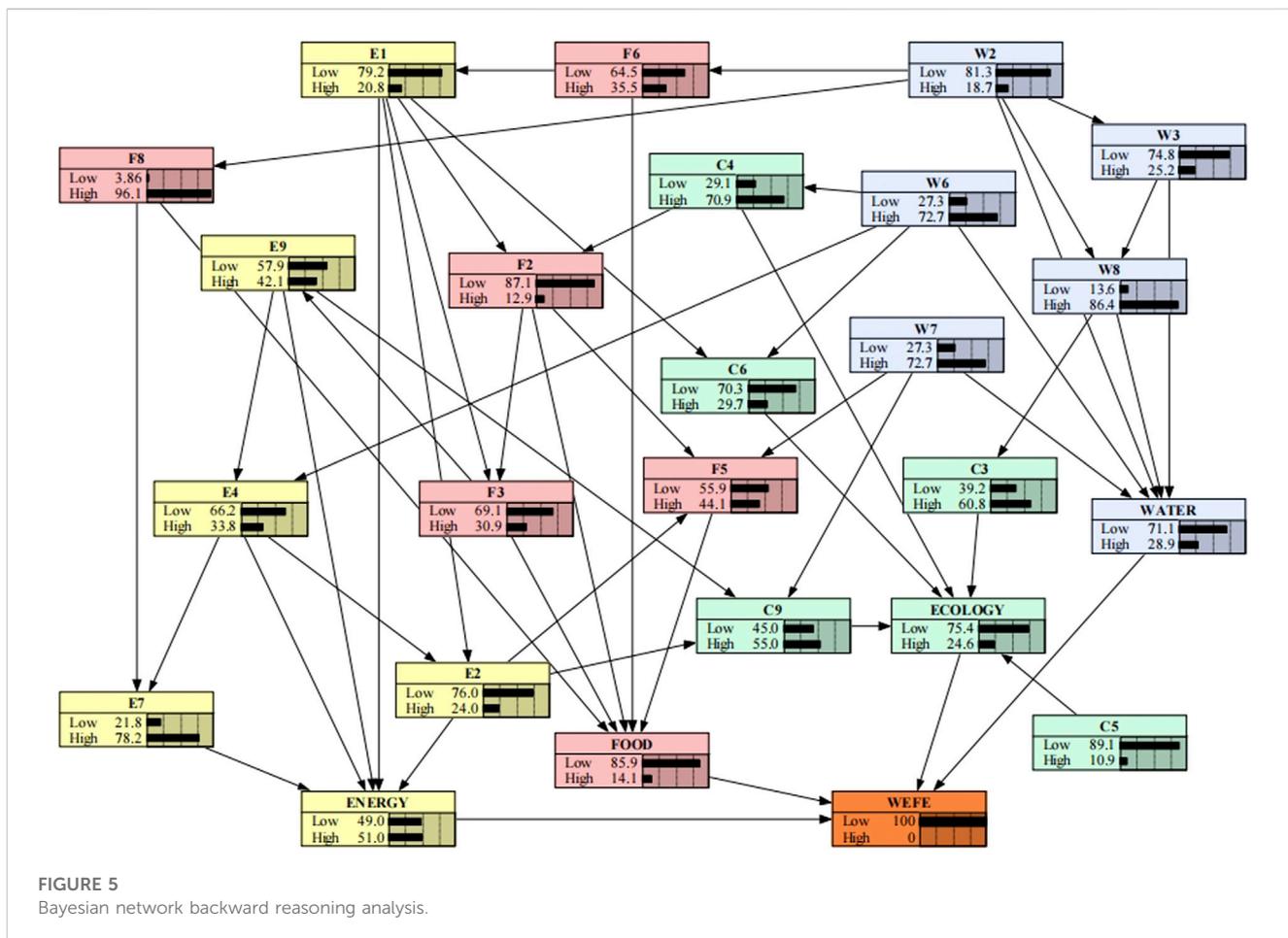


FIGURE 5 Bayesian network backward reasoning analysis.

worth noting that although the changes in the other initial nodes are small, they can trigger larger changes in the intermediate nodes, which in turn trigger changes in the vulnerability of the water-energy-food-ecology nexus. Therefore, good coordination is needed for future development.

3.4 Discussion

Compared with the existing research on the water-energy-food-ecology nexus in the world, this paper focuses more on the vulnerability of the nexus. At present, the research on water-energy-food-ecology nexus is still mainly focus on subsystem research, and more attention is paid to water resources and ecology. For example, In terms of water resources, Kong et al. (2023) analyzed the adaptability between water pollution and advanced industrial structure. Yuan et al. (2023) improved the method of calculating the value of water resources and assessed the efficiency and quality of water use in Hubei Province. In terms of ecosystems, Yuan et al. (2022) analyzed the coordination degree of the industrial-ecological economy in the Yangtze River Economic Belt based on Lotka-Volterra model. However, none of these studies paid attention to the vulnerability of water-energy-food-ecology nexus. Therefore, this paper proposes to study water-energy-food-ecology nexus from the perspective of vulnerability, and constructs the overall framework of water-energy-food-ecology nexus vulnerability research, which widens the existing research perspective of water-energy-food-ecology nexus to

some extent. Additionally, compared to previous research findings, this paper’s conclusions are more beneficial in reducing fragmented comprehension of each element of the water-energy-food-ecology nexus in various departments, which offers a fresh concept for regional governance.

In addition, in terms of research methods, the Bayesian network in this paper also has certain advantages. Compared with existing methods such as system dynamics (Ji et al., 2023), coupling coordination degree model (Wu et al., 2023) and data enveloping analysis (Liu et al., 2023), the Bayesian network adopted in this paper can model the complex causal relationship in the system better, and the form of probability distribution can effectively express the uncertainty of variables. What’s more, it can screen out the key factors affecting the vulnerability of water-energy-food-ecology through sensitivity analysis, and obtain the vulnerability state and corresponding probability of key nodes through forward and backward reasoning, which solves the defect that many existing methods cannot carry out diagnostic reasoning, and makes up for the deficiency of existing research.

4 Conclusion

In this paper, firstly, a vulnerability evaluation index system of water-energy-food-ecology nexus was constructed based on the

VSD framework, and the attribute approximation was performed using neighborhood rough sets. Then, a Bayesian network model was built by structure learning and parameter learning. Finally, sensitivity analysis, forward reasoning, and backward reasoning were performed using Bayesian networks to derive the key influencing factors that hinder the vulnerability reduction of the water-energy-food-ecology nexus, and targeted suggestions were made. The main conclusions of this paper are as follows:

From 2008 to 2019, the development of the water-energy-food-ecology nexus in the Yangtze River Economic Belt is relatively good, and the vulnerability is at a low level overall, especially for the food and ecological subsystems, which have better adaptive capacity and higher security. However, the vulnerability status of the water and energy subsystems is not optimistic, and the probability of the vulnerability of the water-energy-food-ecology nexus being at a high level is still 41.1%, indicating that there is still much room for improvement in the management of water, energy, food and ecosystems in the future. From the indicator level, the key factors that hinder the vulnerability reduction of the water-energy-food-ecology nexus at this stage mainly include the storage capacity of water conservancy projects, wastewater discharge per 10,000-yuan GDP, water consumption per 10,000-yuan GDP, and *per capita* grain sown area. At the subsystem level, the water resources subsystem is the main system affecting the vulnerability of the water-energy-food-ecology nexus, followed by the food and energy subsystems, and the ecological subsystem is the weakest. Although the decrease in the vulnerability of individual subsystems can contribute positively to the decrease in the vulnerability of the water-energy-food-ecology nexus and promote the sustainability of the nexus, it may also cause an increase in the vulnerability of other subsystems. These findings are significant to reduce the fragmented comprehension of each element of the water-energy-food-ecology nexus in various departments and remind managers that in the development process of water, energy, food, and ecosystems, the coordinated development of the four should be prioritized.

This paper has certain innovations and features. Considering the correlation between ecology and water, energy and food systems, the study of the water-energy-food-ecology nexus from the perspective of vulnerability is carried out for the first time and the whole framework of water-energy-food-ecology vulnerability research is constructed. To some extent, this will help broaden the existing research perspective of water-energy-food-ecology nexus and provide new ideas for regional governance. In addition, this paper uses neighborhood rough sets to simplify the attributes of indicators, which reduces the repetition of indicator information and makes the evaluation index system more reasonable. What's more, the key influencing factors are screened by sensitivity analysis, and the potential relationship between key influencing factors and target nodes is explored by using forward and backward reasoning of

Bayesian networks, which has certain scientific merit. At the same time, using Bayesian network to carry out water-energy-food-ecology nexus vulnerability prediction research in the form of probability can solve the defect that many existing prediction methods cannot achieve diagnostic inference, so as to open up a new path for water-energy-food-ecology nexus vulnerability prediction research.

There are certain limitations in this paper. For example, a static Bayesian network model is constructed in this paper, and in the future, we will consider adding the time factor to carry out a more profound study at the city level using dynamic Bayesian networks.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

YC: Writing–original draft, Writing–review and editing. YP: Writing–original draft. MG: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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