Security Assessment Using SPA-VFS and Obstacle Factors Diagnosis of Water-Energy-Food Nexus Based on A PSR Framework

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Abstract
In the context of population growth and increasingly scarce resources, the sustainability of water-energy-food nexus (WEFN) has been considered as a major global challenge. This study presented the evaluation index system of WEFN security based on the pressure-state-response (PSR) model. The set pair analysis and variable fuzzy sets (SPA-VFS) were supplied to evaluate WEFN security, which analyzed the situation and obstacles of WEFN security in Northwest China from 2008 to 2017. The results showed that, (1) In the WEFN, the pressure-subsystem in Shaanxi and Inner Mongolia was in a critical safe level; in the state-subsystem, the security level of Shaanxi was the best and the response-subsystem in Inner Mongolia and Gansu is in an unsafe level; (2) Over the years, the safety level of WEFN in the five provinces of Northwest China had obvious spatio-temporal characteristics, which was always between critical safety and unsafety, but the overall trend was positive. (3) The results of obstacle degree of three subsystems were compared as follows: pressure-subsystem > state-subsystem > response-subsystem. And, their obstacle factors were almost all related to water. The key to improving WEFN security in Northwest China in the future is to deal with the serious mismatch between water resources and energy resources.

Keywords
water-energy-food; pressure-state-response model; set pair analysis; variable fuzzy set; obstacle factors diagnosis; security assessment

Declarations
Funding This study has been funded by the National Natural Science Foundation of China (Grant No. 42071278), the National Key R&D Program of China (Grant No. 2017YFC0404600), the Fundamental Research Funds for the Central Universities of China (Grant No. B200204018, B200207026).

Conflicts of interest/Competing interests The authors declare that there is no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and material The supplementary material contains data.

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1 Introduction

Water, energy and food are the strategic basic resources for human survival and sustainable development. These three resources are inextricably linked, and the mutual influence and interaction (Yang et al. 2018). At present, more and more studies have shown that research on the WEFN can have tremendous impact on the sustainable development of economy, environment and society. The WEFN security has gradually become a much-debated topic for people from all walks of life. In 2011, the Bonn Conference for the first time summarized the relationship between food security, water security and energy security as a "Nexus" (Hoff 2011). The Global Risk Report issued by the World Economic Forum listed the "Water-Energy-Food Risk Group" as one of the three major risks in 2011, emphasizing the importance of WEFN to regional economic and social sustainable development (Davis 2011). With the acceleration of China's urbanization and industrialization, as well as the serious uneven distribution of water, energy and food, national freshwater resource is decreasing, energy demand is rising, and the uncertainty of food supply is grim (Albrecht et al. 2018). The three is becoming increasingly prominent, which is highly sensitive and vulnerable. China has also put its perspective into the research of WEFN security. Domestic and foreign scholars' researches on WEFN security mainly focus on the following three aspects: connotation, influencing factors and evaluation indexes, models.

WEFN security is novel concept based on water security, energy security and food security. Different scholars have given different definitions. In 2000, the term “water security” first appeared at the Water Symposium in Stockholm. Water security was defined by (the UN Water 2013) as “the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability”. Energy security (Ahmad & Abdul-Ghani 2011) was also defined as the ability to reliably meet the needs of energy services in a long-term. Some scholars defined energy security from the perspective of affordability in price (Jansen & Seebregts 2010; Jun et al. 2009) and ecological environment (Sovacool et al. 2012). Food security has global significance and social and economic impact on national development, so it has been widely studied in academic circles (Odfrey et al. 2010). The FAO defined food security as “Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” (World Food Summit 1996). Some others have also studied the relationship from a qualitative perspective (Howarth & Monasterolo 2016; Halbe et al. 2015; Romero-Lankao et al. 2018).

Many scholars at domestic and abroad have studied the influencing factors and evaluation indexes of WEFN security. Five themed workshops were present to explore the impact of climate and weather shocks...
across WEFN and the related barriers to response (Howarth et al. 2016). Zhang et al. (2017) believed that social factors affecting WEFN generally include population growth, urbanization and land use change, and natural factors such as extreme weather, climate change and natural disasters. The evaluation system can be established based on the PSR theoretical framework (Wang et al. 2018). A comprehensive evaluation index system for irrigation sustainability was proposed based on the WEFN (De Vito et al. 2017). There was an index constructed representing the availability and stability of water, energy and food resources to assess the progress of sustainable development in Latin America and other countries (Jürgen & Ramón 2018). And, WEFN security index can be built from two aspects of accessibility and availability (Willis et al. 2016). The relationship among water, energy and food is recently gaining researchers attention. The life cycle assessment (LCA) method (Ghani et al. 2019) and input-output model (Zhang & Vesselinov 2017; White et al. 2018; Bellezoni et al. 2018;) can evaluate the linkage and competitive demand of these resources. Many scholars apply the WEFN as a novel approach to study the sustainable development of environment and economy (Fabiani et al. 2020; De Andrade et al. 2021), and risk assessment (Haji et al. 2020). However, there are few researches on WEFN security model. A global index called WEF index can quantify WEF security (Mohammadpour et al. 2019). Based on WEFN method, a spatiotemporal disaggregated simulation model using System Dynamic was established to evaluate the security food and water supply (Ravar et al. 2019). Sahle et al. (2019) quantified and mapped water-related ecosystem services to ameliorate WEFN security in tropical data-sparse catchment.

By combing the research progress of domestic and foreign scholars on WEF, it can be found that there are many researches on water, energy and food security, but they are basically on the single resource or two resources security, with little regard to incorporating security perspectives. Especially, the research on the security assessment of WEFN is relatively scarce. At present, the commonly assessment approaches applied include Analytic Hierarchy Process (AHP) (Vivoda 2010), Fuzzy Comprehensive Assessment (FCA) (Qi et al. 2013), Principal Component Analysis (PCA) (Ozturk 2015), Comprehensive Index (CI) (Mohammadpour 2019), and System Dynamics (SD) (Cai et al. 2019). Both AHP and FCA need to be scored by experts in the evaluation process, which is more subjective. The PCA is easy to lose important information. The CI method ignores the correlation among the indicators. The SD is a method of computer experiment simulation, with more complex structure and large demand of data.

Set pair analysis (SPA) and variable fuzzy set (VFS) methods have strong applicability and suitability in evaluation research. In this paper, the SPA-VFS coupling model was proposed to evaluate the safety level of WEFN. Then the obstacle degree model (ODM) was utilized to identify the key factors that have great influence on WEFN security. Finally, the paper put forward the corresponding countermeasures for the obstacle factors, which can provide reference for governments to ensure the WEFN security.

2 Data and Methods

2.1 Study Area

Ordos Basin is an important energy base in China. In this paper, the five provinces in the extension of Ordos Basin include Shaanxi, Gansu, Shanxi, Ningxia and Inner Mongolia as the research areas, which are collectively referred to as Northwest China (Fig. 1). The Northwest is the most arid region in China, with dry climate and rare rainfall. The average precipitation in most parts of the whole region is less than 500mm, while the water evaporation is relatively high. It is the only area in China where the water demand of natural vegetation and farmland crops is extremely greater than the precipitation. The Northwest has a complete range of energy resources and abundant reserves, among which oil, and coal natural gas reserves are in the
forefront of China. The reserves of coal are as high as 200 billion tons, accounting for about 40% of the
total coal in China. The oil reserves are about 3.5 billion tons, accounting for about 50% of the total onshore
oil reserves. Energy is the biggest advantage of economic development in Northwest China, and its
economic development depends on a large amount of energy consumption. Furthermore, the Northwest
with a vast territory, accounts for more than one third of China's land area; it has 9.6% of the national
population, but the per capita land area is 2.2 times of the national average. The per capita cultivated land
area is 2.1 mu, which is 1.66 times higher than that of the whole country, but the food output is only 11%
of the national average.

Fig. 1 The location of Northwest China

Northwest China is characterized by deficient water, rich energy and stable food production. Scanty
water resource is the basic factor restricting the development of energy and food industry. Under the
condition of ecological priority, to ensure the WEFN security is an inevitable choice for the long-term
development of economy and society in Northwest China.

2.2 Date Collection and processing

This study utilized annual panel data for Northwest Chain ranging from 2008 to 2017. Water data,
such as irrigation water consumption per mu of farmland and annual average precipitation, was derived
from China Water Conservancy Statistical Yearbook, and provincial water statistical bulletin. Energy
data, such as proportion of energy consumption in agricultural system, was mainly collected from China
Energy Statistical Yearbook. Food data, such as fertilizer application per unit area, came from China
Food Statistical Yearbook. Environmental indicators came from China Environmental Statistical
Yearbook such as agricultural water-saving irrigation rate. Social and economic indicators were mainly
from China Statistical Yearbook and provincial statistical yearbook such as investment proportion in
energy engineering to GDP and per capita GDP.
In order to eliminate the dimensional relationship between indicators, the original data should be standardized.

Positive indicators:

\[ X'_{ij} = (X_{ij} - \min X_j) / (\max X_j - \min X_j), \]  

(1)

Inverse indicators:

\[ X'_{ij} = (\max X_j - X_{ij}) / (\max X_j - \min X_j), \]  

(2)

Where, \( X_{ij} \) and \( X'_{ij} \) represent the original and normalized values of the j-th indicator in i-th year, \( \max X_{ij} \) and \( \min X_{ij} \) represent the maximum and minimum indicators, respectively.

### 2.3 Evaluation Indicators

#### 2.3.1 WEFN based on PSR theory

In the 1980s, OECD (1993) proposed the pressure-state-response (PSR) model to study the impact of human activities on resources and environment. This model can comprehensively take economic, social, natural and environmental factors into account. WEFN can be regarded as a coupling system of "water-energy-food-economy-society-environment". Human is the main body of this system, and the subsystems interact and restrict each other. The security of WEF nexus has dynamic and process attributes. The process can be divided into three time stages, corresponding to the three process elements of pressure, state and response in PSR model: (a) pressure process, that is, the danger of hazard factors or the possibility of system damage; (b) state process, that is, the ability to resist risks in WEF nexus and the state and change under the disturbance of pressure; (c) response process, that is the ability to return to normal in a crisis and to adapt to a new environment after being exposed to risks. From the perspective of process theory and system theory, the dynamic development and coordination process of WEFN security conform to PSR model. The PSR framework of WEFN is shown in Fig. 2.
2.3.2 Evaluation index system and evaluation standard

Based on the PSR framework of WEFN, the evaluation index system was divided into three subsystems, including pressure, state and response. Each subsystem contained three dimensions, respectively. Finally, this paper constructed a WEFN security evaluation index system with 35 indicators (Table 1). According to the international and domestic prevailing standards, and the research results of relevant scholars, the index system and the interval range of each index of WEFN security assessment were determined (Zhang 2017; Fabiani et al. 2020; Li 2020; Li & Zhang 2020) which was combined with the local differences in Northwest China. The evaluation criteria of 35 indicators are shown in the appendix. The evaluation results of each index were divided into five levels, which were described as safety level (I), comparative safety level (II), critical safety level (III), unsafe level (IV) and extremely unsafe level (V).

The entropy weight method was utilized to calculate the weight of indicators. \( m \) assessment objects were constructed, each assessment object had \( n \) indicators, and the judgment matrix of evaluation indicators was \((X'_{ij})_{m \times n}\). The entropy value of each index was determined.

\[
e_j = -q \sum_{i=1}^{n} z_j^i \ln z_j^i, \quad 0 \leq e_j \leq 1,
\]

(3)

Where, \( q = \frac{1}{\ln n} \) and \( z_j^i = \frac{X'_{ij}}{\sum_{i=1}^{n} X'_{ij}}. \)

The entropy weight of the evaluation indexes \( W_j \) can be calculated.
\[(W_j)_{\text{con}} = \left(1 - e_j\right) / \sum_{j=1}^{n} \left(1 - e_j\right)_{\text{con}}, \quad (4)\]

Where, \(0 \leq W_j \leq 1\) and \(\sum_{j=1}^{n} (1 - e_j)_{\text{con}} = 1\).

Table 1 Evaluation index system of WEFN security

| Target Layer | Criteria Layer | Variable Layer |
|--------------|----------------|----------------|
| Resource coordination | Pressure social economy | C1: Irrigation water consumption per mu of farmland (m³/person) |
| C2: Proportion of industrial production water (%) |
| C3: Proportion of energy consumption in water system (%) |
| C4: Proportion of energy consumption in agricultural system (%) |
| C5: Per capita daily water consumption (m³/person) |
| C6: Water consumption per 10,000 yuan of GDP (m³/10000 yuan) |
| C8: Per capita energy consumption (tce/person) |
| C9: Per capita food consumption (kg/person) |
| C10: Disaster rate (%) |
| C11: Fertilizer application per unit area (ton/hectare) |
| C12: Discharge intensity of industrial wastewater (10000 tons / 100 million yuan) |
| C13: Discharge intensity of industrial waste (10000 tons / 100 million yuan) |

| Resource supply State natural environment | C14: Per capita water resources (m³/person) |
| C15: Energy self-sufficiency rate (%) |
| C16: Per capita food production (kg/person) |
| C17: Per capita cultivated area (hectare/person) |
| C18: Average annual precipitation (mm) |
| C19: Forest cover rate (%) |
| C20: Proportion of river length above three categories (%) |
| C21: Labor force per unit area (person/ hectare) |

| Environmental governance | C22: Population growth rate (%) |
| C23: Urbanization rate (%) |
| C24: Per capita GDP (yuan) |
| C25: The standard rate of industrial wastewater discharge (%) |

| Investment management | C26: Urban sewage treatment rate (%) |
| C27: Comprehensive utilization rate of industrial waste (%) |
| C28: Investment proportion in environmental pollution control to GDP (%) |

| Response | C29: Investment proportion in water conservancy to GDP (%) |
| C30: Investment proportion in energy engineering to GDP (%) |
| C31: Energy processing and conversion efficiency (%) |
| C32: Agriculture mechanization (%) |

| Resource efficiency | C33: Agricultural water-saving irrigation rate (%) |
| C34: Irrigation rate of cultivated land (%) |
| C35: Reuse rate of industrial water (%) |

2.4 Research Methods
2.4.1 SPA-VFS Coupling Model

The SPA (Zhang, 1994) is a method of mathematical quantitative analysis of certainty, uncertainty and the interaction between certainty and uncertainty in a system. The VFS (Chen 2005) is put forward on the basis of analyzing the absoluteness and uniqueness of membership degree and membership function in fuzzy set theory. In recent years, this method has been widely used in drought assessment (e.g., Huang et al. 2015), flood risk (e.g., Guo et al. 2014), health of rivers and lakes (e.g., Xu & Liu 2014; Feng et al. 2018), etc., which verifies the applicability of the evaluation model. In this paper, the security assessment model of WEFN based on SPA-VFS was constructed. The concrete steps are as follows:

**Step 1:** Build set pairs. The set $A_k$ is composed of the sample data of indicator $x_{ijkl}(i = 1,2,\ldots,n; j = 1,2,\ldots,m; k = 1,2,\ldots,N_j)$. The standard threshold $s_{gk}$ of the index grade $g$ makes up the set $B_k$. These two sets constitute a set pair $H = A_k, B_k$. Where, $n, m, N_j$ and $G$ are the number of index samples, subsystems, evaluation indicators of subsystems and levels of evaluation standards, respectively.

**Step 2:** SPA is used to construct the single index relation degree $u_{gjkl}$. The core idea of SPA is to quantitatively compare and analyze the attributes of two sets $\{x_{gil}\}$ and $\{s_{gil}\}$ under the given problem background. If they are in the same level, then $u_{gjkl} = 1$; If they are in separate levels, then $u_{gjkl} = -1$; If they are in an adjacent level, then $u_{gjkl} \in [-1,1]$. In this paper, there are five grades of WEFN security evaluation, so the expression of five element connection degree is obtained as follows:

$$u_{gjkl} = \begin{cases} 1 & x_{gil} \in [s_{0jkl}, s_{1jkl}] \\ 1 - 2 \frac{x_{gil} - s_{jk}}{s_{ijkl} - s_{jk}} & x_{gil} \in [s_{ijkl}, s_{2jkl}] \land s_{2jkl} - s_{ijkl} \neq 0 \\ -1 & x_{gil} \in [s_{ijkl}, s_{3jkl}] \end{cases}$$  \hspace{1cm} (5)

$$u_{gjkl} = \begin{cases} 1 - 2 \frac{s_{ijkl} - s_{ijkl}}{s_{ijkl} - s_{ijkl}} & x_{gil} \in [s_{ijkl}, s_{ijkl}] \\ 1 & x_{gil} \in [s_{ijkl}, s_{2jkl}] \land s_{2jkl} - s_{ijkl} \neq 0 \\ -1 & x_{gil} \in [s_{ijkl}, s_{3jkl}] \end{cases}$$  \hspace{1cm} (6)
\[
\begin{align*}
\mu_{ijk} = & \begin{cases} 
-1 & x_{ijk} \in \left[ s_{0,ijk}, s_{1,ijk} \right] \\
1 - 2 \frac{s_{2,ijk} - x_{ijk}}{s_{2,ijk} - s_{1,ijk}} & x_{ijk} \in \left[ s_{1,ijk}, s_{2,ijk} \right] \\
1 & x_{ijk} \in \left[ s_{2,ijk}, s_{3,ijk} \right]
\end{cases} \\
\mu_{ijk} &= \begin{cases} 
-1 & x_{ijk} \in \left[ s_{0,ijk}, s_{1,ijk} \right] \\
1 - 2 \frac{s_{2,ijk} - x_{ijk}}{s_{2,ijk} - s_{1,ijk}} & x_{ijk} \in \left[ s_{1,ijk}, s_{2,ijk} \right] \\
1 & x_{ijk} \in \left[ s_{2,ijk}, s_{3,ijk} \right]
\end{cases} \\
\mu_{ijk} &= \begin{cases} 
-1 & x_{ijk} \in \left[ s_{0,ijk}, s_{1,ijk} \right] \\
1 - 2 \frac{s_{2,ijk} - x_{ijk}}{s_{2,ijk} - s_{1,ijk}} & x_{ijk} \in \left[ s_{1,ijk}, s_{2,ijk} \right] \\
1 & x_{ijk} \in \left[ s_{2,ijk}, s_{3,ijk} \right]
\end{cases}
\end{align*}
\]
Step 6: Fuzzy pattern recognition based on the principle of maximum membership degree is likely to cause distortion. In order to enhance the precision of the assessment results and avoid the occurrence of distortion, hierarchical eigenvalue $h_{ij}$ is used to quantify the evaluation results.

$$h_{ij} = \sum_{g=1}^{G} v_{ijg},$$  \hspace{1cm} (14)

Then, the confidence criterion is used to evaluate the assessment level of the subsystem $L_{ij} \cdot \lambda$ $(\lambda \in 0.5, 0.7)$ is confidence level.

$$L_{ij} = \min \left\{ g \mid \sum_{g=1}^{G} v_{ijg} > \lambda, 1 < g \leq G \right\},$$  \hspace{1cm} (15)

According to the realistic situation of Northwest China, $\lambda = 0.6$. The results of evaluation were divided into five levels: safety, comparative safety, critical safety, unsafe and extremely unsafe, corresponding to the five values $(v_1, v_2, v_3, v_4, v_5)$. If $v_1 + v_2 \geq 0.6$, then WEFN is comparative safety; if $v_1 + v_2 + v_3 \geq 0.6$, then WEFN is critical safety. Others are the same.

2.4.2. Obstacle Degree Model

In order to further discern the main obstacle factors affecting WEFN security, the ODM (Fan & Fang 2020; Wang et al. 2020) was introduced. The ODM uses three indexes: obstacle degree, index deviation degree and factor contribution degree.

The deviation degree of index $T_y$ represents the difference between a certain index and the target value of WEFN.

$$T_y = 1 - d_y,$$  \hspace{1cm} (16)

Factor contribution degree $P_y$ indicates the degree of influence of an evaluation index on the overall goal.

$$P_y = W_y \times T_y,$$  \hspace{1cm} (17)

Obstacle degree $A_y$ and $B_y$ indicate the influence degree of single index and classification index on WEFN security, respectively.

$$A_y = \frac{W_y \times T_y}{\sum_{y=1}^{n} W_y T_y} \times 100\%,$$  \hspace{1cm} (18)

$$B_y = \sum A_y,$$  \hspace{1cm} (19)
3 Results and Discussion

3.1 The Result of Security Assessment

In Northwest China, the Eigenvalue $h$ and safety level of pressure, state and response subsystems of WEFN were calculated, from 2008 to 2017, respectively (Table 2).

3.1.1 Pressure-subsystem

In Table 2, compared with the five provinces in Northwest China, the safety level of pressure-subsystem in Shaanxi and Ningxia was relatively threatening, and most of the safety level in all years was IV, which indicated that the WEFN in these three regions was under heavy pressure from economy, society and environment, and the structure of resource supply and demand was unbalanced. The safety level of Gansu, Shanxi and Inner Mongolia was almost III, which indicated that the safety level of pressure subsystem in these three regions is good, and the negative impact of social, economic, ecological, and environmental factors on the safety level of WEFN is small.

| Year | Province System | P | S | R | P | S | R | P | S | R | P | S | R |
|------|-----------------|---|---|---|---|---|---|---|---|---|---|---|---|
| 2008 | Shanxi h        | 2.48 | 3.23 | 3.55 | 3.43 | 4.14 | 3.61 | 2.78 | 3.75 | 3.74 | 3.39 | 3.57 | 3.23 | 2.80 | 3.13 | 3.58 |
|      | level III       | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV |
| 2009 | Gansu h        | 2.51 | 3.26 | 3.43 | 3.10 | 4.09 | 3.47 | 2.81 | 3.77 | 3.58 | 3.32 | 3.49 | 3.62 | 2.72 | 3.02 | 3.63 |
|      | level III       | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV |
| 2010 | Shanxi h        | 2.79 | 3.11 | 3.37 | 3.01 | 4.03 | 3.47 | 3.12 | 3.65 | 3.52 | 3.48 | 3.39 | 3.09 | 2.78 | 2.97 | 3.07 |
|      | level IV        | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV |
| 2011 | Ningxia h     | 2.72 | 2.99 | 3.14 | 3.11 | 3.89 | 3.51 | 2.92 | 3.58 | 3.63 | 3.44 | 3.36 | 2.90 | 2.75 | 2.89 | 3.42 |
|      | level III       | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV |
| 2012 | Inner Mongolia | 2.92 | 3.07 | 3.00 | 2.96 | 3.81 | 3.26 | 2.69 | 3.65 | 3.51 | 3.22 | 3.29 | 2.79 | 2.57 | 2.90 | 2.96 |
|      | level III       | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV | IV |
| 2013 | Shanxi h        | 2.98 | 3.05 | 3.00 | 2.79 | 3.73 | 3.16 | 2.61 | 3.57 | 3.30 | 3.27 | 3.26 | 2.98 | 2.54 | 2.84 | 2.91 |
|      | level IV        | III | III | III | III | IV | IV | IV | IV | IV | IV | IV | IV |
| 2014 | Ningxia h     | 2.87 | 2.93 | 2.91 | 2.77 | 3.72 | 3.15 | 2.68 | 3.56 | 3.28 | 2.98 | 3.25 | 2.81 | 2.66 | 2.81 | 2.84 |
|      | level IV        | III | III | III | III | IV | IV | IV | IV | IV | IV | IV | IV |
| 2015 | Inner Mongolia | 2.85 | 2.99 | 2.82 | 2.92 | 3.79 | 3.13 | 2.99 | 3.17 | 2.77 | 3.42 | 3.22 | 2.80 | 2.83 | 2.78 | 2.83 |
|      | level IV        | III | III | III | III | IV | IV | IV | IV | IV | IV | IV | IV |
| 2016 | Shanxi h        | 2.59 | 2.59 | 2.73 | 2.82 | 3.69 | 2.98 | 2.93 | 3.35 | 3.29 | 3.50 | 3.18 | 2.80 | 2.75 | 2.81 | 2.77 |
|      | level III       | III | III | III | III | IV | IV | IV | IV | IV | IV | IV | IV |
| 2017 | Ningxia h     | 2.66 | 2.88 | 2.96 | 2.73 | 3.56 | 2.94 | 3.03 | 3.45 | 3.28 | 3.56 | 3.20 | 2.85 | 2.82 | 2.75 | 2.65 |
|      | level III       | III | III | III | III | IV | IV | IV | IV | IV | IV | IV | IV |

As sketched in Fig.3, although the eigenvalues $h$ of Shaanxi, Gansu and Inner Mongolia fluctuated greatly, the overall trend was good, and the eigenvalues $h$ in the pressure-subsystem showed a decreasing trend. The security level of Ningxia and Shanxi has been declining from 2008 to 2014. The best safety status of Shanxi was recorded in 2013, mainly due to less energy consumption of water, and that of Ningxia was in 2014, mainly due to the low disaster rate. However, there was an upward trend after that, especially in Ningxia. Therefore, the two regions should pay special attention to take measures...
to reduce the threat of external pressure on WEFN security.

![Fig. 3 Change trend of eigenvalues $h$ in the pressure-subsystem](image)

3.1.2 State-subsystem

The safety level of state-subsystem of WEFN in Shaanxi had always been III, which indicated that the state-subsystem in this region was in good condition, and the supply of water, energy and food was more sufficient than that in other areas. Most of the security levels of the other four provinces were IV, which indicated that there may be insufficient supply of water, energy and food, bad natural environment, and insufficient carrying capacity of WEFN caused by discordant development of economic and social status of the area.

The safety level of Gansu, Ningxia and Inner Mongolia had always been IV, indicating that their WEFN security were in an uncoordinated state. However, as shown in Fig. 4, their eigenvalues $h$ had been declining steadily, which indicated that the regulation measures in these regions might play a salient role. The security level of Shaanxi and Shanxi of state-subsystems showed a slow decline and then an upward trend, respectively in 2015 and in 2016, indicating that the WEFN security in these regions first improved and then deteriorated. The state-subsystem in Shaanxi was in a critical safe level, which was mainly due to the high energy self-sufficiency rate. The safety state in Shanxi was between safety and unsafety. Thus, measures should be taken to improve the carrying capacity of WEFN system.

![Fig. 4 Change trend of eigenvalues $h$ in the state-subsystem](image)
### 3.1.3 Response-subsystem

In response-subsystem, the three regions including Shaanxi, Shanxi and Ningxia had the highest safety level, that was, the safety status of these regions was worst. The safety level of Gansu in 2007 and Inner Mongolia in 2013 was III, but the safety level in other years was IV, indicating that the social response of the two regions to the safety regulation of WEFN system was insufficient.

As shown in Fig. 5, the fluctuation of eigenvalue \( h \) in Inner Mongolia from 2008 to 2012 was especially large, which was mainly due to the large change of industrial water repetition rate. The safety level of response-subsystem in Gansu and Inner Mongolia was relatively high, but the safety level also had a relatively obvious downward trend from 2008 to 2017. The eigenvalue \( h \) of the response-subsystem of WEFN security in Ningxia increased significantly and reached the peak in 2009. After that, there was a slow downward trend, and it had been in the critical safety level from 2014 to 2017. The eigenvalue \( h \) in Shaanxi decreased steadily from 2008 to 2016, but rose slightly in 2017, mainly due to the decrease of industrial water repetition rate. The eigenvalue \( h \) in Shanxi fluctuated on the edge of safety and unsafety, and had been rising since 2015, which was caused by the decrease of water conservancy investment to GDP and other indicators.

![Fig. 5 Change trend of eigenvalues \( h \) in the response-subsystem](image)

### 3.2 Obstacle Factors Diagnosis

The ODM was applied to diagnose the obstacle factors affecting WEFN security in Northwest China from 2008 to 2017. The order was made according to the degree of obstacle, and the frequency of obstacle factors was counted. This study took the first three obstacle factors (Table 3).

In the pressure-subsystem, obstacle factors are C8, C11 and C1, and their frequencies were 23, 21 and 18, respectively. This indicated that with the economic growth, Northwest China is highly dependent on energy, and a large amount of chemical fertilizers and other substances are applied to nourish the crops, which not only brings benefits, but also causes water pollution and increases the pressure on resources and environment of WEFN. In recent years, the industrial development of Ningxia and Inner Mongolia has been rapid, and the proportion of industrial water has been also increasing year by year, whose obstacle degree was about 20%.

In the state-subsystem, obstacle factors were C14, C17 and C20, and the frequency was 24, 23 and 22, respectively. Especially in Gansu, the obstacle degree of C17 was as high as 40.7%. These three
indicators are all related to water resources. Their frequency was very high, which further verified that the lack of water resource is the central cause for the low safety level of WEFN in Northwest China. Generally speaking, Northwest China has less per capita water resource, less annual average precipitation, and rich land resource. However, due to poor hydrothermal conditions, there is not much land suitable for planting food, and the food yield is low.

Table 3 The obstacle factors of the three subsystems

| Obstacle factors | Pressure-subsystem | State-subsystem | Response-subsystem |
|------------------|--------------------|----------------|-------------------|
| Shaanxi          |                    |                |                   |
| Frequency        | 8                  | 8              | 5                 |
| Obstacle degree  | 16.32%             | 23.62%         | 10.56%            |
| Obstacle factors | C8                 | C11            | C3                |
| Gansu            |                    |                |                   |
| Frequency        | 7                  | 6              | 5                 |
| Obstacle degree  | 26.90%             | 9.32%          | 9.92%             |
| Obstacle factors | C8                 | C1             | C5                |
| Shanxi           |                    |                |                   |
| Frequency        | 8                  | 7              | 4                 |
| Obstacle degree  | 17.90%             | 18.30%         | 7.98%             |
| Obstacle factors | C2                 | C3             | C9                |
| Ningxia          |                    |                |                   |
| Frequency        | 7                  | 6              | 5                 |
| Obstacle degree  | 18.95%             | 13.42%         | 10.88%            |
| Obstacle factors | C2                 | C3             | C9                |
| Inner Mongolia   |                    |                |                   |
| Frequency        | 7                  | 6              | 5                 |
| Obstacle degree  | 21.50%             | 10.80%         | 9.00%             |
| Obstacle factors | C2                 | C1             | C11               |

In the response-subsystem, obstacle factors were C29, C30 and C34, and the frequency was 23, 23 and 14, respectively. And, they appeared more frequently in Ningxia and Inner Mongolia. It could be seen from the data that the investment in water conservancy in Northwest China was relatively small. Although the investment has increased in recent years, it is far behind the proportion of investment in energy projects. Moreover, Gansu, Ningxia and Inner Mongolia have much room for improvement in energy processing and conversion efficiency.

From the perspective of the average obstacle degree of the whole Northwest China (Fig. 6), the pressure-subsystem has the greatest impact on WEFN security. The obstacle degree of the three subsystems were compared as follows: pressure-subsystem > state-subsystem > response-subsystem. The obstacle degree of the pressure-subsystem increased from 7.01% in 2008 to 41.72% year by year, the state-subsystem decreased from 43.04% in 2008 to 26.95% year by year, and the response-subsystem remained at about 30%. The gap between the pressure-subsystem and the response-subsystem was larger after 2011, while the state-subsystem and the response-subsystem was smaller after 2012.

This fully showed that Northwest China itself has the characteristics of water shortage and abundant energy. However, with the rapid development of economy, the consumption of water resource and energy has been increasing, and the waste of resources has been intensified, which has caused great harm to the natural environment. Therefore, it is urgent that some actions should be taken to alleviate the contradiction among the waste of resources in energy development and utilization, the rapid development of economy, and the deterioration of ecological environment.
3.3 Regulatory Countermeasures

The regulation of WEFN security involves multi-region, multi-level and multi-department cooperation, and regulation measures cover administrative, market, economic and other means. The goal of regulation is to reduce and inhibit the negative impact of "pressure", strengthen the robustness of "state" and the positive effect process of "response", improve the safety level of WEFN, so as to ensure the WEFN security in Northwest China, and promote the sustainability of the region. Through obstacle factor analysis, it could be seen that the indicators affecting WEFN security in Northwest China were C11, C8, C11, C14, C17, C20, C29, C30 and C31. Therefore, the countermeasures were put forward from the three aspects: improving the pattern of agricultural development, exploring and saving water, and increasing special investment.

(1) Improving the pattern of agricultural development. It is essential to reduce the irrigation area of crops and adjust the planting structure. While ensuring the self-sufficiency rate of food, provinces should reduce food output and increase food import. These measures can effectively reduce water demand. Moreover, Agricultural departments can combine the characteristics of developed grazing and breeding industry to mobilize farmers to use animal manure as organic fertilizer. Finally, irrigation methods must be improved. Water saving methods suitable for the characteristics of the irrigation area can be selected, such as mulching irrigation, border irrigation, etc.

(2) Exploring and saving water. The main factor affecting WEFN security is the lack of water resource, and the key measure to improve the per capita water resources is to explore and save water. Firstly, it is necessary to further optimize the industrial layout and to reduce water consumption in all aspects of energy exploitation from the aspects of technology and management. Secondly, the government can invest in the construction of rainwater harvesting and water storage projects aiming to fully utilize precipitation resources. Third, it is necessary to enhance public awareness of water-saving and carry out water resource utility education and sensitization. Furthermore, "reclaimed water" can be utilized. For example, washing vegetables and rice can be used to flush toilets. It is also important to overhaul public water supply facilities on time to prevent water leakage.

(3) Increasing special investment. Adhere to the priority of ecological protection, it is necessary to
increase special investment in water conservancy and energy projects to realize green and sustainable development in Northwest China. Firstly, the government needs to rationally distribute water conservancy facilities and energy projects. Meanwhile, the government should also establish large-scale projects in terms of water storage and water-saving, and focus on investment in equipment that can ameliorate the efficiency of energy processing and conversion. Secondly, the government needs to increase the investment in environmental pollution control, and set up special funds, that is, only used for environmental pollution control in a certain place. In order to improve the efficiency and effect of environmental pollution control, the structure and direction of the use of special funds, are clearly defined.

4. Conclusions

Taking Northwest China as the study area, this study used SPA-VFS model to calculate the safety level of the pressure, state and response subsystem in the WEFN, then utilized the ODM to diagnose the obstacle factors of each subsystem. On this basis, we put forward regulation countermeasures, which pointed out the direction for the coordinated security development of WEFN in Northwest China. The conclusions of the study were as follows. Firstly, in the WEFN, the pressure-subsystem in Shaanxi and Inner Mongolia was in a critical safe level; in the state-subsystem, the security level of Shaanxi was the best and the response-subsystem in Inner Mongolia and Gansu was in an unsafe level. Secondly, Over the years, WEFN security in Northwest China has been in a level between critical safety and unsafe, but the overall trend was positive. Thirdly, from the average obstacle degree of the whole Northwest China, the pressure-subsystem had the greatest impact on WEFN security. The results of the three subsystems were compared as follows: pressure-subsystem > state-subsystem > response-subsystem. Fourthly, the obstacle factors of the pressure-subsystem mainly involved per capita energy consumption, fertilizer application per unit area and Irrigation water consumption per mu of farmland. The state-subsystem were mainly per capita water resources, per capita cultivated area and proportion of river length above three categories, and the response-subsystem were investment proportion in water conservancy to GDP, investment proportion in energy engineering to GDP and energy processing and conversion efficiency.

The WEFN is a large and complex system. The research done in this study was only the evaluation and obstacle factors diagnosis of WEFN security in Northwest China at the present stage, but did not predict the future security state of WEFN. The next research plan is to study the evolution rule of WEFN security under different circumstances, so as to clearly put forward a mode that is more consistent with the coordinated development of resources in the WEFN in Northwest China.

Appendix

| Indicators | I    | II   | III  | IV   | V    |
|------------|------|------|------|------|------|
| C1         | 200-350 | 350-450 | 450-550 | 550-600 | 600-1000 |
| C2         | 0-6  | 6-11 | 11-15 | 15-25 | 25-100 |
| C3         | 0.04-0.086 | 0.086-0.132 | 0.132-0.178 | 0.178-0.224 | 0.224-0.27 |
| C4         | 0.6-1.62 | 1.62-2.64 | 2.64-3.66 | 3.66-4.68 | 4.68-5.7 |
| C5         | 20-100 | 100-130 | 130-150 | 150-170 | 170-200 |
| C6         | 5-24  | 24-140 | 140-610 | 610-1060 | 1060-1600 |
| C7         | 0-0.4 | 0.4-0.8 | 0.8-1.2 | 1.2-1.8 | 1.8-4 |
| C8         | 1.99-2.42 | 2.42-3.05 | 3.05-3.58 | 3.58-4.5 | 4.5-20 |
| C9  | 100-200 | 200-300 | 300-400 | 400-500 | 500-1000 |
|-----|---------|---------|---------|---------|----------|
| C10 | 0.5     | 5-8     | 8-11    | 11-16   | 16-100   |
| C11 | 0-0.1   | 0.1-0.25| 0.25-0.4| 0.4-0.5 | 0.5-1    |
| C12 | 2-4.03  | 4.03-5.30| 5.30-7.14| 7.14-8.57| 8.57-45  |
| C13 | 1-1.7   | 1.7-2.4 | 2.4-3.1 | 3.1-3.8 | 3.8-20   |
| C14 | 3000-18000| 2300-3000| 1700-2300| 900-1700| 100-900  |
| C15 | 3-5     | 1.5-3   | 0.95-1.95| 0.7-0.95| 0-0.7    |
| C16 | 600-1500| 500-600 | 400-500 | 250-400 | 100-250  |
| C17 | 0.3-0.5 | 0.2-0.3 | 0.15-0.2 | 0.1-0.15| 0-0.1    |
| C18 | 1100-1600| 800-1100| 400-800 | 200-400 | 0-200    |
| C19 | 50-70   | 40-50   | 25-40   | 15-25   | 0-15     |
| C20 | 95-100  | 90-95   | 85-90   | 75-85   | 0-75     |
| C21 | 0.425-0.525| 0.325-0.425| 0.225-0.325| 0.125-0.225| 0.025-0.125 |
| C22 | 0-2.7   | 2.7-4.25| 4.25-6.16| 6.16-7.76| 7.76-12  |
| C23 | 60-80   | 50-60   | 40-50   | 25-40   | 20-25    |
| C24 | 60000-100000| 40000-60000| 25000-40000| 10000-25000| 0-10000  |
| C25 | 97.5-100| 95-97.5 | 90-95   | 85-90   | 0-85     |
| C26 | 95-100  | 90-95   | 80-90   | 70-80   | 0-60     |
| C27 | 80-100  | 70-80   | 60-70   | 45-60   | 20-45    |
| C28 | 3.5-4.5 | 2.5-3.5 | 1.5-2.5 | 0.8-1.5 | 0-0.8    |
| C29 | 1.5-100 | 1.25-1.5| 1.25-0.87| 0.335-0.87| 0-0.335  |
| C30 | 25-35   | 20-25   | 15-20   | 10-15   | 0-10     |
| C31 | 90-100  | 80-90   | 70-80   | 50-70   | 0-50     |
| C32 | 95-100  | 85-95   | 75-85   | 65-75   | 0-65     |
| C33 | 80-100  | 70-80   | 60-70   | 40-60   | 0-40     |
| C34 | 90-100  | 80-90   | 70-80   | 60-70   | 0-60     |
| C35 | 90-100  | 80-90   | 70-80   | 50-70   | 0-50     |

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