Synergetic assessment of water, energy and food nexus system

T Zhang¹, Q Tan¹,²,³, S Zhang¹ and T Y Zhang¹

¹College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China
²Institute of Environmental & Ecological Engineering, Guangdong University of Technology, Guangzhou 510006, China

E-mail: qian_tan@cau.edu.cn

Abstract. Water, energy and food are three important resources for human to face serious security risks. A systematic perspective, namely Water, Energy and Food Nexus (WEFN), was proposed to achieve the sustainable human development. In this study, a method of hierarchical weight assignment based on synergetic theory and Shannon information theory was applied in the Bayan Nur city, China. Through calculating order degree of order parameter components of resources, society, economic and environmental dimensions, the order degree of order parameters and sub-systems and the order entropy were obtained. It is found that water resources supply, energy supply, energy consumption and food price would dominate the corresponding trends in water, energy and food sub-systems respectively. The water and food sub-system may play a more dominant role in the harmonious assessment of WEFN system in the study area. Although the variance of the order degree of sub-systems and the order entropy were small, the WEFN system was still moving toward an unstable state, which could aggravate the inharmonious degree of WEFN system in the study area.

1. Introduction

Population growth and economic development have led to a growing demand for water, energy, and food. About one-seventh of the world’s population has not access to secure food, clean water or modern energy [1]. Water, energy and food as three essential resources for human, would increase 55%, 50%, and 30%, respectively, from the beginning of 21th to the middle of this century [2-4]. To alleviate this situation, the policymakers of the world have implemented individual artificial techniques such as water conservation programs, energy saving projects, and food production plans [5-7].

Nevertheless, studies that only consider one or two elements do not have the capacity to deal with the three [8,9], and the misapplied new technologies of one element could even lead to two other elements unexpected consequences [10]. Although some integrated approaches were proposed to alleviate the pressures of demand, the past framework of integration still centered on a single element [11]. This way approach would still sacrifice the other two elements as a trade-off to improve a single element [12,13]. To meet the severe demand challenge of the water, energy and food and achieve sustainable development, it is necessary to synergize Water, Energy and Food Nexus (WEFN) [14-16].

Previously, many quantitative evaluation studies were carried out on WEFN system, such as, a framework for a cross-sectoral system that considering Climate, Land-use, Energy-Water strategies (CLEWs) [17], Water-Energy-Food (WEF) Nexus Tool 2.0 [18] and WEF Nexus Rapid Appraisal Tool developed by Food and Agriculture Organization of the United Nations (FAO) at the national level. However, these approaches focused on one or two elements, which may lead to severe sacrifice for the other elements. It is necessary to develop a cross-sectoral system model that considering the three elements for a better sustainable development.
level [19]. Nevertheless, as a burgeoning systematic framework or approach, contemporary theory and technology couldn’t explain the mechanism of WEFN system well. Moreover, one or several main parameters barely represented the whole system changes over time [20]. There is still no set of applicable and systematic evaluation index system for WEFN system. Hence, an evaluation method considering multiple dimensions would be more comprehensive to evaluate WEFN system.

In this study, a hierarchical weight assignment method based on synergetic theory and Shannon information theory was applied in the Bayan Nur city, China. Moreover, order parameter components were selected from resources, society, economic and environmental dimensions. It could provide a universal evaluation approach for WEFN system through calculating order degree of order parameters and sub-systems, and order entropy of WEFN system.

2. Methodology and data

2.1. Study area
Bayan Nur (40°13’–42°28’N, 105°12’–109°53’E) is located at the west of the Inner Mongolia Autonomous Region, China. The average temperature is about 8.8℃, and the highest and lowest temperature are about −12.3℃ in January and 23.8℃ in July, respectively [21]. The mean annual precipitation ranges from 130 to 250mm, about 70% of which occurs from July to September. The mean annual evaporation is ranges from 2100 to 2400 mm and is much greater than the mean annual precipitation. Agriculture in the study area is heavily dependent on irrigation, and the study area consumes about 4.7 billion m³ water diverted from the Yellow River each year. Hetao irrigation area within the territory of the study area is one of three largest gravity-fed irrigation districts in China, which accounts for 17.5% of the area of the total area of Bayan Nur [22]. It is an important base of China for commodity grains and oil seeds.

2.2. The construction of synergetic assessment system of WEFN system
The methodology framework employed in the study as shown in figure 1. Firstly, some evaluation indicators were selected with considering resources, social, economic, and environmental dimensions. Then, these indicators were further divided into order parameter components (hereinafter jointly referred to as ‘components’) according to their sub-systems (water, energy, or food sub-system). Moreover, order degree of order parameters and sub-system were calculated based on components value and hierarch weighting. Finally, the order degree of sub-system was normalized based on Shannon information entropy theory, and then harmonious degree of WEFN system was obtained.

![Figure 1. The framework of synergetic assessment system of WEFN system.](image-url)
2.2.1. Component selection and hierarchical division. Water, energy and food as three resources for WEFN system inevitably existed the relationship of supply and demand [23]. The consumption of water, energy and food could affect ecological environment because of the inseparable relations with human behaviour. Moreover, these two parts were all affected by the price of water, energy and food, especially energy and food. Thus, the supply and consumption of water, energy and food, influences of consumption of the three on ecological environmental, the price of food were defined as order parameters to water, energy and food sub-system (The price of energy data, greenhouse gas emissions from energy consumption were hard to obtain which were omitted). In addition, considering resources, society, economic and environmental dimensions, the hierarchical division of synergetic assessment system of WEFN system (WEFN-SAS) and weights of order parameters and their components shown as in table 1.

Table 1. Synergetic assessment components and weights of WEFN system based on order parameter.

| Target | Sub-System | Order Parameters | Order Parameter Components |
|--------|------------|------------------|---------------------------|
| Water  | Water resources supply (2/5) | The quantity of water transfer from Yellow River (3/5) |
|        | Water resources consumption (2/5) | Precipitation (1/10) |
|        | Water quality (1/5) | Quantity of reclaimed water (1/10) |
|        | WEFN-SAS: Energy | Water consumption per unit cultivated area (1/4) |
|        | Energy supply (2/3) | Water consumption per 10,000-yuan GDP (1/4) |
|        | Energy consumption (1/3) | The ratio of water consumption between energy and agriculture (1/4) |
|        | Food | Gini coefficient between agricultural water consumption and cultivated area (1/4) |
| Food   | Food Supply (2/5) | Amount of nitrogen leaching (1/3) |
|        | Food Price (2/5) | Amount of phosphorus leaching (1/3) |
|        | Crop planting structure (1/5) | Amount of pesticide leaching (1/3) |

Based on data, literature and survey results, the weight of each hierarchy structure was set as follows: (i) The supply of resources was weighted according to the proportion of supply; (ii) If the importance of parameters at the same hierarchy couldn’t be compared, the same weight value was set for them; (iii) On the basis of the above-mentioned two conditions, the denominator of parameters weight ratio at the same level should be as unified as possible, for instance, the denominator of the weight value was the same as the odd number as possible in this study.

2.2.2. Calculation of order degree and WEFN system harmonious degree. In the complex WEFN system $S=(S_1, S_2, S_3)$, where $S_1$, $S_2$, and $S_3$ respectively represent water, energy and food sub-system. Supporting $S_n (n \in [1,3])$ is a random subsystem, and $S_n = \{O_{1n}, O_{2n}, ..., O_{mn}\}, O_{ni}$
(i \in [1,m]) is an order parameter of \( S_n \) sub-system. For each order parameters \( O_{ni} \) may have \( k \) components which represented by \( x_{nij} (j \in [1,k], j \in N^+ ) \), where \( N^+ \) expresses positive set of natural numbers.

Each order parameter component is assumed to have a minimum (\( \beta_{nij} \)) and maximum value (\( \alpha_{nij} \)), i.e., \( \beta_{nij} \leq x_{nij} \leq \alpha_{nij} \). In this study, the maximum values were set as planning value or predicted value, the minimum values were obtained from reference year (2010) or assumed values based on historical data. According to synergetic theory, components could be divided into positive or negative variables based on what they mean. If the order degree of a component increases as value increases, then this component is a positive variable. Contrarily, the component is a negative variable. Supposing there are \( p \) positive components and \( k-p \) negative components. The calculation formula of order degree of components is as follows formula (1).

\[
u(x_{nij}) = \begin{cases} 
\frac{(x_{nij} - \beta_{nij})}{(\alpha_{nij} - \beta_{nij})} & (j \in [1,p], x_{nij} \text{ is a positive component }) \\
\frac{(\alpha_{nij} - x_{nij})}{(\alpha_{nij} - \beta_{nij})} & (j \in [p+1,k], x_{nij} \text{ is a negative component })
\end{cases}
\]

where, \( u(x_{nij}) \) is the order degree of component \( x_{nij} \), \( u(x_{nij}) \in [0,1] \).

The order degree of order parameter \( U(O_{ni}) \) is evaluated by the total contribution of the degree of components under its hierarchy. Generally, it is done using the geometric weight sum. Thus, \( U(O_{ni}) \) is expressed as the formula (2).

\[
U(O_{ni}) = \sum_{j=1}^{k} w_{ij} u(x_{nij})
\]

where, \( w_{ij} \) is the weight of \( x_{nij} \) in the components of \( O_{ni} \), \( w_{ij} > 0 \) and \( \sum_{j=1}^{k} w_{ij} = 1 \).

Same as the expression of order degree of order parameter, the order degree of sub-system \( U(S_n) \) is also represented as formula (3).

\[
U(S_n) = \sum_{i=1}^{m} w_i U(O_{ni})
\]

where, \( w_i \) is the weight of \( O_{ni} \) in the sub-system \( S_n \), \( w_i > 0 \) and \( \sum_{i=1}^{m} w_i = 1 \).

According to Shannon information theory, coupling the order degree of water, energy and food sub-system and normalizing them to the order entropy of WFENS.

\[
U(S) = -\sum_{n=1}^{3} \frac{1}{\sum_{n=1}^{3}(1-U(S_n))} \log_2 \frac{1-U(S_n)}{\sum_{n=1}^{3}(1-U(S_n))}
\]

where, \( U(S) \) is the order entropy of WEFN system, and the less \( U(S) \) is, the more harmonious the corresponding WEFN system. Generally, \( U(S) > 0 \).
2.3. Data sources
In this study, order parameter components data from 2012 to 2016 mainly were collected from Statistical Yearbook, Water Resources Bulletin, Bureau of Animal Husbandry, Electric Power Bureau and National Development and Reform Commission as well as data from the survey in the study area.

3. Results and discussion

3.1. Synergetic assessment of water sub-system
Order degree of components from 2012 to 2016 could be obtained by formula (1) as show in table 2, and then order degree of order parameters and sub-systems could also be calculated with the help of results of table 2 and formulas (2) and (3).

| Order Parameter Components                                      | Order degree |
|----------------------------------------------------------------|--------------|
| The quantity of water transfer from Yellow River                | 0.0363       |
| Precipitation                                                  | 0.9888       |
| Quantity of reclaimed water                                     | 0.0000       |
| Quantity of groundwater                                        | 0.9916       |
| Water consumption for per unit cultivated area                 | 0.5672       |
| Water consumption per 10,000-yuan GDP                          | 0.5021       |
| The ratio of water consumption between energy and agriculture  | 0.2651       |
| Gini coefficient between agricultural water consumption and cultivated area | 0.3740       |
| Amount of nitrogen leaching                                     | 0.3407       |
| Amount of phosphorus leaching                                   | 0.9321       |
| Amount of pesticide leaching                                    | 0.7493       |
| Electric quantity of thermal power plant                       | 0.1754       |
| Electric quantity of wind energy                               | 0.2632       |
| Electric quantity of solar energy                              | 0.0000       |
| Electricity consumption of per unit of grain output            | 0.7024       |
| Coal consumption of thermal power                              | 0.8246       |
| Energy consumption per 10,000-yuan GDP                         | 0.0425       |
| Grain production per cultivated area                           | 0.1461       |
| The price of wheat                                             | 0.5839       |
| The price of corn                                               | 0.3534       |
| Proportion of staple crop                                       | 0.6340       |
| The ration of area of food crops and cash crops                | 0.9926       |

The water sub-system has three order parameters, including water resources supply, water resources consumption and water quality. Their order degrees from 2012 to 2016 are shown in figure 2. The order degree of water resources supply shows significant fluctuations, which implied the uncertainty of water resources supply. The order degree of water consumption emerges a slight rising trend, which explained that the local government had noted water-using contradictions among water users. The implement of some measures and policies, such as water-saving measures for agriculture and energy production, energy polices of energy and agricultural water allocation, have alleviated the conflicts to some extent. The order degree of water quality has decreased year by year, reflecting the deterioration of water quality in the study area.

As shown in figure 2, the order degree of water sub-system also shows the same fluctuations as the water resource supply. This indicates that water sub-system would be greatly affected by the water resources supply. In 2013, maximum order degree of water sub-system was 0.5032, and the minimum order degree was 0.3708 in 2014.
Figure 2. The change of order degree of water sub-system and order parameters in temporal scale.

3.2. Synergetic assessment of energy sub-system
As two order parameters of energy sub-system, (i.e. order degree of energy supply and energy consumption) represent a rising tend from 2012 to 2016, as shown in figure 3. Especially energy consumption, the order degree reached about 0.8 in 2016. The results of order degree of energy consumption indicate that the energy consumption would tend to rationalize. The local government would be concerned about the relationship between economic development and energy consumption.

In terms of the energy sub-system, the order degree appears an increasing trend except for 2015. It could conclude that the development of energy is getting closer and closer to a stable state. Order degree had increased from 0.3031 in 2012 to 0.5028 in 2016. It implies that the energy sub-system is not a limiting factor for the synergetic development of the study area.

Figure 3. The change of order degree of energy sub-system and order parameters in temporal scale.
3.3. Synergetic assessment of food sub-system
As an important indicator for food security, the order degree of food supply increase year by year, as shown in figure 4. This could relate to the expansion of planting area and the improvement of planting technology. The order degree of food price presents a volatile state. It shows that food price could be still unstable situation, which would have some impacts on the production and life of farmers. The order degree of crop planting structure represents a decline state. In order to pursue higher benefits, farmland ecology and food security could be neglected by the study area.

![Figure 4](image)

**Figure 4.** The change of order degree of food sub-system and order parameters in temporal scale.

On the food sub-system front, the order degree manifests the same variation tendency as food price. It indicates that food sub-system could be more affected by food price. Nevertheless, the order degree of food price had a great fluctuation, the order degree of food sub-system would obtain a smaller fluctuation under the combined action of three order parameters.

3.4. Harmonious assessment of WEFN system
Considering the close interactions among water, energy and food, the method of weight assignment is no longer applicable in assessment of WEFN system, instead, the normalized method based on Shannon information entropy theory was calculated by formula (4). The order entropy value of WEFN system raises from 2012 to 2015, and then declines from 2015 to 2016, as shown in figure 5. According to Shannon information entropy theory, the harmonious degree of WEFN system would have the opposite change. In general, the harmonious degree of WEFN system would represent a declined tendency, which could pronounce the nexus of water, energy and food was becoming deteriorative.

On sub-system front, although the variance of the three sub-system shows the fluctuation of water and food were less than energy, they were 0.0025, 0.0011 and 0.0061 respectively, but only the trend of water and food are basically consistent with the harmonious degree of WEFN system. It implies that water and food could play a dominant role in harmonious assessment of WEFN system in the study area. In addition, the fluctuation of sub-systems could induce a smaller fluctuation of WEFN system, only $8.123 \times 10^{-6}$. It demonstrates that micro changes of subsystems were not enough to cause the macro change of the WEFN system in the study area. Nevertheless, the WEFN system would be still moving toward an unstable state, and this bad change would be pronounced over time.
4. Conclusions
From a sub-system perspective, the order degree of water resources supply had the same fluctuation as water sub-system; the order degree of energy supply and energy consumption jointly affected the tendency of energy sub-system; the order degree of food price and foo sub-system changed in the same way. It is inferred that water resources supply, energy supply, energy consumption and food price dominate the trend of the corresponding sub-system respectively in the study area.

From a system perspective, the calculation results show that order entropy of WEFN system would increase from 1.5768 to 1.5834 in 2012 to 2015, and then declined to 1.5413 in 2016. On the contrary, the harmonious degree of WEFN system represent declining trend overall.

In addition, the trend relationship between sub-system and WEFN system could conclude that water and food sub-system played a dominant role in harmonious assessment of WEFN system in the study area. It also demonstrated that micro changes of subsystems probably not enough to cause the macro change of the WEFN system in a short time by the calculation of variance. Nevertheless, the WEFN system could still move toward an unstable state, which could aggravate the inharmonious degree of WEFN system in the study area. Hence, it is necessary to explore the nexus of water, energy and food in the study area.

Certainly, the relationship among sub-systems is not discussed in this study. Moreover, the weights of order parameter components and order parameter also need to couple with objective weight methods. These are works that need to be explored in the following study.

Acknowledgments
This research was supported by National Natural Science Foundation of China (No. 51779255; 51822905; 51861125103).

References
[1] Hoff H 2011 The water, energy and food security nexus Bonn 2011 Nexus Conf. (Stockholm Environment Institute, Stockholm)
[2] FAO 2017 The state of food and agriculture: leveraging food systems for inclusive rural transformation (Rome: Food and Agriculture Organization of the United Nations)
[3] UNESCO 2016 The United Nations world water development report 2016- water and jobs (Pairs: United Nations Educational, Scientific and Cultural Organization) p 23
[4] IEA 2016 World energy outlook 2016 (Paris: The International Energy Agency)
[5] Shang Y Z et al 2018 China’s energy-water nexus: Assessing water conservation synergies of the total coal consumption cap strategy until 2050 Appl. Energy 210 643-60
[6] Zhang Z Q, Zhang H, Tan Y J and Yang H Y 2018 Natural wind utilization in the vertical shaft of a super-long highway tunnel and its energy saving effect Building Environ. 145 140-52
[7] Gao J L, Xu X Y, Cao G Y, Ermoliev Y M, Ermolieva T Y and Rovenskaya E A 2018 Optimizing regional food and energy production under limited water availability through integrated modeling Sustainability 10 1689
[8] Shah T, Scott C A, Berkoff J, Kishore A and Sharma A 2007 Energy-irrigation nexus in South Asia: Pricing versus rationing as practical tool for efficient resource allocation (Wallingford: CAB International)
[9] Einheuser M D, Nejadhashemi A P and Woznicki S A 2013 Simulating stream health sensitivity to landscape changes due to bioenergy crops expansion Biomass Bioenergy 58 198-209
[10] Ahmad A and Khan S 2017 Water and energy scarcity for agriculture: Is irrigation modernization the answer? Irrig. Drain. 66 34-44
[11] Mohtar R H and Lawford R 2016 Present and future of the water-energy-food nexus and the role of the community of practice J. Environ. Stud. Sci. 6 192-9
[12] Cai X M, Wallington K, Shafiee-Jood M and Marston L 2018 Understanding and managing the food-energy-water nexus – opportunities for water resources research Adv. Water Resour. 111 259-73
[13] Momblanch A, Papadimitriou L, Jain S K, Kulkarni A, Ojha C S P, Adeloye A J and Holman I P 2019 Untangling the water-food-energy-environment nexus for global change adaptation in a complex Himalayan water resource system Sci. Total Environ. 655 35-47
[14] FAO 2014 The Water-Energy-Food Nexus- A new approach in support of food security and sustainable agriculture (Rome: Food and Agriculture Organization of the United Nations)
[15] ADB 2013 Thinking about water differently: Managing the water-food-energy nexus (Manila: Asian Development Bank Metro)
[16] Haggerty J H, Smith K K, Weigle J, Kelsey T W, Walsh K B, Coupal R, Kay D and Lachapelle P 2019 Tradeoffs, balancing, and adaptation in the agriculture-oil and gas nexus: Insights from farmers and ranchers in the United States Energy Research & Social Science 47 84-92
[17] Howells M et al 2013 Integrated analysis of climate change, land-use, energy and water strategies Nat. Clim. Chang 3 621-6
[18] Daher B T and Mohtar R H 2015 Water-energy-food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making Water Int. 40 748-771
[19] FAO 2018 Water-energy-food nexus rapid appraisal available at: http://www.fao.org/energy/water-food-energy-nexus/water-energy-food-nexus-ra/en/
[20] Qiao J Y, Wang M, Zhang D Q, Ding C Y, Wang J J and Xu D W 2017 Synergetic development assessment of urban river Sustainability 9 2145
[21] Chen H, Huo Z, Dai X, Ma S, Xu X and Huang G 2018 Impact of agricultural water-saving practices on regional evapotranspiration: The role of groundwater in sustainable agriculture in arid and semi-arid areas Agric. Forest Meteorol. 263 156-68
[22] Wu Y, Shi X, Li C, Zhao S, Pen F and Green T 2017 Simulation of hydrology and nutrient transport in the Hetao irrigation district, Inner Mongolia, China Water 9 169
[23] Halbe J, Pahl-Wostl C, Lange M A and Velonis C 2015 Governance of transitions towards sustainable development – the water–energy–food nexus in Cyprus Water 40 877-94