**Supplementary Information to the paper:**

Spatio-temporal Evolution of Water-Energy-Food System Risk from the provincial perspective: A case study of China

**Part 1.**

**Part 1.1 Entropy weight method**

Entropy weight method is an objective weighting method, which can avoid the bias brought by subjective weight to a certain extent, reduce the influence of human factors on the index weight, and make the evaluation result more objective (Lu et al., 2017; Chen et al., 2019). Therefore, weight determination for different indexes and subsystems of risk evaluation system of WEF nexus could be obtained through entropy weight method.

Firstly, we construct evaluation objects, each evaluation object has indicators, then obtain a judgment matrix of the evaluation indexes.

Then, due to the existence of positive and negative indicators and the difference in data dimensions and orders of magnitude, the original data should be normalized by Eq. (1) and Eq. (2) in advance.

For positive indicators:

|  |  |
| --- | --- |
|   | (1) |

For negative indicators:

|  |  |
| --- | --- |
|  | (2) |

Where,  denotes the index  in year ; and  represent the maximum and minimum values of indicators respectively;  is the standardized value of each indicator.

Furthermore, the entropy of each evaluation index is determined by Eq. (3),

|  |  |
| --- | --- |
| ,  | (3) |

Where, ; . If , then .

 Finally, the entropy weight of each evaluation index can be calculated by Eq. (4),

|  |  |
| --- | --- |
|  | (4) |

Where, , and .

**Part 1.2 Set Pair Analysis**

Set Pair Analysis, proposed by Zhao (2010) from China, is a combination of probability analysis and uncertainty analysis. The basis of set pair analysis is set pair and its key is connection degree. Assuming that set  and a relative set  are combined to form a set pair . In order to study the relationship and judge the good or bad degree of the set pair , the following formula is defined:

|  |  |
| --- | --- |
|  | (5) |

Where,  is the connection degree.  are the identity degree, discrepancy degree and opposite degree of the two sets, .  is the coefficient of discrepancy varying in [−1, 1], and  denotes the coefficient of opposite degree that takes the value of -1.  denotes the total number of features of the set pair.  is the number of identical characteristics.  is the number of discrepant characteristics.  represents the number of contradictory characteristics. .

Firstly, the single index relation number  is constructed by the sample value  and the grade criteria . Assuming that  is the number of evaluation samples.  is the number of subsystems, which are stability, coordination and sustainable subsystems respectively.  denotes the number of indicators in subsystem. If the relation number between sample and an evaluation grade is the largest, the sample is considered to belong to that level (Shen et al., 1999).

If the index is positive,

|  |  |
| --- | --- |
|  | (6) |
|  | (7) |
|  | (8) |
|  | (9) |
|  | (10) |
| If the index is negative, |  |
|  | (11) |
|  | (12) |
|  | (13) |
|  | (14) |
|  | (15) |

Where, , , , .  is the value of  index of  subsystem of  sample.  are the boundary values of grade I to grade V respectively.

Then, the sample relation number  between sample  and grade criteria  is calculated by Eq.(16),

|  |  |
| --- | --- |
|  | (16) |

Where,  is the weight of the  subsystem;  denotes the single index relation number.

The relative membership degree  of sample value  belonging to grade criteria  can be denoted by Eq.(17),

|  |  |
| --- | --- |
|  | (17) |

Furthermore, the normalized relative membership degree of a single index and the normalized relative membership degree  of a subsystem can be determined by Eq.(18) and Eq.(19),

|  |  |
| --- | --- |
|  | (18) |
|  | (19) |

Where,  denotes the weight of  index of  subsystem.

Finally, in order to improve the accuracy of the evaluation results and avoid distortion, this paper adopts level characteristic values to evaluate the risk grade of  sample and  subsystem, namely,

|  |  |
| --- | --- |
|  | (20) |

Where,  represents the risk grade of  sample of  subsystem.

Meanwhile, the evaluation method of the confidence degree is also applied to assess the risk grade of  sample of  subsystem, that is,

|  |  |
| --- | --- |
|  | (21) |

Where,  is the confidence degree, and frequently varied from 0.5 to 0.7. The value of  may be chosen from the view of reliability (Wang et al., 2012). The higher  is, the more conservative and reliable assessment result may be. When  is given,  can be determined by means of Eq. (21).

**3.5 Step 5: Risk matrix**

Risk matrix, proposed by U.S. Air Force Electronic Systems Center in the late 1990s, is applied to recognize the ultimate risk assessment result by qualitatively and quantitatively analyzing the occurring possibilities of risk events and potential impacts33. The core principles of risk matrix include potential impact evaluation of risk factors, possibility calculation for the occurring of risk events, grade evaluation of risk event and countermeasure establishment of risk management. WEF-R was divided into three subsystems including stability, coordination and sustainability subsystems, which could be considered as three risk factors affecting WEF system. In order to evaluate the WEF-R effectively, scholars must focus on the main risk factors and construct the final risk matrix by analyzing, ranking and comparing the importance of different risk factors. The risk matrix of WEF-R assessment was as shown in [Table](http://www-sciencedirect-com-s.vpn.hhu.edu.cn:8118/science/article/pii/S004896971936320X%22%20%5Cl%20%22t0010) S1, which could be employed to determine the overall risk grade of WEF system basing on the determination of risk grade for each subsystem.

As shown in Table S1, the risk matrix of WEF-R was actually established according to the importance and influential intensity of each single or synthesized risk factor. For example, when the sustainability subsystem belonged to grade III, IV and V respectively, it indicated that the regulation capability of the WEF system was very poor, so the synthetic level was the same as the stability level of WEF system. Similarly, when the stability-sustainability synthesized subsystem belonged to grade II, while coordination-sustainability synthesized subsystem was grade III, the entire WEF-R would belong to grade II (as shown in bold in [Table S1](http://www-sciencedirect-com-s.vpn.hhu.edu.cn:8118/science/article/pii/S004896971936320X#t0010)) .

In conclusion, based on the subsystem risk grade characteristic matrix obtained from set pair analysis, the ultimate risk grade of WEF-R could be determined according to the risk matrix synthesizing rules.

**Table S1.** Synthesizing rules of the risk matrix of WEF-R assessment

|  |  |
| --- | --- |
| **Sustainability subsystem**  | **Stability subsystem** |
| **Grade I** | **Grade II** | **Grade III** | **Grade IV** | **Grade V** |
| **Grade I** | I | II | II | III | III |
| **Grade II** | I | II | III | III | IV |
| **Grade III** | **I** | **II** | **III** | **IV** | IV |
| **Grade IV** | **I** | **II** | **III** | **IV** | V |
| **Grade V** | **I** | **II** | **III** | **IV** | V |
| **Sustainability subsystem** | **Coordination subsystem** |
| **Grade I** | **Grade II** | **Grade III** | **Grade IV** | **Grade V** |
| **Grade I** | I | II | II | III | III |
| **Grade II** | I | II | III | III | IV |
| **Grade III** | **I** | **II** | **III** | **IV** | IV |
| **Grade IV** | **I** | **II** | **III** | **IV** | V |
| **Grade V** | **I** | **II** | **III** | **IV** | V |
| **Coordination - Sustainability synthesized subsystem** | **Stability - Sustainability synthesized subsystem** |
| **Grade 1** | **Grade II** | **Grade III** | **Grade IV** | **Grade V** |
| **Grade I** | I | II | II | III | III |
| **Grade II** | I | II | III | III |  IV  |
| **Grade III** | II | **II** | III | IV | IV |
| **Grade IV** | II | III | III | IV | V |
| **Grade V** | III | III | III | IV | V |

**Table S2.** Grade criteria system of WEF nexus security risk in China

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Index** | **Lowest risk** **Grade I**  | **Lower risk****Grade II** | **Moderate risk****Grade III** | **Higher risk Grade IV** | **Highest risk**  **Grade V** |
| C1 | 3000-17000 | 2300-3000 | 1700-2300 | 900-1700 | 70-900 |
| C2 | 0-15 | 15-40 | 40-75 | 75-100 | 100-900 |
| C3 | 0-2 | 2-5 | 5-10 | 10-30 | 30-160 |
| C4 | 5-30 | 2.5-5 | 2.5-1.5 | 1-1.5 | 0-1 |
| C5 | -8-0 | 0-0.4 | 0.4-0.6 | 0.6-1 | 1-10 |
| C6 | 150-500 | 75-150 | 55-75 | 35-55 | 0-35 |
| C7 | 2000-5000 | 1200-2000 | 900-1200 | 450-900 | 50-450 |
| C8 | 800-2000 | 500-800 | 400-500 | 250-400 | 0-250 |
| C9 | 0.5-4.7 | 0.4-0.5 | 0.3-0.4 | 0.25-0.3 | 0-0.25 |
| C10 | 0-10 | 10-30 | 30-50 | 50-100 | 100-1000 |
| C11 | 0-6 | 6-11 | 11-15 | 15-25 | 25-100 |
| C12 | 0-10 | 10-30 | 30-60 | 60-100 | 100-400 |
| C13 | 0-25 | 25-50 | 50-65 | 65-75 | 75-100 |
| C14 | 0-100 | 100-150 | 150-250 | 250-350 | 350-1000 |
| C15 | 5-50 | 50-100 | 100-500 | 500-1000 | 1000-7000 |
| C16 | 90-100 | 80-90 | 70-80 | 60-70 | 0-60 |
| C17 | 10-15 | 8-10 | 6-8 | 4-6 | 2-4 |
| C18 | 0.35-1.62 | 1.62-2.64 | 2.64-3.66 | 3.66-4.68 | 4.68-5.85 |
| C19 | 6-13 | 4-6 | 2.5-4 | 1-2.5 | 0-1 |
| C20 | 5-24 | 24-140 | 140-610 | 610-1060 | 1060-1300 |
| C21 | 0-0.4 | 0.4-0.8 | 0.8-1.2 | 1.2-1.8 | 1.8-3 |
| C22 | 0-2 | 2-4 | 4-6 | 6-8 | 8-12 |
| C23 | 75-90 | 50-75 | 40-50 | 25-40 | 20-25 |
| C24 | 0-200 | 200-400 | 400-600 | 600-800 | 800-3900 |
| C25 | 1100-1600 | 800-1100 | 400-800 | 200-400 | 0-200 |
| C26 | 80-100 | 70-80 | 60-70 | 45-60 | 30-45 |
| C27 | 50-70 | 40-50 | 25-40 | 15-25 | 0-15 |
| C28 | 0-0.1 | 0.1-0.25 | 0.25-0.4 | 0.4-0.5 | 0.5-3.5 |
| C29 | 0-0.8 | 0.8-1 | 1-1.5 | 1.5-2 | 2-35 |

**Table S3.** The weights of indexes and subsystems for risk evaluation system

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Object layer** | **The first layer** | **Weight** | **Elements** | **The first layer** | **Weight 1** | **Weight 2** |
| The risk evaluation index system of WEF-R | Stability | 0.4296 | Water system | C1 | 0.1916 | 0.0944 |
| C2 | 0.0145 | 0.0071 |
| C3 | 0.0459 | 0.0226 |
| Energy system | C4 | 0.2597 | 0.128 |
| C5 | 0.021 | 0.0103 |
| C6 | 0.1779 | 0.0876 |
| Food system | C7 | 0.1135 | 0.0559 |
| C8 | 0.1183 | 0.0583 |
| C9 | 0.0577 | 0.0284 |
| Coordination | 0.2114 | Water-energy | C10 | 0.0411 | 0.0087 |
| C11 | 0.0529 | 0.0112 |
| C12 | 0.072 | 0.0152 |
| Water-food | C13 | 0.1242 | 0.0262 |
| C14 | 0.0714 | 0.0151 |
| C15 | 0.0497 | 0.0105 |
| C16 | 0.2622 | 0.0554 |
| Energy-food | C17 | 0.2572 | 0.0544 |
| C18 | 0.0694 | 0.0147 |
| sustainability | 0.2959 | Economy system | C19 | 0.1858 | 0.055 |
| C20 | 0.0431 | 0.0128 |
| C21 | 0.0545 | 0.0161 |
| Social system | C22 | 0.1006 | 0.0298 |
| C23 | 0.0737 | 0.0218 |
| C24 | 0.0223 | 0.0066 |
| Natural system | C25 | 0.1403 | 0.0415 |
| C26 | 0.1961 | 0.058 |
| C27 | 0.1366 | 0.0404 |
| C28 | 0.0212 | 0.0063 |
| C29 | 0.0257 | 0.0076 |

**Table S4.** Risk levels of all subsystems in 30 provinces of China in 2008, 2013, and 2017

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Province | 2008 | 2013 | 2017 | Province | 2008 | 2013 | 2017 |
| Sta. | Coo. | Sus.  | Sta. | Coo. | Sus.  | Sta. | Coo. | Sus.  | Sta. | Coo. | Sus.  | Sta. | Coo. | Sus.  | Sta. | Coo. | Sus.  |
| Beijing | Ⅴ | Ⅳ | Ⅱ | Ⅴ | Ⅳ | Ⅱ | Ⅴ | Ⅲ | Ⅱ | Henan | Ⅳ | Ⅳ | Ⅳ | Ⅳ | Ⅳ | Ⅲ | Ⅳ | Ⅳ | Ⅲ |
| Tianjin | Ⅳ | Ⅲ | Ⅲ | Ⅳ | Ⅲ | Ⅲ | Ⅳ | Ⅲ | Ⅱ | Hubei | Ⅳ | Ⅳ | Ⅲ | Ⅳ | Ⅲ | Ⅱ | Ⅳ | Ⅳ | Ⅲ |
| Hebei | Ⅲ | Ⅲ | Ⅳ | Ⅲ | Ⅲ | Ⅳ | Ⅲ | Ⅲ | Ⅳ | Hunan | Ⅳ | Ⅳ | Ⅲ | Ⅳ | Ⅳ | Ⅲ | Ⅳ | Ⅲ | Ⅱ |
| Shanxi | Ⅳ | Ⅳ | Ⅳ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅳ | Guangdong | Ⅳ | Ⅳ | Ⅲ | Ⅳ | Ⅳ | Ⅲ | Ⅳ | Ⅲ | Ⅱ |
| Inner Mongolia | Ⅱ | Ⅲ | Ⅳ | Ⅰ | Ⅱ | Ⅳ | Ⅱ | Ⅲ | Ⅳ | Guangxi | Ⅴ | Ⅴ | Ⅳ | Ⅳ | Ⅳ | Ⅳ | Ⅳ | Ⅳ | Ⅳ |
| Liaoning | Ⅳ | Ⅳ | Ⅲ | Ⅳ | Ⅳ | Ⅲ | Ⅳ | Ⅳ | Ⅲ | Hainan | Ⅲ | Ⅲ | Ⅳ | Ⅲ | Ⅲ | Ⅲ | Ⅳ | Ⅳ | Ⅳ |
| Jilin | Ⅳ | Ⅳ | Ⅲ | Ⅲ | Ⅲ | Ⅱ | Ⅳ | Ⅳ | Ⅲ | Chongqing | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅱ | Ⅲ | Ⅲ | Ⅱ |
| Heilongjiang | Ⅲ | Ⅲ | Ⅲ | Ⅱ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Sichuan | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅲ |
| Shanghai | Ⅴ | Ⅳ | Ⅱ | Ⅴ | Ⅳ | Ⅱ | Ⅴ | Ⅳ | Ⅱ | Guizhou | Ⅲ | Ⅲ | Ⅳ | Ⅲ | Ⅲ | Ⅲ | Ⅱ | Ⅱ | Ⅲ |
| Jiangsu | Ⅳ | Ⅳ | Ⅲ | Ⅳ | Ⅲ | Ⅱ |  Ⅳ | Ⅲ | Ⅱ | Yunnan | Ⅲ | Ⅲ | Ⅳ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅲ |
| Zhejiang | Ⅴ | Ⅳ | Ⅱ | Ⅴ | Ⅳ | Ⅱ | Ⅴ | Ⅳ | Ⅱ | Shaanxi | Ⅳ | Ⅳ | Ⅳ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Ⅲ |
| Anhui | Ⅳ | Ⅳ | Ⅳ | Ⅳ | Ⅳ | Ⅲ | Ⅲ | Ⅲ | Ⅲ | Gansu | Ⅳ | Ⅳ | Ⅳ | Ⅲ | Ⅲ | Ⅳ | Ⅲ | Ⅲ | Ⅳ |
| Fujian | Ⅳ | Ⅳ | Ⅲ | Ⅳ | Ⅲ | Ⅱ | Ⅳ | Ⅲ | Ⅱ | Qinghai | Ⅱ | Ⅲ | Ⅳ | Ⅱ | Ⅲ | Ⅳ | Ⅲ | Ⅲ | Ⅲ |
| Jiangxi | Ⅲ | Ⅲ | Ⅳ | Ⅳ | Ⅳ | Ⅲ | Ⅳ | Ⅳ | Ⅳ | Ningxia | Ⅳ | Ⅳ | Ⅳ | Ⅳ | Ⅳ | Ⅳ | Ⅳ | Ⅳ | Ⅳ |
| Shandong | Ⅳ | Ⅳ | Ⅲ | Ⅳ | Ⅳ | Ⅲ | Ⅳ | Ⅳ | Ⅲ | Xinjiang | Ⅱ | Ⅲ | Ⅳ | Ⅱ | Ⅲ | Ⅳ | Ⅱ | Ⅲ | Ⅳ |

Note\*: Sta.: Stability subsystem; Coo.: Coordination subsystem; Sus.: Sustainability system.

**Table S5.** The WEF-R levels in 30 provinces of China in 2008, 2013, and 2017

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Province | 2008 | 2013 | 2017 | Province | 2008 | 2013 | 2017 |
| Beijing | IV | IV | III | Henan | IV | IV | IV |
| Tianjin | III | III | III | Hubei | IV | III | IV |
| Hebei | III | III | III | Hunan | IV | IV | III |
| Shanxi | IV | III | III | Guangdong | IV | IV | III |
| Neimongol | III | III | III | Guangxi | V | IV | IV |
| Liaoning | IV | IV | IV | Hainan | III | III | IV |
| Jilin | IV | III | IV | Chongqing | III | III | III |
| Heilongjiang | III | III | III | Sichuan | III | III | III |
| Shanghai | IV | IV | IV | Guizhou | III | III | II |
| Jiangsu | IV | III | III | Yunnan | III | III | III |
| Zhejiang | IV | IV | IV | Shaanxi | IV | III | III |
| Anhui | IV | IV | III | Gansu | IV | III | III |
| Fujian | IV | III | III | Qinghai | III | III | III |
| Jiangxi | III | IV | IV | Ningxia | IV | IV | IV |
| Shandong | IV | IV | IV | Xinjiang | III | III | III |