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An integrative analytical framework of water-energy-food security for sustainable development at the country scale: A case study of five Central Asian countries

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ABSTRACT

Thoroughly understanding the security of water, energy and food (WEF) and the factors that influence them is essential for sustainable development management in any region. This study proposed a new analytical framework for WEF security evaluation in both individual sectors and the whole system, using the technique for order preference by similarity to an ideal solution (TOPSIS) and four dimensions of security indicators: availability, self-sufficiency, productivity and accessibility. The internal relationships among the three sectors and the main factors influencing WEF security were analysed by Spearman's rank correlation and radar graphs, respectively. The five countries in Central Asia (CA), which are experiencing WEF crises and facing great challenges in achieving their sustainable development goals (SDGs), were chosen as a case study in this paper. Our results showed that Kazakhstan attained the highest WEF security level, followed by Kyrgyzstan, Turkmenistan and Uzbekistan; Tajikistan exhibited the lowest security level from 2000 to 2014. Three types of internal relationships among the three sectors were identified: synergies, trade-offs and unclassified. The unclassified relationship type accounted for the largest share of 54% in CA, suggesting great potential for synergetic improvement among the three sectors. Approaches for improving the country WEF security based on our research are as follows: Kazakhstan should prioritize food allocation and supply, Kyrgyzstan and Tajikistan should increase energy and food production and raise the supply level and usage efficiency of water and food, Turkmenistan should increase the available water resources and food production and improve the supply level and usage efficiency of water and energy, and Uzbekistan should both increase the available amount and enhance the WEF management performance.

1. Introduction

Water, energy and food (WEF) are essential for human survival and sustainable socioeconomic development (Rasul and Sharma, 2016). The water, energy and food security nexus as a whole was first introduced at the World Economic Forum in 2008 and has received increasing attention from researchers, stakeholders and policy-makers since the Bonn Conference in 2011 (Putra et al., 2020; Zhang et al., 2018a; Zhang et al., 2019b). Water, energy and food are traditionally managed by different sectors, and they make up the three resource sectors of WEF (Albrecht et al., 2018; Liu et al., 2017a; Putra et al., 2020; Simpson and Jewitt, 2019). In 2011, the World Economic Forum called for more attention to the nexus among the three sectors (WEF, 2011; Zhang et al., 2019b). Since then, the concept of the WEF security nexus has been interpreted by researchers and international organizations from different perspectives and concerns (FAO, 2014; Zhang et al., 2018a). In general, the WEF security nexus can be interpreted from two aspects. First, the nexus is taken as a method to analyse the relationships between the three resources; second, the nexus is indicated by the interactions among the three resources (Zhang et al., 2018a). Previous investigations identified four aspects of WEF security: availability, self-sufficiency, productivity and accessibility of the three resources (Flammini et al., 2014; Lee et al.,

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2012; Nhamo et al., 2020; Taniguchi et al., 2017; Zarei, 2020), and explored the interactions among the three sectors. However, the concept of the WEF security nexus is still unclear, and more efforts are needed to illustrate it (Reinhard et al., 2017).

Ensuring WEF security to sustain a growing population under climate change and globalization is one of the greatest challenges worldwide (Fuhrman et al., 2020; Momblanch et al., 2019; Zhang et al., 2018b). Moreover, the three sectors exhibit close relationships with sustainable development goal (SDG) 2 (end hunger, achieve food security, improve nutrition and promote sustainable agriculture), SDG 6 (ensure availability and sustainable management of water and sanitation for all) and SDG 7 (ensure access to affordable, reliable, sustainable and modern energy for all) among the 17 SDGs introduced by the United Nations (UN) (Bleischwitz et al., 2018; Nhamo et al., 2020; Pradhan et al., 2017). Therefore, a comprehensive evaluation of the WEF security nexus can help improve the rationality of integrated WEF management and realize the above SDGs (Namany et al., 2019).

Previous studies have analysed the WEF security nexus at the farm, household, city, basin, country, regional and international scales with various models and tools for a range of purposes (Abulibdeh and Zaidan, 2020; Barik et al., 2017; Deng et al., 2020; Fabiani et al., 2020; Hussien et al., 2017; Putra et al., 2020; Smajgl et al., 2016; Zhang et al., 2018a). For example, the WEF nexus has been analysed via life cycle assessment, system dynamics model, footprint theory, network analysis, the Nexus Solutions Tool and Bayesian networks (Ghafoori Kharanagh et al., 2020; Kamrani et al., 2020; Li and Ma, 2020; Ravar et al., 2020; Vinca et al., 2020; Xu et al., 2020a). Although these methods can be applied for qualitative and quantitative assessment of the WEF security nexus at multiple scales and can provide some insights for improving WEF security (e.g., Putra et al., 2020; Ravar et al., 2020), the extensive data requirements are a main limitation for the wide application of these methods, especially in developing areas (Kaddoura and El Khatib, 2017; Liu et al., 2017b).

An overall WEF security assessment at the country scale can provide guidance to decision-makers for integrated WEF management. This topic has been explored in some recent studies. For example, WEF nexus sustainability was evaluated by an improved matter-element extension model (a comprehensive evaluation method suitable for dealing with multiple-factors) in China (Wang et al., 2018). Based on the analysis of transboundary water resource management, resource accessibility and availability, the WEF nexus was explored in Iran, Iraq, and Turkey (Zarei, 2020). WEF nexus sustainability indicators were selected, including water availability and productivity, energy accessibility and productivity, and food self-sufficiency and cereal productivity, and the WEF nexus sustainability was then evaluated in South Africa (Nhamo et al., 2020). For WEF nexus interactions, the relationships of synergies and trade-offs were determined by Spearman's rank correlation in five South Asian countries (Putra et al., 2020). From the perspective of embedded resources, the network approach was applied to analyse the WEF nexus in America, for which extensive data were needed (Mahjabin et al., 2020). However, there is still no sufficient integrative analysis of WEF security and the relationships among the three sectors globally, and studies related to factors that reduce WEF security and methods to improve WEF security are lacking (Albrecht et al., 2018; Putra et al., 2020). These limitations hinder the management and improvement of the WEF security nexus and associated SDGs at the country scale in data-limited regions.

To fill the research gaps, this study develops an assessment indicator system for WEF security and a hybrid framework that integrates the technique for order preference by similarity to an ideal solution (TOPSIS), Spearman's rank correlation and radar graphs to systematically analyse WEF security at the country scale. Designed assessment indicator data are easily acquired from open sources, such as the World Bank, the Food and Agriculture Organization (FAO) online statistical database (FAOSTAT), the U.S. Energy Information Administration (EIA) and the official SDG database. The WEF security degree can be calculated by TOPSIS; the relationships among water, energy and food can be determined by Spearman's rank correlation, and the potential inhibiting factors can be visualized by radar graphs. The five Central Asian countries are taken as an example to validate the proposed framework. We assess the degree of WEF security in the five Central Asian countries during 2000–2014, analyse the spatiotemporal variations in WEF security, reveal the relationships among the three sectors, and identify the factors that positively or negatively determined WEF security. The results of this study are expected to provide illustrative insights into sustainable WEF development in Central Asia (CA).

2. Methodology

2.1. Integrative analytical framework of the WEF security

The proposed evaluation framework of WEF security (Fig. 1) comprises three main phases.

Phase 1 (Constructing the evaluation indicator system for WEF security):

As indicated in Table 1, the essence of resource security includes four pillars: availability, self-sufficiency, productivity and accessibility (Flammini et al., 2014; Lee et al., 2012; Nhamo et al., 2020; Taniguchi et al., 2017; Zarei, 2020). These four aspects demonstrate the security situation for the complete process of resource use, from resource abundance (availability), conflicts between supply and demand (self-sufficiency), and utilization levels (productivity) to human welfare (accessibility). Availability describes the resources accessible to humans and mainly indicates resource abundance. Self-sufficiency determines whether resource production can meet demand and mostly represents the supply and demand management level. Productivity illustrates the economic benefits of the resources used and largely reflects the utilization level. Accessibility indicates whether users can access resources and mainly reflects the human right to consume resources. In addition, to increase the applicability and reproducibility of the introduced method, data availability is also a key issue in the identification of WEF security indicators.

We identify 12 indicators to study WEF security for sustainable development at the country scale in data-limited regions (Table 1) based on the aforementioned SDGs and four essential aspects together with previous studies (Nhamo et al., 2020; Taniguchi et al., 2017; Xu et al., 2020b; Zuo et al., 2020). Although the selected indicators do not totally represent the essence of WEF security, they illustrate the real WEF security level to a large extent. Detailed justifications and limitations of the WEF indicators are listed in Table 2.

Phase 2 (Determining indicator criteria and calculating WEF security):

Determining indicator criteria: As revealed in Table 3, based on previous studies (FAO, 2018a; FAO, 2018b; Nhamo et al., 2020; Zuo et al., 2020), the WEF indicator security levels of W1, W2, W3, W4, E1, E2, E3, F1 and F3 were determined. In addition, we defined the top data points of the 2.5th, 25th, 50th, 75th and 97.5th percentiles of the WEF security indicator performance for all countries in terms of the E4, F2 and F4 indicators as the I, II, III, IV and V level bounds, respectively (Xu et al., 2020b; Zuo et al., 2020). The detailed reasons for these indicator thresholds are provided in the Appendix.

Determining indicator weight: We normalized the indicator original data to a scale from 0 to 1 based on Eqs. (1) and (2) in Section 2.2.1, and the indicator weight was then determined by Eqs. (3) and (4) in Section 2.2.1.

Calculating WEF security: We used TOPSIS to calculate the WEF security degree and the security degree in the water, energy and food sectors. The details of TOPSIS implementation are presented in Section 2.2.2.

Phase 3 (Identification of the WEF security pattern):

We unravelled the relationships among the three sectors based on synergies, trade-offs and unclassified relationship types (Putra et al.,

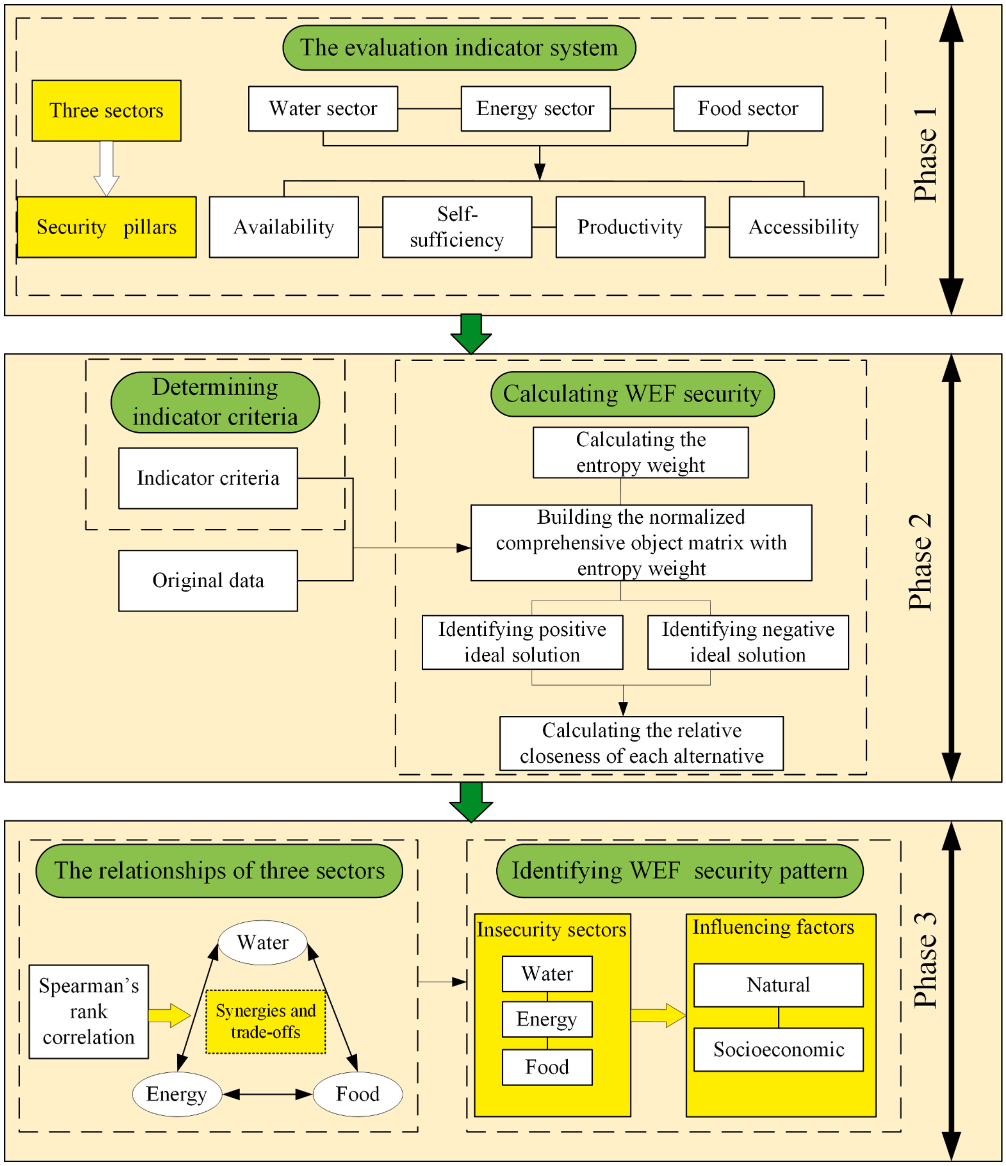

Fig. 1. Flowchart for integrative analysis of WEF security.

Table 1
The indicators of WEF security.

Sectors	IDs	Indicators	Pillars	Groups	Units (Signs)
Water	W1	Available freshwater resources per capita	Availability	Natural	m^3/capita (+)
	W2	Level of water stress	Self-sufficiency	Natural	% (–)
	W3	Water use efficiency	Productivity	Socioeconomic	USD/m^3 (+)
	W4	The proportion of the population using safely managed drinking water services	Accessibility	Socioeconomic	% (+)
Energy	E1	Primary energy production per capita	Availability	Natural	Terajoules/capita (+)
	E2	Production-to-consumption ratios of primary energy	Self-sufficiency	Natural	% (+)
	E3	The energy intensity level of primary energy	Productivity	Socioeconomic	Megajoules/USD (–)
	E4	The proportion of the population with access to electricity	Accessibility	Socioeconomic	% (+)
Food	F1	Food supply quantity per capita	Availability	Socioeconomic	kg/capita (+)
	F2	Production-to-consumption ratios of cereal	Self-sufficiency	Natural	% (+)
	F3	The average value of food production	Productivity	Socioeconomic	International dollars/capita (+)
	F4	Average dietary energy supply adequacy	Accessibility	Socioeconomic	% (+)

Note: USD is United States dollars. "+" denotes a benefit indicator, "-" represents a cost indicator. A benefit indicator means that increases in the indicator represent a better security level. In contrast, a cost indicator means that increases in the indicator indicate a worse security level (Chen, 2020; Lin et al., 2020).

2020) and applied radar graphs to visualize the major indicators that affect WEF security (Nhamo et al., 2020). Furthermore, WEF security is influenced by both natural and socioeconomic factors (Table 1). Therefore, we identified the WEF security pattern based on the possible inhibiting factors and whether they were determined by natural or socioeconomic factors.

Table 2
Justifications and limitations of WEF indicators.

IDs	References	Definitions	Rationalities	Limitations
W1	Indicator related to WEF sustainability (Nhamo et al., 2020); Indicator related to human-water harmony (Zuo et al., 2020).	Internal renewable water resources per capita.	W1 is a classic indicator to measure water availability, which reflects the relationship between water resources and population.	Although unconventional water resources are available, we do not consider them due to the low quantity or lack of data.
W2	SDG indicator 6.4.2; Indicator related to WEF security (Putra et al., 2020).	The ratio of total freshwater withdrawn to total renewable freshwater resources, after considering environmental flow requirements.	W2 is an indicator of water self-sufficiency that integrates the human and environmental water demands.	Water withdrawal may be increased due to some factors, such as water transmission loss.
W3	SDG indicator 6.4.1.	The value added per unit of water used.	W3 is an integrated indicator of water productivity, after considering water use by the agriculture, industry and service sectors.	The economic cost of eco-environmental deterioration caused by water use is not considered due to the large uncertainty.
W4	SDG indicator 6.1.1; Indicator related to WEF security (Putra et al., 2020).	The proportion of the population that can access safely managed drinking water.	There are three main water users: domestic, agricultural and industrial. Domestic water is the priority, and to some extent, it reflects the water management performance. Therefore, we use W4 to represent the integrated water accessibility level.	Agricultural and industrial water accessibility may result in some uncertainties.
E1	Resource security indicator (Nhamo et al., 2020).	Available primary energy production per capita.	E1 is an integrated indicator that takes various energy sources into account, and it represents the real energy availability.	Although potential fossil and renewable energy may increase energy availability, there are some uncertainties due to technology and cost factors. Therefore, we focus on energy production.
E2	Energy security indicator (Taniguchi et al., 2017).	The ratio of domestic primary energy production to consumption.	Integrated energy self-sufficiency takes various energy sources into account.	Energy consumption may not exactly equal real energy demand.
E3	SDG indicator 7.3.1; Indicator related to WEF security (Putra et al., 2020); Indicator related to WEF sustainability (Nhamo et al., 2020).	The total energy used per unit value added.	Integrated energy productivity considers various energy users and types.	The economic cost of eco-environmental deterioration caused by energy use is not considered due to the large uncertainty.
E4	SDG indicator 7.1.1.	The proportion of the population that can access electricity.	Electricity is generated by various sources, such as coal, natural gas, oil, water, wind and nuclear power. To some extent, electricity accessibility represents energy accessibility.	The electricity supply guarantee rate may undermine the real electricity accessibility.
F1	Food security indicator (FAOSTAT).	Food supply quantity per capita.	F1 is an integrated indicator that represents the real availability of cereals, after taking various types of cereals into account. To some extent, it reflects food availability.	To improve the applicability and ease of calculation, we focus on cereals, instead of considering all food types.
F2	Food security indicator (Taniguchi et al., 2017).	The ratio of domestic cereal production to cereal consumption.	Cereals provide essential dietary energy for human survival. Therefore, to some extent, cereal self-sufficiency indicates food self-sufficiency.	Cereal consumption may not exactly equal real cereal demand.
F3	Food security indicator (FAOSTAT).	Food production value per capita.	Food is different from water and energy that are directly used for production activities; food mainly provides nutrition for human survival, and humans then create value. Therefore, value per capita can better reflect the economic benefit of food.	Due to the large uncertainty in the economic cost of eco-environmental deterioration caused by food production, we do not consider economic cost.
F4	Food security indicator (FAOSTAT).	Dietary energy supply (DES) as a percentage of the average dietary energy requirement (ADER).	The ratio of DES to ADER is the accessibility of basic dietary energy, which indicates food accessibility, to some extent.	The accessibility assumes that all have an equal right to the dietary energy supply.

2.2. Methods to determine WEF security

2.2.1. Entropy weight method

Two main types of approaches are available to determine indicator weights, namely, subjective approaches, such as the analytic hierarchy process (AHP), and objective approaches, represented by the entropy weight method (Chen, 2021; Tzeng and Huang, 2011). The entropy

Table 3
WEF security level and its corresponding evaluated indicator.

Level	W1	W2	W3	W4	E1	E2	E3	E4	F1	F2	F3	F4
I	6000	25	100	100	0.61	1.00	3	100	212	1.00	430	100
II	3000	50	80	80	0.44	0.80	5	80	184	0.95	339	95
III	1700	75	40	60	0.10	0.60	9	60	168	0.90	280	90
IV	1000	100	10	40	0.03	0.40	18	40	156	0.85	237	85
V	500	151	0.25	20	0.02	0.20	33	20	113	0.80	108	80

weight method has been successfully applied to determine the index weight in the water, energy, and socioeconomic fields (Duan et al., 2018; Zuo et al., 2020). The weight is calculated as the difference in the information order degree of each indicator based on objective data. The values indicate the data dispersion level and the influence of the various indicators on WEF security (Chen, 2021; Zuo et al., 2020). In this investigation, the indicator values are objective and can be quantified. Therefore, the indicators and data attributes are consistent with those of the entropy weight method (Chen, 2021).

Although policy-maker preferences impact WEF security assessment, there is a gap in the accurate determination of the subjective weights of indicators due to unavailability and uncertainty in subjective government preferences. This study aims to propose a universal framework to analyse WEF security. Therefore, to acquire objective results, we assume that each indicator exhibits almost the same importance from the perspective of the subject, and decision-maker preferences are neglected. This hypothesis is consistent with the entropy weight method (Chen, 2019). Note that following the proposed framework, scientific communities and country policy-makers could choose an appropriate weighting method to determine the weights of indicators and analyse WEF security based on their actual needs.

The steps to calculate the entropy weights are as follows:

First, the raw data of the indicators should be normalized according to Eqs. (1) and (2).

For benefit indicators:

$$x_{ij}^{'} = \frac{x_{ij} - min_{x_j}}{max_{x_j} - min_{x_j}} (\mathrm{i} = 1, 2, \cdots, \mathrm{m}; \mathrm{j} = 1, 2, \cdots, \mathrm{n}) \tag{1}$$

For cost indicators:

$$x_{ij}^{'} = \frac{max_{x_j} - x_{ij}}{max_{x_j} - min_{x_j}} (\mathrm{i} = 1, 2, \cdots, \mathrm{m}; \mathrm{j} = 1, 2, \cdots, \mathrm{n}) \tag{2}$$

where $x_{ij}^{'}$ is the standardized value of the j-th indicator in the i-th country; x_{ij} denotes the value of the j-th indicator in the i-th country; i = 1, 2, …, m and j = 1, 2, …, n are the number of countries and indicators, respectively; max_{x_j} is the maximum value of the j-th indicator among m countries; and min_{x_j} is the minimum value of the j-th indicator among m countries.

Next, the entropy value of the j-th indicator can be calculated with Eq. (3).

$$E_j = -\frac{1}{\ln m}\sum_{i=1}^{m} x_{ij}^{'} \ln x_{ij}^{'} (\mathrm{j} = 1, 2, \cdots, \mathrm{n}) \tag{3}$$

where E_j is the entropy value of the j-th indicator.

Finally, the weight of the j-th indicator can be obtained by Eq. (4).

$$w_j = \frac{1 - E_j}{n - \sum_{j=1}^{n} E_j} \tag{4}$$

where w_j is the weight of the j-th indicator.

2.2.2. Technique for order preference by similarity to an ideal solution (TOPSIS)

WEF security consists of water, energy and food security aspects. Safety in the three sectors depends on WEF availability, self-sufficiency, productivity and accessibility. Therefore, WEF security evaluation is consistent with the characteristics of multicriteria decision analysis (MCDA) (Nhamo et al., 2020). TOPSIS was introduced by C.L. Hwang and K. Yoon in 1981 and performs well in MCDA (Lin et al., 2020; Sari, 2021). Following the method, the best alternative can be identified based on the relative closeness between the alternative and the ideal solution via TOPSIS (Lin et al., 2020). TOPSIS has the advantages of objectivity, logicality and easy calculation. Furthermore, the entropy weight and TOPSIS (E-TOPSIS) method has been successfully applied in various evaluation fields, such as water quality evaluation, safety estimation of coal mines, risk assessment, innovation performance and vulnerability determination (Chen, 2021; Kaynak et al., 2017; Li et al., 2011; Marti and Puertas, 2021).

TOPSIS requires several assumptions. First, all criteria are assumed to be monotonically increasing or decreasing. Second, all outcomes can be quantified. Finally, not all the criteria are equally important (Sánchez-Lozano and Fernández-Martínez, 2016). All the criteria of WEF security, water security, energy security and food security satisfy the abovementioned assumptions. TOPSIS is a compensatory MCDA method that can provide a sound assessment of the aggregated performance of an alternative or practical situation (Banihabib et al., 2017). However, the good performance of one indicator does compensate for the poor performance of one another in TOPSIS (Guitouni and Martel, 1998). To bridge this gap, we determined the security level of each indicator by calculating the relative closeness to the positive and negative ideal solutions. Then, the possible compensatory and non-compensatory indicators of WEF security were revealed based on a comparison of the WEF and indicator security levels.

The TOPSIS steps are as follows:

First, the standardized object matrix $Z = (z_{ij})_{m\times n}$ is constructed based on matrix $R = (r_{ij})_{m\times n}$ of original indicator data and standard matrix $S = (s_{ij})_{m\times n}$ of the levels of the WEF security indicators. Matrix Z represents normalized data of 12 WEF security indicators.

$$R = (r_{ij})_{m\times n} = \begin{pmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{pmatrix} \tag{5}$$

where r_{ij} is the value of the j-th indicator in the i-th country.

$$S = (s_{ij})_{m\times n} = \begin{pmatrix} s_{11} & \cdots & s_{1n} \\ \vdots & \ddots & \vdots \\ s_{m1} & \cdots & s_{mn} \end{pmatrix} \tag{6}$$

where s_{ij} is the value of the j-th indicator in the i-th level (Table 3).

$$Z = (z_{ij})_{m\times n} = \begin{pmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{m1} & \cdots & z_{mn} \end{pmatrix} \tag{7}$$

where z_{ij} is the standardized value of the j-th indicator in the i-th country.

$$z_{ij} = \begin{cases} \dfrac{r_{ij} - s_{1j}}{s_{5j} - s_{1j}} \ \textit{for cost criteria} \\ \dfrac{s_{1j} - r_{ij}}{s_{1j} - s_{5j}} \ \textit{for benefit criteria} \end{cases} \tag{8}$$

where z_{ij} is the standardized value of the j-th indicator in the i-th country; $if z_{ij} < 0, z_{ij} = 0; if z_{ij} > 1, z_{ij} = 1$.

Second, according to Eq. (9), the positive ideal solution z_j^+ and negative ideal solution z_j^- are identified for the 12 indicators. Matrices z_j^+ and z_j^- represent the best security level and the worst level, respectively.

$$\begin{cases} z_j^+ = max\{z_{1j}, z_{2j}, \cdots, z_{mj}\} \\ z_j^- = min\{z_{1j}, z_{2j}, \cdots, z_{mj}\} \end{cases} \tag{9}$$

Third, according to Eq. (10), the weighted Euclidean distances between every alternative and the positive and negative ideal solutions are calculated separately.

$$\begin{cases} D_i^+ = \sqrt{\sum_{j=1}^{n} w_j (z_{ij} - z_j^+)^2} \\ D_i^- = \sqrt{\sum_{j=1}^{n} w_j (z_{ij} - z_j^-)^2} \end{cases} \tag{10}$$

where D_i^+ and D_i^- are the distances of the alternative to the positive and negative ideal solutions, respectively. The values of D_i^+ and D_i^- represent the differences between the real security degree and the values of the best and worst security levels.

Finally, the closeness of each alternative C_i can be calculated with Eq. (11).

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{11}$$

The value of C_i varies between 0 and 1. The closer C_i is to 1, the better the alternative, and the closer C_i is to 0, the worse the alternative. The value of C represents the security level.

2.3. Analysis of the synergies and trade-offs

Synergy can be regarded as the positive effect of two indicators on each other; i.e., a mutually beneficial relationship exists between these two indicators. In contrast, a trade-off suggests that a given indicator negatively affects another indicator; i.e., there exists a mutually detrimental relationship between these two indicators (Fader et al., 2018). Therefore, synergy can occur between two indicators that experience a consistent changing trend, and the trade-off phenomenon is the opposite of synergy. Spearman's rank correlation analysis is one of the most classic analysis methods for the correlation between two variables. Compared with the Pearson correlation coefficient method, Spearman's rank correlation has some advantages: (a) it does not require the relationship between the variables to be linear and can identify nonlinear relationships very well, (b) it does not require the variables to be measured on interval or ratio scales, and (c) there are no assumptions about the frequency distribution of the variables (Hauke and Kossowski, 2011; Spearman, 1904). Moreover, the effectiveness and applicability of the Spearman's rank correlation method have been validated in the analysis of relationships in yearly series data from the water, energy and food sectors (Kroll et al., 2019; Pradhan et al., 2017; Putra et al., 2020; Ronzon and Sanjuán, 2020).

Following previous studies, when the value of Spearman's rank correlation coefficient between two variables is greater than 0.6, this relationship is defined as a synergy; when the value is less than −0.6, the relationship is defined as a trade-off; and when the value varies between −0.6 and 0.6, the relationship is defined as an unclassified relationship (Pradhan et al., 2017; Putra et al., 2020). These three relationships indicate the nexus among the three sectors. Although correlation does not reflect causality, a correlation coefficient greater than 0.6 indicates a consistent change trend between two indicators, and a correlation less than −0.6 suggests an inconsistent or even opposite change trend. Therefore, the determined correlation may reflect causality to a certain extent, and we combine it with previous studies to analyse any possible causality.

3. Case study of Central Asia and data

3.1. Description of the study area

Central Asia (CA) is located at the border between Asia and Europe and includes five countries: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan (Fig. 2). The total area of these five countries is approximately 4 million km^2 (Liu et al., 2020). CA has a continental climate, with a mean annual precipitation of 258 mm, an average temperature of 9 °C, and an average annual evapotranspiration of 220 mm during 2000–2019 (Central Asia Climate Change, n.d.).

Uzbekistan has the largest population of 33.6 million, followed by Kazakhstan (18.5 million), Tajikistan (9.3 million), Kyrgyzstan (6.5 million) and Turkmenistan (5.9 million). The total internal available freshwater resources are 194 km^3, of which 33% occurs in Kazakhstan. Renewable internal freshwater resources per capita are 3722 m^3, 8385 m^3, 7689 m^3, 257 m^3 and 531 m^3 in Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan, respectively. The total oil reserves in Kazakhstan, Turkmenistan and Uzbekistan reach 3.9, 0.1 and 0.1 thousand million tons, respectively; Kazakhstan, Turkmenistan and Uzbekistan contain total proven gas reserves of 2.7, 19.5 and 1.2 trillion cubic metres, respectively; Kazakhstan and Uzbekistan host total proven coal reserves of 25,605 and 1375 million tons, respectively (BP Statistical Review of World Energy, 2020). The energy production and consumption ratios in the five countries are shown in Fig. 2. Agriculture is the largest water user in CA, and Uzbekistan and Kazakhstan consume the most virtual water in agriculture (Yan and Tan, 2020). The average annual net export of virtual water in agricultural products was approximately 9 billion m^3, and Kazakhstan had the largest share of 90% during 1992–2016 (Yan and Tan, 2020). The main agricultural types of virtual water trade were cereals, feeds and cotton (Yan and Tan, 2020). In the past, virtual water flows have exacerbated water scarcity in CA (Lee and Jung, 2018; Porkka et al., 2012).

3.2. Water, energy and food challenges in Central Asia

CA is one of the most typical regions threatened by WEF insecurity at present (Jalilov et al., 2013), and this phenomenon will be exacerbated in the future, which will inhibit SDG achievement. There have been serious water allocation conflicts between upstream and downstream countries in the Aral Sea basin (ASB) in CA due to the limited water resources and different water use goals after the collapse of the Soviet Union in 1991. For instance, upstream countries aimed to develop hydropower to meet energy demand, but downstream countries required adequate water resources for agricultural irrigation, ecology and domestic life. Moreover, the increased crop water demand has increased water insecurity in the Syr Darya River basin (Ruan et al., 2020), and the increasing population and global warming have exacerbated water stress and conflicts in this region (Siegfried et al., 2012; Tian and Zhang, 2020). According to the UN, the population in CA will increase to nearly 100 million by 2050 (World Population Prospects, 2019), and Central Asian countries will face increasing challenges in satisfying the growing WEF demand. Previous studies in CA have focused on the analysis of the WEF nexus in the Amu Darya and Syr Darya river basins based on hydrological models and basin-scale water-trading approaches (Granit et al., 2012; Jalilov et al., 2016; Ma et al., 2020). These investigations have provided useful ideas for integrated WEF management of transboundary rivers in CA. Some previous studies have indicated that there are synergistic and trade-off relationships among the water, energy and food sectors (Albrecht et al., 2018; Fader et al., 2018; Kaddoura and El Khatib, 2017; Putra et al., 2020). Therefore, potential synergies and trade-offs can also be found in CA (Ma et al., 2021; Roidt and de Strasser,

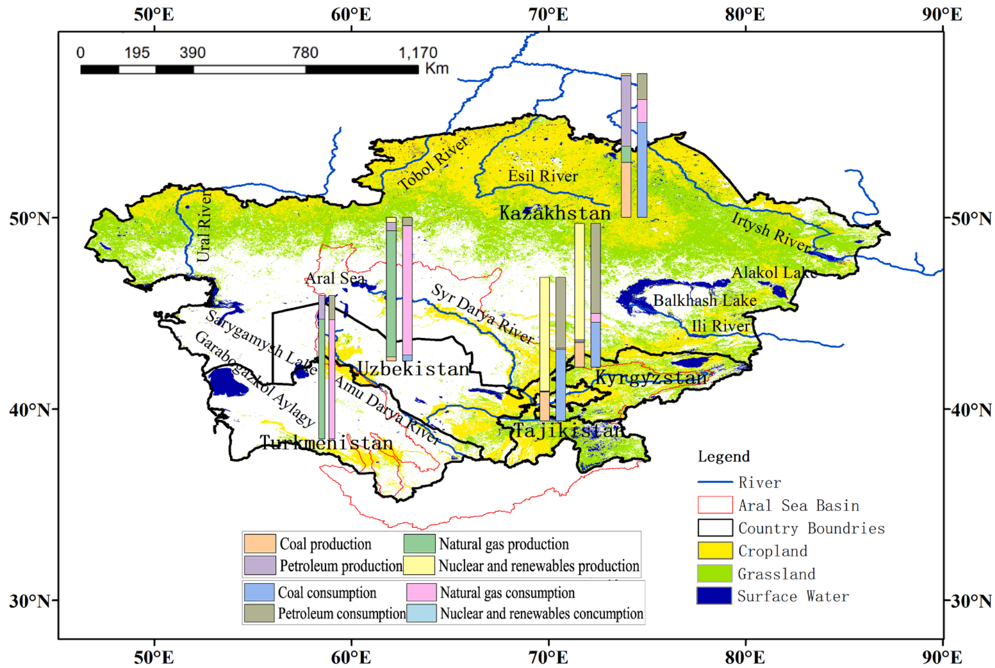

Fig. 2. Surface water, cropland, grassland, and percentages of different types of energy production and consumption in five Central Asian countries.

2018). However, few studies have analysed WEF security for sustainable development at the country scale in CA, and the synergies and trade-offs among the three sectors remain unclear.

3.3. Data

We obtained time-series data for 2000–2014 from various open sources. W2, W3, W4, E3 and E4 were obtained from the official SDG database (https://unstats.un.org/sdgs/indicators/database/), and F1, F3, F4, cereal production and domestic supply quantity were acquired from FAOSTAT (http://www.fao.org/faostat/en/#home), while the total internal available freshwater resources and total population were downloaded from the World Bank (https://data.worldbank.org/indicator). Moreover, primary energy production and consumption were obtained from the EIA (https://www.eia.gov/).

W1 was calculated by dividing the total internal available freshwater by the population. E1 was obtained by dividing primary energy production by the population. E2 was determined by dividing primary energy production by primary energy consumption. F2 was calculated by dividing cereal production by the domestic supply. However, note that the considered F3 and F4 data are 3-year averages; e.g., the average dietary energy supply adequacy (F4) in 2000 is the average value over the period from 2000 to 2002 (http://www.fao.org/faostat/en/#home).

4. Results

4.1. Trends of change in security in the three sectors and overall WEF security

We observed various security change trends among the three sectors in CA (Figs. 3-5). Regarding the water sector, the security degree in the five CA countries revealed a steady or slight increase, except for Kazakhstan (Fig. 3). The security degrees in Kazakhstan, Kyrgyzstan and Tajikistan were higher than those in Turkmenistan and Uzbekistan. The average water security scores in Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan were 0.75, 0.77, 0.68, 0.22, and 0.13, respectively. In addition, the minimum values in Kazakhstan, Kyrgyzstan and Tajikistan were higher than 0.65, but the maximum values in Turkmenistan and Uzbekistan were lower than 0.30. From 2000 to 2014, the water security levels in Turkmenistan, Kyrgyzstan and Uzbekistan increased by 32%, 15% and 13%, respectively, with higher

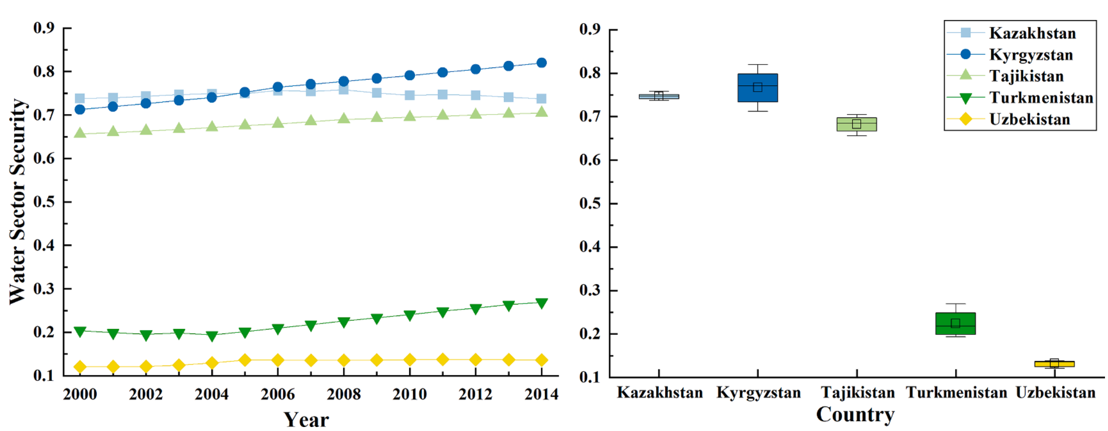

Fig. 3. Change trends (left) and box chart (right) of water sector security.

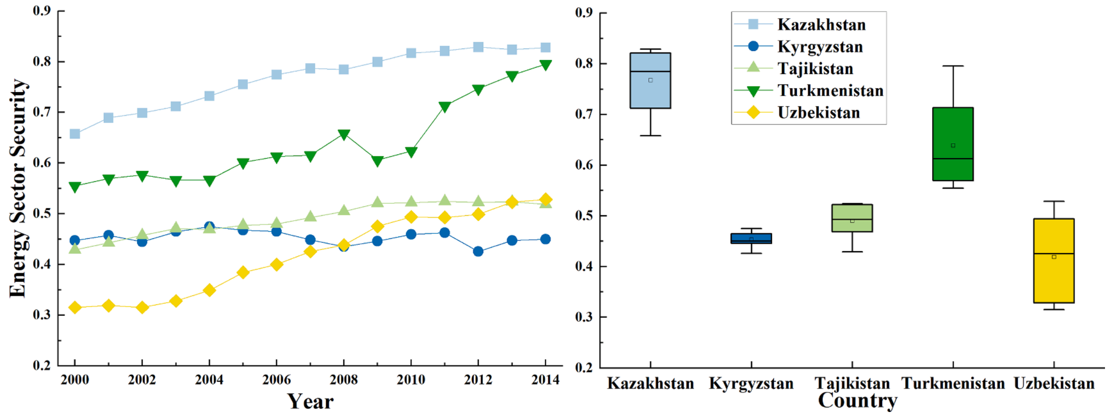

Fig. 4. Change trends (left) and box chart (right) of energy sector security.

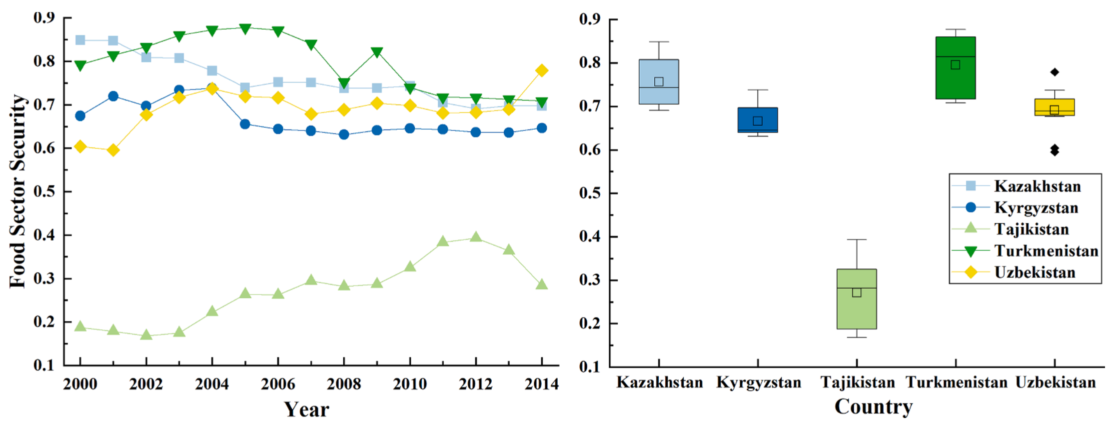

Fig. 5. Change trends (left) and box chart (right) of food sector security.

change rates than those observed in Kazakhstan and Tajikistan.

In the energy sector, Kazakhstan and Turkmenistan attained significantly higher security degrees than Tajikistan, Turkmenistan, and Uzbekistan (Fig. 4). The average energy security degrees in Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan were 0.77, 0.45, 0.49, 0.64, and 0.42, respectively. Moreover, the minimum values in Kazakhstan and Turkmenistan were higher than 0.55, but the maximum values in Kyrgyzstan, Tajikistan and Uzbekistan were lower than 0.50. From 2000 to 2014, there were significant increases in energy security in Uzbekistan and Turkmenistan, with change rates of 68% and 43%, respectively. In contrast, energy sector security remained constant in Kyrgyzstan. In addition, there was a larger fluctuation range for energy security than for water sector security, which increased by more than 20% from 2000 to 2014 in the five CA countries, except for Kyrgyzstan.

In the food sector, the change trends varied significantly among the five CA countries (Fig. 5). In general, Tajikistan attained the lowest food security degree. The average food security levels in Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan reached 0.76, 0.67, 0.27, 0.80, and 0.69, respectively. In addition, we observed fluctuating decreasing trends in food security in Kazakhstan and Turkmenistan and a steady trend in Kyrgyzstan. Moreover, food security varied within a wider range than that observed in the water sector, which indicated that variation rates were higher than 20% between the minimum and maximum values in Kazakhstan, Tajikistan,

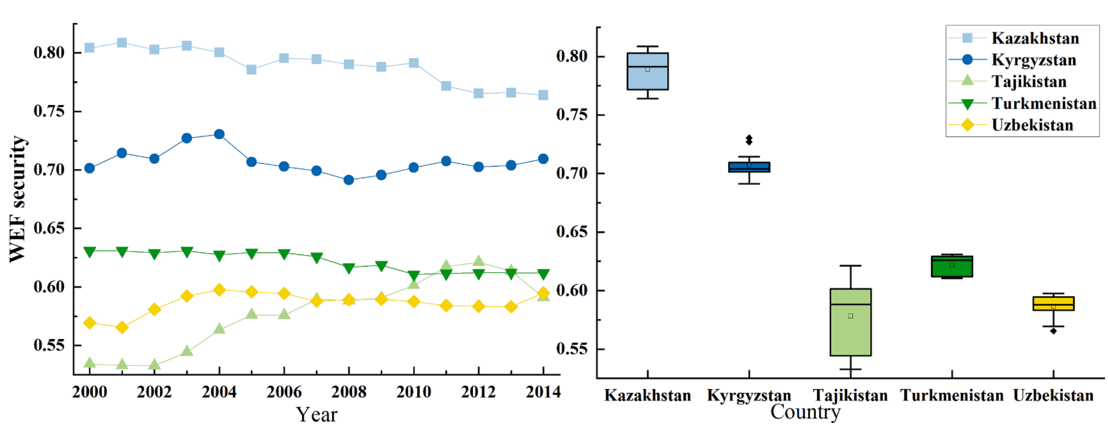

Fig. 6. Change trends (left) and box chart (right) of WEF security.

Turkmenistan and Uzbekistan.

Although there was no significant increase or decrease in WEF security, it varied among the five Central Asian countries (Fig. 6). Additionally, Kazakhstan and Tajikistan attained the highest and lowest WEF security levels, respectively, among the five countries. The average WEF security scores in Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan were 0.79, 0.71, 0.58, 0.62 and 0.59, respectively. Compared to that in 2000, WEF security in 2014 in Tajikistan increased by 11%, which was the largest improvement. In contrast, WEF security slightly decreased by 5% and 3% from 2000 to 2014 in Kazakhstan and Turkmenistan, respectively. Further, WEF security in Tajikistan ranged from 0.53 at the bottom to 0.62 at the top and exhibited the largest fluctuation range (Fig. 6).

4.2. Yearly rates of change in WEF security and security in the three sectors

The results indicated that in the five Central Asian countries, food security fluctuated significantly more than water and energy security (Fig. 7). In Kazakhstan, the numbers of years with increased and decreased WEF security levels were five and nine, respectively, with WEF security remaining relatively constant. The numbers of years with increased and decreased water security levels were eight and six, respectively. Energy security decreased slightly in only two years. Food security increased slightly in 2006, 2009, 2010, 2013 and 2014. In Kyrgyzstan, the numbers of years with increased and decreased WEF and energy sector security levels were eight and six, respectively, with WEF and energy security levels also remaining steady. In addition, increases and decreases in the WEF and energy sector security levels occurred in the same years. From 2000 to 2014, water security continuously increased. The number of years with increased and decreased food security levels were 6 and 8, respectively. In Tajikistan, the numbers of years with increased and decreased WEF and food sector security levels were eight and six, respectively. Water security continuously increased from 2000 to 2014. Energy security decreased in only 2004, 2012 and 2014. In Turkmenistan, the number of years with increased and decreased WEF security levels was seven. Water security decreased in only 2001, 2002 and 2004. Energy security continuously increased, except in 2003 and 2009. In the food sector, the numbers of years with increased and decreased security levels were six and eight, respectively. In Uzbekistan, the numbers of years with increased and decreased WEF security levels were 6 and 8, respectively. The numbers of years with increased and decreased water sector security levels were 8 and 6, respectively. Energy security decreased in only 2002 and 2011. The numbers of years with increased and decreased food security levels were 8 and 6, respectively.

4.3. Patterns of change in WEF security and security in the three sectors

To identify the patterns of change in WEF security in each country, this investigation defined the “steady” type in which the security change rate in 2014 varied between −10% and 10% with respect to the 2000 level. Moreover, we defined the “continuous ascent” type in which two conditions were satisfied: the change rate was higher than 10%, and the absolute value of the number of positive annual change rates minus the number of negative annual change rates was larger than seven. When the change rate was higher than 10% and the absolute value of the number of positive annual change rates minus the number of negative annual change rates was smaller than seven, these conditions defined the “fluctuating ascent” type. In addition, we defined the “continuous decrease” type as having both a change rate lower than −10% and an absolute value of the number of positive yearly change rates minus the number of negative yearly change rates larger than seven. When the change rate was lower than −10% and the absolute value of the number of years with positive change rates minus the number of years with negative change rates was smaller than seven, these conditions defined the “fluctuating decrease” type.

Finally, this investigation concluded that WEF security revealed stability in Kazakhstan, Kyrgyzstan, Turkmenistan and Uzbekistan (Table 4). In regard to water sector security, Kyrgyzstan, Turkmenistan and Uzbekistan indicated ascending change patterns. Energy sector security manifested ascending change patterns in Kazakhstan, Tajikistan, Turkmenistan and Uzbekistan. In contrast, in the food sector, two countries, namely, Kazakhstan and Turkmenistan, exhibited decreases in security (Table 4). Although not all CA countries were facing a serious food crisis, we can infer that food stress may have been one of the negative factors for improvement in sustainable WEF development from 2000 to 2014.

4.4. Synergies and trade-offs of the WEF security indicators

We observed the same shares of synergies and trade-offs among the three sectors in CA and the largest share of unclassified relationships, accounting for 54% of all relationships, reflecting the inconsistent trends of change in the WEF indicators. Furthermore, at the country scale, the shares of the synergies were larger than those of the trade-offs in Kazakhstan and Turkmenistan, while the opposite was the case in Kyrgyzstan, Tajikistan and Uzbekistan (Figs. 8 and 9, respectively).

In Kazakhstan, W1 and F1 attained larger shares of trade-offs with another indicator than of synergies, suggesting that progress in W1 and F1 poses a potential threat to WEF security and sustainable development. Although Kazakhstan contains the largest available water resources in CA, the freshwater resources per capita (W1) are at the intermediate level. With population growth and a growing demand for water in the energy and food sectors, the negative effect of water resources could be considerable. Note that the quantity of the food supply (F1) exhibited a continuing downward trend in Kazakhstan, which could be affected by food policy and dietary habits. In Kyrgyzstan, the energy sector showed unclassified relationships in terms of both the water and food sectors, suggesting that the energy sector did not provide adequate support to the water and food sector over the past few years. Although Kyrgyzstan has a high potential for hydroelectricity generation, it contains the smallest amount of fossil fuels in CA, and the residential sector currently accounts for the largest share of electricity (Meyer et al., 2019; Rakhmatullaev et al., 2018). As a result, the energy sector hinders the sustainability of the water and food sectors in Kyrgyzstan. Between the water and food sectors, there was a larger share of trade-offs than of synergies in Kyrgyzstan, which reflects the unmatched relationships between water and land resources. Kyrgyzstan contains the smallest cultivable area, with the lowest ratio of cultivable area to total land area in the ASB (Zhang et al., 2019a). In contrast, Kyrgyzstan possesses sufficient water resources. Limited land resources impede maximizing the utilization of water resources. In Tajikistan, the share of trade-offs was slightly larger than that of synergies. The WEF security degrees, relationships and related rationales in Tajikistan are comparable to those in Kyrgyzstan as an upstream country in the ASB. The cultivable area and ratio of cultivable area to total area in Tajikistan are slightly greater than those in Kyrgyzstan (Zhang et al., 2019a). Moreover, we observed that most of the indicators attained nearly equal shares of trade-offs and synergies with another indicator, and E4 and F2 exhibited unclassified relationships with almost all other WEF security indicators. Hence, there is great potential for synchronous development of the three sectors. In Turkmenistan, there was a larger share of synergies than of trade-offs among the three sectors. However, in the water sector, the share of trade-offs was larger than that of synergies, indicating that the water crisis was a great challenge to WEF security. Turkmenistan contains the smallest amount of water resources per capita and experiences high water stress (Zhang et al., 2020; Meyer et al., 2019). In contrast, in the ASB, the cultivable area of Turkmenistan is at the intermediate level (Zhang et al., 2019a). Furthermore, Turkmenistan contains the most abundant fossil fuels. There are poor matching relationships among water, cultivable area and energy resources. The water sector poses a

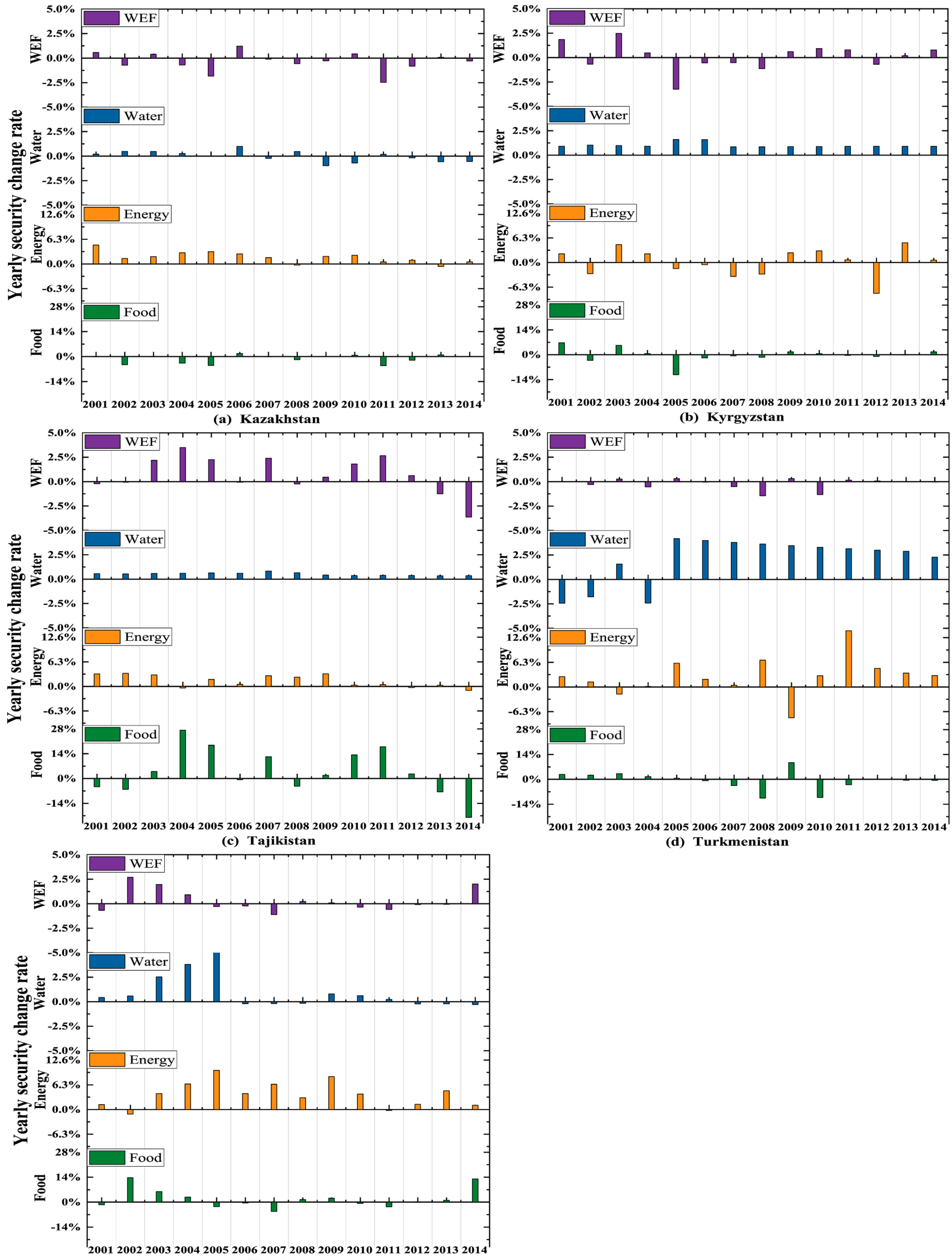

Fig. 7. Yearly rates of change in WEF security and security in the three sectors.

Table 4
Change patterns of WEF security and security in the three sectors.

Countries	Sectors	Change patterns				
		Steady	Ascent		Decrease	
			Continuous	Fluctuating	Continuous	Fluctuating
Kazakhstan	WEF	*				
	Water	*				
	Energy		*			
	Food					*
Kyrgyzstan	WEF	*				
	Water		*			
	Energy	*				
	Food	*				
Tajikistan	WEF			*		
	Water	*				
	Energy		*			
	Food			*		
Turkmenistan	WEF	*				
	Water		*			
	Energy		*			
	Food					*
Uzbekistan	WEF	*				
	Water		*			
	Energy		*			
	Food			*		

Note: "*" indicates that there is an associated change pattern; blank means that there is no associated change pattern.

threat to energy and food security. Although Uzbekistan attained a slightly larger share of trade-offs than of synergies, it displayed the largest share of unclassified relationships among the five Central Asian countries. Furthermore, W2, E2, E4, F1 and F2 revealed unclassified relationships with almost all other WEF security indicators. Therefore, the positive and negative mutual relationships of the WEF security indicators are not significant in Uzbekistan. There is an urgent need to integrate the management of the three sectors in Uzbekistan.

5. Discussion

5.1. Possible factors inhibiting WEF security and security in the three sectors

The shares of WEF synergies and trade-offs were smaller than those of unclassified relationships in the CA countries from 2000 to 2014 (Figs. 8 and 9, respectively). Until recently, the three sectors have provided little support for each other, which indicates that the security in these three sectors does not exhibit a significant synchronized increasing trend. Although we cannot gain insights into WEF security from the perspective of interactions, we can identify the factors that possibly inhibit sustainable WEF development in the three sectors by analysing the relationships between the WEF indicator scores and associated sector security degrees throughout 2000–2014.

In this investigation, i.e., using entropy weights and TOPSIS rather than decision-maker preferences, the greatest WEF security challenges involved the water sector in Turkmenistan and Uzbekistan (Fig. 10a), consistent with a lack of water resources in both countries (Zuo et al., 2020). However, in Kyrgyzstan and Tajikistan, there was an urgent need to improve the performance of the energy and food sectors (Jalilov et al., 2016). Furthermore, considering the water sector (Fig. 10b), although Tajikistan and Kyrgyzstan attained the two highest levels of freshwater resources per capita, the water security in these two countries was mainly limited by the following factors: water accessibility (W4) and water use efficiency (W3) (Chen et al., 2020; FAO, 2018a). Both Turkmenistan and Uzbekistan were negatively influenced by indicators W1, W2 and W3 (FAO, 2018a; FAO, 2018b; Zuo et al., 2020). Moreover, due to the lack of safely managed drinking water services, Uzbekistan exhibited low water accessibility (W4) with a security score of 0.41. Regarding the energy sector (Fig. 10c), energy availability (E1) and self-sufficiency (E2) constrained energy sustainability in Kyrgyzstan, with security scores of 0.24 and 0.01, respectively. The availability of energy (E1) with a score of 0.005 posed a threat to energy security in Tajikistan. The availability (E1) and productivity (E3) of energy imposed a negative influence on energy sustainability in Uzbekistan, with security scores of 0.42 and 0.13, respectively. Interestingly, although Turkmenistan is globally an important natural gas-producing and exporting country, energy sustainability is constrained by a low energy productivity (E3) with a score of 0.40. Considering the food sector (Fig. 10d), the food supply quantity (F1) continuously decreased from 2000 to 2014, which poses a potential threat to food sustainability in Kazakhstan. Self-sufficiency with respect to food (F2) was the most negative indicator of food sustainability in Kyrgyzstan and Tajikistan, with security scores of 0.30 and 0, respectively, due to limited land resources. In contrast, although F2 also threatened food security in Turkmenistan and Uzbekistan, the food insecurity in these two countries was mainly attributed to insufficient water resources for irrigation and consequent low food production (Zhang et al., 2020).

5.2. WEF security patterns

WEF security patterns are the integrated results of the available resources, management performance, technology level and relationships among the three sectors. These factors and associated WEF security indicators can be classified as either natural or socioeconomic factors (Table 1). There are strong correlations between the income level and WEF security and the SDGs. With international trade, good management performance and advanced technology, developed countries can significantly improve their sustainable development levels (Gain et al., 2016; Xu et al., 2020b). In general, developed countries exhibit higher levels of sustainable development related to the three sectors than developing countries (Gain et al., 2016; Wada and Bierkens, 2014). We find that both the gross domestic product (GDP) and per capita GDP of Kazakhstan are the highest among the five Central Asian countries, which is consistent with WEF security being the highest in Kazakhstan. In contrast, the GDP and per capita GDP in Tajikistan are the lowest, along with its WEF security. Uzbekistan attains the second lowest WEF security level, but the GDP and per capita GDP in Uzbekistan are the second and third highest, respectively, in CA. We observe that sustainable water and energy development levels are low in Uzbekistan. For instance, the water stress level is the highest in Uzbekistan across CA. In addition, the water use efficiency in Uzbekistan has decreased over the

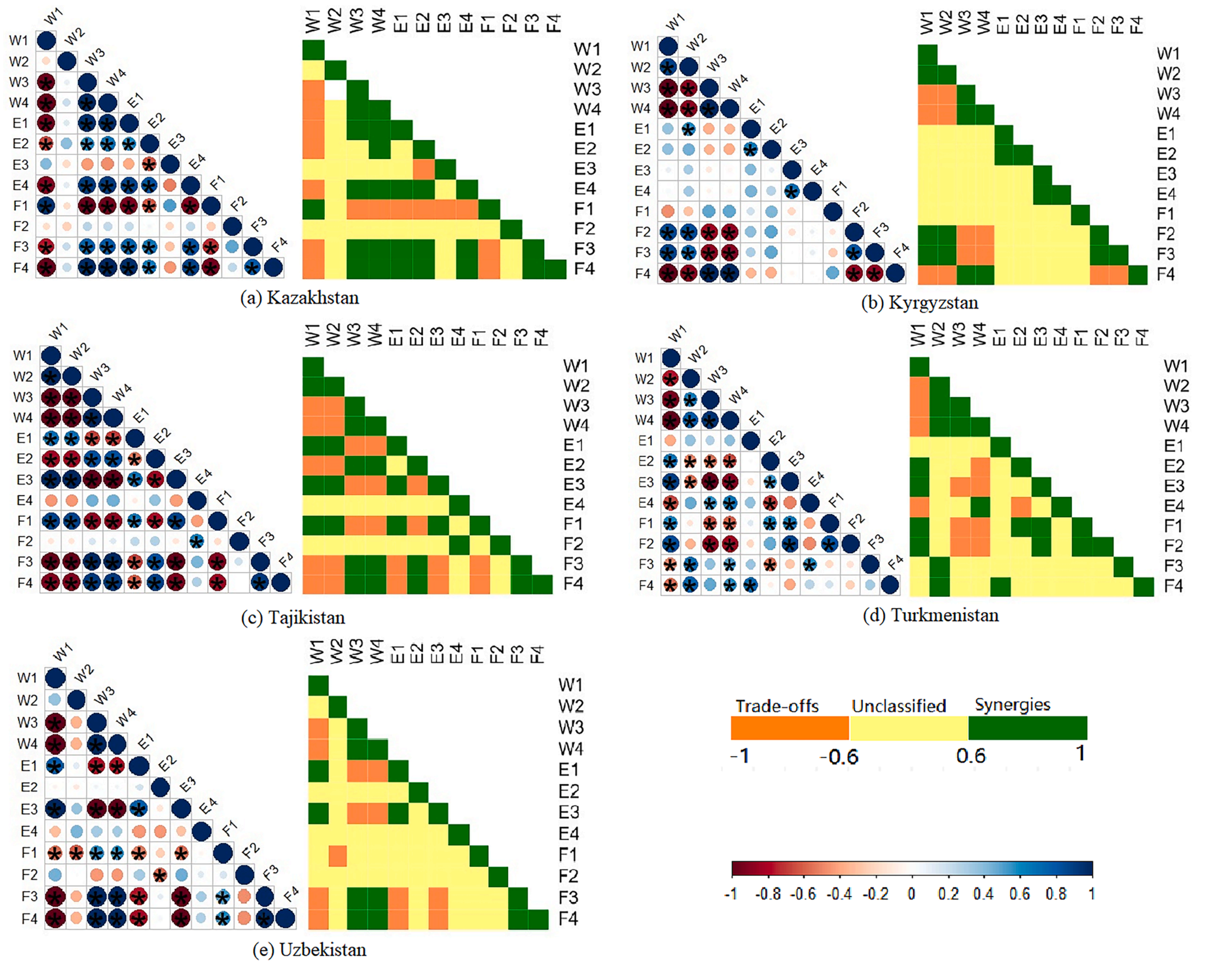

Fig. 8. Correlations (left) and observed relationships (right) of the WEF security indicators, including synergies (green), trade-offs (orange) and unclassified relationships (yellow), where * indicates a correlation with a p value less than 0.05. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

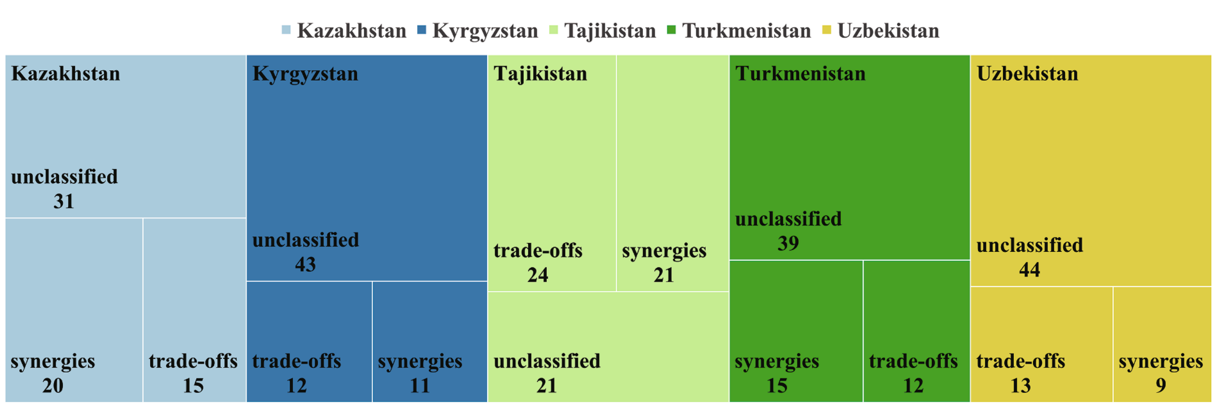

Fig. 9. Numbers of the three types of relationships (synergies, trade-offs and unclassified) between the WEF security indicators.

past few years (Chen et al., 2020).

This investigation aimed to identify the negative factors that are considered obstacles to WEF security in CA. Synthesizing the above results (Figs. 8-10), we classified the WEF security patterns as water constrained, energy constrained, food constrained, water-energy constrained, water-food constrained, energy-food constrained, and water-energy-food constrained. Furthermore, based on the group of critical indicators (Table 1), we revealed the WEF security patterns from the perspective of natural and socioeconomic factors.

As indicated in Table 5, we conclude that the water sector is the critical sector of WEF security in CA. In general, the water crisis is an obstacle to sustainable development in CA, even in water-rich countries.

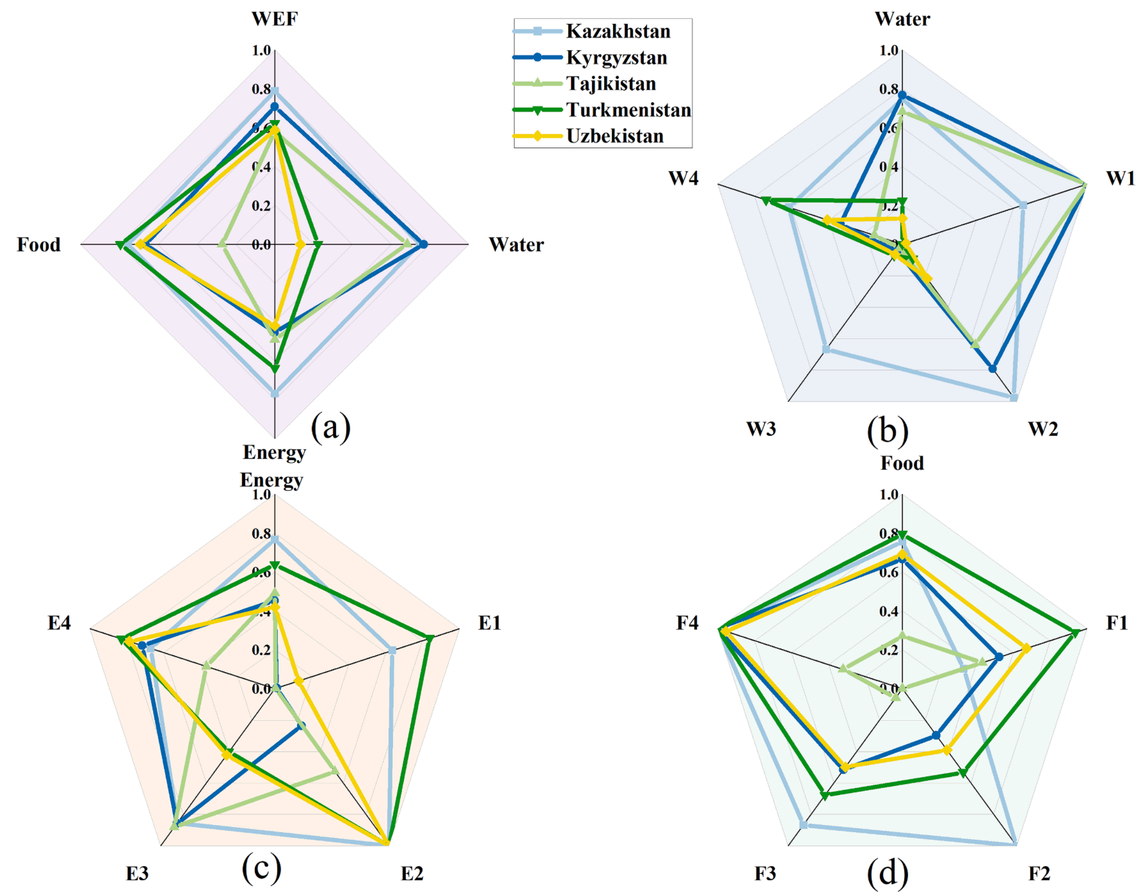

Fig. 10. Comparison of the indicators and their related sector security. (a) Comparison of security in the water, energy and food sectors to WEF security; (b) comparison of the W1, W2, W3 and W4 indicator scores to water sector security; (c) comparison of the E1, E2, E3 and E4 indicator scores to energy sector security; (d) comparison of the F1, F2, F3 and F4 indicator scores to food sector security.

Table 5
WEF security patterns.

Countries	Negative sectors	Natural	Socioeconomic
Kazakhstan	Water		
	Energy		
	Food		*
Kyrgyzstan	Water		*
	Energy	*	
	Food	*	*
Tajikistan	Water		*
	Energy	*	*
	Food	*	*
Turkmenistan	Water	*	*
	Energy		*
	Food	*	
Uzbekistan	Water	*	*
	Energy	*	*
	Food	*	*

Note: "*" indicates that there is an associated security pattern; blank means that there is no associated security pattern.

On the natural side, the total available freshwater resources are the constraining factor on WEF security in Turkmenistan and Uzbekistan. However, in the upstream countries of Kyrgyzstan and Tajikistan, the WEF security patterns are energy-food constrained. On the socioeconomic side, the WEF security patterns in Kazakhstan and Kyrgyzstan are food constrained and water-food constrained, respectively. Turkmenistan attains a low security degree in both the water and energy sectors. Tajikistan has the potential for integrated management of the three sectors. On both the natural and socioeconomic sides, the WEF security patterns in Uzbekistan are water-energy-food constrained, which suggests that the most effort is required for WEF sustainable development in Uzbekistan. The previous paragraphs highlight that natural factors pose a great challenge for WEF security in CA. Regarding the natural conditions of resources, WEF security could be improved by negotiating the water allocation and energy supply amounts between the upstream and downstream countries in the ASB (Jalilov et al., 2016). Regarding socioeconomic aspects, there remains great potential to improve the overall WEF sustainability score via international trade, good management performance and advanced technology, especially in Kyrgyzstan, Tajikistan and Uzbekistan.

5.3. Uncertainties and limitations

Although the 12 selected indicators demonstrate WEF security to a large extent, some uncertainties need to be clarified (Table 2). First, due to data unavailability, some indicators may not capture all aspects of WEF security. We do not consider unconventional water resources due to missing or few data. This may underestimate the water availability (W1). Water loss is difficult to calculate accurately, but it may increase water withdrawal and reduce water self-sufficiency (W2). Access to water (W4) may be overestimated because access to agricultural and industrial water is not considered. Food availability (F1) may have some uncertainties because we focus on cereals. Second, WEF security is a complicated system problem. To increase the applicability and reproducibility of the introduced framework, we make several assumptions and simplifications. Although E1 represents the real availability of primary energy in the past, potential fossil and renewable energy may enhance energy availability in the future (Meyer et al., 2019). Energy and food self-sufficiency (E2 and F2) may be overestimated since consumption may not be entirely equal to real demand. Energy and food accessibility (E4 and F4) may be overestimated, as we assume that everyone could afford energy and food. Moreover, the electricity supply guarantee rate may also undermine access to electricity. Third, we focus on WEF security for sustainable development but do not pay much attention to the environment and ecology. Water and energy productivity (W3 and E3) do not consider environmental and ecological costs associated with water and energy use. This situation is consistent with food production (F3). Environmental and ecological extensions are beyond the scope of this study. Despite the abovementioned uncertainties, the indicator system captures key aspects of WEF security at the country level (Table 2) and systematically evaluates the degree of WEF security.

Furthermore, the developed framework faces certain limitations. Although correlation analysis illustrates the relationships among the WEF security indicators, causality is not determined (Putra et al., 2020). In addition, we classify WEF security patterns from the perspective of natural and socioeconomic factors, but the contributions of these two factors are not quantified due to the complex interactions between the natural conditions of resources and human activities.

6. Conclusions

In this study, we proposed a hybrid framework involving TOPSIS, Spearman's rank correlation and radar graphs to analyse WEF security and the corresponding relationships. This approach was applied in the five Central Asian countries to better understand WEF security and sustainable development at the country scale. Our results indicated that WEF security and the degree of security in the three sectors exhibited steady trends, continuous increasing and decreasing trends, and fluctuating increasing and decreasing trends within the five CA countries. Moreover, the water sector was the most critical variable regarding WEF security in CA, which was verified by the fact that water insecurity poses a threat not only to upstream water resource-rich countries (Tajikistan and Kyrgyzstan) but also to downstream water resource-poor countries (Turkmenistan, Uzbekistan and Kazakhstan).

Furthermore, the WEF crisis in the ASB is a major issue in CA. The potential utilization of hydropower is a beneficial method to ensure energy security in the upstream countries of Kyrgyzstan and Tajikistan, but this may result in a water and food crisis in Kazakhstan, Turkmenistan and Uzbekistan. Moreover, sustainable WEF development is a goal associated with a whole country and should be addressed at the country scale. Therefore, integrative WEF research at the country and basin scales should be conducted to gain insights into the WEF security and nexus mechanisms and to achieve win-win cooperation among the ASB countries.

Data availability

Data used in this study are publicly available from the websites provided in Section 3. In addition, the raw data can be directly downloaded from https://doi.org/10.5281/zenodo.5069499.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2022.127530.

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