# Water-Energy-Food-Ecology Coupling Relationship and Spatiotemporal Differentiation in Five Central Asian Countries: Postprint

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## Abstract

Addressing the complex transboundary water issues in Central Asia, this study investigates the coordination of the Water-Energy-Food-Ecology (WEFE) system from a system coupling perspective at both regional and national levels. First, a WEFE coupling coordination evaluation index system was constructed, and then the coupling coordination degree model was applied to quantitatively evaluate the WEFE coordinated development level and its spatiotemporal evolution characteristics in Central Asia. The results show that: (1) Over the past 20 years, the coupling degree of the WEFE system in Central Asia has remained at a relatively high level, while the coupling coordination degree has shown a slow growth trend but remains at the barely coordinated stage; (2) The coupling coordinated development levels vary significantly among countries, with Kazakhstan exhibiting the optimal coupling coordination level but still at the primary coordination stage, Tajikistan and Kyrgyzstan at the barely coordinated stage, and Turkmenistan and Uzbekistan on the verge of disorder; (3) By comparing the development levels of multiple systems, it was found that Tajikistan and Kyrgyzstan exhibit significant lag in the food subsystem, Turkmenistan belongs to the water-resource-lagged type, and Kazakhstan and Uzbekistan belong to the energy-lagged type, with subsystems failing to achieve good matching, which affects regional coordinated development to a certain extent. The research findings can provide a decision-making basis for WEFE synergistic development in Central Asia and transboundary river development cooperation among countries.

## Full Text

# Coupling Relationship and Spatiotemporal Differentiation of the Water-Energy-Food-Ecology Nexus in Five Central Asian Countries

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### Abstract

To address the complex transboundary water issues in Central Asia, this study examines water-energy-food-ecology (WEFE) system coordination from both regional and national perspectives based on a system coupling approach. First, a WEFE coupling coordination evaluation index system was constructed, and then the coupling coordination degree model was applied to quantitatively assess the coordinated development level and its spatiotemporal evolution in Central Asia. The results indicate that: (1) Over the past two decades, the WEFE system coupling degree in Central Asia has remained at a high level, while the coupling coordination degree has shown a slow upward trend but remains in a state of barely coordinated development. (2) Significant variations exist among countries in their coupling coordination development levels. Kazakhstan exhibits the optimal coupling coordination level, reaching primary coordination, while Tajikistan and Kyrgyzstan are in barely coordinated states, and Turkmenistan and Uzbekistan are on the brink of misalignment. (3) Comparative analysis of multi-system development levels reveals obvious lags in the food system in Tajikistan and Kyrgyzstan, a water system lag in Turkmenistan, and energy system lags in Kazakhstan and Uzbekistan. The subsystems have failed to achieve good matching, which affects regional coordinated development to some extent. These findings can provide a decision-making basis for synergistic WEFE development in Central Asia and cooperation on transboundary river development among countries.

**Keywords:** water-energy-food-ecology; Central Asia; coupling coordination; spatiotemporal evolution

## 1. Introduction

Water, energy, and food are crucial strategic resources for human survival and social development, and they share close and complex interrelationships. Since the "water-energy-food (WEF) nexus"concept was first proposed, scholars worldwide have primarily investigated its connotations, theoretical frameworks, and regional nexus status. Methodologically, research has employed input-output analysis, system dynamics models, coupling coordination degree models, and geographically weighted regression models. Among these, the coupling coordination degree model is frequently used to study inter-system feedback relationships. For instance, Xu et al. used this model to quantitatively evaluate WEF coordinated development in the Yellow River Basin, while Shi et al. examined the coupling relationship between resource-environment carrying capacity and economic development in five Central Asian countries.

Ecosystems serve as crucial carriers for water, energy, food, and other resources, forming interdependent and mutually influential relationships with the WEF nexus. The matching and coupling between ecosystems and WEF are vital for regional development and stability, necessitating the integration of ecological factors into the nexus framework. Previous literature on WEFE coupling coordination has primarily focused on interrelationships and coordination levels among the three systems, with limited attention to the coupling relationship between ecosystems and the food system. Most studies have been conducted at national or provincial levels, with few cross-country or cross-regional analyses, particularly for resource-mismatched and slowly developing regions like Central Asia.

Central Asia is located in an arid inland area with acute transboundary water conflicts, mismatched resource supply and demand, overexploitation of resources, and fragile ecological environments. Past research on Central Asia has concentrated on climate change impacts, transboundary water conflicts, and ecological assessments, with limited studies on WEFE system coordination. Given that multiple Central Asian countries overlap in transboundary river basins and face special challenges of arid climate and ecological fragility, the WEFE system is extremely complex. There is an urgent need for systematic governance and response based on regional and national-level WEFE coordination perspectives. This study selects the five Central Asian countries as typical research objects, constructs a WEFE evaluation index system, and applies the coupling coordination degree model to analyze the coordinated development status and evolution characteristics of subsystems from both temporal and spatial dimensions. The findings can provide references for promoting WEFE coordinated development, protecting fragile ecological environments, and resolving prominent resource utilization contradictions in Central Asia.

## 2. Study Area Overview

Central Asia is situated in the hinterland of the Eurasian continent, far from oceans, and features a typical arid and semi-arid climate. The region comprises five countries—Tajikistan, Kyrgyzstan, Kazakhstan, Turkmenistan, and Uzbekistan—with a total land area of over 4 million square kilometers. The terrain is undulating, generally higher in the southeast and lower in the northwest, with land use dominated by cropland and grassland. The southeast includes the Tianshan Mountains and Pamir Plateau, serving as Central Asia' s "water tower." The western region consists mainly of plains and basins, mostly desert or wasteland, while the north-central area comprises low mountains and hills that constitute the main agricultural zone.

The climate is dry with scarce rainfall and high evaporation, and precipitation is unevenly distributed spatially and temporally, with more precipitation in winter and spring than in summer. Annual precipitation is below 300 mm, concentrated in southeastern mountainous areas, while plains generally receive less precipitation. The Aral Sea Basin is an important transboundary basin in Central Asia, primarily fed by the Amu Darya and Syr Darya rivers. Four of the five Central Asian countries are partially or entirely located in the Aral Sea Basin, with Tajikistan and Kyrgyzstan in the upstream mountainous areas and Kazakhstan, Turkmenistan, and Uzbekistan in the downstream areas. [Figure 1: see original paper] shows the topography and land cover of Central Asia.

Central Asia is rich in oil and gas resources as well as renewable energy sources like wind, solar, and hydroelectric power, but the distribution of water, land, and energy resources among countries is highly uneven. According to World Bank and FAO statistics, in 2019 the total population of the five Central Asian countries was 74.04 million, with a total GDP of 303.9 billion USD (in current prices). The total renewable water resources were 227.5 billion $m^3$, total grain production was 31.2 million tons, and cropland and grassland accounted for 71.2% and 9.81% of land area, respectively, with forest coverage at 3.28%. The downstream three countries hold 93% of oil and 77% of natural gas reserves. Kazakhstan possesses the most abundant resources in terms of land area, water resources, and energy reserves among the five countries.

Due to its arid climate, Central Asia suffers from water scarcity and fragile ecological environments. All five countries rely on irrigated agriculture, and influenced by the Soviet-era economic division of labor, they mainly cultivate water-intensive crops like cotton and rice. Over the past half-century, under global climate change and human activities, Central Asia has experienced continuous degradation of natural vegetation in desert-oasis transition zones, exacerbating water system instability and drought threats, and intensifying water scarcity and transboundary river disputes. In summary, Central Asia is a sensitive region with prominent resource mismatches and seasonal water use contradictions. Overexploitation of water and energy resources and irrational grain production patterns have continuously worsened the ecological environment.

### 2.1 Data Sources

The study period spans 2000–2019. Population, resource, grain, and land use data were obtained from the FAOSTAT database (https://www.fao.org/faostat/en/#data). GDP data were sourced from the World Bank' s World Development Indicators database (https://databank.worldbank.org/source/world-development-indicators). Energy and $CO_2$ emissions data came from the International Energy Agency (https://www.iea.org/data-and-statistics). Protected area data were derived from the World Database on Protected Areas (https://www.protectedplanet.net/), with only terrestrial protected areas selected for this study.

### 2.2 Evaluation Index System

To reflect the coupling coordination level among water, energy, food, and ecology in Central Asia, representative indicators were selected to establish an evaluation index system. Based on the development status of water, energy, food, and ecology in Central Asia and referencing existing literature, the system includes 16 indicators following principles of objectivity, systematicity, rationality, and data availability . To ensure comparability, all monetary values were calculated using constant 2015 USD. Energy production refers to the total output of coal, oil, natural gas, hydropower, wind, and solar energy during a certain period, while energy consumption refers to the total consumption of coal, oil, natural gas, electricity, heat, and biomass energy. According to IEA statistical scope and conversion rules, all energy products are calculated in terajoules (TJ). In the IEA database, hydropower, wind, and solar energy are uniformly selected as electricity as the primary energy form, with the unit gigawatt-hour (GWh) and a conversion coefficient of 3.6 TJ/GWh.

This study uses the improved range standardization method for indicator normalization and the entropy weight method to determine indicator weights.

### 2.3 Coupling Coordination Degree Model

Coupling degree reflects the intensity of interaction and mutual influence among subsystems, while coupling coordination degree quantitatively describes the coordinated development among systems. This study constructs coupling degree and coupling coordination degree models to analyze the interaction degree and coordinated development status.

The subsystem development level evaluation index is calculated through linear weighting for water resources *f(x)*, energy *g(y)*, food *h(z)*, and ecology *q(e)* subsystems:

$f(x) = \Sigma(\text{wj} \times \text{x' ij})$
$g(y) = \Sigma(\text{wj} \times \text{y' ij})$
$h(z) = \Sigma(\text{wj} \times \text{z' ij})$
$q(e) = \Sigma(\text{wj} \times \text{e' ij})$

where $x'_{ij}$, $y'_{ij}$, $z'_{ij}$, and $e'_{ij}$ are standardized values of indicators within each subsystem, and $w_j$ is the weight of each indicator.

The coupling degree $C$ and coupling coordination degree $D$ are calculated as:

$$C = 4 \times [f(x) \times g(y) \times h(z) \times q(e)]^{(1/4)} / [f(x) + g(y) + h(z) + q(e)]$$

$$D = \sqrt{(C \times T)}$$

$$T = \alpha f(x) + \beta g(y) + \gamma h(z) + \phi q(e)$$

where $C$ represents coupling degree (higher values indicate stronger system coupling and tighter association), $D$ represents coupling coordination degree (higher values indicate better coordination), and $T$ is the comprehensive evaluation index representing overall system development capacity. The parameters $\alpha$, $\beta$, $\gamma$, and $\phi$ are weights for water, energy, food, and ecology subsystems, respectively. Considering the equal importance and mutual constraints among subsystems, all weights are set to 1/4.

Referencing existing research, coupling degree and coordination degree are classified as shown in .

## 3. Results and Analysis

Based on the above equations, the comprehensive evaluation index, coupling degree, and coupling coordination degree of the WEFE system for the five Central Asian countries were calculated . Treating the five countries as an integrated region, temporal evolution diagrams of the comprehensive evaluation index and coupling coordination degree were produced [Figure 2: see original paper].

**3.1 Comprehensive WEFE System Level Analysis Temporal Evolution:** The overall comprehensive evaluation index of Central Asia shows a slow upward trend [Figure 2: see original paper]. The water resources, energy, and ecology subsystem indices exhibit rising trends, while the food subsystem shows a slight decline, indicating gradual improvement in water resources, energy, and ecological conditions. The water resources subsystem improved significantly after 2010, mainly due to improved water use efficiency and reduced per capita water consumption and agricultural water proportion. The energy subsystem showed the largest interannual variation, increasing from 0.15 to 0.35, primarily because of enhanced energy development and utilization leading to increased coal production and per capita energy output. The food subsystem fluctuated noticeably, with a significant drop in 2010 due to reduced grain production in Kazakhstan and a decline in Kyrgyzstan in 2019. The ecology subsystem maintained steady growth with relatively high indices, increasing from 0.45 to 0.55, suggesting slight ecological improvement, enhanced awareness and action for environmental protection and Aral Sea preservation, and modest increases in forest coverage.

**Spatial Dimension:** The comprehensive evaluation indices of the five Central Asian countries are generally not high. Kazakhstan has the highest index, reaching only 0.55 in 2019, while Uzbekistan has the lowest at 0.35. Uneven distribution of water and land resources leads to significant differences in subsystem indices. Tajikistan and Kyrgyzstan have higher water resources indices due to abundant per capita renewable water resources (7,000–9,000 $m^3$). Turkmenistan has low water resources indices due to water scarcity and irrational water use structure with high agricultural water proportion. Energy indices are higher in Tajikistan, Kyrgyzstan, and Kazakhstan because of rich hydropower resources and high renewable energy consumption proportions. Food indices are higher in downstream countries that are major grain production bases—Kazakhstan and Uzbekistan have large grain production and extensive planting areas, while Turkmenistan' s relatively small population and large planting area also contribute to high food indices. Kyrgyzstan and Turkmenistan have higher ecology subsystem indices due to high forest coverage and protected area proportions and lower industrial wastewater and $CO_2$ emissions. Overall, upstream countries have similar subsystem development levels and comprehensive indices due to similar resource endowments and geographical environments.

**3.2 Coupling Degree and Coordination Degree Analysis** Overall, the coupling degree and coupling coordination degree of the five Central Asian countries range from 0.65–1 and 0.40–0.70, respectively, indicating strong interactions and associations among water, energy, food, and ecology subsystems, but poor coordination and development levels.

**3.2.1 Temporal Evolution Analysis Coupling Degree (C):** From 2000–2019, the WEFE system coupling degree in Central Asia showed a fluctuating upward trend [Figure 3: see original paper], rising more significantly after 2010. The system coupling degree remained at a high level (mean value 0.95), indicating strong interactions and stable associations among the four subsystems. Spatial differences in coupling degree existed but decreased annually, with standard deviation reducing from 0.15 to 0.05. Tajikistan's coupling degree increased noticeably in 2009, rising from 0.75 to 0.90, but remained in the running-in stage, suggesting weak inter-subsystem relationships. Kyrgyzstan showed small fluctuations. Kazakhstan' s coupling degree remained high, floating around 0.95–0.97. Turkmenistan showed an overall declining trend, while Uzbekistan experienced substantial growth after 2015, gradually shifting from the running-in stage to high-level coupling, indicating strengthened WEFE system interactions.

**Coupling Coordination Degree (D):** The system coupling coordination degree showed a slow growth trend [Figure 3: see original paper], but remained in barely coordinated state (mean value 0.52). The poor coordination is mainly due to low comprehensive evaluation indices across countries, fundamentally resulting from irrational development and utilization of water-soil-energy resources, fragile ecological environments, and severe human interference. All five countries exhibited relatively stable coordination types: Tajikistan and Kyrgyzs-

tan remained in barely coordinated states, Kazakhstan in primary coordination, and Turkmenistan and Uzbekistan on the brink of misalignment. Except for Turkmenistan' s slight decline, the other four countries showed upward trends. Uzbekistan fluctuated significantly (0.40–0.46), while Tajikistan, Kyrgyzstan, Kazakhstan, Turkmenistan, and Uzbekistan ranged from 0.44–0.66, with a mean of 0.53, indicating tighter relationships and better overall balance, though coordination types remained unchanged.

**3.2.2 Spatial Difference Analysis** From the subsystem evaluation indices, the WEFE system in the five Central Asian countries remains unbalanced, with main constraints on coordinated development being: Tajikistan and Kyrgyzstan are food-lag types, indicating the food subsystem contributes little to WEFE; Turkmenistan is water-lag type; Kazakhstan and Uzbekistan are energy-lag types despite rich fossil energy resources, due to low renewable energy consumption proportions (high weight in the index system). The subsystems have not achieved good synergistic development, and lagging single resources affect overall system coordination levels.

Spatial development of coordination degree shows certain differences [Figure 4: see original paper]. Overall, Kazakhstan in the north has the optimal coordination type with relatively small differences among subsystem development levels and balanced development. The other four countries show an east-to-west decreasing distribution. Tajikistan and Kyrgyzstan have higher coordination grades, while Turkmenistan and Uzbekistan have lower grades that have not reached the Central Asian average. In 2000, regional coordination degree ranged from 0.41–0.64 (mean 0.51), with Tajikistan and Kyrgyzstan barely coordinated, Turkmenistan and Uzbekistan on the brink of misalignment, and only Kazakhstan in primary coordination. After 20 years of evolution, coordination types have not fundamentally changed (mean 0.53), but coordination degrees in Tajikistan, Kazakhstan, and Uzbekistan have improved. The different resource endowments and development levels lead to varying WEFE subsystem development and coordination levels. Water and oil-gas resources are both important basic and strategic resources for Central Asian economic development. Water scarcity constrains irrigation agriculture and economic development, while structural contradictions in upstream-downstream water use exacerbate food and energy security issues.

## 4. Discussion

Central Asia' s unique geographical location in the Eurasian hinterland, combined with its arid climate and fragile ecological environment, results in rich energy resources but water shortages, with extremely uneven spatial distribution of water, energy, and land resources. For instance, within the Aral Sea Basin, Tajikistan and Kyrgyzstan are water-rich, while Kazakhstan, Turkmenistan, and Uzbekistan are mineral and energy-rich. These unique natural geographical conditions and geopolitical environments have caused post-independence Cen-

tral Asian countries to face intertwined water-energy-land issues, varying water-energy demands, and diversified ecological problems from overexploitation of water and soil resources, leading to prominent contradictions among WEFE subsystems that affect regional economic development.

Therefore, Central Asian socio-economic development demands influence regional and national WEFE coordination levels, while sustainable development of each country depends on a stable and coordinated regional WEFE system. From a research perspective, compared with two-dimensional resource-environment-economy perspectives, comprehensive four-dimensional WEFE system research can more comprehensively reveal multi-factor coupling coordination for sustainable socio-economic development in Central Asia. Compared with regional or transboundary basin-level studies, national-level studies on WEFE coupling relationships better facilitate decision-making for inter-country cooperation. The WEFE evaluation index system proposed in this study is constructed based on scientific and representative principles, fully considering the influence relationships among water, energy, food, and ecological factors in the study area. Although limited by data availability, the system can comprehensively reflect WEFE characteristics to a certain extent, as verified by comparison with existing literature. Future research could further refine the index system and extend to provincial/state levels within countries to deepen understanding of WEFE spatiotemporal differences and coupling coordination mechanisms.

## 5. Conclusions and Recommendations

**Conclusions:** 1) The comprehensive evaluation index of the WEFE system in Central Asia shows an overall stable upward trend. Water resources, energy, and ecology subsystems align with this trend, while the food subsystem shows a slight decline. Spatial distribution of subsystem development levels is consistent with resource endowments. Tajikistan and Kyrgyzstan, with relatively abundant water resources and hydropower, have better water and energy subsystem development but are food-lag types. Kazakhstan, Turkmenistan, and Uzbekistan have extensive grain planting areas with better food subsystem development; Kazakhstan and Uzbekistan are energy-lag types, while Turkmenistan is water-lag type.

2) The WEFE system coupling degree in Central Asia is relatively high but coordination degree is low, with unbalanced spatial development. Most countries are in high-level coupling stages with strong inter-subsystem correlations showing an overall upward trend. The coupling coordination degree shows slow growth but remains barely coordinated, with mutually constraining relationships among subsystems. Kazakhstan in the north has the highest coupling degree and coordination level (primary coordination). Tajikistan and Kyrgyzstan remain barely coordinated, while Turkmenistan and Uzbekistan have poor coordination levels (on the brink of misalignment).

**Recommendations:** To achieve regional sustainable development and enhance inter-system coordination levels, the following recommendations are proposed based on WEFE coupling coordination development in Central Asia:

1) **Promote synergistic development.** Based on different resource endowments and development statuses, formulate targeted development strategies that balance water, energy, food, and ecology development goals. Focus on improving lagging subsystems in low-coordination regions/countries, promote sustainable resource utilization, enhance coordination levels, and achieve high-quality economic development.

2) **Introduce advanced technologies and strengthen integrated management to overcome constraints.** Improve water use efficiency and optimize water resource allocation. Optimize energy structure and develop clean energy to enhance industrial enterprise technological innovation capabilities. Develop water-saving irrigation technologies, improve natural disaster early warning and emergency response capabilities, and strengthen cropland protection. Enhance regional ecological protection and construction, improve pollution control levels, and promote energy conservation and emission reduction.

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*Note: Figure translations are in progress. See original paper for figures.*