Article
An Evaluation of Coupling Coordination between Rural Development and Water Environment in Northwestern China

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Abstract: Balancing the relationship between rural development and the protection of water resources is a challenging undertaking. This study develops a coupling coordination degree (CCD) model to examine the non-linear interaction between rural development and water environment in the 11 prefectures of Gansu, northwestern China. There are three key findings. First, economic development is the key driver of rural development, whereas social development has relatively little impact. For the water environment subsystem, improved water efficiency has been the key contributor, whereas environmental carrying capacity is secondary. Second, the CCD increased steadily in the studied period, which suggests that the relationship between rural development and water environment has gradually changed from antagonistic to mutually beneficial. However, this change is not occurring rapidly and in fact shows signs of slowing. Third, the complex spatial differences of the CCD are related to the level of economic and social development, the process of urban–rural integration, and regional natural conditions. The findings of this study have great significance for further quantitative analysis of the interaction and mutual feedback mechanism between the rural economy and the water environment in China and support evidence-based policymaking.

Keywords: rural development; water environment; coupling coordination degree; spatiotemporal characteristics; China

1. Introduction

Water is an important natural resource for maintaining ecological health and enabling sustainable development [1,2]. However, rapid economic growth is generally accompanied by increased water consumption, water shortages, and the degradation of the water environment, which become barriers to sustainable development [3,4]. This problem has captured the attention of governments at different levels. For example, one of the Sustainable Development Goals is to ensure the availability and sustainable management of water and sanitation for all [5–7].

Balancing the relationship between socioeconomic development and the quality of the water environment is particularly challenging in the rural context. Owing to biased water supply policies that favor cities and non-agricultural development, water resources in the rural areas have been affected by rapid urbanization and industrialization. Increasing amounts of pollution in urban and peri-urban areas directly result in the deterioration of rural water resources [8]. Further, the proliferation of urban–water transfers in the context of growing urban demand for water has become a key source of conflict [9–11]. At the same time, overexploitation of agriculture and the use of inefficient water consumption practices and technologies owing to inadequate investment have led to the overutilization of water resources in rural areas [12,13]. Thus, rural areas often face more serious water
problems than cities, especially in arid and semi-arid areas suffering from long-term water scarcity that worsens with climate change [14].

There is increasing academic interest in improving the relationship between rural development and water environment, for example, improving water management in rural communities [15–18], reducing rural water pollution problems [19–21] and alleviating agricultural and drinking water poverty [22–24]. The development and analysis of indices and models for the assessment of the economy-water nexus has attracted significant attention [25–28]. The environmental Kuznets curves (EKC) is an influential hypothesis that is frequently used in studies on the relationship between the water environment and economic development [29–33]. The EKC assumes an inverted U-shaped relationship between environmental damage and resource use on the one hand and economic development on the other [34,35]. It assumes environmental damage and resource consumption initially increase with rising income, but subsequently decline [25]. However, the EKC assumes a unidirectional causal relationship between the economy and the environment, which neglects feedback effects from the environment to economic development [36]. Therefore, it might be oversimplistic and inappropriate to use the EKC to model the relationship between economic development and the water environment.

This study develops a coupling coordination degree (CCD) model to capture the relationship between rural development and water environment. Originating from the field of physics, coupling is a concept of which two or more subsystems in a system affect each other via various interactions [37,38]. The CCD indicates the extent to which the interactions among the subsystems are harmonious and contribute to the sustainability of the system [39–41], as well as highlights uncoordinated subsystems that have adverse effects on each other [42]. The CCD has been widely used to model the nonlinear interaction between socioeconomic development and ecological environment [40,43–47]. The evolution of the rural socioeconomic subsystem and the water environment subsystem is a multicomponent process involving multiple disciplines, and insightful analysis requires a systemic method; to this end, the CCD can be used to analyze the degree of coordinated development of water and socioeconomic systems. However, although the method has been adopted in the context of urban water studies [37,45,48], it has seldom been used in rural contexts.

This study explores the temporal and spatial characteristics of coupling coordination between rural development and water environment. Taking Gansu—a semi-arid to arid region of northwestern China that suffers from long-term water shortage—as a case study, we used 11 years of continuous time series data to investigate the dynamic changes in coupling coordination associated with various rural development patterns and water environment conditions. We also applied the results of the coupling coordination study to decision-making so that policymakers can develop strategies for sustainable development in different types of districts. The rest of this paper is organized as follows. Section 2 describes the methods and materials, and Section 3 presents and discusses the primary results. Section 4 presents a conclusion and remarks.

2. Materials and Methods
2.1. Study Area

This study focuses on the Gansu Section of the Silk Road Economic Belt (92°20′–108°45′ E, 34°05′–42°08′ N), which is one of the most important irrigated agricultural areas in northwestern China. The Gansu Section is part of Gansu Province (Figure 1) and is composed of 11 prefectures (Jiuquan, Jiayuguan, Lanzhou, Baiyin, Wuwei, Zhangye, Jinchang, Tianshui, Dingxi, Pingliang, and Qingyang). The Gansu Section extends in the west–east direction, covering an area of 379,856 km², and accounts for 83.6% of the total area of Gansu Province. The entire area is covered by loess and sparse vegetation and exhibits serious soil erosion. The spatial and temporal distribution of water resources in the Gansu Section is extremely uneven, and the degree of utilization of water resources is relatively high. Water scarcity is a major bottleneck hindering rural economic development.
and is a considerable obstacle to poverty reduction. Reducing the pressure on the water environment and achieving sustainable development are the pressing needs of the Gansu Section. Therefore, it is of great practical importance to better understand the relationship between rural economic development and the water resources environment.

Figure 1. Study area.

2.2. Data

We gathered socioeconomic and water resources data from the water resources bulletins of Gansu [49] and statistical yearbooks of Gansu [50]. Considering the differences in both the dimension and the magnitude of each of the selected indicators, the data had to be normalized before they were analyzed. All the indicators can be categorized as positive or negative, where a larger value of a positive indicator represents more favorable conditions for the development of the system (and conversely, a larger value of a negative indicator represents less favorable conditions). The set of indicators used here was divided into these categories, and the indicators were then transformed into nondimensional values using the following equations:

Positive indicator: \[ x'_{ij} = \frac{x_{ij} - \min\{x_{j}\}}{\max\{x_{j}\} - \min\{x_{j}\}} \] (1)

Negative indicator: \[ x'_{ij} = \frac{\max\{x_{j}\} - x_{ij}}{\max\{x_{j}\} - \min\{x_{j}\}} \] (2)

where \( x_{ij} \) denotes the \( j \)-th indicator of the \( i \)-th province in the \( t \)-th year, \( x'_{ij} \) represents the normalized data of \( x_{ij} \), and \( \max\{x_{j}\} \) and \( \min\{x_{j}\} \) are the maximum and minimum values of the \( j \)-th indicator in all prefectures and years, respectively. All index values are within the range [0, 1] after treatment.
2.3. Indices for Evaluating Rural Development and Water Environment

To explore the coupling relationship between rural development and the water environment in the study area, we constructed aggregated index systems on the basis of previously developed indexes [51]. The indicators were selected primarily according to the following general selection criteria: (1) those that are commonly cited in the literature [51] and (2) those that cover the components of socioeconomic development and water environment sustainability. The simplest indicators that constitute the indices were further selected according to the results of a Pearson correlation analysis. The rural development index system comprises three primary indicators and 17 secondary indicators (Table 1). The water environment index system comprises three primary indicators and 14 secondary indicators (Table 2).

| Subsystem               | Weight | Indicator                                      | Direction | Weight |
|-------------------------|--------|-----------------------------------------------|-----------|--------|
| Production conditions   | 0.403  | Per capita cultivated land (km²/people) +     | +         | 0.065  |
|                         |        | Agricultural mechanization level (kW·h/km²) +  | +         | 0.157  |
|                         |        | Effective irrigated area of farmland (km²) +  | +         | 0.064  |
|                         |        | Fertilization efficiency (Yuan/ton) +         | +         | 0.032  |
|                         |        | Agricultural labor productivity (Yuan/people) +| +         | 0.034  |
|                         |        | Agricultural land productivity (Yuan/km²) +    | +         | 0.051  |
| Economic support        | 0.205  | Per capita GDP (Yuan/people) +                | +         | 0.046  |
|                         |        | Government financial capacity (Yuan) +        | +         | 0.051  |
|                         |        | Percentage of nonagricultural population (%) +| +         | 0.059  |
|                         |        | medical level (people/1000 people) +          | +         | 0.014  |
|                         |        | Number of people receiving the minimum living allowance (people) − | − | 0.037  |

Table 2. Index system for water environment.

| Subsystem             | Weight | Indicator                                      | Direction | Weight |
|-----------------------|--------|-----------------------------------------------|-----------|--------|
| Resource endowment    | 0.275  | Water area per unit area (m³/km²) +           | +         | 0.076  |
|                       |        | Water supply modulus (m³/mm) +                | +         | 0.014  |
|                       |        | Per capita water resources (m³/people) +      | +         | 0.028  |
|                       |        | Water resources development rate (m³) +       | +         | 0.153  |
|                       |        | Per capita living water consumption of rural residents (m³) − | − | 0.004  |
| Water efficiency      | 0.401  | Water consumption of per unit grain output (tons/m³) − | − | 0.054  |
|                       |        | 10,000-yuan GDP water consumption (Yuan/m³) −  | −         | 0.114  |
|                       |        | 10,000-yuan industrial value-added water consumption (m³) − | − | 0.128  |
|                       |        | Industrial water quota (m³) −                 | −         | 0.047  |
|                       |        | Ratio of irrigation coverage (%) +            | +         | 0.051  |
|                       |        | Irrigation water quota (m³/km²) −             | −         | 0.007  |
| Environmental carrying capacity | 0.324 | Ratio of drought disaster area (%) −         | −         | 0.041  |
|                       |        | Ratio of ecological environment water consumption (%) + | + | 0.201  |
|                       |        | Ratio of water saving irrigation area (%) +   | +         | 0.075  |

2.4. Evaluation of Rural Development and Water Environment

We employed the entropy method to assign a weight to each indicator according to its relative effects on the CCD [52,53]. The entropy method directly uses the information given by the indicators to calculate the weight. It has the advantage of objectivity, operability, and can enhance the distinguishability of the indicators [53]. Furthermore, the entropy method is a dynamic weighting method and is not affected by whether the data is linearly correlated [54]. The weight of each indicator was calculated according to the information
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entropy and variations in the indicators. The detailed steps for calculating the weight of each indicator are as follows [42,46].

We define $P_{ij}^t$ as the ratio of $x_{ij}^t$ and the corresponding indicator:

$$P_{ij}^t = \frac{x_{ij}^t}{\sum_{i=1}^{m} \omega_j x_{ij}^t}$$  \hspace{1cm} (3)

The information entropy of the $j$-th indicator is computed as follows:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} Y_{ij} \times \ln Y_{ij} \hspace{0.5cm} (0 \leq e_j \leq 1)$$  \hspace{1cm} (4)

where $e_j$ represents the information entropy of the $j$-th indicator, and $m$ is the number of years.

The entropy redundancy, which indicates the difference between the entropy and its maximum possible value, is calculated as follows:

$$f_j = 1 - e_j$$  \hspace{1cm} (5)

Then, we can derive the weight of the $j$-th indicator:

$$\omega_j = f_j / \sum_{j=1}^{n} (0 \leq \omega_j \leq 1)$$  \hspace{1cm} (6)

Next, we calculate the rural composite index:

$$R_{ij}^t = \sum_{j=1}^{n} \omega_j \cdot x_{ij}^t$$  \hspace{1cm} (7)

where $R_{ij}^t$ is the comprehensive rural socioeconomic index of the $i$-th city in the $t$-th year, and $\omega_j$ is the weight of the $j$-th indicator.

Similarly, we can calculate the urbanization composite index:

$$W_{ij}^t = \sum_{j=1}^{n} \omega_j \cdot x_{ij}^t$$  \hspace{1cm} (8)

where $W_{ij}^t$ is the comprehensive water environment index of the $i$-th province in the $t$-th year, and $\omega_j$ is the weight of the $j$-th indicator.

The weight of each indicator in the rural development and water environmental index systems is determined using MATLAB and the entropy method. The results of this process are displayed in Tables 1 and 2, respectively.

2.5. Coupling Coordination Degree Model

The formula of the CCD model is as follows:

$$C = \frac{2 \sqrt{R_{ij}^t \cdot W_{ij}^t}}{R_{ij}^t + W_{ij}^t}$$  \hspace{1cm} (9)

$$T = \alpha \cdot R_{ij}^t + \beta \cdot W_{ij}^t$$  \hspace{1cm} (10)

$$D = \sqrt{C \cdot T}$$  \hspace{1cm} (11)

where $R_{ij}^t$ and $W_{ij}^t$ represent the evaluation indices of the rural development system and water environment system, respectively, in year $t$. $C \in [0, 1]$ is the coupling degree of rural economic development and the water resources environment. $D \in [0, 1]$ is the coupling coordination degree of the two systems. $T$ is the comprehensive coordination.
index and reflects the overall contributions of water environment and rural development; α and β denote the contributions of rural development and the water environment to the entire system, respectively. For the Gansu Section, we assume that rural development and water environment are equally important. Thus, the values of α and β are the same; that is, α = β = 0.5.

The degree of coupling between rural development and the water environment can be divided into four primary development stages, each of which can be further divided into three secondary subclasses. Accordingly, we developed 12 secondary development stages to describe the coupling coordination between \( R_t^i \) and \( W_t^i \). Table 3 describes the resulting comprehensive index of the development stages of coupling coordination and the 12 subdivisions.

### Table 3. The classification of CCD.

| Primary Division | Secondary Division | Tertiary Division |
|------------------|--------------------|-------------------|
| Highly coordinated | 0.7 ≤ D ≤ 1 | High-level coordination |
|                   |                   | \( 0 \leq |R_t^i - W_t^i| \leq 0.1 \) |
|                   |                   | \( W_t^i - R_t^i > 0.1 \) |
|                   |                   | High-level coordination and leading water environment |
|                   |                   | High-level coordination and leading rural development |
| Transition period | 0.5 ≤ D < 0.7 | Basic coordination |
|                   |                   | \( 0 \leq |R_t^i - W_t^i| \leq 0.1 \) |
|                   |                   | \( W_t^i - R_t^i > 0.1 \) |
|                   | Basic coordination and lagging rural development |
|                   | Basic coordination and lagging water environment |
|                   | Low-level coordination |
|                   | \( 0 \leq |R_t^i - W_t^i| \leq 0.1 \) |
|                   | \( W_t^i - R_t^i > 0.1 \) |
|                   | Low-level coordination and lagging rural development |
|                   | Low-level coordination and lagging water environment |
| Uncoordinated    | 0.4 ≤ D < 0.5 | Uncoordinated |
|                   |                   | \( 0 \leq |R_t^i - W_t^i| \leq 0.1 \) |
|                   |                   | \( W_t^i - R_t^i > 0.1 \) |
|                   |                   | Uncoordinated and lagging water environment |
|                   |                   | \( R_t^i - W_t^i > 0.1 \) |
| Uncoordinated    | 0 ≤ D < 0.4 | Uncoordinated |
|                   |                   | \( 0 \leq |R_t^i - W_t^i| \leq 0.1 \) |
|                   |                   | \( W_t^i - R_t^i > 0.1 \) |
|                   |                   | Uncoordinated and lagging water environment |

### 3. Results

#### 3.1. Main Indicators of Rural Development and Water Environment

The three subsystems of rural development were ranked by weight as follows: production conditions (0.403) > living conditions (0.392) > economic support (0.205). The indicators with greater influence are agricultural mechanization level (0.157), rural power level (0.146), and farmer income level (0.075). The combined weight of these three indicators is 37.8%; thus, they significantly impact rural development overall. By contrast, indicators reflecting the status of social development have lower weights, for example, medical level (0.014) and rural family Engel coefficient (0.017). Social development has little impact on the level of rural development. By contrast, economic development has a more significant effect on development. This result is consistent with previous research on China highlighting the importance of improving agricultural infrastructure to effectively promote rural economic growth and increase agricultural production capacity [55,56].

The weights of the three subsystems in the water environment system are water efficiency (0.401) > environmental carrying capacity (0.324) > resource endowment (0.275). This result shows that improving water efficiency is the key to solving regional water shortages and an important means of ensuring an adequate supply of water resources. In 2016, the water consumption per 10,000 yuan of gross domestic product (GDP) in Gansu Province was 222.818 m³, the water consumption per 10,000 yuan of industrial added value was 78.636 m³, and the water consumption per unit of grain was 1865.32 m³; these values were 34%, 2%, and 5% lower, respectively, than those in 2006. Greater water use efficiency has remarkably improved the environmental assessment value of
water resources in the Gansu Section. The eco-environment water consumption, water resources development and utilization rate, and 10,000-yuan industrial added value water consumption indicators have greater weights. The amount of water used in the ecological environment is the amount of runoff water required by the ecosystem to maintain a specific ecological environment service function and to protect and construct the ecological environment. In 2016, the total water resources of the Gansu Section were 11.069 billion m³, and the total water supply was 11.035 billion m³. The water resource utilization rate was 16.6% higher than that in 2006. The construction of water ecological infrastructure in Gansu Province has made some progress in recent years, and the hydrological environment of ecologically fragile rivers such as the Hei and Shiyang rivers has been improved.

3.2. Evaluation Results

Figure 2 shows the evaluation results of rural development for the Gansu Section. The overall development level of rural areas in Gansu Province increased significantly from 2006 to 2016. The evaluation values of the agricultural production condition subsystem, economic support subsystem, and farmers’ living condition subsystem showed an upward trend, among which the economic support conditions grew most rapidly. In 2006–2010, the assessment index grew slowly with fluctuations, whereas in 2011–2016, the assessment index exhibited a rapid and continuous increase. This pattern is associated with the release of the 2011 National Modern Agricultural Development Plan (2011–2015), which establishes specific requirements for strengthening rural infrastructure construction conditions, broadening farmers’ channels for increasing income, and improving farmers’ production and living conditions. According to 2013 data, the total power of agricultural machinery in Gansu Province was 17.2 million kWh, and the per capita net income of farmers was 7081.36 yuan, which are 3.17% and 19.84% higher, respectively, than those in 2011; the effective irrigation area of farmland increased by 68,200 hectares. The average water consumption per unit of grain was 324.78 m³ less than that in 2011. These results are sufficient to confirm that the implementation of the policy effectively promoted agricultural modernization. The multiyear evaluation values of the water resource environment system in the Gansu Section are clustered between 0.4 and 0.5, showing a fluctuating upward trend, but the growth rate was slower (Figure 3). Among the three subsystems, the water efficiency subsystem has the highest evaluation value, which improved significantly in 2006–2009 and remained essentially stable in 2010–2016. The trend of the water efficiency subsystem is similar to that of the economic support subsystem.

![Figure 2. Evaluation values of rural development.](image-url)
3.3. CCD
3.3.1. Temporal Variation of Coupling Coordination

Table 4 lists the mean values of the coupling degree (CD) and CCD of all prefectures under the CCD model. During the study period, the CD between rural development and the water environment in Gansu Section increased slightly, from 0.484 to 0.500, with an annual growth rate of 0.15%. The CCD of the two systems increased more rapidly, from 0.507 in 2006 to 0.578, in 2016, with an annual growth rate of 7%. This is a positive result, suggesting that the coordination of rural development and the water environment improved. However, there is still significant room for improvement in terms of the degree of coordination, and the pace of improvement is lower than that in urban areas, as reported in other studies. This means that rural areas in China still face more challenges in water management than urban areas. The overall development level of the rural regions of Gansu is slightly behind that of the water environment. However, the gap between the improvements in socioeconomic development and the water environment in rural areas is shrinking, and the overall development benefits associated with the underlying conditions of water resources and improvements in environmental carrying capacity and water use efficiency are becoming more obvious.

| Year | CD   | CCD  | $W_{(a)} - R_{(a)}$ |
|------|------|------|---------------------|
| 2006 | 0.484| 0.507| 0.15                |
| 2007 | 0.489| 0.522| 0.133               |
| 2008 | 0.491| 0.519| 0.118               |
| 2009 | 0.492| 0.529| 0.119               |
| 2010 | 0.489| 0.527| 0.14                |
| 2011 | 0.492| 0.543| 0.129               |
| 2012 | 0.497| 0.549| 0.076               |
| 2013 | 0.497| 0.559| 0.087               |
| 2014 | 0.498| 0.562| 0.066               |
| 2015 | 0.5  | 0.572| 0.018               |
| 2016 | 0.5  | 0.578| 0.028               |

3.3.2. Spatial Variation of Coupling Coordination

Figure 4 shows the coordination degree of each prefecture in the Gansu Section. Jiayuguan had the highest values during the entire studied period, whereas Dingxi consistently had the lowest values. Overall, the gap between the CCDs of the 11 prefectures widened with time. The CCD in various prefectures is increasing, and the growth can be roughly divided into two stages: a stage of relatively rapid growth (2006–2011) followed
by a period of decreasing growth rate (2012–2016). In 2011, the Central Poverty Alleviation and Development Work Conference set a new national poverty alleviation standard, and the new standard was set to an annual per capita net income for farmers of 2300 yuan (2010 constant price). This standard is 92% higher than that of 2009. As a result of the higher poverty standard, more low-income people were included in the poverty alleviation area. The number of rural poor people in poverty-stricken areas such as Pingliang and Dingxi increased, which affected the evaluation results of rural development.

Table 4. Mean values of CD and CCD.

| Year | CD     | CCD    |
|------|--------|--------|
| 2006 | 0.484  | 0.502  |
| 2007 | 0.489  | 0.512  |
| 2008 | 0.489  | 0.513  |
| 2009 | 0.489  | 0.514  |
| 2010 | 0.489  | 0.514  |
| 2011 | 0.491  | 0.516  |
| 2012 | 0.489  | 0.514  |
| 2013 | 0.492  | 0.517  |
| 2014 | 0.497  | 0.521  |
| 2015 | 0.498  | 0.524  |
| 2016 | 0.507  | 0.532  |

Figure 4. Temporal variation of CCD in each prefecture.

According to the coupling coordination data of each prefecture in 2016, the CCD was divided into three levels using the Jenks classification method in ArcGIS. The CCD of the Gansu Section generally shows a spatial pattern of decrease from north to south (Figure 5). Northern prefectures have developed industrial systems to some extent, providing the necessary basic conditions for agricultural production, and the overall level of rural development is therefore better. In 2016, the total GDP of the five prefectures of the Hexi Corridor was 39.116 million yuan, which accounted for 61.18% of the total GDP of Gansu Province. The total industrial output value was 13.78 million yuan, which accounted for 60.95% of the total industrial output value of the Gansu Section. In addition, the Hexi Corridor Irrigation Agriculture Zone is the most important agricultural and economic crop production area in northwest China. Oasis agriculture has a long history and solid foundation there. In 2013, Gansu Province launched a national high-efficiency water-saving irrigation project in the Hexi Corridor, which effectively alleviated the shortage of water resources and the conflict between supply and demand in the Hexi Corridor and the Yellow Irrigation District and has produced environmental benefits. By contrast, in prefectures in the eastern and southern parts of the Gansu Section, such as Dingxi, Tianshui, Pingliang, and Qingyang, the degree of coordination between rural development and the water environment is relatively poor. The main reason is that the basic conditions for agricultural production in these areas are poor owing to unfavorable topographical features and fewer arable land resources, little surface runoff, insufficient annual precipitation, and lack of water sources for irrigation.
3.3.3. Type Division

According to the CCD indicator, all the prefectures in the Gansu Section are in the transition coordination state (0.5 ≤ \(D\) < 0.8). When \(E_1 - E_2 > 0.1\), the development of the rural social economy exceeds the water environment; when the absolute value of the difference between \(E_1\) and \(E_2\) is less than 0.1, the development of the rural social economy is adapted to the water environment. When \(E_2 - E_1 > 0.1\), the development of the water environment exceeds the rural social economy. According to the spatial differences in the CCD values reflected in Figure 5 and the differences between the two system evaluation values, we classify the prefectures into four types in order to provide more fine-grained policy recommendations (Table 5).

Table 5. Classification of the 11 prefectures.

| Prefecture | \(E_1\) | \(E_2\) | \(C\) | \(D\) | \(|E_1 - E_2|\) | Type         |
|------------|--------|--------|------|------|----------------|-------------|
| Jiayuguan  | 0.768  | 0.611  | 0.497| 0.646| 0.156          | Very good coordination |
| Jinchang   | 0.550  | 0.513  | 0.500| 0.605| 0.037          | Good coordination    |
| Lanzhou    | 0.547  | 0.460  | 0.498| 0.597| 0.087          | Good coordination    |
| Jiuquan    | 0.505  | 0.494  | 0.500| 0.595| 0.011          | Good coordination    |
| Zhangye    | 0.478  | 0.503  | 0.500| 0.591| 0.025          | Good coordination    |
| Wuwei      | 0.409  | 0.435  | 0.500| 0.569| 0.026          | General coordination |
| Pingliang  | 0.371  | 0.423  | 0.499| 0.559| 0.052          | General coordination |
| Baiyin     | 0.311  | 0.419  | 0.495| 0.543| 0.108          | Low coordination     |
| Tianshui   | 0.310  | 0.427  | 0.494| 0.543| 0.117          | Low coordination     |
| Qingyang  | 0.308  | 0.417  | 0.494| 0.542| 0.109          | Low coordination     |
| Dingxi     | 0.223  | 0.386  | 0.482| 0.508| 0.164          | Low coordination     |

Note: \(E_1\) is evaluation value of rural development; \(E_2\) is evaluation value of water environment.

Type I: Very good coordination. The prefecture (Jiayuguan) has the highest degree of coupling coordination (0.646) in the studied area. With a population urbanization rate of 94%, the prefecture has a small rural population; thus, the pressure on the ecological environment and water supply in rural areas is low. Furthermore, the prefecture has successfully developed non-agricultural industries such as tourism, transportation, and agricultural product processing. These measures improved the water environment, promoted the stable employment of farmers in the secondary and tertiary industries, and broadened the channels for farmers to increase their income.

Type II: Good coordination. The evaluation values of the two systems in these prefectures are approximately 0.5, and the rural development system is at a similar level with the water environment system. These prefectures have relatively good support for agriculture. Furthermore, their large economic aggregate and strong labor absorption capacity are conducive to the transfer of rural labor. Income from labor transfer has promoted the deepening of agricultural capital and improved agricultural labor productivity. The drip effect of urban-scale expansion triggered the urban–rural transfer of technology, knowledge,
capital, and other factors, which promoted agricultural modernization and improvements in water use efficiency, resulting in good coordination between the two systems.

Type III: General coordination of the two systems. In these prefectures, the development status of the two systems is moderate, and the evaluation values are approximately 0.4. These prefectures are trapped in only moderate coordination of the water environment and rural development systems.

Type IV: Low coordination and lagging rural development. The evaluation values reveal that rural development lags the water environment. Furthermore, the poor management of the water environment and insufficient water resources limit the development of the rural economy. For these reasons, agricultural productivity and land productivity are low.

4. Discussion

This study shows that the coupling coordination of rural development and the water environment is both a complex, non-linear, and long-term evolutionary process, and a spatially heterogeneous phenomenon. The in-depth study of its processes, patterns, and mechanisms has significant implications for the macroeconomic development policies of both the studied regions and more generally rural areas in China’s arid and semi-arid regions.

First, at the subsystem level, the findings show that economic development has been the key driver of rural development, whereas social development has relatively little impact. This result suggests that policymakers have neglected social development in rural areas, such as poverty reduction, social inclusion, and the provision of better welfare, which have become a hindrance to rural development [57,58]. In rural China, the problem of rural population aging and hollowing out is serious [59,60]. The remaining peasants are older and less educated. Therefore, the provision of welfare and social services are quickly becoming a key issue to rural development. Regarding the water environment subsystem, improved water efficiency has been the key contributor, and environmental carrying capacity is secondary. This suggests that there is room for improvement in the effects of water consumption on the natural environment [61].

Second, the overall level of CCD increased consistently in the studied period, which suggests that the relationship between rural development and the water environment is no longer antagonistic, but rather is gradually becoming mutually beneficial. However, this change is not occurring rapidly enough, and in fact shows signs of slowing. As such, policymakers need to work to change the resource-intensive, polluting developmental model to one of sustainable development.

Third, policymakers need to consider the spatial complexity of the CCD. In the studied area, the CCD shows a spatial pattern of decrease from north to south in the studied area. The complex spatial differences in the coupled state of development are related to the level of economic and social development, the process of urban–rural integration, and regional natural conditions [62,63]. Thus, there is a need for the regionalization of rural water management. To this end, we developed a classification system that divides the prefectures into four types, which allows policymakers to focus on areas that need more attention, especially those that are trapped in moderate and low levels of coordination.

Owing to the complexity of the system evolution and the reciprocal relationships among various factors within the system, it is difficult for existing quantitative coupling research to scientifically measure the internal factors of the system. In future work, we should use additional water quality data and quantitative data on policy and management to conduct in-depth research that explains the evolution and mechanism of the coordinated development of rural water resources and environmental systems in the arid regions of China. In addition, owing to the limitations of the data, this study is based only on the Gansu Section at a prefecture-level scale. Prefectures are large administrative units and analyses at a more disaggregated level, such as the county level, may provide additional interesting results.
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