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Coupling-Coordination Analysis of Water Resources–Social Economy–Ecological Environment in the Yellow River Golden Triangle Area

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Abstract: Water resources, the social economy, and the ecological environment are interrelated and interacting complex systems, and the relationship among them affects the sustainable development of a region. To explore the interactive relationship and driving factors between water resources, the social economy, and the ecological environment, the Yellow River Golden Triangle region is taken as the research object in this paper. By constructing a coupling-coordination evaluation index system of water resources, the social economy, and the ecological environment system, the coupling-coordination development of this region from 2011 to 2021 is studied using the coupling-coordination degree model, and the influencing factors of coupling-coordination development are identified by gray relational analysis. The results show that from 2011 to 2021, the comprehensive evaluation index of the water resources, social economy, and ecological environment in the Yellow River Golden Triangle region shows a trend of steady development followed by a gradual increase. The water-resources subsystem restricts the development of the coupling system. The coupling-coordination degree increased from a barely coordinated stage in 2011 to a well-coordinated stage in 2021. The social economy subsystem and water-resources subsystem are the main factors affecting the coordinated development of the coupling system.

Keywords: water resources; social economy; ecological environment; Yellow River Golden Triangle; coupling-coordination degree

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1. Introduction

Water resources, as the material basis for human survival, play a crucial role in the development of the social economy and the protection and governance of the regional ecological environment [1]. However, with the development of society, issues such as water resources and the ecological environment have become key factors hindering social and economic development [2]. The Yellow River Golden Triangle (hereinafter referred to as the "Golden Triangle"), located along the Yellow River at the junction of Henan, Shaanxi, and Shanxi provinces, includes Sanmenxia, Weinan, Yuncheng, and Linfen Cities. Currently, the Golden Triangle region faces challenges such as water scarcity, excessive exploitation and utilization of water resources, low-level repeated construction of industries, and a grim situation in regional ecological environmental protection and governance. The contradictions between water resources, the social economy [3], and the ecological environment restrict the development of the Golden Triangle. Therefore, a systematic analysis of water resources, the social economy, and the ecological environment, studying the coupling and coordination relationship between water resources–social economy–ecological environment (WSE), and analyzing the constraining factors of system coordination development are of great practical significance for promoting the rapid development of the Golden Triangle and pushing forward the process of regional integration.

Water resources are one of the most important natural resources, playing an important role in social and economic development and ecological environment protection [4]. Water resources, the social economy, and the ecological environment are mutually restricted and interrelated [5]. The environmental problems caused by water shortage and water pollution hinder economic development [6]. At the same time, with economic development and population growth, the ecological environment is destroyed and water resources fall into short supply. Therefore, how to coordinate the relationship between water resources, the social economy, and the ecological environment and promote the common development of the three is very important. Coupling refers to the interrelationship between two or more systems, where they interact and constrain each other [7]. Early research on the coupling of multiple systems primarily focused on engineering fields and was later extended to economic and ecological areas [8,9]. In recent years, with the development of society and the economy, people have placed increasing importance on the ecological environment, and the coupling between socioeconomic and ecological systems has gradually become a research hotspot [10]. Research on the coordinated development of complex systems is mainly concentrated on the coupling of economic–environmental systems [11], digital economy–tourism–ecological environment coupling [12], economic development–social stability–ecological environment system coupling [13], water–energy–food–land system coupling [14], human–water–ecology–economy system coupling [15], and population–economic–ecological–geological system coupling [16]. In terms of research methods, approaches such as the entropy weight method [17], gray relational analysis [18], obstacle degree analysis [19], spatial autocorrelation methods [20], and the TOPSIS method [18] are commonly used.

Currently, scholars have made abundant achievements in the study of coupled systems, but some deficiencies still exist. Regarding research methods, most weight-determination methods rely solely on the entropy weight method [21,22]. In terms of research content, many studies focus on coupling-coordination degree analysis of the research objects, while few address the influencing factors of coupling coordination, and the influence of evaluation indicators on the system coupling-coordination degree has been overlooked. This study focuses on the Yellow River Golden Triangle, a typical cross-provincial junction area, breaking through the limitations of previous research that primarily centered on single regions or large river basins. From the perspective of cross-provincial collaboration, it examines the coordinated development relationships among different cities within the Yellow River Golden Triangle. By integrating the entropy weight method, analytic hierarchy process, coupling-coordination degree model, and gray relational analysis model, the study constructs an evaluation index system for the water resources–socioeconomic–ecological environment system. It analyzes the coupling coordination of the Yellow River Golden Triangle system from 2011 to 2021, and explores its influencing factors, revealing the interactions between water resources, socioeconomic factors, and the ecological environment across administrative boundaries. The findings provide a theoretical basis for collaborative governance in similar regions.

2. Materials and Methods

2.1. Study Area

The Yellow River Golden Triangle (located at 108°58′–112°34′ E, 33°31′–36°57′ N) is situated in the middle reaches of the Yellow River, at the junction of Shanxi, Shaanxi, and Henan provinces. It encompasses Weinan City in Shaanxi Province, Linfen and Yuncheng Cities in Shanxi Province, and Sanmenxia City in Henan Province (see Figure 1). With a total area of 57,900 square kilometers, it accounts for 10.95% of the combined area of the three provinces. At the end of 2021, the permanent resident population of the four cities was 15.31 million, and their GDP reached CNY 763.23 billion, accounting for 8.84% and

6.86% of the three provinces' total population and GDP, respectively. The Yellow River Golden Triangle stands at the junction of central and western China, connecting North China, Northwest China, and the Central Plains. It boasts a dense railway network and extensive road system. Rich in mineral resources and land, the area enjoys advantageous agricultural production conditions, making it a significant grain-production base. Additionally, it has a solid industrial foundation, forming an industrial system focused on energy and raw material production such as coal, electricity, and non-ferrous metals, as well as equipment manufacturing and agricultural product processing. However, the total water resources in the Yellow River Golden Triangle are limited, with per capita water resources amounting to only 375 m^3, far below China's per capita water resources. Water-resource utilization is relatively extensive, and agricultural water-use efficiency is low. Industrial wastewater and agricultural pollution emissions cause water pollution and ecological damage. The deterioration of the ecological environment and water scarcity, in turn, restrict industrial development, hindering the sustainable economic development of the region. Therefore, it is essential to study the coupling-coordination degree of water resources, socioeconomics, and the ecological environment in the Yellow River Golden Triangle region.

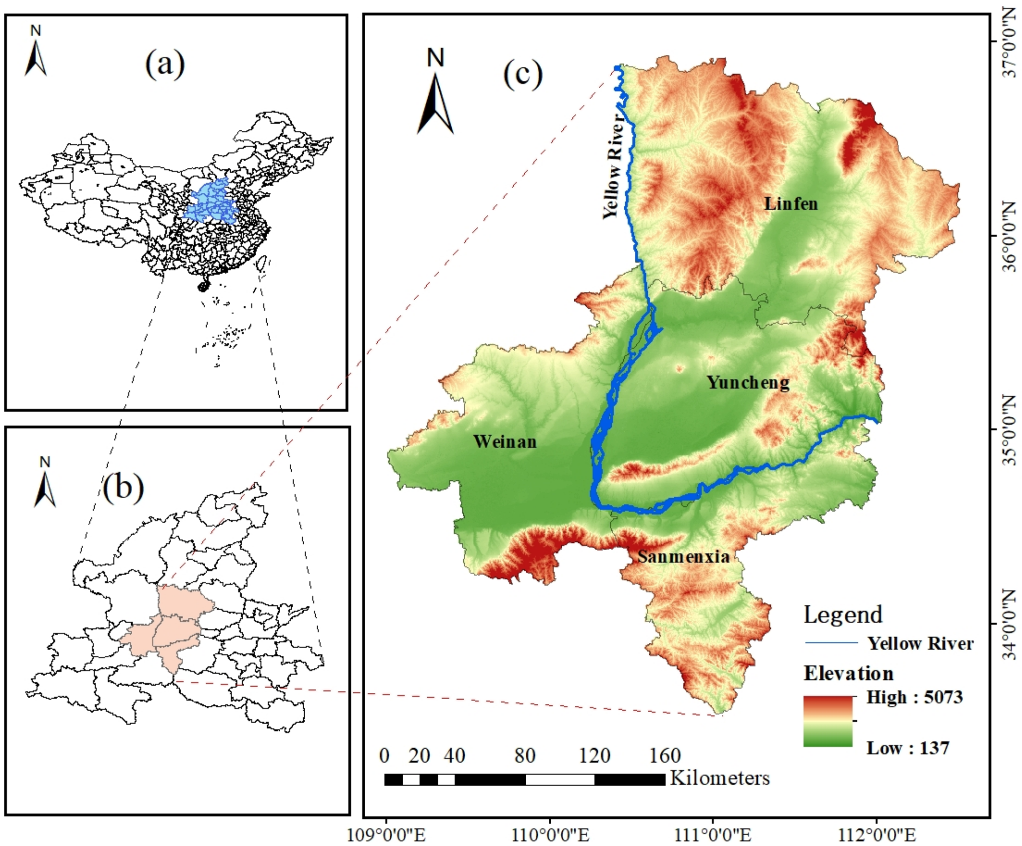

Figure 1. Location of the study area. (**a**) China, (**b**) the three provinces of Shanxi, Shaanxi, and Henan, and (**c**) the Yellow River Golden Triangle region. Created by ArcGIS 10.2 software (https://www.arcgis.com/).

2.2. Data Sources

This study encompasses subsystems for water resources, socioeconomics, and the ecological environment. Data for the water-resources subsystem indicators were sourced from the "Water Resources Bulletin of Henan Province", "Water Resources Bulletin of Shanxi Province", and "Water Resources Bulletin of Shaanxi Province." Data for the socioeconomic and ecological environment subsystem indicators were obtained from the "Henan Statistical Yearbook", "Shanxi Statistical Yearbook", "Shaanxi Statistical Yearbook", various city-specific statistical yearbooks, and the "China City Statistical Yearbook." Additionally, during the calculation of long-term sequence data, due to the missing data of wastewater discharge, sulfur dioxide discharge, and nitrogen oxide discharge of CNY 10,000 GDP in the Yuncheng eco-environment subsystem from 2019 to 2021, an interpolation method was used to complete the missing data.

2.3. Research Methods

2.3.1. Indicator Preprocessing

Due to the different dimensions of the original data for each indicator, direct comparison between them is not feasible. Therefore, it is necessary to standardize the original data of each indicator to eliminate the dimensional differences. In this paper, the range method is used to standardize the original data of each indicator:

$$x'_{\mathrm{ij}} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \text{ (Positive indicator)} \tag{1}$$

$$x'_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \text{ (Negative indicator)} \tag{2}$$

where x_{ij} represents the original data value of the indicator j in the year i, x'_{ij} represents the standardized value of the indicator j in the year i, and $\max(x_j)$ and $\min(x_j)$ are the maximum and minimum values of the indicator j.

2.3.2. Weight Determination Method

In this paper, a combined weighting method based on entropy weight and the Analytic Hierarchy Process (AHP) is used to determine the weight of each indicator. The entropy weight method is an objective weighting method that determines the weight of each indicator based on the differences between the indicator data. That is, the smaller the entropy value of an indicator, the higher the degree of dispersion, and the greater the indicator weight [23]. However, the entropy weight method mainly relies on data analysis and calculation and cannot reflect subjective value judgments. The AHP is a subjective weighting method that determines the judgment matrix of each subsystem through expert scoring, thereby deriving the subjective weights of each indicator [24]. The AHP is subject to human influence and relies heavily on expert experience and judgment. Therefore, combining these two methods in a combined weighting approach can avoid the limitations of both subjectivity and objectivity, making the calculation results more accurate. The specific calculation formulas are as follows [25]:

(1) Entropy Weight Method

$$P_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{m} x'_{ij}} \tag{3}$$

$$E_j = -\frac{1}{\ln m} \sum_{i=1}^{m} P_{ij} \ln P_{ij} \tag{4}$$

$$\omega_j = \frac{1 - E_j}{n - \sum_{j=1}^{n} E_j} \tag{5}$$

where P_{ij} represents the proportion of the indicator j in the year I; m represents the time scale of the data, where m = 9; and E_j represents the information entropy of the indicator j. If $P_{ij} = 0$, then let $P_{ij} \ln P_{ij} = 0$, ω_j represents the weight of the indicator j in the subsystem, and n represents the number of indicators in the subsystem.

(2) Analytic Hierarchy Process (AHP)

The AHP is a method that decomposes elements related to decision-making into levels such as objectives, criteria, and alternatives and performs qualitative and quantitative analysis based on this structure [26]. The main steps are as follows [27]:

Establish a hierarchical structure model. When applying the Analytic Hierarchy Process (AHP) to analyze decision-making problems, it is necessary to rationalize and stratify the problems, and construct a multi-layer structural model including the objective layer, the criterion layer, and the scheme layer.

We construct a judgment matrix. In this paper, the criterion layer represents the indicators of each subsystem. Due to differences in the importance of each indicator within the subsystem, numbers from 1 to 9 and their reciprocals are used to judge the importance level between two indicators (Table 1).

Table 1. Judgment matrix scale definition [28].

Scale	Explanation
1	The two indicators are of equal importance
3	Compared to the latter, the former indicator is slightly more important
5	Compared to the latter, the former indicator is significantly more important
7	Compared to the latter, the former indicator is strongly more important
9	Compared to the latter, the former indicator is extremely more important
2, 4, 6, 8	Intermediate values between the two adjacent judgments
reciprocal	If the importance ratio of indicator i to indicator j is any of the aforementioned numbers, then the importance ratio of indicator j to indicator i is the reciprocal of that number

Hierarchical single sorting and consistency check. The calculation of the consistency index is performed as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{6}$$

where CI represents the consistency index of the judgment matrix, $\lambda_{\max}$ is the largest eigenvalue of the judgment matrix, and n is the order of the judgment matrix.

We then look up the average random consistency index RI (Table 2).

$$CR = \frac{CI}{RI} \tag{7}$$

where CR is the consistency ratio. When $CR < 0.10$, it can be considered that the judgment matrix meets the consistency requirement; if $CR \geq 0.10$, the judgment matrix should be modified to meet the consistency requirement.

Table 2. *RI* of the low-order judgment matrix [29].

m	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

When the consistency check is passed, the eigenvector corresponding to the largest eigenvalue is the weight vector. Standardizing the weight vector gives the weight of the indicator ν_j.

(3) Calculation of combined weights

$$\omega = \alpha\omega_J + (1 - \alpha)\nu_J \tag{8}$$

where ω represents the combined weight; ω_j is the objective weight obtained by entropy weight method; ν_j is the subjective weight obtained by the analytic hierarchy process; and α represent the relative importance of the two weight calculation methods, satisfying $0 \leq \alpha \leq 1$. According to the importance of the two calculation methods, here, $\alpha = 0.6$.

2.3.3. Comprehensive Evaluation Index of WSE

Subsystem Comprehensive Evaluation Index:

$$\begin{cases} f(x) = \sum\limits_{a=1}^{m} \omega_a x'_a \\ g(y) = \sum\limits_{b=1}^{n} \omega_b x'_b \\ h(z) = \sum\limits_{c=1}^{k} \omega_c x'_c \end{cases} \tag{9}$$

where $f(x)$, $g(y)$, and $h(z)$ represent the comprehensive evaluation indices for the water-resource system, socioeconomic system, and ecological environment system, respectively. m, n, and k denote the number of indicators in each subsystem, where in this case, $m = 8$, $n = 9$, and $k = 7$. The combined weights of each indicator in the respective subsystems are denoted as ω_{a}, ω_b, and ω_c. The standardized values of each indicator are represented by x'_a, x'_b, and x'_c.

$$T = \alpha f(x) + \beta g(y) + \gamma h(z) \tag{10}$$

where T represents the comprehensive evaluation index of the water resources–socioeconomic–ecological environment system. α, β, and γ represent the relative importance of the three subsystems. In this case, they are set as equal, i.e., $\alpha = \beta = \gamma = \frac{1}{3}$.

2.3.4. Coupling-Coordination Degree Model

Constructing a coupling-coordination degree model for the water resources–socioeconomic–ecological environment system [30]:

$$C = \frac{3\sqrt[3]{f(x)g(y)h(z)}}{f(x) + g(y) + h(z)} \tag{11}$$

$$D = \sqrt{CT} \tag{12}$$

where C represents the coupling degree. When $C \in [0, 0.3)$, the system is in a low-level coupling stage; when $C \in [0.3, 0.5)$, the system is in an antagonistic phase; when $C \in [0.5, 0.8)$, the system is in a running-in phase; and when $C \in [0.8, 1]$, the system is in a high-level coupling stage. D represents the coupling-coordination degree, $0 \leq D \leq 1$. Based on existing research results [31,32], the coupling-coordination degree is classified as shown in Table 3.

Table 3. Classification of the coupling-coordination degree.

Coupling-Coordination Degree	Coupling-Coordination Level	Coupling-Coordination Degree	Coupling-Coordination Level
[0.0~0.1)	Extreme disorder	[0.5~0.6)	Barely coordinated
[0.1~0.2)	Severe disorder	[0.6~0.7)	Preliminary coordination
[0.2~0.3)	Moderate disorder	[0.7~0.8)	Intermediate coordination
[0.3~0.4)	Mild disorder	[0.8~0.9)	Good coordination
[0.4~0.5)	Nearly dysfunctional	[0.9~1.0]	High-quality coordination

2.3.5. Gray Relational Analysis

Gray relational analysis is a multi-attribute decision-making method proposed by Kuo et al. [33]. This method judges the closeness of different sequences by the similarity of the geometric shape of the sequence curves. Through gray relational analysis, the key factors affecting the coupling-coordination degree can be identified. The gray relational degree between the coupling-coordination degree and the selected indicators of each city in the Golden Triangle of the Yellow River is calculated, with the coupling-coordination degree selected as the reference sequence and each indicator as the comparison sequence. The calculation formula is as follows:

$$\varsigma_i(k) = \frac{\min_i \min_k |x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|} \quad (13)$$

where $\varsigma_i(k)$ is the correlation coefficient; ρ is the resolution coefficient, its value range is [0, 1], and it often taken as 0.5; $x_0(k)$ is the reference sequence, representing the coupling-coordination degree; and $x_i(k)$ is a comparison sequence, representing various evaluation indicators, k = 1, 2, …, n; i = 1, 2, …, m; here, m = 24, and n = 10.

$$\varepsilon_i = \frac{1}{n}\sum_{k=1}^{n} \varsigma_i(k) \quad (14)$$

where ε_i is the gray relational degree.

3. Results

3.1. Indicator System Construction

Based on principles of scientificity, systematicness, comprehensiveness, indicator accessibility [34], and previous research results [35,36], this paper constructs three subsystems for the four cities in the Golden Triangle of the Yellow River region: water resources, socioeconomic, and ecological systems. For the water-resource system, eight indicators are selected from three aspects: water-resource endowment, water-usage structure, and water-resource utilization degree. For the socioeconomic system, nine indicators are chosen from two perspectives: regional economic structure and social development level. For the ecological environment system, seven indicators are picked from ecological conditions and environmental pressure. Altogether, 24 indicators are selected to construct the evaluation indicator system for the water resource–socioeconomic–ecological environment system in the Golden Triangle of the Yellow River, as shown in Table 4.

Table 4. The coupling-evaluation index system of WSE system in the Yellow River Golden Triangle region.

Subsystem	Indicators	Attribute	Unit	Combined Weight
Water resources	Per capita water resources/X_1	+	m^3	0.247
	Proportion of industrial water use/X_2	+	%	0.092
	Proportion of domestic water use/X_3	+	%	0.107
	Per capita water consumption/X_4	+	m^3	0.149
	Water production modulus/X_5	+	10,000 m^3/km^2	0.193
	Irrigation water per mu of farmland/X_6	−	m^3	0.072
	Water consumption per CNY 10,000 of GDP/X_7	−	m^3/CNY 10,000	0.050
	Proportion of groundwater supply/X_8	−	%	0.090
Social economy	Per capita GDP/Y_1	+	CNY/person	0.187
	The proportion of primary industry in GDP/Y_2	−	%	0.095
	The proportion of secondary industry in GDP/Y_3	+	%	0.160
	The proportion of tertiary industry in GDP/Y_4	+	%	0.139
	Per capita net income of rural residents/Y_5	+	CNY	0.109
	Per capita disposable income of urban residents/Y_6	+	CNY	0.101

Table 4. *Cont.*

Subsystem	Indicators	Attribute	Unit	Combined Weight
Social economy	Urbanization rate/Y_7	+	%	0.080
	Population density/Y_8	+	Person/km^2	0.060
	Total retail sales of consumer goods/Y_9	+	CNY 10^8	0.069
Ecological environment	Green coverage rate of built-up area/Z_1	+	%	0.071
	Proportion of water used for ecological environment/Z_2	+	%	0.207
	Per capita green park area/Z_3	+	㎡	0.106
	Comprehensive utilization rate of solid waste/Z_4	+	%	0.130
	Waste water discharge per CNY 10,000 of GDP/Z_5	−	Tons/CNY 10,000	0.197
	Sulfur dioxide emissions per CNY 10,000 of GDP/Z_6	−	Tons/CNY 10,000	0.172
	Nitrogen oxide emissions per CNY 10,000 of GDP/Z_7	−	Tons/CNY 10,000	0.117

Note: + represent the positive indicator, and − represent the negative indicator.

3.2. Comprehensive Evaluation of the WSE System in the Golden Triangle Region of the Yellow River

The comprehensive evaluation index reflects the integrated development level of water resources, socioeconomics, the ecological environment, and their coupled system in the Golden Triangle Region of the Yellow River, as shown in Figure 2.

According to Figure 2a, the development level of water resources in the Golden Triangle Region of the Yellow River is not high, generally below 0.5 from 2011 to 2019, but it has significantly improved from 2020 to 2021. The development of water resources in Sanmenxia City is relatively unstable, showing a fluctuating state overall. It reached the worst development level in 2017 (0.223) and then fluctuated upward, reaching the best development level (0.739) in 2021. The development of water resources in Weinan City showed a trend of first decreasing and then increasing. After reaching the worst development level in 2016 (0.152), it gradually improved to the best level (0.769), with an increase of 406%. The water resources in Yuncheng City showed a steady upward trend overall. In 2012, it reached the lowest water-resources development index value of 0.122 among the four cities, and then gradually increased to the highest water-resources development index value of 0.913 among the four cities, with an increase of 648%. The development of water resources in Linfen City was relatively stable before 2020, but the development level was not high. It began to increase significantly in 2020.

According to Figure 2b, the socioeconomic development in the Golden Triangle Region of the Yellow River shows a trend of gradual improvement overall. The socioeconomic subsystem development level of Sanmenxia City is the best among the four cities, with the socioeconomic evaluation index increasing from 0.289 in 2011 to 0.762 in 2021. Weinan City has the fastest socioeconomic development among the four cities, with the socioeconomic evaluation index increasing from 0.161 in 2011 to 0.651 in 2021, an increase of 304%. The socioeconomic development of Yuncheng City and Linfen City is similar, but Yuncheng City's development is more stable. From 2011 to 2021, the socioeconomic evaluation index never decreased, steadily increasing from 0.265 in 2011 to 0.732 in 2021.

According to Figure 2c, the ecological environment development in the Golden Triangle Region of the Yellow River shows an upward trend overall. The development level of the ecological environment subsystem in the four cities was not high before 2016, generally below 0.4. However, after 2016, the development level of the ecological environment in the four cities rapidly improved. Among them, the development level of the ecological environment in Sanmenxia City was the worst among the four cities before 2016, and its ecological environment evaluation index was below 0.2. The comprehensive evaluation index of the ecological environment in Weinan City has grown steadily, showing a steady upward trend overall. The development level of the ecological environment in Yuncheng

City was higher than that in Linfen City before 2014. After 2014, the ecological environment of Yuncheng City showed a gradual growth trend, while the ecological environment of Linfen City showed an upward trend overall, but the upward trend was unstable.

According to Figure 2d, the development of the water resources–socioeconomic –ecological environment system in the Golden Triangle Region of the Yellow River can be divided into two stages: the low-level development stage from 2011 to 2016, and the rapid development stage from 2016 to 2021. Before 2016, the comprehensive evaluation index of the WSE coupling system was less than 0.4, which represents a relatively low development level. During this period, the comprehensive evaluation index of the coupling system in Linfen City and Yuncheng City fluctuated somewhat. After 2016, the comprehensive evaluation index of the coupling system in the four cities rose rapidly. Sanmenxia City was in a leading position before 2020, but due to the impact of water resources, the comprehensive evaluation index has decreased, putting it in a backward position. Linfen City has developed the fastest, with an increase from 0.260 in 2011 to 0.836 in 2021, an increase of 221%.

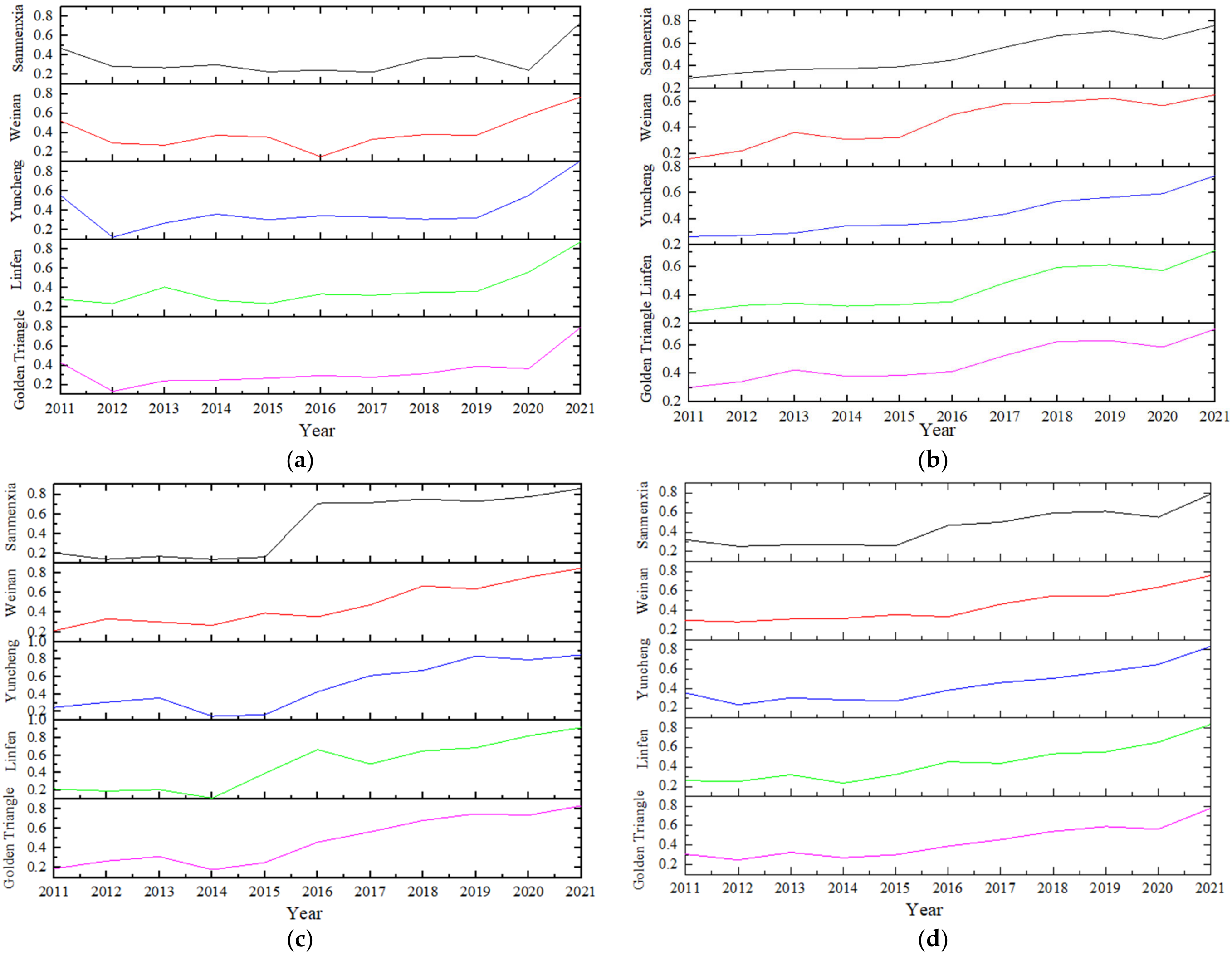

Figure 2. Comprehensive evaluation index of each subsystem and coupling system of WSE. (**a**) water resources, (**b**) social economy, (**c**) ecological environment, (**d**) WSE coupling system.

3.3. Analysis of WSE Coupling-Coordination Degree

Based on the coupling-coordination degree model, the coupling degree and coupling-coordination degree of the WSE coupling system for various cities in the Golden Triangle of the Yellow River region from 2011 to 2021 are calculated, as shown in Figures 3–5.

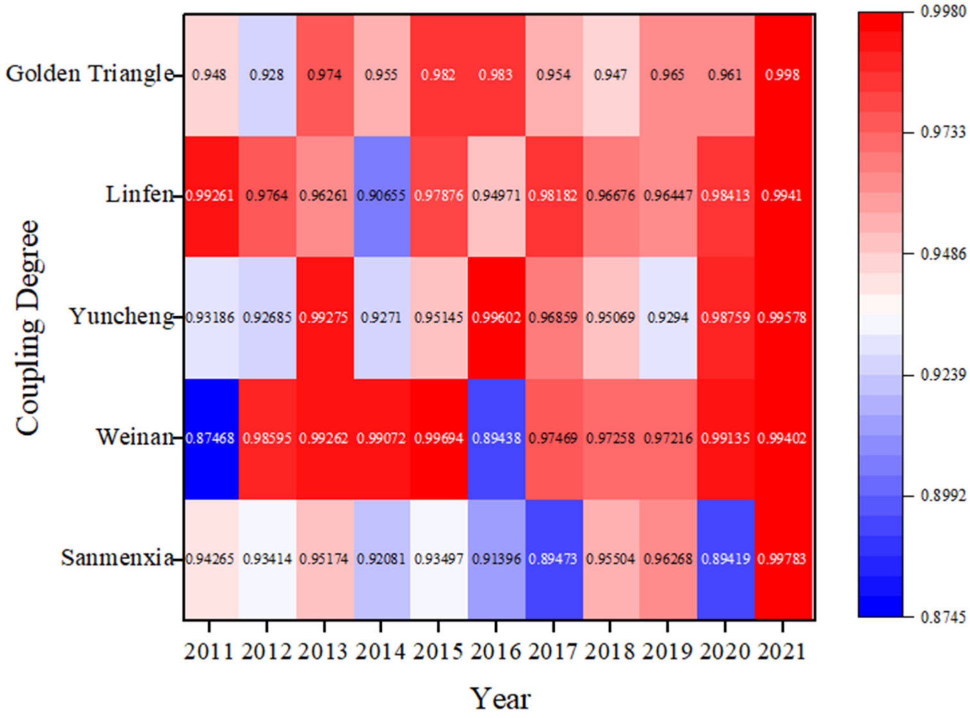

Figure 3. WSE coupling degree of four cities in the Yellow River Golden Triangle region.

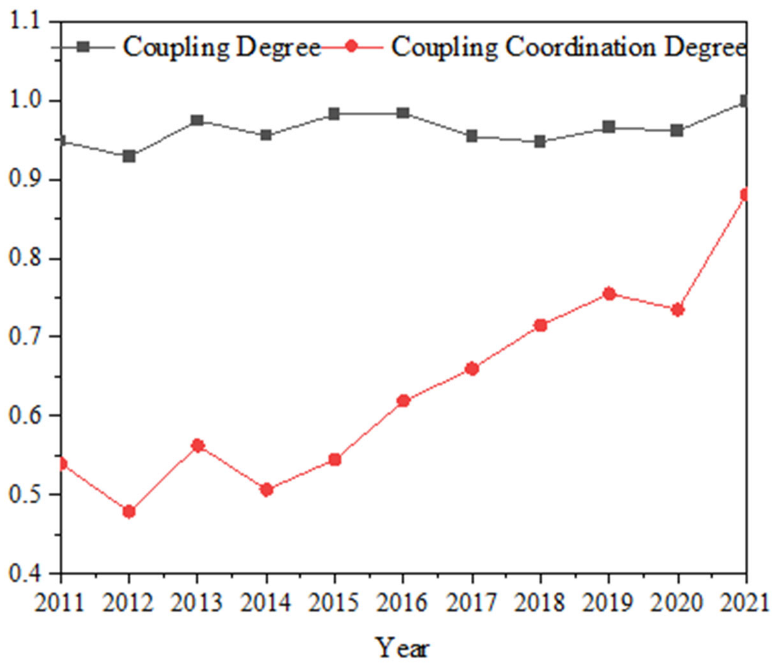

Figure 4. WSE coupling degree and coupling-coordination degree of the Yellow River Golden Triangle.

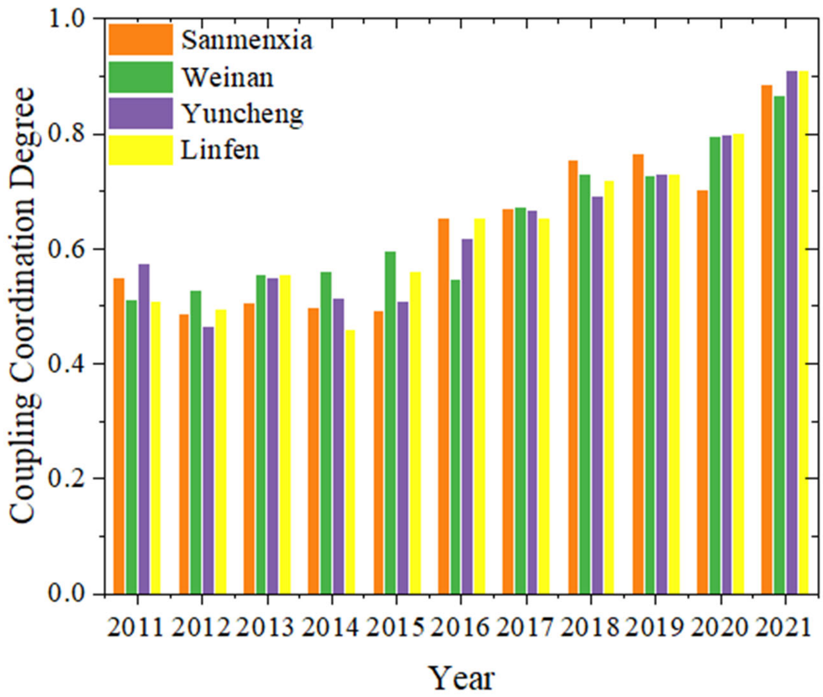

Figure 5. WSE coupling-coordination degree in the Yellow River Golden Triangle region.

According to Figure 3, the WSE coupling degrees of the four cities in the Golden Triangle of the Yellow River region from 2011 to 2021 are all higher than 0.8, indicating a high-level coupling stage. This suggests that the water-resources subsystem, socioeconomic subsystem, and ecological environment subsystem in each city of the Golden Triangle of the Yellow River region are closely connected, and the subsystems strongly interact with each other. However, there were fluctuations in the coupling degree of each city during development. For example, the WSE coupling degree of Sanmenxia City dropped from 0.963 in 2019 to 0.894 in 2020. This indicates that although the WSE system in each city is well-coupled, the subsystem development is not stable, which affects the coordinated development of the WSE coupling to some extent.

According to Figure 4, the coupling-coordination degree of the WSE system in the Golden Triangle of the Yellow River region shows a trend of steady development followed by a gradual increase. From 2011 to 2015, there was little change in the coupling-coordination degree, but it rose from a barely coordinated stage in 2016 to a well-coordinated stage in 2021.

As can be seen from Figure 5, before 2016, the subsystems of water resources, socioeconomics, and the ecological environment in the four cities of the Golden Triangle of the Yellow River were not highly developed, keeping the coupling-coordination degree of the WSE system at the nearly dysfunctional or barely coordinated stage. However, since 2016, with the economic growth and improvement of the ecological environment in various cities, the coupling-coordination degree of the WSE system in each city has begun to gradually increase. Among them, Yuncheng and Linfen have seen the largest increase in the coupling-coordination degree, rising from a barely coordinated stage to a high-quality coordinated stage. Although the coupling-coordination degree of the WSE system in Sanmenxia has increased, it declined in 2020 due to the influence of the water-resources subsystem, showing a fluctuating upward trend. In 2021, the development of water resources, socioeconomics, and the ecological environment in the four cities was relatively similar. The three subsystems interacted and promoted development together, resulting in a significant increase in the coupling-coordination degree of the four cities.

3.4. Analysis of Influencing Factors

The influencing factors of the coupling-coordination degree of the WSE system in the cities of the Golden Triangle of the Yellow River are shown in Figure 6. Indicators with a gray correlation degree exceeding 0.9 are selected as the main influencing factors. The socioeconomic subsystem is the most critical subsystem affecting the coupled and coordinated development of the WSE system in Sanmenxia City. The socioeconomic subsystem has the largest proportion of indicators (42.9%), while the ecological environment subsystem has the smallest proportion (25.2%). Among them, the indicator with the highest correlation degree is Y_1 (per capita GDP), followed by Y_6 (per capita disposable income of urban residents). Most indicators of the socioeconomic subsystem have a correlation degree of 0.9. The proportion of subsystem indicators in Weinan, Yuncheng, and Linfen is similar, with the water-resources subsystem accounting for approximately 34%, the socioeconomic subsystem accounting for approximately 41%, and the ecological environment subsystem accounting for approximately 25%. Among the factors influencing the coupling-coordination degree of the WSE system in Weinan City, the indicator with the highest gray correlation degree is Y_6 (per capita disposable income of urban residents), followed by Y_1 (per capita GDP), Y_7 (urbanization rate), and Z_3 (per capita park green area). X_3 (proportion of domestic water use), Y_4 (proportion of tertiary industry in GDP), and Y_5 (per capita net income of rural residents) also have a correlation degree of 0.9. Among the factors affecting the coupling-coordination degree of the WSE system in Yuncheng City, the indicators with the highest gray correlation degree are Y_6 (per capita disposable income of urban residents) and Y_9 (total retail sales of social consumer goods), followed by Y_1 (per capita GDP). For the coupling-coordination degree of the WSE system in Linfen City, the indicator with the highest gray correlation degree is Y_1 (per capita GDP), followed by Y_6 (per capita disposable income of urban residents), Y_9 (total retail sales of consumer goods), and X_3 (proportion of domestic water use).

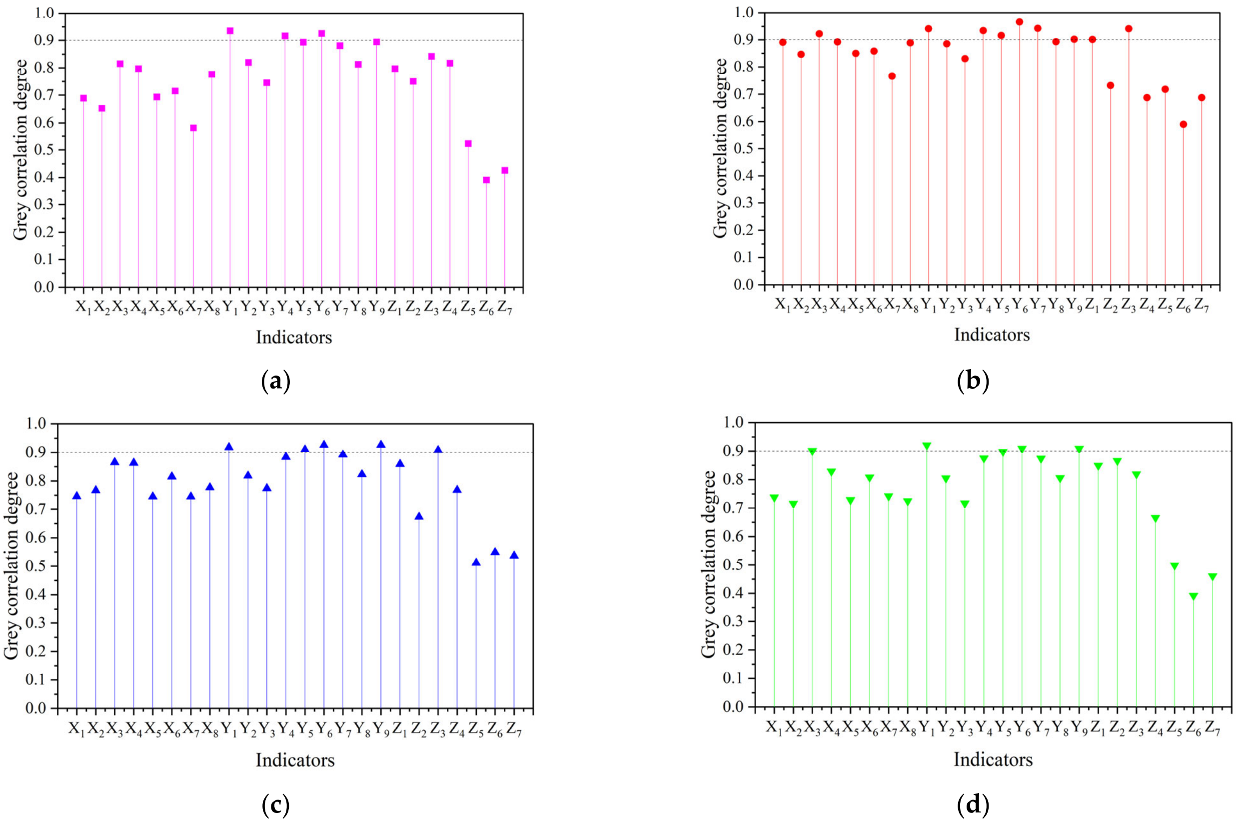

Figure 6. Influence factors of the coupling-coordination degree of the WSE system in cities of the Yellow River Golden Triangle region. (**a**) Sanmenxia, (**b**) Weinan, (**c**) Yuncheng, (**d**) Linfen.

4. Discussion

The evaluation indices for water resources, socioeconomic, ecological environment, and the comprehensive evaluation index of the coupling system in the Golden Triangle of the Yellow River region indicate that there were minimal differences among the systems before 2016. However, after 2016, the comprehensive evaluation indices for socioeconomic and ecological environment increased. With the implementation of the 13th Five-Year Plan, the government has strengthened its supervision of high-polluting enterprises, significantly reducing wastewater and exhaust emissions, leading to a substantial increase in the ecological environment evaluation index. Simultaneously, as the industrial structure has gradually shifted from "secondary, tertiary, primary" to "tertiary, secondary, primary", with the tertiary industry surpassing the secondary industry in proportion, the service industry has gradually become the leading sector driving economic growth, further promoting economic development [37]. The water-resources evaluation index remained at a relatively low level until 2020. The increase in the evaluation index from 2020 to 2021 was primarily attributed to abundant rainfall, with the average rainfall in 2021 increasing by more than 50% compared to the multi-year average. As economic growth and urbanization have accelerated, the demand for water resources has further increased. However, due to the limitation of total water resources, the water-resources evaluation index remains low, exacerbating the contradiction between socioeconomic development, ecological environmental protection, and water-resource development and utilization. The lack of water resources has hindered the development of the Golden Triangle of the Yellow River.

The coupling-coordination degree of the WSE system in the cities of the Golden Triangle of the Yellow River region generally shows a trend of steady development followed by a gradual increase, This is consistent with other research findings [38]; however, the level of change in the coupling-coordination degree may differ due to the inconsistency in the evaluation indicators and the weights assigned to them. From 2011 to 2015, the coupling-coordination degree of the four cities in the Golden Triangle of the Yellow River was in a barely coordinated stage. During this period, the economic development of the Golden Triangle of the Yellow River was backward, and the urbanization rate was low. To achieve rapid economic growth, protection of the ecological environment was ignored, resulting in massive emissions of wastewater and exhaust. Additionally, due to water scarcity, an unreasonable water-use structure, and insufficient supervision of water-intensive industries, water-resource utilization was inefficient. From 2016 to 2021, the coupling-coordination degree of the WSE system in the cities of the Golden Triangle of the Yellow River rose from a barely coordinated stage to a well-coordinated stage. During this period, with the implementation of the 13th Five-Year Plan, the economy developed rapidly, the urbanization rate continuously increased, and ecological environmental governance achieved remarkable results. The socioeconomic and ecological environments influence each other [39]: the comprehensive evaluation indices of the socioeconomic subsystem and ecological environment subsystem increased, elevating the coupling-coordination degree of the WSE system. In 2021, abundant rainfall in the Golden Triangle of the Yellow River region, coupled with improvements in water equipment in water-intensive industries, led to improved water-resource allocation. This resulted in a notable upward trend in the comprehensive evaluation index of water resources, which further promoted economic development and ecological environmental improvement, ultimately leading to a well-coordinated stage of coupling coordination.

The identification of impact factors indicates that the indicators of the socioeconomic subsystem are the main factors affecting the coupled and coordinated development of the WSE system in the Golden Triangle of the Yellow River region; this is consistent with other research findings [40], but it should be noted that due to the differences in the research area, the proportion of the secondary industry in GDP has little impact on the system coupling coordination in this study. The main influencing factors in this study include indicators such as GDP per capita, the proportion of the tertiary industry in GDP, disposable income per capita of urban residents, net income per rural resident, and total retail sales of social consumer goods. At the same time, indicators such as the proportion of domestic water consumption and green park area per capita also greatly affect the coupled and coordinated development of the WSE system in the Golden Triangle of the Yellow River. Therefore, while accelerating economic development, optimizing industrial structure, and increasing residents' income, the Golden Triangle of the Yellow River should also rationally develop and utilize water resources, optimize water-resource allocation, and focus on the development of water resources and the ecological environment while emphasizing economic development.

5. Conclusions

Based on the coupling-coordination degree model of the water resources, social economy, and ecological environment in the Golden Triangle of the Yellow River, an evaluation index system for the coupled and coordinated development of the water resources, social economy, and ecological environment system in the Golden Triangle of the Yellow River was constructed. The comprehensive evaluation index, coordination degree, and coupling-coordination degree trends of the water resources, social economy, and ecological environment systems of various cities from 2011 to 2021 were studied. Gray correlation analysis was used to study the influencing factors that affect the coupled and coordinated development of the water resources, social economy, and ecological environment system in the Golden Triangle of the Yellow River. The main conclusions are as follows:

(1) The comprehensive evaluation index of the Golden Triangle of the Yellow River indicates that the comprehensive evaluation index of the socioeconomic subsystem, ecological environment subsystem, and coupling system shows a trend of steady development followed by a gradual increase. There were large fluctuations in the ecological environment subsystems of Yuncheng and Linfen during their development, and the water-resources subsystem was poorly developed before 2020, restricting socioeconomic development and ecological environmental protection and governance.

(2) The coupling degree of the three subsystems in the Golden Triangle of the Yellow River has always been at a high level of coupling stage. The three subsystems are closely connected and strongly influence each other. The coupling-coordination degree of the coupling system shows a trend of steady development followed by a gradual increase, rising from a barely coordinated stage to a good coordinated stage. Among them, Yuncheng and Linfen have risen to a superior coordination stage, showing a good overall development trend.

(3) According to gray correlation analysis, the socioeconomic subsystem has the greatest impact on the coupled and coordinated development of the water resources, social economy, and ecological environment in the Golden Triangle of the Yellow River, followed by the water-resources subsystem. Among them, indicators such as GDP per capita, the proportion of the tertiary industry in GDP, disposable income per capita of urban residents, net income per rural resident, and water consumption per capita are the most important factors affecting the coupled and coordinated development of the water resources, social economy, and ecological environment in the Golden Triangle of the Yellow River.

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