Article

Study on Coupling Coordination Relationship between Water Use Efficiency and Economic Development

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Abstract: In order to realize the sustainable utilization of water resources and the sustainable development of economy, the evaluation index system of water use efficiency system and economic development system was constructed. Entropy weight method and comprehensive evaluation method were adopted to determine the index weights and conduct comprehensive evaluation for the two systems. The coupling coordination model was used to calculate the coupling degree, coordination degree and coupling coordination degree of the two systems. The annual coupling stage and coupling coordination intensity of the two systems were analyzed and determined. The results showed that the comprehensive evaluation values of both water use efficiency system and economic development system in Jinan City increased greatly from 2008 to 2017, and showed a changing trend of ups and downs. The two systems were in the antagonistic stage, and were gradually approaching the running-in stage, indicating that they were in the state of common development. The coupling coordination degree of the two systems gradually increased in waves, progressed from the moderately to the highly coordinated coupling. In the future, if the water control path appropriate to Jinan City can be explored actively, the water-saving kinetic energy of economic development can be increased constantly, and the linkage effect between economic development and water resources utilization can be given full play to, the two systems will be in the orbit with the benign interaction and healthy harmonious development.

Keywords: water use efficiency; economic development; comprehensive evaluation; coupling coordination; Jinan City

1. Introduction

As the basic natural resources and strategic economic resources, water resources are of great significance to the sustainable economic development under the strategy of ecological civilization construction. Water resources shortage, water pollution and water ecological deterioration are the main restricting problems of water resources utilization in China at present. The strategy research report of sustainable water resources in China shows that improving water use efficiency and constructing water-saving society are the key to solve Chinese water problems and the sustainable utilization of water resources and promote sustainable economic development. Therefore, it is urgent to analyze the coordination degree between water use efficiency and economic development, so as to provide information supports for formulating economic development strategies coordinated with water use efficiency, facilitate scientific management and protection of water resources, and promote the coordinated and orderly development of water resources and economy.

Scholars have made some achievements in the researches of the relationship between water resources and economic development in recent years. Using the strengths, weaknesses, opportunities

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and threats/political, economic, social, technological, legal and environmental (SWOT/PESTLE) analysis, Nazari explored 40 internal and external factors that influence irrigation water management in Iran and recognizes legal, social, technological and political dynamics as the major reasons for failure of irrigation water management in the country [1]. Gedefaw developed a water evaluation and planning (WEAP) model to allocate the water supplies to demanding sectors based on an economic parameter to maximize the economic benefits [2]. Arain explored the empirical relationship between foreign direct investment (FDI), population, energy production, and water resources in South Asia [3]. Alexandratos discussed the efforts to manage watersheds and model their responses to severe weather events along with efforts to improve the predictability of their function [4]. Hao-Zhe Yu, Yi Cui, Yong-Xin Xu, Wei-Wei Xu and Yu-Ping Han et al. studied on the relationship between water resources utilization and economic growth [5-10]. Xu-Hui Ding, Guo-Yu Zhang, Mian-Hao Hu, Feng-Xia Yan and Chen-Yue Liu et al. analyzed the temporal and spatial variations of water use efficiency [11-16]. Wei Zhang, Zhong-Wen Pan, Ning Li, Dan Wu, Xiang-Yi Meng, Wei Chen, Guo-Ping Tong, Hai-Liang Ma, Bao-Qiang Wang, Hong-Li zhu and An-E Pan et al. conducted the decoupling analysis of water resources utilization and economic growth [17-27]. Jun Ma, Yue Zhang and Chen-Jun Zhang et al. studied on the relationship between economic development and water use efficiency based on the environmental Kuznets theory [28-30]. Mian-Hao Hu, Xiao Nie, Zhao-Rong Hu, Fang Geng, Mei Gai, Ai-Jun Sun and Yong-Hong Xie et al. studied on coupling coordinated development of water use efficiency and economic development [31-37].

In the study of the coupling coordination relationship between water use efficiency and economic development, the key problems are to construct a comprehensive and systematic evaluation index system and choose a realistic evaluation model. Therefore, in this paper, Jinan City in China taken as the research area, the water use efficiency system is constructed from the four aspects of synthesis, production, life and ecology, and the economic development system is constructed from the three aspects of economic scale, economic structure and economic vitality. Entropy weight method and comprehensive evaluation method are used to determine the weight of each index of the two systems and to evaluate them comprehensively. The coupling coordination model is used to calculate the coupling degree, coordination degree and coupling coordination degree of the two systems. The coupling stage and coupling coordination intensity of the two systems are analyzed and determined annually. This paper reveals the factors influencing the coordinated development of water resources and economy, and discusses the policies and measures to promote the evolution of water use efficiency and economic development into the coordinated, orderly, healthy and sustainable development, so as to provide theoretical basis and practical guidance for realizing the benign interaction between urban water use efficiency and economic development under the strategy of ecological civilization construction.

2. Materials and Methods

2.1. Construction of the Evaluation Index System

According to the actual situation of Jinan City, the integrated system of water use efficiency and economic development is divided into water use efficiency subsystem and economic development subsystem. The water use efficiency subsystem includes thirteen evaluation indexes in four aspects: comprehensive, production, domestic and ecological water use efficiency (hereinafter referred to as CWUE, PWUE, DWUE and EWUE). Nine evaluation indexes are selected for the economic development subsystem in terms of economic scale, economic structure and economic vitality (hereinafter referred to as ESC, EST and EV). The coupling coordination evaluation index system of the integrated system of water use efficiency and economic development in Jinan City is shown in Table 1.

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Table 1. The coupling coordination evaluation index system of the integrated system of water use efficiency and economic development in Jinan City.

The target layer	The first-order index	The second-order index	The third-order index	Weight
The integrated system of water use efficiency and economic development	Water use efficiency subsystem	CWUE	Water consumption per ten thousand yuan of GDP (X_1)	0.060
			Integrated water consumption per capita (X_2)	0.067
		PWUE	The proportion of industrial water consumption in total water consumption (X_3)	0.054
			Water consumption per ten thousand yuan added value of industry (X_4)	0.077
			The proportion of irrigation water consumption in total water consumption (X_5)	0.077
			Water consumption per ten thousand yuan added value of agriculture (X_6)	0.074
			Water consumption per unit area for irrigation (X_7)	0.102
		DWUE	Daily domestic water consumption per capita (X_8)	0.083
			The proportion of domestic water consumption in total water consumption (X_9)	0.094
		EWUE	Waste water discharge of 100 million yuan GDP (X_{10})	0.073
			Sewage treatment rate (X_{11})	0.064
			Annual precipitation (X_{12})	0.074
			The proportion of ecological water consumption in total water consumption (X_{13})	0.103
	Economic development subsystem	ESC	GDP per capita（X_{14}）	0.106
			Per capita disposable income of urban residents (X_{15})	0.113
			Total fixed assets investment (X_{16})	0.120
		EST	The proportion of the added value of the tertiary industry in GDP (X_{17})	0.105
			Rural Engel's Coefficient (X_{18})	0.110
			The proportion of non-agricultural production value in GDP (X_{19})	0.087
			The proportion of fiscal spending in GDP (X_{20})	0.092
		EV	The growth rate of GDP (X_{21})	0.148
			The labor productivity of the whole society (X_{22})	0.120

2.2. Sources of Data

The data are obtained from the statistical yearbook of Jinan City, bulletin of water resources of Jinan City, statistical bulletin of national economy and social development of Jinan City, relevant statistical data and planning reports of Jinan City.

2.3. Comprehensive Evaluation Method

Entropy weight method is a weighting method based on the law of statistical change of data. By calculating formula, the weight of each index is obtained. With no artificial and subjective factors involved, the assignment is relatively objective, and the result is authentic [38]. The entropy weight method and the comprehensive evaluation method are combined to evaluate the water use efficiency system (hereinafter referred to as WUES) and the economic development system (hereinafter referred to as EDS).

1. Construct the judgment matrix X of n samples and m evaluation indexes, which is expressed as $X = \left(x_{ji}\right)_{n\times m}$.

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2. Normalize the judgment matrix X and obtain the normalized judgment matrix B, which is expressed as $B=\left(b_{ji}\right)_{n\times m}$.
3. Calculate the entropy weight w_i of the *i*th evaluation index.
4. Calculate the comprehensive evaluation value of each system, which can be calculated using the following formula:

$$R=\sum_{i=1}^{m} b_{ji} w_i \qquad \left(j=1,2,\cdots,n\right) \tag{1}$$

The weights of the coupling coordination evaluation indexes of WUES and EDS in Jinan City are shown in Table 1.

2.4. Coupling Coordination Degree Model

Coupling originates from the test and research on the interaction and correlation of multiple systems in Physics. By referring to the coupling method, the degree of synergy between WUES and EDS can be measured. According to the concept of volumetric coupling and the volumetric coupling coefficient model [35], the coupling degree model between the two systems is as follows:

$$C=\left[\frac{R_1 R_2}{\left(R_1+R_2\right)^2}\right]^{1/2} \tag{2}$$

In Formula (2), C is the coupling degree. R_1 and R_2 are the comprehensive evaluation values of WUES and EDS.

According to the segmented method of the coupling coordination degree proposed by many scholars, when C equals to 0, the coupling degree is minimal, the two systems or internal elements of the same system are irrelevant and the two systems develop into disorder. When C is in the range of $\left(0,0.3\right]$, $\left(0.3,0.5\right]$, $\left(0.5,0.8\right]$ or $\left(0.8,1\right)$,the two systems are in the low level coupling, antagonistic, running-in or high level coupling stage. When C equals to 1, the coupling degree is maximal, and the benign resonance and efficient coordination between the two systems are achieved.

In order to better judge the coordination degree of interaction coupling between WUES and EDS, we refer to Liao 's model of coordinated development [39]. The two formulas in Liao's model are as follows:

$$T=\sqrt{\alpha R_1+\beta R_2} \tag{3}$$

$$D=\sqrt{C\cdot T} \tag{4}$$

In Formula (3), T is the comprehensive coordination index of WUES and EDS, reflecting the integrated synergistic effect of the two systems. α and β are the weight coefficients. Since the improvement of WUE is as important as ED, we make α and β equal to 0.5.

In Formula (4), D is the coupling coordination degree of WUES and EDS. When D is in the range of $\left[0,0.4\right]$, $\left(0.4,0.5\right]$, $\left(0.5,0.8\right]$ or $\left(0.8,1\right]$, the two systems are at the state of low degree , moderately, highly or extreme coordinated coupling.

The coupling coordination degree model can be used to judge the coupling coordination level of WUES and EDS, but it cannot be used to determine the relative development level between the two systems. In order to make up for the deficiency, the relative development degree [39] is introduced as follows:

$$E=\frac{R_1}{R_2} \tag{5}$$

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In Formula (5), E is the relative development degree. When E is in the range of $[0, 0.8]$, the level of WUE is low, ED is fast, the former restricts the social and economic development, the use of water resources is in the extensive use stage. When E is in the range of $(0.8, 1.2)$, WUES and EDS are in the stage of benign interaction, mutual promotion and balanced coordination. When E is greater than or equals to 1.2, the level of water resources utilization is ahead of ED, the quality of ED is not high, and water resources are in the stage of overexploitation.

3. Results

3.1. Comprehensive Evaluation of WUES and EDS

Calculated with Formulas (1) and (5), the comprehensive evaluation values and the relative development degrees of WUES and EDS in Jinan City from 2008 to 2017 are shown in Table 2. According to Table 2, the temporal changes of the comprehensive evaluation values and the relative development degrees are shown in Figures 1–3.

Table 2. The comprehensive evaluation values and the relative development degrees of WUES and EDS in Jinan City from 2008 to 2017.

Year	Comprehensive evaluation value									Relative development degree
	CWUE	PWUE	DWUE	EWUE	WUES	ESC	EST	EV	EDS	
2008	0.041	0.015	0.141	0.039	0.236	0.000	0.068	0.148	0.217	1.092
2009	0.077	0.066	0.088	0.103	0.333	0.027	0.113	0.132	0.272	1.224
2010	0.112	0.102	0.159	0.149	0.521	0.067	0.137	0.170	0.374	1.394
2011	0.065	0.101	0.041	0.137	0.343	0.093	0.110	0.139	0.343	1.002
2012	0.061	0.156	0.038	0.115	0.371	0.130	0.106	0.122	0.358	1.035
2013	0.073	0.203	0.018	0.150	0.445	0.172	0.235	0.137	0.545	0.817
2014	0.076	0.212	0.003	0.103	0.394	0.217	0.283	0.134	0.635	0.621
2015	0.076	0.291	0.062	0.180	0.609	0.248	0.303	0.116	0.666	0.914
2016	0.072	0.315	0.072	0.268	0.727	0.291	0.324	0.108	0.723	1.006
2017	0.060	0.383	0.025	0.257	0.726	0.338	0.377	0.126	0.840	0.864

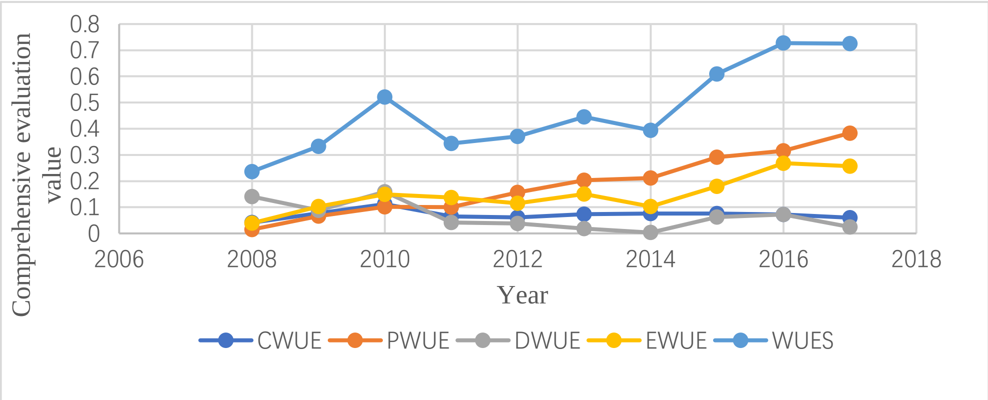

Figure 1. The temporal changes of the comprehensive evaluation values of WUES in Jinan City from 2008 to 2017.

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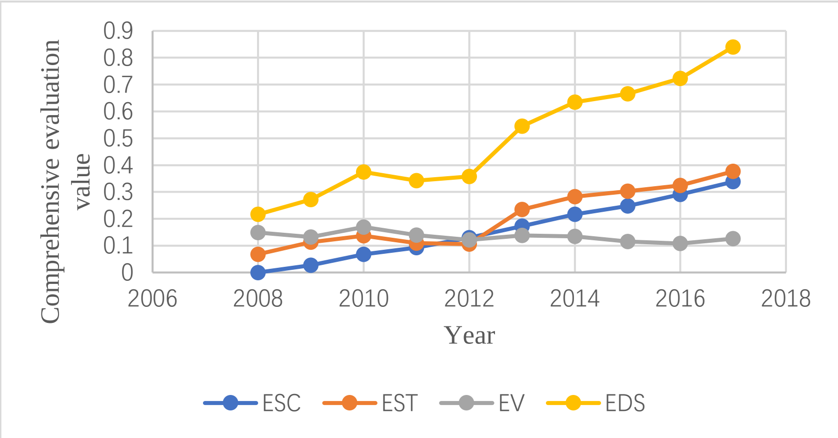

Figure 2. The temporal changes of the comprehensive evaluation values of EDS in Jinan City from 2008 to 2017.

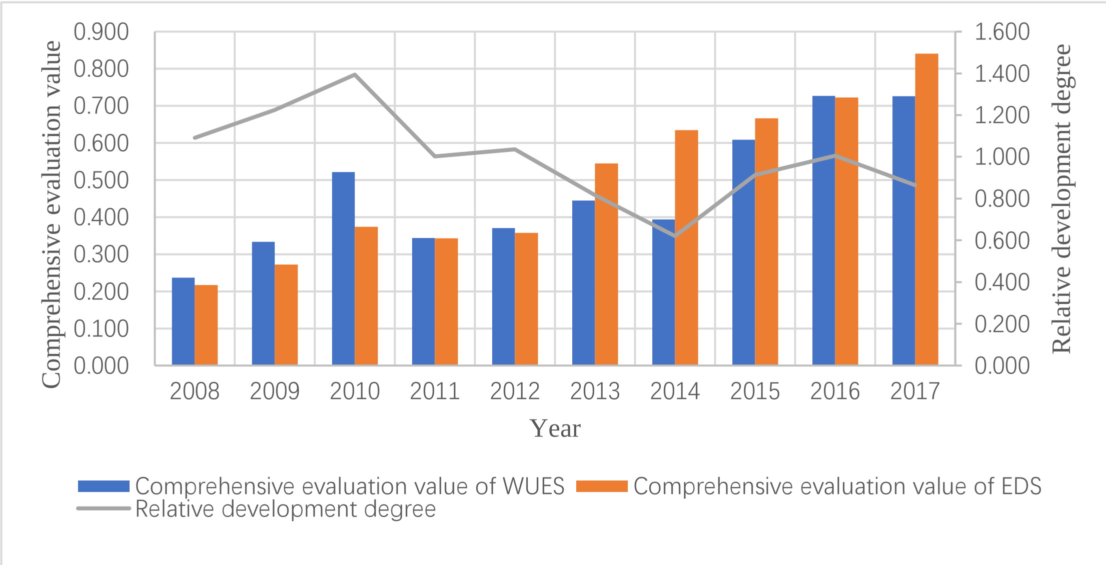

Figure 3. The temporal changes of the comprehensive evaluation values and the relative development degrees of WUES and EDS in Jinan City from 2008 to 2017.

3.1.1. Comprehensive Evaluation of WUES

As can be seen from Figure 1, from 2008 to 2017, the comprehensive evaluation values of WUES in Jinan City increased as a whole. There was an obvious decline in 2011, a slight decline in 2014 and the maximum value in 2016. In 2011, the CWUE, DWUE, PWUE and EWUE all declined, resulting in a sharp decline of WUE, with the comprehensive evaluation value of WUES dropping from 0.521 in 2010 to 0.343.The reasons might be as follows :(1) The precipitation in 2011 was significantly lower than that in 2010, which resulted in a larger proportion of agricultural water consumption. While the WUE of agriculture was lower than that of industry and ecology, which was mainly reflected in the higher water consumption per unit area for irrigation and the higher water consumption per ten thousand yuan of agricultural GDP.(2) Although the precipitation decreased, both daily domestic water consumption per capita and the proportion of domestic water consumption in total water consumption increased obviously compared with 2010.(3) Both water consumption per ten thousand yuan of GDP and integrated water consumption per capita increased significantly compared with 2010. The main reason for the slight decline in the comprehensive evaluation value of WUES in 2014 might be the decline in precipitation and the increase of daily domestic water consumption per

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capita and integrated water consumption per capita compared with 2013.The reason why the comprehensive evaluation value of WUES reached the maximum value in 2016 might be that although the comprehensive evaluation value of CWUE decreased slightly compared with that in 2015, the values of PWUE, DWUE and EWUE increased significantly compared with those in 2015.

3.1.2. Comprehensive Evaluation of EDS

As can be seen from Figure 2, from 2008 to 2017, the comprehensive evaluation values of EDS in Jinan City increased as a whole, with only a slight decline in 2011 and the maximum value in 2017.The reason for the slight decline in the comprehensive evaluation value of EDS in 2011 might be that the increase of rural Engel's Coefficient and the decrease of GDP growth rate resulted in a slight decline in the comprehensive evaluation values of EST and EV. From 2012 to 2017, the comprehensive evaluation values of EDS increased from 0.343 to 0.840, indicating that the economy developed rapidly in the past six years. The previous extensive pattern of economic development had been changed into a pattern with low energy consumption and high efficiency. Energy conservation, emissions reduction and ecological environment improvement were paid more attention to. Industrial structure was adjusted. The development of service industries, such as water conservancy environment, was speeded up. Innovative industries were constantly introduced. Although the reduction of GDP growth rate led to the slight decline of EV, both ESC and EST had a greater degree of consolidation and improvement. Particularly, ESC grew most obviously, promoting the rapid development of the economy.

3.1.3. Relative Development Degree of WUES and EDS

As can be seen from Figure 3, from 2008 to 2017, the relative development degrees of WUES and EDS in Jinan City fluctuated greatly, focusing on the range of [0.621, 1.394] and showing an up-down-up-down unstable state. In 2008, from 2011 to 2013, and from 2015 to 2017, the relative development degrees were in the range of (0.8, 1.2), indicating that WUES and EDS were in a relatively balanced, synchronized and coordinated state. From 2009 to 2010, the relative development degrees were greater than 1.2, indicating that the quality of ED was not high, the level of ED lagged behind that of WUE, and there was the problem of excessive use of water resources. In 2014, the relative development degree was less than 0.8, indicating that the level of WUE lagged behind that of ED, restricting social and economic development, and water resources are in the stage of extensive use.

3.2. Coupling Coordination Degree between WUES and EDS

The calculated results of coupling degree, coordination degree and coupling coordination degree between WUES and EDS in Jinan City from 2008 to 2017 are shown in Table 3. According to Table 3, the temporal variation diagram of coupling degree, coordination degree and coupling coordination degree between WUES and EDS is shown in Figure 4.

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Table 3. The evaluation results of coupling coordination development of WUES and EDS in Jinan City from 2008 to 2017.

Year	Coupling degree	Coordination degree	Coupling coordination degree	Coupling stage	Coupling coordination intensity
2008	0.500	0.476	0.488	Antagonistic stage	Moderately coordinated coupling
2009	0.497	0.550	0.523	Antagonistic stage	Highly coordinated coupling
2010	0.493	0.669	0.574	Antagonistic stage	Highly coordinated coupling
2011	0.500	0.586	0.541	Antagonistic stage	Highly coordinated coupling
2012	0.500	0.604	0.549	Antagonistic stage	Highly coordinated coupling
2013	0.497	0.704	0.592	Antagonistic stage	Highly coordinated coupling
2014	0.486	0.717	0.590	Antagonistic stage	Highly coordinated coupling
2015	0.499	0.798	0.632	Antagonistic stage	Highly coordinated coupling
2016	0.500	0.851	0.652	Antagonistic stage	Highly coordinated coupling
2017	0.499	0.885	0.664	Antagonistic stage	Highly coordinated coupling

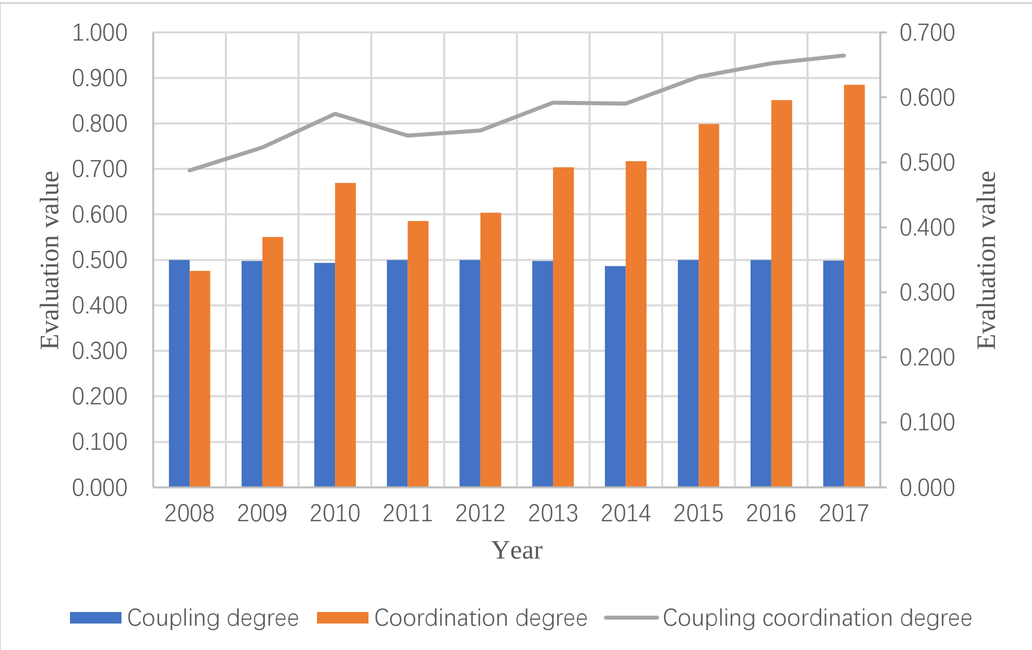

Figure 4. The temporal changes of coupling coordination degree of WUES and EDS in Jinan City from 2008 to 2017.

As can be seen from Table 3 and Figure 4, the coupling degrees between WUES and EDS in Jinan City from 2008 to 2017 were in the range of [0.486, 0.500], and the two systems were in the antagonistic stage, that is, the state of common development. The coupling degrees were close to or equal to the inflection point value of 0.5, indicating that the two systems would gradually move towards coordination and enter the running-in stage.

From 2008 to 2017, the coordination degrees between WUES and EDS in Jinan City increased on the whole, indicating that the coordination between the two systems was improving continuously. The reason for the decrease of coordination degree in 2011 might be that the level of WUE dropped sharply and that of ED dropped slightly, that is, the synergistic effect of the two systems decreased.

From 2008 to 2017, the coupling coordination degrees between WUES and EDS in Jinan City were in the range of [0.488, 0.664] with less fluctuation and overall rise. Except at the moderately coordinated coupling stage in 2008, coupling and coordination intensities from 2009 to 2017 were at the highly coordinated coupling stage, indicating that the two systems influenced each other, constantly broke-in and jointly developed.

4. Discussions

From 2008 to 2017, the comprehensive evaluation values of WUES in Jinan City increased from 0.236 to 0.726, with a very large overall improvement. In the process, it showed a changing trend of ups and downs. The reasons why the state of "low start and fast development" occurred might be: Jinan City had become one of the first ten national water-saving cities in China since 2002. The long-term water saving management mechanism construction had been highly regarded. Government-led, social participation and universal action combined, the organizational structure improved, capital investment increased, infrastructure construction strengthened and water conservation management strictly carried out, water-saving work had made remarkable achievements.

From 2008 to 2017, the comprehensive evaluation values of EDS in Jinan City increased from 0.217 to 0.840, with a great overall improvement. In the process, except for a slight decline in 2011, all the other years showed a rising trend. The reasons why the state of "low start and fast development" similar to that of WUES occurred might be: during the study period, the severe impact of the international financial crisis was overcome and the growth was achieved. Economic structure was positively adjusted. Agriculture industrialization level increased persistently. Industrial production grew steadily. The key industries continued to present a good momentum. Industrial economic benefits continued to improve.

From 2008 to 2017, the relative development degrees of WUES and EDS in Jinan City varied between 0.621 and 1.394. Only in 2014, the relative development degree was less than 0.8, indicating that the use of water resources was extensive and inefficient. From 2009 to 2010, the relative development degrees were greater than 1.2, indicating the use of water resources was excessive. In the other years, the relative development degrees were in the range of (0.8, 1.2), indicating that the water consumption structure had been improved, and the two systems had increased synchronously and promoted each other.

From 2008 to 2017, the coupling degrees between WUES and EDS in Jinan City were in the range of [0.486, 0.500]. The results showed that the coupling degrees changed slightly and the two systems were in antagonistic stage during the study period. The overall economic development degree was low, and WUE was constrained. The two systems hardly developed towards an orderly and coordinated direction. The evolution trend that the coupling degrees were very close to 0.5 indicated that the two systems would enter the running-in stage after years of binding development, and they would be in a state of benign interaction.

From 2008 to 2017, the coupling coordination degrees between WUES and EDS in Jinan City were in the range of [0.488, 0.664]. The results showed that the two systems developed from the moderately to the highly coordinated coupling during the study period. The two systems constantly broke-in under the function of restraining and promoting each other. The whole system advanced from the medium to the high level of coupling coordination relationship.

5. Conclusions

In this study, the comprehensive evaluation values and relative development degrees of WUES and EDS were calculated, and the coupling coordination degree model was used to analyze the coupling degree, coordination degree and coupling coordination degree of the two systems.

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During the study period, the comprehensive evaluation values of WUES and EDS in Jinan City were greatly improved, and showed the changing trend of ups and downs. The two systems were in the antagonistic stage, and were gradually approaching the running-in stage, indicating that the two systems were in the state of common development. The coupling coordination degrees between WUES and EDS in Jinan City increased gradually in waves. The two systems advanced from the moderately to the highly coordinated coupling. In the future, if the water control path appropriate to Jinan City can be explored actively, the water-saving kinetic energy of economic development can be increased constantly, and the linkage effect between economic development and water resources utilization can be given full play to, the two systems will be in the orbit with the benign interaction and healthy harmonious development.

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