

## Article

# Spatio-Temporal Coupling Coordination Analysis between Urbanization and Water Resource Carrying Capacity of the Provinces in the Yellow River Basin, China

Ran Qiao <sup>1,\*</sup>, Huimin Li <sup>2,3</sup>  and Han Han <sup>1</sup> <sup>1</sup> Business School, Hohai University, Nanjing 211100, China; 170212070002@hhu.edu.cn<sup>2</sup> Department of Construction Engineering and Management, North China University of Water Resources and Electric Power, Zhengzhou 450046, China; lihuimin3646@163.com<sup>3</sup> Henan Key Laboratory of Water Environment Simulation and Treatment, Zhengzhou 450045, China

\* Correspondence: qiaoran@hhu.edu.cn; Tel.: +86-138-3985-2205

**Abstract:** With the rapid expansion of the Chinese economy in recent years, the urbanization process of the provinces in the Yellow River Basin (YRB) has put serious pressure on the sustainability of the water resources carrying capacity (WRCC). It is necessary to analyze and diagnose the coordination state between urbanization and the WRCC. In this study, based on the Population-Economic-Social-Spatial (PESS) framework and Pressure-State-Response (PSR) model, we developed two index systems for the urbanization and WRCC, respectively. At the basis of the two index systems, the coupling coordination degree (CCD) of the two systems is calculated by applying the improved CCD model. Based on the calculated CCD for each province, the spatio-temporal analysis was performed to analyze the characteristics of CCD in the YRB. The obstacle factor model is utilized to obtain the main obstacle factors. The results show that: (1) the coordination state between the urbanization and WRCC systems was improved to some extent in 2017, compared to 2008, but there are differences in the coordination state of the different provinces in the YRB. (2) In terms of the level of urbanization, the gap between the seven provinces' performance levels widened because urbanization grew at different rates. The WRCC system's performance presented a fluctuating downward trend from 2008 to 2017 in the YRB. (3) The pressure subsystem had a significant impact on the two systems' coordination state in the YRB, while the social urbanization and response subsystem had a less significant impact on the urbanization system and the WRCC system, respectively. Due to the growth of urbanization, the imbalanced development of the WRCC and urbanization has become the principal contradiction that must be solved in order to achieve sustainability in the YRB. The analysis of the coupling relationship between urbanization and WRCC may guide the policy makers in planning for realistic goals. The results provide a guide for high-quality development in the YRB.

**Keywords:** water resource; urbanization; improved CCD model; coordination state; obstacle factor; Yellow River Basin



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## 1. Introduction

Water resources are considered essential elements for promotion of urban development [1]. Since the 1950s, the process of urbanization around the world has accelerated. Rapid urbanization has caused an excessive waste of water resources, water pollution, water ecological imbalance, and other environmental issues, which threatens the security of water resource system and negatively affects urbanization to some extent [2–4]. The global urban population has soared from 50 million in 1950 to 4.2 billion in 2019, accounting for 55% of the world's total population [5]. Developing countries, such as China and India, have experienced a particularly evident urbanization expansion policy [6]. Due to the limited resources and environment, the urbanization rate increased from 17% in 1951 to 35% in 2017 in India [7]. According to the China Statistical Yearbook, since the reform

and opening-up of 1978, Chinese urbanization has presented a rapid upward trend, from 17.9% in 1978 to 59.58% in 2018 [8]. It is predicted that the global urbanization rate will reach 68% in 2050 [5]. It is believed that this process will threaten the environment and resources, leading to an imbalance and depletion of water resources [9]. These problems will eventually become serious obstacles to sustainable urban development [10]. In the framework of the future earth plan and 2030 agenda for sustainable development, scholars have suggested that urbanization should be mindful of the eco-environment and emphasize that urbanization must accommodate the resources capacity [11]. In this context, the coordination and interaction between urbanization and the environment have become a useful research issue.

WRCC is the ability of water resources to support the coordinated development of the population, society, economy and environment in a region [12]. The rational way that human's use water resources makes it possible to push toward the development of the economy and society [13]. However, water resources are significantly unevenly distributed in China, where water is abundant in the south and scarce in the north. According to the research of Chinese scholars [14], cities in northern China are confronted with water problems, including less rainfall, water eutrophication and water environmental pollution, which have caused a water shortage [15]. It is noteworthy that the imbalanced development of WRCC and urbanization has become the principal contradiction that must be solved in order to achieve sustainability in the northern regions. In consideration of this, it is necessary to coordinate the relationship between urbanization and WRCC and design a scientific management framework for guiding the sustainable development of cities in the future.

The previous studies on Chinese urban development have focused on the Yangtze River economic belt region [16] and the Jing-Jin-Ji region [17] whereas the YRB region did not stand out. After the 1980s, after the rapid economic and social development of the YRB, various provinces were shown to be excessively exploiting their natural resources [18]. However, the economic gap among the provinces in the YRB is growing, so it is challenging to transform the mode of production in traditional industries [19]; the ecological environment deteriorated rapidly. These phenomena have seriously restricted the coordinated development of the economy, society, and the ecological environment [20]. The analysis of WRCC is a prerequisite for the planning of sustainable urban development; however, there is a lack of empirical studies on the relationship between WRCC and urbanization.

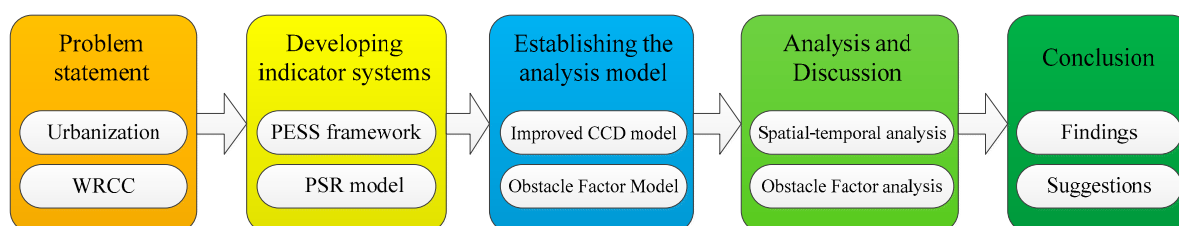
The research on the coupling relationship between urbanization and WRCC is based on the urbanization–environment perspective. Many scholars have used the Environmental Kuznets curve (EKC) hypothesis to examine the relationship between urbanization and eco-environment [21]. Grossman and Krueger proposed a curve reflecting the relationship between the economic level and environment after exploring the relationship between urban development and air pollution in North America in 1991. It is called the EKC hypothesis [22]. The EKC hypothesis reveals an inverted “U”-shape evolution law between the eco-environment and economic level [23]. Some scholars have verified the realistic relationship between economic growth and environmental pollution shown in EKC theory [24,25]. Other scholars have pointed out that the EKC curve has different shapes due to the different backgrounds of economic levels, industrial structures, and environmental protection policies in different countries [26]. In addition, the EKC theory assumes that urban development is independent upon the eco-environment, but the interaction and restriction exist among economic and social development and the eco-environment. While the EKC theory has some defects [27,28], it can still be applied to the study of urbanization development and environment [29].

In the 1970s, Haken, a famous German physicist, first proposed the concept of “coupling” [30], and elaborated it in his concept of “advanced synergetics”. Coupling reflects the interaction between two or more systems [31,32]. According to the synergetics theory, the coordination state reflects the trend of the system from disorder toward order. CCD shows the degree of mutual influence and coordination between systems in the develop-

ment process. It describes the coordination status of various elements or subsystems within a system. Because of its applicability, it has been widely applied in different disciplines, such as physics [33,34] and biology [35]. Coupling relationship between urbanization and the eco-environment presents the sum of the interactions among all the elements of the two systems [36]. In recent years, the CCD model has been used to investigate the relationship between the eco-environment and sustainable development [37]. For instance, Arike et al. [38] analyzed the relationship between urbanization and the eco-environment by taking advantage of the coupling coordination theory based on multi-source remote sensing data. Kurniawan et al. [39] utilized CCD as a tool for examining the relationship between the social-ecological status and sustainable development of small island tourism.

In the CCD model, the contribution coefficient shows the impact of the target system on the overall coordination states [40]. However, the contribution coefficients were defined subjectively in the traditional CCD model. A large number of scholars have believed that the contributions of the two systems were equal and determined the value of the contribution coefficient to be 0.5 [40–43]. However, some scholars, such as Li et al. (2012), believed that the subjectivity had negative impact on the evaluation of the coordination state [44]. Some scholars, such as He et al. [45], Shen [46], found that the value of the CCD varied significantly when the contribution coefficient was found to have subjective disparate values. It cannot show the actual relationship between urbanization and WRCC systems. Based on the synergy theory, Shen developed an improved CCD model by proposing an alternative method for defining contribution system [46]. The synergy theory reveals that the underdeveloped system should be developed to improve the coordination state of two systems [31]. The high CCD would be obtained only if the performance gap between the system is small [47]. The improved CCD model has been verified in practice [48,49]. The high performance of urbanization and WRCC systems is conducive to sustainable development [50]. Thus, the improved CCD model provides an effective way to investigate the interaction relationship between WRCC and urbanization systems.

The purpose of this paper is to explore the relationship between urbanization and the regional WRCC in the YRB. Firstly, based on the PESS framework and PSR model, we establish two index systems for the urbanization and WRCC, respectively. Secondly, at the basis of the two index systems, we investigate the coupling coordination states between urbanization and WRCC in the YRB using the improved CCD model. The spatio-temporal analysis is conducted to obtain the characteristics of the spatial gradients, temporal scales and evolution law. This analysis provides empirical support for the high-quality development of urbanization and WRCC in the YRB. Finally, the obstacle factor model enables us to ascertain and analyze the obstacle factors that restrain the coordinated development of the urbanization and WRCC and discuss the mechanism of the influence on the two-coupling system. The flow diagram of the structure is shown in Figure 1. The WRCC, a crucial factor of the urbanization process, is inextricably linked with the economic and social development in the YRB [51]. This study provides theoretical support and policy recommendations for urban development and management.



**Figure 1.** Flow diagram of the structure.

This paper's structure is as follows: the research materials and methods are shown in Section 2. The results analysis and discussion, including trend analysis, spatial-temporal

characteristics analysis, and obstacle analysis are provided in Section 3. In Section 4, the conclusions and suggestions are provided.

## 2. Materials and Methods

### 2.1. Study Area and Data

The YRB is located in Northern China. As the second-longest river in China, the Yellow River is regarded as the birthplace of Chinese culture and the mother river of the Chinese people. The YRB's spatial scope is Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong provinces. In 2018, the YRB population was 420 million and the average level of urbanization was approximately 40.0%, which is below the national average. The gross domestic product (GDP) of the YRB is 2.39 trillion Yuan. The annual growth rate is as high as 14.1% [52]. With the rapid development of the economy and the acceleration of urbanization, the balance between urbanization development and WRCC has been broken, leading to the deterioration of the environment. The primary statistics for each province in the study area are shown in Table 1.

**Table 1.** The primary statistics for each province in 2018.

Province	Population (10 <sup>4</sup> Person)	Water Resource Amount (10 <sup>8</sup> m <sup>3</sup> )	GDP (10 <sup>12</sup> Yuan)	Non-Agricultural Population Rate (%)	Water Consumption Amount (10 <sup>8</sup> m <sup>3</sup> )
Shandong	10,047	343.3	7.65	61.18	212.7
Henan	9605	339.8	4.81	51.71	234.6
Shanxi	3718	121.9	1.68	58.41	74.3
Shaanxi	3864	371.4	2.44	58.13	93.7
Mongolia	2534	461.5	1.73	62.71	192.1
Ningxia	688	14.7	0.37	58.88	66.2
Gansu	2637	333.3	0.82	47.69	112.3

However, according to the State Council's guiding opinions on promoting the development of the Yangtze River Economic Belt, Sichuan Province, which relies on the golden waterway (GF [2014] No. 39), has been integrated into the major national strategy of the Yangtze River economic belt. The Yellow River only flows through Aba Autonomous Prefecture and Ganzi Tibetan Autonomous Prefecture in Sichuan Province. The Autonomous Prefecture population and total economic volume account for 0.7% and 0.3% of the YRB. Qinghai Province is in the western part of China, and the economic and social development level of the two provinces is relatively low. The impact of these two provinces on the economic and social development pattern of the YRB is weak. Based on the above considerations, the YRB includes Gansu, Ningxia, Inner Mongolia (except the eastern region), Shanxi, Shaanxi, Henan, and Shandong, as shown in Figure 2.

### 2.2. Index System and Weights

To accurately explore the coupling relationship between urbanization and WRCC in the YRB, it is essential to establish an indicator system for urbanization and WRCC. The population–economic–social–spatial (PESS) framework and pressure–state–response (PSR) model provides the urbanization indicator system and the WRCC indicator system with a fundamental basis. There are four general and primary principles used to determine indicators: (a) Choose the most appropriate and typical indicators; (b) select comprehensive indicators to reflect the components of urbanization and WRCC; (c) pick the indicator with quantifiable panel data; (d) ensure that the indicators are in line with the urbanization policies or ecosystem reports issued by the Chinese government, such as the National New Urbanization Report [53] and, the Water Pollution Prevention Action Plan [54]. The framework of the method is shown in Figure 3.

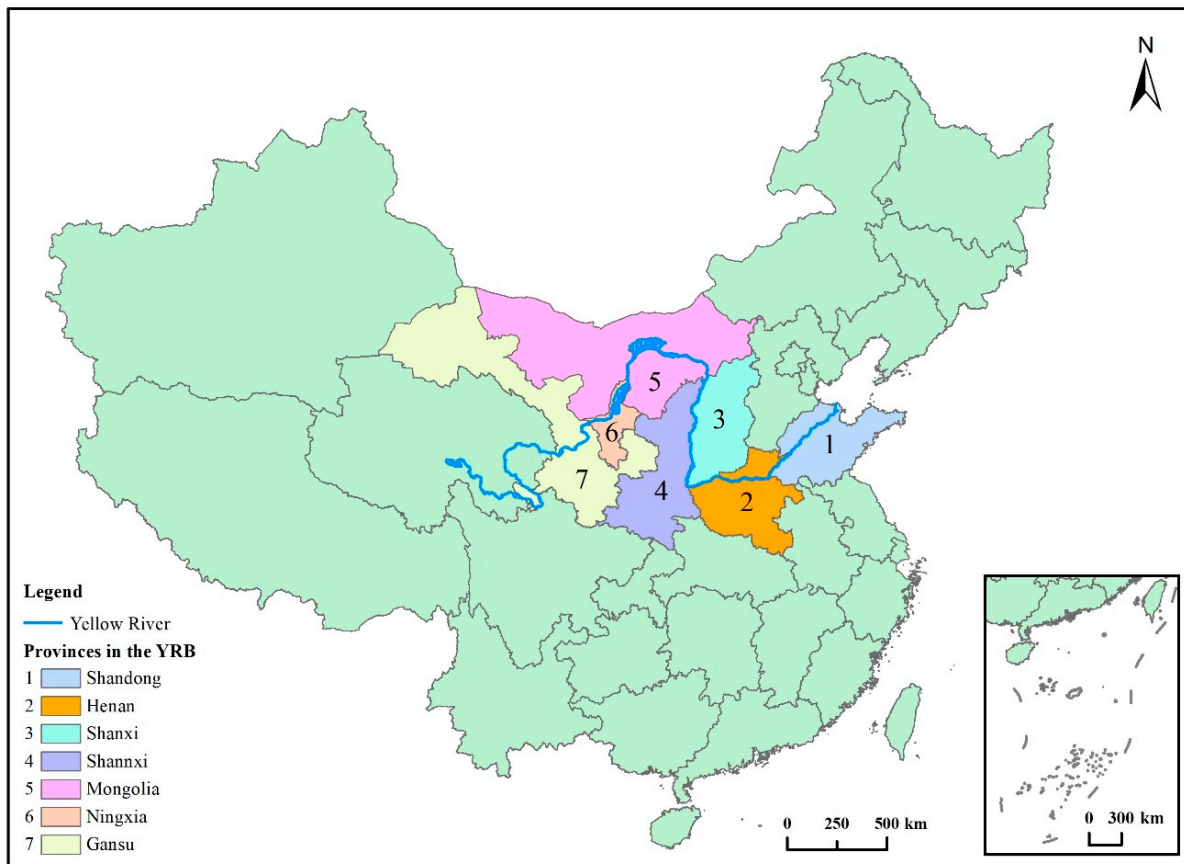


Figure 2. Provinces in the YRB.

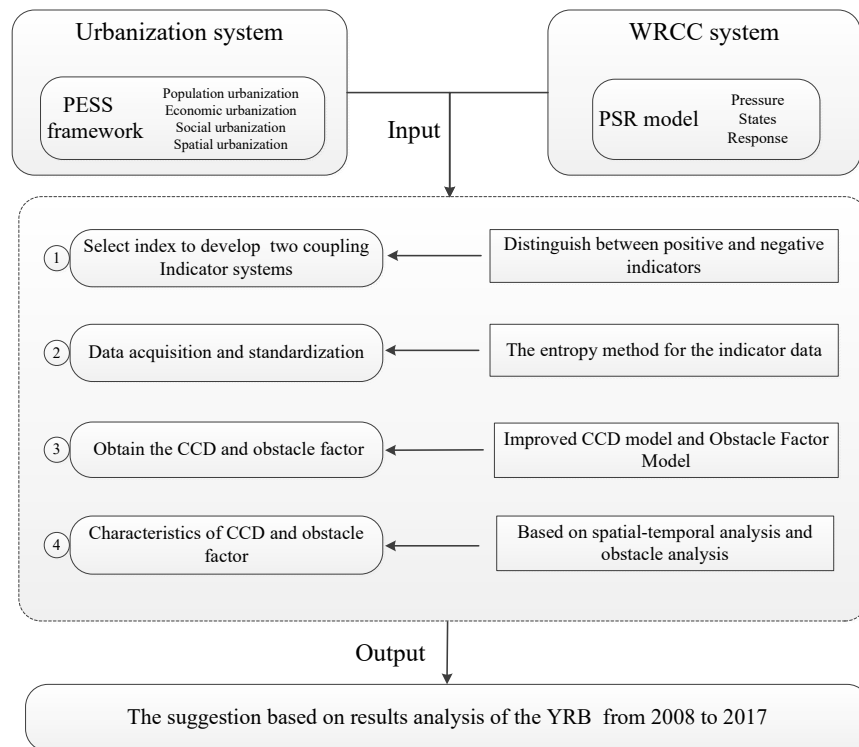


Figure 3. The framework of the method proposed in this study.



### 2.2.1. PESS Framework

The PESS framework is composed of four dimensions/subsystems, namely population, economy, society, and space. It was adopted to evaluate the performance level of urbanization [55]. Urbanization has a significant impact on the development of human beings in terms of their social, political, and economic life [56]. Urbanization is a complex and changeable process influenced by various factors, including politics, economy, resources, the population, the industrial structure, and other multi-dimensional factors [57]. Since the advent of the urbanization evaluation model in China, there have been many discussions on different dimensions of its applicability [58–61]. The PESS framework, covering economic, social, and spatial urbanization, was constructed to evaluate Chinese urbanization development [17]. In our study area, urbanization is controlled by regional development and the environment in the YRB [62]. After considering both factors, 14 indicators of urbanization corresponding to the four aspects were selected, as shown in Table 2.

**Table 2.** Index system for urbanization.

Subsystem	Secondary Indicators	Unit	Direction <sup>1</sup>
Population urbanization	X1 nonagricultural population rate	%	+
	X3 Population growth rate	%	+
	X2 Urban population density	Person/km <sup>2</sup>	-
Economic urbanization	X4 GDP per capita	Yuan	+
	X5 Per Capita Disposable Income	Yuan	+
	X6 Proportion of tertiary industries to GDP	%	+
	X7 Per capita investment in fixed assets	10 <sup>4</sup> Yuan	+
Social urbanization	X8 Per capita education funds	10 <sup>4</sup> Yuan	+
	X9 Beds in health care industry per 10 <sup>4</sup> people	Bed	+
	X10 Number of public transportation vehicles	Vehicle	+
	X11 Number of college students	Person	+
Spatial urbanization	X12 Urban road area per capita	km <sup>2</sup> /person	+
	X13 Proportion of built-up areas in total areas	%	+
	X14 Park green area per capita	m <sup>2</sup> /person	+

<sup>1</sup> Direction represents the positive or negative impact of the indicators on the system.

### 2.2.2. PSR Model

The PSR model consists of three subsystems: the pressure, state, and response. It is regarded as a scientific framework for assessing WRCC. The PSR model was first proposed by the Organization for Economic Cooperation and Development (OECD) (1993), located in Paris, and was designed to analyze the relationship between human activities and the natural environment [63,64]. As shown in Figure 4, the PSR model has been widely utilized in the field of environmental assessment, water resource security, and other ecological research. The studies by Pissourios (2013) [65], Das et al. (2020) [66], and Dong et al. (2018) [67] are some examples. The PSR model reflects the system's characteristics in terms of pressure, state, and response in a cycling mechanism (see Figure 4). As for the three subsystems, the pressure subsystem reflects the load imposed by the development of urbanization on WRCC; the state subsystem illustrates the situation of WRCC under pressure [68]; and the response subsystem indicates the result of a series of government adjustments in policies and protective measures [69]. Based on the PSR model and existing relevant research, we chose 14 indicators to define the index system of the WRCC, as shown in Table 3.

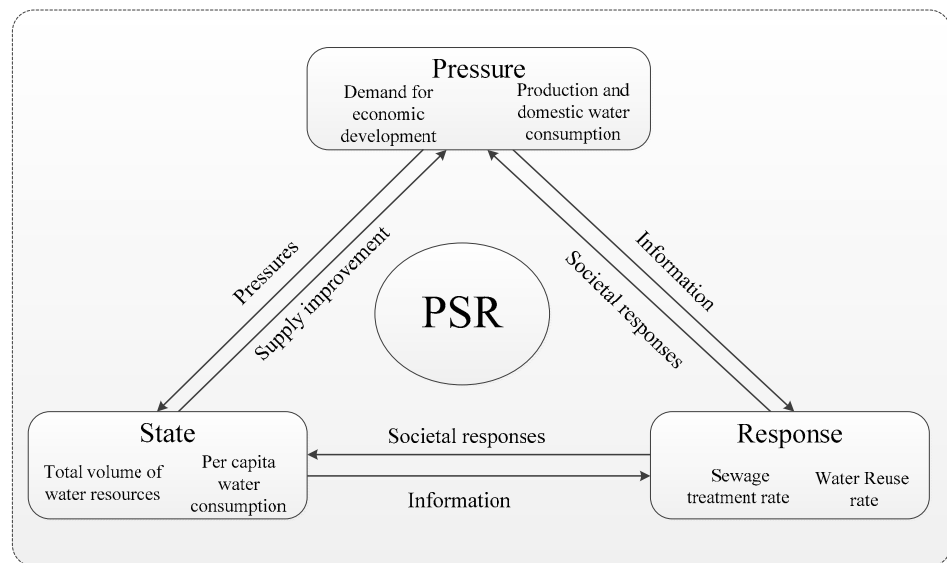


Figure 4. The relationship between different states in the PSR model.

Table 3. Index system for the WRCC.

Subsystem	Secondary Indicators	Unit	Direction <sup>1</sup>
Pressure	Y1 Water consumption per unit of GDP	10 <sup>8</sup> m <sup>3</sup>	-
	Y2 Water consumption of agricultural irrigation	10 <sup>8</sup> m <sup>3</sup>	-
	Y3 Water consumption of industrial output	10 <sup>8</sup> m <sup>3</sup>	-
	Y4 Household water consumption	10 <sup>8</sup> m <sup>3</sup>	-
	Y5 Urban sewage discharge	10 <sup>8</sup> m <sup>3</sup>	-
	Y6 Annual precipitation	mm	+
State	Y7 Total volume of water resources	10 <sup>8</sup> m <sup>3</sup>	+
	Y8 Per capita water occupancy volume	m <sup>3</sup>	+
	Y9 Per capita water consumption	m <sup>3</sup>	+
	Y10 Water production coefficient	%	+
Response	Y11 Industrial water pollution control investment	10 <sup>4</sup> Yuan	+
	Y12 Urban sewage treatment rate	%	+
	Y13 Urban water reuse rate	%	+
	Y14 Urban water supply rate	%	+

<sup>1</sup> Direction represents the positive or negative impact of the indicators on the system.

### 2.3. Data Sources and Preprocessing

The annual WRCC and urbanization data of the Provinces in the YRB were derived from the China Statistical Yearbook (2008–2017) [70], the China Urban Statistical Yearbook (2008–2017) [71], and the China Water Resources Bulletin (2008–2017) [72]. The average annual growth rate determines the valuation for individual missing values. Considering that the index system includes both positive and negative indicators, these two types of indicators have different impact on performance levels. The data are standardized through Formulas (1) and (2) to eliminate the dimension’s influences, magnitude, positive and negative orientations:

$$r_{ij} = \frac{x_{ij} - \min(x_{ij})_j}{\max(x_{ij})_j - \min(x_{ij})_j} \tag{1}$$

$$r_{ij} = \frac{\max(x_{ij})_j - x_{ij}}{\max(x_{ij})_j - \min(x_{ij})_j} \tag{2}$$

where  $x_{ij}$  is the original data of the indicators in the  $j$ -th year,  $\min(x_{ij})_j$  and  $\max(x_{ij})_j$

represents the minimum and maximum values of all indicators, respectively, and  $r_{ij}$  is the standardized value of  $x_{ij}$ ,  $i \in [1, m], j \in [1, n]$ .

2.4. The Improved CCD Model

The entropy method is used in the determination of index weight. The process of the entropy method in calculating the index weight of the urbanization system and the WRCC system is as follows:

$$f_{ij} = r_{ij} / \sum_{i=1}^m r_{ij} \tag{3}$$

$$H_j = -\frac{1}{\ln m} \sum_{i=1}^m f_{ij} \ln f_{ij}, j \in [1, n] \tag{4}$$

$$w_j = \frac{1 - H_j}{n - \sum_{j=1}^n H_j} \tag{5}$$

where  $f_{ij}$  represents the proportion of the value  $r_{ij}$  in the line  $r_j$ ,  $H_j$  is the information entropy value of the target  $i$  in the index  $j$ ,  $w_j$  is the entropy weight.

The evaluation model of performance level is as follows:

$$E_1 = \sum_{i=1}^k w_i^{S_1} \cdot r_{ij}^{E_1} \tag{6}$$

$$E_2 = \sum_{i=1}^t w_i^{E_2} \cdot r_{ij}^{E_2} \tag{7}$$

where  $E_1$  and  $E_2$  stands for the comprehensive evaluation level of the urbanization index system and WRCC system, respectively.  $w_i^{S_1}$  and  $w_i^{E_2}$  denote the weight of the WRCC and urbanization indicators, respectively.  $r_{ij}^{E_2}$ ,  $r_{ij}^{E_1}$   $k$  and  $t$  represent the normalized value, the number of indicators in the WRCC system and the urbanization index system, respectively.

The improved CCD model can be described as follows:




$$C = \left\{ \frac{E_1 \cdot E_2}{[(E_1 + E_2)/2]^2} \right\}^{1/p} \tag{8}$$

$$T = \alpha E_1 + \beta E_2 \tag{9}$$

$$D = \sqrt{C \times T} \tag{10}$$

where  $C$  denotes the coupling level between the WRCC and urbanization index system  $C \in [0, 1]$ .  $p$  is the adjustment coefficient, which is generally  $p \geq 2$ . Considering the WRCC and urbanization,  $p$  is taken as 2 in this study.  $T$  denotes the comprehensive coordination index, representing the coordination state's overall performance level for the two systems.  $\alpha$  and  $\beta$  are the contribution coefficients, representing the contribution of urbanization and the WRCC to the coordination state.  $D$  stands for the CCD between urbanization and the WRCC. The classification standard is shown in Table 4.

**Table 4.** Classification standard and the types of CCD.

Coordination State	Coupling Level	D Value	Corresponding Color
Serious imbalance	Low coupling	$D \leq 0.25$	
Imbalance	Antagonism stage	$0.25 < D \leq 0.45$	
Basic coordination	Running-in stage	$0.45 < D \leq 0.65$	
Coordination	Coupling stage	$0.65 < D \leq 0.75$	
Good coordination	Highly coupling	$0.75 < D \leq 1$	

Based on the synergy theory, it is necessary to develop underdeveloped systems to improve the coupling level of two system. The contribution coefficients of the underdevel-



oped system should be defined at a higher value. The contribution coefficients are given in the following formulas:

$$\alpha^* = E_2 / (E_1 + E_2) \quad (11)$$

$$\beta^* = E_1 / (E_1 + E_2) \quad (12)$$

where  $\alpha^*$  and  $\beta^*$  represent the contribution coefficients of the urbanization system and the WRCC system, respectively.

### 2.5. Obstacle Factor Model

The purpose of the obstacle factor model is to analyze and diagnose the main obstacle factors that affect the coordinated development of the WRCC and urbanization. On the basis of the obstacle analysis, the government can formulate and adjust the urbanization development and ecological environment protection policies in a targeted manner. The obstacle degree model is described as follows:

$$Q_i = I_i \cdot w_i / \sum_{i=1}^m I_i \cdot w_i, \quad I_i = 1 - r_{ij} \quad (13)$$

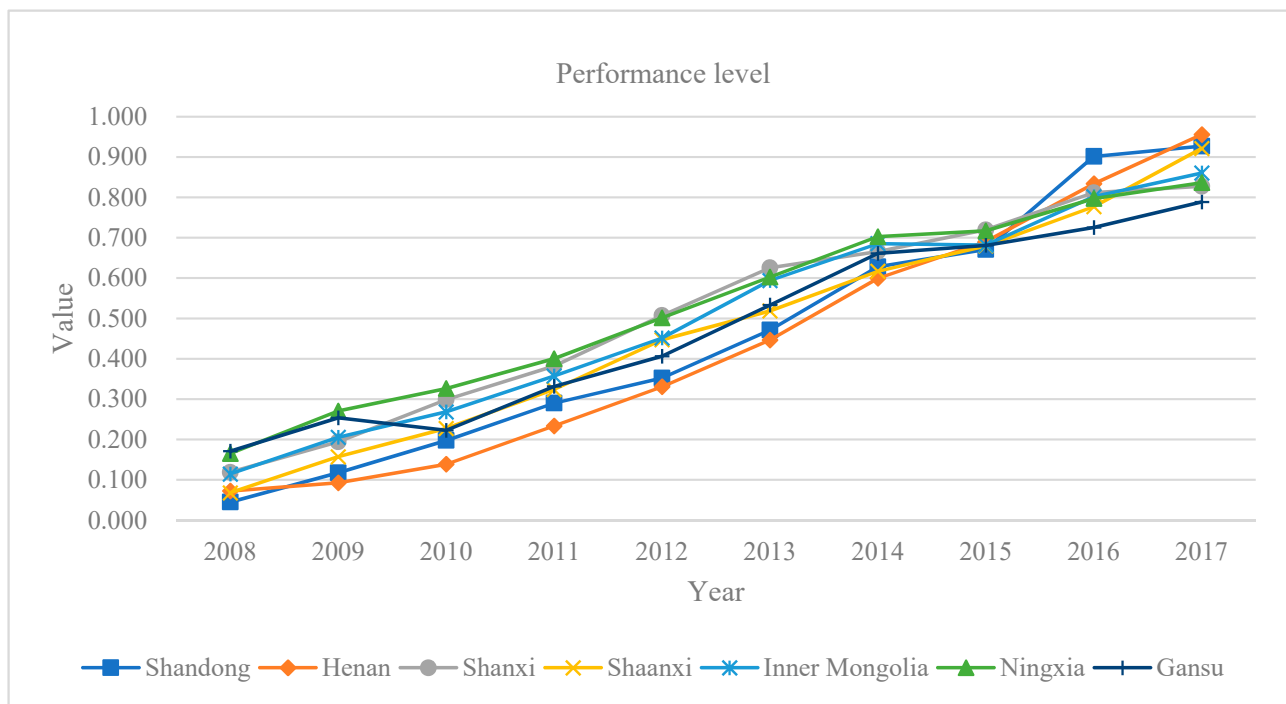
$$O_i = \sum Q_i \quad (14)$$

where  $r_{ij}$  represents the normalized value of indicator.  $I_i$  is the index deviation, which represents the gap of each index between the actual value and the optimal value.  $Q_i$  is the obstacle degree, which reflects the influence of indicators  $i$  on the CCD of urbanization and WRCC system, and  $O_i$  is the obstacle degree for the subsystem in the urbanization and WRCC systems.

## 3. Results Analysis and Discussion

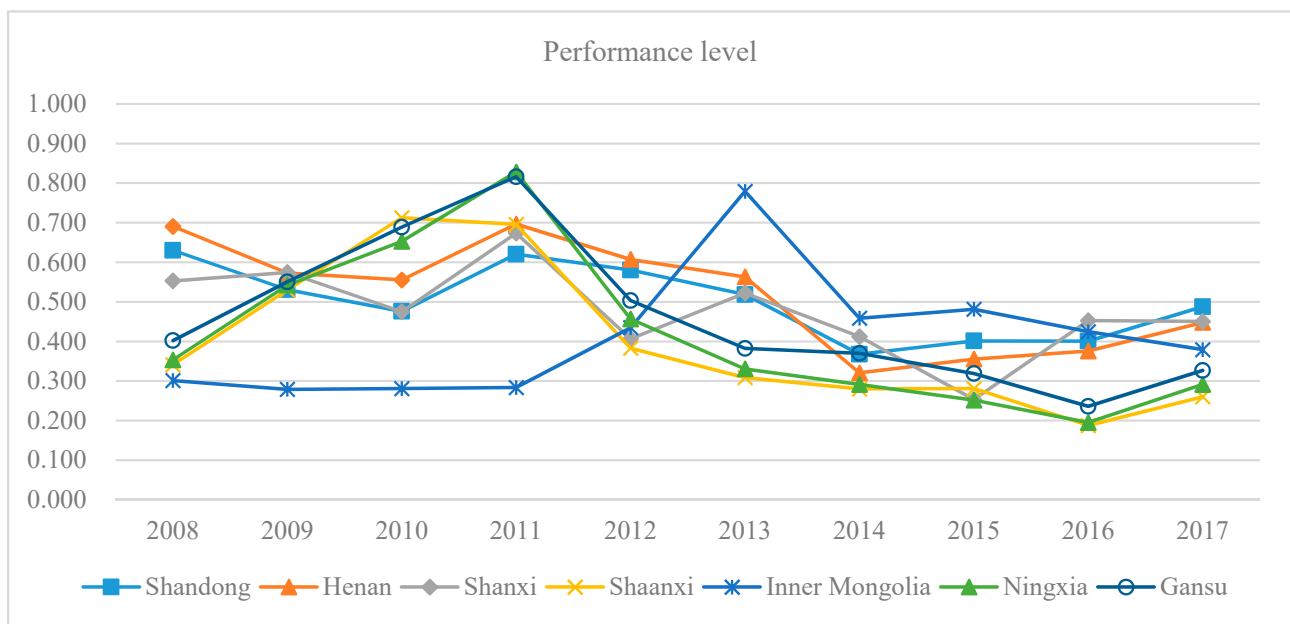
### 3.1. Trend Analysis of Urbanization and WRCC

The comprehensive evaluation value of the urbanization index system  $E_1$  could be determined by Equation (6). Figure 5 displays the  $E_1$  performance level of seven provinces in the YRB from 2008 to 2017. As shown in Figure 5, during 2008–2017, the overall trend of the seven provinces' urbanization level's was an increasing one, except for that of Gansu Province, which experienced a slight decline in 2010. The reason for decline in Gansu was that the population growth rate was the lowest in the period 2008–2017. The decline in the population growth rate had a negative impact on the population urbanization [73]. In addition, the scale reduction of the tertiary industry in Gansu is also an important reason [74]. The seven provinces' urbanization performance values were the lowest—the highest values occurred in 2017. This indicates that the urbanization level of the seven provinces in the YRB has achieved varying degrees of development. Henan province experienced the highest growth trend, rising from 0.072 in 2008 to 0.956, with the highest in 2017. Secondly, Shandong province also experienced significant growth, increasing from its lowest point of 0.045 and reaching 0.927 in the past ten years. By contrast, Gansu province had the slowest urbanization development from 2008 to 2017. It is noteworthy that the performance level of the seven provinces showed a stable trend in 2015, especially Inner Mongolia. The reasons for the slow urbanization rate of Inner Mongolia in 2015 were the decrease in population growth rate. Since the Paris Climate Agreement of 2015, China has promoted economic transition to reduce carbon emissions. In the seven provinces with high carbon emissions, economic transition may have a negative impact on urbanization of seven provinces [75]. Overall, the seven provinces maintained a low urbanization performance level in 2008 and then maintained a continuous upward trend from 2008 to 2017.



**Figure 5.** The seven provinces' urbanization performance trend in the YRB from 2008 to 2017.

Applying Equation (7) to deal with the dates of the seven provinces in the YRB, we can obtain the performance levels of the WRCC systems  $E_2$  during the decade from 2008 to 2017. Figure 6 shows the water resource performance trend of different provinces in the YRB, to be an irregular spindle shape. On the ends of the fusiform, these two provinces, Henan province and Inner Mongolia, had the highest and lowest performance levels in 2008; on the other ends, Shandong province was at the top, and Shaanxi province was at the bottom in 2017. However, these provinces have undergone a drop in their performance values, before prominently increasing from 2008 to 2011. The performance level of the seven provinces' water resources decreased gradually from 2011 to 2017, except that of Inner Mongolia, which declined from 2013. In 2011, the precipitation of these seven provinces (except Inner Mongolia) reached or approached the maximum. The water resources amount increased, but the water consumption was less than that in 2012–2017. Therefore, the WRCC performance reached the highest level in 2011. In 2013, the performance of Inner Mongolia suddenly rose to the peak because of the increase in precipitation. In addition, the water resources amount and water production coefficient of Inner Mongolia in 2013 were higher than in other years. Increase in precipitation improve WRCC [76]. The rise of Shandong, Henan and Shanxi from 2015 to 2017 was likely due to the operation of water transfer projects, such as the South-to-North Water Transfer Project. These water transfer projects alleviate the pressure of WRCC in northern China [77]. While the WRCC performance level of the seven provinces in the YRB show various fluctuation trends, they followed a gradual downward trend in the past decade from 2008–2017.



**Figure 6.** The water resource performance trend of the seven provinces in YRB from 2008 to 2017.

### 3.2. The Spatial Characteristics Analysis Based on CCD

By applying an improved CCD model to calculate the data from the seven provinces in the YRB, we obtain the value for the period from 2008 to 2017. According to the five intervals for the coupling level and coordination state, shown in Table 3, the  $D$  values of the seven provinces are divided into different states. Then, the spatial distribution characteristics of the coordination state between urbanization and WRCC from 2008 to 2017 were visualized using ArcGIS software. The spatial distribution of the coordination state between urbanization and WRCC in the provinces in the YREB is shown in Figure 7. In 2008, Shandong Province was in a severely imbalanced state, which was the worst state; five provinces (Henan, Shanxi, Shaanxi, and Inner Mongolia) were in an unbalanced state; and Ningxia and Gansu reached the state of basic coordination. Considering the regional spatial distribution, we found that the upstream region is better than the downstream region in terms of the coordination state. In 2011, five provinces were in the basic coordination state, and the remaining two provinces (Ningxia and Shanxi) entered the coordination state. At this time, the coupling coordination level of each province improved to varying degrees. In 2014, four provinces (Shandong, Shanxi, Inner Mongolia, and Gansu) were in the coordinated state, and the rest remained in a state of basic coordination. In 2017, Shandong was in the good coordination state. Henan, Shanxi, and Inner Mongolia were in the coordinated state and close to the good coordination state, whereas the other three provinces' coordination level declined and fell into the basic coordination state. Considering the spatial distribution, the YRB's western region is lower than the eastern region in terms of the coordination state.

### 3.3. The Temporal Characteristics Analysis Based on CCD

According to the interval color requirement of the  $D$  value in Table 3, Figure 8 was obtained. In Figure 8, by considering the changes of the CCD of the seven provinces with time in Figure 7, combined with the performance trend of the urbanization and WRCC system, we divide the decade from 2008 to 2017 into three periods, namely 2008–2011, 2011–2014, and 2014–2017, in order to conveniently analyze the temporal characteristics of the seven provinces in the YRB.

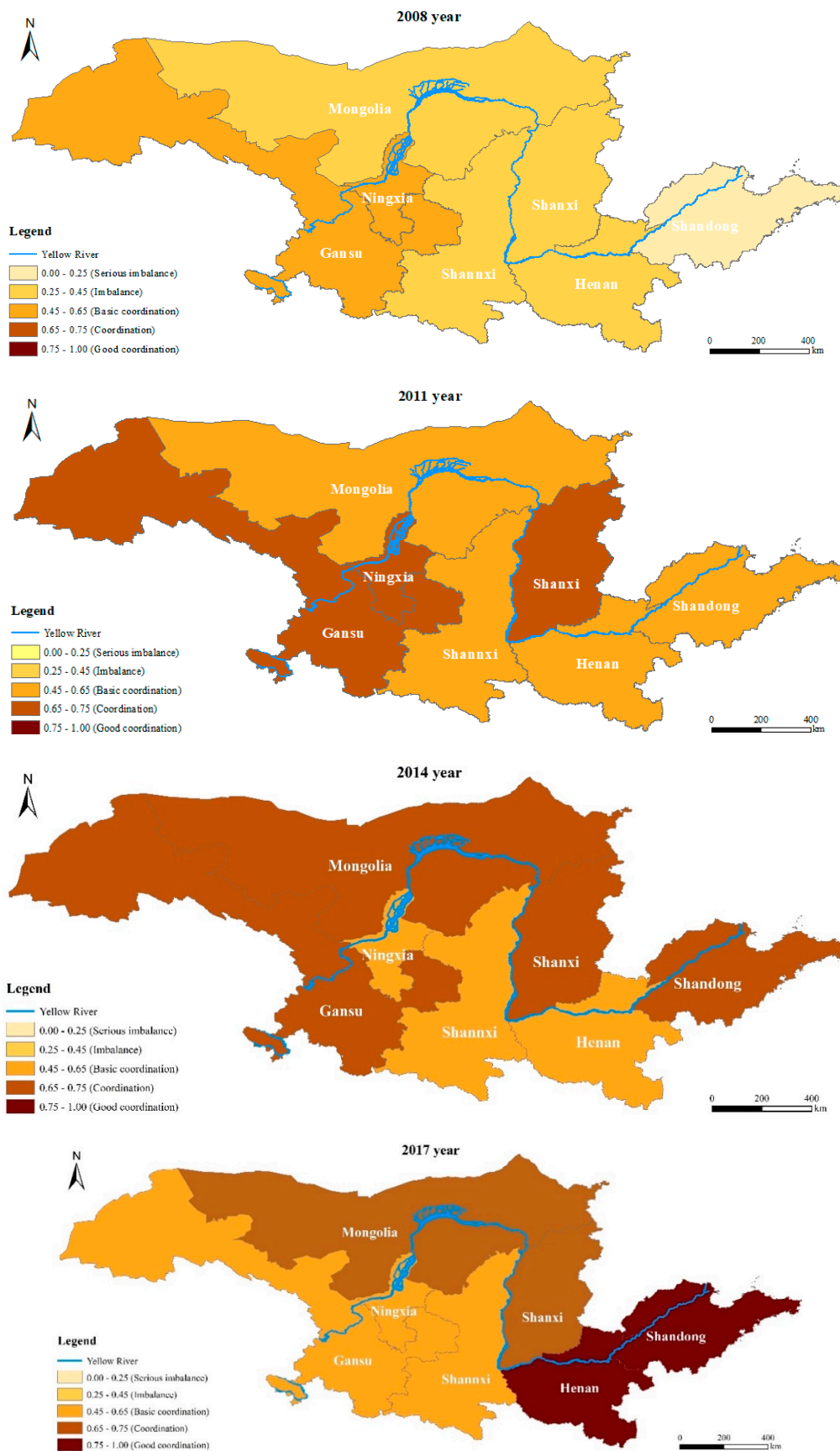


Figure 7. Spatial distribution of coordination state in provinces in the YRB.

D value	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Shandong	0.20	0.39	0.50	0.61	0.65	0.70	0.67	0.70	0.72	0.78
Henan	0.28	0.33	0.42	0.55	0.64	0.70	0.63	0.67	0.69	0.76
Shanxi	0.39	0.50	0.60	0.68	0.67	0.75	0.70	0.57	0.75	0.75
Shaanxi	0.29	0.45	0.54	0.64	0.64	0.61	0.60	0.60	0.49	0.58
Mongolia	0.38	0.48	0.52	0.56	0.67	0.82	0.73	0.75	0.73	0.70
Ningxia	0.46	0.58	0.64	0.71	0.69	0.64	0.61	0.57	0.50	0.61
Gansu	0.47	0.57	0.54	0.65	0.67	0.66	0.67	0.64	0.55	0.65
	Lowest								Highest	

Figure 8. Variation tendency of the coordination state in the YRB from 2008 to 2017.

- (1) From 2008 to 2011: The coordination state of urbanization and WRCC system was in an imbalanced state or even worse. Nevertheless, the situation would be improved in the next three years. In 2008, the lowest performance level of the urbanization system and the quality of the WRCC varied considerably, causing the gap between the *D* value of the seven provinces. From 2009 to 2011, in the rapidly changing urbanization process, the WRCC was adequate to satisfy the requirement of urbanization development. The coordination state of the two systems then began to be significantly improved; each province's CCD achieved the state of basic coordination or coordination.
- (2) From 2011 to 2014: The CCD of the seven provinces were in or close to the coordination state. The coordination state of seven provinces remained in the same state from 2011 to 2014, including Shanxi, Shanxi, and Gansu. For example, the other provinces' coordination state (e.g., Henan and Inner Mongolia) experienced continued improvement from 2011–2013 but declined in 2014. Overall, the connection between the two investigated systems was gradually strengthened, and the coordination state started to be slowly improved.
- (3) From 2014 to 2017: During this period, the CCD remained in a relatively stable state, except for the constant improvement of coordination in some areas. Since 2014, the Chinese Government has tried to protect the resource and environment to the best of its ability and adopted a series of resource and environmental protection measures, such as sponge-city construction, sewage treatment plant alterations, and rainwater and sewage diversion, in order to improve the WRCC. To a certain extent, these situations made it possible to ensure the two systems' coordinated development. It was virtually impossible to synchronize the development of the urbanization and WRCC due to the shortage of water resources in the YRB. This problem resulted in the failure of the two systems to achieve high-quality development and maintain a state of good coordination. After the operation of the south-to-north water diversion project in 2014, Henan and Shandong experienced an improved WRCC. The coordination state of the two provinces was in or close to a good coordination state. Undeniably, the seven provinces' coordination state was on a different level in 2017; some provinces will need continuous improvements in the future.

### 3.4. Obstacle Factor Analysis of the Urbanization System and the WRCC System

According to the available data, the two systems' sub-system obstacle value is calculated by Equations (13) and (14), in the same way as the obstacle value of indicators. The diagnoses and analysis of the obstacle factors were performed in a particular sequence of the value. For the sake of convenience, the top five obstacle factors were determined, listed, and analyzed according to the size of the obstacle value. The results are shown in Tables 5 and 6.

**Table 5.** Subsystem obstacle degree of the urbanization and WRCC.

System	Urbanization				WRCC		
Subsystem	Population Urbanization	Economic Urbanization	Social Urbanization	Spatial Urbanization	Pressure	State	Response
Shandong	0.411	0.214	0.261	0.113	0.560	0.189	0.250
Henan	0.200	0.275	0.232	0.293	0.411	0.385	0.204
Shanxi	0.258	0.353	0.200	0.189	0.507	0.261	0.232
Shaanxi	0.328	0.228	0.188	0.256	0.378	0.267	0.355
Mongolia	0.228	0.325	0.259	0.188	0.366	0.547	0.087
Ningxia	0.395	0.252	0.243	0.110	0.438	0.333	0.229
Gansu	0.363	0.252	0.198	0.187	0.445	0.274	0.281

**Table 6.** Obstacle degree of Indicators in urbanization and WRCC.

System	Order	Shandong	Henan	Shanxi	Shaanxi	Inner Mongolia	Ningxia	Gansu
Urbanization	1	X2	X2	X3	X13	X3	X3	X13
	2	X3	X13	X6	X2	X6	X5	X14
	3	X10	X6	X7	X3	X10	X8	X6
	4	X1	X10	X12	X9	X5	X2	X9
	5	X11	X14	X13	X5	X13	X1	X5
Water Resource	1	Y1	Y10	Y11	Y14	Y10	Y11	Y1
	2	Y2	Y1	Y1	Y2	Y3	Y3	Y11
	3	Y11	Y7	Y3	Y11	Y7	Y8	Y5
	4	Y5	Y5	Y8	Y9	Y8	Y1	Y4
	5	Y13	Y8	Y7	Y3	Y9	Y7	Y12

### 3.4.1. Subsystem Obstacle Factors

Considering the subsystem obstacle value listed in Table 5, the main factors restricting the two systems’ coordinated development in the seven provinces in the YRB are discovered. There are some differences in the obstacle degree of the four subsystems in relation to the urbanization performance between the seven provinces’ urbanization system. From the specific value, it can be seen that the population urbanization subsystem is the maximum obstacle degree in Shandong, Shaanxi, Ningxia, and Gansu; in Shanxi and Inner Mongolia, the Economic Urbanization subsystem, as the greatest obstacle, is restricting the coordination between the urbanization and WRCC system, whereas it is transformed into a spatial urbanization subsystem in Henan. By contrast, the spatial urbanization subsystem has become the lowest obstacle in the seven provinces except for Henan. This finding indicates that there are almost as many major or least important subsystem obstacles as there are provinces; it is necessary to choose a suitable strategy according to the specific situation. In the WRCC system, the pressure subsystem is the most critical obstacle factor in the seven provinces (except Inner Mongolia), whereas the least obstacle is different for the seven provinces. In general, the pressure system is the most important factor restricting the two systems’ coordination, and more attention should therefore be devoted to it.

### 3.4.2. Obstacle Factors of Index

As shown in Table 6, the top five indicators are mainly distributed in population urbanization, economic urbanization, and spatial urbanization. The indicators of X<sub>3</sub> (Urban population density) and X<sub>13</sub> (Proportion of built-up areas to urban areas) occur with the highest frequency, while the indicators of X<sub>2</sub> (Population growth rate), X<sub>5</sub> (Per Capita Disposable Income), and X<sub>6</sub> (Proportion of the contributions of tertiary industries to GDP) appears with the second-highest frequency. The main five indexes of the seven provinces (except Shandong) contain at least three of these indicators, which is in agreement with obstacle analysis of the seven provinces. While there is a distinction in terms of the obstacle indicators between the different provinces, the five indicators significantly impact the urbanization system. This means that the population scale, economic level, and urbanization area of northern China cannot meet coordinated development requirements of the two systems. In the WRCC system, the indicators with the highest frequency belong



to the pressure and state subsystems, such as  $Y_1$  (Water consumption per unit of GDP),  $Y_3$  (Water consumption of industrial output),  $Y_7$  (Total volume of water resources),  $Y_8$  (Per capita water occupancy volume) and  $Y_{11}$  (Industrial water pollution control investment). The top five obstacle factors of all provinces (except Shandong and Shaanxi) contain at least four indicators from the pressure and state subsystem. These indicators are regarded as the most important factors affect WRCC, which was verified in the subsystem obstacle analysis.

### 3.5. Discussion

Due to the limitation of contribution coefficient ( $\alpha$  and  $\beta$ ), which is subjectively defined, the traditional CCD model provides an unreliable evaluation result of regarding the coordination between the urbanization system and the WRCC system is inappropriate in the traditional CCD model. An inaccurate assessment will mislead the government to initiate policies that contribute little to high-quality development. In addition, the evaluation results of the traditional CCD model cannot effectively compare the D values among provinces [78]. If the value of the contribution coefficient ( $\alpha$  and  $\beta$ ) is given, the size of  $\alpha$  and  $\beta$  will affect the value of D, so it is impossible to make an effective comparison. In this respect, the improved CCD model provides an effective and feasible method to achieve the research objective.

The historical data collected and analyzed by the improved CCD model in this study present the coordination relationship between the urbanization and WRCC systems of the provinces in the YRB. The performance curve of the urbanization and WRCC systems from 2008 to 2017 shows that the urbanization performance level experienced a rapidly rising process in the YRB. China's economy was developing rapidly from 2008 to 2017. The economic growth can facilitate the rapid urbanization in the YRB. Moreover, the seven province's urbanization level trends began to converge in 2015, but the gap widened in 2017. The reason for this phenomenon is that the economic level of the seven provinces grew at different rates. The performance of the WRCC system presented a fluctuating downward trend, especially in Henan and Shandong. Overall, the urbanization system's performance developed rapidly, without the simultaneous improvement in the WRCC system, from 2008 to 2017. This means that the development of urbanization had a seriously negative effect on the resources and environment to a certain extent. Omer et al. [79] also supports this view. The local government should pay more attention to the conservation and protection of the environment.

Based on the CCD, we analyzed the spatial-temporal characteristics and evolution regularities of the YRB's coordination state. For the spatial-temporal dimension, the coordination state's tendency in the western region of the YRB, such as Gansu, Ningxia, and Inner Mongolia, presents an inverted U-shape. The trend of the coordination state in the eastern region, such as Shandong, Henan, and Shanxi, was still upwards. From the spatial dimension perspective, the western regions' coordination state was better than that of the eastern regions in 2008, whereas the result was quite the opposite in 2017. The resources were better protected, and the environment was benefited from the sparse population and the economically backward western regions in the YRB [80]. In contrast, the extensive development method of industry and agriculture and the increasing population density significantly damaged the resources and environment [81], resulting in the worse initial coordination state of the two systems in the eastern region than in the western region. With the gradual improvement of the WRCC in the eastern region, the economic development and industrial transformation in this region became conducive to the promotion of the coordinated development of the urbanization and WRCC systems [19]. On the contrary, the western region ignored the protection of water resources in the urbanization process [82], leading to the western region falling behind the eastern region in 2017. From the temporal dimension perspective, the two systems' coordination state in different regions had various evolution trends. From 2008 to 2011, the coordination state was improved to a varying extent. The relationship between the two systems in Shandong, Henan, and other provinces entered the running-in stage from the low coupling or antagonistic stage, while Gansu and

Ningxia remained in the running-in stage. During this period, the economic growth of the eastern provinces was faster than that of the western in the YRB, which promoted the development of urbanization [83]. From 2011 to 2014, the provinces were in different stages, maintaining stable growth. From 2014–2017, Shandong, Henan, and Shanxi continued to maintain growth and entered or approached the good coordination state; Shaanxi and Inner Mongolia maintained basic coordination and coordination respectively, while Ningxia and Gansu gradually fell into the basic coordination state. The reason behind this phenomenon is that the development of the WRCC in the western region cannot meet urbanization requirements with the development of urbanization after 2014. The claim has also been supported by another study [84]. The South-to-North Water Transfer Project improved the WRCC of the eastern region [77,85] and ensures the two systems' coordinated development. This is one of the main causes of the gap in coordination among the provinces. In short, the coordination state of each province was gradually improved as time went by, and the spatial difference in the coordination state of the seven provinces grew—a symptom of a widening gap in WRCC, which has far-reaching consequences.

As is illustrated in the obstacle analysis, the pressure subsystem had a more significant impact on the coordination state of the two systems in the YRB, while the social urbanization and response subsystem had a less significant impact on the coordination state. Precipitation has a great influence on WRCC [86]. In recent years, the YRB experienced drought [79], and the pressure subsystem had a significant impact on the coordination state. However, the difference in the coordination state is reflected in the obstacle factors analysis. The distribution of the seven provinces' main obstacle factors is relatively discrete in the urbanization and WCRR system. There are differences in the key subsystems of the different provinces, and thus the main obstacle indicators. This result is consistent with the current situation where there are gaps in terms of the economy, society, resources, environment, industrial structure, and other factors among the provinces in the YRB [84].

#### 4. Conclusions

The ecological protection and high-quality development of the YRB is a Chinese national strategy. It is essential for analyzing the relationship between urbanization and WRCC in the YRB. This study developed an evaluation model of the urbanization and WRCC systems by applying the PESS and PSR models. Then, an improved CCD model was established to evaluate the coordination state between the urbanization and WRCC quantitatively from 2008 to 2017. The evolution trend and characteristics of the CCD between the two systems were analyzed from the spatial–temporal dimension. The main factors that affect the coordination state were clarified and analyzed using the obstacle model. This study's results can enrich the content of the EKC theory's and develop the coupling framework of urbanization and WRCC. In contrast, the results reveal the spatiotemporal evolution law of CCD and provide an empirical and effective basis for high-quality development in the YRB. The main contributions are as follows:

Firstly, the research indicates that the urbanization performance level experienced a rapidly rising process in the YRB. The gap between the seven provinces' performance levels widened, because the urbanization grew at different rates. In the WRCC system, the WRCC system's performance presented a fluctuating downward trend from 2008 to 2017 in the YRB.

Secondly, the study confirms that, during 2008–2017, the coordination state between the urbanization and WRCC systems was improved to some extent, but there are differences in the coordination state of the different provinces in the YRB. In terms of the spatial–temporal dimension, the tendency of the coordination state in the western region of the YRB, such as Gansu, Ningxia, and Inner Mongolia, presents an inverted U-shape. The trend of the coordination state in the eastern region, such as Shandong and Henan, was still upwards. The coordination state of each province was gradually improved as time went by, and the spatial difference in the seven provinces' coordination state grew.

Finally, based on the obstacle factors analysis, we discovered the main impact subsystems and key indicators for the two systems' coordination state. The pressure subsystem had a great impact on the two systems' coordination state in the YRB, while the social urbanization and response subsystems had little impact. The major indicators restricting the coordination state of the urbanization system and WRCC system include  $X_3$  (Urban population density),  $X_{13}$  (Proportion of built-up areas to urban areas),  $Y_1$  (Water consumption per unit of GDP),  $Y_3$  (Water consumption of industrial output),  $Y_7$  (Total volume of water resources),  $Y_8$  (Per capita water occupancy volume), and  $Y_{11}$  (Industrial water pollution control investment).

The results show that the local governments in the YRB should pay more attention to the urban space, urban population, and economic development. City planning should be carried out scientifically and reasonably. We should upgrade industries, develop green industries, and increase personal income and the employment rate. To alleviate the pressure of the WRCC, intensive industrial and agricultural production modes should be adopted to reduce water consumption. On the other hand, the government can increase its investment in environmental protection to control industrial sewage discharge. In addition, the construction of a water resources allocation project might be implemented, and the utilization efficiency of water resources should be improved. Considering the difference in resource endowments in the YRB, the local government should formulate sustainable development plans according to their own coordination status and obstacle factors.

This paper's index system was designed for the urbanization system and the WRCC system of the provinces in the YRB and may therefore not be applicable to other regions, but it can provide other countries or regions with an effective approach or reference to study a similar problem.

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