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A Comprehensive Evaluation Model of Regional Water Resource Carrying Capacity: Model Development and a Case Study in Baoding, China

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Abstract: Scientific water resource carrying capacity (WRCC) evaluations are necessary for providing guidance for the sustainable utilization of water resources. Based on the driving-pressure-state-impact-response feedback loop, this paper selects 21 indicators under five dimensions to construct a regional WRCC comprehensive evaluation framework. The projection pursuit clustering (PPC) method is implemented with the matter-element extension (MEE) model to overcome the limitations of subjective deviation and indicator attribute incompatibility in traditional comprehensive assessment methods affecting the accuracy of evaluations. The application of the integrated evaluation model is demonstrated in Baoding city in the Jing-Jin-Ji area from 2010 to 2017. The results indicate that the economic water consumption intensity is the most influential factor that impacts the WRCC change in Baoding, and the pressure subsystem and response subsystem are dominant in the entire system. The WRCC in Baoding significantly improved between 2010 and 2017 from a grade V extremely unsafe state to a grade III critical state. Natural water shortages and large population scales are the main negative factors during this period; however, the existing measures are still insufficient to achieve an optimal WRCC status. Considering the future population and industry inflow, additional actions must be proposed to maintain and promote harmonious conditions.

Keywords: water resource carrying capacity; comprehensive evaluation; DPSIR framework; project pursuit clustering; matter-element extension; Baoding

1. Introduction

Due to the acceleration of industrialization and urbanization, the limited capacity of regional water resources to support the growing population and economy has become a bottleneck of sustainable urban development. The water resource carrying capacity (WRCC) can be defined as the maximum capacity of regional water resources to support social and economic development based on a given living standard and production technology without degrading the water environment [1]. The WRCC is an important concept in judging the relationship between regional human activities and water resources [2]. Especially in recent years, the government requires that the principle of "water determines the population, production and city" must be implemented in water shortage areas, illustrating that the WRCC has become an important policy tool for decision makers in optimizing resource patterns and supporting the construction of ecological civilization. Therefore, scientifically evaluating the carrying capacity of water resources is helpful to provide reference for decision-makers to formulate water resources strategic plans, and it has directive significance for realizing the coordinated and sustainable development of regional water resources, the ecological environment, and the social economy.

At present, the research on the evaluation of WRCC mainly focuses on the concept provision or qualitative analysis [3,4], while the theory and method of quantitative evaluation are still under discussion. Quantitative evaluation methods that are wildly used include the system model method [5], geographic information technology method [6,7], multi-objective analysis method [8], and comprehensive evaluation method [9,10], which have their own advantages and applicable conditions. System dynamics is a computer experiment simulation method for rapid analysis, but its application is limited by the huge demand for data and complex structure. The geographic information technology methods, such as GIS and remote sensing, have high technical requirements, and there are problems related to the insufficient accuracy of remote sensing images or incomplete data acquisition. The multi-objective analysis method transforms the multi-objective problem into a single objective programming by evolutionary algorithm, and multi-objective function solution and dimension reduction algorithm are the difficulties. The comprehensive analysis method obtains the evaluation result by constructing an evaluation index system, determining indicator weights, and selecting a comprehensive evaluation model. Compared with the other methods mentioned above, the comprehensive evaluation method can not only integrate various indicators reflecting social, economic, environmental, and resource conditions into one comprehensive evaluation index, but it also has the advantages of flexible calculation and a relatively simple operation [11]. The key and difficult point lies in the selection of a comprehensive evaluation model.

The extensively used evaluation models include the fuzzy analytic hierarchy process, principal component analysis, multi-objective decision analysis, etc. (1) Overall, most of the comprehensive index methods integrate the scattered information through the model and evaluate the level of the research object according to the index classification. However, they cannot identify the degree of membership between each index and the evaluation grade, and it is impossible to avoid missing part of the evaluation information between indicators. (2) The bivariate extreme value evaluation result is usually obtained through the above classical mathematical methods, but things in nature are often in a transitional state. (3) As WRCC assessment is a complex multi-dimensional system involving many indicators that are difficult to quantity, the evaluation results of each single indicator are often inconsistent, introducing uncertainty to the comprehensive evaluation results. Differently, the matter-element extension (MEE) model proposed by Cai [12] uses matter elements such as logical cells as a logical unit and realizes element transformation through matter-element replacement, decomposition, addition, and deletion. The correlation function of the model is extended from the closed interval [0,1] to $(-\infty, +\infty)$, and all the information of each indicator is integrated without loss, which solves the incompatibility among components and does not affect the extraction of comprehensive quality information regarding the indicators. Lang et al. used the MEE model to evaluate the groundwater quality in semiarid areas in northwestern China [13]; Wang et al. used the same method to evaluate the sustainability of China's water–energy–food nexus [14]. The MME model has been shown to be a more scientific and reasonable multi-element analysis method for addressing contradictions in complex systems and is applicable to WRCC evaluations.

However, the results of matter-element analyses depend on the indicators' weights to some extent; thus, a scientific weight calculation is the premise of using the MEE model for an accurate evaluation. In contrast to traditional methods that subjectively determine the indicator weights, such as the analytic hierarchy process, Delphi, principal component analysis, and entropy weight method [15,16], the projection pursuit clustering (PPC) model established by Friedman [17] has become a powerful tool in recent years for solving multi-attribute decision-making problems by clustering indicator information from the original characteristics. In addition, this method can be used for a preliminary exploratory analysis through system discrimination to evaluate, providing information that is difficult to obtain using other methods to decision-makers [18,19].

Based on these considerations, an integrated evaluation modeling framework for regional WRCC combined with the MEE model and PPC model is developed in this paper. MEE is used to solve the problem of fuzzy incompatibility among the indicators, while PPC is used to eliminate the possible deviation of subjective judgment in the MEE evaluation results via a process of index weight calculation and verify the MEE evaluation results based on preliminary judgment results. The framework is applied to a WRCC assessment in Baoding from 2010 to 2017 to provide a reference for local water resource managers.

2. Materials and Methods

2.1. Study Area

Baoding is a core and crucial region belonging to the Jing-Jin-Ji area and covers an area of 22,019 km^2 that spans from 113°10′ to 116°20′ E and 38°10′ to 40°00′ N. As a typical city lacking water located in the middle of the North China Plain (Figure 1), Baoding had a regional volume of water resources per capita of 193 m^3 in 2017 [20], which was less than 1/10 of the national average (2075 m^3). However, there is a population of 10.47 million (the highest proportion in Hebei Province), and a gross regional product (GRP) of 32.27 million [21] needs to be supported. In addition, Baoding is the typical agricultural city with the most arable land in Hebei and an important food production base in China, which requires a lot of irrigation water. To meet the expansion of water demand, the groundwater, accounting for more than 90% of the water supply, has been significantly over-exploited since the 1980s, subsequently resulting in ecological problems, such as land subsidence and soil salinization. Another serious issue is the low standard rate of surface water quality (less than 45%) caused by the increase in household and industrial wastewater discharge and over-fertilization. Under the existing circumstances, the water resources of Baoding can hardly support the growing population and economy, which has become the biggest obstacle to its sustainable development. Therefore, the study of Baoding's WRCC is representative and of profound practical significance.

On the other hand, Baoding was included in the central functional region of Jing-Jin-Ji and was regarded as a regional central city and an important carrying area for noncapital functions in 2015, thus setting higher requirements for the carrying capacity of water resources. In 2017, China's Central Government announced the official establishment of the Xiong'an New Area, which straddles three counties that previously belonged to Baoding as "a strategy crucial for the millennium to come". With the aggregation of production factors, water represents a core strategic resource in this future demonstration area for innovative development with priority given to eco-environmental protection and green living environments. Therefore, as the core hinterland of Jing-Jin-Ji coordinated development and Xiong'an New Area, Baoding urgently needs researchers to carry out research concerning WRCC revaluation and comprehensive utilization to provide guidance for further water resource planning and management. In view of the above, Baoding was selected as the study area.

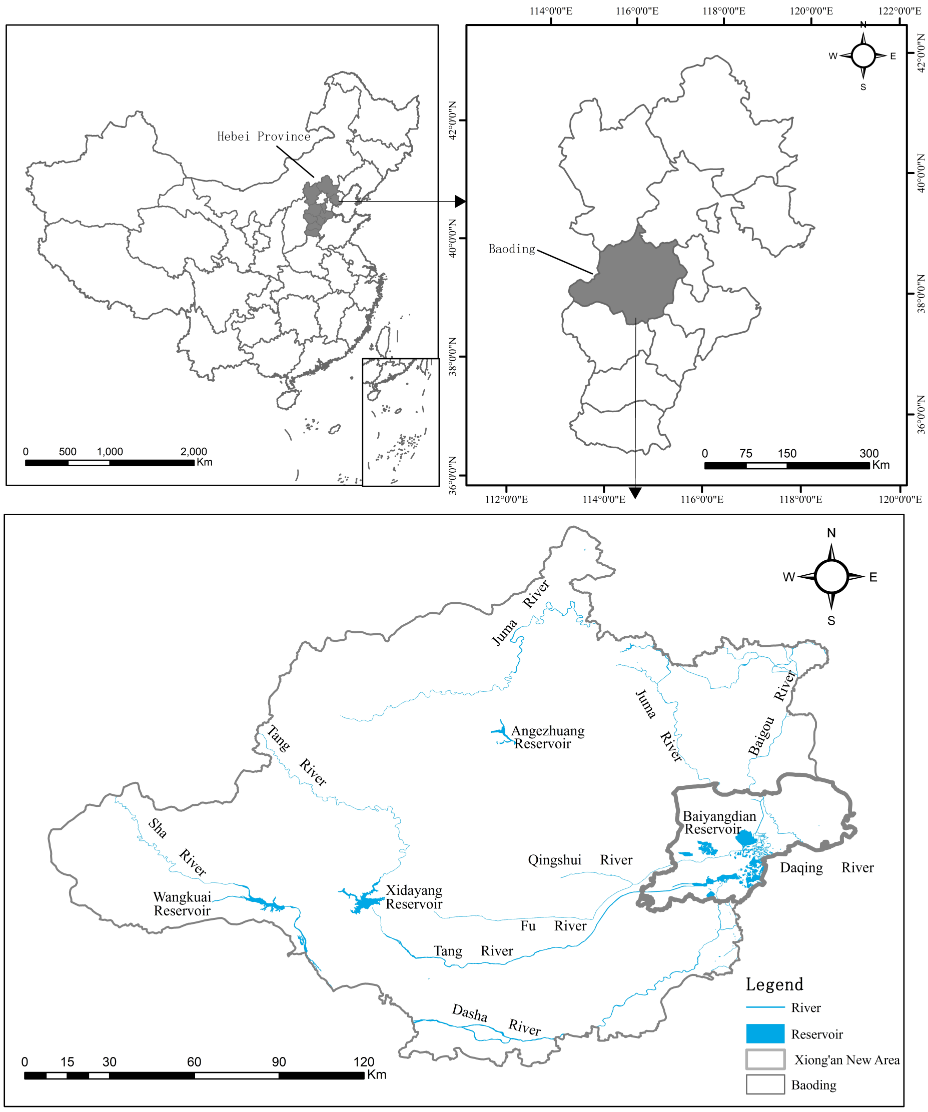

Figure 1. Location of Baoding.

2.2. *Model Development*

2.2.1. Evaluation Indicator System Construction

The WRCC is a complex concept that involves water resources, societal and economic factors, and different types of interactions and feedback mechanisms. Therefore, organizing data in a meaningful way for subsequent analysis and quantitative modeling is the basis for an accurate evaluation [22]. The driving-pressure-state-impact-response (DPSIR) framework developed by the European Environmental Agency (EEA) [23] serves as a powerful tool for performing detailed analyses by describing the "cause–effect" relationships among interacting societal, economic, and natural system factors [24].

The logic of the DPSIR framework in this paper is described as follows: the increasing water demand and sewage discharge produced from social and economic development (D subsystem) exert pressure (P subsystem) on water resources. Consequently, the water resources state (S subsystem) changes, thereby impacting human welfare (I subsystem). In response, the government or society implements actions (R subsystem) that could provide feedback to any part of this framework. These five dimensions form an organic feedback loop system. The specific feedback path is shown in Figure 2.

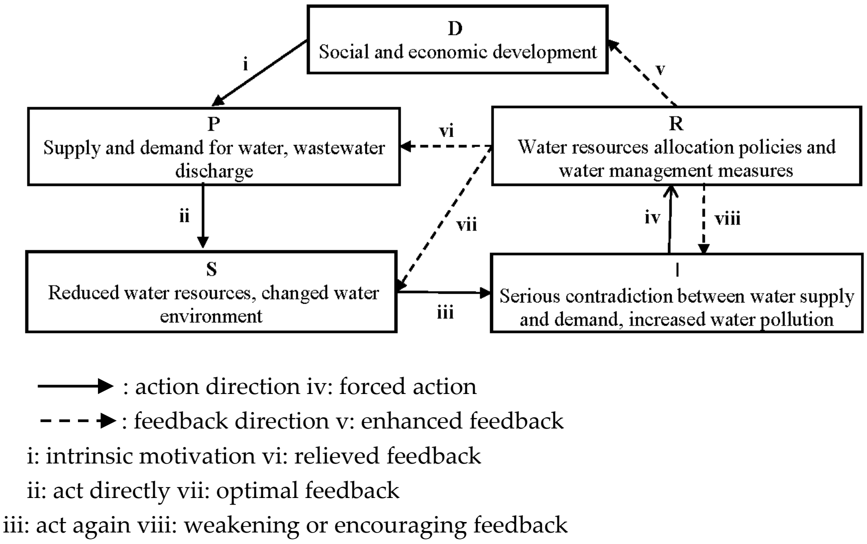

Figure 2. Driving-pressure-state-impact-response (DPSIR) feedback loop in water resource carrying capacity (WRCC).

Based on previous research [9,16,22,25–35], this paper establishes an evaluation index system by combining a theoretical analysis and frequency statistics. Indicators frequently used in the relevant literature are included under the DPSIR framework. After deleting some indicators that cannot meet the requirements of generality and practicality, we selected 17 common evaluation indicators as shown in Table 1.

In addition to the 17 universal indicators, this paper added additional 4 special indicators based on the practical problems of local water system in Baoding as well as the opinions of experts of Baoding Water Resources Bureau. Considering the fact that Baoding, which is the important grain production base with the largest cultivated land in Hebei Province, is plagued by huge agricultural irrigation water demand and increasing nonpoint source pollution caused by the continuous chemical fertilizer use, this paper consulted the local Water Resources Bureau experts' opinions and supplemented the indicators of the farmland chemical fertilizer consumption coefficient and the farmland irrigation water consumption coefficient in the P subsystem. Given that the special situation of the groundwater supply accounts for more than 80% of the total water supply, and the series of ecological problems such as land subsidence caused by the excessive groundwater exploitation, the indicators of the proportion of groundwater supply and the exploitation rate of groundwater were added in the S and I systems, respectively.

In summary, this paper constructs a comprehensive WRCC evaluation indicator system for Baoding that includes 21 indicators under the DPSIR framework. To avoid the influence of data distortion by processing errors on the evaluation results, comprehensive indicators, such as percentage and per capita, are preferred. The indicator descriptions are provided in Table 2.

2.2.2. Level and Threshold Division

The level division of the indicators intuitively enhances the understanding of WRCC assessment results. This division is the basis of the carrying capacity evaluation by the MEE model. The WRCC is classified into five levels (I–V). Level I is the highest level of the WRCC and represents the perfect coordination of the development and utilization of water resources with the development of the social economy. The WRCC has a completely ideal safe status. Level II represents that the development and utilization of water resources can meet the needs of the social economy, and the WRCC is in a relatively sate state. Level III represents a critical state in which water resource development and social economic development are basically balanced, but this balance is very unstable. Level IV represents a state in which the development and utilization of water resources is close to overload, which can hardly achieve long-term sustainable utilization, and the WRCC is in an unsafe state. Level V is the lowest level of the WRCC and represents an extremely unsafe status in which the water resources are completely unable to meet the demand for social economic development, and the WRCC is under strong pressure. Different levels correspond to different index value ranges, and the adjustment of the R subsystem can drive levels to the adjacent status. As the level of the WRCC increases from I to V, the pressure on water resources increases, and the capacity of the regional water resource systems to support the economy and society weakens.

Table 1. Source of partial carrying capacity evaluation indicators.

	Per capita GRP	Annual GRP Growth Rate	Population Density	Permanent Population Growth Rate	Water Consumption per Unit GRP	Water Consumption per Unit Industrial Added Value	Per capita Daily Consumption of Domestic Water	Industrial Sewage Discharge per Unit Industrial Value Added	Exploitation and Utilization Rate of Water Resources	Water Resources per Capita	Water Resources Modulus	Rate of Reaching Water Quality Standards of River	Coverage Rate of Forest	Centralized Treatment Rate of Urban Sewage	Proportion of Investment in Environmental Protection to GRP	Proportion of Tertiary Industrial Added Value to GRP	Water consumption rate in the ecological environment
Cheng et al., 2016 [9]	√		√	√	√	√		√		√			√	√	√		√
Wei et al., 2019 [16]	√		√		√	√	√	√		√		√		√	√		
Zhang et al., 2014 [22]						√		√		√			√	√			√
Wang et al., 2015 [25]	√		√		√	√	√		√	√		√	√		√	√	√
Wang et al., 2019 [26]		√		√		√	√			√			√		√	√	√
Lu et al., 2019 [27]	√	√	√	√		√	√		√	√	√		√			√	√
Wu et al., 2018 [28]	√		√			√	√		√		√		√				√
Du et al., 2011 [29]	√	√	√	√			√	√	√	√	√		√			√	√
Zhang et al., 2018 [30]	√				√	√	√			√	√	√		√		√	√
Zhang et al., 2019 [31]						√			√	√	√			√			
Yang et al., 2019 [32]	√				√	√	√						√	√	√		
Sun et al., 2017 [33]	√	√	√	√	√		√	√		√	√	√	√	√	√	√	
Chen et al., 2004 [34]	√		√	√	√	√	√	√	√	√		√	√		√		√
Gu et al., 2016 [35]			√			√	√			√	√						√

Note: The table shows 17 evaluation indicators that are frequently used in WRCC studies; √ denotes the indicators used in this study, and the blanks denote indicators that were not used.

Table 2. Evaluation index system for the WRCC in Baoding.

Subsystem	Indicator Layer	Calculation	Significance	Attribute
Drive	Per capita gross regional product (GRP), C_1 (Yuan/PER),	Total GRP/Total population	Individuals' use of water resources	Negative
	Annual GRP growth rate (%), C_2	$(GRP_t\text{-}GRP_{t-1})/GRP_{t-1}$	Level of economic development	Negative
	Population density (PER/km^2), C_3	Total population/Total regional area	Regional population carrying status and vigor of the population density to water resource–water environment carrying capacity	Negative
	Permanent population growth rate (%), C_4	$(Population_t\text{-}population_{t-1})/Population_{t\text{-}1}$		Negative
Pressure	Water consumption per unit GRP (m^3/YUAN), C_5	Total amount of water consumption/GRP	Water resource utilization efficiency indirectly reflecting the level of water reuse	Negative
	Water consumption per unit industrial added value (m^3/YUAN), C_6	Industrial water consumption/Industrial added value	Efficiency and effectiveness of water consumption in industrial production and pressure of industrial economic development on water resources	Negative
	Farmland irrigation water consumption coefficient (m^3/km^2), C_7	Irrigation water consumption/Total irrigated area	Use efficiency of water resources by farming	Negative
	Per capita daily consumption of domestic water (m^3/PER), C_8	Daily domestic water consumption/Total population	Pressure of life on water resources	Negative
	Industrial sewage discharge per unit industrial value added (m^3/YUAN), C_9	Industrial wastewater discharge/Industrial added value	Pressure of industrial economic development on water environment	Negative
	Farmland chemical fertilizer consumption coefficient (kg/km^2), C_{10}	Amount of chemical fertilizer consumption/Total cultivated area	Pressure of point source pollution	Negative
State	Exploitation and utilization rate of water resources (%), C_{11}	Exploitation and utilization amount of water resources/Gross amount of water resources	Degree of exploitation of water resources	Negative
	Proportion of groundwater supply (%), C_{12}	Groundwater supply/Total amount of water supply	Degree of reliance on the groundwater supply	Negative
	Water resources per capita (m^3/PER), C_{13}	Gross amount of water resources/Total population	Water scarcity status and development potential of the study area	Positive
	Water resources modulus (m^3/km^2), C_{14}	Gross amount of water resources/Total regional area	Potential of regional water resources	Positive
Impact	Rate of reaching water quality standards in rivers (%), C_{15}	Length of rivers whose water quality is up to standard (grade III or better)/Total river length	Water quality conditions of rivers	Positive
	Exploitation rate of groundwater (%), C_{16}	Amount of groundwater exploitation/Total amount of groundwater resources	Current situation of regional groundwater exploitation	Negative
	Coverage rate of forest (%), C_{17}	Total area of forest and grass/Total regional area	Water resources renewal capacity	Positive
Response	Centralized treatment rate of urban sewage (%), C_{18}	Amount of treated urban sewage/Total amount of urban sewage discharge	Status of urban sewage treatment	Positive
	Proportion of investment on environmental protection to GRP (%), C_{19}	Investment in environmental protection/GRP	Attention level of decision-makers to the regional environment protection	Positive
	Proportion of tertiary industrial added value to GRP (%), C_{20}	Tertiary industries added value/GRP	Level of socioeconomic development and level of industrial structure	Positive
	Water consumption rate in the ecological environment (%), C_{21}	Water consumption in the ecological environment/Total water consumption	Regional ecological environment level	Negative

Regarding the threshold determination of the indicators used in previous research, we draw upon the division in the related literature and perform appropriate adjustments according to the standards issued by the state and industry, including the "National Technical Outline for Monitoring and Early Warning of Water Resources Carrying Capacity" [36], "Technical Guideline of Stipulation for Norm of Water Intake" [37], and "Environmental Quality Standards for Surface Water" [38]. Regarding the unique indicators selected in this paper, the local actual development status and related regulation or planning, such as "The 13th Five-Year Plan for the Development of Water Conservancy of Baoding" [39], "Baoding City Environmental Quality Report 2017" [40], and "The 13th Five-Year Plan of Ecological Environment Protection of Baoding" [41] are comprehensively considered for the threshold division.

2.2.3. Evaluation of the WRCC with the MEE Model

The matter element of the WRCC can be represented as an ordered triple R = (M, C, X), where M represents the level of the WRCC, C represents the characteristics of the WRCC, and X represents the value corresponding to C. The model building involves the following steps.

Step 1. Determination of the classical domain, nodal domain, and evaluated matter element

1. The classical domain R_r refers to the value range of the indicators corresponding to evaluation level M_r of the WRCC—namely, an allowed range of values of an indicator under a certain level division. It can be expressed as follows:

$$R_r\left(M_r, C_j,\ X_r\right) = \left\{\begin{matrix} M_r & C_1 & X_{r1} \\ & C_2 & X_{r2} \\ & \vdots & \vdots \\ & C_P & X_{rP} \end{matrix}\right\} = \left\{\begin{matrix} M_r & C_1 & (a_{r1}, b_{r1}) \\ & C_2 & (a_{r2}, b_{r2}) \\ & \vdots & \vdots \\ & C_P & (a_{rp}, b_{rp}) \end{matrix}\right\}, \tag{1}$$

where M_r represents the rank of the WRCC evaluation (for example, M_{I} represents level I); C_j represents the indicator at each level (for example, C_1 represents the per capita gross domestic product); X_r represents the numerical range of C_j; and (a_{rj}, b_{rj}) represents the classical domain.

2. The limited domain R_k refers to the rational value ranges of indicators under all evaluation levels. It is the union of classical domains and can be expressed as follows:

$$R_k\left(M_k, C_j,\ X_k\right) = \left\{\begin{matrix} M_k & C_1 & X_{k1} \\ & C_2 & X_{k2} \\ & \vdots & \vdots \\ & C_P & X_{kP} \end{matrix}\right\} = \left\{\begin{matrix} M_j & C_1 & (a_{k1}, b_{k1}) \\ & C_2 & (a_{k2}, b_{k2}) \\ & \vdots & \vdots \\ & C_P & (a_{kp}, b_{kp}) \end{matrix}\right\}, \tag{2}$$

where M_k represents the overall rating of the indicators to be evaluated; $X_k = (a_{kj}, b_{kj})$ represents the range of values of C_j; a_{kj} is the minimum value; and b_{kj} is the maximum value.

3. The expression of the matter element to be evaluated is R_0 = (M_0, C_0, X_0), where M_0 represents the level of matter element to be evaluated, C_0 represents the indicators, and X_0 represents the measured value of each indicator.

Step 2. Calculation of the correlation degree and WRCC level

1. The single indicator degree of correlation $K_r(x_j)$ can be calculated as follows:

$$K_r\left(x_j\right) = \begin{cases} \frac{-\rho\left(x_j, X_{rj}\right)}{\left|X_{rj}\right|}, & x_j \in X_{rj} \\ \frac{\rho\left(x_j, X_{rj}\right)}{\rho\left(x_j, X_{kj}\right) - \rho\left(x_j, X_{rj}\right)}, & x_j \notin X_{rj} \end{cases}, \tag{3}$$

where x_j is the actual value of an indicator; $\rho(x_j, X_{rj})$ represents the distance between x_j and $X_{rj} = (a_{rj}, b_{rj})$; and $\rho(x_j, X_{kj})$ represents the distance between x_j and $X_{kj} = (a_{kj}, b_{kj})$, which can be calculated as follows:

$$\rho\left(x_j, X_{rj}\right) = \left|x_j - \frac{1}{2}\left(a_{rj} + b_{rj}\right)\right| - \frac{1}{2}\left(b_{rj} - a_{rj}\right), \tag{4}$$

$$\rho\left(x_j, X_{kj}\right) = \left|x_j - \frac{1}{2}\left(a_{kj} + b_{kj}\right)\right| - \frac{1}{2}\left(b_{kj} - a_{kj}\right). \tag{5}$$

2. The comprehensive correlation degree $K_r(\mathrm{R}_0)$ can be calculated as follows:

$$K_r(\mathrm{R}_0) = \sum_{j=1}^{p} \omega_j K_r\left(x_j\right), \tag{6}$$

where ω_j is the weight of each evaluation indicator, which is calculated using the following PPC model. According to the principle of maximum subordination, when $maxK_r(\mathrm{R}_0) = K_k(\mathrm{R}_0)$, the evaluation level of the WRCC belongs to level k (k = I, II, . . . V). This approach is also applicable to the determination of the level of a single index.

2.2.4. Weight Determination Based on the PPC Model

The basic principle of PPC is to map original high-dimensional data to a low-dimensional subspace and find the projection vector that can reflect the structure or characteristics of the high-dimensional data by optimizing the projection objective function to achieve the purpose of dimension reduction analysis [42]. This approach provides a new method to determine the weight of the indicators in the MEE model.

The specific steps are shown in Table 3. The first step is to standardize the original dataset $\left\{x^*_{ij}\middle|i = 1, 2, \ldots, \mathrm{n},\ j = 1, 2, \ldots, \mathrm{p}\right\}$ by (7) to reduce the impact of different dimensions and value ranges. Second, the p dimension data are mapped onto one dimension projective value $z(i)$ with the unit projection vector a by (8); then, the projective index function Q(a) is constructed by (9)–(11). The projection value must be as dense as possible locally but as scattered as possible overall to extract as much variation information as possible. The window radius of the local density R in (11) is the only parameter in the model, and its value is directly related to the degree of data structure characteristic exposure. Based on the research conducted by Lou [43], $\frac{r_{max}}{5} \leq \mathrm{R} \leq \frac{r_{max}}{3}$ is generally chosen; in this study, we set $\mathrm{R} = 0.3 \times r_{max}$.Third, because different projective directions reflect different data structure characteristics and the optimal projection direction retains the most original information, we estimate the optimal projection direction by solving the optimal problem by (12). The optimization procedure is crucial and could be regarded as a space optimization problem of a nonlinear vector. The genetic algorithm is used in this paper to solve the intractable optimization problem. Finally, the weight of each indicator ω_j and subsystem can be calculated using (13). All procedures described above were programmed and processed in MATLAB 7.0.

Table 3. Steps of the weight determination process by projection pursuit clustering (PPC).

The sample set of indicators is set as $\{x^{*}_{ij}\|i=1,2,\ldots,n, j=1,2,\ldots,p\}$, where n and p are the numbers of samples and indicators, respectively.		
Step 1 Nondimensionalization of the data	For positive indicators (Profit-type): $x_{ij} = \frac{x^{*}_{ij}-x_{min}(j)}{x_{max}(j)-x_{min}(j)}$; for negative indicators (Cost-type): $x_{ij} = \frac{x_{max}(j)-x^{*}_{ij}}{x_{max}(j)-x_{min}(j)}$, where x^{*}_{ij} is the original value of the j-th indicator of the i-th sample, x_{ij} is the normalized indicator value, and $x_{max}(j)$ and $x_{min}(j)$ are the maximum and minimum values of the j-th evaluation indicator, respectively.	(7)
Step 2 Construction of the projective objective function	(1) The projected characteristic value could be considered a composite index of the i-th sample defined as follows: $z(i) = \sum_{j=1}^{p} a_j x_{ij}$, where $z(i)$ is the projected characteristic value of the *i*-th sample, and a_j is the projective direction vector.	(8)
	(2) The projective index function is constructed as follows: $\mathrm{Q(a)} = S_z D_z$, where S_z is the standard variance of $z(i)$, and D_z is the local density of $z(i)$.	(9)
	$S_Z = \sqrt{\sum_{i=1}^{n}[z(i)-\overline{z}]/(n-1)}$,	(10)
	$D_z = \sum_{i=1}^{n}\sum_{j=1}^{n}\left(\mathrm{R}-r_{ij}\right)\mu\left(\mathrm{R}-r_{ij}\right)$, where $\overline{z}$ is the mean of the series z(i); $r_{ij} = \left\|z(i)-z(j)\right\|$ is the distance between z(i) and z(j); $\frac{r_{max}}{5} \leq \mathrm{R} \leq \frac{r_{max}}{3}$ is the window radius of the local density and is chosen as $0.3r_{max}$; and $\mu\left(\mathrm{R}-r_{ij}\right)$ is the unit pulse function, which has a value of 1 if $\left(\mathrm{R}-r_{ij}\right) \geq 0$ and 0 otherwise.	(11)
Step 3 Optimization of the projection indicator function	(1) The objective function is maximized as follows: $\max\mathrm{Q(a)} = S_z D_z$, s.t: $\sum_{j=1}^{p} a_j^2 = 1, 0 \leq \mathrm{a}_j \leq 1$. (2) The genetic algorithm toolbox in MATLAB is used to obtain the global optimal solution.	(12)
Step 4 Calculation of the indicator weight	The weight of each index is calculated as follows: $\mathrm{w}_j = \frac{\sum_{i=1}^{n} a_j x_{ij}}{\sum_{i=1}^{n} z(i)}$.	(13)

2.3. Data Sources

The data used in this study mainly include socioeconomic and water utilization data. The socioeconomic data were mainly collected and calculated based on the Baoding Statistical Yearbook [20]. The hydrologic data were provided by the Baoding Water Resources Bureau [21], and the water environmental data were obtained from the Baoding City Environmental Quality Report [40].

3. Results

3.1. Contribution Weights of the Indicators and Subsystems

Under the DPSIR framework, Baoding's WRCC evaluation index system was established as shown in Table 1. The data from 2010 to 2017 were inputted into the PPC model using (7)–(13) in Table 3. In the control parameter design of the genetic algorithm, after the trial and test tuning, the population size was fixed to 200; the crossover and mutation rates were selected as 0.8 and 0.05, respectively; and the maximum number of generations was limited to 100 iterations. The calculation results of the projected characteristic value $z(i)$ were 0.0924, 0.1933, 0.9978, 1.1789, 1.1121, 1.4101, 1.8469, and 2.1693. The corresponding weights of the indicators and subsystems are shown in Figure 3.

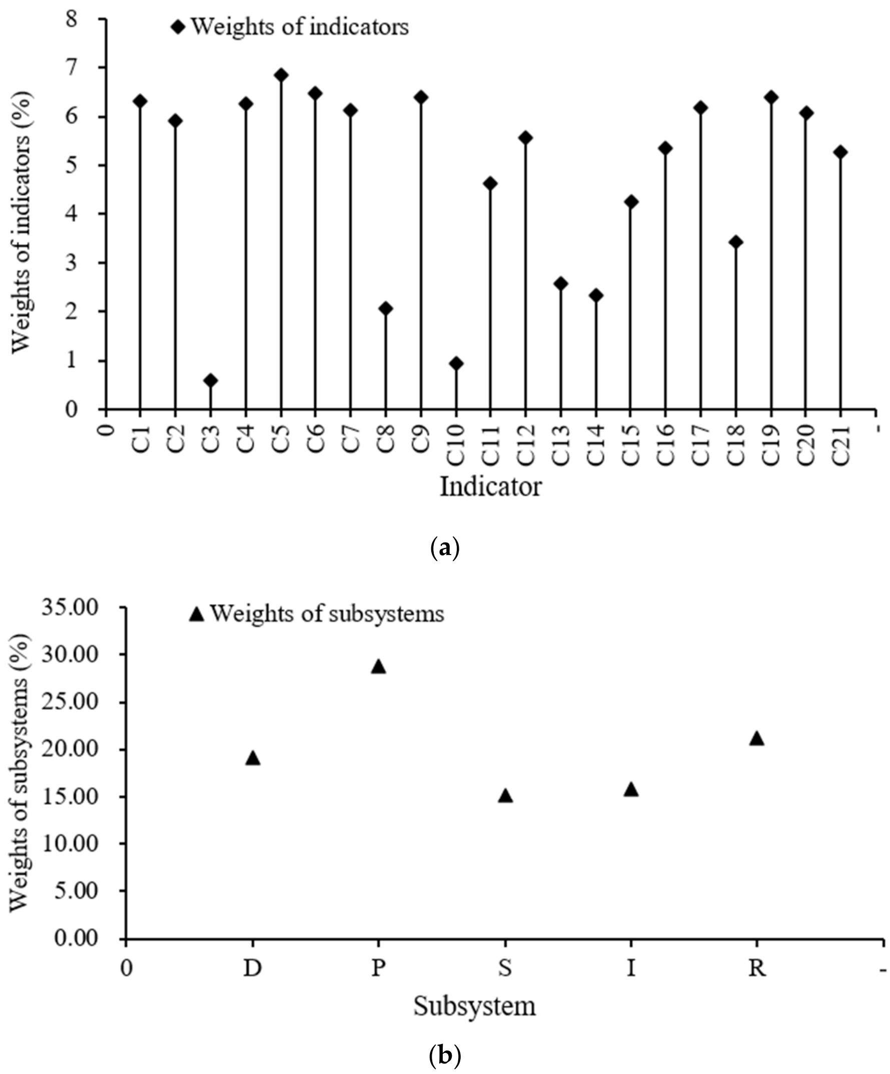

Figure 3. Weights of the indicators (**a**) and subsystems (**b**) in the WRCC indicator system.

As shown in Figure 3a, the top 10 indicators that have the greatest impact are water consumption per unit GRP (C_5, 0.0686), water consumption per unit industrial added value (C_6, 0.0648), proportion of investment in environmental protection to GRP (C_{19}, 0.064), industrial sewage discharge per unit industrial value added (C_9, 0.0639), per capita GRP (C_1, 0.0631), permanent population growth rate (C_4, 0.0626), coverage rate of forests (C_{17}, 0.0618), farmland irrigation water consumption coefficient (C_7, 0.0612), proportion of tertiary industrial added value to GRP (C_{20}, 0.0608), and annual GRP growth rate (C_2, 0.0591). The change in these ten indicators over time is the main reason for the differences in the WRCC across different years.

The contribution rate of the subsystems to the WRCC is the sum of the indicator influence weights in the same subsystem. The weights of the D, P, S, I, and R subsystems are 0.1908, 0.2884, 0.1511, 0.1578, and 0.2119, respectively (Figure 3b). The P subsystem and R subsystem had the most significant influence on the WRCC relative to the other subsystems. If the two subsystems slightly deteriorate, the remaining three subsystems would need to be greatly improved to maintain the WRCC in a harmonious condition.

3.2. Evaluation Results of the WRCC

By referring to relevant studies and actual situations, we classify all values of the indicators into five levels. The methods described in Sections 2.2.2 and 2.2.3 are used to determine the classic domain R_I~R_V and the limited domain R_k, as shown in Table 4.

Table 4. Classification of the WRCC ranks, classic domain, and limited domain.

Indicators	Classical Fields					Limited Field (R_k)
	Ideally Safe (R_I)	Relatively Safe (R_{II})	Critically Safe (R_{III})	Unsafe (R_{IV})	Extremely Unsafe (R_V)	
C_1	(70,100)	(25,7)	(7,25)	(3,7)	(0,3)	(0,100)
C_2	(0,2)	(2,4)	(4,6)	(6,9)	(9,12)	(0,12)
C_3	(0,25)	(25,50)	(50,100)	(100,300)	(300,1500)	(0,1500)
C_4	(0,0.4)	(0.4,0.8)	(0.8,1.0)	(1.0,1.5)	(1.5,2)	(0,2)
C_5	(0,2)	(2,6)	(6,15)	(15,25)	(25,50)	(0,50)
C_6	(0,1.5)	(1.5,5)	(5,10)	(10,15)	(15,20)	(0,20)
C_7	(0,2250)	(2250,3000)	(3000,4500)	(4500,6750)	(6750,15,000)	(0,15,000)
C_8	(0,50)	(50,100)	(100,150)	(150,200)	(200,500)	(0,500)
C_9	(0,0.3)	(0.3,0.5)	(0.5,0.8)	(0.8,1.5)	(1.5,3)	(0,3)
C_{10}	(0,75)	(75,150)	(150,225)	(225,300)	(300,500)	(0,500)
C_{11}	(0,10)	(10,20)	(20,40)	(40,60)	(60,100)	(0,100)
C_{12}	(0,40)	(40,55)	(55,70)	(70,80)	(80,100)	(0,100)
C_{13}	(2500,5000)	(1700,2500)	(1000,1700)	(500,1000)	(0,500)	(0,5000)
C_{14}	(600,1000)	(350,600)	(200,350)	(150,200)	(0,150)	(0,1000)
C_{15}	(90,100)	(80,90)	(75,80)	(70,75)	(0,75)	(0,100)
C_{16}	(0,0.6)	(0.6,0.8)	(0.8,1.2)	(1.2,1.4)	(1.4,3)	(0,3)
C_{17}	(50,100)	(40,50)	(20,40)	(10,20)	(0,10)	(0,100)
C_{18}	(95,100)	(90,95)	(80,90)	(65,80)	(0,65)	(0,100)
C_{19}	(3,5)	(2,3)	(1,2)	(0.5,1)	(0,0.5)	(0,5)
C_{20}	(75,100)	(60,75)	(45,60)	(30,45)	(0,30)	(0,100)
C_{21}	(0,1)	(1,2)	(2,3)	(3,5)	(5,10)	(0,10)

By inserting the measured value in each year into Equations (1)–(6), the comprehensive correlation degree in Baoding during the period 2010–2017 can be calculated. Table 5 provides detailed information regarding the evaluation results of the WRCC determined by the maximum subordination principle.

Table 5. Calculation results of the matter-element evaluated from 2010 to 2017.

Year	Comprehensive Correlative Degree					WRCC Evaluation Results
	K1	K2	K3	K4	K5	
2010	−0.5977	−0.4282	−0.3131	−0.3092	−0.1111	V
2011	−0.4749	−0.3231	−0.2763	−0.2966	−0.2168	V
2012	−0.4467	−0.3051	−0.2649	−0.236	−0.2626	IV
2013	−0.4032	−0.2459	−0.2398	−0.2376	−0.2921	IV
2014	−0.4758	−0.2958	−0.253	−0.2665	−0.2587	III
2015	−0.4395	−0.2056	−0.1704	−0.1899	−0.2809	III
2016	−0.4288	−0.1925	−0.1244	−0.14	−0.2866	III
2017	−0.4262	−0.2261	−0.1539	−0.2948	−0.3016	III

3.3. Sensitivity Analysis

To measure the influence of the error in measurement on the evaluation results of the WRCC, this paper uses the local sensitivity analysis method to analyze the sensitivity of 21 indicators over eight years. We increased and decreased the measured value of each indicator by 10% and recorded the change in the maximum correlation degree and evaluation level while maintaining the other indicators unchanged. The calculation results of the indicator sensitivity analysis of 2010 are shown in Table 6.

Table 6. Index sensitivity analysis results.

Indicators	Maximum Correlative Degree			Evaluation Level		
	−10%	0	+10%	−10%	0	+10%
C_1	0.319	0.355	0.390	3	3	3
C_2	0.150	0.167	0.183	5	5	5
C_3	0.232	0.258	0.283	5	5	5
C_4	0.216	0.240	0.264	5	5	5
C_5	0.363	0.403	0.443	4	4	4
C_6	0.270	0.300	0.330	2	2	2
C_7	0.159	0.177	0.195	4	4	4
C_8	0.442	0.491	0.541	2	2	2
C_9	0.428	0.476	0.523	5	5	5
C_{10}	0.345	0.383	0.421	5	5	5
C_{11}	0.284	0.315	0.347	5	5	5
C_{12}	0.384	0.427	0.470	5	5	5
C_{13}	0.295	0.328	0.361	5	5	5
C_{14}	0.393	0.437	0.481	5	5	5
C_{15}	0.206	0.229	0.252	5	5	5
C_{16}	0.030	0.033	0.037	5	5	5
C_{17}	0.003	0.004	0.004	3	3	3
C_{18}	0.233	0.259	0.284	3	3	3
C_{19}	0.212	0.235	0.259	3	3	3
C_{20}	0.198	0.220	0.242	4	4	4
C_{21}	0.284	0.316	0.347	3	3	3

After increasing and decreasing each index in 2010 by 10%, the value of the maximum correlation degree changed accordingly. However, the evaluation level of each indicator and the comprehensive WRCC were still consistent with the value before the change. Similarly, the calculation showed that the evaluation grades of the indicators in the remaining years remain unchanged when changed in the same range. The comprehensive evaluation model is considered stable and reliable.

3.4. Discussion and Suggestions

3.4.1. Change Trend of the WRCC from 2010 to 2017

According to the MEE results, the WRCC in Baoding during the 2010–2017 period showed an improving trend from level V (extremely unsafe) to level III (critical state). This result is basically consistent with the change trend in the projected characteristic value $z(i)$, which could be used to characterize the WRCC obtained through the PPC model. Notably, although the evaluation grades in some years remain unchanged as shown in Figure 4, the comprehensive correlation degrees indicate different development trends in the WRCC. For example, the assessment results of the WRCC from 2014 to 2017 continued to be at level III; however, the maximum value of the multi-index correlation degree in 2014 (−0.253) from the adjacent levels II and IV was 0.0335 and 0.0057, respectively, indicating that the WRCC maintained a trend toward level IV in 2014. In 2017, the maximum value of the multi-index correlation (−0.1539) from the adjacent levels II and IV was 0.0722 and 0.1409, respectively, indicating that the assessment result of WRCC trended toward level II. The WRCC in 2017 was slightly higher than that in 2014. In summary, the WRCC in Baoding continued to improve during the assessment period.

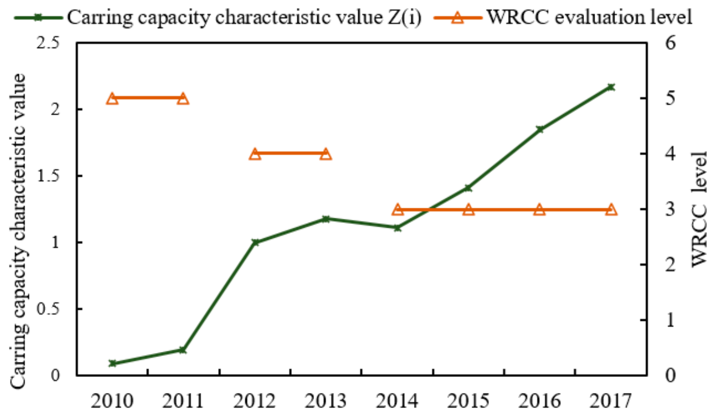

Figure 4. WRCC development trend in Baoding from 2010 to 2017.

The evaluation results are consistent with the real-world situation. Before 2010, Baoding paid inadequate attention to sustainable development. Economic growth was the primary decision-making factor, which led to the excessive exploitation of water resources and continuous deterioration of the water environment. Thus, the WRCC in 2010 exhibited the lowest level V. Nevertheless, the moving trend toward level IV shows that the city gradually realized the vulnerability of the WRCC. In 2017, the concept of sustainability was highly valued by the government and residents. Compared with 2010, the allocation of water resources was further optimized, and the water utilization efficiency was significantly improved; however, due to the requirement of economic development and the lack of further targeted measures, the sustainable utilization of water resources was unstable in 2017, and the WRCC was at a critical status. This consistency further verified the credibility of the evaluation results.

3.4.2. Change Trend in WRCC Indicators from 2010 to 2017

Of all 21 indicators from 2010 to 2017, 9 indicators maintained the same evaluation levels (5 continued to be extremely unsafe), 1 indicator deteriorated, and 11 indicators improved (as shown in Figure 5); additionally, the annual GRP growth rate (C_2), permanent population growth rate (C_4), and exploitation rate of groundwater (C_{16}) changed the most, improving by at least two levels. Among the top 10 indicators in the weight calculation results, 7 indicators improved, and 3 indicators remained at the same level. Since the overall WRCC presents a trend of optimization, these results suggest that the impact of the rising levels is greater than that of the declining levels.

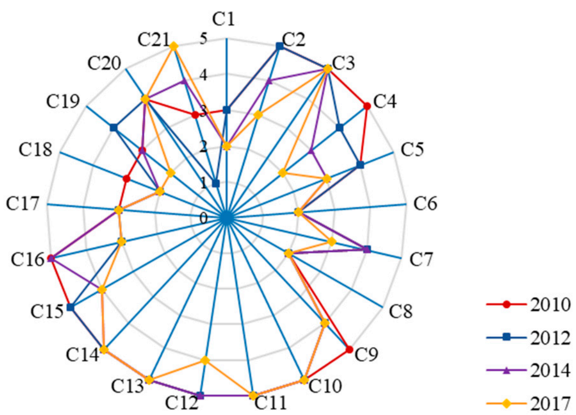

Figure 5. Radar map of the indicator change trends in 2010, 2012, 2014, and 2017.

Based on the raw data analysis, the GRP annual growth rate (C_2) was 15% in 2010 and decreased to 6% in 2017, and the permanent population growth rate (C_4) declined from 0.56% in 2010 to 0.42% in 2017.

Benefitting from the establishment and implementation of the strictest water resource management system in Baoding since 2012, the water consumption per unit GRP (C_5), water consumption per unit industrial added value (C_6), and industrial sewage discharge per unit industrial value added (C_9) decreased by 44.8%, 35.4%, and 60.2% from 2010 to 2017, respectively. In addition, Baoding was selected as an official pilot city for the comprehensive treatment of groundwater over-exploitation in 2016. Through the implementation of seasonal fallow and the promotion of winter wheat water conservation and stable production supporting technology, the farmland irrigation water consumption coefficient (C_7) and exploitation rate of groundwater (C_{16}) were reduced by 14.2% and 28.8% in 2017 relative to the values in 2010, respectively. To support the above policies, the proportion of investment in environmental protection to GRP (C_{19}) increased from 1.76% in 2012 to 2.29% in 2017. However, the population density (C_3), water utilization rate (C_{11}), water resources per capita (C_{13}), and water resources module (C_{14}) were still at the lowest level V and represented the main sources of the negative impact on the WRCC. This result suggests that the effectiveness of the current measures is limited by severe natural water shortages and existing large population scales, and further measures from the perspective of increasing water resources are urgently required.

Regarding the DPSIR framework, the P subsystem and R subsystem performed the best in the five aspects of the indicators, and the S subsystem performed the worst. This result shows that people have enough awareness of the pressure on water resources and have begun to actively respond to such pressure; however, the breadth and depth of the measures are still insufficient to fundamentally change the current condition. Further improvements are needed to reach the optimal status of the WRCC.

3.4.3. Evaluation Results and Future Trend Analysis of the WRCC in 2017

The optimal projected characteristic value in 2017 was 2.1693, which was the highest since 2010. The evaluation result was level III, and the water resources and social economic development were basically in balance in this critical state. Among the top 10 indicators in the weight calculation results, 4 indicators (C_1, C_4, C_6, and C_{19}) were in a relatively safe state, 4 indicators (C_2, C_5, C_7, C_{17}) were in a critical state, and 2 indicators (C_9, C_{20}) were in a transitional unsafe state. The overall WRCC achieved great progress compared with that in 2010. However, the critical status indicates an unstable situation, and the indicator evaluation results indicate problems, such as insufficient water resources per capita, over-exploitation of water resources, a low water quality standard rate, and a high ecological water use rate.

It could be easily predicted that due to the deepening of the Jing-Jin-Ji integration and the promotion of the construction of the Xiong'an New Area, a large number of people and industries will flood Baoding and stimulate negative changes in the main influencing indicators. If no further optimization measures are implemented, the increase in water consumption of domestic and industrial sources and sewage discharge will inevitably increase the pressure on the WRCC, worsen the water resources carrying state, cause negative impacts, and make it difficult to maintain the current evaluation state. Therefore, targeted polices and investment are necessary to ensure that the water resources are bearable and reach a safer bearing state.

3.4.4. Suggestions

Further improvement of the WRCC requires comprehensive efforts. According to the above calculation results, the P subsystem and R subsystem primarily control the change in the WRCC, and natural water shortages and population expansion are the most intractable risk sources of the water system. Therefore, efforts should first be exerted to maintain the healthy growth of the economy and population to alleviate the pressure on the WRCC. Considering that Baoding is in a special stage of rapid industrialization and urbanization, specific response measures should be sufficient to maintain the whole complex system in a harmonious state. Some response suggestions are proposed as follows.

1. Comprehensive water conservation should be promoted and water resource utilizations efficiency should be improved. In agriculture, efficient water-saving irrigation projects should be

implemented, and the crop planting structure of winter wheat with high water consumption should be adjusted to adapt to the local water resource carrying level. In industry, the integrated water-saving mode of "water saving technology transformation + remote water monitoring information system + step water price + supervision and assessment" must continue to be implemented. Additionally, public awareness of water savings and water environmental protection should be strengthened.

2. New sources of water resources within the basin should be explored, and water diversion projects should be conducted outside the basin. The rainwater utilization project and river system connection project should be completed as soon as possible to fully exploit the effectiveness of Baiyangdian Lake as well as four large reservoirs and nine rivers in Baoding. In addition, obtaining resources from the South-to-North Water Diversion Project can maximize the amount of available water resources.
3. The sewage treatment capacity should be improved to protect the existing water resources from pollution. In particular, because of the large amounts of rural domestic sewage and nonpoint source pollution, new sewage treatment plants are required, and treatment technologies must be updated.
4. The strictest water resource management system should continue to be implemented. The red line for the control of water resource exploitation should be scientifically defined to guarantee the benchmark range of water resources. A water quantity and quality allocation plan must be formulated according to the local situation to reduce unnecessary water loss.

In addition, the effectiveness of water resource management should be included in the performance assessment system of relevant departments to improve the focus on water management.

4. Conclusions

WRCC evaluations can positively and significantly guide the coordination of human social and economic activities and the utilization and protection of water resources. Based on the DPSIR framework, this paper implements the PPC method with the MME model and applies the comprehensive evaluation model to Baoding from 2010 to 2017. The credibility of the evaluation results is verified by a sensitivity analysis and the consistency with the actual situation.

In the evaluation index system, the contributing proportion of each indicator to the WRCC is quite different. The top five indicators in the weight calculation results are water consumption per unit GRP, water consumption per unit industrial added value, proportion of investment in environmental protection to GRP, and industrial sewage discharge per unit industrial value added and per capita GRP. The economic water consumption intensity is the most influential factor. The P subsystem and R subsystem are dominant within the entire DPSIR framework.

Baoding's WRCC showed an optimization trend from the extremely unsafe state in 2010 to the critical state in 2017; however, based on the specific indicators, improvements are required to achieve the optimal state. The high population density, high exploitation and utilization rate of water resources, and inadequate per capita water resources and water resource modules are the main factors negatively influencing the WRCC. Problems associated with natural water shortages and large population scales are difficult to overcome. In 2017, Baoding's WRCC was at a critical state and progressing toward a relatively safe level. However, considering its regional positioning and urban planning, the sustainable utilization of water resources in this city in the future is not optimistic. Although appropriate economic and population growth should be a primary concern, additional targeted suggestions are proposed to guide decision-makers in achieving continuous coupling among society, the economy, and water resources.

The comprehensive evaluation indicator system for WRCC built in this paper is a further improvement of the existing regional WRCC evaluation index system. We try to propose an integrated model and apply it as a new comprehensive assessment method to the evaluation of regional WRCC.

It can not only solve the problems of subjective one-sidedness, incompatibility of evaluation indicators, and information omission that are common in traditional comprehensive evaluation methods, so as to greatly improve the accuracy of the assessment, but also display the transition state in nature in the form of membership function, which gets rid of the limitation of bivariate extreme value evaluation results. For regional water resources managers, this method can be used not only for the dynamic evaluation of sequence data to better understand the change trend in the regional WRCC but also for the static evaluation of sectional data; additionally, this approach can be extended to comparative studies of multiple regions. This comprehensive evaluation model can be applied to other areas by adjusting the indicator system according to different areas with different specific actual situations. For example, the indicators related to groundwater should be removed in areas where groundwater problems are not serious.

However, there are still some problems are worthy of further consideration. (1) The comprehensive evaluation system of WRCC has not yet reached a unified evaluation index system, and it is almost impossible to completely clarify all the influencing factors. A more appropriate index system, especially a more scientific and quantitative treatment of qualitative quantities, needs to be further explored. (2) Although the integrated model ensures the objectivity of index weight, the definition of threshold cannot completely exclude the subjectivity of experts and decision makers. (3) Considering the availability of data, this paper performs statistical calculations based on municipal administrative units. However, the larger the area of the statistical unit, the higher the average evaluation results might be, which could affect the evaluation results. Therefore, if conditions permit, administrative units, such as counties or towns, should be taken as basic units to retain more details in Evaluation. (4) The practical significance and application value of the WRCC evaluation are determined by the feasibility of regulation policies. Future research could be extended to the quantitative relationship between the WRCC and regulation measures.

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