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Evaluation and Optimization of Agricultural Water Resources Carrying Capacity in Haihe River Basin, China

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Abstract: The shortage and uneven spatial and distribution of agricultural water resources has greatly restricted the sustainable development of regional society and economy. In this study, an improved five-element connection number set pair analysis model, which subdivides the same–different–opposite connection number in the set pair analysis theory to enhance the integrity and effectiveness of the original ternary connection numbers is constructed to evaluate the agricultural water resources carrying capacity (AWRCC) in the Haihe River Basin. Based on this evaluation result, an optimization model (AROL model) is proposed to optimize the effective irrigation area and groundwater exploitation to achieve a “better level” of AWRCC. The evaluation result shows that the current AWRCC of the Haihe River Basin is relatively low. The AWRCC in Shanxi, Inner Mongolia, and Liaoning is Level III and the current agricultural water resources are not overloaded but have little carrying potential. The AWRCC of Beijing, Tianjin, Hebei, Henan, and Shandong are rated IV and overloaded, among which Shandong has the lowest comprehensive score and the most serious overload. The optimization result shows that the extraction and conservation of groundwater in most areas of the Haihe River Basin is unbalanced and the effective irrigation area needs to be increased. With different current conditions in different areas, the groundwater exploitation and the effective irrigation area is adjusted correspondingly. Among the areas, the adjustment of groundwater exploitation and the effective irrigation area in Hebei are the most significant.

Keywords: agricultural water resources carrying capacity; set pair analysis; AROL optimization; Haihe River Basin

1. Introduction

Water is an irreplaceable basic natural and strategic resource for human survival and development. The shortage and uneven spatial and temporal distribution of water resources have seriously restricted the sustainable development of the regional economy and society. With the current situation of agricultural water resources in China becoming more severe, the studies related to improving the utilization efficiency of agricultural water resources has attracted more attention in recent years [1,2]. As the nation’s political, cultural, and educational center, the Haihe River Basin is located in North China, with a land area of 318,000 km². With less than 1.3% water resources of the country, it is responsible for 11% of arable land, 10% of the population, and 12% of agricultural products [3]. Additionally, as the water supply gives priority to domestic water and industrial water, agricultural water is continuously declining. The rapid population expansion and the growth of agricultural water

demand are causing severe agricultural problems in the Haihe River Basin. During 1960 to 1999, the groundwater depth in the Haihe River Basin had dropped by 11.5 m. In the meantime, the area for sprinkler irrigation, micro-irrigation, and pipe irrigation is only 43.1×10^4 ha, which accounts for 38.1% of the area suitable for water-saving irrigation and leaves great potential for saving water. Therefore, research on agricultural water resources carrying capacity (AWRCC), groundwater, and the effective irrigation area optimization based on the current situation of AWRCC is of great significance.

Water resource carrying capacity (WRCC) is the ability of the water resource to carry the economic, social, and ecological environment [4], and the studies of WRCC are considered the foundation of sustainable development and water security strategy formulation [5]. Agricultural water resources carrying capacity (AWRCC) is a branch of WRCC research. The study of AWRCC is the basic work of sustainable development of agriculture. Since Xinjiang Water Resources Soft Science Research Group first proposed the concept of water resources carrying capacity, the concept of the carrying capacity of water resources was extensively studied in the late 1990s and early 2000s. Several studies concluded that the carrying capacity of water resources means that maintaining a healthy social system requires water resources [6,7]. Other researchers believe that the carrying capacity of water resources is the greatest threshold for water resources to maintain human activities [8]. However, few studies consider water resources carrying capacity as a single object, and most of the studies are incorporated into the sustainable development system [9]. Since 2000, a series of research studies were carried out on the theory and calculation methods of water resources carrying capacity in China and abroad [10–12].

There are many studies on the concept and evaluation methods of water resources carrying capacity, but there is still no unified definition, especially for the study of agricultural water resources carrying capacity. At present, there is little research on the AWRCC. This study considers that agricultural water resources carrying capacity is closely connected with social, economic, and technical factors. Thus, its definition should be based on foreseeable technological and social-economic levels and its perspective should rely on technological means and social developments scale in the future. Based on the induction and analysis of the concepts of carrying capacity and water resources carrying capacity, and in combination with the characteristics of agricultural water resources, the concepts of AWRCC are proposed as follows, 'At a specific planning and development stage in the area, take sustainable development as the principle, foreseeable economic, technological and social development level as the basis, and, on the basis of the balance between supply and demand of water resources in the area, the carrying capacity of water resources available for agriculture for the sustainable development of population and agriculture in the area'. Various calculation methods have emerged to quantify WRCC, and most WRCC research methods can also be applied to AWRCC. Falkenmark et al. have studied the use limits of water resources in some developing countries by calculating the agricultural, domestic, and industrial water needed per person per year, which has laid a foundation for special research on water resources' carrying capacity [13]. On the basis of principal component analysis, Yuan selected three major cities in the upper, middle, and lower reaches of the Ganjiang River basin as evaluation objects respectively, and concluded that the water resources' carrying capacity in the upper and middle reaches of the basin was significantly higher than that in the lower reaches [14]. The principal component analysis was also applied to water resources' research. However, due to the fuzziness of the principal component description and ignorance of the connection between indicators, the extracted principal component sometimes cannot give an explanation that conforms to the actual situation. Zhang used a fuzzy comprehensive evaluation method to evaluate and predict the water resources' carrying capacity of the Hailaer River Basin and find out that the water resources' supply will be difficult to meet the demand in 2030 [15]. The fuzzy comprehensive analysis method is a comprehensive evaluation method based on fuzzy mathematics. It is mostly combined with an analytic hierarchy process. The evaluation result is a vector, not a point value, which contains more information and can accurately depict the evaluated object. However, the calculation of this method is complicated and the determination of the index weight vector is subjective. Yu established different situation prediction models based on system dynamics, and found that the water resources under

the four situations can meet the needs of production and life [16]. This method can quantitatively analyze the relationship between the structure and function of various complex systems and its suitability for long-term dynamic trend research. However, inaccurate model parameters often lead to unreasonable results. Rijsberman et al. have incorporated the carrying capacity of water resources into the measurement standard of the urban water resources system security and applied it to urban development planning [17].

Most research studies on agricultural water resources carrying capacity focus on comprehensive evaluation. Duan first proposed the concept of agricultural water resources' carrying capacity on the irrigation area scale, and according to the diversity of crop species and the water supply and demand process in different stages, the calculation model of agricultural water resources' carrying capacity was established [18]. Mitchell et al. established a prediction model for regional irrigation water storage based on the principle of sustainable development, micro-simulation, and econometrics [19]. Liu et al. studied the carrying capacity of agricultural water resources in large irrigation districts in Northern China by means of system dynamics simulation combined with set pair analysis and fuzzy comprehensive evaluation [20]. Xiong et al. used the analytic hierarchy process to analyze and predict the carrying capacity of agricultural water resources in Qitai County of Xinjiang. The evaluation scale is a county-level administrative region, which has a certain guiding significance for large-scale popularization and application [21]. He et al. calculated the grain output that the Songhua River agricultural water resources can bear by converting multi-objective planning into single-objective planning through constraints, so as to reflect the impact of agricultural water resources on the social economy [22]. Liu et al. used set pair analysis to evaluate the carrying capacity of groundwater resources in the Sanjiang Plain irrigation area [23]. Among these methods, set pair analysis (SPA) is clear in concept, simple in calculation, and comprehensive in information consideration. It depicts the certainty and uncertainty systematically from three aspects and five-element connection number SPA subdivides the same–different–opposite connection number in the original theory into same, partial same–different, different, partial opposite–different and opposite connection numbers, which enhances the integrity and effectiveness of the theory [24]. Therefore, this paper uses five-element connection number SPA to evaluate the agricultural water resources' carrying capacity in the Haihe River Basin.

The Haihe River Basin is one of the three major grain production bases in China, and water resources of this area have been extensively studied [25–27]. Most of the research studies on the carrying capacity of the Haihe River Basin focus on the evaluation of the water resources' carrying capacity. There are few studies on the optimization of the main factors based on evaluation results, with even fewer studies on the AWRCC. In order to better understand the impact of optimization on results, two main factors: groundwater and effective irrigation area, are used to optimize the AWRCC of the Haihe River Basin. By reducing groundwater exploitation and increasing effective irrigation area, respectively, using AROL (Aiming to raise one level up) model, the AWRCC of different areas in Haihe River Basin is optimized to achieve a "better level." In order to change the influencing factors to upgrade the levels, clear and distinct results are provided to decision makers.

The main purpose of this study is to evaluate the agricultural water resources' carrying capacity in the Haihe River Basin in 2012 and to upgrade the AWRCC by optimizing the main factors based on previous evaluation results. In this case, a five-element connection number set pair analysis model of AWRCC was built to evaluate the current level of AWRCC in different regions of the Haihe River Basin. Based on this result, an optimization model of the groundwater exploitation rate and the effective irrigation area is established to provide the decision-making basis for future agricultural water utilization, social and economic development, and groundwater protection programs. In Section 2, the study area and data are presented. Then the methodologies for the evaluation and optimization of AWRCC are introduced. Section 3 involves the results and discussion. In Section 4, the evaluation results and optimization results are discussed. Lastly, Section 5 concludes the paper and makes some recommendations.

2. Materials and Methods

2.1. Study Area and Data Sources

2.1.1. Study Area

The Haihe River Basin is located in North China. The basin covers eight provinces (autonomous regions and municipalities directly under the central government), including Beijing and Tianjin, Hebei, Henan, Shandong, Shanxi and Inner Mongolia, and Liaoning provinces (Figure 1). The total area of the whole basin is 318,000 km², which accounts for 3.31% of the total area of the whole country, of which plain and mountainous areas account for 40% and 60%, respectively. The Haihe River Basin is located in the semi-humid and semi-arid continental monsoon climate zone with an annual average temperature of 10.36 °C.

The Haihe River Basin is rich in light and heat and land resources, suitable for crop growth. With a population of 1.37×10^8 , agricultural products are largely demanded. In order to meet such great demand, unreasonable agriculture has been developed and led to some serious problems. The total utilization of water resources in the basin is about 98%. Shallow groundwater in the basin is severely over-exploited, with an area of 46,000 km² [28]. The area of general over-exploited area and serious over-exploited area reach 54% and 46%, respectively, with the total exploitation and utilization degree of 110.4% [29]. Additionally, the pollution of agricultural water and soil resources in the Haihe River Basin is very serious. A large amount of wastewater is directly used for agricultural irrigation without treatment, which threatens the agricultural ecological environment and food quality and safety in the basin. In the meantime, the utilization coefficient of agricultural water in the Haihe River Basin is low, and groundwater overdraft is serious because of agricultural needs. The irrigation water utilization coefficient of large-scale irrigation areas is only 0.48, of which 13 irrigation areas have an irrigation water coefficient lower than 0.4 (10 in Hebei and 3 in Henan). The area for sprinkler irrigation, micro-irrigation, and pipe irrigation is only 43.1×10^4 ha, which accounts for 38.1% of the area suitable for water-saving irrigation. Lower irrigation efficiency exacerbated the crisis in agricultural development [30].

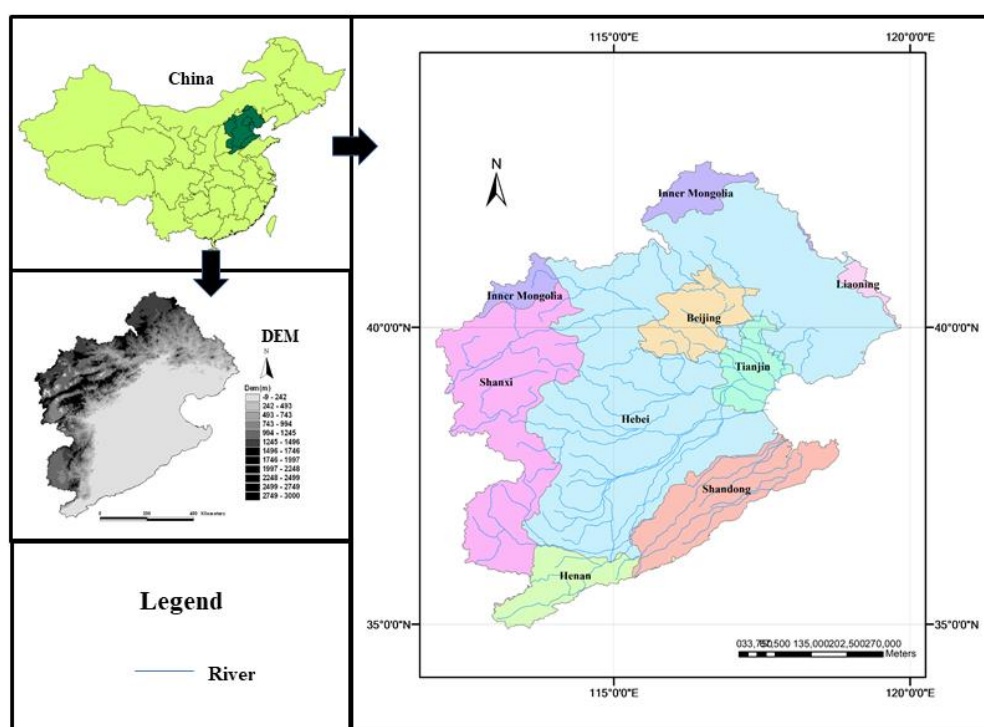


Figure 1. Map of the study area location.

2.1.2. Data Sources

The base year of this paper is 2012. The data in this paper are mainly from the water resources bulletin of the Haihe River Basin from 1998 to 2012 and from many reports such as the Comprehensive Planning of Haihe River Basin, the Evaluation of Water Resources in Haihe River Basin, the Haihe River Basin Water Conservancy Manual, and the China Statistical Yearbook. The raw data, including hydrological data of years, the numbers of livestock, and stockbreeding water use amount, etc., were obtained from the China National Digital Library, the China Meteorological Science Data Sharing Service Network, and the Haihe River Water Conservancy Commission (Table 1).

Table 1. Data and data sources.

Date	Data Sources and Links	Date	Data Sources and Links
Effective irrigation area	Hiahe Yearbook 2013 (http://cyfd.cnki.com.cn/N2017110269.htm)	Water supply quantity	China Statistical Yearbook 2013 (http://www.stats.gov.cn/tjsj/ndsj/2013/indexch.htm)
Irrigated area		Total water consumption	
Agricultural water consumption		Irrigation water	
Annual groundwater supply quantity		Irrigated land area	China National Digital Library (http://www.nlc.cn/)
Exploitable amount of groundwater resources		Calculated land area	
Surface water supply quantity		Population	Haihe River Water Conservancy Commission, MWR (http://www.hwcc.gov.cn/hwcc/static/szygb/gongbao2013/index.htm)
Available amount of surface water resources		Water saving irrigation data	

2.1.3. Framework

This paper attempts to combine the optimization model with the evaluation model for AWRCC, as Figure 2 shows. It is mainly composed of two parts: (1) The evaluation model is applied to evaluate the current AWRCC situation of each area by a five-element connection number SPA for the optimization model. (2) Take upgrading AWRCC of each area to a higher level as the goal. The optimization model (ARLO model) is used to calculate the changes in the groundwater exploitation rate and effective irrigation area to achieve the goal.

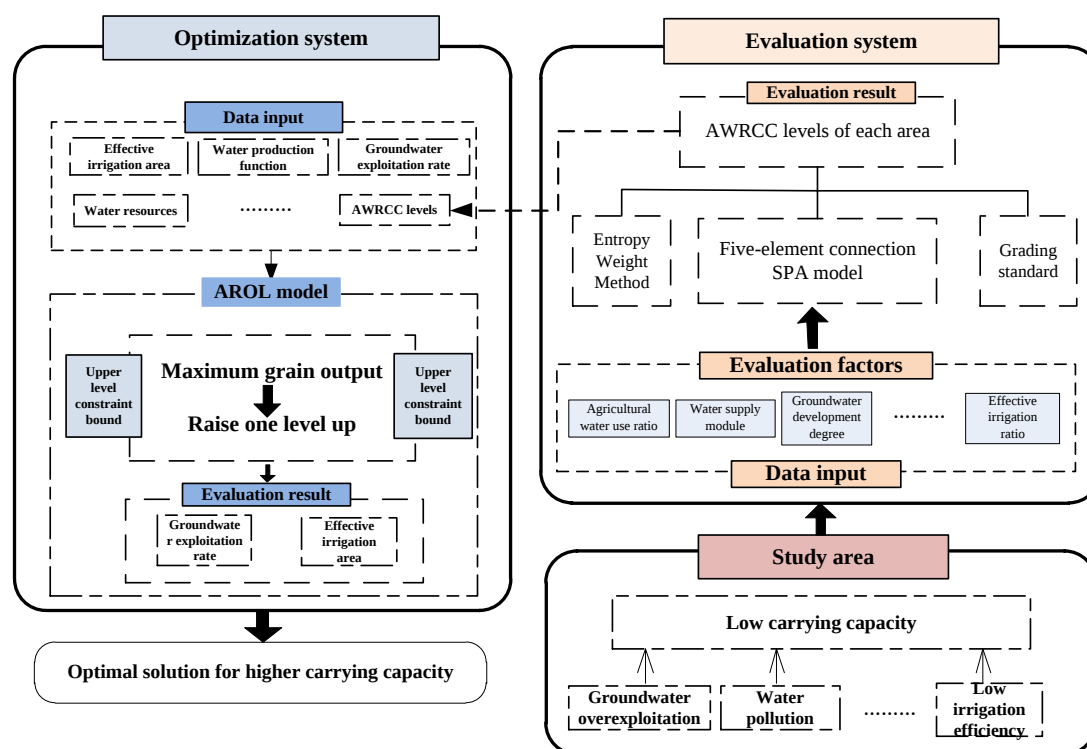


Figure 2. System framework.

2.2. Construction of AWRCC Evaluation System and Gradation of Evaluation Factors

The basic indexes of the evaluation system of agricultural water resources carrying capacity should be able to clearly and concisely express the complicated relationship among water resources, agricultural water use level, and irrigation and water conservancy infrastructure. Under operable, representative, systematic, universal, and data availability principles, six evaluation indexes are selected, and the AWRCC evaluation system of the Haihe Basin is constructed as follows.

Effective irrigation ratio R_e : reflects the regional irrigation infrastructure or equipment allocation. Effective irrigation area refers to the area of cultivated land where irrigation works are basically equipped with infrastructure, the land is relatively flat and has a certain water source, and the effective irrigation ratio is higher. These factors indicate that the less water is wasted such as traditional flood irrigation in the field, the higher the agricultural production carried by agricultural water resources is. The formula is as follows.

$$R_e = \frac{S_{ei}}{S_a} \quad (1)$$

where S_{ei} is the effective irrigation area, 10^4 ha. S_a is the irrigated area, 10^4 ha.

Water supply module M_w : ratio of water supply W_s to calculated land area S , representing the degree of water supply per unit land area. Based on the basic balance between water supply and water use, the water supply per unit area basically reflects the water use per unit land area. On the premise that the total production value and total resources remain constant, the lower the water use per unit land area is, the greater the space is and the greater the carrying potential is. The formula is as follows.

$$M_w = \frac{W_s}{S} \quad (2)$$

where W_s is the water supply quantity in 10^4 m³. S is the calculated land area in km².

Agricultural water use ratio R_a : represents the agricultural water use level. At this stage, under the background of regional resource shortage, production water has changed from “supply by demand” to “supply by demand,” which is significantly affected by water management and other water-related systems. The lower the proportion of water used in agriculture, the more water will be transferred to other production activities such as industry. On the premise of ensuring food production safety, the higher the social and economic output value is. In addition, the stronger the ability to feed agriculture is, the greater the potential of agricultural production activities that can be carried. The formula is as follows.

$$R_a = \frac{W_a}{W} \quad (3)$$

where W_a is agricultural water consumption in 10^4 m³, and W is the total water consumption in 10^4 m³.

Average irrigation water consumption per ha Q_w : reflects irrigation water consumption and is significantly affected by rainfall. The mechanical growth of the population determines that grain production has met a stable guarantee rate, so the continuous development and popularization of efficient water-saving technologies are needed as strong support. Under certain conditions of grain production, the lower the average irrigation water consumption per ha is and the less the total amount of water needed. The more agricultural production that can be carried by the agricultural available water resources is, the greater the carrying potential is. The formula is as follows.

$$Q_w = \frac{W_i}{S_i} \quad (4)$$

where W_i is irrigation water in m³, and S_i is the irrigated land area in ha.

Groundwater development degree D_{gw} : It reflects the development potential of groundwater resources and has a direct impact on ecological and environmental issues such as river recharge, land subsidence, and seawater intrusion. When there is a serious excess of groundwater exploitation in the

area, it will easily lead to the formation of a large-scale underground water-lowering funnel, which will lead to the ground subsidence, farmland destruction, ground fissures, and collapse of agricultural buildings. It also greatly reduces the carrying capacity of agricultural water resources. The formula is as follows.

$$D_{gw} = \frac{W_{us}}{W_u} \quad (5)$$

In the formula, W_{us} is the annual groundwater supply quantity in 10^4 m^3 . W_u is the exploitable amount of groundwater resources in 10^4 m^3 .

Surface water development degree D_{sw} : reflects the development degree and potential of surface water resources. The surface water resources in the Haihe River Basin are unevenly distributed in time and space, and the development and utilization of surface water have diverted the ecological environment water in the river channel and led to a sharp decline in wetlands in some areas. Excessive exploitation of surface water resources is not conducive to the protection of the ecological environment and reduces the carrying capacity of agricultural water resources.

$$D_{sw} = \frac{W_{ss}}{W_{as}} \quad (6)$$

where W_{ss} is the surface water supply quantity in 10^4 m^3 ; W_{as} is the available amount of surface water resources in 10^4 m^3 .

Based on the discussion above and the previous research literature of equality and definition standards [31,32], the impact of the above AWRCC evaluation factors are divided into five levels I ~ V (Table 2). Among them, Level I represents a good situation, which means the regional AWRCC is at a relatively high level, and the water resources have great carrying potential for agricultural production. Level II shows that, although the development of agricultural irrigation has a certain scale, it still has carrying potential. Level IV indicates that the carrying capacity is saturated and the poor condition is overload. Level V represents a bad situation, which means the regional AWRCC is low and the situation is very poor. There is already a serious shortage of water for agriculture. Level III is between Level II and IV and is in a critical state, with no excess load but no overload.

Table 2. The evaluation system and grading standard of agricultural water resource carrying capacity.

Index	Unit	Grading Standards				
		I	II	III	IV	V
R_e	%	90	70	50	30	10
M_w	$10^4 \text{ m}^3/\text{km}^2$	4.3	5.7	7.1	8.6	10
R_a	%	32	43	54	64	75
Q_w	m^3/ha	180	215	250	285	320
D_{gw}	%	13.7	18.3	22.8	27.4	31.9
D_{sw}	%	40.9	54.5	68.2	81.8	95.4

2.3. Evaluation of AWRCC by Five-Element Connection Number Set Pair Analysis Model Based on the Entropy Weight Method

2.3.1. Determination of the Weight Coefficient by the Entropy Weight Method

The entropy weight method is widely used in weight determination because of its objectivity and accuracy. The greater the degree of variation between evaluation units, the more information the index contains and the higher the weight value accordingly [33]. Therefore, in order to make the evaluation result more accurate and objective, the entropy method is used to determine the index weight. The specific steps of this method are as follows.

A judgment matrix of n evaluation indexes of m evaluation objects is constructed.

$$R = (x_{ij})_{mn}, (i = 1, 2, \dots, m, j = 1, 2, \dots, n) \quad (7)$$

where x_{ij} is the value of the j -th evaluation area of the i -th evaluation factor.

Normalize the judgment matrix R to obtain a normalized judgment matrix B .

$$b_{ij} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} \quad (8)$$

where $x_{\max}$, $x_{\min}$, respectively, indicate the most satisfied and the least satisfied among different evaluation factors under the same area.

According to the definition of entropy, the entropy of each evaluation index can be determined as follows.

$$H_j = -\frac{1}{\ln m} \left(\sum_{i=1}^m f_{ij} \ln f_{ij} \right) \quad (9)$$

$$f_{ij} = \frac{1 + b_{ij}}{\sum_{j=1}^m (1 + b_{ij})} (i = 1, 2, \dots, n, j = 1, 2, \dots, m) \quad (10)$$

The entropy weight of each evaluation area is shown below.

$$w_i = \frac{1 - H_j}{n - \sum_{j=1}^n H_j}, \left(\sum_{j=1}^n w_j = 1 \right) \quad (11)$$

where w_i is the entropy weight of the j -th evaluation factor.

2.3.2. Five-Element Connection Number Set Pair Analysis Model

Set Pair Analysis (SPA) is a systematic analysis method for studying uncertain systems. It has been widely used in many fields of science and social sciences such as management, decision-making, and artificial intelligence. The five-element connection number is the improvement of the identical, discrepancy, and contrary connection number in set pair analysis theory, which can be more thoroughly used for system uncertainty analysis. The advantage of the five-element connection number set pair analysis not only reflects the unity of the problem but also takes into account the opposition and difference of the problem.

The number of connections is a structural function used to describe the certainty and uncertainty of these items and the interaction between them. The basic form of the connection number is $U = A + B_i$, which is also known as "binary connections numbers." Expand binary connection numbers to ternary connection numbers: $U = A + B_{i1} + C_j$; expand the ternary connection numbers to the quaternion connection numbers: $U = A + B_{i1} + C_{i2} + D_j$. Expand the quaternion connection numbers to five-element connection numbers: $U = A + B_{i1} + C_{i2} + D_{i3} + E_{jk}$.

Let set A and set B share N characteristics, of which S are shared by two sets in a set pair, the two sets are opposite on the other P characteristics, and the relation between the two sets is uncertain on the other F characteristics. Then the relation between the two sets is shown below.

$$\mu = \frac{S}{N} + \frac{F}{N}i + \frac{P}{N}j \quad (12)$$

If $a = S/N$, $b = F/N$, $c = P/N$, and $a + b + c = 1$ are satisfied, the formula can be abbreviated below.

$$\mu = a + bi + cj \quad (13)$$

In the formula, μ is the degree of connection, which can systematically and comprehensively describe the anti-identical connections between pairs of research sets. The same degree $a \in [0,1]$, the difference degree $b \in [0,1]$, the opposition degree $c \in [0,1]$, the relative determination of a , b , and c , relative uncertainty of b , and satisfaction of $a + b + c = 1$. In addition, i is the difference coefficient, $i \in [-1,1]$. The closer i is to 0, the greater the uncertainty information contained in the system. j is the opposition coefficient, and the constant value is -1 to indicate that the opposition degree P/N is opposite of the same degree S/N .

The five-element connection number subdivides the same - different - opposite connection number in the set pair analysis theory into the partial same - different connection numbers and partial opposite - different connection numbers, which enhances the integrity and effectiveness of the original ternary connection numbers, analyzes, and describes the uncertain information in the system more accurately. The formula is shown below.

$$\mu = a + b_1 i_1 + b_2 i_2 + b_3 i_3 + c j \quad (14)$$

where: $a \in [0,1]$, $b \in [0,1]$, $c \in [0,1]$, and $a + b_1 + b_2 + b_3 + c = 1$; $i \in [-1,1]$, $j = -1$. a represents the same, b_1 represents partial same, b_2 represents the difference, b_3 represents partial opposite, and c represents the opposite.

The set pair analysis model of the five-element connection number is shown below.

$$\mu_s = \sum_{j=1}^n (w_j \mu_{sj}) = a + b_1 i_1 + b_2 i_2 + b_3 i_3 + c j \quad (15)$$

where μ_s is the total degree of connection in the region. w_k is the weight of each index, μ_{sk} is the k -th index connection degree, $n = 6$. A , b_1 , b_2 , b_3 , and c represent the correlation coefficients between the carrying capacity of agricultural water resources and levels I to V in the sense of comprehensive indicators. According to the "principle of equal distribution," $[-1,1]$ is divided into five parts, $[-1, -0.6]$, $[-0.6, -0.2]$, $[-0.2, 0.2]$, $[0.2, 0.6]$, $[0.6, 1]$ corresponding to V, IV, III, II, and I, respectively. If $i_1 = 0.5$, $i_2 = 0$, $i_3 = -0.5$, $j = -1$, the corresponding number and corresponding level of the comprehensive evaluation of agricultural water resources carrying capacity in each region can be calculated using the formula below.

$$\mu_s = a + 0.5 \cdot b_1 + 0 \cdot b_2 + (-0.5) \cdot b_3 + (-1) \cdot c \quad (16)$$

The calculation method of the five-element connection number of agricultural water resources carrying capacity is shown in Table 3, and the parameters a , b_1 , b_2 , b_3 , and c of each index are calculated, respectively.

Table 3. The calculation method of five-element connection numbers.

Five-Element Connection Numbers μ_{sk}	Cost Index	Benefit Index
$1 + 0i_1 + 0i_2 + 0i_3 + 0$	$x \leq k_1$	$x \geq k_1$
$\left \frac{x-k_2}{k_1-k_2} \right + \left \frac{x-k_1}{k_1-k_2} \right i_1 + 0i_2 + 0i_3 + 0j$	$k_1 \leq x \leq k_2$	$k_2 \leq x \leq k_1$
$0 + \left \frac{x-k_3}{k_2-k_3} \right i_1 + \left \frac{x-k_2}{k_2-k_3} \right i_2 + 0i_3 + 0j$	$k_2 \leq x \leq k_3$	$k_3 \leq x \leq k_2$
$0 + 0i_1 + \left \frac{x-k_4}{k_3-k_4} \right i_2 + \left \frac{x-k_3}{k_3-k_4} \right i_3 + 0j$	$k_3 \leq x \leq k_4$	$k_4 \leq x \leq k_3$
$0 + 0i_1 + 0i_2 + \left \frac{x-k_5}{k_4-k_5} \right i_3 + \left \frac{x-k_4}{k_4-k_5} \right j$	$k_4 \leq x \leq k_5$	$k_5 \leq x \leq k_4$
$0 + 0i_1 + 0i_2 + 0i_3 + j$	$x \geq k_5$	$x \leq k_5$

2.4. AROL Optimization Model

Based on the evaluation of the current AWRCC in the Haihe River Basin by using set pair analysis, the highest per ha grain yield is taken as the objective function, to raise one level higher than the current level of each region as a constraint condition. The optimization model (AROL model) is established.

2.4.1. Construction of the AROL Model

In the traditional deterministic planning model, the objective function is usually a single or multiple conflicting objectives, with limited resources and various requirements as constraints [34]. The specific forms are shown below.

$$\begin{cases} \text{Min } f(x) = \{f_1(x), f_2(x), \dots, f_3(x)\} \\ \text{s.t. } g_{k_1}(x) \leq 0 & (k_1 = 1, 2, \dots, l_1) \\ h_{k_2}(x) = 0 & (k_2 = 1, 2, \dots, l_2) \\ x = [x_1, x_2, \dots, x_{l_3}]^T & x_{k_3\min} \leq x_{k_3} \leq x_{k_3\max} (k_3 = 1, 2, \dots, l_3) \end{cases} \quad (17)$$

where: $f(x)$ is the objective function, l is the number of objective functions, $g(x)$ is an inequality constraint, l_1 is the number of inequality constraints, $h(x)$ is an equality constraint, l_2 is the number of equality constraints, x is the decision variable, l_3 is the number of decision variables, $x_{k_3\min}$ is the minimum value of decision variables x_{k_3} , and $x_{k_3\max}$ is the maximum value of the decision variable x_{k_3} .

When there are uncertain factors in the actual problem, it is more reasonable to express the objective function and the parameters in the constraint conditions as interval numbers. Meanwhile, the decision variables and the objective function will also be expressed as intervals in which the specific forms are as follows:

$$\begin{cases} \text{Min } f^\pm(x^\pm, a^\pm) = \{f_1^\pm(x^\pm, a^\pm), f_2^\pm(x^\pm, a^\pm), \dots, f_l^\pm(x^\pm, a^\pm)\} \\ \text{s.t. } g_{k_1}^\pm(x^\pm, a^\pm) \leq b_{k_1}^\pm & b_{k_1}^\pm = [b_{k_1}^-, b_{k_1}^+] & (k_1 = 1, 2, \dots, l_1) \\ h_{k_2}^\pm(x^\pm, a^\pm) = b_{k_2}^\pm & b_{k_2}^\pm = [b_{k_2}^-, b_{k_2}^+] & (k_2 = 1, 2, \dots, l_2) \\ x^\pm = [x_1^\pm, x_2^\pm, \dots, x_{l_3}^\pm]^T & x_{k_3\min} \leq x_{k_1}^\pm \leq x_{k_3\max} & (k_3 = 1, 2, \dots, l_3) \\ a^\pm = [a_1^\pm, a_2^\pm, \dots, a_{l_4}^\pm]^T & a_{k_4}^\pm = [a_{k_4}^-, a_{k_4}^+] & (k_4 = 1, 2, \dots, l_4) \end{cases} \quad (18)$$

where: $f^\pm(x^\pm, a^\pm)$ is the interval objective function; $g^\pm(x^\pm, a^\pm)$ is an interval inequality constraint, $b_{k_1}^\pm$ is the constraint interval of the inequality k_1 , $h^\pm(x^\pm, a^\pm)$ is an interval equality constraint, $b_{k_2}^\pm$ is the constraint interval of equation k_2 , $x^\pm$ is an interval decision vector of l_3 dimension, and $a^\pm$ is the interval parameter vector of l_4 dimension.

2.4.2. AROL Model of Groundwater Exploitation Rate and Effective Irrigation Area

The problem of overexploitation of groundwater resources is widespread in the Haihe River Basin, and the popularization rate of agricultural water-saving projects is relatively low in some areas. Groundwater resources are often over-exploited for agricultural uses in the Haihe River Basin, as well as in other basins around the world, from the Middle East to South America [35–38]. Research has shown how management of transboundary groundwater resources is more likely to happen at the local level rather than at the national or transboundary level, as users have a direct interest in preserving quantity and quality of its water [39,40]. SDG 6, although not perfect, gives important guidelines and sets goals for improving the sustainable use of water resources [41,42]. Therefore, on the basis of the comprehensive evaluation of agricultural water resources carrying capacity based on set pair analysis, this paper takes the highest grain yield of irrigated grain fields as the objective function, the effective irrigation area x_1 , and groundwater exploitation rate x_5 as the decision variables. It also takes the carrying capacity evaluation level of each region as the constraint condition. Taking the upper and

lower boundary values of the existing level as the constraint condition, by adjusting the exploitation rate of groundwater and effective irrigation area to raise each area one level up. Among the eight districts evaluated, Beijing, Shanxi, Inner Mongolia, and Liaoning were set up to upgrade from Level III to Level II, while Tianjin, Hebei, Henan, and Shandong were upgraded from Level IV to Level III. The concrete form of the AROL model is as follows.

Objective function:

$$\max f^{\pm} = \frac{c^{\pm} \cdot (W_1 + W_2 \cdot x_5^{\pm} + W_3) \cdot r_1^{\pm} \cdot r_2}{x_1^{\pm} \cdot r_3^{\pm}} \quad (19)$$

where: $c^{\pm}$ is the grain moisture productivity, W_1 is the surface water supply, W_2 is the groundwater resources, x_5 is the groundwater exploitation rate, and W_3 is the water supply from other sources. $r_1^{\pm}$ is the proportion of water used for irrigation in grain fields to the total water used, and is set as 5% fluctuation of the current proportion of water used for irrigation. r_2 is the proportion of grain output in irrigated grain fields to total grain output, and $x_1^{\pm}$ is the effective irrigation area and is set to fluctuate up and down by 1×10^4 ha. $r_3^{\pm}$ is the proportion of irrigated grain field area to total irrigated area, and is set as 5% fluctuation of current irrigation water consumption.

Constraint condition:

$$\mu_s^{\pm} \leq K^{\pm} \quad (20)$$

$$\mu_s^{\pm} = \sum_{j=1}^n w_j \cdot \mu_{sj}^{\pm} = \sum_{j=2,3,4,6} w_j \cdot \mu_{sj}^{\pm} + w_1 \cdot \mu_{s1}^{\pm} + w_5 \cdot \mu_{s5}^{\pm} \quad (21)$$

$$\mu_{s1}^{\pm} = \begin{cases} 1 + 0i_1 + 0i_2 + 0i_3 + 0j & x_1^{\pm} \geq k_1 \\ \frac{x_1^{\pm} - k_2}{k_1 - k_2} + \frac{k_1 - x_1^{\pm}}{k_1 - k_2} i_1 + 0i_2 + 0i_3 + 0j & k_2 \leq x_1^{\pm} < k_1 \\ 0 + \frac{x_1^{\pm} - k_3}{k_2 - k_3} i_1 + \frac{k_2 - x_1^{\pm}}{k_2 - k_3} i_2 + 0i_3 + 0j & k_3 \leq x_1^{\pm} < k_2 \\ 0 + 0i_1 + \frac{x_1^{\pm} - k_4}{k_3 - k_4} i_2 + \frac{k_3 - x_1^{\pm}}{k_3 - k_4} i_3 + 0j & k_4 \leq x_1^{\pm} < k_3 \\ 0 + 0i_1 + 0i_2 + \frac{x_1^{\pm} - k_5}{k_4 - k_5} i_3 + \frac{k_4 - x_1^{\pm}}{k_4 - k_5} j & k_5 \leq x_1^{\pm} < k_4 \\ 0 + 0i_1 + 0i_2 + 0i_3 + j & 0 \leq x_1^{\pm} \leq k_5 \end{cases} \quad (22)$$

$$\mu_{s5}^{\pm} = \begin{cases} 1 + 0i_1 + 0i_2 + 0i_3 + 0j & 0 \leq x_5^{\mp} < k'_1 \\ \frac{x_5^{\mp} - k'_2}{k'_1 - k'_2} + \frac{k'_1 - x_5^{\mp}}{k'_1 - k'_2} i_1 + 0i_2 + 0i_3 + 0j & k'_1 \leq x_5^{\mp} < k'_2 \\ 0 + \frac{x_5^{\mp} - k'_3}{k'_2 - k'_3} i_1 + \frac{k'_2 - x_5^{\mp}}{k'_2 - k'_3} i_2 + 0i_3 + 0j & k'_2 \leq x_5^{\mp} < k'_3 \\ 0 + 0i_1 + \frac{x_5^{\mp} - k'_4}{k'_3 - k'_4} i_2 + \frac{k'_3 - x_5^{\mp}}{k'_3 - k'_4} i_3 + 0j & k'_3 \leq x_5^{\mp} < k'_4 \\ 0 + 0i_1 + 0i_2 + \frac{x_5^{\mp} - k'_5}{k'_4 - k'_5} i_3 + \frac{k'_4 - x_5^{\mp}}{k'_4 - k'_5} j & k'_4 \leq x_5^{\mp} < k'_5 \\ 0 + 0i_1 + 0i_2 + 0i_3 + j & x_5^{\mp} \geq k'_5 \end{cases} \quad (23)$$

$$c_3 \leq x_1^{\pm} \leq 100$$

$$k_1 = 90, k_2 = 70, k_3 = 50, k_4 = 30, k_5 = 10$$

$$k'_1 = 13.7, k'_2 = 18.26, k'_3 = 22.86, k'_4 = 27.39, k'_5 = 31.96$$

In the formula, K^+ and K^- are respectively the upper and lower constraint bounds of the comprehensive scores of the corresponding levels after the evaluation of level modulation by one level, c_3 is the actual effective irrigation area, $k_1 \sim k_5$ is the level boundary value of the effective irrigation area, $k'_1 \sim k'_5$ is the level boundary value of the groundwater exploitation rate, x_1 is the effective irrigation area, and x_5 is the groundwater exploitation rate.

3. Results

3.1. Evaluation Factor Weights

According to the simulation results of water resource allocation, the weights of each index are calculated using Equations (7)–(11) and are shown in Table 4. The groundwater development degree has the highest evaluation index and the greatest impact on the agricultural water resources' carrying capacity (AWRCC). This shows that the carrying capacity of agricultural water resources in the Haihe River Basin is closely related to the imbalance of groundwater. It can be seen from the DEM map (Figure 1) that the imbalance of groundwater is deepening from the alluvial flood plain in front of the northwest mountain to the eastern plain. When over-exploitation of local water leads to an imbalance of storage and branch, it is easy to induce the formation of a large-scale groundwater depression funnel, and cause a large drop in groundwater level, which results in land subsidence, ground fissures, collapse of agricultural buildings, destruction of farmland, and a significant reduction in the carrying capacity of agricultural water resources.

Table 4. Evaluation factors weights calculated by the entropy weight method.

Index	Weight	Index	Weight
R_e	0.164	Q_w	0.139
M_{tw}	0.199	D_{gw}^{gw}	0.217
R_d	0.156	D_{sw}^{sw}	0.126

3.2. Evaluation Results

We selected 2012 as the baseline year when the AWRCC of 8 sub-regions in the Haihe River Basin under actual conditions was evaluated by the five-element connection SPA model. The results are shown in Table 5, and the spatial distribution of the agricultural water resources carrying level is shown in Figure 3.

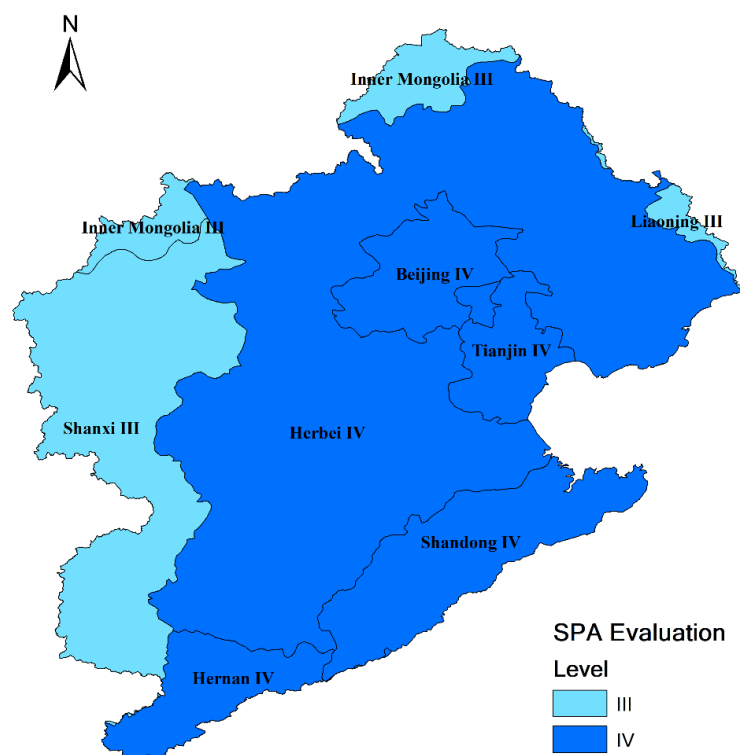


Figure 3. Assessment of agricultural water resources carrying level in the baseline year.

Table 5. Annual AWRCC set pair analysis results of the Haihe district provinces and cities.

Districts	Set Pair Analysis Method for Comprehensive Evaluation	Corresponding Level
Beijing	−0.2145	IV
Tianjin	−0.3890	IV
Hebei	−0.3771	IV
Shanxi	0.1351	III
Henan	−0.4944	IV
Shandong	−0.5140	IV
Inner Mongolia	−0.0850	III
Liaoning	0.1311	III

It can be seen in Table 5 that the agricultural water resources carrying capacity of Beijing, Tianjin, Hebei, Henan, and Shandong are level IV, which are in an overloaded state. Beijing's comprehensive evaluation results are at the boundary between level III and IV. Shandong has the lowest comprehensive score and it is the most serious area in the above provinces and cities. Shanxi, Inner Mongolia, Liaoning have AWRCC of level III and have little carrying potential.

3.3. Optimization Results

After programming and running the model in the Lingo 11.0 environment, the optimization results under the current effective irrigation area ratio and groundwater exploitation rate of various regions are shown in Table 6, and the spatial schematic diagrams are shown in Figure 4, Figure 5, Figure 6, and Figure 7.

Table 6. Adjustment interval of the effective irrigation area and the groundwater exploitation rate.

Districts	Actual Effective Irrigation Rate %	Actual Effective Irrigation Area 10^4 ha	Appropriate Range of Effective Irrigation Area after Adjustment 10^4 ha	Actual Groundwater Exploitation Rate %	Actual Groundwater Exploitation Rate 10^8 m ³	Appropriate Interval of Groundwater Exploitation after Adjustment 10^8 m ³
Beijing	91.13	23.1	[23.1,23.2]	112	25.6	[3.71,8.02]
Tianjin	77.70	34.9	[34.6,39.5]	132	5.71	[0.78,1.37]
Hebei	74.81	446.4	[447.1,524.5]	143	118.06	[16.17,28.91]
Shanxi	30.70	44.3	[46.1,57.2]	41	32.4	[4.44,8.87]
Henan	77.98	61.0	[60.4,69.4]	115	18.32	[2.51,3.53]
Shandong	86.22	128.6	[140.8,145.7]	45	31.54	[4.32,5.99]
Inner Mongolia	38.80	4.5	[7.4, 16.7]	100	2.64	[0.36, 0.53]
Liaoning	59.92	1.1	[1.0,1.2]	37	0.66	[0.09,0.19]

Figure 4 presents the current situation of the effective irrigation area in the Haihe River Basin. The actual effective irrigation rate in the five regions are relatively high, which are Beijing, Tianjin, Hebei, Henan, and Shandong, which accounts for 62.5% of the total number of cities and provinces. According to the results in Table 6 on the basis of the current effective irrigation area in various regions, the appropriate range of effective irrigation area after adjustment in the two large cities Beijing and Tianjin are $21.10 \sim 23.20 \times 10^4$ ha and $0.00 \sim 4.57 \times 10^4$ ha, which are not clear in 2012. The appropriate range of effective irrigation area in Hebei was optimized to increase by $0.65 \times 10^4 \sim 78.10 \times 10^4$ ha over that in 2012, with an increase rate of 0.15% to 17.50%. Similar to Hebei, Henan, and Shandong are also major grain producing areas in the Haihe River Basin. Since only part of areas in Henan and Shandong are in the Haihe River Basin, the increase in the irrigation area is not very clear. The appropriate range of the effective irrigation area after adjustment in Shanxi is 46.1×10^4 to 57.2×10^4 ha, which is an increase of 1.72×10^4 to 12.85×10^4 ha from 2012. Only a small part of Liaoning is located in the Haihe River Basin. The appropriate range of the effective irrigation area after adjustment in Liaoning is 1.0×10^4 to 1.2×10^4 ha, which is similar to Inner Mongolia.

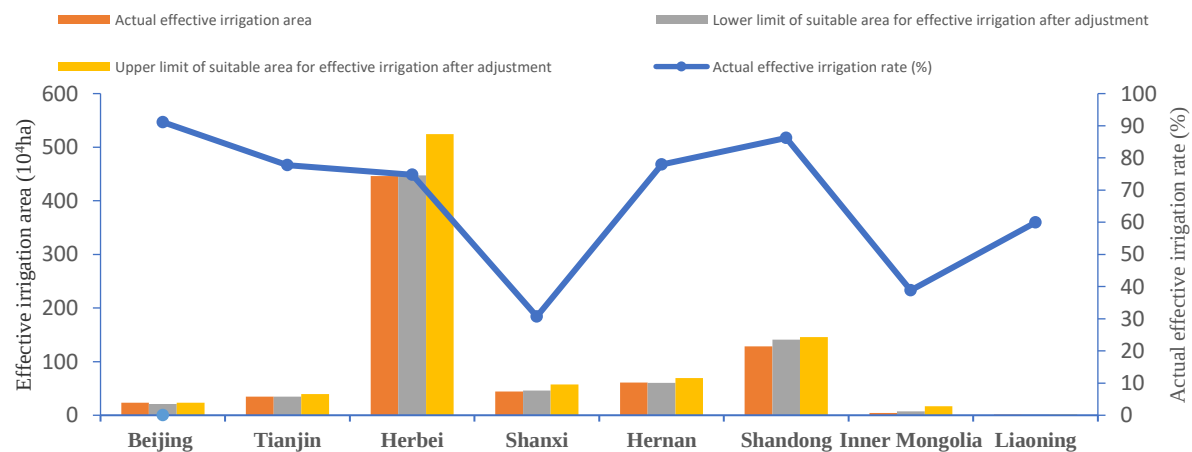


Figure 4. Actual effective irrigation area, rate, and suitable effective irrigation area after adjustment.

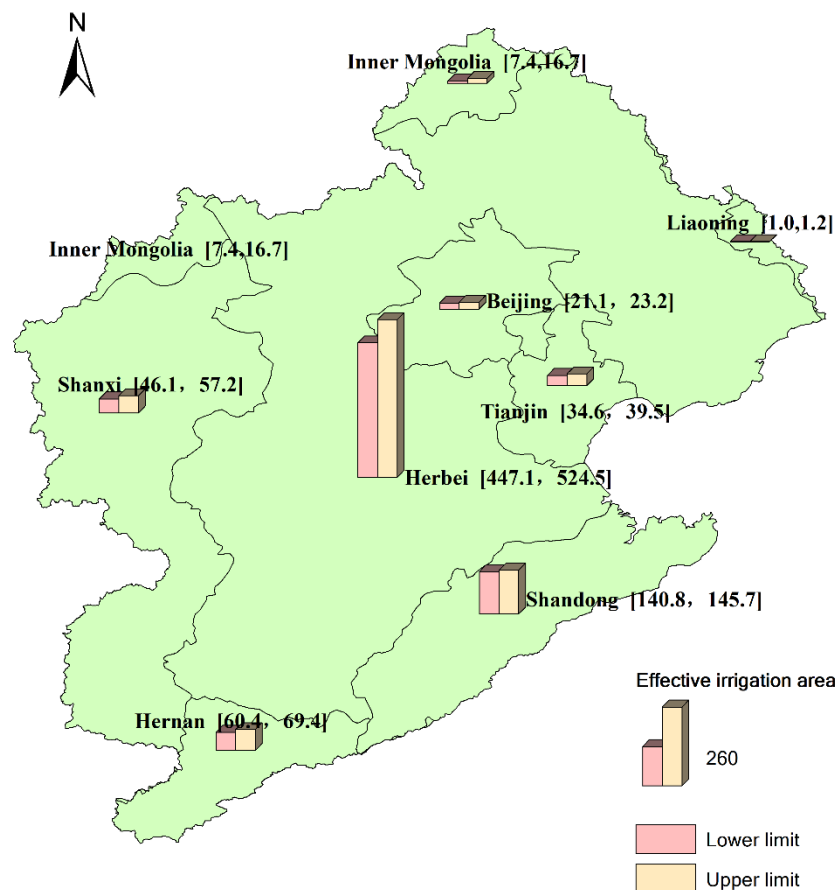


Figure 5. Optimization results of the effective irrigation area in the Haihe River Basin (10⁴ ha).

Figure 6 presents the current situation of groundwater resources exploitation in the Haihe River Basin. The actual groundwater exploitation rate in the five regions are extremely high, which are Beijing, Tianjin, Hebei, Henan, and Inner Mongolia, accounting of 62.5% of the total number of cities and provinces. The appropriate interval of groundwater exploitation after adjustment in Beijing and Tianjin are $3.71 \sim 8.02 \times 10^8 \text{ m}^3$ and $4.34 \sim 4.93 \times 10^8 \text{ m}^3$, respectively. Hebei is the region with the most serious groundwater overdraft in the Haihe River Basin. The appropriate range of groundwater exploitation in Hebei was optimized to decrease by 89.15 to $101.89 \times 10^8 \text{ m}^3$ over that in 2012, with a decreasing rate of 75.51% to 86.30%. Henan, Shandong, and Inner Mongolia were optimized to decrease groundwater exploitation with a decreasing rate of over 80%. The three provinces use more

than 3500 m³ of irrigation water per hectare, with the highest irrigation water consumption in Inner Mongolia being 4245 m³. Most of the overexploited groundwater is used for farmland irrigation, so it is essential to greatly reduce groundwater exploitation if the AWRCC in the above provinces is to be upgraded to a higher level.



Figure 6. Actual groundwater resource, exploitation rate, and suitable groundwater exploitation after adjustment.

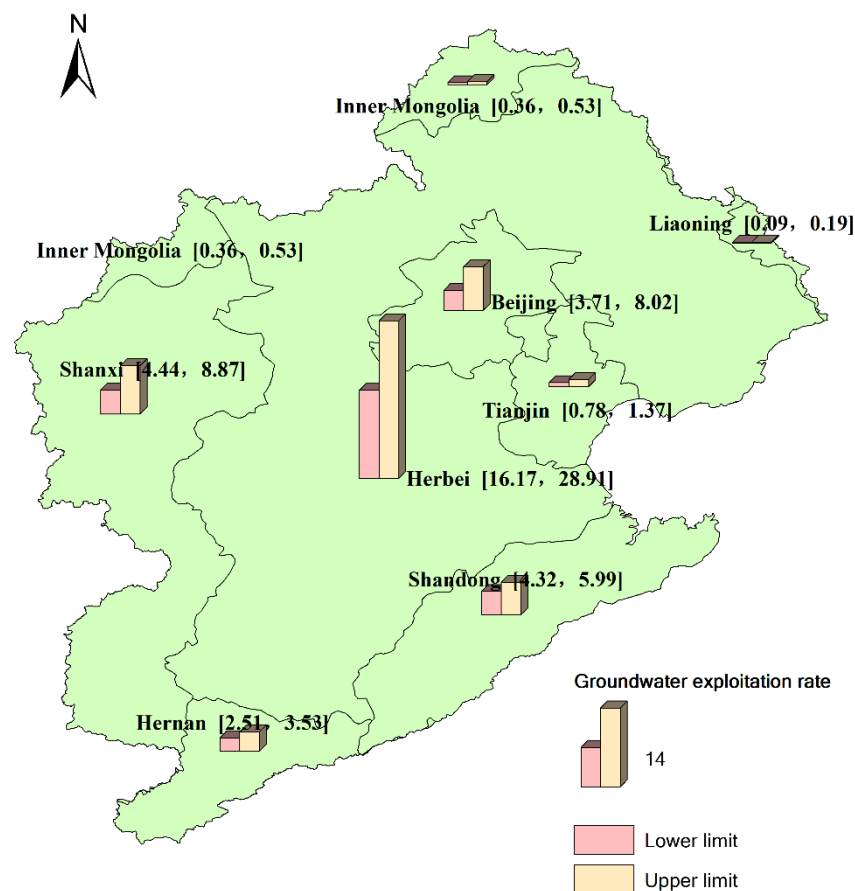


Figure 7. Optimization results of the groundwater exploitation range in the Haihe River Basin (10⁸ m³).

4. Discussion

The carrying potential of agricultural water resources in Shanxi, Inner Mongolia, and Liaoning is in a critical state of level III. However, it is not overloaded. The current carrying potential is low. The effective irrigation area ratios in the above three regions are 31%, 39%, and 60%, respectively. Further infrastructure construction for irrigation projects, strengthening water-saving agricultural transformation, and adjusting agricultural irrigation models are needed to improve the carrying capacity of agricultural available water resources for agricultural production.

Beijing and Tianjin are China's political, economic, and cultural center, and are the region with the fastest urbanization and population mechanization growth in the Haihe River Basin. The irrigation and water conservancy infrastructure are relatively perfect, but the proportion of urban domestic water consumption has been increasing and exceeding 40% of the total water consumption in the past decade. It is still increasing. Agricultural water consumption has been squeezed out continuously, and the carrying potential of agricultural water resources is at level IV. Due to population factors, the carrying potential of agricultural water resources has been overloaded and will not be significantly increased in the future.

A large funnel group connects the funnel areas in the Hebei and Shandong Province. Overexploitation of groundwater seriously affects the ecological environment of the basin, which shrinks and pollutes the wetland area. It also affects the sustainable development of agriculture and the carrying capacity of agricultural water resources is very low. The Shandong Province has the lowest comprehensive score, and the AWRCC is the most serious among the above provinces and cities. Shandong Province is in short supply of water resources, with a per capita resource share of only 283 m³, and the contradiction between supply and demand is prominent. However, the agricultural water use efficiency, which accounts for about 60% of the total water consumption, is very low. The irrigation water utilization coefficient in the irrigation area is less than 0.40 on average, which is seriously wasted and the agricultural water resource carrying capacity is relatively low.

As the optimized result of effective irrigation area shows, Beijing and Tianjin are the first and second largest cities with a large urban population in the Haihe River Basin. The agricultural land has been squeezed out in large numbers in the process of urbanization. Agricultural development is highly modernized and the actual effective irrigation rate is very high. Thus, the promotion potential is very small.

Hebei is the largest province in the Haihe River Basin with a high level of agricultural development, which is located in the North China Plain with the most arable land. Due to a large irrigation area and relatively low actual effective irrigation rate compared with Beijing and Tianjin, Hebei could additionally increase 78.1×10^4 ha in the future, with an increasing rate of 0.15% to 17.50%. The Shanxi Province is located in the Loess Plateau. As a region rich in mineral resources and not suitable for cultivation, Shanxi's economic pillar is industry rather than agriculture. Thus, its agricultural development is relatively backward. Additionally, due to its special geographical conditions, it is difficult and costly to develop high-standard modern agriculture. Only a small part of Inner Mongolia and Liaoning are located in the Haihe River Basin and the increase in the irrigation area is small.

Groundwater exploitation in Beijing and Tianjin is mainly due to the increasing use of domestic water. The South-to-North Water Diversion Project will greatly improve this situation. As a result of a large amount of groundwater overdraft for a long time, seven large groundwater funnel areas have been formed, which causes geological disasters such as land subsidence, seawater backflow, subsidence, and ground fissures. In addition, the water shortage problem will still exist after the implementation of the South-to-North Water Transfer Project and other projects. The groundwater overdraft in Hebei is the most serious in the Haihe River Basin. As a result of a large amount of groundwater overdraft for a long time, seven large groundwater funnel areas have been formed, which cause geological disasters such as land subsidence, seawater backflow, subsidence, and ground fissures. Shanxi is rich in coal resources, and years of coal mining have continuously expanded the scope of groundwater lowering funnels in Shanxi. According to the *'Impact and Evaluation of Coal Exploitation on Water Resources in*

Shanxi Province organized and completed by Shanxi Province, 2.48 tons of groundwater will be lost for every ton of coal dug in the Shanxi Province. Coal mining not only damages the existing groundwater resources but also damages the recharge, runoff, and discharge laws of shallow, medium, and deep groundwater. Since 2007, Shanxi has issued a number of policies to protect groundwater resources. The water supply structure has changed fundamentally from groundwater to surface water.

At present, the extraction and conservation of groundwater in most areas of the Haihe River Basin is in an unbalanced state, with groundwater exploitation rates of more than 100% in Beijing, Tianjin, and Hebei. The degree of imbalance has continuously expanded from the alluvial flood areas in western piedmont to the eastern plains, and groundwater exploitation in all areas should be reduced by more than 68% in order to ensure groundwater safety and ecological safety. As one of China's major grain producing areas, the Haihe River Basin is mainly due to agricultural irrigation. It is feasible to increase AWRCC by reducing groundwater exploitation, but it is not enough to build large-scale water conservancy infrastructure. Due to the particularity of China's agricultural development, there is currently a contradiction between the publicity of water conservancy facilities and the decentralized management of farmers. Decentralized management of irrigation water leads to the reduction of irrigation efficiency and the reduction of an effective irrigation area. At the national level, the construction of water-saving facilities should continue to be promoted. At the individual level, the establishment of farmers' irrigation cooperative organizations is the future trend.

5. Conclusions

This study applies a five-element connection number set pair analysis theory to the evaluation of AWRCC for the first time. Based on the evaluation of the baseline year, an AROL model is proposed to optimize the effective irrigation area and groundwater exploitation to achieve a "higher level" of AWRCC. The following conclusions are drawn:

(1) An evaluation system of AWRCC was proposed based on six indicators. Among them, the weight of groundwater extraction rate is highest, followed by the water supply module, and the groundwater development degree has the lowest weight.

(2) According to the evaluation results of the model, the AWRCC of all cities and provinces in the Haihe River Basin is between level III (no excess capacity but no overload) and level IV (overloaded). Among them, Shandong has the lowest comprehensive score. It is the most serious overloaded area in the above provinces and cities. Apart from the natural environment of the Haihe River Basin itself, the reason for this situation is the growing demand for agricultural product leads to over-exploitation of water resources.

(3) Based on the goal of raising one level higher than the current level, the effective irrigation area and groundwater exploitation were optimized. According to the optimization results, the total effective irrigation area increase is 17.39 to 133.52×10^4 ha. As the largest area in the basin, Hebei contributes the most to the increase with 0.65 to 78.1×10^4 ha, which accounts for 3.73% to 58.49%. As megacities, Beijing and Tianjin do not have much potential to increase the effective irrigation area. Liaoning and Inner Mongolia have little scope for optimization because only a few regions are located in the Haihe River Basin. Total groundwater exploitation decrease is $177.52 \sim 202.55 \times 10^8$ m³ and Hebei contributes the most to the decrease with 89.15 to 101.89×10^8 m³. The groundwater exploitation in all areas should be reduced by more than 68% and, for most areas, by more than 80%. This is mainly due to long-term groundwater overexploitation. The extraction and conservation of groundwater in most areas of the Haihe River Basin are out of balance with the extraction rate of groundwater in Beijing, Tianjin, and Hebei reaching more than 100%. For the sustainable development of agriculture, it is necessary to reduce groundwater exploitation greatly.

There are several suggestions for improving the AWRCC in the Haihe River Basin based on the results.

(1) The weight of the groundwater exploitation rate is relatively high, which has the greatest impact on the carrying capacity of agricultural water resources. The over-exploitation of groundwater should

be gradually reduced, and the transformation from water-consuming agriculture to the water-saving agriculture should be accelerated.

(2) Even though some areas have a good water-saving irrigation infrastructure, agricultural water is still significantly wasted. It is very urgent to establish an economic compensation and reward mechanism for water-saving irrigation to implement water conservation.

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