water

MDPI

Article

Evaluation of Sustainable Use of Water Resources in the Beijing-Tianjin-Hebei Region Based on S-Type Functions and Set Pair Analysis

Baohui Men * and Huanlong Liu

Beijing Key Laboratory of Energy Safety and Clean Utilization, North China Electric Power University, Renewable Energy Institute, Beijing 102206, China; 1172211082@ncepu.edu.cn

* Correspondence: menbh@ncepu.edu.cn; Tel.: +86-010-6177-2451

Received: 5 June 2018; Accepted: 10 July 2018; Published: 12 July 2018

check for updates

Abstract: Beijing-Tianjin-Hebei is an area with insufficient per capita water resources. This study evaluates the current status and development trend of sustainable use of water resources in the region, and identifies specific factors influencing sustainable development so as to provide a theoretical basis and data support for the management of water resources in the Beijing-Tianjin-Hebei region. Applying the compound system of social, economic and ecological environment, this study established an evaluation index system. The evaluation index data is obtained through the relevant calculations based on the National Economic and Social Development Announcement, the Water Resources Bulletin and the National Bureau of Statistics data. The index weights are calculated using a combination of rough set and fuzzy theory. The obtained weights were added to the set pair analysis method to acquire evaluation results. Based on the traditional set pair analysis method, this study proposes a new set pair analysis method (Method 4) using S-type functions (Formula (11)) instead of the addition weighted synthesis method (Formula (10)) in the calculation of weighted connections. In order to verify the feasibility of this method, the Spearman correlation coefficient method was used to calculate the correlation coefficient between evaluation results of Method 4 and evaluation results of other traditional methods. In addition, the set pair exponential potential is adopted to determine the impact indicators of the sustainable utilization of water resources in Beijing-Tianjin-Hebei in this study. The results show that in the Beijing-Tianjin-Hebei region, the overall level of sustainable use of water resources has been gradually raised in the past 12 years. The results of the set pair analysis method that cites S-type functions have obtained higher Spearman correlation coefficients than traditional methods. The values of the correlation coefficients are 0.9954, 0.9910, and 0.9928 respectively in Beijing, Tianjin and Hebei. Moreover, according to the results of set pair exponential potential, the indicators in the region are quasi-inverse potential or strong inverse potential, including per capita water resources and the ecological environment water use rate. Thus, a dense population with scarce water resources, and a lack of ecological water are the common problems that Beijing, Tianjin and Hebei have to face.

Keywords: set pair analysis; S-type functions; set pair exponential potential; sustainable use of water resources; Beijing-Tianjin-Hebei region

1. Introduction

As the total population of the Beijing-Tianjin-Hebei region has surpassed 100 million, it is facing a series of problems such as the continuous deterioration of the ecological environment and insufficient water resources per capita. Thus, in the region, it is of great importance to scientifically evaluate the status quo and the development trend of water resources, find out the specific factors affecting sustainable development, and provide theoretical basis and data support for water resource management [1].

In 1989, Chinese scholar Zhao Keqin put forward set pair analysis theory. So far, this theory has been widely used and developed [2]. In the past set pair analysis model, the most common methods of determining the difference degree coefficient I is the special value method. This method requires the subjective determination of the value of the difference coefficient; it reflects the intention of the decision maker so that the decision and evaluation results own strong subjective randomness. For example, Hou et al. proposed the set pair analysis as a new method to build an ensemble surrogate model to select a better ensemble surrogate modeling pattern for the surfactant-enhanced aquifer remediation strategy optimization problems [3]. Wang et al. combined wavelet de-noising and Rank-Set Pair Analysis to improve the forecasting of hydro meteorological time series [4]. Wei et al. used a set pair analysis model to predict the development trend of integrated carrying capacity [5]. Kumar and Garg attempted to score different preferences of subjects based on the set pair analysis [6]. Li et al. through the combination of analysis and social computing, to expand the study of social characteristics, proposed a new method to describe the relationship between nodes in social networks [7]. Pan et al. applied the system evaluation method based on contact function to the evaluation of natural disaster risk, and assessed the natural disaster risk in Chinese provinces [8]. Yue et al. applied hybrid life cycle and fuzzy set pair analysis methods to comprehensively evaluate the impact of industrial wastewater under uncertain conditions [9].

Some scholars proposed to establish a triangular fuzzy number or apply "two known points" method to determine the value of difference coefficient in order to enhance the theoretical basis of mathematics. For example, Wu et al. established a set pair analysis model based on the triangular fuzzy interval cut set number as a new method for evaluating the impact of urban floods [10]. Liu used a set pair analysis model to accomplish the assessment of the environmental quality and its quantity [11]. In the process of calculating the weighted connection degree, the most common method is the additive weighted synthesis method. For example, Li et al. established a comprehensive model based on k-means cluster analysis and set pair analysis to evaluate the level of water pollution in water sources [12]. Wang and Chen proposed a new model to analyze the risk of expansion and contraction of expansive soils by using the coupled set pair analysis and stochastic simulation of triangular fuzzy numbers [13]. Wang et al. attempted to evaluate the flood disaster based on set pair analysis [14]. Chong et al. applied the theory to analyze the hazards of coal mine occupation [15]. The maximum membership criteria method is used in the process of determining the evaluation grade. For example, Su et al. used the set pair analysis method to assess the health level of the urban ecosystem [16]. However, this method may cause distortion. Common methods for determining rating levels include the level characteristic formula and the confidence criterion, the confidence criterion method requires subjective determination of a confidence level λ [17].

In conclusion, to avoid the impact of subjective factors on the evaluation results, this study uses "attribute recognition method" to determine the degree of connectivity, then proposes to use the S-type function in the process of calculating the weighted connection degree, and uses the level feature formula in determining the evaluation grade to establish a new complete objective evaluation model finally (method 4). The model fully exploited the internal links between data and provided references for the methods of water resources sustainable use assessment.

First of all, this paper established an evaluation index system, and then used a combination of rough set and fuzzy set theory to determine the index weights [18]. Then the weights were brought into the new set pair analysis method (method 4) and existing set pair analysis methods to evaluate the sustainable use of water resources in the Beijing-Tianjin-Hebei region from 2004 to 2015. In order to verify the feasibility of method 4, the Spearman correlation coefficient method was used to analyze the correlation of multiple groups of evaluation results [19]. Besides, in order to improve the sustainable use level of water resources in Beijing-Tianjin-Hebei, the specific influence factors of the Beijing-Tianjin-Hebei area were determined by using the set pair exponential potential so as to provide a theoretical basis and data support for the future management of water resources [20].

2. The Establishment of an Evaluation Index System

2.1. Preliminary Determination of Indicators

The basic indicators of the three subsystems are determined through references and data, based on the principles established in the evaluation index system for the socio-economic-ecological environment complex system and combined with the economic, social and environmental situations and performance of the Beijing-Tianjin-Hebei region in recent years.

2.1.1. Economic Subsystem

The economic subsystem is the core of the entire compound system. The realization of the efficient use of water resources is of great significance for the sustainable use of the entire system. These indicators can be divided into overall characterizations and individual characterizations of water use departments. As for overall characterizations, they are mainly reflected by Gross Domestic Product (GDP)-related indicators such as unit GDP water consumption, GDP growth rate, and ten thousand Yuan GDP water consumption [21]. According to the characterizations of water use departments, they can be further categorized into agricultural, industrial and service sectors. A large part of agricultural water use comes from planting. In this sector, the efficiency of irrigation is taken into consideration, such as the average water resource per mu, water quota, water yield per grain, water-saving irrigation area [22], total irrigation area, guaranteed irrigation water supply rate and irrigation water use factor [23]. The efficiency of industrial water use is measured mainly by economic benefits. This sector includes many relevant indicators such as industrial water recycling rate, unilateral water industrial output value, industrial water quota, ten thousand Yuan added value water withdrawal, process water reuse rate, and industrial water supply guarantee the compliance rate [24]. In view of the ongoing economic transformation in the Beijing-Tianjin-Hebei region, as the service industry is an important pillar of economic development, the water efficiency of this sector should by no means be ignored. The main indicators for the service sector involve the percentage of the tertiary industry in GDP etc. [25].

2.1.2. Ecological Subsystem

The ecological subsystem can be regarded as the foundation of the entire compound system. Without a healthy ecological environment, there is no sustainable use of water resources. Ecological subsystems are subdivided into ecological environment deterioration and ecological environment maintenance [26]. The deterioration of the ecological environment is related to surface water, groundwater, and ecological problems affecting the water environment. Surface water is an important source of water and its quality is very important. Relevant indicators include the comprehensive index of water pollution, the rate of pollution control, the water quality compliance rate, and the water function areas water quality standards. Groundwater is an essential source of water supply, especially for inland areas and regions that are lack of rivers and lakes. Groundwater depletion is engendered by improper conducts such as the over-exploitation of groundwater. Relevant indicators include funnel area and total area ratio [27], use rate of groundwater development, rate of change of groundwater level, and the proportion of salinized area [28]. The overall ecological environment also has a relatively large impact on the sustainable use of water resources. The most obvious one is soil erosion, and soil erosion is also the cause of water pollution. Relevant indicators involve forest coverage [29], green percentage, the proportion of salinization area and the proportion of soil erosion area [30].

When it comes to ecological environment maintenance, it aims to counteract the negative impact that is brought about by the deterioration of the ecological environment and it needs the improvement of people's awareness to protect the ecological environment. Good environmental and ecological system maintenance measures are conducive to prevent further deterioration and even accelerate the recovery of the ecosystem. Relevant indicators can be listed as the reuse rate of recycled water, the rate of water and soil erosion treatment, the ratio of unconventional water supply to total water supply, the satisfaction rate of eco-environmental water demand, the rate of sewage treatment, and the rate of water use in the ecological environment [31].

2.1.3. Social Subsystem

Indicators that characterize social subsystems are divided into two aspects: population and cities. People are the main body of society. The sustainable use of water resources also intends to leave a better world for next generations. Related indicators include natural population growth rate, per capita water consumption, per capita water resources, per capita daily living water, population density, total population and the quota of water consumption per capita. The city is the very place that human beings are rooted in, and urban water consumption occupies a considerable part of the world's water use. Related indicators include urbanization level, tap water penetration rate, water fee and household income ratio, water saving awareness, urban residents Engel coefficient and per capita education level [32].

2.2. The Selection of Index

According to the actual situation in the Beijing-Tianjin-Hebei region, full consideration is given to the connotation of each indicator and its data sources [33]. According to the index selection method in Reference [17], this paper effectively screens the above-mentioned evaluation indicators that characterize the sustainable use of water resources (see Table 1).

Table 1. Evaluation index system of the sustainable use of water resources.

Rule Layer	Index	Unit
Economic subsystem	Ten thousand Yuan GDP water consumption, I_1	$m^3/10^4$ Yuan
	The grain yield per unit water, I_2	kg/m^3
	The value of industrial output per unit water, I_3	Yuan/m^3
	Percentage of the tertiary industry in GDP, I_4	%
Ecological subsystem	Attainment rate of water quality in water function areas, I_5	%
	Forest coverage, I_6	%
	Sewage disposal rate, I_7	%
	Eco-environmental water use rate, I_8	%
	Annual drawdown of groundwater water level, I_9	m
Social subsystem	Per capita domestic water consumption, I_{10}	L/person
	Population density, I_{11}	person/km^2
	Level of urbanization, I_{12}	%
	Average per capita water resources, I_{13}	m^3/person/year

2.3. Index Ideal Set Partition

For the principle of grading, on the basis of referring to the relevant regulations of the state, and adopting the five-level standard division method in combination with the actual situation in the Beijing-Tianjin-Hebei area [34]; for commonly accepted indicators, divide them according to international regulations and standards. For some of the indicators that are not yet in common agreement, divide them referring to actual development situation. The target ideal set is determined by ideal (I), good (II), general (III), early warning (IV), and bad (V) 5 levels, respectively. The division results are shown in Table 2.

Table 2. Results of standardization of evaluation index grades.

Index	I	II	III	IV	V
I_1	<50	50~150	150~250	250~350	>350
I_2	>1.8	1.5~1.8	1.2~1.5	0.8~1.2	<0.8
I_3	>800	600~800	400~600	200~400	<200
I_4	>75	75~60	60~50	50~40	<40
I_5	>80	70~80	60~70	45~60	<45
I_6	>60	50~60	30~50	10~30	<10
I_7	>95	85~95	75~85	65~75	<65
I_8	>30	20~30	15~20	10~15	<10
I_9	<0	0~0.3	0.3~0.6	0.6~1	>1
I_{10}	<160	160~180	180~200	200~220	>220
I_{11}	<200	200~500	500~800	800~1200	>1200
I_{12}	>85	75~85	65~75	55~65	<55
I_{13}	>2600	1700~2600	1000~1700	500~1000	<500

3. Methods

The basic idea of the set pair analysis method is to set the data set of the evaluation object as the index $A = \{x_j | j = 1, 2 \cdots J\}$, x_j is indicator, J is the total number of indicators.

The standard set of evaluation criteria is $B = \left\{ S_{j(k)} \middle| k = 1, 2 \cdots K \right\}$, $S_{j(k)}$ is the threshold value of the grade standard, K is the Number of levels of the grade standard. A and B_k are constructed as a set pair of $H(A, B_k)$, carry out symbol quantization evaluation objects A and symbols of quantitative grading standard B_k, and then the grade standard of A each with respect to the corresponding attribute in the comparison, if you fall into the k level, then the index belong to the class k; at last we will do the corresponding symbol of A and B_k element comparison, statistics the same number of symbols, and reference contact degree concept is the idea expressed in a mathematical formula [35,36].

3.1. Fuzzy Correlation Degree

There are two basic methods for the determination of correlation, namely direct analysis and indirect analysis [37]. Currently we use more of the indirect analysis method adopted to determine the correlation. The indirect analysis method includes two ways, one is on the set pair analysis about the characteristics of analysis of tectonic expression "functional" as fuzzy connection degree, such as "attribute recognition method"; the other is to use the "function" to construct the connection component, and to establish the expression of the fuzzy relation degree, such as the "identical-discrepancy-contrary hierarchy method" [5,38].

3.1.1. Attribute Recognition Method

Lee Fanxiu etc. proposed a "wide area style" contact function structure method to determine the correlation of calculation formula, through analyzing the closeness of the actual value of the indicator and the evaluation level k, the same, different, and opposite quantitative analysis of this attribute is performed, and then the reverse of quantitative analysis. If the index of the actual values and a certain rating are at the same level, then $\mu_{jk} = 1$; if the index of the actual values is adjacent to a certain rating, then $\mu_{jk} \in [-1, 1]$, the closer the sample value x_j is to the rank k, the closer μ_{jk} is to 1, or closer to -1 [9]. The specific calculation formula is shown below.

(1) Evaluation index j connection degree for I level

$$\mu_{j1} = \begin{cases} 1 & a : x \geq S_{j(1)} & b : x \leq S_{j(1)} \\ 1 + \frac{2(x - S_{j(1)})}{S_{j(1)} - S_{j(2)}} & a : S_{j(1)} > x \geq S_{j(2)} & b : S_{j(1)} < x \leq S_{j(2)} \\ -1 & a : x < S_{j(2)} & b : x > S_{j(2)} \end{cases} \quad (1)$$

(2) Evaluation index j connection degree for II level

$$\mu_{j2}=\begin{cases} 1+\frac{2(x-S_{j(1)})}{S_{j(1)}-S_{j(0)}} & a: x\geq S_{j(1)} \quad b: x\leq S_{j(1)} \\ 1 & a: S_{j(1)}>x\geq S_{j(2)} \quad b: S_{j(1)}<x\leq S_{j(2)} \\ 1+\frac{2(x-S_{j(2)})}{S_{j(2)}-S_{j(3)}} & a: S_{j(2)}>x\geq S_{j(3)} \quad b: S_{j(2)}<x\leq S_{j(3)} \\ -1 & a: x<S_{j(3)} \quad b: x>S_{j(3)} \end{cases} \tag{2}$$

(3) Evaluation index j connection degree for III level

$$\mu_{j3}=\begin{cases} -1 & a: x\geq S_{j(1)} \quad b: x\leq S_{j(1)} \\ 1+\frac{2(x-S_{j(2)})}{S_{j(2)}-S_{j(1)}} & a: S_{j(1)}>x\geq S_{j(2)} \quad b: S_{j(1)}<x\leq S_{j(2)} \\ 1 & a: S_{j(2)}>x\geq S_{j(3)} \quad b: S_{j(2)}<x\leq S_{j(3)} \\ 1+\frac{2(x-S_{j(3)})}{S_{j(3)}-S_{j(4)}} & a: S_{j(3)}>x\geq S_{j(4)} \quad b: S_{j(3)}<x\leq S_{j(4)} \\ -1 & a: x<S_{j(4)} \quad b: x>S_{j(4)} \end{cases} \tag{3}$$

(4) Evaluation index j connection degree for IV level

$$\mu_{j4}=\begin{cases} -1 & a: x\geq S_{j(2)} \quad b: x\leq S_{j(2)} \\ 1+\frac{2(x-S_{j(3)})}{S_{j(3)}-S_{j(2)}} & a: S_{j(2)}>x\geq S_{j(3)} \quad b: S_{j(2)}<x\leq S_{j(3)} \\ 1 & a: S_{j(3)}>x\geq S_{j(4)} \quad b: S_{j(3)}<x\leq S_{j(4)} \\ 1+\frac{2(x-S_{j(4)})}{S_{j(4)}-S_{j(5)}} & a: x<S_{j(4)} \quad b: x>S_{j(4)} \end{cases} \tag{4}$$

(5) Evaluation index j connection degree for V level

$$\mu_{j5}=\begin{cases} -1 & a: x\geq S_{j(3)} \quad b: x\leq S_{j(3)} \\ 1+\frac{2(x-S_{j(4)})}{S_{j(4)}-S_{j(3)}} & a: S_{j(3)}>x\geq S_{j(4)} \quad b: S_{j(3)}<x\leq S_{j(4)} \\ 1 & a: x<S_{j(4)} \quad b: x>S_{j(4)} \end{cases} \tag{5}$$

In the formula: a represents the forward indicator, b represents the opposite index, $S_{j(0)}$ and $S_{j(5)}$ represents the left and right extremum of the standard value respectively. When no value is given, for the forward type indicator $S_{j(0)}=+\infty$, $S_{j(5)}=0$, for the reverse type indicator $S_{j(0)}=0$, $S_{j(5)}=+\infty$.

3.1.2. Identical-Discrepancy-Contrary Hierarchy Method

According to set pair analysis hierarchy theory, to establish the identical discrepancy contrary hierarchy [12], connection degree expression can be expressed as $\mu=a_1+a_2+b_1I_1+b_2I_2+b_3I_3+c_1J_1+c_2J_2$, for the level threshold with a lack of left extreme value $S_{j(0)}$ and right extreme value $S_{j(5)}$, the identical degree a_1 and a_2 can be merged into a, and the contrary degree c_1J_1 and c_2J_2 can be merged into cJ, the corresponding connection degree expression for

$$\mu_{jk}=\begin{cases} 1+0I_1+0I_2+0I_3+0J & a: x\geq S_{j(1)} \quad b: x\leq S_{j(1)} \\ \frac{x-S_{j(2)}}{2(S_{j(1)}-S_{j(2)})}+0.5I_1+\frac{S_{j(1)}-x}{2(S_{j(1)}-S_{j(2)})}I_2+0I_3+0J & a: S_{j(1)}>x\geq S_{j(2)} \quad b: S_{j(1)}<x\leq S_{j(2)} \\ 0+\frac{x-S_{j(3)}}{2(S_{j(2)}-S_{j(3)})}I_1+0.5I_2+\frac{S_{j(2)}-x}{2(S_{j(2)}-S_{j(3)})}I_3+0J & a: S_{j(2)}>x\geq S_{j(3)} \quad b: S_{j(2)}<x\leq S_{j(3)} \\ 0+0I_1+\frac{x-S_{j(4)}}{2(S_{j(3)}-S_{j(4)})}I_2+0.5I_3+\frac{S_{j(3)}-x}{2(S_{j(3)}-S_{j(4)})}J & a: S_{j(3)}>x\geq S_{j(4)} \quad a: S_{j(3)}>x\geq S_{j(4)} \\ 0+0I_1+0I_2+0I_3+1J & a: x<S_{j(4)} \quad b: x>S_{j(4)} \end{cases} \tag{6}$$

In the formula, the value I range of the difference coefficient is $[-1, 1]$. In this paper, the principle of the intermediate value is taken according to the special value method. In addition to the expressions

$I_1 = -0.5,\ I_2 = 0, I_3 = -0.5$, the contrary degree $J = -1$. In addition to the above expression, the adjacent hierarchical contact components are determined according to the principle of "attribute recognition", and the correlation calculation formula can also be expressed as:

$$\mu_{jk} = \begin{cases} 1 + 0I_1 + 0I_2 + 0J & a : x \geq S_{j(1)} \quad b : x \leq S_{j(1)} \\ \frac{x - S_{j(2)}}{S_{j(1)} - S_{j(2)}} + \frac{S_{j(1)} - x}{S_{j(1)} - S_{j(2)}} I_1 + 0I_2 + 0J & a : S_{j(1)} > x \geq S_{j(2)} \quad b : S_{j(1)} < x \leq S_{j(2)} \\ 0 + \frac{x - S_{j(3)}}{S_{j(2)} - S_{j(3)}} I_1 + \frac{S_{j(2)} - x}{S_{j(2)} - S_{j(3)}} I_2 + 0J & a : S_{j(2)} > x \geq S_{j(3)} \quad b : S_{j(2)} < x \leq S_{j(3)} \\ 0 + 0I_1 + \frac{x - S_{j(4)}}{S_{j(3)} - S_{j(4)}} I_2 + \frac{S_{j(3)} - x}{S_{j(3)} - S_{j(4)}} J & a : S_{j(3)} > x \geq S_{j(4)} \quad a : S_{j(3)} > x \geq S_{j(4)} \\ 0 + 0I_1 + 0I_2 + 1J & a : x < S_{j(4)} \quad b : x > S_{j(4)} \end{cases} \tag{7}$$

In the formula, the difference coefficient I is determined by applying the triangular fuzzy number [39]. In this method, the fuzzy number of parameters is constructed by evaluating the threshold value of the class as fuzzy number, and the difference coefficient is calculated by the difference between the left extreme value $S_{j(0)}$ and the right extreme value $S_{j(5)}$.

$$I_1 = \begin{cases} 0 & a : x \geq S_{j(1)} \quad b : x \leq S_{j(1)} \\ \frac{S_{j(1)} - x}{3(S_{j(1)} - S_{j(2)})} & a : S_{j(1)} > x \geq S_{j(2)} \quad b : S_{j(1)} < x \leq S_{j(2)} \\ \frac{x - S_{j(3)}}{3(S_{j(2)} - S_{j(3)})} & a : S_{j(2)} > x \geq S_{j(3)} \quad b : S_{j(2)} < x \leq S_{j(3)} \\ 0 & a : x < S_{j(3)} \quad b : x > S_{j(3)} \end{cases} \tag{8}$$

$$I_2 = \begin{cases} 0 & a : x \geq S_{j(2)} \quad b : x \leq S_{j(2)} \\ -\frac{S_{j(2)} - x}{3(S_{j(2)} - S_{j(3)})} & a : S_{j(2)} > x \geq S_{j(3)} \quad b : S_{j(2)} < x \leq S_{j(3)} \\ -\frac{x - S_{j(4)}}{3(S_{j(3)} - S_{j(4)})} & a : S_{j(3)} > x \geq S_{j(4)} \quad b : S_{j(3)} < x \leq S_{j(4)} \\ 0 & a : x < S_{j(4)} \quad b : x > S_{j(4)} \end{cases} \tag{9}$$

3.2. *The Determination of the Comprehensive Contact Degree*

3.2.1. Addition Weighted Synthesis Method

Additive weighted synthesis method is a common method to determine the comprehensive correlation degree; the method is to calculate the above link degrees multiplied by the weight of each index ω_j corresponds respectively, and then all the indicators of the weighted summation is taken as the contact degree [12], the calculating formula is

$$\mu_k = \sum_{j=1}^{m} \mu_{jk} \times \omega_j \tag{10}$$

3.2.2. S-Type Functions

In this paper, S-type functions in variable fuzzy set theory are used as a method to calculate the comprehensive connection degree [40]. In the evaluation method of the past, there are a number of scholars that make the theory of variable fuzzy sets theory and set pair analysis conducted coupling, but S-type functions as a comprehensive connection degree calculation method and set pair analysis method to determine the connection degree are not combined yet. The calculation formula of this function is

$$\mu_k = \left\{ 1 + \left[\frac{\sum_{j=1}^{m} \omega_j \times (1 - \mu_{jk})}{\sum_{j=1}^{m} \omega_j \times \mu_{jk}} \right]^2 \right\}^{-1} \tag{11}$$

3.3. Determine the Evaluation Level

Since the application of the maximum membership criterion determines that the evaluation level may cause distortion, several other common methods for determining the evaluation level are listed now. For example, when using the attribute recognition method to determine the contact degree, the level characteristic or the confidence criterion is used as the evaluation rank value, and the corresponding formula is Formulas (12) and (13) respectively [17]. By putting forward a level method in determining the connection degree, the available connection degree and evaluation level mapping relationship to determine the evaluation of the level value, Formula (14) is based on the special value method to determine the assessment level mapping function, Formula (15) as the evaluation grades of mapping function is determined based on the trigonometric function type [15,38].

$$h_i = \sum_{k=1}^{K} (0.5 + 0.5 \times \mu_k) \times k \tag{12}$$

$$h_i = \min\left\{ k \middle| \sum_{k=1}^{K} (0.5 + 0.5 \times \mu_k) \geq \lambda, 1 \leq k \leq K \right\} \tag{13}$$

$$h_i = -2 \times \mu_k + 3 \tag{14}$$

$$h_i = \begin{cases} 3 \times e^{-1.47\mu_k} & \mu_k \geq 0 \\ 6 - 3 \times e^{1.47\mu_k} & \mu_k \leq 0 \end{cases} \tag{15}$$

3.4. Determine Influencing Factors

The set pair potential reflects the trend of identical discrepancy contrary correlation degree of the two sets in specific problems. Pan Zhengwei etc. argued for the use of exponential functions to improve the traditional set pair potential, and named the set pair exponential potential [22]. The detailed calculation steps are as follows:

(1) Apply Formula (6) to calculate the contact number of each index.

(2) Calculate the diversity factor b according to formula $b = b_1 + b_2 + b_3$.

(3) Determine the set pair exponential potential, and calculate the formula as

$$shi(H)_e = e^{\sum a - \sum c} \tag{16}$$

(4) The influence degree of each indicator on the evaluation system is determined according to the state of set pair exponential potential, and the state table is shown in Table 3.

Table 3. The state table of set pair exponential potential.

Exponential Potential	Diversity Factor	State of Exponential Potential (SEP)	
$shi(H)_e > 1$	$b = 0$	Quasi-isomorphic potential, T_1	Isomorphic potential
	$b < 0.618$	Strong isomorphic potential, T_2	
	$b = 0.618$	Weak isomorphic potential, T_3	
	$b > 0.618$	Differential identical potential, T_4	
$shi(H)_e = 1$	$b = 0$	Quasi-homogeneous Equilibrium, T_5	Equilibrium
	$b < 0.618$	Strong Equilibrium, T_6	
	$b = 0.618$	Weak Equilibrium, T_7	
	$b > 0.618$	Micro Equilibrium, T_8	
$shi(H)_e < 1$	$b = 0$	Quasi inverse potential, T_9	Inverse potential
	$b < 0.618$	Strong inverse potential, T_{10}	
	$b = 0.618$	Weak Inverse potential, T_{11}	
	$b > 0.618$	Micro Inverse potential, T_{12}	

4. Evaluation of Sustainable Use of Water Resources in the Beijing-Tianjin-Hebei

4.1. Data

Beijing-Tianjin-Hebei is an area with insufficient per capita water resources (see Figure 1). This article selects the sustainable use of water resources in the Beijing-Tianjin-Hebei region from 2004 to 2015 as the evaluation target. The data of the evaluation indicators are from the National Economic and Social Development Announcement of each province and municipality from 2005 to 2016, the Water Resources Bulletin, and the statistics of the National Bureau of Statistics, and are obtained through relevant calculations. The specific index data are shown in Table 4.

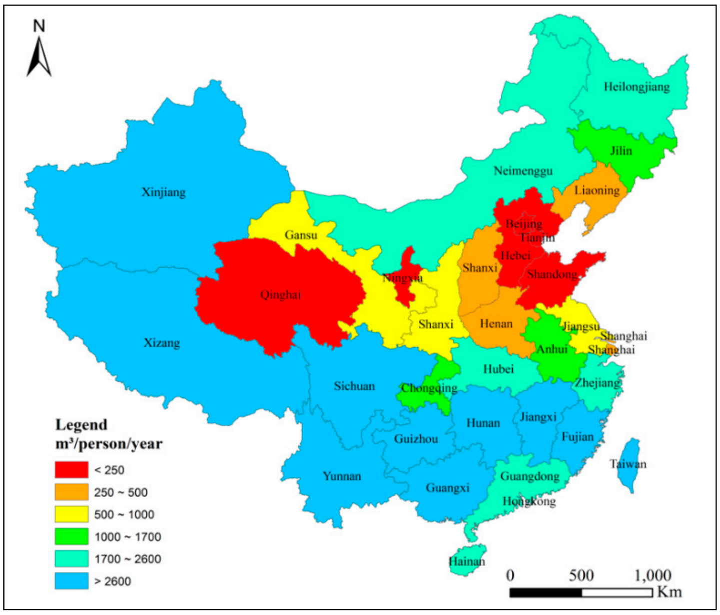

Figure 1. Per Capita Water Resources of Each Province in China in 2015.

Table 4. Indicator Data for Beijing-Tianjin-Hebei in 2004–2015.

Region	Index	2004	2005	2006	2007	2008	2009	2010	2012	2013	2014	2015
Beijing	I_1	57.27	49.5	42.25	35.35	31.56	29.21	24.94	20.07	18.92	17.08	16.6
	I_2	0.54	0.75	0.91	0.87	1.11	1.1	1.07	1.22	1.06	0.78	0.98
	I_3	203.2	251	293.8	362.2	409.9	442.9	546.2	673.7	696.6	736.1	976.6
	I_4	68	70	72	73	75	76	75	77	78	76	80
	I_5	57.9	54	58.7	49	47.5	46	48	48.5	46	47	53.4
	I_6	35.4	35.5	35.9	36.5	36.5	36.7	37	38.6	40.1	41	41.6
	I_7	53.9	62.4	73.2	76.2	78.9	80.3	81	83	84.6	86.1	87.9
	I_8	2.9	3.19	4.72	7.82	9.12	10.14	11.29	15.8	16.27	19.33	27.3
	I_9	0.71	1.71	1.31	1.27	0.13	1.15	0.85	−0.67	0.25	1.14	0.09
	I_{10}	226.8	152.9	154.7	166.8	187.2	192.1	174.9	171.8	196.9	187.5	183.8
	I_{11}	910	937	976	1021	1079	1133	1196	1261	1289	1311	1323
	I_{12}	79	83.6	84.3	84.5	84.9	85	85.9	86.2	86.3	86.3	86.5
	I_{13}	143	151.2	141.5	148.2	205.5	126.6	124.2	193.2	118.6	95.2	124
Tianjin	I_1	70.91	59.12	51.45	44.49	33.23	31.07	24.38	17.94	16.45	15.32	15.54
	I_2	1.02	1.01	1.06	1.06	1.15	1.22	1.46	1.38	1.4	1.51	1.45
	I_3	305.7	434.1	510.5	633.8	897.3	832.7	913.2	1203	1245	1321	1318
	I_4	42.42	42.46	42.63	42.84	42.96	45.27	45.95	46.99	48.33	49.57	52.15
	I_5	15	12	15	10.9	9	6	16	3.8	5.6	12	9
	I_6	8.1	8.1	8.1	8.1	8.1	9.9	9.9	9.9	9.9	9.9	9.9
	I_7	53.7	58	58.9	61.4	72.4	80.1	85.3	88.2	90	91	91.6
	I_8	2.12	2.12	2.12	2.13	2.14	2.25	2.29	2.34	2.4	2.46	2.59
	I_9	0.23	0.08	−0.03	0.06	−0.43	0.06	0.07	−0.91	0.88	0.65	−0.21
	I_{10}	124.9	123.6	130.4	122.4	129.3	133.2	132.0	134.1	142.3	124.3	119.6
	I_{11}	859	875	902	936	987	1030	1090	1186	1235	1273	1298
	I_{12}	74.9	75.07	75.72	76.32	77.21	78.01	79.6	81.53	82	82.27	82.61
	I_{13}	139.7	102.2	95.5	103.3	159.8	126.8	72.8	238.0	101.5	83.6	83.6

Table 4. *Cont.*

Region	Index	2004	2005	2006	2007	2008	2009	2010	2012	2013	2014	2015
Hebei	I_1	231.1	201.5	177.9	148.8	121.8	112.4	94.97	73.5	67.25	65.54	62.81
	I_2	1.69	1.73	1.82	1.87	2.03	2.02	2.07	2.27	2.44	2.41	2.49
	I_3	151.4	183.3	209.2	260.9	312.9	336.7	414.3	495.9	523.0	544.6	561.2
	I_4	33.09	33.36	33.97	33.81	32.95	35.21	34.93	35.31	36.14	37.25	40.19
	I_5	25.5	31.3	28	27.7	33.3	45.04	47.2	48.5	48.57	46.04	49.64
	I_6	23.25	23.25	23.25	23.25	23.25	23.25	23.25	27	28	29.2	31
	I_7	25.9	28.74	38.91	37.99	40.62	41.61	49.37	52.3	55.53	55.79	60.27
	I_8	1.02	1.1	0.57	1	1.63	1.39	1.48	1.94	2.43	2.62	2.67
	I_9	0.26	0.56	0.48	0.44	−0.15	0.18	0.39	−0.34	−0.1	0.93	0.37
	I_{10}	145.2	144.6	132.6	125.4	125.1	124.8	123.0	126.2	125.8	116.9	119.1
	I_{11}	361	363	365	368	370	373	381	386	388	391	393
	I_{12}	36.57	37.69	38.76	40.26	41.89	43.74	44.5	46.8	48.11	49.32	51.33
	I_{13}	226.5	197.0	156.1	173.1	231.1	201.3	195.3	324.2	240.6	144.3	182.5

4.2. Results

4.2.1. Weight Calculation Results

When it comes to analyze the analytic hierarchy process model, Professor Chen proposed the non-structural decision fuzzy set theory [41]. In this study, the weights of ecological, social and economic subsystems are determined by using the method, and the specific calculation process is as follows.

(1) Set an index set $P = \{p_1, p_2, p_3\}$, p_1, p_2, p_3 to represent social subsystems, economic subsystems and ecological subsystems respectively, compare the elements P_k and P_l of the index set. If P_k is more important than P_l, then $e_{kl} = 1, e_{lk} = 0$. If P_k is as important as P_l, then $e_{kl} = e_{lk} = 0.5$. If P_l is more important than P_k, then $e_{kl} = 0, e_{lk} = 1$. The binary comparison matrix E is finally obtained, and specific conversion relationships are shown in Table 5.

Table 5. Relationship tables of fuzzy mood operators and the fuzzy scales.

Fuzzy Mood	Equal	Slightly	Somewhat	Rather	Obvious
Fuzzy Scale	0.5	0.55	0.6	0.65	0.7
Remarkably	**Very**	**Extra**	**Exceeding**	**Extreme**	**Incomparable**
0.75	0.8	0.85	0.9	0.95	1

(2) Add all rows of the comparison matrix E and arrange the results in descending order to obtain the order of importance of each index, and the result is shown as follows.

(3) According to the importance of sorting, combining with Table 5, build the binary comparison matrix β, and the result is shown as follows.

$$E = \begin{pmatrix} 0.5 & 1 & 1 \\ 0 & 0.5 & 1 \\ 0 & 0 & 0.5 \end{pmatrix} \beta = \begin{pmatrix} 0.5 & 0.6 & 0.7 \\ 0.4 & 0.5 & 0.65 \\ 0.3 & 0.35 & 0.5 \end{pmatrix}$$

(4) Sum each row of the matrix β to get feature vector of P (without the fuzzy scale value of self-comparison which is 0.5), the result is $\omega' = (1.3,\ 1.05,\ 0.8)$.

(5) Normalize the vector to get the weight of the index set, the normalized weights of the social subsystems, economic subsystems and ecological subsystems were: 0.413, 0.333 and 0.254.

Rough set theory was proposed by Poland scholar Pawlak in 1982 [42]. After that, the theory was applied to many fields by a lot of scholars. In this study, the method is used to determine the weights of index layer.

(6) Assume that $K = (U, K)$ is a knowledge base, $U/R = \{R_1, R_2, \ldots, R_n\}$ represents the division of a domain formed by the knowledge R, then the granularity of the knowledge R is denoted as

GD(R), and $GD(R) = |R|/(Card(U))^2 = \sum_{i=1}^{n}(Card(R_i))^2/(Card(U))^2$. The resolution of R is recorded as $Dis(R) = 1 - GD(R)$, among them $|R| = \sum_{i=1}^{n}(Card(R_i))^2$, $Card(X)$ represents the cardinality of the set X.

As defined above, the larger the granularity of knowledge, the smaller the resolution. When R is an equal relation ($|R| = |U|$), the granularity of R gets the minimum value $1/Card(U)$, when R is a domain relation ($|R| = |U|^2$) the granularity of R is 1 [18].

(7) Assume $x \subseteq C$ is an attributes set, $x \subseteq C$ is an attribute, the importance of x for X, denoted by $Sig_x(X)$, which is defined as $Sig_x(X) = 1 - |X \cup \{x\}|/|X|$. Among which, $U/X = \{X_1, X_2, \ldots, X_n\}$, $|X| = \sum_{i=1}^{n}|X_i|^2$.

$|X| - |X \cup \{x\}|$ represents an increase in resolution caused by the addition of attribute x in X. Thus, the bigger the $Sig_x(X)$, the more important x is than X. However, if the X is not distinguishable after adding x, it will make the attribute significance becomes 0. Therefore, add the importance of the attribute itself in the final weight determination scheme.

(8) Assume $x \subseteq C$ is an attribute, the importance of x itself is denoted as $Sig(x)$, and defined as $Sig(x) = 1 - |\{x\}|/(Card(U))^2$.

(9) The final attribute importance of the index is denoted as $SIG(x)$, and defined as $SIG(x) = Sig_x(X) + Sig(x)$.

(10) Normalize the vector to get the weight of the index, and the results are shown in Table 6.

Table 6. The weight calculation results of index layer.

Rule Layer	Index	$Sig_x(X)$	$Sig(x)$	$SIG(x)$	Weight
Economic subsystem	I_1	0.000	0.406	0.406	0.339
	I_2	0.224	0.058	0.282	0.236
	I_3	0.302	0.000	0.302	0.252
	I_4	0.126	0.080	0.206	0.173
Environmental subsystem	I_5	0.078	0.470	0.548	0.214
	I_6	0.053	0.247	0.300	0.117
	I_7	0.297	0.278	0.575	0.225
	I_8	0.000	0.589	0.589	0.230
	I_9	0.548	0.000	0.548	0.214
Social subsystem	I_{10}	0.224	0.337	0.561	0.378
	I_{11}	0.202	0.026	0.228	0.153
	I_{12}	0.080	0.000	0.080	0.054
	I_{13}	0.000	0.616	0.616	0.415

(11) The weights of the index layer (Table 6) obtained are multiplied by the weights of the corresponding subsystems to obtain the final index weights. The weights of the final indicators were 0.113, 0.078, 0.084, 0.057, 0.054, 0.030, 0.057, 0.058, 0.054, 0.156, 0.063, 0.022 and 0.171.

4.2.2. Evaluation Grade Results

In the evaluation process, when the "attribute identification method" is used to determine the degree of connection, the Formulas (1)–(5) are used to determine the degree of connection of each index to the corresponding level. The evaluation criteria established in this paper do not include left extreme value and right extreme value. For the positive index $S_{j(0)} = +\infty$, $S_{j(5)} = 0$, for the inverted index $S_{j(0)} = 0$, $S_{j(5)} = +\infty$. Then use the additive weighted synthesis Formula (10) and S-type functions Formula (11) to determine the overall degree of connection between the sample and the evaluation grade. The results are shown in Tables 7 and 8 (Take Beijing as an example).

Table 7. Comprehensive degree of connection determined by additive weighted synthesis.

Grade	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
I	−0.71	−0.35	−0.33	−0.43	−0.55	−0.61	−0.54	−0.39	−0.32	−0.52	−0.49	−0.25
II	−0.60	−0.30	−0.33	−0.34	−0.32	−0.47	−0.20	−0.05	−0.12	−0.26	−0.15	0.03
III	−0.58	−0.70	−0.53	−0.45	−0.12	−0.20	−0.23	−0.21	−0.24	−0.11	−0.34	−0.35
IV	0.20	−0.05	−0.02	0.00	0.02	0.12	−0.17	−0.33	−0.33	−0.14	−0.28	−0.44
V	0.29	0.05	−0.14	−0.12	−0.33	−0.19	−0.24	−0.40	−0.45	−0.37	−0.17	-0.40

Table 8. Comprehensive Degree of Connection Determined by S-type functions.

Grade	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
I	0.01	0.04	0.04	0.03	0.02	0.02	0.02	0.04	0.06	0.03	0.03	0.07
II	0.01	0.04	0.04	0.04	0.05	0.03	0.06	0.10	0.11	0.06	0.07	0.12
III	0.01	0.01	0.02	0.02	0.07	0.06	0.05	0.06	0.05	0.08	0.04	0.04
IV	0.19	0.11	0.11	0.12	0.12	0.15	0.07	0.05	0.05	0.08	0.05	0.03
V	0.30	0.19	0.12	0.12	0.06	0.10	0.09	0.06	0.04	0.07	0.12	0.06

Finally, the level of characteristic Formula (12) and the confidence criterion Formula (13) are respectively used to determine the specific evaluation level value. The confidence degree of the paper is taken as 0.55. The evaluation results obtained are shown in Table 9 as results 3–6 respectively.

When the "identical discrepancy contrary hierarchy method" is used to determine the degree of connection, the Formulas (6) and (7) are used to determine the degree of connection of each index to the corresponding level. When using Formula (6) to determine the degree of connection, the degree of difference coefficient I is assumed by the special value method, and Formula (14) is used as the mapping function formula for determining the evaluation level based on the special value method. The evaluation results are shown in the result 1 in Table 9. When using Formula (7) to determine the degree of connection, the degree of the difference coefficient I is calculated using the triangular fuzzy number Formulas (8), (9) and (15) is used as the mapping function formula for determining the evaluation grade based on the triangular fuzzy number. The results are shown in the result 2 in Table 9.

Table 9. Evaluation results of different methods (Beijing-Tianjin-Hebei).

Region	Result	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Beijing	1	4.26	3.51	3.33	3.63	3.47	3.54	3.44	3.32	3.18	3.40	3.55	3.13
	2	4.63	3.83	3.55	3.73	3.58	3.95	3.49	2.89	2.71	3.37	3.46	2.56
	3	3.78	3.29	3.19	3.26	3.21	3.39	3.17	2.92	2.84	3.11	3.14	2.79
	4	4.47	3.95	3.69	3.75	3.50	3.84	3.47	2.94	2.73	3.32	3.46	2.67
	5	4	4	4	4	4	4	3	3	3	3	3	3
	6	5	5	4	4	4	4	4	3	3	4	4	2
Tianjin	1	3.69	3.62	3.50	3.41	3.04	3.10	3.10	3.10	3.00	3.19	3.14	2.99
	2	3.93	3.75	3.59	3.51	3.13	3.01	2.77	2.81	2.77	3.12	2.93	2.61
	3	3.35	3.24	3.18	3.13	3.01	2.92	2.82	2.84	2.85	2.97	2.89	2.76
	4	4.09	3.97	3.84	3.78	3.34	3.26	3.10	3.08	2.94	3.38	3.16	2.85
	5	4	4	4	4	4	3	3	3	3	3	3	3
	6	5	5	5	5	4	4	3	4	3	5	4	2
Hebei	1	3.79	3.79	3.61	3.58	3.40	3.46	3.43	3.38	3.26	3.25	3.44	3.35
	2	4.00	4.01	3.87	3.72	3.43	3.49	3.44	3.24	3.05	2.99	3.40	3.09
	3	3.33	3.35	3.28	3.22	3.10	3.10	3.08	2.99	2.96	2.94	3.08	2.96
	4	4.11	4.11	4.04	3.89	3.56	3.59	3.51	3.31	3.11	3.08	3.53	3.19
	5	4	4	4	4	4	4	3	3	3	3	4	3
	6	5	5	5	5	4	4	4	4	4	4	4	4

4.2.3. Analysis of Results

In order to verify the feasibility of the proposed evaluation method (method 4) in the evaluation of the sustainable use of water resources in the Beijing-Tianjin-Hebei Region, the Spearman correlation coefficient method was applied to execute overall correlation analysis. The results are shown in Table 10. According to the results of the analysis based on the Spearman correlation coefficient method, Method 4 has obtained high correlation coefficients in the Beijing-Tianjin-Hebei area, with correlation coefficients of 0.9954, 0.9910, and 0.9928. It demonstrated the possibility that S-type functions can be used to calculate the weighted relation degree in the traditional set pair analysis method. The evaluation results of this method (method 4) are used as a result of the evaluation of the sustainable use of water resources in the Beijing-Tianjin-Hebei region to analyze the trend of sustainable use of regional water resources (see Figure 2).

Table 10. Spearman correlation coefficient analysis results (Beijing-Tianjin-Hebei).

Region	Result	1	2	3	4	5	6	Average
Beijing	1	1.000	0.996	0.996	0.996	0.992	0.979	0.9931
	2	0.996	1.000	0.993	1.000	0.994	0.988	0.9950
	3	0.996	0.993	1.000	0.993	0.990	0.967	0.9897
	4	0.996	1.000	0.993	1.000	0.995	0.988	0.9954
	5	0.992	0.994	0.990	0.995	1.000	0.979	0.9917
	6	0.979	0.988	0.967	0.988	0.979	1.000	0.9835
Tianjin	1	1.000	0.998	0.997	0.998	0.994	0.944	0.9884
	2	0.998	1.000	0.996	0.998	0.995	0.947	0.9889
	3	0.997	0.996	1.000	0.991	0.988	0.923	0.9825
	4	0.998	0.998	0.991	1.000	0.997	0.963	0.9910
	5	0.994	0.995	0.988	0.997	1.000	0.958	0.9885
	6	0.944	0.947	0.923	0.963	0.958	1.000	0.9557
Hebei	1	1.000	0.999	0.994	0.998	0.993	0.965	0.9914
	2	0.999	1.000	0.993	0.999	0.995	0.967	0.9922
	3	0.994	0.993	1.000	0.989	0.984	0.933	0.9821
	4	0.998	0.999	0.989	1.000	0.996	0.974	0.9928
	5	0.993	0.995	0.984	0.996	1.000	0.969	0.9896
	6	0.965	0.967	0.933	0.974	0.969	1.000	0.9679

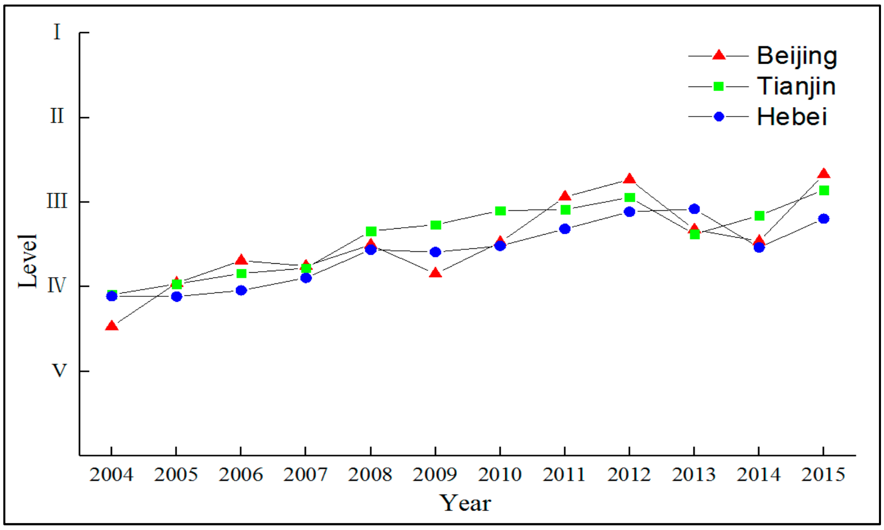

Figure 2. Evaluation of Sustainable Use of Water Resources in Beijing-Tianjin-Hebei Region.

Figure 2 demonstrates that the sustainable use of water resources in the Beijing-Tianjin-Hebei region is on the rise as a whole. The sustainable use of water resources in Tianjin is better than that of

Hebei province, and the fluctuation of Beijing is relatively large. Now we have to analyze the reasons. In Beijing, the grain yield per unit water, the value of industrial output per unit water, and sewage disposal rate in 2004 were the lowest in nearly 12 years. In addition, the grain yield of unilateral water was 0.54 kg, which was lower than Tianjin and Hebei. This value was 1.02 kg and 1.69 kg respectively in these two regions at the same year. The reduced value of groundwater water level was 0.71 m, and the population density was 910 persons per km^2. Beijing is higher than Tianjin and Hebei in both of these indicators in 2004. These reasons lead to the lowest level of sustainable use of water resources in 2004 in Beijing.

With the increasing of people's awareness of water resources protection and the development of science and technology, compared with 2004, the standardized rate of various indexes in Beijing has been improved obviously since 2005. Compared with 2004, the output value of unilateral water industry and unilateral water grain in Beijing increased by 23.5% and 38.9% in 2005, respectively. Compared with 2004, the daily water consumption per capita decreased by 48.3% which resulted in the order of evaluation for 2005 being good. This result indicated that improving industrial and agricultural water utilization efficiency applying scientific technology methods and increasing people's awareness of water conservation can effectively improve water resources sustainable utilization situation. Referring to the relevant data and sources, we found out that in 2007 the alien population in Beijing increased by 33.2%. The alien population in Beijing lacked water saving concepts and had a weak sense of water resources protection which resulted in higher daily water consumption per capita than in adjacent years. Besides, compared with 2006, the attainment rate of water quality in water function areas reduced by 16.5% in 2007. These reasons finally resulted in a low evaluation grade in 2007.

In 2009, the per capita daily water consumption in Beijing was 192.1 L, which is higher than the adjacent years and is higher than Tianjin and Hebei. This value was 133.2 L and 124.8 L respectively in these two regions at the same year. In addition, the reduced value of groundwater water level was 1.15 m, which was higher than Tianjin and Hebei. This value was 0.06 m and 0.18 m respectively in these two regions at the same year. These reasons lead to the lowest level of sustainable use of water resources in 2009 in Beijing. This result shows that excessive use of groundwater will lead to a decrease in the level of sustainable use of water resources, which is very important.

In 2013, the level of sustainable assessment of water resources in Beijing and Tianjin has been reduced compared to 2012. The per capita daily water consumption in Beijing was 196.9 L, which was the highest in nearly 12 years. Compared with 2012, the average per capita water resources decreased by 38.61%. The reduced value of groundwater water level was 0.88 m in Tianjin, which was the highest in nearly 12 years. Compared with 2012, the average per capita water resources decreased by 57.36%. In 2014, the reduced value of the groundwater water level in Beijing was 1.14 m, which was higher than the adjacent years. The average per capita water resources was 95.2 L, which was the lowest in nearly 12 years. The reduced value of groundwater water level in Hebei was 0.93 m, which was the highest in nearly 12 years. The average per capita water resources in Hebei was 144.3 L, which was the lowest in nearly 12 years. These reasons lead to a lower level of sustainable use of water resources in 2014 than in the adjacent years in Beijing and Hebei. In order to more accurately determine the impact indicators of the sustainable utilization of water resources in Beijing-Tianjin-Hebei, the influence factors were analyzed by using the set pair exponential potential.

4.2.4. Calculation Results of Influencing Factors

Firstly, Formula (6) is used to calculate the contact number of each indicator, and then the difference degree b is calculated. Finally, the set pair exponential potential is calculated according to Formula (16), and the degree of influence of each index on the evaluation system is determined according to Table 3. As shown in Figure 3 and Table 11.

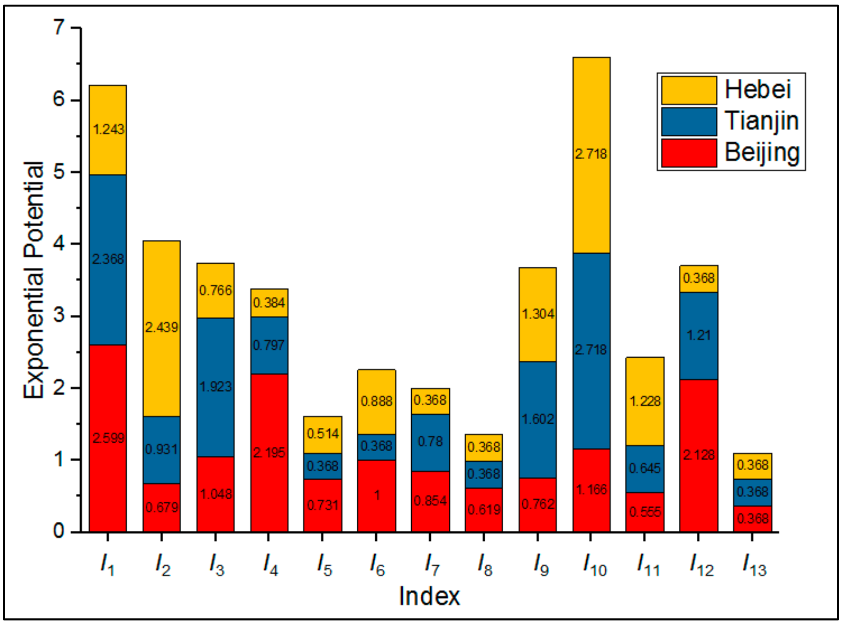

Figure 3. The state figure of set pair exponential potential in Beijing-Tianjin-Hebei Region.

Table 11. The state table of set pair exponential potential in Beijing-Tianjin-Hebei.

Beijing				Tianjin				Hebei			
Index	***shi*(H)$_e$**	***b***	**EPS**	**Index**	***shi*(H)$_e$**	***b***	**EPS**	**Index**	***shi*(H)$_e$**	***b***	**EPS**
I_{13}	0.368	0.000	T_9	I_5	0.368	0.000	T_9	I_7	0.368	0.000	T_9
I_{11}	0.555	0.232	T_{10}	I_6	0.368	0.000	T_9	I_8	0.368	0.000	T_9
I_8	0.619	0.460	T_{10}	I_8	0.368	0.000	T_9	I_{12}	0.368	0.000	T_9
I_2	0.679	0.614	T_{10}	I_{13}	0.368	0.000	T_9	I_{13}	0.368	0.000	T_9
I_5	0.731	0.686	T_{12}	I_{11}	0.645	0.562	T_{10}	I_4	0.384	0.042	T_{10}
I_9	0.762	0.318	T_{10}	I_7	0.780	0.560	T_{10}	I_5	0.514	0.334	T_{10}
I_7	0.854	0.809	T_{12}	I_4	0.797	0.773	T_{12}	I_3	0.766	0.733	T_{12}
I_6	1.000	1.000	T_8	I_2	0.931	0.926	T_{12}	I_6	0.888	0.881	T_{12}
I_3	1.048	0.749	T_4	I_{12}	1.210	0.809	T_4	I_{11}	1.228	0.795	T_4
I_{10}	1.166	0.679	T_4	I_9	1.602	0.460	T_2	I_1	1.243	0.782	T_4
I_4	2.128	0.245	T_2	I_3	1.923	0.307	T_2	I_9	1.304	0.666	T_4
I_{12}	2.195	0.214	T_2	I_1	2.368	0.138	T_2	I_2	2.439	0.108	T_2
I_1	2.599	0.045	T_2	I_{10}	2.718	0.000	T_1	I_{10}	2.718	0.000	T_1

According to Table 11 and Figure 3, the indicators of the quasi-backward levels in the Beijing-Tianjin-Hebei region are per capita water resources, indicating that the area is experiencing acute water shortage. Besides, the common problem of large population but limited water resources adversely affects people living in the area. In addition, Tianjin's indicators of quasi-backward levels include the attainment rate of water quality in water function areas, forest coverage, eco-environmental water use efficiency, showing that the quality of surface water environment in many places of Tianjin does not meet the requirements of the corresponding functional water bodies, and the awareness of the significance of the ecological environment should be further raised. Similarly, the indicators of Hebei's quasi-backward levels involve sewage disposal rate, eco-environmental water use efficiency, as well as the level of urbanization, indicating that Hebei Province needs to control the discharge of pollutants, increase the amount of environmental water use, and promote urbanization.

Last but not the least, Beijing's indicators of strong inverse potential levels can be seen from population density, eco-environmental water use efficiency, grain yield per unit water and annual drawdown of groundwater; Tianjin's indicators of strong inverse potential levels are population density and the sewage disposal rate; Hebei's indicators of strong inverse potential levels are reflected in the percentage of the tertiary industry in GDP as well as the attainment rate of water quality in water function areas.

Generally speaking, a dense population with scarce water resources, and lack of ecological water are the common problems that Beijing, Tianjin and Hebei have to face. Moreover, they also have to tackle myriad problems of their own. For instance, groundwater recharge in Beijing has been reducing significantly. The pollution of rivers in Tianjin becomes increasingly serious. The sewage disposal rate in Hebei province stays fairly low and the level of urbanization is not high. Therefore, comprehensive measures such as strengthening the management of water resources, improving the efficiency of the use of water resources, controlling the numbers of the population, increasing the amount of water used in the ecological environment and promoting water conservation are supposed to be taken by local authorities to achieve the sustainable development of regional water resources.

5. Conclusions

This paper divided the water resources composite system into three parts: social subsystem, economic subsystem, as well as the ecological environment subsystem. It constructed an evaluation index system for the sustainable use of the Beijing-Tianjin-Hebei water resources, and applied a combination of rough sets and fuzzy theory to determine the weight of each indicator. The weights were brought into several common set pair analysis evaluation methods to obtain the evaluation results. Based on the traditional set pair analysis method, this study proposed a new set pair analysis method (method 4) using S-type functions (Formula (11)) instead of the addition weighted synthesis method (Formula (10)) in the calculation of weighted connections. In this study, data from 2004 to 2015 in the Beijing-Tianjin-Hebei region was taken as the research object and situations of sustainable use of water resources in the region for the past 12 years were also evaluated. In order to verify the feasibility of Method 4, the Spearman correlation coefficient method was used to calculate the correlation coefficient between evaluation results of Method 4 and evaluation results of other traditional methods. After analysis, the results of the set pair analysis method that cites S-type functions obtained higher Spearman correlation coefficients than the existing methods. This method more accurately evaluates the current status and development trend of the sustainable use of water resources in the region. This can also provide a new method for the evaluation of sustainable use of water resources. Besides, in order to improve the sustainable use level of water resources in Beijing, Tianjin and Hebei, the influence factors were analyzed by using the set pair exponential potential so as to provide a theoretical basis and data support for the future management of water resources.

Author Contributions: B.M. conceived the research theme; H.L. provided data and designed the analytical approach proposed; H.L. and B.M. wrote the paper.

Funding: This research was funded by the National Key R& D Program of China (No. 2016YFC0401406), and the Famous Teachers Cultivation planning for Teaching of North China Electric Power University (the Fourth Period).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hoekstra, A.Y.; Chapagain, A.K.; Oel, P.R.V. Advancing Water Footprint Assessment Research: Challenges in Monitoring Progress towards Sustainable Development Goal 6. *Water* **2017**, *9*, 438. [CrossRef]
2. Yang, Y.; Liu, Y.; Cao, S.; Cheng, Y. A Method of Evaluating Water Resource Assets and Liabilities: A Case Study of Jinan City, Shandong Province. *Water* **2017**, *9*, 575. [CrossRef]
3. Hou, Z.; Lu, W.; Xue, H.; Lin, J. A comparative research of different ensemble surrogate models based on set pair analysis for the DNAPL-contaminated aquifer remediation strategy optimization. *J. Contam. Hydrol.* **2017**, *203*, 28–37. [CrossRef] [PubMed]
4. Wang, D.; Borthwick, A.G.; He, H.; Wang, Y.; Zhu, J.; Lu, Y.; Xu, P.; Zeng, X.; Wu, J.; Wang, L.; et al. A hybrid wavelet de-noising and Rank-Set Pair Analysis approach for forecasting hydro-meteorological time series. *Environ. Res.* **2018**, *160*, 269–281. [CrossRef] [PubMed]

5. Wei, C.; Dai, X.; Ye, S.; Guo, Z.; Wu, J. Prediction analysis model of integrated carrying capacity using set pair analysis. *Ocean Coast. Manag.* **2016**, *120*, 39–48. [CrossRef]
6. Kumar, K.; Garg, H. Connection number of set pair analysis based TOPSIS method on intuitionistic fuzzy sets and their application to decision making. *Appl. Intell.* **2017**. [CrossRef]
7. Li, K.; Li, H.; Wang, H. Situation analysis of relationship in social networks based on link entropy. *Mod. Phys. Lett. B* **2015**, *29*, 1550061. [CrossRef]
8. Pan, Z.; Jin, J.; Liu, L.; Liu, X. Risk evaluation of natural disasters based on connection function. *Chin. J. Popul. Resour. Environ.* **2013**, *11*, 118–124. [CrossRef]
9. Yue, W.; Cai, Y.; Rong, Q.; Li, C.; Ren, L. A hybrid life-cycle and fuzzy-set-pair analyses approach for comprehensively evaluating impacts of industrial wastewater under uncertainty. *J. Clean. Prod.* **2014**, *80*, 57–68. [CrossRef]
10. Wu, K.; Jin, J.L.; Pan, Z.W. Set pair analysis model based on triangle fuzzy intervals and its application to impact rating evaluation of urban flood. *J. Hydraul. Eng.* **2010**, *41*, 711–719.
11. Liu, Y. Study on Environment Evaluation and Protection Based on Set Pair Analysis—A Case Study of Chongqing. *Energy Procedia* **2012**, *14*, 14–19. [CrossRef]
12. Li, C.; Sun, L.; Jia, J.; Cai, Y.; Wang, X. Risk assessment of water pollution sources based on an integrated k-means clustering and set pair analysis method in the region of Shiyan, China. *Sci. Total Environ.* **2016**, *557*, 307–316. [CrossRef] [PubMed]
13. Wang, M.; Chen, G. A novel coupling model for risk analysis of swell and shrinkage of expansive soils. *Comput. Math. Appl.* **2011**, *62*, 2854–2861. [CrossRef]
14. Wang, Z.; Ma, H.; Lai, C.; Song, H. Set Pair Analysis Model Based on GIS to Evaluation for Flood Damage Risk. *Procedia Eng.* **2012**, *28*, 196–201.
15. Chong, T.; Yi, S.; Che, H. Application of set pair analysis method on occupational hazard of coal mining. *Saf. Sci.* **2017**, *92*, 10–16. [CrossRef]
16. Su, M.R.; Yang, Z.F.; Chen, B.; Ulgiati, S. Urban ecosystem health assessment based on emergy and set pair analysis—A comparative study of typical Chinese cities. *Ecol. Model.* **2009**, *220*, 2341–2348. [CrossRef]
17. Pan, Z.; Jin, J.; Wu, K.; Xu, Y. Set pair analysis model for water safety evaluation of Chaohu Watershed. *Water Resour. Protect.* **2017**, *35*, 5–10. (In Chinese)
18. Men, B.; Liu, H.; Tian, W.; Liu, H. Evaluation of Sustainable Use of Water Resources in Beijing Based on Rough Set and Fuzzy Theory. *Water* **2017**, *9*, 852. [CrossRef]
19. Scanlan, M.; Filion, Y.R. Influence of Topography, Peak Demand, and Topology on Energy Use Patterns in four Small to Medium-Sized Systems in Ontario, Canada. *Water Resour. Manag.* **2018**, *31*, 1–19. [CrossRef]
20. Pan, Z.; Wu, C.; Zhou, Y.; Jin, J. Driving Factors Analysis of Basin Water Resources System Vulnerability Based on Set Pair Exponential Potential. *Water Resour. Power* **2014**, *32*, 39–43. (In Chinese)
21. Yin, Z.; Jia, B.; Wu, S.; Dai, J.; Tang, D. Comprehensive Forecast of Urban Water-Energy Demand Based on a Neural Network Model. *Water* **2018**, *10*, 385. [CrossRef]
22. Condon, A.G.; Richards, R.A.; Rebetzke, G.J.; Farquhar, G.D. Breeding for high water-use efficiency. *J. Exp. Bot.* **2004**, *55*, 2447–2460. [CrossRef] [PubMed]
23. Braude, E.; Hauser, S.; Sinuany-Stern, Z.; Oron, G. Water Allocation between the Agricultural and the Municipal Sectors under Scarcity: A Financial Approach Analysis. *Water Resour. Manag.* **2015**, *29*, 3481–3501. [CrossRef]
24. Colla, V.; Matino, I.; Branca, T.A.; Fornai, B.; Romaniello, L.; Rosito, F. Efficient Use of Water Resources in the Steel Industry. *Water* **2017**, *9*, 874. [CrossRef]
25. Cherp, A.; Jewell, J.; Vinichenko, V.; Bauer, N.; De Cian, E. Global energy security under different climate policies, GDP growth rates and fossil resource availabilities. *Clim. Chang.* **2016**, *136*, 83–94. [CrossRef]
26. Gendron, C. Beyond environmental and ecological economics: Proposal for an economic sociology of the environment. *Ecol. Econ.* **2014**, *105*, 240–253. [CrossRef]
27. Rahman, H.A.E. Evaluation of Groundwater Resources in Lower Cretaceous Aquifer System in Sinai. *Water Resour. Manag.* **2001**, *15*, 187–202. [CrossRef]
28. Xiao, Y.; Gu, X.; Yin, S.; Pan, X.; Shao, J.; Cui, Y. Investigation of Geochemical Characteristics and Controlling Processes of Groundwater in a Typical Long-Term Reclaimed Water Use Area. *Water* **2017**, *9*, 800. [CrossRef]

29. Yuan, G.; Zhu, X.; Tang, X.; Du, T.; Yi, X. A Species-Specific and spatially-Explicit Model for Estimating Vegetation Water Requirements in Desert Riparian Forest Zones. *Water Resour. Manag.* **2016**, *30*, 3915–3933. [CrossRef]
30. Kim, H.; Jeong, H.; Jeon, J.; Bae, S. The Impact of Impervious Surface on Water Quality and Its Threshold in Korea. *Water* **2016**, *8*, 111. [CrossRef]
31. Knüppe, K.; Pahl-Wostl, C. A Framework for the Analysis of Governance Structures Applying to Groundwater Resources and the Requirements for the Sustainable Management of Associated Ecosystem Services. *Water Resour. Manag.* **2011**, *25*, 3387–3411. [CrossRef]
32. Bao, C.; Fang, C.L. Water Resources Flows Related to Urbanization in China: Challenges and Perspectives for Water Management and Urban Development. *Water Resour. Manag.* **2012**, *26*, 531–552. [CrossRef]
33. Gallardo, B.; Gascón, S.; Quintana, X.; Comín, F.A. How to choose a biodiversity indicator—Redundancy and complementarity of biodiversity metrics in a freshwater ecosystem. *Ecol. Indic.* **2011**, *11*, 1177–1184. [CrossRef]
34. Delgado, A.; Romero, I. Environmental conflict analysis using an integrated grey clustering and entropy-weight method. *Environ. Model. Softw.* **2016**, *77*, 108–121. [CrossRef]
35. Xu, F.; Zheng, X.; Zhang, J.; Fu, Z.; Zhang, X. A hybrid reasoning mechanism integrated evidence theory and set pair analysis in Swine-Vet. *Expert Syst. Appl.* **2010**, *37*, 7086–7093. [CrossRef]
36. Hu, J.; Yang, L. Dynamic stochastic multi-criteria decision making method based on cumulative prospect theory and set pair analysis. *Syst. Eng. Procedia* **2011**, *1*, 432–439. [CrossRef]
37. Wu, F.F.; Wang, X. Eutrophication Evaluation Based on Set Pair Analysis of Baiyangdian Lake, North China. *Procedia Environ. Sci.* **2012**, *13*, 1030–1036. [CrossRef]
38. Tao, J.; Fu, M.; Sun, J.; Zheng, X.; Zhang, J.; Zhang, D. Multifunctional assessment and zoning of crop production system based on set pair analysis—A comparative study of 31 provincial regions in mainland China. *Commun. Nonlinear Sci. Numer. Simul.* **2014**, *19*, 1400–1416. [CrossRef]
39. Wu, Q.; Law, R. The complex fuzzy system forecasting model based on fuzzy SVM with triangular fuzzy number input and output. *Expert Syst. Appl.* **2011**, *38*, 12085–12093. [CrossRef]
40. Wang, W.C.; Xu, D.M.; Chau, K.W.; Lei, G.J. Assessment of River Water Quality Based on Theory of Variable Fuzzy Sets and Fuzzy Binary Comparison Method. *Water Resour. Manag.* **2014**, *28*, 4183–4200. [CrossRef]
41. Ke, L.N.; Wang, Q.M.; Geng, Y.D.; Zhang, L. The island sustainable development evaluation model and its application in Changhai County based on the non-structural decision fuzzy set theory. *Trans. Oceanol. Limnol.* **2013**, *1*, 159–166. (In Chinese)
42. Pawlak, Z. Rough sets and intelligent data analysis. *Inf. Sci.* **2002**, *147*, 1–12. [CrossRef]