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Water Environmental Quality Evaluation of the Karst Water in Beijing

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ABSTRACT

Karst water is an important element of underground water in Beijing and is characterized by abundance of supply and high quality. Karst water is an ideal water source for alleviating the supply and demand discrepancy of water resources and providing water for the city. The water environment of karst landforms is relatively fragile and requires additional attention. So the rational use of karst water requires the establishment of scientific and effective models of water quality evaluation. Taking several karst water distribution areas as examples, this study established an index and standard of estimation according to set pair analysis (SPA). The study subsequently built the corresponding connection and determined the weighting factor according to the degree of association. Basic indicators of water quality were processed and analyzed through comprehensive evaluation principles to provide a foundation for the actual management and the rational use of karst water distribution areas in Beijing.

INTRODUCTION

With the continuous development of human society, water shortages and the unrestricted use of water resources have led to a growing discrepancy between the supply of and demand for these resources. The development of new back-up water sources for cities is necessary (Li et al. 2007). Beijing is highly dependent on groundwater for its water supply. Owing to erratic precipitation with uneven distribution in terms of time and space, the growing population and the country's rapid economic development, the urban water supply is becoming more and more strained. The existing water shortage seriously restricts construction and economic development in Beijing (Hu et al. 2010). Karst water, which has abundant reserves, a good supply, high water quality and other characteristics, is an important part of the groundwater in Beijing. It is also an ideal urban and domestic water source. However, owing to its vulnerability, groundwater is very sensitive to human activities. Once pollution and destruction of groundwater occur, the water cannot be completely restored in a short time (Zhu et al. 2007). However, there is no scientific and objective model for systematic research and the in-depth evaluation of the karst water distribution area in Beijing. Hence, the partition, classification and responsible utilization of karst water distribution cannot be carried out smoothly. Adopting a scientific model to evaluate karst groundwater quality in Beijing is important for the rational utilization of karst water and decreasing the discrepancy between the supply and demand of water resources (Li et al. 2012).

Water quality evaluation is an important aspect of environmental water management. There have been many studies evaluating karst water quality both domestically and internationally. Common methods of water quality evaluation include the following:

1. Set pair analysis models: We make a standard for data monitoring and evaluation and build the corresponding relational expression according to the association degree (Balas et al. 2010). At the same time, we calculate the comprehensive contact or contact number based on the index weight. Finally, we determine the level of environmental water quality according to the corresponding standards (Wang et al. 2002).

2. Other evaluation methods: The matter-element analysis method is based on matter-element analysis theory. The fuzzy comprehensive evaluation method establishes the membership function and weight coefficient. And then use the neural network evaluation method to determine the nature of water bodies to be identified. We adopt the single-factor evaluation method, which selects the worst category of all project categories of water quality. Through various mathematical methods, the purpose of partial is synthetically operated to a composite index, which represents the water quality assessment scale. We use the grey evaluation method to determine the water quality level. First, we calculate the water quality of each factor in the measured concentrations and correlation of water quality standards at all levels, and then we determine the water quality assessment scale according to the correlation (Dahiya et al. 2007).

At present, the overall effect of set pair analysis and evaluation on water quality is relatively good. Feng et al. (2011) summarized the characteristics of the set pair analysis method as including objective recognition, system description, quantitative characterization, specific analysis and wide use. It is used in both microscopic and macro analysis of the system. Furthermore, it can conduct certainty or uncertainty analysis and analyse simple or complex systems. Meng et al. (2009) also believes that the model for dealing with uncertainty is has a great application value.

To evaluate the quality of the karst water in Beijing, this research takes the Bai Yang Ditch, Wang Jia Yuan Reservoir, Baqi Cave, Jingdong Caverns (underground river) and Jingdong Caverns (underground springs) as five representative examples of the karst water for water sample collection. After the experimental determination, five basic water quality index determination data were obtained for each area. The five basic water quality indicators are pH, hardness, turbidity, chemical oxygen demand (COD) and ammonia nitrogen.

Based on the set pair analysis evaluation model, we evaluated the quality of the karst water in Beijing and then provided data support for the actual area of management and the rational use of karst water (Ji et al. 2003).

MATERIALS AND METHODS

Basic concept: The basic idea (Yang et al. 2006) of set pair analysis is to make the similarity and anisotropy analysis on the characteristics of the two sets in the certain context of the problem and get the expression of the degree of similarity and difference of the two sets. Next, this problem is extended to the case when the system is composed of M (m>2) sets, and then on this basis to expand the study of the problem.

According to the need of the problem *W*, the set pair *H* is analyzed, and *N* features are obtained. Among them, there are *S* characteristics which are common to two sets in the set pair, and there are *P* characteristics which are opposite. In the remaining *F = N-S-P* characteristics, neither opposite, nor same, known as differences. *S/N* is the degree of identity of the two sets under the problem *W*, or is represented by a; *F/N* is the degree of difference of the two sets under the problem *W*, or is represented by *b*; *P/N* is the degree of opposition of the two sets under the question *W*, or is represented by *c*. The theory of the above problems can be expressed as follows:

$$\mu = \frac{S}{N} + \frac{F}{N} i + \frac{P}{N} j \qquad \ldots(1)$$

where *i* is the difference coefficient, and *j* is the antagonism degree coefficient.

This can be abbreviated as follows:

$$\mu = a + b \times i + c \times j \; (a + b + c = 1) \qquad \ldots(2)$$

Determination of the Association Degree: Based on the basic idea of set pair analysis, when used in the water environment evaluation, the index of water to be evaluated and the criterion of evaluation are regarded as a set pair. Assuming there are *N* evaluation indexes and different evaluation levels, the general form of the degree of association extended by Eq. (1) is as follows.

$$\mu = \frac{S}{N} + \frac{F_1}{N} i_1 + \frac{F_2}{N} i_2 + \cdots \frac{F_m}{N} i_m + \frac{P_1}{N} j_1 + \frac{P_2}{N} j_2 + \cdots + \frac{P_n}{N} j_n \qquad \ldots(3)$$

The formula can be abbreviated as follows:

$$\mu = a + b_1 i_1 + b_2 i_1 + \ldots b_m i_m + c_1 j_1 + c_2 j_2 + \ldots + c_n j_n \qquad \ldots(4)$$

Where, i_m is the coefficient of difference; j_n is the coefficient of opposition; and the values of *a*, *b* and *c* can qualitatively determine the range of grades in which the water quality is evaluated (Li et al. 2008).

Because the actual water contains different components, and different substances have different effects on water quality, even if the water quality is at the same level, it will vary according to the content of indicators. Therefore, it is necessary to further make the same, different and opposite set analysis as to the classification criteria.

Taking *n* pollution factors in the evaluation process, take the measured value of a pollution factor *i* of k^{th} water sample as x_{ki}, the j-level standard value of it as c_{it} $(i=1,2,\ldots,n; t=1,2,\ldots,m)$.

For the reverse index (e.g. chemical oxygen demand, COD), the concentration values heavier than the class c_{it} are counted as class *t*, and for positive indicators (such as dissolved oxygen, DO), the concentration values below c_{it} are counted as class *t*. And the clean water quality (class I water quality) is considered as identity, *t* class water quality is considered as opposition, and in between the two water quality is considered different. Using the dimensionless treatment method of cost type index and benefit type index, the association degree μ_{ik} $(k = 1, 2, \ldots, n)$ of one reverse index (or positive index) *k* can be written as Eq.(5) or (6) (Li et al. 2012).

$$\mu_{ik} = \begin{cases} 1+0j & x_{ki} \le c_{i1} \\ \frac{c_{i2}-x_{ki}}{c_{i2}-c_{i1}} + \frac{x_{ki}-c_{i1}}{c_{i2}-c_{i1}} i_1 + 0i_2 + \cdots + 0i_{m-2} + 0j & c_{i1} < x_{ki} \le c_{i2} \\ \vdots \quad \vdots & \\ 0+0i_1 + \cdots + 0i_{n-3} + \frac{x_{ki}-c_{im-1}}{c_{im}-c_{im-1}} i_{m-2} + \frac{c_{im+1}-x_{ki}}{c_{im}-c_{im-1}} j & c_{im-1} < x_{ki} \le c_{im} \\ 0+1j & x_{ki} > c_{im} \end{cases} \qquad \ldots(5)$$

$$\mu_{ik} = \begin{cases} 1+0j & x_{ki} \le c_{i1} \\ \frac{x_{ki}-c_{i1}}{c_{i2}-c_{i1}} + \frac{c_{i2}-x_{ki}}{c_{i2}-c_{i1}} i_1 + 0i_2 + \cdots + 0i_{m-2} + 0j & c_{i1} < x_{ki} \le c_{i2} \\ \vdots \quad \vdots & \\ 0+0i_1 + \cdots + 0i_{n-3} + \frac{x_{ki}-c_{im-1}}{c_{im}-c_{im-1}} i_{m-2} + \frac{c_{im+1}-x_{ki}}{c_{im}-c_{im-1}} j & c_{im-1} < x_{ki} \le c_{im} \\ 0+1j & x_{ki} > c_{im} \end{cases} \quad \ldots(6)$$

Let e_{im} be the coefficient corresponding to each item of μ_{ik}, and construct the evaluation relation matrix R, as follows:

$$R = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1m} \\ e_{21} & e_{22} & \cdots & e_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ e_{i1} & e_{i2} & \cdots & e_{im} \end{bmatrix}$$

Determination of the weight factor: In the comprehensive evaluation, the difference of the level of the individual indicators in the overall effect of pollution is different. It is not only related to the measured data, but also related to the allowable concentration of each element in the water. If the measured data are the same, the standard with low concentration is allowed to have low influence on the degree of pollution (Soriano et al. 2007). Therefore, in the comprehensive evaluation process, we need to use the pollutant concentration exceeding the standard weighting method to calculate the weight (Wang et al. 2008), as follows:

$$w_{ki} = \frac{x_{ki}}{s_i} \quad \ldots(7)$$

In the formula:

$$a_{ki} = \frac{w_{ki}}{\sum_{i=1}^{m} w_{ki}} \quad a_{ki} = \frac{w_{ki}}{\sum_{i=1}^{m} w_{ki}} \quad \ldots(8)$$

The normalization of w_{ki} is as follows:

$$s_i = \frac{1}{m}(c_{i1} + c_{i2} + \cdots + c_{im}) \quad \ldots(9)$$

Where, w_{ki} is the weight factor, x_{ki} is the measured value of the i-th factor of the sample K, c_{im} is the standard value of the concentration at all levels in the evaluation standard, s_i is the evaluation value of the water standard of the i-th factor, and a_{ki} is the weighting value of the i-th factor in sample K.

The measured values of the single factor are also substituted into the above formula, so the weight of single factor values and the weight matrix A can be obtained. And A is the factor weight set:

$$A = \{a_{k1}, a_{k2}, \cdots, a_{km}\} \quad \ldots(10)$$

Evaluation principle: The comprehensive evaluation results (Fulazzaky et al. 2010) are obtained through the combined operations of A and R, namely, the weighted calculation of evaluation factors $A \bullet R$.

The choosing big or small algorithm is adopted in the process of the matrix composite operation, i.e.:

$$A \bullet R = \max \min(a_{ij}, b_{ij}) \quad \ldots(11)$$

The evaluation results are determined by the principle of maximum degree of membership, of which the largest membership grade of water is the water quality for level positioning. If two of the maximum values are equal in the evaluation results, consider the second largest value principle. Of the two maximum values, that which is closer to the secondary value will be positioned as the level for the evaluation results (EB/OL).

RESULTS AND DISCUSSION

Connecting degree values: From October to December 2014, the research group went to the Bai Yang Ditch, Wang Jia Yuan Reservoir, Baqi Cave, Jingdong Caverns (underground river) and Jingdong Caverns (underground springs) to collect water samples. And the water quality of water samples was measured (Table 1).

pH values of water quality measured indicators are fixed. Hardness (mg/L), turbidity (NTU), COD (mg/L), ammonia nitrogen (mg/L) and other indicators are cost types. The fixed-type (pH) index was standardised using the following equation.

$$x'_{ij} = |x_{ij} - 7|$$

The cost type indexes do not need to be standardized, and can be directly normalized.

The average of each index sample is taken as the measured value. We then obtained each index's association degree calculation table and the evaluation relation matrix R (Table 2). The weighting factors of index are obtained (Table 3). According to the data in Table 1 and Table 2, we obtained evaluation results with equation (11) (Table 4). The data obtained by comparing composite index method recommended are shown in Table 5.

Contrasting the concentration of each area, Wang Jia Yuan Reservoir and Baqi Cave both had pH values greater than the class III critical value, indicating a need for neutralisation treatment. The hardness of the Bai Yang Ditch

Table 1: The measured indicators for six stations.

Location	Weight factor	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Bai Yang Ditch	pH	8.16	8.10	8.08	8.14	8.22	8.08
	COD	10.00	9.63	9.93	9.80	10.44	10.25
	Ammonia nitrogen	0.04	0.02	0.06	0.04	0.03	0.02
	Hardness	443.35	448.01	445.38	444.50	446.19	441.77
	Turbidity	1.33	1.36	1.24	1.38	1.38	1.24
Wang Jia Yuan Reservoir	pH	8.77	8.84	8.69	8.81	8.74	8.81
	COD	18.33	17.96	18.78	18.01	18.16	18.81
	Ammonia nitrogen	0.04	0.03	0.05	0.06	0.04	0.05
	Hardness	317.84	313.02	296.01	283.37	315.79	314.27
	Turbidity	2.90	2.94	2.96	2.88	2.89	2.86
Baqi Cave	pH	8.76	8.68	8.74	8.67	8.78	8.77
	COD	7.67	7.83	7.30	7.54	7.61	7.36
	Ammonia nitrogen	0.04	0.05	0.05	0.02	0.06	0.03
	Hardness	313.40	310.12	317.33	311.46	311.97	317.00
	Turbidity	1.51	1.57	1.52	1.59	1.49	1.57
Jingdong Caverns (underground river)	pH	7.47	7.41	7.44	7.44	7.57	7.48
	COD	4.36	4.15	4.97	4.05	3.63	3.41
	Ammonia nitrogen	0.03	0.03	0.03	0.02	0.03	0.03
	Hardness	356.78	355.96	360.15	358.57	352.09	354.56
	Turbidity	1.77	1.84	1.76	1.69	1.79	1.84
Jingdong Caverns (underground water)	pH	7.88	7.79	7.97	7.89	7.95	7.88
	COD	4.97	5.56	6.68	6.64	6.67	6.92
	Ammonia nitrogen	0.04	0.03	0.02	0.05	0.03	0.02
	Hardness	390.67	393.49	392.58	386.20	387.23	389.44
	Turbidity	1.25	1.22	1.27	1.30	1.20	1.21

area was close to the critical value of class III; thus, the Ditch also must be treated. The substance concentrations of the rest areas are far less than the class III critical values and therefore do not require treatment, which can be used in centralised drinking water sources, industry and agriculture.

Model evaluation: Water quality evaluation is a systematic project, which needs to take into account the properties of multiple indicators. Many factors, such as physical, chemical and biological water quality assessments, entail many uncertainties, and the evaluation factors and water quality maintain a complex nonlinear relationship. Water quality also has dynamic characteristics, making its assessment very complicated. There are many methods of water quality evaluation. In this paper, the "set-pair analysis model" is a kind of system analysis method which is used to characterize and study the identity, opposition and difference characteristics of the system. Its simple concept is rich in content, placing relative importance on information processing and ambiguity, and it does not lose intermediate information (Wang et al. 2010). The comprehensive evaluation results are relatively objective and practical and are obviously rational.

Compared with the fuzzy comprehensive evaluation method, the set pair analysis method is easy to use, calculate, and utilise. The results of the evaluation principles are more intuitive, accurate and reliable. This method improves the existing problems in the past evaluation index system, that is, the specific numerical value is used as the grading standard, so that we usually ignore the fact that the evaluation index has the identity, opposition and difference characteristics in different evaluation levels. The model used here also more objectively reflects water quality under the multi-factor interactions (Zhou et al. 2006). Therefore, the conclusion is more in line with the objective reality, and water quality evaluation results are more accurate and reasonable. This is a more scientific and effective water quality quantitative evaluation method.

Comprehensive evaluation: First, this study took the Bai Yang Ditch, Wang Jia Yuan Reservoir, Baqi Cave, Jingdong Caverns (underground river) and Jingdong Caverns (underground springs) as the research objects. And according to the evaluation object, evaluation purpose, and environmen-

Table 2: Association degree values for six stations.

Location	Membership function	y1	y2	y3	y4	y5
Bai Yang Ditch	pH	0.33	0.33	0.33	0	0
	COD	0.5	0.5	0.5	0	0
	Ammonia nitrogen	0	0.92	0.08	0	0
	Hardness	0	0.03	0.97	0	0
	Turbidity	0.33	0.33	0.33	0	0
Wang Jia Yuan Reservoir	pH	0	0	0	1	0
	COD	0	0.33	0.67	0	0
	Ammonia nitrogen	0	0.86	0.14	0	0
	Hardness	0	0.96	0.04	0	0
	Turbidity	0.33	0.33	0.33	0	0
Baqi Cave	pH	0	0	0	1	0
	COD	0.5	0.5	0.5	0	0
	Ammonia nitrogen	0	0.88	0.12	0	0
	Hardness	0	0.91	0.09	0	0
	Turbidity	0.33	0.33	0.33	0	0
Jingdong Caverns (underground river)	pH	0.33	0.33	0.33	0	0
	COD	0.5	0.5	0.5	0	0
	Ammonia nitrogen	0	0.96	0.04	0	0
	Hardness	0	0.62	0.38	0	0
	Turbidity	0.33	0.33	0.33	0	0
Jingdong Caverns (underground water)	pH	0.33	0.33	0.33	0	0
	COD	0.5	0.5	0.5	0	0
	Ammonia nitrogen	0	0.94	0.06	0	0
	Hardness	0	0.4	0.6	0	0
	Turbidity	0.33	0.33	0.33	0	0

Table 3: The weight of each index factor for six stations.

Location	pH	COD	Ammonia nitrogen	Hardness	Turbidity
Bai Yang Ditch	0.351	0.22	0.073	0.235	0.12
Wang Jia Yuan Reservoir	0.373	0.273	0.066	0.109	0.179
Baqi Cave	0.49	0.151	0.081	0.151	0.128
Jingdong Caverns (underground river)	0.225	0.14	0.089	0.293	0.253
Jingdong Caverns (underground water)	0.347	0.172	0.083	0.257	0.141

Table 4: The values of the calibrated coefficients in the SPA model for six stations.

Location	pH	COD	Ammonia	Hardness	Turbidity	Evaluation results
Bai Yang Ditch	0.267	0.343	0.5	0	0	Class III water, good
Wang Jia Yuan Reservoir	0.06	0.311	0.256	0.373	0	Grade IV water, poor
Baqi Cave	0.118	0.326	0.142	0.49	0	Grade IV water, poor
Jingdong Caverns (underground water)	0.229	0.498	0.343	0	0	Class II water, good
Jingdong Caverns (underground river)	0.248	0.429	0.408	0	0	Class II water, good

tal background, we chose several factors as evaluation indexes which play a main role in the pollution of the water environment, the ecological environment, human health, and social economy. These factors are pH, COD, hardness, turbidity, and ammonia nitrogen. Thus, the conclusion is more practical and feasible.

Second, in this paper, the water quality evaluation model is constructed by the set pair analysis theory. Samples were firstly analysed qualitatively with certainty-to-uncertainty analysis, and water quality is quantitatively evaluated by calculating the degree of association. After comparing the advantages and disadvantages with the weight assignment

Table 5: Results according to the composite index method.

Items	Bai Yang Ditch	Wang Jia Yuan Reservoir	Baqi Cave	Jingdong Caverns (underground water)	Jingdong Caverns (underground water)
pH	3	6	6	0	1
COD	3	3	1	1	1
Ammonia nitrogen	2.3	3	2.7	2.7	2.3
Hardness	3	3	2.3	3	3
Turbidity	1.3	2.9	1.5	1.8	1.2
The average value	2.52	3.58	2.7	1.7	1.7
The maximum value	3	6	6	3	3
F	2.77	4.94	4.65	2.44	2.44
The evaluation results	Class III water, good	Class IV water, poor	Grade IV water, poor	Class II water, good	Class II water, good

method, the "pollutant concentration exceeding the weighting method" is adopted, and the principle of "big or small algorithm" is applied in the matrix compound operation process. Considering the interaction between the indexes, the weight coefficient of water quality is consistent with the actual water quality, and the evaluation result is more intuitive and reliable (Wei et al. 2003).

In this text, the set pair analysis evaluation model was used to evaluate the quality of the karst water in Beijing. It not only reflects the water quality under the influence of various factors but also identifies the main pollutants and pollution types (Tong et al. 2008). This provides an important theoretical basis for the zoning and grading management of regional environmental quality of karst water distribution in Beijing, and also provides guidance for the formulation of environmental protection policies, project development, economic development and implementation of pollution prevention and control measures..

CONCLUSIONS

The set pair analysis theory is used to construct "set pair analysis and evaluation model", and through the calculation of contact degree we make a quantitative evaluation of water quality. In the process of determining the weight of the evaluation index we use the pollutant concentration exceeding the weighted method. Through the above methods, the paper comprehensively and objectively evaluates the main pollutants and pollution types, and objectively reflects the water quality status under the multi-factor interaction. It provides a more scientific and reasonable evaluation and decision-making method for water environment evaluation.

Based on the theoretical analysis and the establishment of mathematical model, the paper provides important data support and theoretical basis for the environmental evaluation and the actual treatment of karst water distribution area and the rational utilization of karst water in Beijing.

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