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A mathematical model for groundwater environmental quality evaluation based on entropy weight and uncertainty measure theory

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ABSTRACT

Groundwater environmental quality evaluation is of great significance for ecological balance as well as social and economic development, but it is still very difficult to realize timely and objective evaluation of groundwater environmental quality by existing evaluation methods. According to the characteristics of groundwater environmental quality evaluation and based on systematical analysis of the groundwater system control factors, this paper established a mathematical model of groundwater environmental quality evaluation based on entropy weight and uncertainty measure theory. In this model, uncertainty influence factors were analyzed quantitatively and qualitatively on the basis of real situation, uncertainty measure functions were constructed according to the experimental data, and the weights of indexes were provided based on the entropy weight theory. Finally, the groundwater environmental quality level could be determined based on the credible degree recognition criterion. This model was applied in the groundwater environmental quality evaluation of eight sections in Dalian city, and the evaluation results could fully reflect the comprehensive situation of water pollution. It is believed that the proposed model has good practicability and can provide an effective way for the environmental quality evaluation groundwater in the future.

Keywords: Groundwater environmental quality; Entropy weight; Uncertainty measure; Comprehensive evaluation

1. Introduction

Groundwater resource is the most important part of water resources system, which plays an important role in ensuring domestic water, industrial water and agricultural water, maintaining ecological balance and supporting social and economic development. However, in recent years, with the rapid development of modern industry, the continuous expansion of urban scale and the large use of chemical reagents such as pesticide, chemical fertilizer and herbicide have caused serious groundwater pollution. In order to grasp groundwater quality changes caused by groundwater pollution and provide scientific basis for controlling groundwater pollution and formulating urban water resources policies, it is of great urgency to develop timely and objective evaluation methods for monitoring the groundwater environmental quality.

The evaluation of groundwater environmental quality is actually a qualitative or quantitative assessment process on the utilization conditions of groundwater, by using certain evaluation parameters, relevant standards and specific evaluation methods [1]. With the development of computer technology and in-depth investigation on various mathematical methods, many evaluation methods and models have been proposed for water quality evaluation all around the world. Before and in the early stage of the

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1980s, the methods of water environmental quality evaluation were mostly index methods, including single factor index methods and comprehensive index methods. For example, Horton [2] proposed the index method of water quality evaluation (QI) in 1965; Brown et al. [3] put forward the quality index method (WQI) of water quality evaluation in 1970; in 1974, Nemerow [4] put forward the Nemerow method to assess the pollution of some surface water in New York, etc. However, these various index methods are prior evaluation models or adopt subjectively assumed parameters, so that the evaluation results have certain subjectivity and limited applicability [1,5]. In the late 1980s, the modern mathematical theory began to be applied to water environmental quality evaluation. Since then, various water environmental quality evaluation methods have been developed based on the fuzzy theory [6–10], the grey system theory [11,12], the statistical theory [13,14], the artificial neural network [15–17], the geographic information system (GIS) [18,19], etc. These mathematical quantitative methods have made some progress, but their practical applications encounter great obstacles due to various shortcomings. The fuzzy comprehensive evaluation method uses the linear weighted average value model, and the evaluation set is prone to distortion, failure or jumping; meanwhile, the water environmental quality grade evaluation is not allowed by this model, so that the operability is poor [1]. The grey comprehensive evaluation method has the problems of equalization, and it should deal with the complex calculation. Similarly, the artificial neural network method also faces the problems of equalization, and its principles and calculation processes are complex. In view of these reasons, this paper establishes a comprehensive evaluation model of groundwater environmental quality based on entropy weight and uncertainty measure theory. This theoretical model meets the criteria of "non minus, additivity, unitary and timing" and uses the recognition criterion of credible degree. The advantage of the attribute comprehensive evaluation model based on uncertainty measure mathematics is that it will not lose the useful information when making judgments, and the credible degree criterion will not cause unclear or unreasonable classification such as the maximum membership principle. In particular, the classification degree of ordered partition class is more accurate and more detailed [20].

This model was applied in the groundwater environmental quality evaluation of eight sections in Dalian city. At first, according to the definition of single index measure function, the classification standard and the monitoring data, single index measure functions were constructed to get the measure value of each evaluation index, and in the light of single index measure functions, single index evaluation matrixes of the selected eight sections were calculated. Then, the evaluation indexes weights were determined by the entropy weight theory. Finally, the groundwater environmental quality level was determined based on the credible degree recognition criterion. The results show that the model overcomes the shortcomings of other methods and improves the practicability and scientificity of evaluation, and is an ideal evaluation method.

The remainder of this paper is organized as follows. Section 2 describes entropy weight theory and uncertainty measure theory. Section 3 builds the evaluation indexes system for groundwater environmental quality. Section 4 took the groundwater quality monitoring data of Dalian city in 2015 as the example, gave the comprehensive evaluation model of groundwater environmental quality based on entropy weight and uncertainty measure theory, and analyze its performance. Conclusions are summarized in Section 5.

2. Methodology

2.1. Entropy weight theory

"Entropy" describes an irreversible phenomenon about the motion of ions or molecules in thermodynamics. It was initially used to represent the uncertainty of different experimental results and to characterize the disorder degree of the system in information theory. Entropy weight method is to determine the weight of each evaluation index according to the information contained in each index [21,22]. It has simple calculation procedure and can effectively use the data of all indexes, so that it is widely used in weight determination.

The initial evaluation matrix is composed of m evaluation indexes and n evaluation objects as follows:

$$(x_{ij})_{m\times n} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

All index values x_{ij} in matrix $(x_{ij})_{m\times n}$ (i = 1, 2, …, m; j = 1, 2, …, n) are normalized according to Eq. (2):

$$x'_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}} \quad (2)$$

Then, the entropy of each evaluation index can be obtained as follows:

$$e_i = \frac{\sum_{j=1}^{n} x'_{ij} \ln x'_{ij}}{\ln n} \quad (3)$$

The weight of each evaluation index can be calculated by Eq. (4):

$$w_i = \frac{1 - e_i}{\sum_{i=1}^{m} \left(1 - e_i\right)} \quad (4)$$

where w_i is the weight of the index, satisfying $\sum_{i=1}^{m} w_i = 1$. The greater the entropy weight, the greater the effect of the index on the scheme. Namely the index contains and transmits more decision information, and has greater impact on the final evaluation decision.

2.2. Uncertainty measure theory

2.2.1. Uncertainty measure of single index

$x_1, x_2, \ldots, x_n$ are set as n objects to be classified or have been classified, namely the index space $X = \{x_1, x_2, \ldots, x_n\}$. There are m single evaluation index spaces for each object, namely $I = \{I_1, I_2, \ldots, I_m\}$. Then, x_i can be represented as an m-dimensional vector $x_i = \{x_{i1}, x_{i2}, \ldots, x_{im}\}$. x_i has p assessment degrees, and thus the assessment degree space $U = \{C_1, C_2, \ldots, C_p\}$, where C_k denotes the k degree. Here, k degree is higher than $k+1$ degree, namely $C_k > C_{k+1}$, and then $\{C_1, C_2, \ldots, C_p\}$ is called an ordered partition class of the evaluation space U.

According to the definition of uncertainty measure, the single index measure function $\mu_{ijk} = \mu(x_{ij} \in C_k)(i = 1,2,\cdots,n; j = 1,2,\cdots,m; k = 1,2\cdots,p)$ can be built to calculate each index measure value μ_{ijk} of the evaluation factor x_i, and then matrix $(\mu_{ijk})_{m\times p}$ is named the single index evaluation matrix:

$$(\mu_{ijk})_{m\times p} = \begin{bmatrix} \mu_{i11} & \mu_{i12} & \cdots & \mu_{i1p} \\ \mu_{i21} & \mu_{i22} & \cdots & \mu_{i2p} \\ \vdots & \vdots & \vdots & \vdots \\ \mu_{im1} & \mu_{im2} & \cdots & \mu_{imp} \end{bmatrix} \quad (5)$$

2.2.2. Multiple indexes comprehensive measure

According to the index weight determined by the entropy weight theory, multi-index comprehensive measure of evaluating object $\mu_{ik} = \sum_{j=1}^{m} w_j \mu_{ijk} \left(i = 1,2,\ldots,n; j = 1,2,\ldots,m; k = 1,2,\ldots,p\right)$ can be obtained, wherein $0 \le \mu_k \le 1, \sum_{k=1}^{p} \mu_{ik} = 1$. Then, μ_{ik} is known as the uncertainty measure, and $\{\mu_{i1}, \mu_{i2}, \ldots, \mu_{ip}\}$ is the multi-index comprehensive evaluation measure vector of x_i.

2.2.3. Recognition criterion of credible degree

If $C_1 > C_2 > > C_p$, credible degree recognition criterion is introduced, and λ is set as the credible degree ($\lambda \ge 0.5$, usually $\lambda = 0.6$ or 0.7). Then, $k_0 = \min\left(k : \sum_{l=1}^{k_p} \mu_{il} \ge \lambda, 1 \le l \le k\right)$ is considered to belong to C_{k_0} [21–27].

3. Determination of evaluation indexes

The evaluation system of groundwater environmental quality is very complex, since many factors can affect groundwater environmental quality. Based on national standard of the People's Republic of China "quality standard for groundwater" (GB/T 14848-93) and standard of geological and mineral industry of the People's Republic of China "quality standard for groundwater" (DZ/T 0290-2015) [28,29], this paper selects total hardness (counting in $CaCO_3$), total dissolved solids, chloride, iron, nitrate (counting in N) and ammonia nitrogen (counting in N) as evaluation indexes. With the standard shown in Table 1, the level of ground water quality is graded into class I, II, III, IV and V.

4. Engineering example

Dalian is located at the south of Liaodong peninsula in Liaoning Province, along the coast of the Yellow and Bohai Sea, and across the sea with Shandong peninsula. It is an important economic centre, trade port, industry hub and tourism city in the eastern coastal areas of China. With the rapid development of industry and the acceleration of urbanization, a great amount of industrial waste water, domestic wastewater and other wastes are being produced continuously but have not been disposed reasonably enough, thus resulting in increasingly serious groundwater pollution. In this study, the groundwater quality monitoring data of Dalian city in 2015 are selected as the research object [30], and the entropy weight and uncertainty theory are used to evaluate the groundwater quality. Table 2 gives the monitoring data of groundwater quality in Dalian in 2015.

4.1. Single index measure functions of uncertainty measure

When an uncertainty measure set describes the phenomenon of "uncertainty", the key is to construct a reasonable uncertainty measure function. According to the definition of single index measure function, the classification standard in Table 1 and the monitoring data in Table 2, single index measure functions are constructed to get the measure value of each evaluation index. At present, the construction methods of single index measure function mainly include linear, exponential, parabola, sinusoidal, etc. Linear type uncertainty measure function is currently the most widely used and the simplest measure function, so this paper also uses linear type uncertainty measure function. Figs. 1–6 show the specific single index measure functions for all evaluation indexes, respectively.

In the light of single index measure functions above mentioned, and combined with the monitoring data in Table 2, single index evaluation matrixes of the selected eight sections can be calculated. Throughout this study, Xingmin is set as a research object, and its single index evaluation matrix is shown as follows:

$$(\mu_{1jk})_{6\times 5} = \begin{bmatrix} 0 & 0.43 & 0.57 & 0 & 0 \\ 0 & 0.62 & 0.38 & 0 & 0 \\ 0.57 & 0.43 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0.06 & 0.94 & 0 & 0 \\ 0.7 & 0.3 & 0 & 0 & 0 \end{bmatrix} \quad (6)$$

4.2. Multiple index measure evaluation matrix calculation

To determine evaluation index weights by the entropy weight theory, the weights of evaluation indexes of Xingmin are set as $[w_1\ w_2\ w_3\ w_4\ w_5\ w_6] = [0.14\ 0.14\ 0.14\ 0.24\ 0.20\ 0.14]$. In the light of single index measure matrix and multiple index calculation formula, the multiple index vector is $\mu_1 = \varpi_1 \cdot (\mu_{1jk})_{6\times 5} = \left[0.42 \quad 0.26 \quad 0.32 \quad 0 \quad 0\right]$.

Table 1
Classification standard of groundwater environmental quality evaluation index (unit: mg/L)

Number	Index	I	II	III	IV	V
1	Total hardness (counting in $CaCO_3$)	≤150	≤300	≤450	≤600	>600
2	Total dissolved solids	≤300	≤500	≤1,000	≤2,000	>2,000
3	Chloride	≤50	≤150	≤250	≤350	>350
4	Iron	≤0.1	≤0.2	≤0.3	≤2	>2
5	Nitrate (counting in N)	≤2	≤5	≤20	≤30	>30
6	Ammonia nitrogen (counting in N)	≤0.02	≤0.10	≤0.50	≤1.50	>1.50

Table 2
Monitoring data of groundwater quality in Dalian in 2015

Monitoring sections	Total hardness	Total dissolved solids	Chloride	Iron	Nitrate	Ammonia nitrogen
Xingmin	386	690.0	92.7	0.05	19.1	0.044
Fujia	430	726.5	86.6	0.08	28.1	0.109
Ershili	285	405.4	47.4	0.01	20.7	0.02
Huangqi	206	343.0	43.0	0.01	7.58	0.041
Sujia	833	1,454.5	212	0.02	32.2	0.047
Yinjia	331	529.5	118	0.01	9.79	0.094
Nanyaluzui	457	807.5	164	0.07	15.4	0.097
Xiaoheishi	526	1,008.5	249	0.09	20.6	0.033

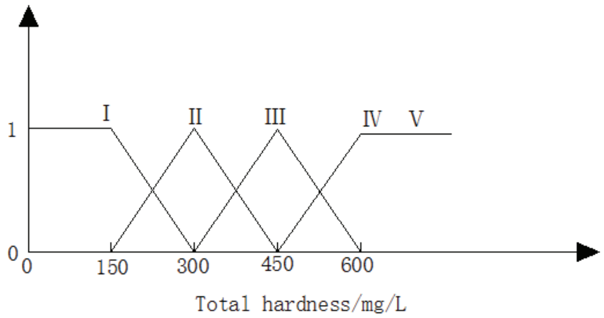

Fig. 1. Single index measure function of total hardness.

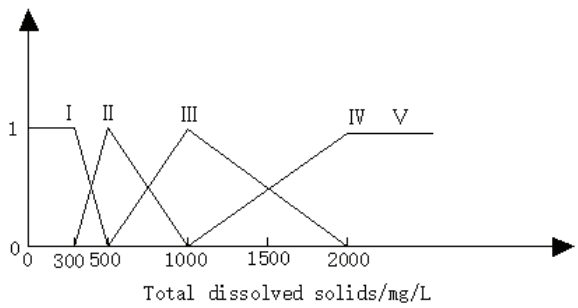

Fig. 2. Single index measure function of total dissolved solids.

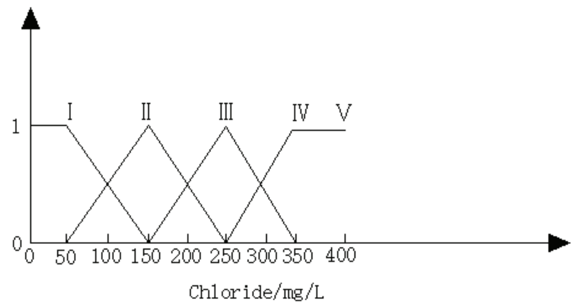

Fig. 3. Single index measure function of chloride.

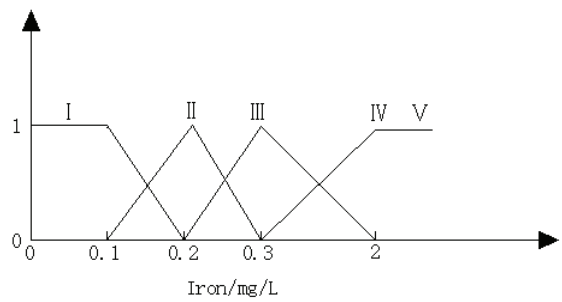

Fig. 4. Single index measure function of iron.

4.3. Credible degree recognition

Assume that credible degree λ = 0.7, and then multiply λ by index comprehensive evaluation measure vector and credible evaluation criterion formula, it can be obtained that $k_0 = 1 > 0.7$. Hence, the grade of Xingmin is determined to be class III. Other seven sections can be evaluated following similar steps, and the evaluation results are shown in Table 3. For comparison, the evaluation results based on the Nemerow index evaluation method are also provided in Table 3 [30].

As can be seen from Table 3, the comprehensive evaluation levels of groundwater quality in each monitoring section based on the entropy weight and uncertainty

Table 3
Comparisons for the evaluation results by the entropy weight and uncertainty measure model and the Nemerow index method

Monitoring sections	Comprehensive uncertainty measure					Evaluation results	Evaluation results based on the Nemerow index method
	I	II	III	IV	V		
Xingmin	0.42	0.26	0.32	0	0	III	III
Fujia	0.30	0.34	0.24	0.12	0	III	IV
Ershili	0.64	0.20	0.15	0.01	0	II	IV
Huangqi	0.72	0.25	0.07	0	0	I	II
Sujia	0.30	0.09	0.14	0.05	0.42	V	V
Yinjia	0.28	0.64	0.08	0	0	II	III
Nanyaluzui	0.22	0.40	0.37	0.01	0	III	IV
Xiaoheishi	0.32	0.02	0.59	0.07	0	III	IV

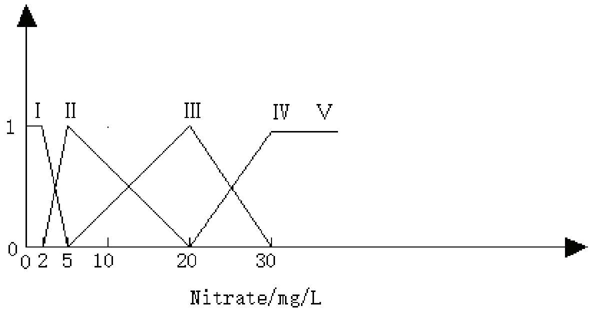

Fig. 5. Single index measure function of nitrate.

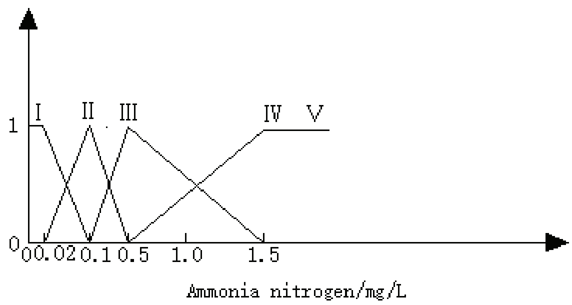

Fig. 6. Single index measure function of ammonia nitrogen.

measure are higher than those based on the Nemerow index method. To be specific, the groundwater quality in Ershili is upgraded from class IV to class II; that in Fujia, Nanyaluzui and Xiaoheishi is from class IV to class III; that in Yinjia is from class III to class II; and that in Huangqi is from class II to class I. According to the evaluation results by the entropy weight and uncertainty measure model, only the groundwater quality of Sujia does not meet class III water standard, whereas those of other seven monitoring sections all reach to the national drinking water standard. Although the Nemerow index method has convenient and simple mathematical operation process as well as clear physical concept, the influence of weight is not taken into account in the calculation process. Instead, the calculation process uses the arithmetical average, and does not consider the influences of different evaluation factors on the environmental poison rationality, the degradation difficult position and the removal difficult position. As a result, the comprehensive evaluation values by the Nemerow index method are generally higher than those by the entropy weight and uncertainty measure model.

5. Conclusions

(1) The mathematical model of groundwater environmental quality evaluation based on the entropy weight and uncertainty measure theory was established considering the influence factors and classification criterion of groundwater quality, and the groundwater environmental quality of eight monitoring sections in Dalian was evaluated using this model. According to the evaluation results, the groundwater quality of Sujia monitoring section was class V; that of Xingmin, Nanyaluzui and Xiaoheishi was class III; that of Yinjia was class II; and that of Huangqi was class I. That is, only the groundwater quality of Sujia did not meet class III water standard, whereas those of other seven monitoring sections all reached to the national drinking water standard.

(2) Compared with the Nemerow index comprehensive evaluation method, the entropy weight and uncertainty measure theory adopted variable weights to deal with the interrelated evaluation factors and considered the contribution of all evaluation factors to groundwater environmental quality, so that it could fully reflect the comprehensive situation of groundwater pollution. The engineering example analysis indicated that the entropy weight and uncertainty measure evaluation model was more scientific, objective and reasonable than the Nemerow index comprehensive evaluation method. It is believed that the proposed mathematical model provides a new idea for groundwater environmental quality evaluation.

(3) In the future research work, the further research is needed on how to make more reasonable scientific selection of evaluation index and how to determine the weight of the index, so as to enhance the universal applicability and conscientiousness of the method. In particular, with the continuous development and improvement of groundwater environmental quality evaluation techniques, the value accuracy of the index influenced on groundwater environmental quality can be further improved, and more accurate evaluation results can be obtained.

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