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Evaluation of the environmental quality associated with near-surface groundwater characteristics in coal-mining areas based on rough set and uncertainty measure theory

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ABSTRACT

It is important to assess detrimental environmental effects, including those associated with groundwater, in arid and semi-arid areas of western China where coal mines are located. Here, we analyze geological and hydrogeological data for these coal-mining areas to better understand the environmental quality and conditions, and groundwater characteristics. Using rough set and uncertainty measure theory, we establish a model for evaluating the environmental conditions and effects associated with variations in near-surface groundwater characteristics (chemistry, circulation, and distribution) in coal-mining areas. Rough set theory is used to analyze the data of various evaluation indexes used for measuring environmental conditions and groundwater characteristics as well as to optimize the number of indexes by removing redundant/unimportant indexes and to assign the relative weightings of the remaining indexes. By using uncertainty measure theory to construct the uncertainty function of the evaluation index and to calculate the uncertainty evaluation vector, the level of environmental quality is determined according to the criterion of confidence recognition. To test the application and effectiveness of the model, it is used to evaluate the environmental quality and conditions associated with near-surface groundwater characteristics in five coal-mining areas in western China. The evaluation results are compared with the results obtained using the fuzzy comprehensive evaluation method and uncertainty measure theory without a reduction in the number of indexes in the evaluation. The results show that the model is appropriate for environmental studies, has a high level of applicability, and establishes a good reference for future evaluations of environmental and groundwater changes associated with coal-mining or other environmental disturbance.

Keywords: Rough set; Uncertainty measure; Groundwater; Near-surface environmental conditions

1. Introduction

Western China has abundant geological resources, including coal, natural gas, halite, and minerals. In the process of mining coal, chemicals are released and underground properties are changed, potentially contaminating local groundwater and producing other adverse environmental effects. Coal mining may alter the chemical composition of groundwater, its circulation, and its horizontal and vertical distribution, leading to a gradual depletion of water resources, the destruction of vegetation, and desertification, amongst other problems [1,2]. In addition, water resources pressure has been increasing dramatically over the last two decades in response to the rising population and the development of

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agriculture and industry. In mining areas, the scale and type of development far exceed the carrying capacity of the fragile environment of the host areas [3–6]. Therefore, it is important to conduct research that will inform the coordinated development of underground water resources and coal mining while also protecting the environment.

Because of the uncertainties associated with determining how groundwater characteristics may vary over space and time, it is difficult to accurately evaluate environmental conditions and groundwater characteristics in coal-mining areas. Various index systems for evaluating environmental quality and conditions have been developed for application in coal-mining areas. Some of these systems use a single index, meaning that the evaluation may be neither comprehensive nor accurate. Therefore, for evaluating environmental quality and conditions associated with variations in groundwater characteristics, multiple indexes are commonly used. However, owing to the different sensitivities of the indexes used, variations may arise in the effectiveness of environmental evaluations. Furthermore, some indexes do not contribute to the evaluation results when they are combined, and this situation may arise if indexes overlap in terms of the environmental condition or characteristic that they capture. Thus, it is important to choose indexes carefully when undertaking evaluations that combine multiple indexes.

Given the above concerns, scholars have developed mathematical methods such as fuzzy comprehensive evaluation theory [4], artificial neural networks [7], and support vector machine (SVM) models [8], all of which have been applied to the evaluation of epigenetic environmental effects associated with variations in groundwater conditions. However, these methods have their own particular limitations. For example, the fuzzy evaluation method does not meet the measure criteria of being non-negative, bounded, additive, and unitary, and there is also a deficiency in its principle of "taking large and small" [9], especially when determining weights, as there is a degree of subjectivity in any scoring method devised by experts. Neural networks are prone to local optimality and have limited ability to solve small-sample problems. Furthermore, the selection of kernel functions and their parameters in SVM models is complicated [10].

Considering the aforementioned issues with the various mathematical methods, we establish a model for evaluating the environmental conditions and effects associated with variations in near-surface groundwater characteristics in coal-mining areas based on rough set and uncertainty measure theory. At first, we use rough set theory [11] in the present study to optimize the number and weighting of evaluation indexes used to measure environmental conditions. We conduct attribute dependency analysis to remove the relatively unimportant or redundant indexes and to optimize the weight distribution of the remaining indexes. Furthermore, we construct the uncertainty measure function of each index using uncertainty measure theory [12,13], with the evaluation level of each index being determined according to the criterion of confidence degree recognition. Finally, using the developed method, we obtain the results for the evaluation of the environmental conditions and effects associated with near-surface groundwater characteristics in the selected coal-mining areas. The method used here synthesizes the advantages of attribute reduction and objective weight distribution given by rough set theory with the advantages of the analysis of uncertainty present in the information given by uncertainty measure theory. The method is soundly based and can be suitably applied to most types of environmental assessment.

The remainder of this paper is organized as follows. Section 2 introduces rough set reduction algorithm and uncertainty measure model. Section 3 constructs a comprehensive evaluation model for the evaluation of the environmental quality associated with near-surface groundwater characteristics in coal-mining areas, and applies this model to evaluate the environmental quality and conditions associated with near-surface groundwater characteristics in five coal-mining areas in western China. Section 4 summarizes the conclusions.

2. Methodology

2.1. Rough set reduction algorithm

Rough set theory, which was proposed by the Polish mathematician Pawlak in 1982 [14], is a mathematical method for handling uncertain, incomplete, and/or inconsistent data.

2.1.1. Indistinguishable relationships

Rough set theory is a mathematical approach to dealing with imperfect knowledge/information (i.e., knowledge/information that is vague, imprecise, uncertain, and/or inconsistent). The theory considers that knowledge is closely related to classification, with the aim of classification being to group objects into categories based on the degree of the similarity. The theory is able to generate rules through the classification of relational databases and to create knowledge through the classification of the equivalence relation. A knowledge (attribute value) system can be expressed as follows:

$$K = (U, R) \quad (1)$$

where U is a non-empty finite set and is termed the domain, and R is an equivalence relationship in U. U/R is all equivalence families of R. $[X]_R$ represents an equivalence class of R that contains elements $x \in U$. If $P \subseteq R$ and $P \neq \Phi$, then the intersection of all equivalence relations in P is also an equivalence relationship, termed the indistinguishable relationship in P; that is:

$$\text{ind}(P), [X]_{\text{ind}(R)} = \bigcap_{R \in P} [X]_R, P \subseteq R \quad (2)$$

2.1.2. Upper approximation, lower approximation, and boundary for the rough set

The concept of imprecision for the rough set is expressed by defining two exact sets: the upper approximation and the lower approximation to the target set, with the former defining the set of objects that can be definitely ruled out as members of the target rough set, and the latter defining the set of objects that can be unambiguously identified as belonging to the target rough set. Given a knowledge system

$K = (U,R)$, two subsets are defined for each subset $x \in U$ as well as an equivalence relationship $R \in \text{ind}(K)$, as follows: $R\_(X)$ and $R^-(X)$ are termed the R lower approximation set and the R upper approximation set of X, respectively, and the R boundary domain of X is defined as follows:

$$bn_R(X) = R^-(X) - R\_(X) \quad (3)$$

Furthermore, $\text{pos}_R(X) = R^-(X)$ is R plus the domain of X, and $\text{neg}_R(X) = U - R\_(X)$ is R minus the domain of X.

2.1.3. Information systems and the decision-making table

A knowledge system, also known as an information system, is expressed in the form of a relational table. A knowledge system with conditional attributes and decision attributes is termed a decision table. The expression

$$S = (U, A, V) \quad (4)$$

is established as a knowledge system, where $S = (x_1, x_2, \ldots, x_n)$ is a finite set of objects; $A = (a_1, a_2, \ldots, a_n)$ is the finite set of attributes; V is the domain formed by the attribute A; $f{:}U \times A \rightarrow V$ is an information function, for which when any element in U takes the attribute a in V, there is a uniquely determined value; and $A = C \cup D$, C is the collection of conditional attributes where D is the collection of decision attributes.

2.1.4. Simplification of the decision table

Simplification of the decision table involves simplifying the conditional attributes in the table. The simplified decision table has the same function as the original (pre-simplified) decision table, but the simplified decision table has fewer conditional attributes compared with the original table. Therefore, the simplification of decision tables is an important step in practical applications of rough set theory, because the decision is able to be based on fewer conditions (i.e., the same result is obtained, but through simpler means). The steps for simplifying the decision table are as follows: (1) simplify the conditional attributes (i.e., eliminate certain columns from the decision table); (2) eliminate the repeated lines; and (3) remove the redundant values of the attribute [11–17]. The present study used these steps to identify and remove the redundant indexes with regard to evaluating the environmental quality and conditions associated with near-surface groundwater characteristics.

2.2. Uncertainty measure model

$x_1, x_2, \ldots, x_n$ are a set of n objects to be evaluated, represented as $X = \{x_1, x_2, \ldots, x_n\}$, which is termed the domain. Each evaluation object has m one-way evaluation index spaces, represented as $I = \{I_1, I_2, \ldots, I_m\}$, with x_{ij} being denoted as the observed value of the object x_i under the index I_j $U = \{C_1, C_2, \ldots, C_p\}$ is set as an evaluation space, wherein C_k represents the k evaluation level, and the k level is higher than the $k + 1$ level; that is, $C_k > C_{k+1}$.

2.2.1. Uncertainty measure for a single index

When the observed value x_{ij} of the index I_j for the object x_i is different, this index makes the evaluation level of x_i different, and the C_k degree of the k evaluation level of x_{ij} means that x_i is set in terms of $\mu_{ijk} = \mu(x_{ij} \in C_k)$ ($i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, m$; $k = 1, 2, \ldots, p$), where μ_{ijk} is a measure of the degree. As a measure, it must meet the criteria of being non-negative, bounded, additive, and unitary. The single-index measure function $\mu(x_{ij} \in U)$ ($i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, m$) is constructed based on the definition of an uncertainty measure, and it is used to find each index measure value μ_{ijk} of the evaluation index x_i. The matrix formed by μ_{ijk} is termed the single-index measure evaluation matrix; that is, μ_{ijk} meets the following criteria:

$$0 \le \mu(x_{ij} \in C_k) \le 1 \quad (i = 1,2,\ldots,n; \quad j = 1,2,\ldots,m; \quad k = 1,2,\ldots,p) \quad (5)$$

$$\mu(x_{ij} \in U) = 1 \quad (i = 1,2,\ldots,n; \quad j = 1,2,\ldots,m) \quad (6)$$

$$\mu(x_{ij} \in \bigcup_{l=1}^{k} C_l) = \sum_{l=1}^{k} \mu(x_i \in C_l) \quad (k = 1,2,\ldots,p) \quad (7)$$

The μ_{ijk} that meets the above three measure criteria is an uncertainty measure and

$$(\mu_{ijk})_{m \times p} = \begin{bmatrix} \mu_{i11} & \mu_{i12} & \cdots & \mu_{i1p} \\ \mu_{i21} & \mu_{i22} & \cdots & \mu_{i2p} \\ \vdots & \vdots & \vdots & \vdots \\ \mu_{im1} & \mu_{im2} & \cdots & \mu_{imp} \end{bmatrix} \quad (8)$$

is termed the measure evaluation matrix for a single index.

2.2.2. Determination of weights for classification indexes

$w_j (0 \le w_j \le 1, \sum_{j=1}^{m} w_j = 1)$ is set to represent the importance of I_j relative to other indexes, where w_j is the weight of I_j ($j = 1, 2, \ldots, m$). The weight of each index is determined according to information entropy theory; that is:

$$v_j = 1 + \frac{1}{\lg p} \sum_{i=1}^{p} \mu_{ijk} \lg \mu_{ijk} \quad (9)$$

$$w_j = \frac{v_j}{\sum_{i=1}^{m} v_i} \quad (10)$$

2.2.3. Integrated evaluation system

According to the index weightings determined, a comprehensive multiple-index measure for evaluating the object

$$\mu_{ik} = \sum_{j=1}^{m} w_j \mu_{ijk} \quad (i = 1,2,\cdots,n; \quad j = 1,2,\cdots,m; \quad k = 1,2\cdots,p) \quad (11)$$

is obtained, where if $0 \le \mu_k \le 1, \sum_{k=1}^{P} \mu_{ik} = 1$, then μ_{ik} is the uncertainty measure and $\{\mu_{i1}, \mu_{i2}, \ldots, \mu_{ip}\}$ is the comprehensive multiple-index evaluation uncertainty measure vector of x_i.

2.2.4. Evaluation criterion

The classification of the evaluation level is orderly, and the C_k of k evaluation levels is better than the C_{k+1} of $k + 1$ evaluation levels. Therefore, the maximum measure identification criterion is not suitable, and the confidence recognition criterion is used. λ is set at a credible degree ($\lambda \ge 0.5$), usually a value of 0.6 or 0.7 is taken),

$$k_0 = \min\left(k : \sum_{l=1}^{k_p} \mu_{il} \ge \lambda, 1 \le l \le k \right) \tag{12}$$

and C_{k_0} is considered for the k_0 evaluation level of x_i [12,13,18–23].

3. Case study: evaluation of the environmental quality and conditions associated with near-surface groundwater characteristics in coal-mining areas

The Jurassic coalfield in the Ordos Basin of western China is a key area being developed for large-scale coal exploitation by the state government. The coal reserves account for more than 67% of the country's reserves, but the host area is also an arid and water-deficient area and is environmentally fragile. Long-term coal mining has already caused a series of serious environmental–geological problems. On the one hand, the mining has affected the environmental–geological environment of the area and has restricted the level of sustainable socio-economic development. On the other hand, the environmental damage has had a strong feedback effect on the exploitation of coal resources and on the use of water and land resources in coal-mining areas. Therefore, to promote the sustainable development and utilization of water resources and to better manage the natural environment in coal-mining areas of western China, it is necessary to investigate and evaluate the environmental quality and conditions associated with variations in groundwater characteristics (the chemistry, circulation, and vertical/horizontal distribution of groundwater) in this area.

Here, we examine elected coal-mining areas in western China by taking into account both the established evaluation indexes of the environmental conditions associated with variations in groundwater characteristics [3–7] and our field survey data collected in this area. On the basis of our examination, we constructed a comprehensive index-based evaluation system, divided into 3 levels and 11 indexes. The qualitative indexes of the system, namely geomorphologic type, vadose zone lithology, vadose zone structure, and groundwater chemistry type, are evaluated based on qualitative or semi-quantitative methods. The quantitative indexes, namely groundwater depth, groundwater mineralization, vadose zone water content, vadose zone salt content, rainfall, evaporation, and river baseflow reduction, are evaluated based on observed/measured values. The classification values for each index and their evaluations are presented in Table 1. Each index is divided into five value-range levels in the classification, and the evaluation set is $\{C_1, C_2, C_3, C_4, C_5\}$ (which, for evaluating the environmental quality associated with near-surface groundwater characteristics, corresponds to levels I, II, III, IV, and V), which represent good, fairly good, moderate, fairly poor, and poor environments with respect to quality, respectively. The status of selected coal-mining areas in western China with respect to the 11 evaluation indexes used is presented in Table 2.

3.1. Attribute reduction of the rough set

The raw data of each mining area (Table 2) were discretized using the criterion of evaluation index function score (Table 1), enabling construction of the decision table (Table 3).

3.2. Reduction of attributes in the decision-making table

The exhaustion algorithm in Rosetta data analysis software (developed by researchers from the University of Warsaw and the Norwegian University of Science and Technology) was used to reduce the attributes of the decision table. This resulted in three redundant indexes being removed (vadose zone water content, vadose zone salt content, and river baseflow reduction), leaving eight indexes remaining in the table.

3.3. Single-index measure function of the uncertainty measure

Under uncertainty measure theory, each index is graded and valued. Although it is clear that the criteria for constructing uncertainty measure need to be satisfied in uncertainty theory, no specific construction method is given. Considering that linear uncertainty measure function is the most widely used and simplest measure function in the construction method of uncertainty measure function commonly used, so we also constructed the uncertainty measure function of each individual index by linear type uncertainty measure function. The specific single-index uncertainty measure functions for the four qualitative and four quantitative indexes are shown in Figs. 1–5, respectively.

3.4. Construction of the multiple-index evaluation matrix

To verify the feasibility and applicability of the model, and using the values in Table 2 and the single-index uncertainty measure function above, the single-index uncertainty measure evaluation matrix of the five mine areas can be calculated. Shangwan mine is taken as the example mine for demonstrating the calculation. The evaluation matrix of the single-index uncertainty measure is calculated as follows:

$$\begin{bmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{13}$$

Table 1
Classification of the environmental conditions associated with groundwater characteristics for the 11 evaluation indexes used in the present study

Evaluation index		Evaluation level				
		Good environment (C_1)	Fairly good environment (C_2)	Moderate environment (C_3)	Fairly poor environment (C_4)	Poor environment (C_5)
Geological and geomorphological factors	Geomorphological type	River valley terrace area(5)	Loess gully hilly area (4)	Lake group high plain (3)	Sand covered hilly area (2)	Maowusu desert area (1)
	Lithology of vadose zone	Silty subclay, subsandy soil (5)	(4)	Silty subsandy soil subclay (3)	Fine sand, subsandy soil (2)	Subsandy soil, sandy gravel (1)
	Structure of vadose zone	$Q_3 + Q_2$(5)	(4)	Q_2 (3)	(2)	Q_{3s} (1)
Hydrogeological factors	Groundwater depth (m)	1–3	<1	3–5	5–8	>8
	Groundwater mineralization (g/L)	<1	1–3	3–10	10–50	>50
	Groundwater chemistry type	HCO_3–Ca (5)	HCO_3–Ca·Mg (Mg·Ca) (4)	HCO_3–Ca·Na·Mg (3)	HCO_3·SO_4–Ca·Mg HCO_3–Ca·Mg (2)	SO_4·Ca·Mg (Cl·Na) (1)
	Water content in vadose zone (%)	>6	4.667–6	3.333–4.667	2–3.333	<2
	Salt content of vadose zone (%)	<0.2	0.2–1.0	1.0–2.0	2.0–3.0	>3.0
Meteorological and hydrological factors	Rainfall (mm)	>440	430–440	420–430	410–420	<410
	Evaporation (depth of groundwater level) (m)	Slight influence (>3)	2.7–3.0	Moderate influence (2.6–2.7)	2.5–2.6	Strong influence (<2.5)
	River baseflow reduction (%)	<10	10–20	20–30	30–40	>40

Table 2
Survey statistical table of evaluation indexes in selected coal-mining areas

Evaluation index		Mine Data				
		Shangwan mine	Baode mine	Jinjie mine	Cuncaota mine	Yujialiang mine
Geological and geomorphological factors	Geomorphological type	Wind accumulation sand hilly area (2)	Loess gully hilly area (4)	Wind accumulation sand hilly area (2)	Plateau erosive hill (4)	Loess gully hilly area (4)
	Lithology of vadose zone	Fine sand, subsandy soil (2)	Yellow sandy soil, subsandy soil (2)	Fine sand, subsandy soil (2)	Sandy gravel, wind accumulation sand (1)	Silty subclay, subsandy soil (5)
	Structure of vadose zone	$Q_2 + Q_3 + Q_4$(5)	$Q_2 + Q_3 + Q_4$(5)	$Q_3 + Q_2$(5)	Q_{4al+pl}(1)	$Q_3 + Q_2$(5)
Hydrogeological factors	Groundwater depth (m)	>8	2–5	>8	0.8–2.6	>8
	Groundwater mineralization (g/l)	<1	<1	<1	<1	1–3
	Groundwater chemistry type	HCO_3–Ca·Mg (Mg·Ca) (4)	$HCO_3 \cdot SO_4$–Ca·Mg HCO_3–Ca·Mg (2)	HCO_3–Ca (5)	HCO_3–Ca·Mg (3)	HCO_3–Ca·Mg (Mg·Ca) (4)
	Water content in vadose zone (%)	<2	<2	<2	<2	<2
	Salt content of vadose zone (%)	1	1	1	1	1
Meteorological and hydrological factors	Rainfall (mm)	369	500	410	369	410
	Evaporation (depth of groundwater level) (m)	Strong influence (<2.5)	Strong influence (<2.5)	Slight influence (>3)	Strong influence (<3)	Strong influence (<2.5)
	River baseflow reduction (%)	10–20	<10	<10	10–20	10–20

Table 3
Discrete evaluation data table

Evaluation index		Mine data				
		Shangwan mine	Baode mine	Jinjie mine	Cuncaota mine	Yujialiang mine
Geological and geomorphological factors	Geomorphological type	2	4	2	4	4
	Lithology of vadose zone	2	2	2	1	5
	Structure of vadose zone	5	5	5	1	5
Hydrogeological factors	Groundwater depth (m)	1	3	1	5	1
	Groundwater mineralization (g/l)	5	5	5	5	4
	Groundwater chemistry type	4	2	5	3	4
	Water content in vadose zone (%)	1	1	1	1	1
	Salt content of vadose zone (%)	3	3	3	3	3
Meteorological and hydrological factors	Rainfall (mm)	1	5	2	1	2
	Evaporation(depth of groundwater level) (m)	1	1	5	1	1
	River baseflow reduction (%)	4	5	5	4	4
Environmental level		C_4	C_3	C_4	C_5	C_2

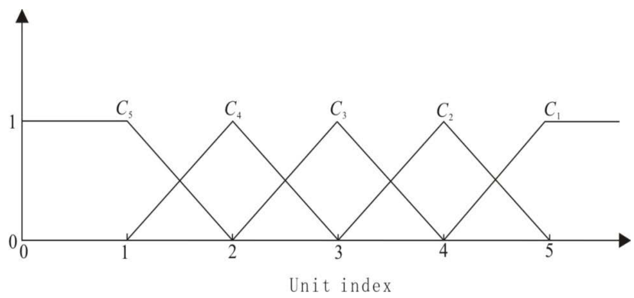

Fig. 1. Single-index uncertainty measure function of the qualitative indexes (geomorphological type, vadose zone lithology, vadose zone structure, and groundwater chemistry type).

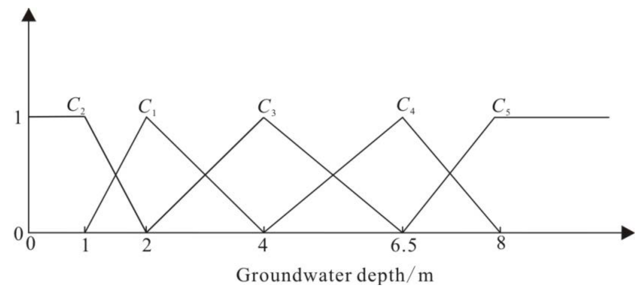

Fig. 2. Single-index uncertainty measure function of groundwater depth.

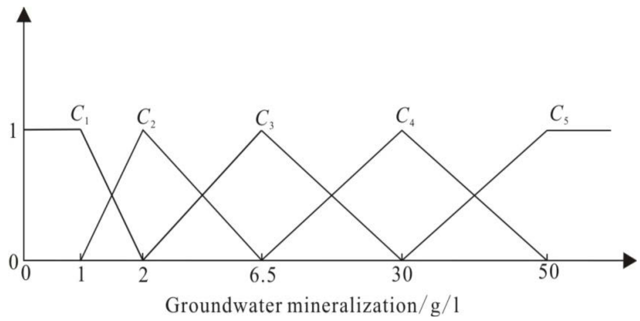

Fig. 3. Single-index uncertainty measure function of groundwater mineralization.

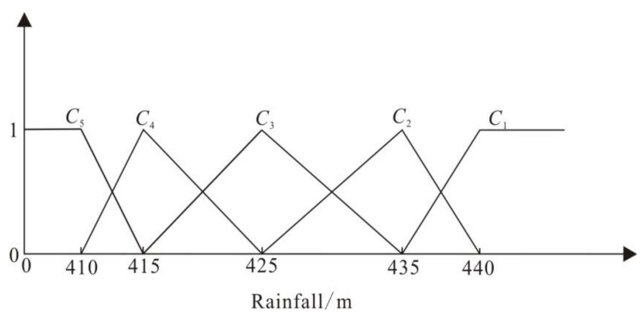

Fig. 4. Single-index uncertainty measure function of rainfall.

According to the entropy weight calculation methods of Eqs. (9) and (10), the weights of each evaluation index are determined as $\left[w_1 \quad w_2 \quad w_3 \quad w_4 \quad w_5 \quad w_6 \quad w_7 \quad w_8\right]$, with the weights of the evaluation index for Shangwan mine being equal to $\left[0.125 \quad 0.125 \quad 0.125 \quad 0.125 \quad 0.125 \quad 0.125 \quad 0.125 \quad 0.125\right]$. According to the single-index uncertainty measure matrix

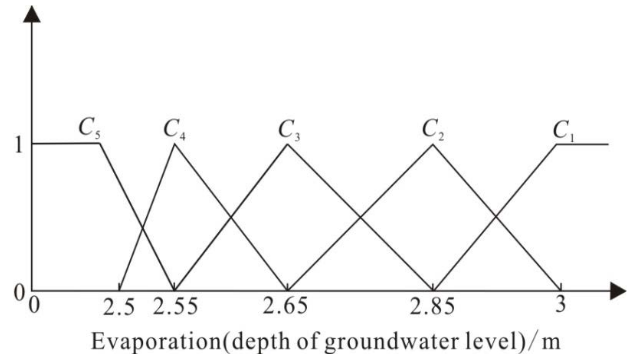

Fig. 5. Single-index uncertainty measure function of evaporation(with respect to the depth to groundwater).

and the multiple-index uncertainty measure calculation formula, the multiple-index uncertainty measure vector is $\mu_1 = \varpi_1 \cdot \mu_{A_1} = \begin{bmatrix} 0.25 & 0.125 & 0 & 0.25 & 0.375 \end{bmatrix}$.

3.5. Credible degree recognition

Taking the credible degree λ as 0.6, k_0 = 0.625 is greater than 0.6, and therefore the environmental level in Shangwan mine is classified as IV. Similarly, the four other mine areas were evaluated, with the results for all five mines being reported in Table 4. The table also compares the evaluation results obtained using the uncertainty measure method with those obtained using the fuzzy comprehensive evaluation method. The results given by the uncertainty measure method in the case where the number of indexes was reduced are consistent with those yielded by the uncertainty measure method and the fuzzy comprehensive evaluation method without index reduction. Compared with other evaluation models, the evaluation model based on rough set and uncertainty measure theory provides useful results and has a high level of applicability, as it is able to perform the same evaluation but with fewer indexes.

4. Conclusions

- We used rough set theory and measure uncertainty theory to evaluate the environmental quality and conditions associated with variations in groundwater characteristics (chemistry, circulation, and distribution of groundwater) in mining areas in western China. The application of rough set theory reduced the number of indexes from 11 to 8 by identifying and removing the least important ones, allowing the number and composition of the indexes used in the evaluation to be optimized. Rough set theory was then applied to determine the relative weights of the remaining indexes.
- The environmental conditions and groundwater characteristics have accompanying information uncertainty. The uncertainty measure evaluation method was used to define the single-index measure functions of the uncertainty measure as well as the uncertainty evaluation vector. Accordingly, a rough set and uncertainty measure model for the evaluation of the environmental quality and conditions associated with groundwater characteristics was able to be established.
- A field application of the model to mining areas in western China shows that the model constructed to evaluate the environmental quality and conditions associated with groundwater characteristics is well based in scientific terms and in terms of its applicability. The evaluation results yield a good representation of the observed environmental conditions and groundwater characteristics, suggesting that the model is suitable for evaluating environmental problems.
- Because the evaluation of the environmental quality associated with near-surface groundwater characteristics in coal-mining areas contains many uncertain information, the research on these information is not yet in-depth and systematic. Therefore, it is necessary to continuously study and improve the evaluation model in order to achieve scientific and accurate the evaluation of environmental quality and conditions associated with near-surface groundwater characteristics in coal-mining areas.

Table 4
Evaluation results for the near-surface environmental conditions associated with groundwater characteristics based on rough set and uncertainty measure theory

Mining area	Uncertainty measure after reduction					Evaluation result	Evaluation without reduction	
	I	II	III	IV	V		Evaluation result based on uncertainty measure	Evaluation result based on fuzzy comprehensive evaluation
Shangwan mine	0.25	0.125	0	0.25	0.375	IV	IV	IV
Baode mine	0.375	0.125	0.125	0.25	0.125	III	III	III
Jinjie mine	0.5	0	0	0.375	0.125	IV	IV	IV
Cuncaota mine	0.25	0.125	0	0.125	0.5	V	V	V
Yujialiang mine	0.25	0.375	0	0.125	0.25	II	II	II

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