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Original Research

Fuzzy Comprehensive Evaluation Method for Geological Environment Quality of Typical Heavy Metal Mines

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Abstract

Zhaotong City, at the junction of Yunnan, Guizhou and Sichuan provinces in China, is rich in mineral resources, and high-intensity mining has brought great challenges to the mine geological environment. The evaluation of mine geological environment quality is still a complex and systematic work. The geological environment of different regions is very different, and it is difficult to adopt a unified standard for quantification. Therefore, a general evaluation method has not been formed 22 factors, including cumulative value of surface subsidence, earthquake intensity, debris flow source volume, ground crack length, fault density, number of mine pits, ponding area, aquifer thickness, annual rainfall, groundwater level drop, river erosion area, groundwater impact range, proportion of goaf area, soil heavy metal concentration, water pollution volume, PM2.5, integrity factor, weathering coefficient, joint density, uniaxial compressive strength, population density, annual per capita GDP, which affect the geological environment quality of the mine, are selected as evaluation factors. By applying the principles and methods of fuzzy evaluation, The geological environment quality of Maoping lead-zinc mine is divided into four grades: excellent, good, commonly and inferior. The evaluation results can provide decision-making reference for the current geological environment protection research and future renovation planning of Maoping lead-zinc mine.

Keywords: metal mines, geological environment, fuzzy evaluation, analytic hierarchy process

Introduction

Maoping lead zinc mine is located at 205° in the center of Yiliang County, Zhaotong City, Yunnan Province, with a straight-line distance of 12 km. The administrative district belongs to Luozehe Town, Yiliang County, Zhaotong City. The total area of the mining area is 20.05 km^2. The geographic extreme coordinates of the mining area are 103°58′05″~104°00’21″E and 27°29′49″~27°31’38″N [1]. The geographic location map is shown in Fig. 1. The mining area is located in the connecting zone between Sichuan Basin and Yunnan Guizhou Plateau. The regional tectonic line is generally consistent with the trend of the mountain range, and most of them

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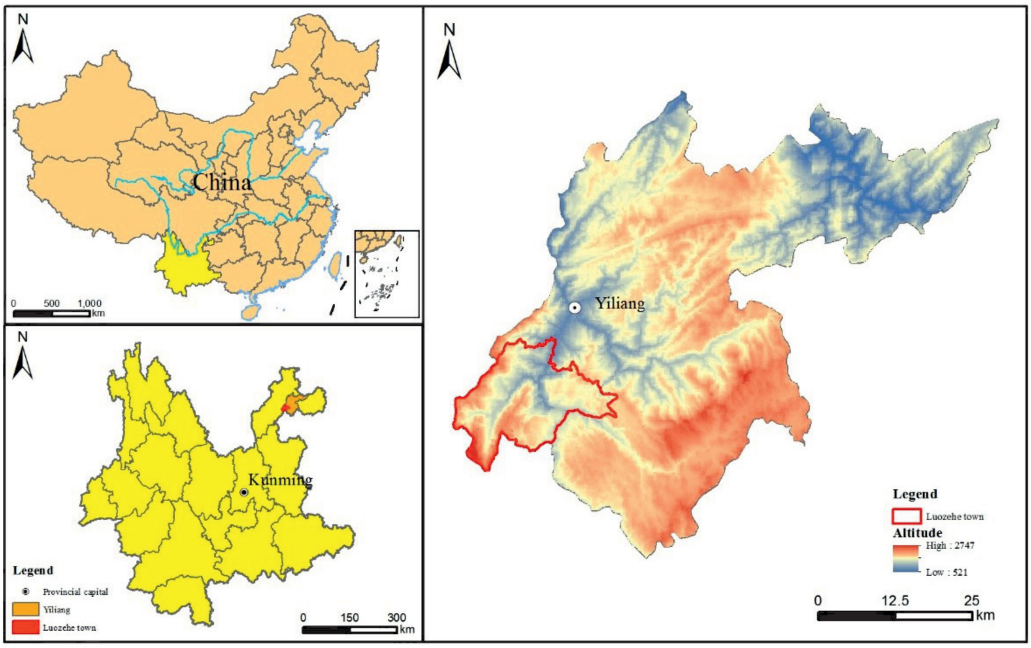

Fig. 1. Geographic location and altitude distribution map of Maoping mining area.

are NNE trending mountains. The deposit is located in the lead-zinc metallogenic belt from Northeast Yunnan to Northwest Guizhou. The mining area is located at the intersection of Wumengshan Jinshajiang fault zone and Yadu Ziyun fault zone [2]. It is rich in lead-zinc mineral resources.

While mineral resources have made great contributions to national construction, they have also caused a series of environmental problems, especially mine geological environment problems. Continuous years of mining have caused frequent landslides, mudslides and mining earthquakes in the mining area and adjacent areas [3]. The water environment, rocks, soils and aquifers in the mining area have been damaged to varying degrees, and the geological environment of the mining area has been greatly threatened [4], seriously restricting the development and utilization of mineral resources and the sustainable development of local ecology and economy [5].

At present, there are many methods to evaluate the geological environment quality of mines, such as grid method [6], vector polygon method [7], buffer zone method GIS layer overlay analysis method [8], RS method [9] et al., however, for a complex system with multiple factors and multiple coupling, the environmental problems caused by the development of mineral resources in different regions are not the same, and it is difficult to comprehensively, comprehensively and objectively reflect the real situation by overemphasizing one or some factors. As a mathematical method that attempts to comprehensively quantify from multiple angles, the fuzzy comprehensive evaluation method can cover most of the evaluation factors, and this method is adopted. The purpose is to make a fine evaluation of the complicated geological environment quality of the mining area, and obtain a multi-level solution to the problem according to multiple different possibilities. It improves the reliability of geological environment assessment, eliminates the subjective judgment of experience, and has certain rationality, superiority and expansibility. The accurate evaluation of the geological environment quality of the mine is conducive to the long-term safe operation of the mine, especially in the application of rock mass support. The accurate geological environment quality evaluation can save a lot of early repetitive work for the selection of rock mass support means [10], and is more accurate and reliable than the use of rock mass quality grading [11]. At present, China is advocating "carbon neutrality", and accurate evaluation of mine geological environment quality will become more important in the future [12]. This paper applies the fuzzy comprehensive evaluation method to the geological environment quality evaluation of Maoping lead zinc mine in Zhaotong City, Yunnan Province, and has achieved good results.

Materials and Methods

Fuzzy Evaluation

Fuzzy Evaluation Principle

Fuzzy comprehensive evaluation is a method that comprehensively considers the influence of various factors and uses the fuzzy mathematics principle to comprehensively evaluate the research object [13].

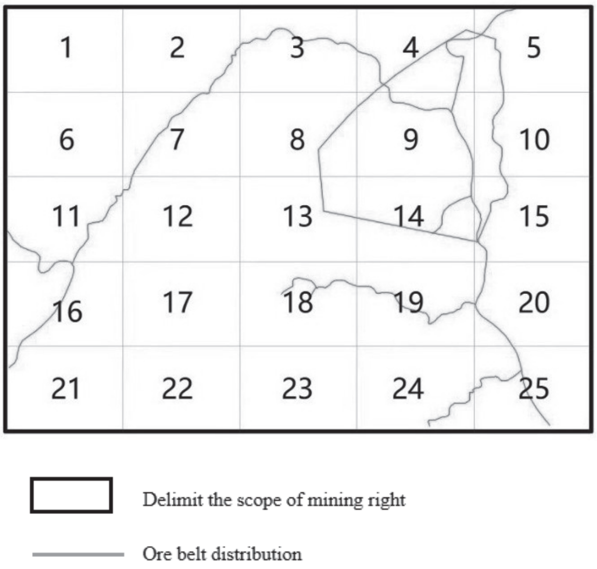

Fig. 2. Schematic diagram of grid management zoning in Maoping mining area.

In essence, it is a fuzzy transformation of each evaluation factor and grade. The specific process is as follows:

- The evaluation objective is regarded as a fuzzy set composed of multiple factors (called factor set U)
- Then set the evaluation levels that can be selected by these factors to form a fuzzy set of comments (called evaluation set V)
- Perform single factor evaluation on all elements in u to obtain the single factor evaluation matrix [R] ∈ f (U × V)
- Determine the fuzzy transformation from U to V, [B] = [A] * [b], where [b] is the result of comprehensive evaluation
- According to the principle of maximum membership, the research object should belong to the rating level corresponding to the maximum value in [B]

In order to fine manage the real geological quality in the study area, the manager of the study area proposed a grid management method according to 1 × 1 km^2. The research area is divided into 20 evaluation grids within 1 km^2, and the geological environment quality within the grid is managed by special personnel. As shown in Fig. 2. The research of this paper is in line with the field, and the grid management method used by the managers is adopted. During the geological environment quality evaluation of the mining area, 20 research grids are divided to evaluate the geological environment quality.

Construction of Evaluation Index System

Selection of Evaluation Factors

The selection of evaluation factors must follow three principles [14]: 1) Clarity. The evaluation factors must directly affect the geological environment quality of the study area. 2) Quantifiable. The main characteristics of evaluation factors need to have digital expression 3) Stability. The evaluation factors should have a long-term, stable or regular continuous impact on the research object.

Based on the selection principles of the above evaluation factors, combined with the field investigation of the geological environment of the study area and referring to the important documents of experts and scholars [15], it is finally determined that the geological environment quality of the study area is affected by 22 secondary evaluation indexes under the 5 primary evaluation indexes. The geological environment quality evaluation index system established in this paper is shown in Fig. 3.

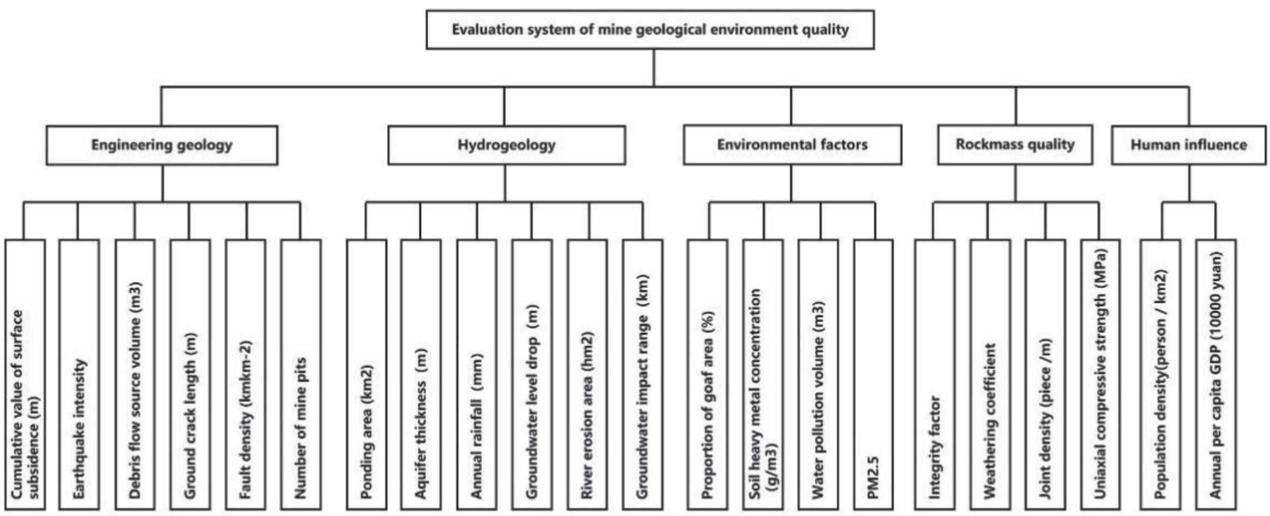

Fig. 3. Evaluation system of mine geological environment quality.

Evaluation Grade Division

The quality of the geological environment in the study area is divided into four grades of "Excellent", "Good", "Commonly" and "Inferior" according to the dangerous objects of geological disasters, the destructive ability, the degree of impact on the ecological environment and the difficulty of restoration and treatment [16].

Standardization of Evaluation Factors

In order to meet the operational requirements of fuzzy evaluation and carry out quantitative treatment for each evaluation factor, according to the actual situation of the site [17], in combination with the treatment methods on similar problems in previous literature [18], the evaluation expert group analyzes and studies the change trend of the mine geological environment in combination with the field investigation [19], and divides the mine geological environment quality under the current conditions into four grades: Excellent, Good, Commonly and Inferior. According to the division standards of code for investigation and evaluation of mine geological environment DD2014-05 [20], code for investigation of geotechnical engineering GB50021-2001 [21] and code for engineering geological investigation [22], and in combination with the actual situation of the study area, the evaluation factors are assigned according to the degree of impact on geological environment quality to calculate the degree of membership (Table 1).

Determine the Weight of Evaluation Factors

In order to objectively, fairly and comprehensively evaluate the geological environment quality of the mine [23], the analytic hierarchy process is selected to determine the weight of each index. The analytic hierarchy process adopts a scale of 1-9 [24]. Each expert independently compares the relative importance of the factors in each layer to the objectives of the previous layer, constructs a judgment matrix, and after discussion and modification by all experts, until all experts have

Table 1. Standardized values of geological environment quality assessment factors of Mines.

Level I indicator layer	Secondary evaluation index	Evaluation grade			
		Excellent	Good	Commonly	Inferior
Engineering geology	Cumulative value of surface subsidence (m)	<0.5	0.5~1	1~2	>2
	Earthquake intensity (degree)	I~ III	IV~VI	VII~IX	X~XII
	Debris flow source volume (m^3)	<1	1~10	10~100	<20
	Ground crack length (m)	<1	1~10	10~50	>50
	Fault density ($km \cdot km^{-2}$)	<0.6	0.6~1.2	1.2~1.8	>1.8
	Number of mine pits	<4	4~7	8~12	>12
Hydrogeology	Ponding area (km^2)	<0.2	0.2~0.4	0.4~0.6	>0.6
	Aquifer thickness (m)	<0.1	0.1~0.2	0.2~0.3	>0.3
	Annual rainfall (mm)	<200	200~300	300~400	>400
	Groundwater level drop (m)	<80	80~160	160~240	>240
	River erosion area (hm^2)	<0.1	0.1~0.5	0.5~1	>1
	Groundwater impact range (km)	>1.2	0.8~1.2	0.4~0.8	<0.4
Environmental impact factors	Proportion of goaf area (%)	<1	1~5	5~10	>10
	Soil heavy metal concentration (g/m^3)	<0.1	0.1~0.6	0.6~1.0	>1
	Water pollution volume (m^3)	<100	100~500	500~1000	>1000
	PM2.5(um)	<35	35~55	55~75	>75
Rock mass quality	Integrity factor(K_V)	0.75	0.55~0.75	0.35~0.55	<0.35
	Weathering coefficient(K_f)	>0.8	0.6~0.8	0.4~0.6	<0.4
	Joint density (piece /m)	<3	3~10	10~30	>30
	Uniaxial compressive strength (MPa)	>60	40~60	20~40	<20
Human influence	Population density(person / km^2)	<200	200~400	400~600	>600
	Annual per capita GDP (10000 yuan)	<2	2~4	4~6	>6

Table 2. Grade I index evaluation standard.

	X_1	X_2	X_3	X_4	X_5	W	Consistency test results
X_1	3	1	1/3	1/5	1/3	0.095	CR = 0.064, Meet consistency requirements
X_2	1	3	1/5	1	5	0.200	
X_3	7	1	3	5	1/3	0.320	
X_4	1/3	5	1	3	1/7	0.185	
X_5	5	1	3	1/5	1	0.200	

no opinions on the comprehensive judgment matrix [25], calculates the largest eigenvalue and the corresponding eigenvector, and performs the consistency test of the matrix (Table 4 ~ Table 8).

The consistency inspection method in Table 2 is given below. The process is divided into three steps:

First, calculate the maximum eigenvalue of the judgment matrix λ_{max} and consistency index *CI*, where the calculation formula of *CI* is shown in (1):

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

Where: *n* is the dimension of the matrix.

Step 2: According to the size of *n*, find the average random consistency index *RI* according to Table 3. N and RI parameter selection table.

In practical application, n rarely exceeds 15. If the number of indicators exceeds 15, a secondary indicator evaluation system can be considered.

The last step is to calculate the consistency ratio *CR*, calculation method is shown in Equation (2):

$$CR = \frac{CI}{RI} \quad (2)$$

Table 3. N and RI parameter selection.

n	1	2	3	4	5	6	7	8
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41
n	9	10	11	12	13	14	15	
RI	1.46	1.49	1.52	1.54	1.56	1.58	1.59	

Table 4. X_1 index layer weight.

	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	W_1	Consistency test results
X_{11}	1	5	1/3	3	1/5	1/5	0.196	CR = 0.033, Meet consistency requirements
X_{12}	1/3	1	1/7	1/5	1/9	1/5	0.040	
X_{13}	1/5	1/7	3	1	1/5	1	0.111	
X_{14}	3	1	1	1/3	1	1/3	0.134	
X_{15}	5	3	3	1	3	1/3	0.308	
X_{16}	1/7	1/3	5	1	1	3	0.211	

Table 5. X_2 index layer weight.

	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}	X_{26}	W_2	Consistency test results
X_{21}	3	1	1/3	1/3	3	1	0.157	CR = 0.021, Meet consistency requirements
X_{22}	1	5	1/3	1/7	1/5	1/3	0.127	
X_{23}	3	1	1/5	1/3	1	1/3	0.107	
X_{24}	1/7	1/3	3	1	5	1	0.190	
X_{25}	5	1/3	1/5	1/3	1	3	0.179	
X_{26}	3	1/5	1	5	5	3	0.240	

Table 6. X_3 index layer weight.

	X_{31}	X_{32}	X_{33}	X_{34}	W_3	Consistency test results
X_{31}	3	1/5	1	3	0.245	CR = 0.028, Meet consistency requirements
X_{32}	5	3	1	1/3	0.209	
X_{33}	1/3	1/7	3	1	0.117	
X_{34}	3	1	1/5	1/7	0.429	

Table 7. X_4 index layer weight.

	X_{41}	X_{42}	X_{43}	X_{44}	W_4	Consistency test results
X_{41}	5	1	3	1	0.284	CR = 0.034, Meet consistency requirements
X_{42}	1/3	1	1/5	3	0.368	
X_{43}	1	1/5	1/3	1	0.177	
X_{44}	3	1	5	1/3	0.171	

Table 8. X_5 index layer weight.

	X_{51}	X_{52}	W_5	Consistency test results
X_{51}	5	1	0.600	CR = 0.067, Meet consistency requirements
X_{52}	1	3	0.400	

If *CR*<0.1, it can be considered that the consistency of the judgment matrix is acceptable; otherwise, the judgment matrix needs to be modified. Since the lines of the judgment matrix are multiples, the method of doubling is usually used to modify a line of the judgment matrix to make it meet the requirements of consistency.

Determination of Membership Function

The degree of membership reflects the possibility that each evaluation index can be rated as the geological environment quality of the mine, which is generally determined by the degree of membership function [26]. According to the influence factors of geological environment of Maoping mine and the composition characteristics of influence factors, the semi trapezoidal distribution function is adopted as the membership function of fuzzy evaluation.

(1) For the evaluation factors with larger evaluation index value and greater negative impact on the mine geological environment [27], the reduced half trapezoidal distribution function is used to describe their membership degree (Fig. 4a) [28]. Then the membership degree functions of each factor corresponding to the four levels in the evaluation set are (3)~(6):

$$R_1(x) = \begin{Bmatrix} 1, & 0 \le x \le A_1 \\ \frac{A_2 - x}{A_2 - A_1}, & A_1 < x < A_2 \\ 0, & x \ge A_2 \end{Bmatrix} \quad (3)$$

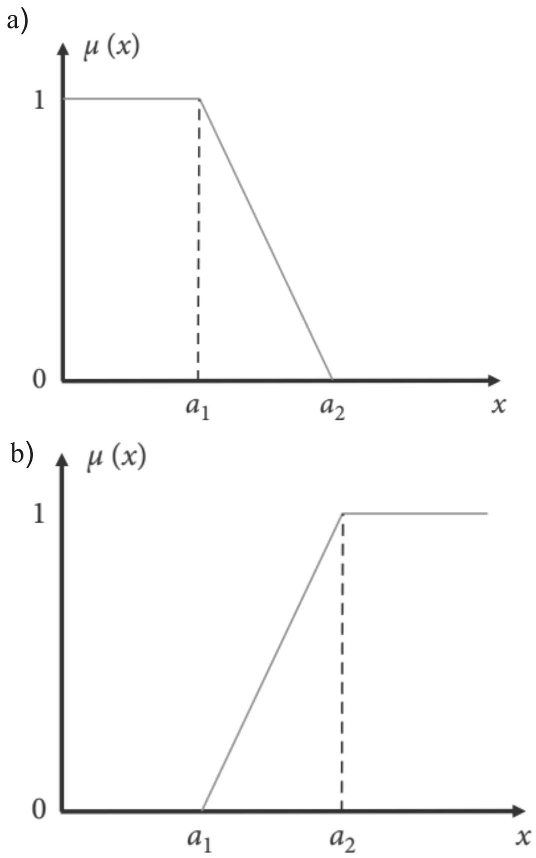

Fig. 4. Two types of trapezoidal membership function images: a) Small, b) Large.

$$R_2(x)=\begin{cases}0, & x\le A_1,\ x\ge A_3\\ \frac{x-A_1}{A_2-A_1}, & A_1<x<A_2\\ 1, & x=A_2\\ \frac{A_3-x}{A_3-A_2}, & A_2<x<A_3\end{cases} \tag{4}$$

$$R_3(x)=\begin{cases}0, & x\le A_2,\ x\ge A_4\\ \frac{x-A_2}{A_3-A_2}, & A_2\le x\le A_3\\ 1, & x=A_3\\ \frac{A_4-x}{A_4-A_3}, & A_3<x<A_4\end{cases} \tag{5}$$

$$R_4(x)=\begin{cases}0, & x<A_3\\ \frac{x-A_3}{A_4-A_3}, & A_3\le x\le A_4\\ 1, & x>A_4\end{cases} \tag{6}$$

(2) The higher the evaluation index value and the greater the positive impact on the mine geological environment, the higher trapezoidal distribution function is used to describe the membership degree (Fig. 4b). Then the membership degree functions of each factor corresponding to the four levels in the evaluation set are (7)~(10):

$$R_1(x)=\begin{cases}1, & x\ge A_1\\ \frac{x-A_2}{A_1-A_2}, & A_2<x<A_1\\ 0, & 0\le x\le A_2\end{cases} \tag{7}$$

$$R_2(x)=\begin{cases}0, & x\ge A_1,\ x\le A_3\\ \frac{A_1-x}{A_1-A_2}, & A_2<x<A_1\\ 1, & x=A_2\\ \frac{x-A_3}{A_2-A_3}, & A_3<x<A_2\end{cases} \tag{8}$$

$$R_3(x)=\begin{cases}0, & x\le A_2,\ x\ge A_4\\ \frac{A_2-x}{A_3-A_2}, & A_3<x<A_2\\ 1, & x=A_3\\ \frac{A_4-x}{A_3-A_4}, & A_3<x<A_4\end{cases} \tag{9}$$

$$R_4(x)=\begin{cases}0, & x<A_3\\ \frac{A_3-x}{A_3-A_2}, & A_3\le x\le A_4\\ 1, & x>A_4\end{cases} \tag{10}$$

Where: RI represents the membership degree of the evaluation index corresponding to the level standard specified in A_1 or A_2 or A_3 or A_4; X_i represents the measured value of the evaluation index; A_1, A_2, A_3 and A_4 respectively represent the standard values of quality at all levels of an indicator.

Fuzzy Matrix Compound Operation and Comprehensive Evaluation

The membership degree of all evaluation factor sets is taken as a row vector to form a single factor evaluation matrix R, i.e. the fuzzy evaluation matrix of the evaluated object [29]. The first line of R represents the first indicator (e.g. geological background indicator) and the degree to which the evaluation object (mine geological environment quality) is affected by each evaluation grade (Excellent, Good, Commonly and Inferior); The first column indicates the degree to which each indicator takes the first evaluation level (Excellent), and so on [30].

W and [R] are combined according to a certain algorithm and expressed by the formula [B] = W* [R]. The first level comprehensive evaluation is $[B]_i = W_i * [R]_i$ (i is the factor of index layer, i = 1, 2, 3, 4, 5); The second level comprehensive evaluation fuzzy relation matrix R is composed of the first level evaluation result $[B]_i$, and the second level fuzzy transformation B = W * R is carried out. In order to highlight the role of weight and make full use of the information of R, M (•, ⊕) algorithm is adopted as the fuzzy operator [27]. The operation rule is as follow (11):

$$b_j = min\left[1,\ \sum_{i=1}^{n} W_i R_{ij}\right] \tag{11}$$

Where: W_i is the weight of the indicator, and R_{ij} is the membership degree of the indicator i to the jth level in the comment set.

Evaluation Process and Results

Evaluation Process

Taking Unit 13 as an example, this paper briefly introduces the fuzzy evaluation method of mine geological environment quality. The type of rock mass in unit 13 is medium thick ~ thick massive dolomite and limestone mixed with a small amount of shale. The weathering resistance is weak, the fault density is 1.6 km/km^2, the longitudinal slope of the trench bed is 800‰, the catchment area is 0.72 km^2, the joints are relatively developed, and the relative height difference is 540 m; The collapse volume is 7.2×10 km^2, landslide volume of 8.8×10.5 km^2, debris flow source amount reaches 3×10 km^2, surface cracks are relatively developed, most of which are tens of meters long, and the maximum accumulated settlement is 1.20 m; The underground water level dropped by 130 m, the water and soil loss area reached 0.45 km^2, the Pb content in the water was 0.05 mg/L, the Zn content was 1.05 mg/L, the Pb content in the soil was 250 mg/kg, and the Zn content was 215 mg/kg; There are 6 pits and 3 goafs. The industrial site covers an area of 1.6 hm^2 and the waste slag covers an area of 7.62 km^2; The cumulative average rainfall in rainy season is 525.8 mm, and the vegetation coverage rate is 28%. The fuzzy evaluation process is as follows:

(1) According to the standardized value of each evaluation factor, the fuzzy evaluation matrix of factor sets X_1, X_2, X_3, X_4 and X_5 is established

$$R_1 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 0.5 & 0.5 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$R_3 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$R_4 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$R_5 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

(2) Calculate the fuzzy comprehensive evaluation value

For indicator layer:

$$B_1 = W_1 * R_1 = (0,\ 0,\ 0.333,\ 0.667)$$
$$B_2 = W_2 * R_2 = (0,\ 0.229,\ 0.771,\ 0)$$
$$B_3 = W_3 * R_3 = (0,\ 0.3,\ 0.7,\ 0)$$
$$B_4 = W_4 * R_4 = (0.328,\ 0,\ 0,\ 0.672)$$
$$B_5 = W_5 * R_5 = (0,\ 0,\ 0.6,\ 0.4)$$

The evaluation matrix of the criterion layer is obtained from the evaluation results of the index layer:

$$R = [B_1,\ B_2,\ B_3,\ B_4,\ B_5]^T = \begin{bmatrix} 0 & 0 & 0.333 & 0.667 \\ 0 & 0.229 & 0.771 & 0 \\ 0 & 0.6 & 0.4 & 0 \\ 0 & 0.38 & 0.62 & 0 \\ 0 & 0 & 0.5 & 0.5 \end{bmatrix}$$

And then the evaluation result of the criterion layer is obtained:

$$S = W * R = [0,\quad 0.217,\quad 0.624,\quad 0.158]$$

According to the principle of maximum membership degree, the geological environment quality of this unit is commonly under the current conditions; Judging from the indicator layer, the geological environment quality of the unit is commonly under the influence of geological background; Under the influence of geological disasters, the geological environment of this unit is commonly, Under the influence of water and soil environment damage, the geological environment quality of this unit is good; Under the influence of mining development activities, the geological environment of this unit is commonly; Under the influence of hydrology and vegetation, the geological environment quality of this unit is commonly.

Evaluation Results

The geological environment quality grade of each unit is obtained through the membership degree calculation of each unit one by one, as shown in Fig. 5. The evaluation results are closely related to the factors affecting the geological environment of the mine. For example, in the middle of the north side of the study area, the terrain is steep and the relative height difference is large. The lithology is distributed from soft rock, semi hard rock to hard rock group. The structure is developed, and geological disasters are frequent. There are many mines distributed, which are greatly affected by mining activities [31]. Affected by the above factors, the geological environment quality of this area is Inferior.

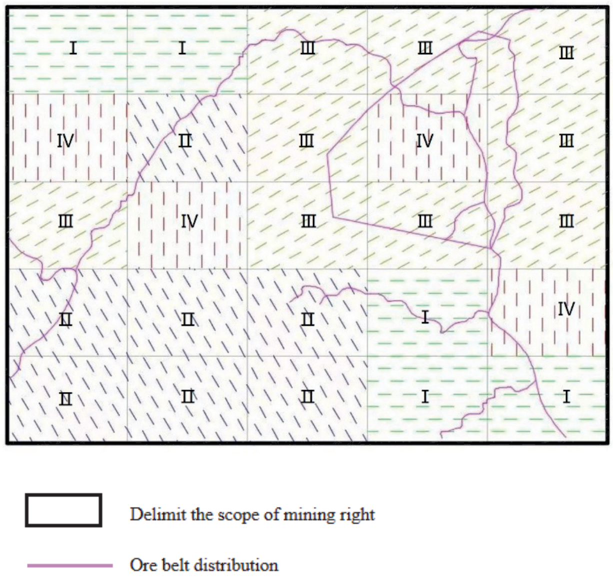

Fig. 5. Geological environment quality zoning results of Maoping mine.

The prediction results in this paper are basically consistent with the evaluation results in accordance with the code for the preparation of mine geological environment protection, treatment and restoration program, which indicates that the selection of rating factors is reasonable, the method is appropriate, and the results are relatively satisfactory.

Conclusion

In this paper, the fuzzy comprehensive evaluation method is applied to study the mine geological environment quality in the study area. It is found that the fuzzy comprehensive evaluation method can not only make full use of the multi factor complexity of the mine geological environment system, The evaluation results reflect the current situation of geological environment quality of Maoping lead zinc mine. Therefore, it is feasible to apply the fuzzy comprehensive evaluation method in the evaluation of mine geological environment quality, and the results provide a reliable basis for mine safety production and geological environment restoration and renovation, which is a method worthy of popularization and application.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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