

Risk Assessment of Ground Water Inrush from Underlying Aquifers Based on Fuzzy Comprehensive Evaluation and its Application

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Abstract: Mining operations in China are often threatened by frequent water inrushes from confined karst aquifers. We need to evaluate the risk from water-inrush from coal floors in order to have safe production in mines. water inrush risk assessment method based on fuzzy comprehensive evaluation is introduced in this paper. A secondary fuzzy comprehensive evaluation system is constructed to evaluate the risk of floor water invasion in coal mines. Four first-grade indices and fifteen second-grade indices are determined based on the principles. The weight of every index is rationally distributed by analytic hierarchy process (AHP). Finally applying the evaluation model based on fuzzy comprehensive evaluation to evaluate floor water disasters of Yuzhou coalmine in Hebei, the evaluation results are accurate. It can provide certain reference and basis for the evaluation of water-inrush from coal floor forecast for the future.

Keywords: Analytic hierarchy process, coal floors, fuzzy comprehensive evaluation, water-inrush

1. INTRODUCTION

Coal has been one of the main natural resources in China. Safe, efficient, and environmental-friendly mining plays an important role in the nation's economy and social development. However, water disasters in mines have often restricted their production rates. Because of complicated geological and hydrogeological conditions, approximately 27% of the proved coal reserves are threatened with water hazards. According to the latest statistics from Chinese coal mines in 2008 to 2012, it is found that coal mine water damage frequently occur, resulting in huge casualties and economic loss (Table 1).

Table 1. Mine water accidents from 2008 to 2012 in China.

Year	Accidents Times	Death Toll
2008	49	200
2009	21	135
2010	18	183
2011	13	100
2012	7	104

In recent years, coal mining developed gradually to the deeper and formed the high stress areas, accompanied with the requirements of mine production and efficiency, mining needs growing exploitation space and increasing

mechanization, which obviously increase the chance of ground water inrush during mining underlying aquifers. If not take appropriate control measures promptly, not only water inrush continue to increase, but also the large number of mines threatened by water damage will scrap early. It can be said that the threat from the floor karst high confined water damage has seriously hampered coal mining of China, So the warning and prevention technology of Ground water inrush during mining underlying aquifers should adapt to the new situation. study in-depth on the basic theory of the floor water control and prevention and take more practical innovative research on the prevention method.

The research of water inrush has been popular in recent years with methods varied. Shi *et al.* evaluated water inrush of coal seam floor by integrating the water inrush coefficient and the information of water abundance [1]; Hu *et al.* established a simplified mechanical model to analysis water inrush from the mining floor [2]; Li *et al.* used the microseismic monitoring technique to monitor and analyze information carried in the seismic waves generated from either mining-induced rock fracturing or active blasting so as to detect unknown water bodies and reduce water-inrush risk in underground mines [3]; Hua *et al.* setted up a nonlinear dynamic mathematical model based on the catastrophe theory to predict the risk of water-inrush [4]; Wu *et al.* systematically analyzes typical cases about water inrush from coal seam floor in the researched area [5]; Wang *et al.* constructed the fault tree model of mine water-inrush to assess the risk of water-inrush of Yangzhuang mine [6]; Gao *et al.* evaluated water inrush from coal floor combined with experts' experiences and artificial intelligence technology [7]; These diverse theories show the complexity of water inrush phenomena. But some of these simplify conditions or factors and fail to profoundly reveal the quantifying relation

between water inrush and its affecting indices, while others exist some limitations despite their uniqueness to manage the problem of water inrush. The mining and hydrogeological conditions call for new methods to evaluate water inrushes. The method of comprehensive evaluation for risk of floor water inrush proposed based on the theory of fuzzy mathematics fully takes into the main indices affecting water inrush with the advantages from qualitative to quantitative and of high accuracy and universal application.

2. FUZZY COMPREHENSIVE EVALUATION MODEL

Fuzzy comprehensive evaluation method is a comprehensive evaluation method based on fuzzy mathematics. Fuzzy comprehensive evaluation method to determine the boundaries are to be completed by the membership function. Maximum membership degree principle is to be applied to grading evaluation objectives. The method fully reflects the impact of the coal floor water bursting factors and the relationship between these factors. General procedure is as follows [8, 9]:

Step 1: Evaluation object U by some attributes into m subsets (u_1, u_2, \dots, u_m), m means the number of total subsets, that is to say we evaluate the objects from m aspects.

Step 2: Making comprehensive evaluation for every subset (u_1, u_2, \dots, u_m), The evaluation set indicated by V : $V=(v_1, v_2, \dots, v_n)$, n means the number of total evaluation sets.

Step 3: Quantify the objects' every factor, that is to determine the object's membership grade of each level fuzzy subsets, and then get the fuzzy relational matrix:

$$R = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{pmatrix}$$

Step 4: Determine the weight vector of every factor to reflect the importance of the factors. The factor weights are determined by analytic hierarchy process in this paper. a_i indicate the weight of factor i , and $1 \geq a_i \geq 0$; $\sum a_i = 1$. matrix $A=(a_1 \ a_2 \ \cdots \ a_m)$.

Step 5: The fuzzy comprehensive evaluation vector B is obtained by composite matrix A and the fuzzy relational matrix R with appropriate composition operator:

$$B = A \circ R = (a_1, a_2, \dots, a_m) \circ \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{pmatrix}$$

3. MAIN FACTORS OF COAL FLOOR WATER BURSTING

In order to evaluate inrush risk of coal floor water, we must first determine the appropriate evaluation factors.

Mining practice over the years illustrate the factors which influence the evaluation of mine water inrush is multifaceted [10]. According to the feasibility, representativeness and accuracy, this paper chooses four main factors:

3.1. The Nature of Floor Aquifer

The nature of floor aquifer is one of the key factors for coal floor water disaster. Water inrush accident will happen only in strong water-rich region, when the water guide passage is formed under the action of water pressure. If in the water-poor region, it will not cause much harm even water guide channel can reach the aquifer. In this paper, water pressure of aquifer, specific yield, coefficient of permeability and aquifer thickness were considered to judge the nature of the aquifer.

3.2. Geological Structure

The relationship between geological structure and water damage is very close. The nature of the geological structure will have an impact on the water abundance. Construction would undermine the integrity of the impermeable layer, and some faults and fractures will become a channel of water inrush. So geological structure is an important factor for assessment of ground water inrush, in this paper, structural nature, structure density, development situation of karst collapse column and development situation of fractured were considered to judge the nature of geological structure.

3.3. Confining Layer

Confining layer is the key to prevent water inrush from coal floor, and is natural geological protection for preventing water inrush. The ability of confining layer to prevent water inrush is mainly reflected in the aquiclude thickness, mechanical strength and integrity of the aquiclude. Large thickness, well integrity and strong compressive can effectively reduce the height of water which flow through fractured zone. The above three aspects were considered to judge the nature of confining layer.

3.4. Mining Disturbance

Along with mining progresses, the floor surrounding rock will form rock pressure damage zone. Rock pressure damage zone is an important incentive for water inrush. Coal seam thickness, mining depth, working face length and coal seam dip were considered to judge the nature of mining disturbance. The larger coal seam thickness, the deeper seam depth, the longer the working length and the steeper seam inclination, the more likely to cause water inrush.

4. EVALUATION INDICES AND GRADING STANDARDS

In this paper, the risk assessment of water bursting is divided into four grades, small (I), relatively small (II), relatively large (III), large (IV). After considering China's national standards, industry standards, and results of previous studies, establishing the coal floor water-irruption evaluation index system and grading standards integrating

Table 2. Grading standard of influencing factors.

Factors		Evaluation Grading Standards			
		I	II	III	IV
Floor aquifer	water pressure of aquifer (Mpa)	small	relatively small	relatively large	large
	specific yield (L/(sm))	0.01	1	5	10
	Coefficient of Permeability (cm/s)	10-6	10-4	10-2	1
	Aquifer thickness	small	relatively small	relatively large	large
Confining layer	Aquiclude thickness	Large	relatively large	relatively small	small
	The compressive strength of the rock (Mpa)	54.6	29.1	19.6	8.5
	The integrity index of the rock	0.75	0.55	0.35	0.15
Geological structure	Structural complexity	Complex	relatively simple	relatively complex	complex
	Fracture density (%)	2	5	8	10
	development situation of karst collapse column	Little	relatively little	Relatively multi	multi
	structure density	small	relatively small	relatively large	large
Mining disturbance	Coal seam thickness (m)	0.5	1.3	3.5	8
	mining depth	small	relatively small	relatively large	large
	working face length	small	relatively small	relatively large	large
	coal seam dip (°)	5	15	25	45

the quantitative and qualitative indicators, evaluation criteria in Table 2.

5. DERIVATION OF MEMBERSHIP FUNCTIONS OF INDICES

5.1. Quantitative Indexes

In this paper linear fuzzy number membership function is chosen to get membership functions of quantitative indices. Formula is as follows:

When $j = 1$,

$$r_{ij} = \begin{cases} 1 & x_i \leq u_{ij} \\ \frac{u_{ij+1} - x_i}{u_{ij+1} - u_{ij}} & u_{ij} < x_i \leq u_{ij+1} \\ 0 & x_i \leq u_{ij+1} \end{cases} \quad (1)$$

when $1 < j < m$,

$$r_{ij} = \begin{cases} 0 & x_i \leq u_{ij-1} \text{ OR } x_i \geq u_{ij+1} \\ \frac{x_i - u_{ij-1}}{u_{ij} - u_{ij-1}} & u_{ij-1} < x_i \leq u_{ij} \\ \frac{u_{ij+1} - x_i}{u_{ij+1} - u_{ij}} & u_{ij} \leq x_i \leq u_{ij+1} \end{cases} \quad (2)$$

when $j=m$,

$$r_{ij} = \begin{cases} 0 & x_i \leq u_{ij-1} \\ \frac{x_i - u_{ij-1}}{u_{ij} - u_{ij-1}} & u_{ij-1} < x_i < u_{ij} \\ 1 & x_i \geq u_{ij} \end{cases} \quad (3)$$

r_{ij} —The membership of i measured values belong j level;
 x_i —The measured value of i evaluation indicators; u_{ij} — j level standard value corresponds to i evaluation indicators.

5.2. Qualitative Indexes

The qualitative indexes are divided into four levels, namely I (Very Low), II (Low), III (High risk), and IV (Very High risk). Corresponding critical value is 1, 2, 3, 4. membership functions of qualitative indexes calculated as follows:

$$r_I(x) = \begin{cases} 1 & x < 1 \\ 2 - x & 1 \leq x < 2 \\ 0 & 2 \leq x \end{cases} \quad (4)$$

$$r_{II}(x) = \begin{cases} 0 & x < 1 \\ x - 1 & 1 \leq x < 2 \\ 3 - x & 2 \leq x < 3 \\ 0 & 3 \leq x \end{cases} \quad (5)$$

$$r_{III}(x) = \begin{cases} 0 & x < 2 \\ x - 2 & 2 \leq x < 3 \\ 4 - x & 3 \leq x < 4 \\ 0 & 4 \leq x \end{cases} \quad (6)$$

$$r_{IV}(x) = \begin{cases} 0 & x < 3 \\ x - 3 & 3 \leq x < 4 \\ 1 & 3 \leq x \end{cases} \quad (7)$$

6. ANALYTIC HIERARCHY PROCESS

The determination of factor index weight in this paper use Analytic Hierarchy Process (AHP), be put forward by operation researcher of USA Saaty in 1980s [11], AHP is a decision making method of practical and multi-program or multi-objective. Its main feature is that it reasonably combines qualitative and quantitative decisions together, making decision process hierarchical and quantitative in accordance with the laws of thinking and psychology. The method is rapidly applied in various fields of the social economy for the advantage of system and flexible and concise as well as the character that process various decision factors by the combination of qualitative and quantitative, such as energy systems analysis, urban planning, economic management, research evaluation etc. both has been noticed and used widely, the detailed steps include [12] :

- (1) Make the complex issue hierarchical and form a hierarchical structure composed by the target layer, criteria layer and index layers, in which the index layer elements are affiliated to the one or more elements of criteria layer;
- (2) adopt “1-9 scale method” to form a judgment matrix (Table 3);
- (3) test the consistence of the judgment matrix;
- (4) get the weight of the index layer to the target layer weight by calculating layer by layer.

7. APPLICATION EXAMPLES

7.1. General Situation of Study Area

In this paper, the evaluation model is applied to evaluate the floor water inrush risk of Yuzhou mining area 6102 N working face, Yuzhou mining area is located in Hebei Province of China, 6 km south to Yuzhou town and 200 km south to Baoding, 130 km north to Xuanhua and 21 km west to Guanglin town in Shanxi Province. The mine is geographically convenient to the railways from Shacheng to Yuzhou, from Beijing to Baotoum, and from Beijing to Shacheng (Fig. 1).

The main aquifers in this study area are (1) fractured karst aquifer of Upper Cambrian and Lower Ordovician, (2) fissured bedrock aquifer in the coal measure strata, and (3) overlying unconsolidated porous-medium aquifer. According to the exploration data and field statistics, the karst aquifer of Ordovician is characterized with well-developed fissures, high water yield, and faults and folds. The karst aquifer is confined and is the main water bearing strata which influence the safety of mining in the area.

7.1.1. The Nature of Face Floor Aquifer

Below coal is mainly limestone of Ordovician, most of gray limestone and argillaceous limestone. Limestone aquifer thickness is 40~80 m, water pressure 0.7~ 1.1 Mpa, permeability coefficient is 3.24×10^{-6} cm / s, specific yield is 0.0048-0.008 L / (sm), karst rate is 11.2 ~ 29.2 %.

7.1.2. The Nature of Confining Layer

Lithology is mainly mudstone, siltstone and fine sandstone and coal. Rock is relatively integrity and few fissures. The compressive strength of the rock is $22 \square 47.7$ Mpa, and aquiclude thickness is $40 \square 70$ m.

7.1.3. The Nature of Mining Disturbance

Coal seam thickness is relatively stable in the entire 6102 N working face. Coal thickness between 3.0 ~ 3.5 m, stratigraphic occurrence is relatively flat, seam dip between 5 ~ 15 °, face length is 150 m, coal mining depth between 360 ~ 390 m. (4) The nature of geological structure

Geological structure is relatively simple in 6102 N work face. There are three faults, and all faults are normal faults, fault throw 0 ~ 3 m. Meanwhile fault fracture zone diagenetic consolidation, poor hydraulic conductivity performance, small impact on mining.

7.2. Index Weights Determined

According to the AHP method, after set up hier-archical structure model, constructed pairwise matrix, and calculated the consistency ratio. Finally, we get weight results, the results is in the Table 4.

7.3. Fuzzy Comprehensive Evaluation with Engineering Practice

Based on the hydrogeological data above, the fuzzy judgment matrices of second-grade indices are established

Table 3. Proportional scale and meaning.

Scale	Meaning
one	The two compared elements has the same importance
three	Two elements compares, one is slightly more important than the other
five	Two elements compares, one is obviously more important than the other
seven	Two elements compares, one is strongly more important than the other
nine	Two elements compares, one is extremely more important than the other
The reciprocal of two, four, six, eight	When the difference of the pair things between the both, take the middle value of the adjacent judgments above

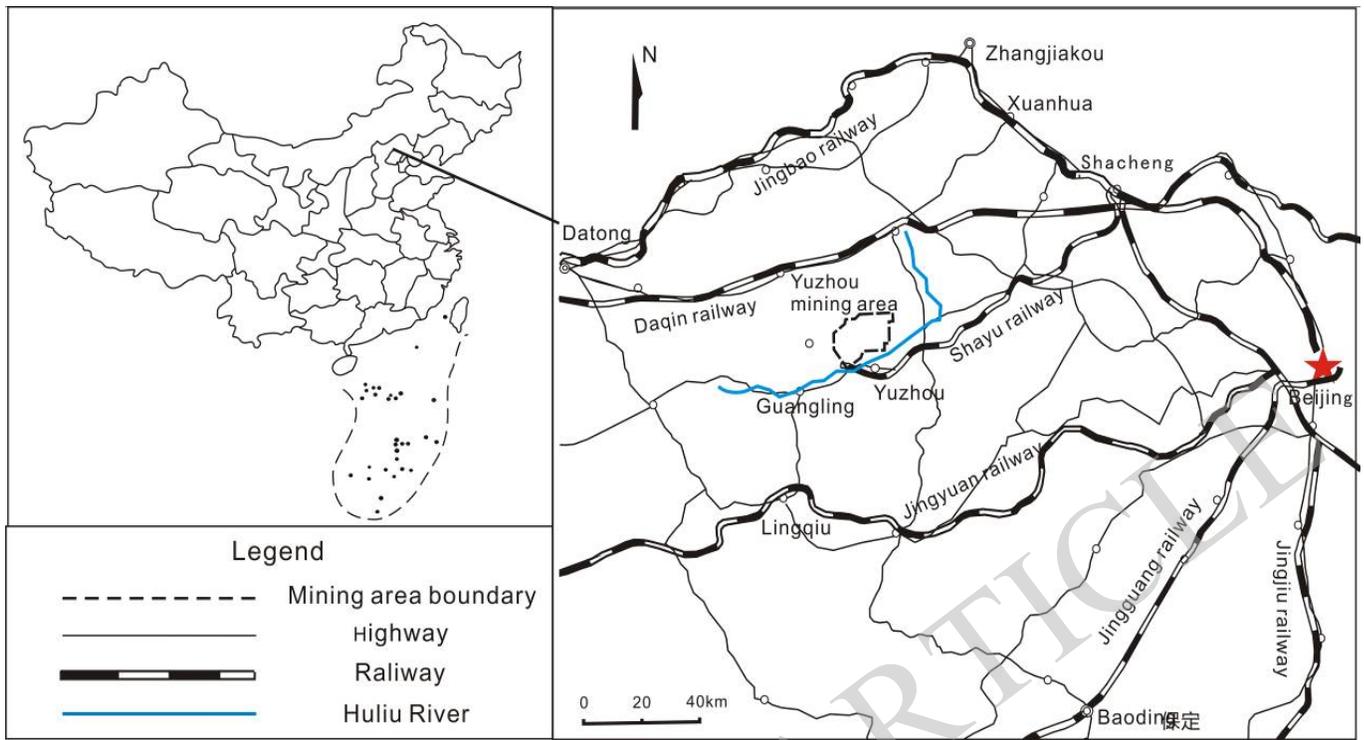


Fig. (1). Site location.

according to the membership of each second-grade index corresponding to risk grade of floor water inrush. Thus fuzzy judgment matrices of second-grade indices are:

$$R_1 = \begin{pmatrix} 0.40 & 0.60 & 0.00 & 0.00 \\ 1.00 & 0.00 & 0.00 & 0.00 \\ 0.977 & 0.023 & 0.00 & 0.00 \\ 0.00 & 0.70 & 0.30 & 0.00 \end{pmatrix}$$

$$R_2 = \begin{pmatrix} 0.6 & 0.4 & 1 & 0 \\ 0 & 0 & 0.802 & 0.198 \\ 1 & 0 & 0 & 0 \end{pmatrix}$$

$$R_3 = \begin{pmatrix} 0.50 & 0.50 & 0.00 & 0.00 \\ 0.333 & 0.667 & 0.00 & 0.00 \\ 1.00 & 0.00 & 0.00 & 0.00 \\ 0.70 & 0.30 & 0.00 & 0.00 \end{pmatrix}$$

$$R_4 = \begin{pmatrix} 0.00 & 0.137 & 0.863 & 0.00 \\ 0.00 & 0.00 & 0.80 & 0.20 \\ 0.00 & 0.40 & 0.60 & 0.00 \\ 0.50 & 0.50 & 0.00 & 0.00 \end{pmatrix}$$

Fuzzy evaluation result B_i of first-grade indices corresponding to second-grade ones is achieved by choosing appropriate fuzzy operators combined with weight vectors of second-grade index set, taken as membership vector of first-grade indices one valuation set, and fuzzy judgment matrix is constructed with membership vectors of first-grade indices. Results are obtained as follows:

$$B_1 = A_1 \cdot R_1 = (0.597 \ 0.339 \ 0.064 \ 0.000)$$

$$B_2 = A_2 \cdot R_2 = (0.396 \ 0.604 \ 0.000 \ 0.000)$$

$$B_3 = A_3 \cdot R_3 = (0.667 \ 0.333 \ 0.000 \ 0.000)$$

$$B_4 = A_4 \cdot R_4 = (0.097 \ 0.225 \ 0.620 \ 0.058)$$

Thus, the fuzzy judgment matrix of first-grade index is:

$$R = \begin{pmatrix} 0.597 & 0.339 & 0.064 & 0.000 \\ 0.396 & 0.604 & 0.000 & 0.000 \\ 0.667 & 0.333 & 0.000 & 0.000 \\ 0.097 & 0.225 & 0.620 & 0.058 \end{pmatrix}$$

With weight vector of first-grade indices considered, fuzzy operators of weighted average are chosen to calculate the final evaluation vector as follows:

$$B = A \cdot R = (0.366 \ 0.232 \ 0.278 \ 0.124) \cdot R \\ = (0.508 \ 0.385 \ 0.100 \ 0.007)$$

Risk grade of water inrush turns to be very low in 6102 N working face of Yuzhou mining area according to evaluation result and maximum membership principle. And the fact that floor water inrush never occurs in actual coalface mining is in accordance with this result.

CONCLUSION

- (1) This paper puts forward a water inrush risk assessment method based on fuzzy comprehensive evaluation. Compared with other water inrush method, our method takes into account various indices and their relationship simply and fast, accurately and practicably, with evaluation results reliable after actual engineering test.
- (2) Using the fuzzy comprehensive evaluation method to make comprehensive evaluation, Indicators and the values of weights are very important for accuracy of evaluation results. In actual mining process, not only indices above are considered but also increasing or decreasing indices according to different hydrogeology conditions. Calculation of weights should also be reasonable.

Table 4. Results of the indicators weight.

Target Layer	Guidelines Layer	Weights	Index layer	Weights
Water inrush risk assessment	Floor aquifer	0.366	water pressure of aquifer (Mpa)	0.3123
			specific yield (L/(sm))	0.3189
			Coefficient of Permeability (cm/s)	0.1565
			Aquifer thickness	0.2123
	Confining layer	0.232	Aquiclude thickness	0.425
			The compressive strength of the rock (Mpa)	0.315
			The integrity index of the rock	0.26
	Geological structure	0.278	Structural complexity	0.3135
			Fracture density (%)	0.163
			development situation of karst collapse column	0.2987
			structure density	0.2248
	Mining disturbance	0.124	Coal seam thickness (m)	0.2981
mining depth			0.2905	
working face length			0.2176	
coal seam dip (°)			0.1938	

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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