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Research Article

A New Evaluation Method for Water Blocking Performance of Coal Seam Floor: Model Construction, Case Application, and Water-Preserved Strategy

Baobin Gao,[1,2,3,4] **Chuangnan Ren** [iD],[1,2] **and Shaopeng Song**[1,2]

[1]*State Collaborative Innovation Center of Coal Work Safety and Clean-Efficiency Utilization, Jiaozuo, Henan 454000, China*
[2]*State Key Laboratory Cultivation Base for Gas Geology and Gas Control, Henan Polytechnic University, Jiaozuo,
454000 Henan, China*
[3]*Key Laboratory of Resources, Environment and Disaster Monitoring of Shanxi Province, Taiyuan, 030000 Shanxi, China*
[4]*Henan Key Laboratory of Underground Engineering and Disaster Prevention (Henan Polytechnic University), Jiaozuo,
454000 Henan, China*

Correspondence should be addressed to Chuangnan Ren; chuangnanrcn@163.com

In order to scientifically guide the water-preserved mining of the coal seam floor and make up for the shortcomings in the conventional evaluation of water blocking performance of the coal seam floor, according to the system resilience theory, the difference between the vulnerability and resilience of the coal seam floor is analyzed, and three elements and nine indicators for evaluating water resistance toughness of the coal seam floor are determined. In the evaluation process, first of all, the maximum difference normalization method is used to conduct a dimensionless analysis of quantifiable indicators to determine the importance of the corresponding indicators, and the AHP software yaahp10.1 is used to determine the weight vector of each indicator. Secondly, the single-factor membership degree is determined according to the single-factor resilience grade classification criterion and membership function and finally combined with the weight vector for fuzzy synthesis calculation and comprehensive evaluation. The model is applied to a specific project. Research has shown that in the water hazard threat area of No. 10 coal seam floor in Jiegou Coal Mine, Anhui Province, the performance of system vulnerability elements is weak, the performance of system recoverability elements is better, and the performance of system adaptability elements is extremely poor. From the perspective of the whole life cycle, determining the treatment target area, optimizing the rock formation modification and repairing materials, and enhancing the water resources carrying capacity can improve the water resistance toughness of the coal seam floor. Related conclusions verify the effectiveness of the evaluation model. Furthermore, an optimized strategy for coal seam floor water retention mining is proposed: the technology system of water-preserved mining for coal seam floor contains 3 stages and 3 detections, which provides a scientific basis for the in situ protection of high-pressure limestone water from coal seam floor.

1. Introduction

With the needs of national economic development, since 1999, the coal industry has developed rapidly, and a series of environmental problems caused by coal development have emerged [1]. Under the background of the new era, the situation of water resources and water environmental protection is urgent, and the protection of water resources

in the mining of coal resources has attracted much attention, especially in areas where limestone water is an important water source for local industrial, agricultural, and domestic water and mine limestone water resources. The in situ protection has become an important part of water-preserved mining and has been included in the green mining system [2, 3]. In 2003, Academicians Qian et al. proposed water-preserving mining technology for coal mines [4].

Subsequently, the water-preserving coal mining team represented by Fan et al. proposed "a reasonable selection of development areas and appropriate coal mining methods" in 2005 to realize coal mining. Research ideas for water resources protection in the process. In recent years, relevant scholars have conducted a lot of theoretical innovation and technical application research on coal seam roof and floor water-preserved mining. In terms of coal seam floor water-preserved mining, Fan et al.'s team [5] from the Key Laboratory of Exploration and Comprehensive Utilization of Mineral Resources, Xi'an, China, Dong et al.'s team from Xi'an Research Institute of China Coal Technology Engineering Group [6, 7], and Zhang et al.'s team from China University of Mining and Technology [8, 9] have used drilling and grouting techniques to carry out engineering practices in China's central and western coal fields and initially achieved effective results.

As a key indicator of coal seam floor, water blocking performance is one of the main research points in the field of floor water hazard prevention and water-preserved mining on confined water. Over the years, domestic and foreign scholars have paid more attention to the vulnerability of the floor system in the research on the water blocking performance of coal seam floor [10–12]. Vulnerability refers to the possibility of damage to the system's subsystems and components under external pressure. Resilience was originally a concept in physics, representing the ability of a material to absorb energy during plastic deformation and fracture. In the 1970s, ecologist Holling firstly used resilience to describe the persistence of natural systems and the ability to absorb various changes and disturbances; Bi et al. believe that the definition of resilience should focus on three capabilities: the system's ability to reduce the probability of being affected by adverse events, the ability to absorb disturbances after an adverse event occurs, and the ability to quickly rebuild system performance [13]. At present, in the field of urban system disaster prevention and mitigation engineering, it is generally believed that resilience and reliability, vulnerability, and adaptability are all important concepts of security risk management. From the perspective of the full life cycle of the system, vulnerability is an important stage in the evolution of system performance; resilience can be understood as corresponding to the entire process of system performance evolution. The research from vulnerability to system resilience reflects the cognitive transformation process of the concept of disaster prevention and mitigation from rigid resisting confrontation emphasizing resistance to flexible resolution emphasizing adaptation [14, 15], which can help decision-makers formulate more scientific and reasonable water-preserved mining plans for coal seam floor. In the past, most of the evaluation of the water blocking performance of the coal seam floor focused on the evaluation of the risk of water inrush from the floor [16–18]. As a staged safety assessment, the water inrush risk assessment provides a scientific basis for further floor water damage management. However, it should be noted that the water blocking performance of the coal seam floor will change with the intervention of safety technology and the impact of the ecological environment. Traditional floor water blocking performance evaluation is limited by the staged thinking in the evaluation index system and does not fully consider the impact of water-preserved mining technology. At the same time, it ignores the relevant factors related to the ecological environment of the mining area [19]. In addition, in terms of evaluation methods, expert scoring methods are usually used to obtain weights and membership degrees. For quantifiable index factors, dimensionless processing is rarely used to obtain weights. With the continuous development of the theory and technology of water-preserving mining on confined water, this type of evaluation model is obviously unable to meet the needs of evaluation.

In view of this, based on the system toughness theory and from the perspective of the whole life cycle, a water resistance toughness evaluation model applicable to the water retention mining of coal seam floor is provided. Further, the model is applied to specific engineering cases. As a whole life cycle evaluation model, the model is not limited to a certain stage of system development and was aimed at providing a whole life cycle evaluation and optimization basis for in situ protection of highly pressurized tuff water in coal seam floor to achieve the protection of water resources and water environment in coal mines.

2. Evaluation Model Construction

2.1. Selection of Evaluation Indicators

2.1.1. The Water Resistance Toughness of Coal Seam Floor. Regarding the relationship between vulnerability and resilience, both are considered to be the intrinsic properties of the system and are easily affected by the external environment. The difference is that vulnerability focuses on the risk of damage to the system under the influence of disturbances when a disaster occurs, involving the partial phases of the system's life cycle, while resilience emphasizes the system's ability to withstand disasters and the ability to recover from disasters, corresponding to the entire life cycle of the system [20]. Vulnerability analysis is an essential part of maintaining system stability, preventing system damage, and improving system resilience. It is reflected in the risk analysis and control before disturbance events. Resilience analysis focuses on the whole process of system performance recovery and readaptation when the disturbance event occurs afterwards. According to the evolution law of system resilience under disturbance, the water resistance toughness of coal seam floor should include four stages: stabilization, destruction, recovery, and adaptation [21]. Based on the above point of view, from the perspective of the life cycle of the system, the resilience evolution curve of the coal seam floor under disturbance is shown in Figure 1.

According to Figure 1, when the system's resilience drops to a minimum, the system's performance changes from vulnerability to resilience. Generally, it takes a long time to realize self-recovery and readaptation with the help of system ontology elements, so technical intervention needs to be considered. Moreover, the final system performance improvement or degradation depends on the degree of compatibility of the system with the external environment. In
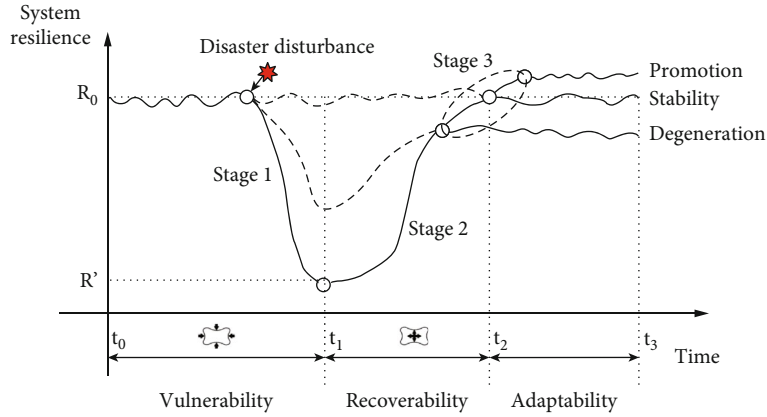
FIGURE 1: The resilience evolution curve of coal seam floor under disturbance.

summary, it can be initially obtained that the key elements that affect the performance of the system should include three elements: system vulnerability, system recoverability, and system adaptability. This is similar to the viewpoints of the four important elements of man-machine-environment-management in safety system engineering. The difference is that safety system engineering focuses on phased risk management and control, and system resilience theory is based on the sustainable development of the whole life cycle. The water resistance toughness of the coal seam floor is a key indicator for water-preserved mining on confined water, and it needs to be considered from the perspective of the system's full life cycle.

(1) Stage 1 ($t_0 - t_1$) corresponds to system vulnerability, where the scientific level involves engineering geological features and the technical level should focus on the identification of target areas for treatment. At this stage, the system can still operate normally, but the risk already exists. If the risk can be effectively controlled in the early stage and not allowed to continue to evolve into an accident potential, the system can remain stable. In theory, it exists, but it is usually unrealistic in specific projects, and there is no absolute safe state. When the risk further evolves into an accident potential, the system has developed to stage 1. The factors affecting the development of stage 1 are related to the mining engineering geology, including the original geological factors and the influence of mining on geological factors, collectively referred to as system vulnerability elements

(2) Stage 2 ($t_1 - t_2$) corresponds to systematic restorability, and the scientific level involves the mechanism of coal seam floor restoration, and the technical level should focus on the modification of rock seam restoration. This stage occurs after stage 1, where the accident potential has caused some accident damage, but the system still maintains some robustness. In turn, the system performance starts to recover under the condition of self-repair or external technical inter-

vention. Self-repair is rare, so the factors affecting the development of stage 2 are related to the coal seam floor water damage management technology, involving drilling, grouting, and other key technical parameters, collectively referred to as system recoverability elements

(3) Stage 3 ($t_2 - t_3$) corresponds to system adaptability, the scientific level involves the water carrying capacity of the coal mine, and the technical level should focus on the evaluation of the effect of water preservation mining. This stage is influenced by the resilience and ecological compatibility of the system and may result in three types of outcomes: promotion, stability, or degeneration, which to some extent reflects the adaptability of the system. Factors affecting stage 3 include surface ecological governance and water resources carrying capacity, which are collectively referred to as system adaptability elements

2.1.2. Establishment of Evaluation Index System. In summary, according to the analysis of the water resistance toughness of the coal seam floor, the criterion layer of the evaluation index for the water resistance toughness of the floor is determined: system vulnerability elements *A*, system recoverability elements *B*, and system adaptability elements *C*. Among them, system vulnerability elements are consistent with the vulnerability evaluation indicators. The difference is that the resilience evaluation considers its compression resistance and self-recoverability, and the vulnerability considers the possibility of damage. System recoverability elements involve the modification and repair of the floor rock. At present, the commonly used technical method is grouting reinforcement, so technical indicators related to drilling, grouting, and detection need to be considered. System adaptability elements involve the surface and mine water environmental carrying capacity. If the surface ecology of the mining area is poor and the groundwater is seriously polluted, it will indirectly affect the water resistance toughness of the coal seam floor. The evaluation index system is detailed in Table 1.

TABLE 1: Evaluation index system of water resistance toughness of coal seam floor.

Target layer	Criterion layer	Indicator layer
		Coal seam mining impact A1
	System vulnerability elements A	Performance of the water-resisting strata A2
		Water inrush intensity of aquifer A3
Water resistance toughness of coal seam floor X		Influence of geological structure A4
		Drilling technology B1
	System recoverability elements B	Reinforcement technology B2
		Detection technology B3
	System adaptability elements C	Surface ecological governance C1
		Water resources carrying capacity C2

Coal seam mining impact A1 can be further refined into influencing factors such as coal seam mining depth, coal seam inclination, coal seam mining height and thickness, working surface size, coal seam mining intensity, and overburden rock load. Performance of the water-resisting strata A2 can be further refined into influencing factors such as waterproof rock layer thickness, lithology and strata combination, location of the water-retaining rock formation, the inclination angle of the water-resistant rock formation, and development height of conduction zone. Water inrush intensity of aquifer A3 can be further refined into influencing factors such as water pressure of aquifer, water richness of aquifer, and permeability of aquifer. Influence of geological structure A4 can be further refined into influencing factors such as fault development degree, location of folds, karst collapse column situation, and ancient weathering crust situation. Drilling technology B1 can be further refined into influencing factors such as selection of drilling method, drilling layout plan, and drilling construction technology. Reinforcement technology B2 can be further refined into influencing factors such as selection of grouting method, grouting materials and pulping process, and determination of grouting parameters. Detection technology B3 can be further refined into influencing factors such as geological exploration before drilling, detection of grouting effect, and advance detection before mining. Surface ecological governance C1 can be further refined into influencing factors such as vegetation coverage rate, mining subsidence degree, and surface water status. Water resources carrying capacity C2 can be further refined into influencing factors such as mine water replenishment status, pollution degree of mine water, and utilization rate of mine water.

2.2. Construction of Evaluation Model

2.2.1. Evaluation Methods

(1) Maximum Difference Normalization Method. Since the different dimensions of each influencing factor will affect the final result, the data needs to be normalized. The normalization formula is shown in formulas (1) and (2).

For the index factors that can improve the performance of the system, the larger the quantified value, the positive correlation formula is selected to normalize, such as the waterproof rock layer thickness d.

$$X_i = \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)}. \tag{1}$$

For the index factors that reduce the performance of the system, the smaller the quantified value, the negative correlation formula is selected to normalize, such as the water pressure of aquifer p.

$$X_i = \frac{\max(x_i) - x_i}{\max(x_i) - \min(x_i)}. \tag{2}$$

In the formulas, $\max(x_i)$ is the maximum value of a certain index factor; $\min(x_i)$ is the minimum value of a certain index factor x_i; X_i is the value after removing the dimensions. For the quantifiable indicators that can be tested in the field, similar model tests, or numerical simulations, the indicators are dimensionless by means of polarization, and their importance is ranked according to the slope of the fitted curve [22].

(2) AHP. Combining the above dimensionless analysis, construct a judgment matrix according to the 1-9 scale judgment table in the analytic hierarchy process, perform calculations, and determine the weight vector W of each indicator. In order to evaluate the consistency of the calculation results of the total ranking of levels, it is necessary to calculate the consistency index (CI), the random consistency index (RI), and the consistency ratio (CR) for consistency testing. If $CR < 0.1$, the judgment matrix is considered to have satisfactory consistency. Among them, the calculation method of each index is as follows:

$$CI = \sum_{j=1}^{m} W_{aj} CI_j,$$

$$\text{RI} = \sum_{j=1}^{m} W_{aj}\text{RI}_j,$$

$$\text{CR} = \frac{\text{CI}}{\text{RI}}. \qquad (3)$$

In the formulas, W_{aj} represents the total ranking weight of the element A_j in the a level; CI is the total ranking consistency index of the level; CI_j is the consistency index of the judgment matrix of the next level corresponding to A_j; RI is the random total ranking of the level Consistency index; RI_j is the random consistency index of the judgment matrix in the next level corresponding to A_j; CR is the random consistency ratio of the total ranking of the level. In this paper, AHP auxiliary software yaahp10.1 is used to construct the judgment matrix, check the consistency, and process the calculation results.

(3) Fuzzy Comprehensive Evaluation Method. Firstly, determine the factor set U and the judgment set V of the judgment object.

$$U = (u_1, u_2, \cdots, u_n),$$
$$V = (v_1, v_2, \cdots, v_m). \qquad (4)$$

Secondly, construct the fuzzy relationship matrix. Each factor u_i in the evaluation factor set U belongs to the membership degree r_{ij} of each level v_j, and then, the membership degree of the factor u_i relative to each level in the evaluation set is

$$R_i = (r_{i1}, r_{i2}, \cdots, r_{im}). \qquad (5)$$

Then, the membership degree set R of all influencing factors in the factor set U is obtained, which is called the fuzzy relationship matrix.

$$R = (r_{ij}) \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ r_{21} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix} (i = 1, 2, \cdots, m/j = 1, 2, \cdots, n). \qquad (6)$$

2.2.2. Model Architecture. Based on the above evaluation method selection, the key links of the evaluation model structure are determined as follows: (1) analysis and determination of index weights, (2) single-factor toughness ranking and affiliation determination, and (3) fuzzy comprehensive evaluation. The specific evaluation model architecture is shown in Figure 2.

Through single-factor toughness grade division, membership function, and Delphi method, the membership degree of the evaluation index is comprehensively determined, and then combined with the determined weight vector W, the fuzzy synthesis calculation is carried out according to the following formula. According to the principle of maximum membership degree, the final evaluation result is obtained.

$$Z = W \times R = (W_1, W_2, \cdots, W_n) \times (R_1, R_2, \cdots, R_n), \qquad (7)$$

3. Case Application

3.1. Engineering Application of the Model. The No. 10 coal seam in the lower mining area of East-10, Jiegou Coal Mine, Anhui Province, China, was affected by the hidden water hazard of the floor high-pressure limestone during mining. In 2019, the mine adopted multibranch horizontal well grouting for advanced regional grouting reinforcement treatment. It is planned to evaluate the effect of water-retaining mining through the water resistance toughness evaluation model of coal seam floor and at the same time provide an evaluation basis for further improving the water environment of the mining area and realizing the in situ protection of coal seam floor high-pressure limestone water.

3.1.1. Analysis and Determination of the Weight of Each Index. Select indicators that can be processed quantitatively: coal seam mining impact $A1$, performance of the water-resisting strata $A2$, water inrush intensity of aquifer $A3$, and influence of geological structure $A4$, and analyze the degree of influence. Among them, coal seam mining impact $A1$ selects the coal seam dip angle: α as the characterization parameter; performance of the water-resisting strata $A2$ selects the waterproof rock layer thickness: d as the characterization parameter; water inrush intensity of aquifer $A3$ selects water richness: p as the characterization parameter; influence of geological structure $A4$ selects the distribution density of faults: ρ as the characterizing parameter. The maximum water pressure Ps that the coal seam floor can withstand is used as the toughness parameter. The impact of α, d, p, and ρ on it is shown in Figure 3.

Specific parameters of the No. 10 coal seam of Jiegou Coal Mine are selected, physically modelled, and numerically simulated for analysis. For the indicators $A1$, $A2$, $A3$ and $A4$, which can be quantified, the dimensionless analysis was carried out using the extreme difference standardisation method. The range of values for α is 0-50°, d is 0-20 m, p is 0-5 L/s•m, and ρ is 0-1. The fitted curve of the maximum water pressure that the coal seam floor can withstand under the influence of different factors is plotted. Based on the rate of change of the slope of the fitted curve, a preliminary judgement can be made on the order of importance of each indicator: A4 > A2 > A3 > A1. According to Figure 3, the maximum water pressure Ps that the coal seam floor can withstand increases with increasing collapse overburden load q and water barrier thickness d and decreases with
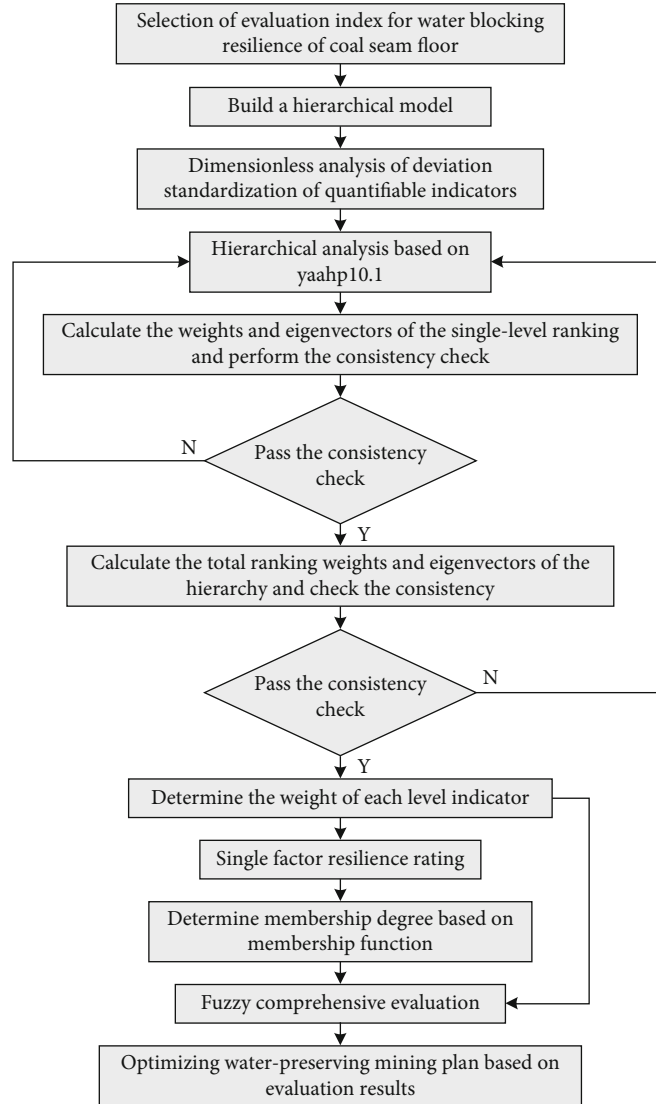
Figure 2: Framework of evaluation model for water resistance toughness of coal seam floor.

increasing aquifer water richness p and fault distribution density ρ. Among them, the related factors of geological structure and water-resisting layer have the most obvious influence on the water-resisting performance of the coal seam floor.

Usually, in evaluation models, weights usually need to have a certain degree of generalisability. For indicators that can be quantified and analyzed, the ranking of the weights needs to be combined with more similar projects and experience for weighting if there are deviations from experience. The above data is taken from the specific case of Jiegou Coal Mine and is consistent with experience. Drilling technology $B1$, reinforcement engineering $B2$, detection technology $B3$, surface ecological management $C1$, and water resources carrying capacity $C2$, which cannot be quantified, can be combined with similar projects. Before carrying out the level analysis, build the bottom water resistance toughness hierarchical structure model, as shown in Figure 4.

The weight is determined using AHP software yaahp10.1 for hierarchical structure model division, judgment matrix construction, and calculation result processing. The judgment matrixes are as follows:

$$X = \begin{bmatrix} 1 & 3 & 2 \\ 1/3 & 1 & 1/2 \\ 1/2 & 2 & 1 \end{bmatrix},$$

$$A = \begin{bmatrix} 1 & 1/4 & 1/3 & 1/5 \\ 4 & 1 & 3 & 1/3 \\ 5 & 3 & 1 & 1/4 \\ 3 & 1/3 & 1/4 & 1 \end{bmatrix},$$

$$B = \begin{bmatrix} 1 & 1/3 & 1/5 \\ 3 & 1 & 1/2 \\ 5 & 2 & 1 \end{bmatrix},$$

$$C = \begin{bmatrix} 1 & 1/2 \\ 2 & 1 \end{bmatrix}. \tag{8}$$

The consistency of the judgment matrix is 0.0089, 0.0688, 0.0036, and 0.000, respectively, satisfying the consistency requirement. The calculated weight vector is as follows:

$$\begin{aligned} W_1 &= [0.071, 0.268, 0.141, 0.520], \\ W_2 &= [0.110, 0.309, 0.581], \\ W_3 &= [0.333, 0.667], \\ W &= [0.539, 0.164, 0.297]. \end{aligned} \tag{9}$$

3.1.2. Single-Factor Toughness Ranking and Affiliation Determination. The determination of the affiliation degree is the core part in the fuzzy comprehensive evaluation. Based on the specific engineering practice, the affiliation degree determination in the evaluation of similar projects is analyzed, and the toughness level of each index factor is divided, as shown in Table 2.

The index factors of the water resistance toughness of the floor can be broadly divided into two categories, namely, qualitative factors and quantitative factors. For example, coal seam mining impact $U11$, performance of the water-resisting strata $U12$, water inrush intensity of aquifer $U13$, and influence of geological structure $U14$ are quantifiable index factors, which can be determined by the membership function according to the quantified value. Establish the following membership function:

$$f_1(u) = \begin{cases} 1, & u < a_1, \\ \dfrac{a_2 - u}{a_2 - a_1}, & a_1 \le u < a_2, \\ 0, & a_2 \le u < a_3, \\ 0, & u \ge a_3, \end{cases} \tag{10}$$

$$f_2(u) = \begin{cases} 0, & u < a_1, \\ \dfrac{u - a_1}{a_2 - a_1}, & a_1 \le u < a_2, \\ 0, & a_2 \le u < a_3, \\ 0, & u \ge a_3, \end{cases} \tag{11}$$

$$f_3(u) = \begin{cases} 0, & u < a_1, \\ 0, & a_1 \le u < a_2, \\ \dfrac{a_3 - u}{a_3 - a_2}, & a_2 \le u < a_3, \\ 0, & u \ge a_3, \end{cases} \tag{12}$$

$$f_4(u) = \begin{cases} 0, & u < a_1, \\ 0, & a_1 \le u < a_2, \\ \dfrac{u - a_2}{a_3 - a_2}, & a_2 \le u < a_3, \\ 1, & u \ge a_3. \end{cases} \tag{13}$$

As coal seam mining impact $U11$, water inrush intensity of aquifer $U13$, and influence of geological structure $U14$ increase, the resilience is negatively correlated with a decreasing trend. Select (13) to determine the degree of membership of the "extremely good resilience" grade, and select (10) to determine the degree of membership of the "extremely poor resilience" grade. With the enhancement of performance of the water-resisting strata $U12$, the resilience shows a positive correlation enhancement trend. Select (10) to determine the degree of membership of the "extremely poor resilience" grade, and select (13) to determine the "extremely good resilience" grade. The degrees of membership, such as drilling technology $U21$, reinforcement technology $U22$, detection technology $U23$, surface ecological governance $U31$, and water resources carrying capacity $U32$, are factors that cannot be accurately quantified. The membership of these factors can be based on actual engineering and similar projects. It is determined in combination with the Delphi method. According to the specific conditions of Jiegou Coal Mine, the membership degree of each index factor of the water resistance toughness of the coal seam floor in the treatment area and the membership degree matrix of the criterion layer are further obtained as follows:

$$\begin{aligned} R_1 &= \begin{bmatrix} R_{11} \\ R_{12} \\ R_{13} \\ R_{14} \end{bmatrix} = \begin{bmatrix} 0.05, 0.20, 0.50, 0.25 \\ 0.10, 0.45, 0.30, 0.15 \\ 0.20, 0.65, 0.10, 0.05 \\ 0.20, 0.50, 0.25, 0.05 \end{bmatrix}, \\ R_2 &= \begin{bmatrix} R_{21} \\ R_{22} \\ R_{23} \end{bmatrix} = \begin{bmatrix} 0.05, 0.20, 0.50, 0.25 \\ 0.05, 0.15, 0.60, 0.20 \\ 0.20, 0.45, 0.25, 0.10 \end{bmatrix}, \\ R_2 &= \begin{bmatrix} R_{21} \\ R_{22} \end{bmatrix} = \begin{bmatrix} 0.60, 0.25, 0.10, 0.05 \\ 0.65, 0.20, 0.15, 0.00 \end{bmatrix}. \end{aligned} \tag{14}$$

The plot shows curves with equations:
$$y = -1.42 x^2 - 1.43 x + 9.76$$
$$y = -3.46 x^2 - 7.04 x + 11.21$$
$$y = 9.56 x^2 - 0.66 x + 0.41$$
$$y = 10.83 x^2 - 20.45 x + 10.18$$

Legend:
◆ Coal seam dip angle: α
▲ Water-richness: p
■ Waterproof rock layer thickness: d
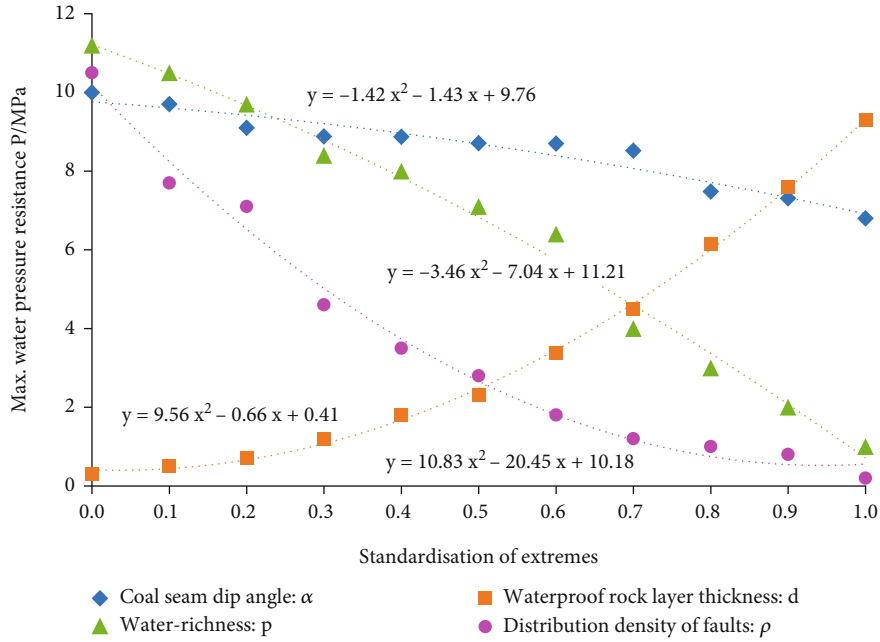● Distribution density of faults: ρ

FIGURE 3: The relationship curve between the maximum water pressure P and system vulnerability elements of coal seam floor.
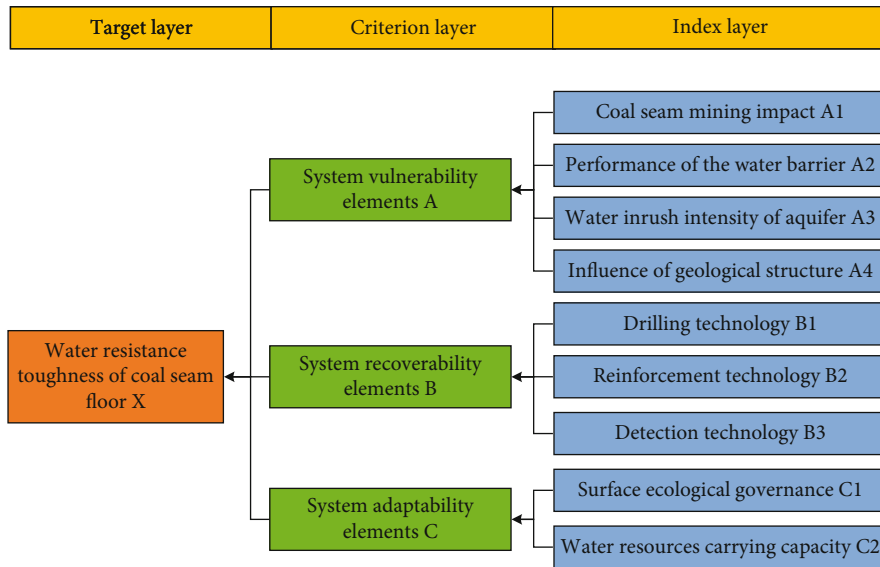

FIGURE 4: Hierarchical structure model of water resistance toughness of coal seam floor.

3.1.3. Fuzzy Comprehensive Evaluation.

Fuzzy comprehensive evaluation is a compound operation of the weight and the judgment matrix of each influencing factor. The first-level fuzzy evaluation results are as follows:

$$Z_1 = W_1 \times R_1 = [0.163, \mathbf{0.486}, 0.260, 0.091],$$
$$Z_2 = W_2 \times R_2 = [0.137, 0.330, \mathbf{0.386}, 0.147], \qquad (15)$$
$$Z_2 = W_3 \times R_3 = [\mathbf{0.633}, 0.217, 0.133, 0.017].$$

After finishing Z_1, Z_2, and Z_3, the matrix R is obtained, and the second-level fuzzy evaluation operation is performed. The results are as follows:

$$Z = W \times R = [0.298, \mathbf{0.381}, 0.243, 0.078], \qquad (16)$$

where Z represents the comprehensive evaluation result, and Z_1, Z_2, and Z_3 represent the criterion-level evaluation result.

TABLE 2: Single-factor toughness rating.

Index factor		Toughness evaluation level criteria			
		Very bad	Worse	Better	Excellent
$U1$	U11	$\alpha \geq 45°$	$25° < \alpha < 45°$	$8° < \alpha < 25°$	$\alpha \leq 8°$
	U12	$d \leq 0$	$0 < d < 10\,m$	$10\,m < d < 20\,m$	$d \geq 20\,m$
	U13	$p > 5\,L/s\bullet m$	$3\,L/s\bullet m < p < 5\,L/s\bullet m$	$1\,L/s\bullet m < p < 3\,L/s\bullet m$	$p < 1\,L/s\bullet m$
	U14	$\rho > 0.8$	$0.5 < \rho < 0.8$	$0.2 < \rho < 0.5$	$\rho < 0.2$
$U2$	U21	Serious damage to the key rock formation	Poor matching of construction technology	Good match of construction technology	Less damage to the key rock formation
	U22	Widespread pollution	Local pollution	No obvious pollution	Green and ecofriendly
	U23	Basic geophysical prospecting	Multi-mode combined detection	Whole process detection	Real-time dynamic detection
$U3$	U31	Poor governance	General governance	Ecological restoration is in progress	Green ecology
	U32	High pollution index	Average pollution index	Limited water carrying capacity	High water carrying capacity

3.2. Result Analysis. According to the principle of maximum degree of membership, the water resistance toughness level of the floor of the No. 10 coal seam treatment area in Jiegou Coal Mine is judged. From the perspective of the life cycle of the system, according to Z, the water resistance toughness of the floor system of the No. 10 coal seam is weak. The detailed analysis is as follows:

(1) According to Z_1, the performance of system vulnerability elements is weak. This reflects that after advanced regional grouting and reinforcement treatment, as the coal seam is further mined, there are still dangerous areas with greater water inrush risk. Under the combined action of faults, karst collapse columns, and high-pressure limestone water, the self-repairing ability of the key water-resisting strata of the coal seam floor is poor. Therefore, it is necessary to continuously repair and strengthen the regional aquifer on the basis of advanced detection and carry out decompression or transformation of the aquifer. From the perspective of accuracy and efficiency, the determination of the governance target area should be focused on

(2) According to Z_2, it can be concluded that system recoverability elements are with better resilience, because the treatment area has previously adopted multibranch horizontal well grouting for advanced treatment. However, the traditional drilling and grouting method will inevitably cause damage to the original rock formation. Rock formation damage caused by multibranch drilling is irreversible, and it is difficult to achieve in situ water retention. At the same time, the selected grouting material (mainly cement) cannot achieve resilience repair well. Therefore, it is urgent to optimize and upgrade the in situ water-preserved technology. The impact of grouting materials on the groundwater environment should be determined, and the hardening and water-resisting and durability properties of the materials under the influence of groundwater should be explored. The properties of various materials need to be mastered, and then, low-cost, harmless, high-performance pressure-bearing floor rock water channel blocking green materials and floor rock self-repairing materials can be developed

(3) According to Z_3, system adaptability elements have extremely poor resilience. Generally, water-preserved mining in mining areas mainly focuses on subsequent safe production, and less attention is paid to the effect of groundwater resources protection. Combining the specific conditions of the Jiegou Coal Mine, and according to the corresponding monitoring data in five dimensions of water volume, water quality, water area, hydrodynamic force, and water and heat capacity, it can be obtained that the groundwater carrying capacity of Jiegou Coal Mine is poor, which indirectly affects the water blocking performance of the coal seam floor. From the side, it reflects the relevance of the improvement of the water resistance toughness of the coal seam floor and the ecological environment. Therefore, when carrying out water-preserving mining on confined water, attention should be paid to the improvement of the ecological environment of the mining area after the implementation of water-preserving mining technology, so as to achieve the coordination between safe mining and ecological environmental protection

4. Discussions

4.1. Strategies for Improving the Water Resistance Toughness of Coal Seam Floor. In summary, relying on the whole life cycle perspective, the whole process evolution of water-resisting toughness can effectively guide the implementation
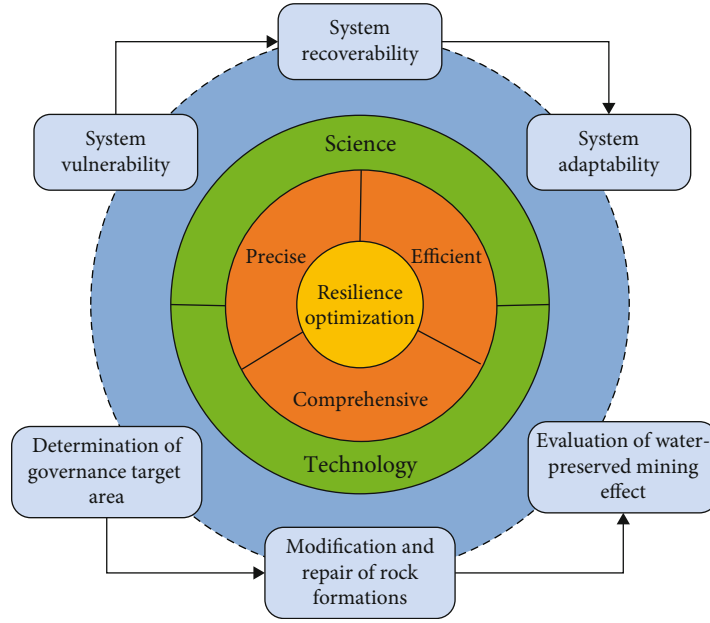
FIGURE 5: Optimization strategy for water resistance toughness of coal seam floor.

of the whole stage of water conservation mining project. The process of coal seam floor from mining damage characteristics to toughness recovery and then to water bearing capacity enhancement contains the whole process of toughness evolution. It also corresponds to 3 stages of the project: determination of governance target area, modification and repair of rock formations, and evaluation of water-preserved mining effect. Based on the above analysis, the optimization strategy for water resistance toughness of coal seam floor is obtained, as shown in Figure 5.

The core of the idea of optimizing the water resistance toughness of coal seam floor is "precise, efficient, and comprehensive": "precision" refers to making the determination of the floor treatment target area more precise; "efficient" refers to the provision of technical routes for modification and repair of rock formations to improve construction efficiency; "comprehensive" means to make up for the lack of attention to the effect of water resources protection in the evaluation of the effect of water-preserved mining.

4.2. New Technology System of Water-Preserved Mining for Coal Seam Floor. Based on the above analysis, the technology system of water-preserved mining for coal seam floor is constructed, and the specific technology system framework is shown in Figure 6. The system is based on 3 stages: "determination of governance target area, modification and repair of rock formations, and evaluation of water-preserved effects". The 3 stages are all based on detection technology, forming 3 detections including "advanced detection, detection while drilling, and detection before mining" to ensure safe construction and mining.

(1) The first stage is the determination of governance target area, including two links: vertical horizon determination and lateral target determination

According to the calculation formula of the broken ring depth of the floor, the development depth of the broken zone under the influence of mining is estimated, and the ideal depth of the grouting target area is preliminarily determined according to the principle that the modified aquifer should avoid the broken zone as much as possible. Further, combined with the mine hydrogeological data, analyze the lithology and rock formation combination, divide the aquifer and aquifer, and determine the final optimal grouting layer.

Calculation of the maximum failure depth of the floor rock mass at the edge of the stope:

$$h_1 = \frac{1.57\gamma^2 H^2 L_x}{4R_c^2}. \tag{17}$$

Calculation of the maximum failure depth of the bottom rock mass of the longwall working face:

$$h_2 = \frac{(n+1)H}{2\pi}\left(\frac{2\sqrt{K}}{K-1} - \arccos\frac{K-1}{K+1}\right) - \left(\frac{R_c}{\gamma(K-1)}\right), \tag{18}$$

where γ is the bulk density of the rock mass, N/m³; H is the mining depth, m; L_x is the slope length of the working face, m; R_c is the uniaxial compressive strength of the rock mass, MPa; n is the maximum stress concentration factor, usually taken 1.5~5; φ_0 is the friction angle in the rock body, °; and $K = (1 + \sin\varphi_0)/(1 - \sin\varphi_0)$.

The horizontal target position is determined on the basis that the vertical horizon has been determined, using geological detection methods such as multifrequency continuous electrical method, GIS spatial analysis tools, and borehole television method. The relevant parameters are accurately
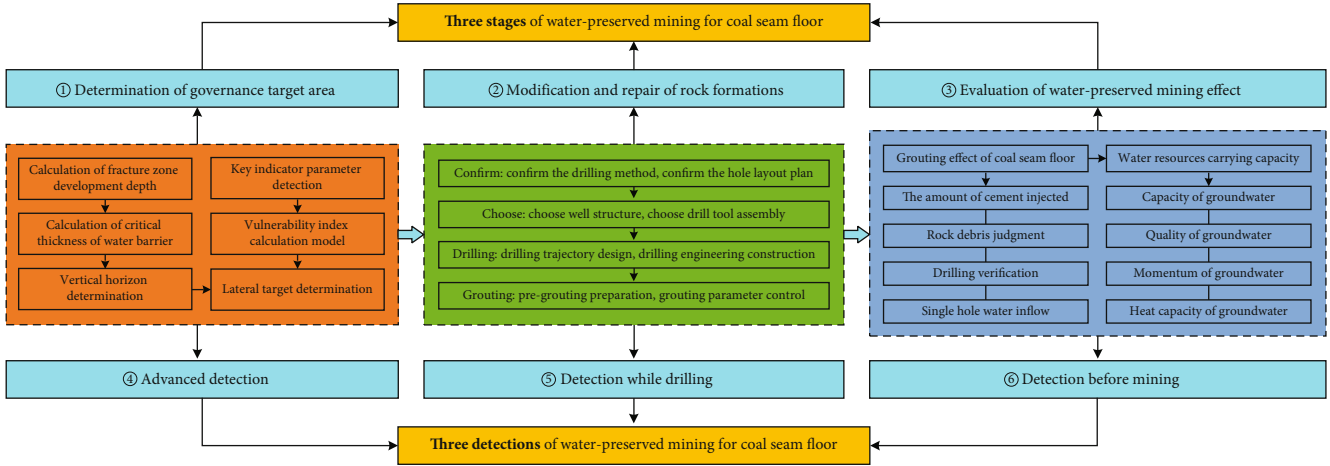
FIGURE 6: Framework of in situ water-preserved technology system for coal seam floor.

detected. The spatial analysis function of ArcGIS is used for interpolation analysis to generate a normalized thematic map of key index parameters. With the help of the position coordinates of the thematic map, the single-factor influence value function $f_i(x, y)$ is given. Fuzzy analytic hierarchy process (FAHP) is used to calculate the AHP weight of each factor, and the entropy weight method (EW) is used to calculate the entropy weight of each factor. Calculate the composite weight according to formula (19), and according to formula (20) of vulnerability index, integrate three factors of aquifer, confined aquifer, and geological structure, and evaluate the weak interval of water-resisting as a lateral grouting target.

$$W_i = \frac{w_i x_i}{\sum_{i=1}^{n} w_i x_i}, \tag{19}$$

$$VI = \sum_{i=1}^{n} W_i \cdot f_i(x, y). \tag{20}$$

In the formulas, w_i is the single-factor level analysis weight; x_i is the single-factor entropy weight; n is the number of factors; and (x, y) is the geographic coordinates.

(2) The second stage is the modification and repair of the rock formation, including the four steps of determination, selection, drilling, and grouting

At present, most of the grouting schemes only consider the reconstruction of the aquifer but do not fully consider the repair of the original aquifer, so that the two can form a joint water blocking body with stronger continuity and integrity. Rock grouting modification repair is a commonly used method and means to change the hydrogeological conditions of rock mass. According to the first stage, the treatment target area, that is, the construction location, can be preliminarily determined. Before the project is carried out, it is necessary to fully consider the ground construction conditions, the buried depth of the coal seam, and the water pressure of the coal seam floor, comprehensively determine

the drilling method (surface or underground), and then determine the hole layout plan and drilling sequence. According to the drilling method, select the wellbore structure and drilling tool combination. Taking the multibranch horizontal drilling technology as an example, the drilling usually adopts a three-split and two-stage cased wellbore structure. After that, the design and construction of drilling engineering and grouting engineering are carried out.

(3) The third stage is the evaluation of water retention effect, including the evaluation of rock grouting effect and the evaluation of water resources carrying capacity restoration

According to the provisions of the relevant standards, in the area where the ground area treatment is implemented, the geophysical method should be used to test the effect before the excavation. If there is no abnormality, the excavation can be carried out normally; if any abnormality is found, drilling is used to verify and control the standards. Before mining, geophysical exploration and drilling methods should be used to verify the effect to ensure that no large water inrush points occur in the grouting diffusion area of branch holes. The grouting effect of the coal seam floor can be verified by four indicators: the amount of injected mud and water, judgment of cuttings, drilling verification, and single-hole gushing volume.

From the perspective of mine groundwater ecological protection, taking the restoration of water resources carrying capacity as the breakthrough point, and based on the results of the topographic, geomorphological, and hydrogeological exploration of the coal field, the key indicators for the evaluation of the water protection effect of the floor limestone are proposed, including water quantity, water quality, hydrodynamics and water quality, and heat capacity. By grasping the key indicators of mine water resources ecological protection and the corresponding thresholds, the groundwater conditions of the floor can be objectively and clearly reflected in a quantitative form. At the same time, it can solve the problem of insufficient attention to the mine

ecological environment in the evaluation of water conservation and mining effects.

5. Conclusions

(1) Based on the theory of system resilience, an evaluation index system for water resistance toughness of coal seam floor was established, which specifically included three types of evaluation elements: system vulnerability elements A, system recoverability elements B, and system adaptability elements C, in detail, including 9 evaluation indicators: coal seam mining impact $A1$, performance of the water-resisting strata $A2$, water inrush intensity of aquifer $A3$, influence of geological structure $A4$, drilling technology $B1$, reinforcement technology $B2$, detection technology $B3$, surface ecological governance $C1$, and water resources carrying capacity $C2$

(2) The range standardization-AHP-fuzzy comprehensive evaluation method is adopted to construct an evaluation model with index weight analysis and determination, resilience grade division and membership determination, and fuzzy comprehensive evaluation as the main links. The integration of the maximum difference normalization method and the membership function overcomes the deficiencies of experts' scoring to a certain extent and solves the problem of determining the weight of multiple indicators in a semiquantitative manner

(3) The evaluation model is applied to the specific engineering practice. According to the evaluation results Z_1, Z_2, Z_3, and Z, it can be seen that improving the water resistance toughness of coal seam floor requires determining the treatment target area, optimizing the modification and repair of rock formations materials, and improving the water resources carrying capacity. To a certain extent, this verifies the validity of the evaluation index and the practical value of the evaluation model. It should be noted that the evaluation index system is not yet complete, and further adjustments and optimizations should be made to the actual project

(4) According to the view of the whole life cycle, the whole process evolution of water resistance toughness can effectively guide the implementation of the whole stage of engineering technology. The in situ water retention technology system of coal seam floor is proposed, with 3 stages as the main body and 3 detections as the backing. 3 stages involve "determination of governance target area, modification and repair of rock formations, and evaluation of water-preserved mining effect"; 3 detections involve " advanced detection, detection while drilling, and detection before mining". The purpose is to provide strategies and measures for water protection in mining, to form an effective technical solution for in situ water protection of coal seam floor

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