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Research on the evaluation model of emergency rescue capability of coal mine water penetration accident

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In order to effectively solve coal mine water penetration accident and improve emergency rescue capability and evaluation accuracy, a emergency rescue capability evaluation model of coal mine water penetration accident is proposed, which combines an improved combination weighting method with the marine predator algorithm (MPA) optimizing BP neural network (BPNN). First of all, the evaluation index system of emergency rescue capability of coal mine water penetration accident is constructed, including four primary indicators, emergency rescue prevention capability, emergency rescue preparation capability, emergency rescue response capability, rehabilitation recovery capability, and sixteen secondary indicators. Secondly, the subjective and objective weighting of the evaluation indicators are determined by the best worst method (BWM) and the criteria importance though intercrieria correlation (CRITIC) method. Lagrange function is introduced to build a decision model, and combination weighting are obtained by coupling the subjective and objective weighting through the euclidean distance function. Thirdly, the combined weight value is used as the input of the MPA-BPNN model, and the expected value as the output for linear regression prediction. Finally, the model is applied in a coal mine in Shanxi and compared with the BPNN model, GA-BPNN model, and PSO-BPNN model. The results show that mean absolute error of MPA-BPNN model has decreased by 6.5%, 4.3% and 3.5% respectively compared with other models, which proves the effectiveness and accuracy of the model. Therefore, MPA-BPNN is applicable to the evaluation of emergency rescue capability for coal mine water penetration accident.

Keywords Water penetration accident, Combination weighting method, Emergency rescue, MPA, BPNN, Evaluation model

Coal mine water penetration accident is a relatively common disaster in mine production. Due to the influence of geological formations, hydrogeological conditions of coal seams, mining techniques and mining history, water in the coal seam suddenly flows into the mine roadway so that water level inside the mine rise sharply, with the characteristic of a wide range of affected areas, rescue difficulties[1]. In recent years, with the continuous increase in coal mining intensity and depth, old goaf water, floor pressurized water and roof water enter into mining face through infiltration, leaching and other channels, threatening safety production of mine[2,3]. According to statistics, more than 100 water penetration accidents occurred in China's coal mines from 2011 to 2021, with a death toll of 584 people[4,5]. The research shows that when a mine water penetration accident occurs, intensity of emergency rescue capacity determines the effectiveness of rescue. Therefore, evaluation of emergency rescue capacity of coal mine water penetration accident in advance facilitates to understand the level of emergency rescue capacity of coal mine enterprises, then formulates effective avoidance measures to improve deficiencies

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of emergency rescue in time, which reduces casualties and property losses. It is of important guiding significance for the emergency rescue work of water penetration accident.

In order to further recognize the shortcomings of emergency rescue in accidents, improve the emergency rescue capability of accidents and reduce the losses, some scholars begin to evaluate the emergency rescue capability. For example, Jian et al.[6] proposed a temporal dynamic assessment model for evaluating the emergency response and rescue capabilities of hybrid hydrogen-gasoline fueling stations. The model merges with information-driven theory on the basis of dynamic scenario construction, which evaluates the risk evolution process at different stages of accidents and offers a new analytical perspective for emergency management in hybrid hydrogen-gasoline fueling stations. Li et al.[7] summarized the emergency rescue characteristics of urban gas pipeline networks accidents, and established a assessment model of urban gas pipeline networks accidents emergency rescue capability by fuzzy comprehensive evaluation method, which assessed the rescue capability. In this way, study results can provide theoretical basis and feasible methods for the development, improvement and assessment of emergency response measures for gas pipeline networks accidents. Meanwhile, many scholars have carried out in-depth research centering emergency rescue of coal mine accidents. For example, based on gray system theory and gray evaluation method, Lei et al.[8] established a risk assessment model for fire emergency rescue of Lugou coal mine, which evaluated the fire rescue capability of the coal mine. According to evaluation results, corresponding control measures were formulated, which optimized and improved the emergency rescue capability of fire in Lugou coal mine and reduced fire loss. Zhang et al.[9] constructed an evaluation model of mine fire emergency rescue capability based on fuzzy priority programming and interval extension theory, improving the reliability of mine emergency rescue capability decision-making. Chen et al.[10] constructed an evaluation model for emergency rescue capability of water penetration accidents based on combination weighting, which was applied to a mine in Heilongjiang province. According to application results, the model is reliable. The above research evaluated and analyzed the emergency rescue capability of coal mines from different perspectives by different methods. However, few scholars have combined mathematical methods with machine learning to analyze and evaluate the emergency rescue capability of coal mine water penetration accident. Due to the numerous factors that affect the emergency rescue capability of coal mine water penetration accident, as well as the uncertainties in the evaluation factors, the evaluation methods are too single and subjective, resulting in low reliability of the evaluation results. Therefore, the comprehensiveness and depth of the relevant research methods need to be further improved.

In view of this, in order to further strengthen the emergency rescue capability of coal mine water penetration accident, combining the best worst method (BWM) with the improved criteria importance though intercriteria correlation (CRITIC), Euclidean distance function is introduced to determine the subjective and objective weighting. Marine predator algorithm (MPA) is used to optimize the weighting and thresholds in the BPNN, thereby overcoming strong subjectivity of BPNN. An evaluation model of emergency rescue capability of coal mine water penetration accident combining improved combined weighting with the MPA-BPNN is constructed, which is applied to a coal mine in Shanxi. The results are compared with the evaluation results of BPNN, GA-BPNN, and PSO-BPNN models to test the rationality and effectiveness of the model, so as to provide reference for the evaluation of emergency rescue capability in coal mine water penetration accident.

Construction of evaluation index system for emergency rescue capability of coal mine water penetration accident

Background and objective of emergency rescue of coal mine water penetration accident

Emergency rescue refers to the process that various measures and actions are taken to save lives, reduce property losses and environmental pollution, and restore social order as soon as possible in emergencies, such as fires, earthquakes, accidents, etc. The background of emergency rescue ability evaluation of coal mine flooding accident is frequent occurrence of coal mine safety accidents. Furthermore, water penetration accident is a serious disaster type in coal mine safety accidents, which brings huge economic losses and threats life and property safety of the country and people. Although China has formulated a series of policies and regulations in emergency rescue, there are still problems such as imperfect emergency rescue system, insufficient practicability of emergency plan, low quality of rescue team and low level of equipment and technology.

Emergency rescue of coal mine water penetration accident often exhibits emergency rescue ability problems, such as slow response speed, ineffective rescue measures, unreasonable allocation of resources and so on. The evaluation and improvement of the emergency rescue ability aims to reduce the incidence and loss of coal mine flooding accident. Its main objectives are as follows:

(1) Analyze the deficiencies of existing emergency rescue capabilities. The evaluation of emergency rescue capabilities can understand problems and deficiencies in the emergency rescue system in time to make specific improvements, improving the efficiency of emergency rescue.
(2) Prevent occurrence of accidents. The evaluation of emergency rescue ability can strengthen the prevention awareness and response ability of mines emergencies to reduce the probability of accidents.
(3) Strengthen the implementation of emergency plan. The evaluation of emergency rescue capability helps to test the practicability and operability of the emergency rescue plan of mine water disaster accidents, and ensure that the emergency plan can play the expected role in the actual rescue process.
(4) Improve mine disaster resistance. The evaluation of emergency rescue capabilities and emergency training can improve the disaster resistance of miners and rescue teams and fighting capacity of rescue teams, and ensure that mines can quickly resume normal production in the face of emergencies.

(5) Improve the efficiency of emergency rescue. Studying the emergency rescue ability of coal mine water penetration accident aims to improve the efficiency of emergency rescue operations, find and rescue trapped miners as soon as possible, ensure the safety of trapped miners and reduce accident losses.
(6) Meet requirements of laws and regulations. According to relevant regulations such as the Regulations on Emergency Response to Production Safety Accidents, enterprises should regularly evaluate emergency rescue capabilities to ensure observe laws and regulations.
(7) Promote safety production. The evaluation of emergency rescue capability helps enterprises to better implement the safety production responsibility system, strengthen safety production management, and prevent the occurrence of accidents.

Analysis of influence factors

The analysis of influence factors of emergency rescue capability of coal mine water penetration accident is the basis of constructing evaluation index system. The emergency rescue process of coal mine water penetration accident is shown in Fig. 1. From Fig. 1, efforts should be made to enhance the emergency rescue capabilities of coal mine water penetration accident from four aspects:

(1) Accident prevention and control is the core of emergency rescue work. On the one hand, prediction and monitoring of coal mine water penetration should be strengthened. On the other hand, mine drainage system and related hydraulic facilities should be regularly overhauled to identify and deal with hidden dangers that may lead to water penetration accident in time.
(2) Necessary emergency preparedness work can minimize the losses and avoid more accidents. Developing a reasonable emergency plan, clarifying the emergency organization, arranging necessary equipment and materials, and conducting regular emergency drills can effectively shorten the emergency response time and rescue process.
(3) During the emergency rescue process, rescue team should accurately locate accident location, conduct on-site hazard assessment, and draw up appropriate rescue plans. At the same time, emergency rescue person-

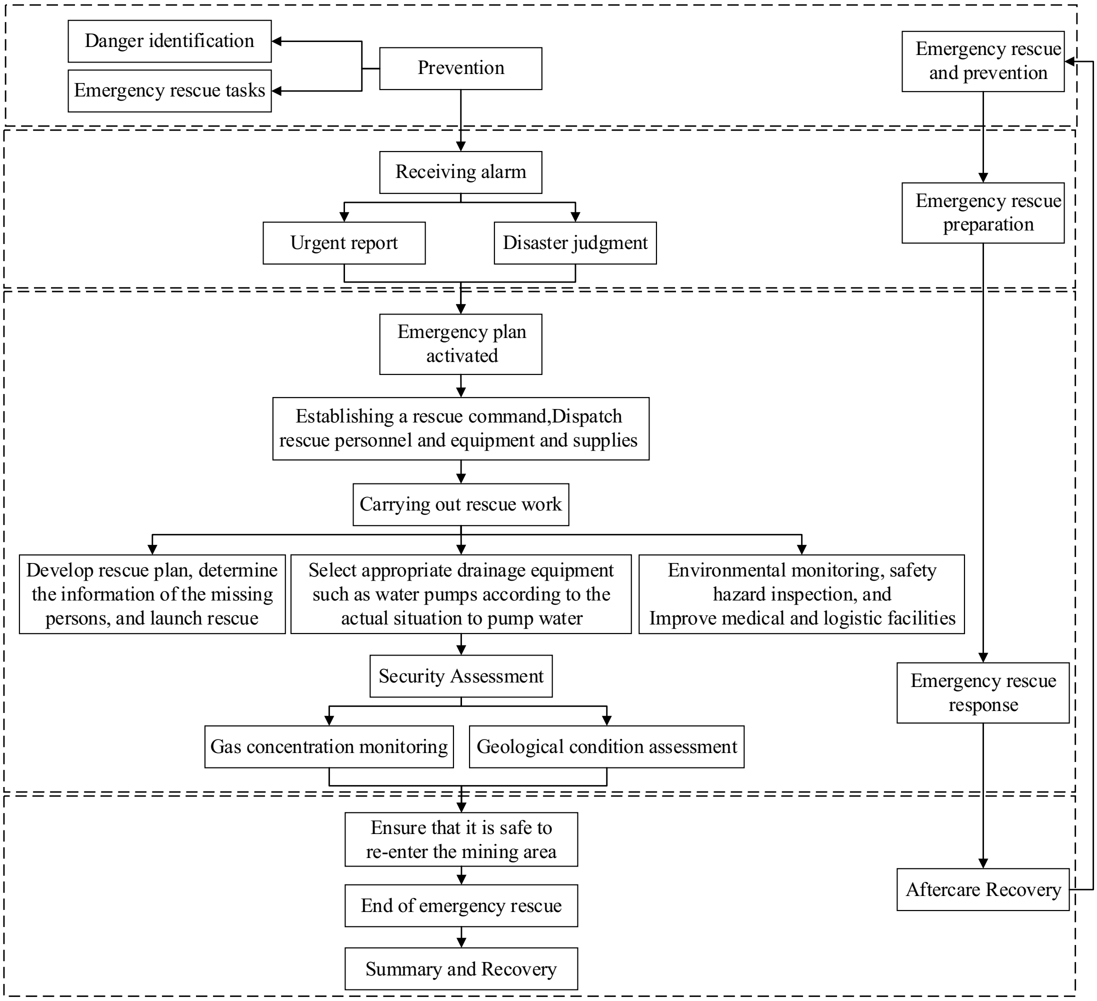

Figure 1. Emergency rescue process of coal mine water penetration accident.

nel should arrive at the scene for rescue in the shortest time to avoid the impact caused by the expansion of the accident.

(4) After a coal mine water penetration accident occurs, it is necessary to carry out a detailed recovery plan in time, rebuild the spiritual confidence of personnel, strengthen accident education, and constantly improve the emergency plan.

Construction of evaluation index system

Based on the background of emergency rescue and the purpose of emergency rescue capability evaluation of coal mine flooding accident, more than 100 coal mine water disaster accidents occurring in China from 2011 to 2021 are analyzed. At the same time, actual situation of coal mine production is combined with the relevant regulations of *Coal Mine Safety Regulations*, *Coal Mine Water Control Regulations*, *Production Safety Accident Emergency Plan Management Measures*[11–13], the evaluation index system of emergency rescue capability of coal mine water penetration accident is established, which covers 16 indexes in 4 aspects, including emergency rescue and prevention capability, emergency rescue preparation capability, emergency rescue response capability and rehabilitation recovery capability, as shown in Fig. 2.

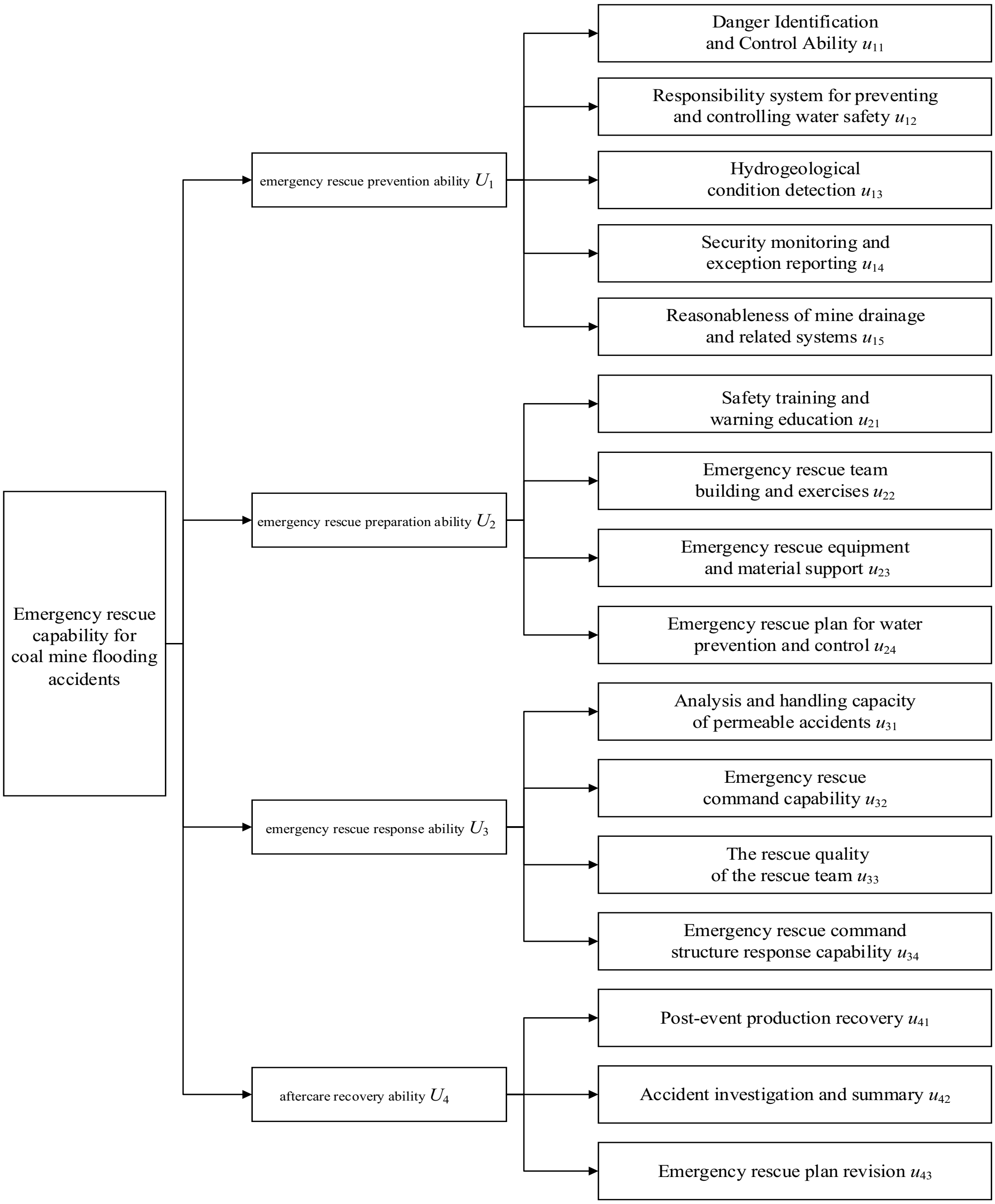

Figure 2. Evaluation index system of emergency rescue capability of coal mine water penetration accident.

Principle of evaluation method

Improved combinatorial weighting method

Determination of subjective weighting by BWM method

The BWM method, a weight determination method, was proposed by Jafar Rezaei[14] in 2015. It has the advantage that consistent results can be obtained with less comparative information. The steps are as follows:

(1) Determine the set of indicators: $U = \{U_1, U_2, \ldots, U_n\}$, where n denotes the total number of indicators.
(2) Determine the best indicator U_b and the worst indicator U_w.
(3) Determine the weight of the optimal indicator U_b with respect to the other indicators and express its degree with the numbers 1–9, thus constructing the comparison matrix $A_b = (a_{b1}, a_{b2}, \ldots, a_{bn})$.
(4) Similarly, construct a comparison matrix $A_w = (a_{1w}, a_{2w}, \ldots, a_{nw})^T$ T for the weighting of other indicators relative to the worst indicator.
(5) Solve to obtain the optimal set of indicator weighting $(w_1, w_2, \ldots, w_n)$, as follows:

$$\begin{cases} \min \delta \\ \left| \frac{w_b}{w_j} - a_{bj} \right| \le \delta \\ \left| \frac{w_j}{w_w} - a_{jw} \right| \le \delta \\ \sum\limits_{j=1}^{n} w_j = 1 \\ w_j > 0 \\ j = 1, 2, \cdots, n \end{cases} \tag{1}$$

where: w_b is the weight of A_b; A_j is the criterion vector; w_j is the weighting of A_j; w_w is the weighting of A_w; a_{bj} is the value of the importance of A_b to A_j; a_{jw} is the value of the importance of A_j to A_w.

(6) The δ value obtained is expressed as δ^*, and consistency ratio C_R is obtained with value interval [0,1]. The lower the C_R value is, the more reliable the weight result is. The formula is as follows:

$$C_R = \frac{\delta^*}{CI} \tag{2}$$

where CI is the consistency coefficient, and its value can be referred to Table 1.

Determination of objective weighting by improve CRITIC method

The basic principle of the CRITIC method is to determine objective weighting by comparing intensity and conflicting of the indicators[15]. In order to comprehensively consider the correlation between indicators and the degree of discretization between index data, entropy and Pearson coefficient are introduced to improve it. The calculation process is as follows:

(1) The initial evaluation matrix from evaluation index system is constructed.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} \\ x_{21} & x_{22} & \cdots & x_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} \end{bmatrix} \tag{3}$$

where x_{ij} denotes the i-th evaluation index of the j-th sample.

(2) In order to eliminate the influence of different dimensions on the evaluation results, it is necessary to normalize the evaluation indexes of the emergency rescue capability of coal mine flooding accident, and obtain the decision matrix L.

$$x_{ij} = \begin{cases} \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})}, \ \textit{The bigger the better} \\ \textit{if} \ \max(x_{ij}) - \min(x_{ij}) = 0, \ \textit{else} \ x_{ij} = 1 \\ \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})}, \ \textit{The smaller the better} \end{cases} \tag{4}$$

where $\max(x_{ij})$ and $\min(x_{ij})$ denote the maximum and minimum values in the set of evaluation indicators respectively.

(3) The entropy value of each indicator factor is calculated.

a_{bw}	1	2	3	4	5	6	7	8	9
Consistency coefficient	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Table 1. Consistency coefficient (CI).

$$P_{ij} = \frac{x_{ij}}{\sum\limits_{i=1}^{n} x_{ij}}, \; i = 1, 2, \cdots, n; \; j = 1, 2, \cdots, m \tag{5}$$

$$E_j = -\frac{1}{\ln n} \sum_{i=1}^{n} P_{ij} \cdot \ln P_{ij} \tag{6}$$

$$W_{Ej} = \frac{1 - E_j}{K - \sum\limits_{j=1}^{m} E_j} \tag{7}$$

$$\sum_{j=1}^{m} W_{Ej} = 1 \tag{8}$$

In equations (5)–(8), p_{ij} is the indicator characteristic weight; E_j is the entropy weight of the j-th indicator; W_{Ej} is the weight obtained by the entropy weight method.

(4) The coefficient of variationis calculated.

$$\overline{x_j} = \frac{1}{n} \sum_{i=1}^{n} x_{ij} \tag{9}$$

$$v_j = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_{ij} - \overline{x_j})} \tag{10}$$

$$h_j = \frac{v_j}{\overline{x_j}} \tag{11}$$

(5) The decision matrix L is subjected to the Pearson coefficient calculation method to obtain the conflict coefficients.

$$R_j = \sum_{i=1}^{n} (1 - r_{ij}) \tag{12}$$

(6) The amount of information for each indicator is determined.

$$C_j = h_j \times R_j \tag{13}$$

(7) The objective weighting is determined.

$$W_j = \frac{C_j}{\sum\limits_{j=1}^{n} C_j} \tag{14}$$

Combination weighting

In order to achieve unity of subjective and objective attributes, combinatorial optimization model is constructed by Lagrange function and subjective and objective weight relation equation are constructed by the euclidean distance function so as to obtain a reasonable combination weight, thus eliminating the influences of subjective and objective factors on indicator weighting[16,17]. The specific steps for its implementation are as follows:

(1) Combinatorial optimization model is built.

$$\begin{cases} W_j = \alpha W_{sj} + \beta W_{oj} \\ \alpha + \beta = 1 \end{cases} \tag{15}$$

where: W_j is the combination weighting; W_{sj} is the subjective weighting; W_{oj} is the objective weighting; α、β are the linear combination coefficient of the subjective and objective weighting.

(2) The Euclidean distance function D ($W_{sj} - W_{oj}$) is introduced.

$$\begin{cases} D(W_{sj} - W_{oj}) = \sqrt{\sum\limits_{j=1}^{n} (W_{sj} - W_{oj})^2} \\ D(W_{sj} - W_{oj})^2 = (\alpha - \beta)^2 \end{cases} \tag{16}$$

(3) By combining Eqs. (15) and (16) and solving them, it can be concluded that α, β and W_j.

MPA-BPNN integrated evaluation model

MPA principle

MPA algorithm is a biology-based heuristic optimization algorithm proposed by Faramarzi[18] in 2020, simulating the interaction between predators and prey in marine ecosystems with the advantages of stability, scalability, and strong search ability[19]. Main idea is to view the problem solving process as an ecological competition and collaboration process, and the solution of the optimization problem as an ecosystem, where each solution and parameter is a biological individual, and the individuals interact and compete with each other by feeding, chasing and escaping to achieve the optimization goal. The specific steps for its implementation are as follows:

(1) The Elite matrix (*Elite*) and Prey matrix (*Prey*) are initialized. The initialization method for each element x_{ij} in the *Prey* matrix is $x_{ij} = x_{\min} + \text{rand}(x_{\text{man}} - x_{\min})$, ultimately obtaining the *Prey* matrix. For each *Prey* individual $x_i = [x_{i,1}, x_{i,2}, \ldots, x_{i,d}]$, its fitness is calculated. The best fitness individual x^I is used to replicate n copies to form an *Elite* matrix.

$$\Pr ey = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,d} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,d} \\ x_{3,1} & x_{3,2} & \cdots & x_{3,d} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ x_{n,1} & x_{n,2} & \cdots & x_{n,d} \end{bmatrix}_{n \times d} \tag{17}$$

$$Elite = \begin{bmatrix} x^I_{1,1} & x^I_{1,2} & \cdots & x^I_{1,d} \\ x^I_{2,1} & x^I_{2,2} & \cdots & x^I_{2,d} \\ x^I_{3,1} & x^I_{3,2} & \cdots & x^I_{3,d} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ x^I_{n,1} & x^I_{n,2} & \cdots & x^I_{n,d} \end{bmatrix}_{n \times d} \tag{18}$$

In Equations (17)–(18), n is the population size; d is the position of each dimension; the dimension of *Elite* is the same as that of *Prey*.

(2) The optimization process is divided into three types according to different speed ratios as follows:

High speed ratio phase, that is, when the number of iterations is less than one-third of the maximum number of iterations, the calculation formula is as follows:

$$\begin{cases} S_i = R_B \otimes (Elite_i - R_B \otimes \Pr ey_i) \\ \Pr ey_i = \Pr ey_i + P \cdot R \otimes S_i \end{cases} \tag{19}$$

where: R_B is a vector composed of random numbers generated by Brownian random walks; S_i represents the step size of the movement; i takes values in the range of 1 to n; P is a constant, usually taken as $P = 0.5$; R is a vector consisting of random numbers uniformly distributed between [0,1]. R_B is equivalent to a generalized Gaussian distribution, where the R_{Bi} is calculated as follows:

$$R_{Bi} = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \tag{20}$$

Equal velocity ratio phase, that is, when the number of iterations is greater than one-third of the maximum number of iterations but less than two-thirds of it, the population is divided into two parts for operation at this stage, one for local optimization and the other for global search.

The local optimization search formula is as follows:

$$\begin{cases} S_i = R_L \otimes (Elite_i - R_L \otimes \Pr ey_i) \\ \Pr ey_i = \Pr ey_i + P \cdot R \otimes S_i \end{cases} \tag{21}$$

where: R_L is a vector of random numbers consisting of Levy distributions; i takes values in the range 1to n/2. Each element R_{Li} in R_L is calculated as follows:

$$R_{Li} = C \times \frac{x}{y^{1/a}} \tag{22}$$

where: C and a are constants, usually taken as $C = 0.05$, $a = 1.5$; $x = \text{Normal}(0, \sigma 2\ x)$, $\text{y} = \text{Normal}(0, \sigma 2\ y)$.

The global search formula is as follows:

$$\begin{cases} S_i = R_B \otimes (R_B \otimes Elite_i - \Pr ey_i) \\ \Pr ey_i = Elite_i + P \cdot CF \otimes S_i \end{cases} \tag{23}$$

where: i takes values in the range n/2 to n; CF is an adaptive parameter with step size S_i. The calculation formula is as follows:

$$CF = \left(1 - \frac{Iter}{Max\_Iter}\right)^{\left(2\frac{Iter}{Max\_Iter}\right)} \tag{24}$$

where: $Iter$ is the number of iterations; Max_Iter is the maximum number of iterations.

Low speed ratio phase, that is, when the number of iterations is greater than two-thirds of the maximum number of iterations, the calculation formula is as follows:

$$\begin{cases} S_i = R_L \otimes (R_L \otimes Elite_i - \Pr ey_i) \\ \Pr ey_i = Elite_i + P \cdot CF \otimes S_i \end{cases} \tag{25}$$

where i takes values in the range of 1 to n.

(3) The vortex formation and *FADs* effect are solved. The operation allows algorithm to jump out of the local optimal solution as much as possible during the iterative process, thus achieving a better accuracy of the search. Its calculation formula is as follows:

$$\Pr ey_i = \begin{cases} \Pr ey_i + CF[x_{\min} + R \otimes (x_{\max} - x_{\min})] \otimes U, \ r \le FADs \\ \Pr ey_i + [FADs(1-r) + r](\Pr ey_{r1} - \Pr ey_{r2}), \ r \ge FADs \end{cases} \tag{26}$$

where: r is a random number; *FADs* are constants that affect the optimization process, usually taken as $FADs = 0.2$; $r1$ and $r2$ are two random subscripts in the *prey* matrix; U is a binary vector consisting of 0 s and 1 s, and each of its elements U_i is defined as follows:

$$U_i = \begin{cases} 0, \ random \le FADs \\ 1, \ random > FADs \end{cases} \tag{27}$$

where *random* is a random number in the range [0,1].

(4) Marine memory. It mainly updates the *Elite* matrix. For each individual $Prey_i$ in the *Prey* matrix, its fitness is calculated. If the fitness equals the fitness of the corresponding position in the *Elite* matrix, the individual in the *Prey* is substituted for individual in the original *Elite* matrix. Then the fitness of the optimal individual in the whole *Elite* matrix is calculated. If it meets the requirements, the algorithm ends, otherwise the iteration continues.

Basic principle of BPNN

BPNN is a common artificial neural network algorithm, whose main idea is to use error back propagation to train the weighting and thresholds of the neural network, so as to achieve the modeling of the relationship between inputs and outputs. BPNN generally consists of 3 neuron layers: input layer, implicit layer and output layer[20]. Its topology structure is shown in Fig. 3. The specific implementation steps are as follows:

(1) Initialize the weighting and thresholds in the network.
(2) Propagate forward to obtain the expectation values of the output and loss function of each layer.
(3) Calculate the error terms of the output unit and the hidden unit according to the loss function.
(4) Update the weighting and thresholds in the neural network.
(5) Repeat steps from (2) to (4) until the loss function is less than a pre-given threshold or the number of iterations is exhausted. At the moment, output the parameters is best parameters.

Construction of emergency rescue capability evaluation model

The evaluation process of emergency rescue capability evaluation model for coal mine water penetration accident by combining improved combination weighting and MPA-BPNN model is shown in Fig. 4. The computational flow of the MPA-BPNN model is shown in Fig. 5, and its specific steps are as follows:

(1) Data pre-processing. The data are divided into training samples and test samples and normalized.
(2) Initialize the population and BPNN structure. The initial position and speed of the population is determined.
(3) Optimize the MPA. The stage selection is carried out according to the principle of MPA algorithm and the current number of iterations, and the predator position is updated.
(4) Solve vortex formation and update prey position according to FADs. The predator location is updated based on prey location.

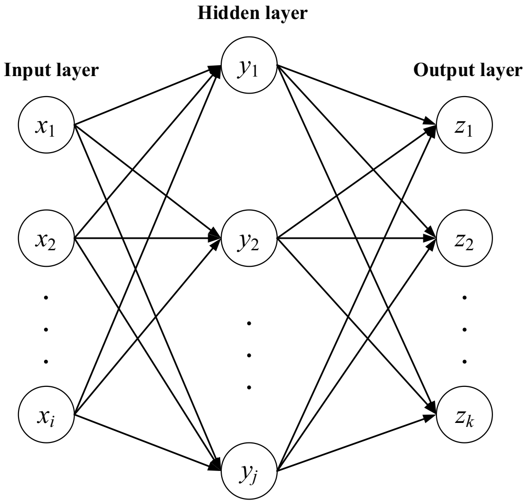

Figure 3. Topology structure of BPNN.

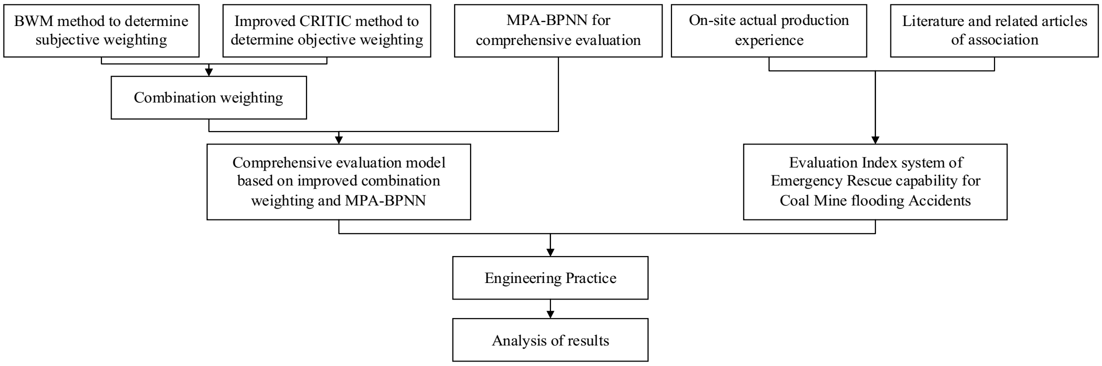

Figure 4. Comprehensive evaluation process based on improved combination weighting and MPA-BPNN model.

(5) Calculate individual fitness values. Judge whether the fitness requirement is met, if it is satisfied, the optimal network weighting and threshold values are output; if not, return to step 3) until the fitness value requirement is met.
(6) Do Training and simulation forecast for BPNN.
(7) Output results.

Engineering practice applications

Taking a coal mine in Shanxi province as an example, 20 experts in mining and safety engineering industry is visited to evaluate the emergency rescue capability of mine water penetration accident by the improved combination weighting and the MPA-BPNN model. The average thickness of the NO. 22 coal seam is 17.27 m; the hydrogeological type is medium; the main source of water is the water accumulation in the goaf; there are 18 water accumulation points in the underground roadway with the estimated water accumulation of 9009.66 m^3, the normal water inflow of 2400 m^3/day, the maximum water inflow of 3600 m^3/day. With the increase of mining depth and the change of geological conditions, the risk of water penetration accident is increasing. In order to ensure the life safety of miners and the stable production of mines, it is urgent to evaluate the emergency rescue ability of water penetration accident.

Determination of each weight

The subjective and objective weighting of the emergency rescue capability evaluation indexes is determined according to the BWM method and the improved CRITIC method respectively. Then its subjective and objective weighting coefficients are calculated as $\alpha = 0.61$, $\beta = 0.39$ by Eqs. (15) and (16) which calculate the combination weighting. The calculation results are shown in Table 2.

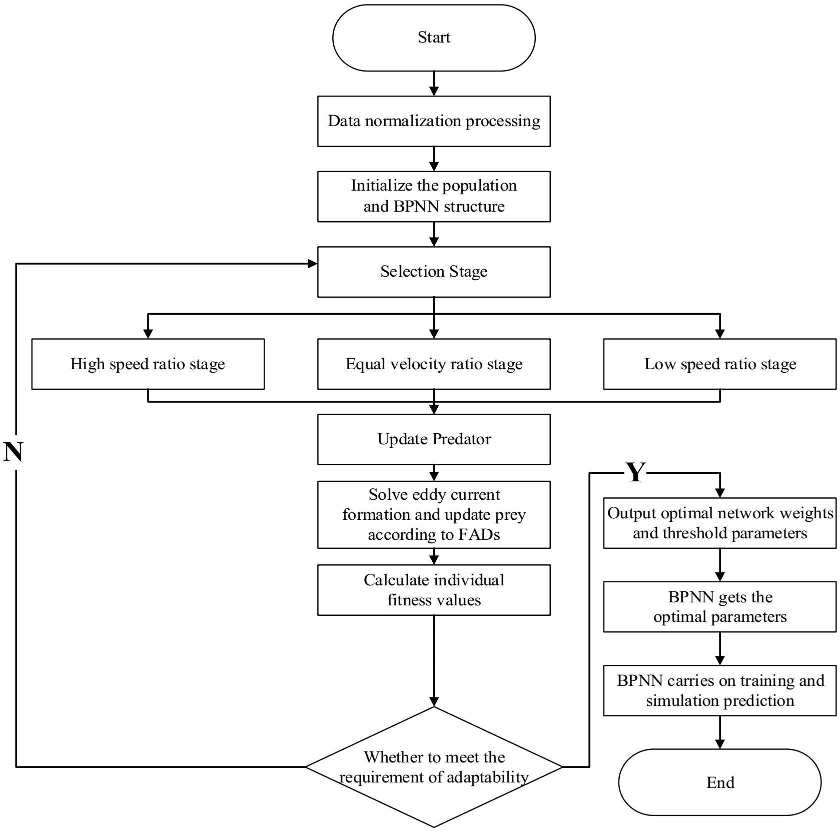

Figure 5. Calculation flow of MPA-BPNN model.

Primary index	Weighting	Secondary index	BWM method weighting	Improved CRITIC method weighting	Combination weighting
U_1	0.17	u_{11}	0.023	0.054	0.035
		u_{12}	0.01	0.07	0.034
		u_{13}	0.045	0.052	0.048
		u_{14}	0.018	0.061	0.035
		u_{15}	0.074	0.08	0.076
U_2	0.253	u_{21}	0.022	0.056	0.035
		u_{22}	0.125	0.053	0.097
		u_{23}	0.035	0.066	0.047
		u_{24}	0.07	0.055	0.064
U_3	0.485	u_{31}	0.13	0.051	0.099
		u_{32}	0.087	0.055	0.075
		u_{33}	0.039	0.054	0.045
		u_{34}	0.23	0.082	0.172
U_4	0.092	u_{41}	0.05	0.089	0.065
		u_{42}	0.027	0.053	0.037
		u_{43}	0.015	0.069	0.036

Table 2. Calculation results of each weighting.

The index weighting radar chart is plotted by Origin software, as shown in Fig. 6. According to Fig. 6, reasonableness of mine drainage and related systems (u_{15}), construction and exercises of emergency rescue team (u_{22}), analysis and handling capacity of water penetration accident (u_{31}), the command capability of emergency rescue (u_{32}) and emergency rescue command structure response capability (u_{34}) has a great influence on the emergency rescue capability of coal mine water penetration accident. In addition, the degree of impact on emergency rescue capability shows $u_{34} > u_{31} > u_{22} > u_{15} > u_{32}$. Therefore, more attention should be paid to these

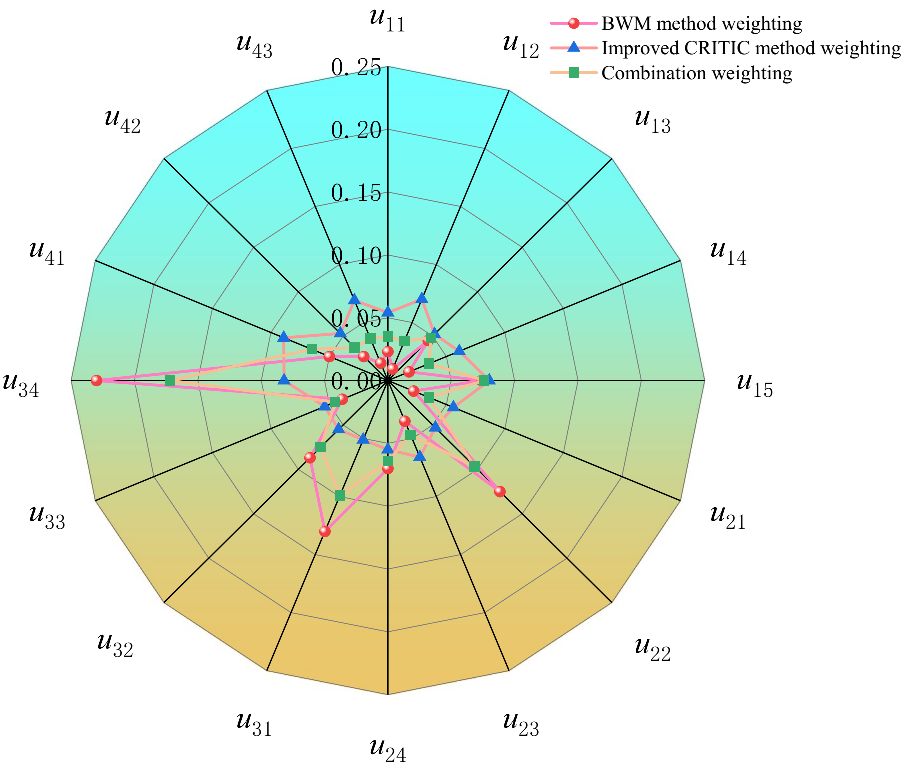

Figure 6. Radar chart of index weighting.

aspects in daily production and emergency rescue of water penetration accident. In addition, the combination weighting obtained by the BWM method and the modified CRITIC method is more distributed by comparing and analyzing the weighting of various indicators, indicating that the combination weighting method can balance the influence of subjectivity and objectivity on the weighting of various indicators.

Evaluation results and comparative analysis

The MPA-BPNN model is used to evaluate the emergency rescue capability of coal mine water penetration accident. By consulting literature and analyzing the evaluation cases of accident emergency rescue capability, the evaluation level of emergency rescue capability for coal mine water penetration accident is divided into five levels[21,22], that is, excellent, well, general, discrepancy and worst. The specific level scales are shown in Table 3.

The expert scoring results is normalized as the sample input data for the MPA-BPNN model and divided into training and test samples in the ratio of 7:3, as shown in Table 4. The expected value in the sample data is the result of normalizing of multiplying the expert scores with the combined weight values of each evaluation index.

The prediction results of the BPNN model, the GA-BPNN model and the PSO-BPNN model are introduced to compare with that of the MPA-BPNN model. The number of populations and iterations in models are uniformly set to 30 and 100. The number of hidden layer nodes in BPNN is determined according to the empirical formula $N = \mathrm{sqrt}(N_1 + N_0) + L$[23], where N is the number of hidden layer nodes; N_1 is the number of input layer nodes; N_0 is the number of output layer nodes; and L is an integer between 1 and 10. The number of training sessions is 1000; learning efficiency is 0.01; and learning error is 1×10^{-6}. The test sample results are shown in Table 5. The comparison between the predicted results of each model and the actual expected values is shown in Fig. 7. The comparison chart of the average relative error of the predicted results of each model is shown in Fig. 8.

Evaluation grade	Grade scale
Excellent	(0.9,1]
Well	(0.8,0.9]
General	(0.7,0.8]
Discrepancy	(0.6,0.7]
Worst	(0,0.6]

Table 3. Evaluation grade of emergency rescue capability for water penetration accident in coal mine.

u_{11}	u_{12}	…	u_{21}	u_{22}	…	u_{31}	u_{32}	…	u_{41}	u_{42}	…	Expected value	Grade
0.976	0.761	…	0.707	0.774	…	0.945	0.962	…	0.658	0.927	…	0.921	Excellent
0.524	0.935	…	0.810	0.887	…	0.800	0.887	…	0.684	0.927	…	0.807	Well
0.333	0.804	…	0.500	0.358	…	0.655	0.642	…	0.526	0.582	…	0.516	Worst
0.405	0.326	…	0.707	0.585	…	0.982	0.736	…	0.289	0.545	…	0.759	General
0.738	0.761	…	0.828	0.811	…	0.655	0.736	…	0.447	0.709	…	0.741	General
0.905	0.609	…	0.707	0.792	…	0.727	0.962	…	1.000	0.964	…	0.811	Well
0.786	0.370	…	0.862	0.868	…	0.527	0.472	…	0.447	0.327	…	0.689	Discrepancy
0.619	0.913	…	0.776	0.623	…	0.673	0.774	…	0.237	0.455	…	0.664	Discrepancy
0.714	0.696	…	0.586	0.698	…	0.655	0.604	…	0.842	0.818	…	0.731	General
0.667	0.717	…	0.638	0.660	…	0.964	0.906	…	0.579	0.836	…	0.926	Excellent
0.810	0.587	…	0.517	0.547	…	0.800	0.509	…	0.500	0.436	…	0.755	General
0.548	0.457	…	0.362	0.566	…	0.745	0.623	…	0.868	0.800	…	0.583	Worst
0.929	0.630	…	0.603	0.604	…	0.945	0.943	…	0.474	0.873	…	0.892	Well
0.810	0.783	…	0.483	0.755	…	0.618	0.830	…	0.579	0.818	…	0.781	General
0.810	0.587	…	0.724	0.830	…	0.545	0.547	…	0.763	0.473	…	0.717	General
0.714	0.435	…	0.569	0.774	…	0.782	0.528	…	0.763	0.691	…	0.787	General
0.952	0.565	…	0.828	0.604	…	0.873	0.962	…	0.447	0.618	…	0.825	Well
0.714	0.565	…	0.931	0.849	…	0.600	0.415	…	0.605	0.745	…	0.749	General
0.571	0.870	…	0.879	0.811	…	0.600	0.660	…	0.868	0.545	…	0.670	Discrepancy
0.524	0.348	…	0.690	0.604	…	0.855	0.585	…	0.658	0.782	…	0.773	General

Table 4. Sample data.

		BPNN		GA-BPNN		PSO-BPNN		MPA-BPNN	
Actual expected value	Actual grade	Value	Grade	Value	Grade	Value	Grade	Value	Grade
0.717	General	0.637	Discrepancy	0.614	Discrepancy	0.613	Discrepancy	0.782	General
0.787	General	0.643	Discrepancy	0.646	Discrepancy	0.671	Discrepancy	0.711	General
0.825	Well	0.881	Well	0.888	Well	0.876	Well	0.867	Well
0.749	General	0.554	Worst	0.817	Well	0.798	General	0.782	General
0.670	Discrepancy	0.694	Discrepancy	0.630	Discrepancy	0.623	Discrepancy	0.688	Discrepancy
0.773	General	0.842	Well	0.719	General	0.711	General	0.812	Well

Table 5. Test sample results of each model.

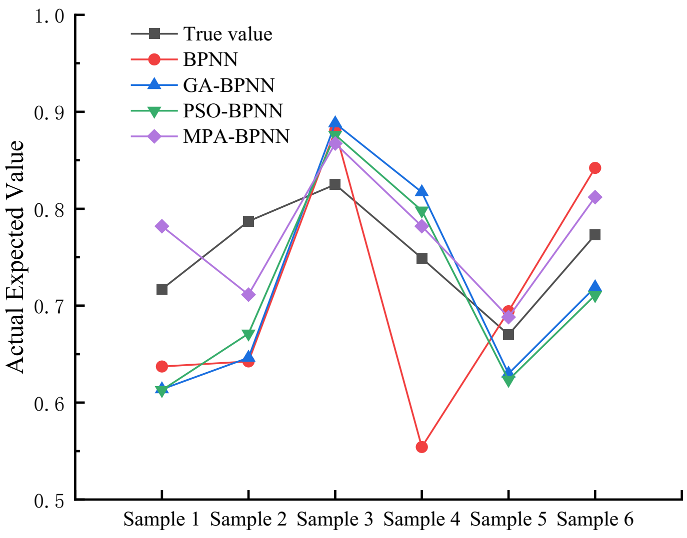

Figure 7. Comparison between predicted results of various models and actual expected values.

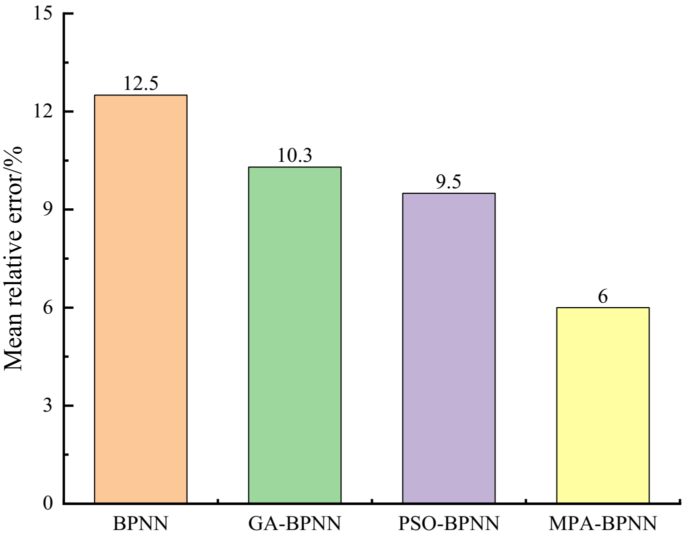

Figure 8. Comparison of average relative errors of various prediction models.

From Fig. 7, the predicted values of the MPA-BPNN model are closest to the true values compared with the other models. According to Table 5 and Fig. 8, there are only two sample evaluation levels that are accurately predicted in the BPNN model, with an average relative error of 12.5%. There are three sample levels of GA-BPNN model that are predicted accurately with the average relative error of 10.3%. There are four sample levels of PSO-BPNN model that are predicted accurately with the average relative error of 9.5%. The MPA-BPNN model has 5 predicted sample levels that are consistent with the actual level with the average relative error of 6%. Compared with that of the BPNN model, the GA-BPNN model and the PSO-BPNN model, the average absolute error values of the MPA-BPNN model decreased by 6.5%, 4.3% and 3.5% respectively. In summary, the MPA-BPNN model is more suitable for evaluating the emergency rescue capability of coal mine water penetration accident.

Measures of improving emergency rescue capacity

According to the opinions of 20 experts and combined weight value in Table 2, it can be seen as follows: The response capability of the emergency rescue command organization (u_{34}) is the most important for the emergency rescue of the mine sudden water penetration accident, but the actual evaluation of the experts on the mine is more poor. Emergency rescue equipment and material support (u_{23}) and water emergency rescue plan (u_{24}) are more important in the emergency rescue process, but the actual evaluation of experts on the mine is very poor. Hydrogeological condition detection (u_{13}) is important in the process of prevention and rehabilitation, but the actual evaluation of the mine by experts is relatively poor. The rescue quality (u_{33}) of the rescue team is relatively important in the emergency rescue response and actual rescue process, but the experts' evaluation on the quality of the mine rescue team is more poor. Therefore, in order to improve the mine's emergency rescue ability in response to water penetration accidents and reduce its impact on miners' life safety and social order, the following measures are proposed as follows:

(1) Improve the emergency plan. Feasible emergency plans in detail is formulated in view of characteristics and possible situations of coal mine water penetration accidents, ensure that the rescue work can be carried out orderly and efficiently when the accident occurs.
(2) Increase equipment investment. Ensure that rescue equipment is advanced and applicable with good performance which provides a strong guarantee for the rescue work. At the same time, the equipment is regularly maintained and checked to ensure that the equipment can be used normally at critical moments.
(3) Strengthen the construction of rescue teams. The organizational construction of rescue teams is strengthened to improve the cohesion, execution and fighting capacity of the team. The ideological and political work of rescue teams is put emphasis to establish a sense of responsibility and mission of rescue workers. At the same time, emergency command personnel should strengthen training to improve their professional quality, leadership and communication and coordination ability, which can ensure that the command personnel can quickly make decisions and effectively command rescue in the occurrence of accidents.
(4) Strengthen geological environment monitoring. Complete hydrogeological database is established, while professional teams regularly investigate the hydrogeological conditions around the coal mine. When it is necessary, monitoring facilities are deployed in coal mine and surrounding areas, such as groundwater level, rainfall, to achieve real-time monitoring hydrogeological conditions and timely grasping abnormal changes.

Conclusions

(1) The BWM method and the improved CRITIC method is used to assign subjective and objective weighting respectively. Lagrange function and euclidean distance function are introduced to combine subjective and objective weighting, obtaining more reasonable combination weighting. In this way, the influence of subjectivity and objectivity on the weight of each indicator is effectively reduced.

(2) According to the combined weight calculation results, reasonableness of mine drainage and related systems (u_{15}), emergency rescue team building and exercises (u_{22}), analysis and handling capacity of water penetration accident (u_{31}), emergency rescue command capability (u_{32}), emergency rescue command organization response capability (u_{34}) has a great influence on the emergency rescue capability of coal mine water penetration accident, and the degree of impact on emergency rescue capability shows $u_{34} > u_{31} > u_{22} > u_{15} > u_{32}$.

(3) Compared the prediction results with the true expectation values of MPA-BPNN model, BPNN model, GA-BPNN model, and PSO-BPNN model, mean absolute errors of MPA-BPNN model decreased by 6.5%, 4.3%, and 3.5% respectively than the other models. It indicates that the evaluation results of MPA-BPNN model are more accurate and effective, and have good prospects for engineering applications.

(4) In view of the shortcomings in the evaluation of the mine's emergency rescue capability, four measures are put forward, including improving the emergency plan, increasing the input of equipment, strengthening the construction of rescue team and strengthening the geological environment monitoring, to improve its emergency rescue capability for the mine water inrush incident, which reduces the accident loss and ensure the safety of the country and people's lives and property.

Data availability

All data generated or analysed during this study are included in this published article and its Supplementary information files.

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Author contributions

Wei WANG was mainly responsible for the writing and conception of the paper. Xinchao CUI was mainly responsible for establishing models and calculations of the paper. Yun QI was responsible for checking the rationality of the content of the paper. Kailong XUE was mainly responsible for organizing data and analyzing results of the paper. Jiao LIU was mainly responsible for data sorting and chart making. All authors reviewed the manuscript. Chen ZUO was mainly responsible for organizing data and analyzing results of the paper. All authors reviewed the manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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