

# Assessment of Water Inrush Risk Using the Fuzzy Delphi Analytic Hierarchy Process and Grey Relational Analysis in the Liangzhuang Coal Mine, China

Mei Qiu<sup>1,2</sup> · Longqing Shi<sup>1,2</sup> · Chao Teng<sup>1</sup> · Yan Zhou<sup>3</sup>

Received: 24 June 2015 / Accepted: 5 February 2016 / Published online: 16 February 2016  
© Springer-Verlag Berlin Heidelberg 2016

**Abstract** The exploitation of deep coal seams in North China's coalfields is seriously threatened by water inrush. Water inrush is controlled by multiple factors and its processes are often not amenable to mathematical expression. To predict and prevent water inrush from the underlying Ordovician aquifer during mining of the No. 13 coal seam in the Liangzhuang coal mine, we used an innovative combination of methods to assess the risk of water inrush based on the fuzzy Delphi analytic hierarchy process (FDAHP) and grey relational analysis (GRA). Expert opinions and GRA were applied to obtain the relative importance of each of the major controlling factors, and the total weights of all factors were assigned using FDAHP. This allowed us to develop a risk index map in which the

study area was divided into two zones and four subzones based on the risk index.

**Keywords** FDAHP · GRA · Risk index · Expert opinion

## Introduction

Eastern China is a major coal-producing area in which Permo-Carboniferous coal seams are extracted from underground. Mine water inrush events sometimes occur because of the complicated hydrogeological conditions there, resulting in considerable economic losses, and even loss of life in some cases (Shi and Han 2004). Water inrush through the coal seam floor accounts for many of the mine water inrush events. With the increased depth and intensity of mining, hydrogeological conditions are becoming more complicated, increasingly threatening safe production above confined aquifers. Hence, water inrush from a confined aquifer beneath the coal seam has been given careful consideration during recent decades and several methods have been developed to assess risk.

The water inrush coefficient method has been widely used to assess the safety of mining and played an active role in assessing the risk of water inrush from underlying aquifers in high water pressure zones in China (Liu 2009). The water inrush coefficient formula, in which the water pressure was simply divided by the aquifer thickness, has been modified several times to better reflect actual water inrush conditions. However, the method only considers two factors: the potentiometric pressure of the underlying confined aquifer and the thickness of the aquifer that functions as a water barrier between the coal seam and the underlying aquifer, neglecting other important factors and oversimplifying the water inrush mechanism.

**Electronic supplementary material** The online version of this article (doi:10.1007/s10230-016-0391-7) contains supplementary material, which is available to authorized users.

✉ Longqing Shi  
cattony2002@126.com

Mei Qiu  
skdqiumei@126.com

Chao Teng  
tengchao5566@163.com

Yan Zhou  
13608978580@163.com

<sup>1</sup> College of Earth Science and Engineering,  
Shandong University of Science and Technology,  
Qingdao 266590, China

<sup>2</sup> Shandong Provincial Key Laboratory of Depositional  
Mineralization and Sedimentary Minerals,  
Qingdao 266590, China

<sup>3</sup> College of Information Science and Engineering,  
Shandong University of Science and Technology,  
Qingdao 266590, China

Wu et al. (2007a, b, c) proposed a vulnerability index method based on the multi-source information theory. The method consists of data analysis and processing using an artificial neural network (ANN), weight of evidence, logistic regression, the analytic hierarchy process (AHP), inversion modeling, and training calibration (Wu and Zhou 2008). The method incorporated use of the geographic information system (GIS), more accurately reflecting the differences and relationships between various vulnerability aspects (Wu et al. 2009). Compared to the water inrush coefficient method traditionally used in China, this vulnerability method had many potential advantages in assessment of the probability of water inrush.

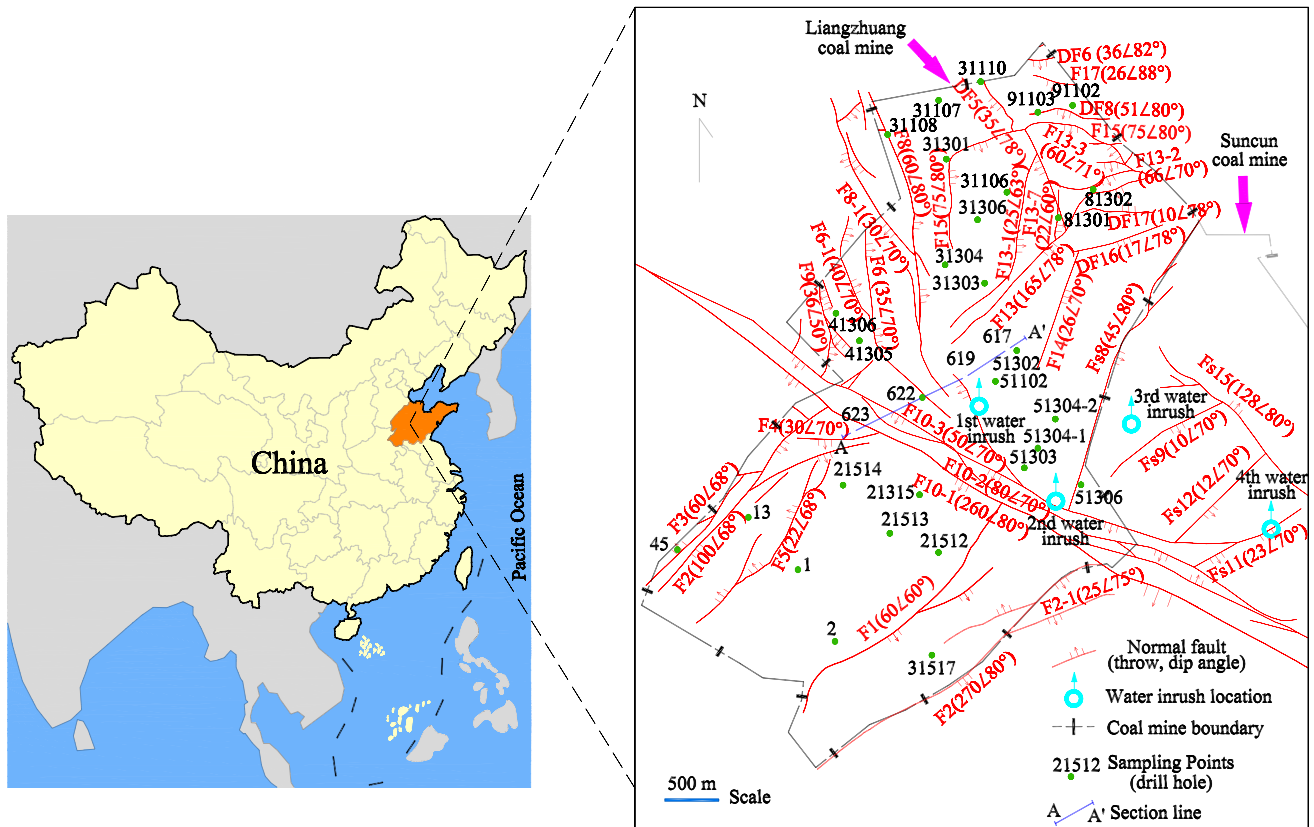
In this study, we aimed at improving the AHP vulnerability index method by using expert opinions and grey relational analysis (GRA) to determine the relative importance of each of the major controlling factors, decreasing the subjectivity of traditional expert analysis. In addition, the total weights of the factors were assigned using the fuzzy Delphi analytic hierarchy process (FDAHP). We considered four water inrush cases in the study area and an adjacent coal mine. Partition thresholds were determined according to the risk index of areas where

safety extraction was achieved and where various degrees of water inrush occurred.

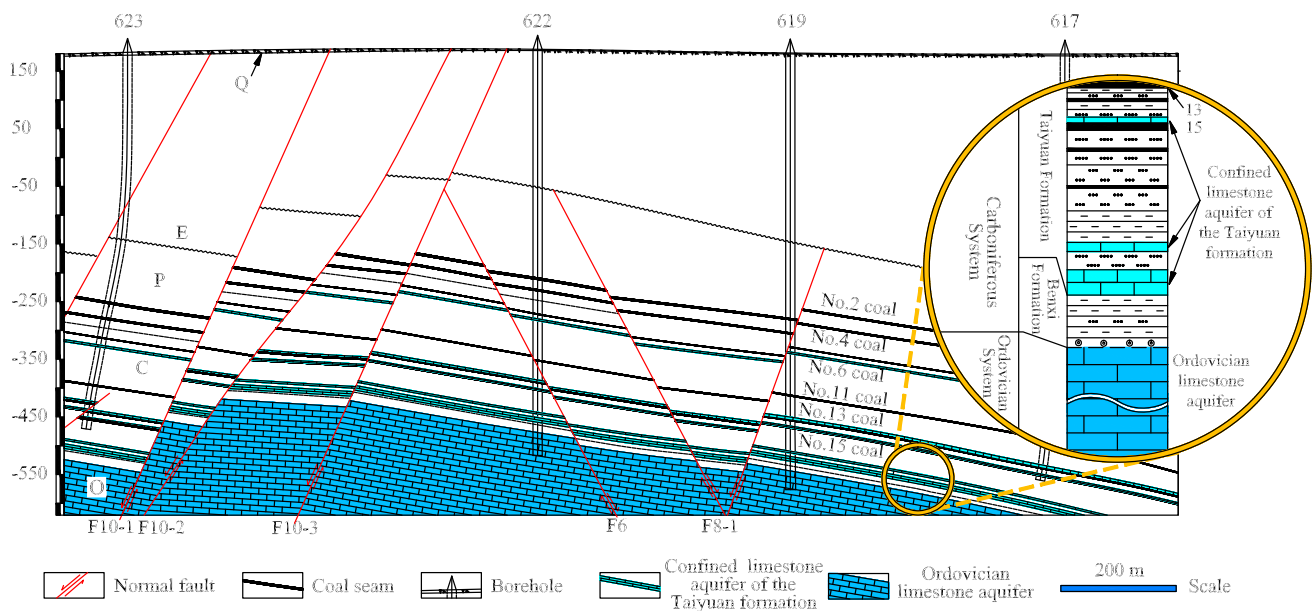
### Study Area

The Liangzhuang coal mine is located in the centre of the Xinwen coal field, about 9 km southwest of Xintai City, Shandong province, in eastern China. The mine is irregularly developed, extending between 35°52′–35°56′N and 117°38′–117°42′E, covering an area of around 14.42 km<sup>2</sup>. The mine is found in a monocline dipping gently NNE, (<25°), with mainly NW, NNW, and NE striking faults that are well developed in this area (Fig. 1).

According to the borehole data, the lithology in the study area consists of Quaternary (Q), Paleogene (E), Jurassic (J), Permian (P), Carboniferous (C), and Ordovician (O) strata from top to bottom. The main coal-bearing strata, the Taiyuan and Shanxi groups of the Permo-Carboniferous system, include six minable seams, i.e. Nos. 2, 4, 6, 11, 13, and 15 (Fig. 2), of which the Nos. 2, 4, 6, and 11 coal seams have been depleted and the No. 13 coal mine is being mined at present.



**Fig. 1** Geographic location of the Liangzhuang coal mine, its fault distribution, and sampling locations



**Fig. 2** Geological profile of A–A’

The target coal seam for the risk assessment of floor water inrush is the No. 13 coal seam. The No. 13 coal seam is minable throughout the field, with a thickness ranging from 0.62 to 2.20 m with an average of 1.40 m. Figure 2 shows the stratigraphy of the No. 13 coal seam floor. The thickness of the strata between the No. 13 coal seam and the Ordovician aquifer ranges from 69.9 to 101.4 m, with an average of 79 m. Between the No. 13 coal seam and the Ordovician aquifer is the Carboniferous Taiyuan–Benxi formation, comprising mudstone, siltstone, fine sandstone, coal, and limestone. The confined limestone aquifer of the Carboniferous Taiyuan formation is a direct water source with a poor yield, which does not pose a serious threat. In contrast, the confined Ordovician aquifer, which is an indirect water source, is the primary threat. The Ordovician aquifer is about 800 m thick. Thirty hydrogeologic boreholes were drilled into the confined Ordovician aquifer; the water inflows of the wells range from 0 to 110 m<sup>3</sup>/h, indicating high water yield and permeability in the tense-shearing fault zone. According to water level measurements, the potentiometric surface of the Ordovician limestone aquifer is from –9.8 to –417.9 m, and the hydraulic pressure exerted over the upper confining bed is between 0.4 and 7.4 MPa. In addition, the strata between the Ordovician aquifer and the No. 13 coal seam, which function as the water barrier, are permeable and weaker in the tense-shearing fault zone. Water inrushes are more likely to occur in weak structure belts (Wu et al. 2009). Two large inrushes from the Ordovician aquifer have occurred in the coal mine. The largest event, in August 2004, occurred at the No. 51302 working face and exceeded 1920 m<sup>3</sup>/h. Another water-inrush event, in July 2000,

reached 772.2 m<sup>3</sup>/h. Two lesser inrush events from the same aquifer have occurred in an adjacent coal mine, where maximum water yield reached 78 and 50 m<sup>3</sup>/h, respectively.

## Determination of Assessment Factors

### Major Controlling Factors

Six factors were used in this study to evaluate the floor water inrush risk by a synthetic analysis of the geological and hydrogeological conditions of the Liangzhuang coal mine: the water yield property and the hydraulic pressure of the Ordovician aquifer, the fault intensity index, the quantity of fault intersections and endpoints, the effective thickness of the aquifuge, and the percentage of brittle rock within the entire water-resisting zone.

#### Water Yield Property of the Ordovician Aquifer

The water yield property refers to the storativity and hydraulic conductivity of the aquifer. The water production from boreholes can be used to measure the water yield property of an aquifer. This index can be obtained by pumping tests.

#### Hydraulic Pressure of the Ordovician Aquifer

Water inrush events through the coal seam floor occur due to pressure on the upper confining bed of the aquifer below. High pressure increases the probability of water bursts and

increased water yield. The hydraulic pressure of the Ordovician aquifer can be determined by observing the groundwater level in wells.

#### *Fault Intensity Index*

The fault intensity index (FII) is calculated by the following equation (Xu et al. 1991):

$$FII = \frac{\sum_{i=1}^n H_i \cdot L_i}{S} \quad (1)$$

where  $H$  is the fault throw and  $L$  is the corresponding strike length;  $S$  is the area of the grid cell; and  $n$  is the number of faults encountered in the grid cell. The larger the fault intensity index, the greater the probability of water bursts. According to the distribution characteristics of the faults in the studied area, a grid was established using 500 m  $\times$  500 m grid units. The fault throw and the corresponding strike length were counted in each grid unit to calculate its fault intensity index.

#### *Quantity of Fault Intersections and Endpoints*

The quantity of fault intersections and endpoints is the total number of the fault intersections and endpoints in each grid unit, reflecting the extent of fracturing of the coal seam and surrounding rock. At the intersections and endpoints of faults where ground stress tends to concentrate, the rock is more crushed and fractures are more developed (Wu et al. 2011). Such areas have a higher risk of water intrusions (Wu and Zhou 2008).

#### *Effective Thickness of the Aquifuge*

The strata between the No. 13 coal seam and the confined Ordovician aquifer were divided into three main zones according to the “Lower Three Zone” theory (Li 1999, Xu et al. 2015): the mine-damaged zone, the entire water-resisting zone, and the natural upward penetration zone (Supplemental Figure 1). The water-resisting zone represents the portion of the floor strata that retains its integrity, which is the effective upper confining bed. The water resistance of the floor strata mainly depends on this zone, until groundwater intrusion cannot be prevented any longer (Xu et al. 2015). The greater the zone’s thickness, the less likelihood there is of water inrush (Wu and Zhou 2008). The effective thickness of the aquifuge is the height of the entire water-resisting zone, calculated using the following equation (Li 1999):

$$h_2 = h - h_1 - h_3 \quad (2)$$

where  $h_2$  is the effective thickness of the aquifuge (m);  $h$  and  $h_3$  are the total thickness of aquifuge (m) and the height

of the natural upward penetration zone (m), respectively, which can be obtained from the data of the hydrogeologic wells;  $h_1$  is the height of the mine-damaged zone (m), which can be calculated by using the following empirical formula (National Bureau of Coal Industry of China 2000):

$$h_1 = 0.0085H + 0.1665\alpha + 0.1079L - 4.3579 \quad (3)$$

where  $h_1$  is the height of the mine-damaged zone (m);  $H$  is the mining depth (m);  $\alpha$  is the dip angle of the No. 13 coal seam ( $^\circ$ );  $L$  is the mining width of the mining face (m).

#### *Percentage of Brittle Rock Within the Entire Water-resisting Zone*

Brittle rock tends to have greater mechanical strength (Meng et al. 2012), so the greater the percentage of brittle rock within the entire water-resisting zone, the less likely is water inrush (Wu and Zhou 2008). The percentage of brittle rock within the entire water-resisting zone of each hydrogeologic wells was calculated by dividing brittle rock thickness by the effective thickness of the aquifuge.

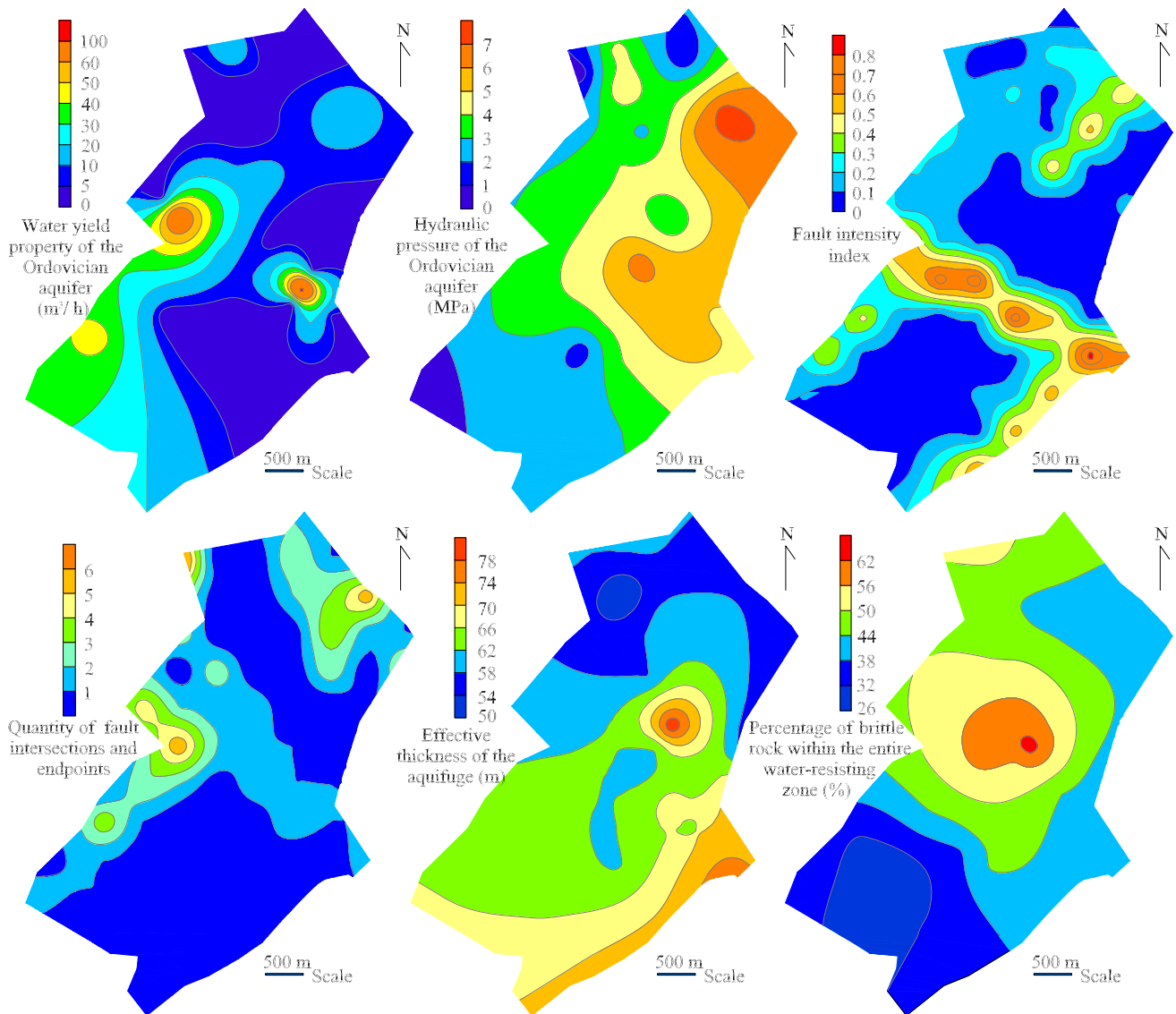
#### **Data Collection**

First, six major controlling factors were calculated, and then six continuous type raster data files were generated by inputting the values of the quantified major controlling factors and geospatial data into Golden Software Surfer 8.0. Finally, six thematic maps were created (Fig. 3), and the six factors were quantified for the 30 hydrogeologic wells (Fig. 1). Data of four water inrush cases were gathered for establishment of major factor comparison matrices and determination of the partition threshold. Supplemental Table 1 shows the results.

#### **Normalization**

Data were normalized after collection because the different dimensions of the major controlling factors would unduly influence the evaluation. During normalization, the potential positive and negative correlations of the controlling factors with the target had to be considered. The more the quantification value of the factor positively correlated with floor water inrush, the more likely it was that water inrush would happen, while the greater the negative correlation with floor water inrush, the less likely a water inrush was. The factors positively and negatively correlated with floor water inrush were normalized by Eq. (4) and (5), respectively (Wu et al. 2011).

$$A_i = \frac{(b - a)(x_i - \min(x_i))}{(\max(x_i) - \min(x_i))} + a, \quad i = 1, 2, \dots, n \quad (4)$$



**Fig. 3** Thematic maps of each of the major controlling factors

$$A_i = \frac{(b - a)(\max(x_i) - x_i)}{(\max(x_i) - \min(x_i))} + a, \quad i = 1, 2, \dots, n \quad (5)$$

where  $A_i$  is the normalized data;  $a$  is the lower and  $b$  is the upper limit of the normalization range (in this paper,  $a = 0.1$  and  $b = 0.9$ );  $x_i$  is the original data before normalization;  $\min(x_i)$  is the minimum of each of the major controlling factor’s original data, and  $\max(x_i)$  is the maximum of each of the same factor’s original data.

In this study, of the six major controlling factors, four were positively correlated with floor water inrush: the water yield property and the hydraulic pressure of the Ordovician aquifer, the fault intensity index, and the quantity of fault intersections and endpoints, which were normalized by Eq. (4). Two factors were negatively correlated with floor water inrush: the effective thickness of

the aquifuge and the percentage of brittle rock within the entire water-resisting zone, as normalized by Eq. (5). Supplemental Table 2 shows the normalized data.

## Methods

### Assessment Steps

Four steps were followed to assess the water inrush risk:

- (a) A hierarchical structure model for assessment of water inrush risk was built by determining assessment factors. Assessment of risk of floor water inrush is the target in our hierarchical structure model, and all major controlling factors

form the decision layer in the hierarchical structure model.

- (b) Expert opinions and GRA were used to obtain the relative importance of each of the major controlling factors, and the total weights of all factors were assigned using FDAHP.
- (c) Following these steps, the risk index of water inrush at each hydrogeologic well location was calculated as (Wu et al. 2013):

$$RI = \sum_{i=1}^n W_i \cdot f_i(x, y) \quad (6)$$

where  $RI$  is the risk index of water inrush;  $W_i$  is the weight of the  $i$ th factor;  $f_i(x, y)$  is the normalized data of the  $i$ th factor at the geographic location  $(x, y)$  of each of the hydrogeologic wells and water inrush cases; and  $n$  is the number of major controlling factors.

- (d) Risk indexes of areas where safe extraction was achieved and various degrees of water inrush occurred are used to determine the partition thresholds. Then, the risk of water inrush through the seam floor can be classified into categories using the thresholds and developing a zoning map of water inrush risk.

### Establishment of Comparison Matrices

The relative importance of the major controlling factors is essential to establish comparison matrices. In the traditional method, relative importance is defined by collecting expert opinions, based on the Saaty (1980) rating scale (Supplemental Table 3). The traditional expert analysis has considerable subjectivity. In addition to the experts' ranking, GRA was used to determine the relative importance of each major factor.

GRA is a system analysis technique and one of the main elements of Deng's gray system theory (Deng 1982, 1989, 2005). It is used to determine the degree of relationship, based on the geometric distance between the reference sequence and the compared sequences (Yin et al. 2010). In addition, it is used to calculate relevancy, which serves as the marker to weight the close relation and mutual comparison. Three steps were followed to determine the degree of close relationship between the factors and the risk of water inrush using GRA:

- (a) Determine the reference and compared sequences. The reference sequence were the volumetric flow rates of the actual water inrush cases (Supplemental Table 1) and the risk was defined by the maximum water yield, according to the Regulations for Mine Water Prevention and Control (Ministry of Coal

Industry 2009); the compared sequences were the major controlling factors of the water inrush cases.

- (b) We calculated the absolute difference for each water inrush case between the compared sequence and the reference sequence, then identified the absolute maximum and minimum difference. The absolute difference was calculated (Yin et al. 2010):

$$\Delta(k) = |y_0(k) - y(k)| \quad (7)$$

where  $\Delta(k)$  is the absolute difference of the  $k$ th water inrush case between compared and reference sequence;  $y_0(k)$  is the reference value of the  $k$ th water inrush case, and  $y(k)$  is the compared sequence value of the  $k$ th water inrush case.

- (c) We calculated the grey relational coefficient (Yin et al. 2010):

$$r(k) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta(k) + \zeta \Delta_{\max}} \quad (8)$$

where  $r(k)$  is the grey relational coefficient of the  $k$ th water inrush case between the compared and reference sequence;  $\Delta_{\min}$  is the absolute minimum difference;  $\Delta_{\max}$  is the absolute maximum difference;  $\zeta \in [0, 1]$  is the identify factor, and the value is 0.5 in this study.

Following the above outlines, each factor's grey relational coefficient was calculated based on each water inrush case using GRA, which indicated the closeness of the relationship between the controlling factors and risk of water inrush. Four expert opinions were collected based on the Saaty rating scale and four water inrush cases were used to calculate the grey relational coefficients between the controlling factors and the water inrush risk (Table 1). The value of these coefficients was multiplied by 9 to align with the Saaty rating scale. Table 1 shows the relative importance of the risk assessment factors, based on the expert opinions and water inrush cases.

$F_1, F_2, \dots, F_n$  represents a set of factors, while  $b_{ij}$  represents a quantified judgment on a pair of factors,  $F_i$  and  $F_j$ , are obtained by dividing  $F_i$  by  $F_j$ . This generates a pairwise comparison matrix  $\mathbf{B}$  (Hoseinie et al. 2009):

$$\mathbf{B} = [b_{ij}] = \begin{bmatrix} 1 & b_{12} & \cdots & b_{1n} \\ 1/b_{12} & 1 & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/b_{1n} & 1/b_{2n} & \cdots & 1 \end{bmatrix} \quad (9)$$

### Establishment of Total Weights

Two steps should be followed to establish the total weight of the major controlling factors, using the fuzzy Delphi method (Reza et al. 2013):

**Table 1** Relative importance of risk assessment factors according to expert opinions and water inrush cases

	1st expert (E1)	2nd expert (E2)	3rd expert (E3)	4th expert (E4)	1st case (E5)	2nd case (E6)	3rd case (E7)	4th case (E8)
Water yield property of the Ordovician aquifer (F1)	8	7	6	7	5	3	9	9
Hydraulic pressure of the Ordovician aquifer (F2)	7	9	3	7	6	9	5	5
Fault intensity index (F3)	9	5	5	8	7	9	9	4
Quantity of fault intersections and endpoints (F4)	6	4	4	6	8	3	9	6
Effective thickness of the aquifuge (F5)	7	7	4	7	9	6	6	9
Percentage of brittle rock within the entire water-resisting zone (F6)	5	6	4	6	9	6	4	6

(a) To establish the fuzzy pair-wise comparison matrix, the triangular fuzzy numbers (TFNs)  $a_{ij}$  were computed (Hayaty et al. 2014):

$$a_{ij} = (\alpha_{ij}, \beta_{ij}, \gamma_{ij}) \tag{10}$$

where  $\alpha_{ij}$  indicates the lower bound and  $\gamma_{ij}$  indicates the upper bound;  $\beta_{ij}$  indicates the geometric mean;  $\alpha_{ij} \leq \beta_{ij} \leq \gamma_{ij}$  are obtained from the following Eqs. (11)–(13):

$$\alpha_{ij} = \text{Min}(b_{ijk}), \quad k = 1, \dots, m \tag{11}$$

$$\beta_{ij} = \left( \prod_{k=1}^m b_{ijk} \right)^{1/m}, \quad k = 1, \dots, m \tag{12}$$

$$\gamma_{ij} = \text{Max}(b_{ijk}), \quad k = 1, \dots, m \tag{13}$$

where  $b_{ijk}$  indicates the relative intensity of importance between parameters  $i$  and  $j$  of expert  $k$ ; and  $m$  is the total number of experts and cases. Then a fuzzy positive reciprocal matrix  $A$  was calculated:

$$A = \begin{bmatrix} (1, 1, 1) & (\alpha_{12}, \beta_{12}, \gamma_{12}) & \dots & (\alpha_{1n}, \beta_{1n}, \gamma_{1n}) \\ (1/\gamma_{12}, 1/\beta_{12}, 1/\alpha_{12}) & (1, 1, 1) & \dots & (\alpha_{2n}, \beta_{2n}, \gamma_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (1/\gamma_{1n}, 1/\beta_{1n}, 1/\alpha_{1n}) & (1/\gamma_{2n}, 1/\beta_{2n}, 1/\alpha_{2n}) & \dots & (1, 1, 1) \end{bmatrix} \tag{14}$$

(b) Calculate the total weights of the major controlling factors. First, the relative fuzzy weights of the factors were calculated (Rezaei et al. 2015):

$$r_i = (a_{i1} \otimes a_{i2} \otimes \dots \otimes a_{in})^{1/n} \tag{15}$$

$$w_i = r_i \otimes (r_1 \oplus r_2 \oplus \dots \oplus r_n)^{-1} \tag{16}$$

where  $\otimes$  denotes the multiplication of fuzzy numbers and  $\oplus$  denotes the addition of fuzzy numbers;  $i = 1, \dots, n$ ;  $n$  indicates the number of factors.  $w_i$  is

the row vector that consists of a fuzzy weight of the  $i$ th factor  $w_i = (w_i^L, w_i^M, w_i^U)$ . To calculate Eqs. (15) and (16), the following algorithms were used (Chatterjee et al. 2015):

$$a \otimes b = (a_1 \times b_1, a_2 \times b_2, a_3 \times b_3) \tag{17}$$

$$a \oplus b = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \tag{18}$$

$$(b)^{-1} = (1/b_3, 1/b_2, 1/b_1) \tag{19}$$

where  $a = [a_1, a_2, a_3]$  and  $b = [b_1, b_2, b_3]$  are two triangular fuzzy numbers.

Defuzzification (changing the fuzzy number to a real number) followed, based on the geometric average method (Kaufmann and Gupta 1988):

$$w'_i = (w_i^L \cdot w_i^M \cdot w_i^U)^{1/3} \tag{20}$$

Finally, the total weight of the major controlling factors was normalized (Yuen 2012):

$$W_i = \frac{w'_i}{\sum_i w'_i} \tag{21}$$

where  $W_i$  is the total weight of the  $i$ th factor, which was normalized, and  $w'_i$  is the real number of the  $i$ th factor.

### Determination of Partition Thresholds

The data for areas where safe extraction was achieved and where water inrush occurred were used to determine the

partition threshold (PT), which divide the risk of floor water inrush into distinct zones by:

$$PT_{sf-s} = (\max(RI_{sf}) \cdot \min(RI_s))^{1/2} \tag{22}$$

where  $RI_{sf}$  indicates the risk index of water inrush in the region where safe extraction was achieved, and  $RI_s$  indicates the risk index of water inrush in the region where small-scale water inrush occurred;  $PT_{sf-s}$  is the partition threshold by which the safe areas and areas where water inrushes are prone to occur can be separated. Thus, risks of water inrush through the coal seam floor were classified as: Zone I:  $RI < PT_{sf-s}$ , safe areas; and Zone II:  $RI \geq PT_{sf-s}$ , more dangerous areas.

The dangerous area (Zone II) was then further divided into four categories according to the magnitude of water inrush. The magnitude of water inrush was divided into four categories by the maximum water yield ( $Q$ ). According to the Regulations for Mine Water Prevention and Control in China: the first class is a small-scale water inrush with  $Q \leq 60 \text{ m}^3/\text{h}$ ; the second is a medium-scale water inrush with  $60 < Q \leq 600 \text{ m}^3/\text{h}$ ; the third is a large-scale water inrush with  $600 < Q \leq 1800 \text{ m}^3/\text{h}$ ; and the fourth class is an extra-large-scale water inrush with  $Q > 1800 \text{ m}^3/\text{h}$ . The partition thresholds were calculated as:

$$PT_{s-m} = (\max(RI_s) \cdot \min(RI_m))^{1/2} \tag{23}$$

$$PT_{m-l} = (\max(RI_m) \cdot \min(RI_l))^{1/2} \tag{24}$$

$$PT_{l-o} = (\max(RI_l) \cdot \min(RI_o))^{1/2} \tag{25}$$

In these equations,  $RI_s$  indicates the risk index of water inrush where a small-scale water inrush occurred;  $RI_m$  indicates the risk index where a medium-scale water inrush occurred;  $RI_l$  indicates the risk index where a large-scale water inrush occurred;  $RI_o$  indicates the risk index where an extra-large-scale water inrush occurred;  $PT_{s-m}$  is a partition threshold by which the small- and medium-scale water inrush areas can be separated;  $PT_{m-l}$  is a threshold between the medium- and large-scale water inrush areas; and  $PT_{l-o}$  is a threshold that separate large-scale and extra-large-scale water inrush areas. Thus, Zone II can be classified into four subzones:

- Zone II-1:  $PT_{sf-s} \leq RI < PT_{s-m}$ , the small-scale water inrush area;
- Zone II-2:  $PT_{s-m} \leq RI < PT_{m-l}$ , the medium-scale water inrush area;
- Zone II-3:  $PT_{m-l} \leq RI < PT_{l-o}$ , large-scale water inrush area;
- Zone II-4:  $RI \geq PT_{l-o}$ , the extra-large-scale water inrush area.

### Results and discussion

A comparison matrix of factors based on the data in Table 1 is required to establish the fuzzy pair-wise comparison matrix by using the FDAHP method. Since there were 6 factors and 8 experts (4 subjective experts and 4 water inrush cases), eight  $6 \times 6$  pair-wise comparison matrixes (Supplemental Tables 4–11) were established for the following calculations. In this research, a fuzzy pair-wise comparison matrix was established (Table 2) as described above and the total weights (Table 3) were determined. Based on these calculations, the importance ranking of factors' influence on water inrush is:  $F5 > F3 > F2 > F1 > F6 > F4$ . The result shows that the fault intensity index and the effective thickness of the aquifuge are the most crucial factors, and the quantity of fault intersections and endpoints and the percentage of brittle rock within the entire water-resisting zone have relatively little effect on floor water inrush.

**Table 3** Total weights of factors resulted from FDAHP

Major controlling factors	Total weight
Water yield property of the Ordovician aquifer (F1)	0.161
Hydraulic pressure of the Ordovician aquifer (F2)	0.172
Fault intensity index (F3)	0.181
Quantity of fault intersections and endpoints (F4)	0.147
Effective thickness of the aquifuge (F5)	0.187
Percentage of brittle rock within the entire water-resisting zone (F6)	0.152

**Table 2** Fuzzy pair-wise comparison matrix

B	F1	F2	F3	F4	F5	F6
F1	(1.00, 1.00, 1.00)	(0.33, 1.06, 2.00)	(0.33, 0.96, 2.25)	(0.63, 1.18, 1.75)	(0.50, 0.96, 1.50)	(0.50, 1.15, 2.25)
F2	(0.50, 0.95, 3.00)	(1.00, 1.00, 1.00)	(0.56, 0.90, 1.80)	(0.56, 1.12, 3.00)	(0.56, 0.91, 1.50)	(0.67, 1.09, 1.50)
F3	(0.44, 1.04, 3.00)	(0.56, 1.11, 1.80)	(1.00, 1.00, 1.00)	(0.67, 1.24, 3.00)	(0.44, 1.00, 1.50)	(0.67, 1.20, 2.25)
F4	(0.57, 0.85, 1.60)	(0.33, 0.89, 1.80)	(0.33, 0.81, 1.50)	(1.00, 1.00, 1.00)	(0.50, 0.81, 1.50)	(0.50, 0.97, 2.25)
F5	(0.67, 1.05, 2.00)	(0.67, 1.11, 1.80)	(0.67, 1.00, 2.25)	(0.67, 1.24, 2.00)	(1.00, 1.00, 1.00)	(1.00, 1.20, 1.50)
F6	(0.44, 0.87, 2.00)	(0.67, 0.92, 1.50)	(0.44, 0.83, 1.50)	(0.44, 1.03, 2.00)	(0.67, 0.83, 1.00)	(1.00, 1.00, 1.00)



Equation 6 was used to build the risk index model for the No. 13 coal seam in the Liangzhuang coal mine as follows:

$$RI = \sum_{i=1}^6 W_i \cdot f_i(x, y) = 0.161f_1(x, y) + 0.172f_2(x, y) + 0.181f_3(x, y) + 0.147f_4(x, y) + 0.187f_5(x, y) + 0.152f_6(x, y) \tag{26}$$

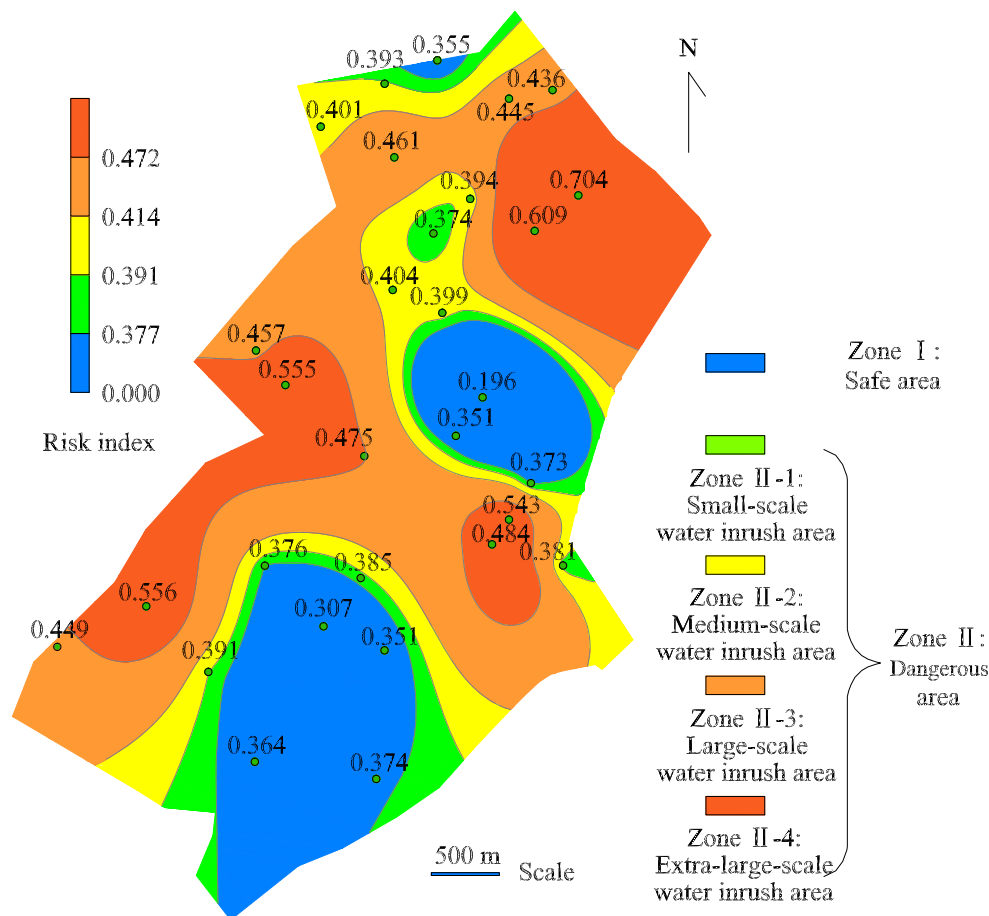
Then, the risk index of water inrush at each location of the hydrogeologic wells and the water inrush cases was calculated (Table 4).

Accordingly, the partition thresholds (PT) were calculated based on Table 4 as:  $PT_{sf-s} = 0.377$ ,  $PT_{s-m} = 0.391$ ,  $PT_{m-l} = 0.414$ , and  $PT_{l-o} = 0.472$ . Risks of water inrush from the aquifer through the seam floor were classified by these thresholds into two zones and four subzones (Fig. 4):

- Zone I:  $RI < 0.377$ , the safe area;
- Zone II:  $RI \geq 0.377$ , the dangerous area;
  - Zone II-1:  $0.377 \leq RI < 0.391$  the small-scale water inrush area;
  - Zone II-2:  $0.391 \leq RI < 0.414$ , the medium-scale water inrush area;

**Table 4** Risk index of water inrush at each location of the hydrogeologic wells and the water inrush cases

Hydrogeologic well or water inrush case	Risk index of water inrush	Notes
No. 31110	0.355	The No. 13 coal seam has not been mined
No. 31107	0.393	The No. 13 coal seam has not been mined
No. 91103	0.445	The No. 13 coal seam has not been mined
No. 91102	0.436	The No. 13 coal seam has not been mined
No. 31108	0.401	The No. 13 coal seam has not been mined
No. 31301	0.461	The No. 13 coal seam has not been mined
No. 31106	0.394	The No. 13 coal seam has not been mined
No. 81302	0.704	The No. 13 coal seam has not been mined
No. 31306	0.374	The No. 13 coal seam has not been mined
No. 81301	0.609	The No. 13 coal seam has not been mined
No. 31304	0.404	The No. 13 coal seam has not been mined
No. 31303	0.399	The No. 13 coal seam has not been mined
No. 41306	0.457	The No. 13 coal seam has not been mined
No. 41305	0.555	The No. 13 coal seam has not been mined
No. 51302	0.196	The No. 13 coal seam has not been mined
No. 51102	0.351	The No. 13 coal seam has not been mined
No. 622	0.475	The No. 13 coal seam has not been mined
No. 51304-2	0.373	The No. 13 coal seam has not been mined
No. 51304-1	0.543	The No. 13 coal seam has not been mined
No. 51303	0.484	The No. 13 coal seam has not been mined
No. 51306	0.381	The No. 13 coal seam has not been mined
No. 21514	0.376	Safe extraction was achieved
No. 21315	0.385	The No. 13 coal seam has not been mined
No. 21513	0.307	Safe extraction was achieved
No. 21512	0.351	Safe extraction was achieved
No. 13	0.556	The No. 13 coal seam has not been mined
No. 45	0.449	The No. 13 coal seam has not been mined
No. 1	0.391	The No. 13 coal seam has not been mined
No. 2	0.364	Safe extraction was achieved
No. 31517	0.374	Safe extraction was achieved
1st case	0.426	$Q = 772.2 \text{ m}^3/\text{h}$ , large-scale water inrush
2nd case	0.524	$Q = 1920 \text{ m}^3/\text{h}$ , extra-large-scale water inrush
3rd case	0.403	$Q = 78 \text{ m}^3/\text{h}$ , medium-scale water inrush
4th case	0.379	$Q = 50 \text{ m}^3/\text{h}$ , small-scale water inrush



**Fig. 4** Water inrush risk zones of the No. 13 coal seam

- Zone II-3:  $0.414 \leq RI < 0.472$ , the large-scale water inrush area;
- Zone II-4:  $RI \geq 0.472$ , the extra-large-scale water inrush area.

As shown in Fig. 4, only small parts of the No. 13 coal seam, in the southern and eastern parts of the area, were classified as relatively safe. While water inrushes are unlikely in such areas, this does not mean there is no risk. If water yielding structures (unknown faults or fractures) are exposed by mining, and the water yield of the Ordovician aquifer is high, water inrushes can still occur. Where such structures are present, preventive measures should still be taken. However, dangerous zones occupy most of the area and most of them were found to have a high probability of large-scale or extra-large-scale water inrushes. Appropriate measures should be taken to prevent the occurrence of water inrush during mining of these areas. One must pay attention to the working faces and the Ordovician limestone water level changes at all time, exploring the weak zone of the aquifuge, the local properties of the Ordovician limestone aquifer, and the potential of water-conducting

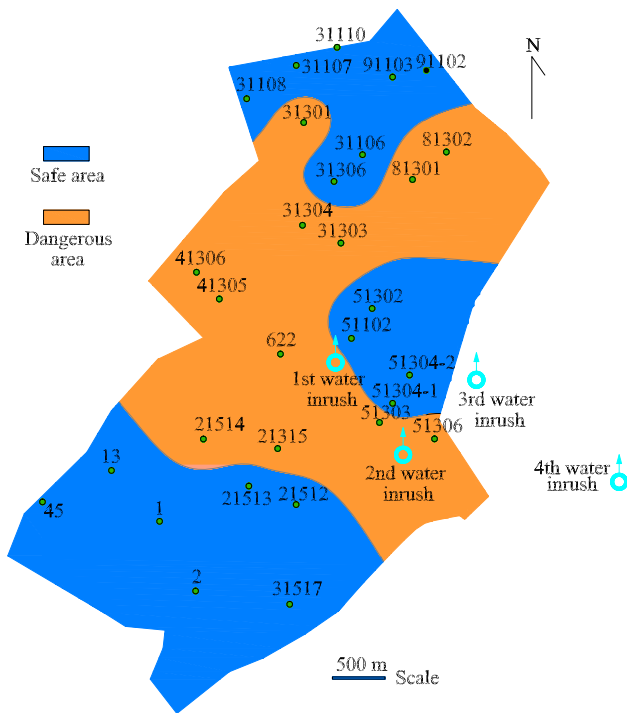
faults by means of geophysical prospecting, drilling, and other means. Grouting to reinforce the aquifuge and reconstruction of the corresponding aquifer should be implemented and, if it is feasible, impermeable barriers should be left as an additional safety measure for sealing the permeable fractures. If conditions permit, the Ordovician limestone aquifer should be depressurized by dewatering to decrease the head of the confined aquifer.

### Comparison of the Risk Index of Water Inrush and Water Inrush Coefficient

The water inrush coefficient, reflecting the bearing pressure of the unit aquifuge thickness, can be calculated as (Ministry of Coal Industry 2009):

$$T = \frac{P}{M} \quad (27)$$

where  $T$  is the water inrush coefficient (MPa/m);  $P$  is the water pressure sustained by the coal seam floor (MPa), and  $M$  is the thickness of the coal seam floor (m). According to



**Fig. 5** Risk zoned by the water inrush coefficient for the No. 13 coal seam

the Regulations for Mine Water Prevention and Control (Ministry of Coal Industry 2009), water inrush will tend not to occur if the water inrush coefficient is less than 0.06 MPa/m in areas with structural weakness, and <0.1 MPa/m in areas without. Otherwise, the areas are considered to be prone to water inrush. The water inrush coefficient at each location of the hydrogeologic wells and water inrush cases was calculated using Eq. (27). Figure 5 shows the risk zoned by the water inrush coefficients for the No. 13 coal seam.

There are obviously large differences between the two evaluations. Compared with our risk index of water inrush assessment (Fig. 4), the water inrush coefficient method neglects several key factors, such as the percentage of brittle rock within the entire water-resisting zone and the geological structures. For example, at the location of the 3rd water inrush case, the water inrush coefficient, which was 0.09 MPa/m, indicates that water inrush should not occur, while in fact, a medium-scale water inrush did occur, presumably, due to a too low percentage of brittle rock within the water-resisting zone. The differences are relatively obvious around faults F5, F3, F2, DF5, F15, and F13 (Fig. 1). The result predicted by our risk index indicates that these areas are most dangerous (Fig. 4), while the water inrush coefficient method suggests that they are safe for mining (Fig. 5). Presumably, this discrepancy is

because the water inrush coefficient method does not consider the complexity of the faults. Rather than simply classifying an area as safe or dangerous, the risk index method further classifies the dangerous areas into 4 sub-zones based on experienced water inrush events. This more detailed classification better reflects the relative degree of water inrush risk, which allows an operator to adopt pertinent countermeasures, especially for the extra-large-scale and large-scale water inrush areas.

In comparison with the traditional water inrush coefficient method, our method for assessing water inrush risk based on GRA and FDAHP shows a better overall analysis of the likelihood of a floor water inrush accident. Our risk index method is more comprehensive and provides more representative guidance for safe mining with respect to risk of water inrush. The quality of the conclusions derived by this method regarding the relative safety of mines will be further improved as more data is added.

### Conclusions

Compared with the traditional water inrush coefficient method, the risk index method can consider more than two factors affecting the probability of water inrush. Water inrush from the confined Ordovician limestone aquifer into the overlying No. 13 coal seam in the Liangzhuang coal mine was found to be affected by six major factors: the water yield property and the hydraulic pressure of the Ordovician aquifer, the fault intensity index, the quantity of fault intersections and endpoints, the effective thickness of the aquifuge, and the percentage of brittle rock within the entire water-resisting zone. GRA and FDAHP were used to determine the total weights of these six factors. The total weights of the water yield property of the Ordovician aquifer, the hydraulic pressure of the Ordovician aquifer, the fault intensity index, the quantity of fault intersections and endpoints, the effective thickness of the aquifuge, and the percentage of brittle rock within the entire water-resisting zone were 0.161, 0.172, 0.181, 0.147, 0.187, and 0.152, respectively. The risk index model allowed subdivision of the coal seam 13 floor area into 2 zones and 4 subzones, providing a more detailed scientific basis for safe production and control of water inrush.

**Acknowledgments** The authors thank the editors and two anonymous reviewers for their careful work and thoughtful suggestions. The authors also thank Dr. Mona Pelkey for her help with this manuscript. We gratefully acknowledge the financial support of the National Natural Science Foundation of China (41572244), the Ministry of Education Research Fund for the doctoral program (20133718110004), the SDUST Research Fund (2012KYTD101), the Taishan Scholars Construction Projects, and the SDUST Graduate Innovation Fund (YC150104).

## References

- Chatterjee S, Singh JB, Roy A (2015) A structure-based software reliability allocation using fuzzy analytic hierarchy process. *Int J Syst Sci* 46(3):513–525. doi:[10.1080/00207721.2013.791001](https://doi.org/10.1080/00207721.2013.791001)
- Deng J (1982) Control problems of grey systems. *Syst Control Lett* 1(5):288–294. doi:[10.1016/S0167-6911\(82\)80025-X](https://doi.org/10.1016/S0167-6911(82)80025-X)
- Deng J (1989) Introduction to grey system theory. *J Grey Syst* 1(1):1–24
- Deng J (2005) The primary methods of grey system theory. Huzhong University of Science and Technology Press, Wuhan (in Chinese)
- Hayati M, Tavakoli Mohammadi MR, Rezaei A, Shayestehfar MR (2014) Risk assessment and the ranking of metals using FDAHP and TOPSIS. *Mine Water Environ* 33:157–164. doi:[10.1007/s10230-014-0263-y](https://doi.org/10.1007/s10230-014-0263-y)
- Hoseinie SH, Ataei M, Osanloo M (2009) A new classification system for evaluating rock penetrability. *Int J Rock Mech Min Sci* 46:1329–1340. doi:[10.1016/j.ijrmms.2009.07.002](https://doi.org/10.1016/j.ijrmms.2009.07.002)
- Kaufmann A, Gupta MM (1988) Fuzzy mathematical models in engineering and management science. Elsevier, Amsterdam
- Li BY (1999) Down three zones in the prediction of the water inrush from coalbed floor aquifer-theory, development and application. *J Shandong I Min Technol (Nat Sci)* 18(4):11–18 (in Chinese)
- Liu Q (2009) A discussion on water inrush coefficient. *Coal Geol Explor* 37(4):34–42. doi:[10.3969/j.issn.1001-1986.2009.04.009](https://doi.org/10.3969/j.issn.1001-1986.2009.04.009) (in Chinese)
- Meng Z, Li G, Xie X (2012) A geological assessment method of floor water inrush risk and its application. *Eng Geol* 143–144:51–60. doi:[10.1016/j.enggeo.2012.06.004](https://doi.org/10.1016/j.enggeo.2012.06.004)
- Ministry of Coal Industry (2009) Regulations for mine water prevention and control. Beijing Publ House of Coal Industry, Beijing (in Chinese)
- National Bureau of Coal Industry of China (2000) Pillar design and mining regulations under buildings, water, rails and major roadways. China Coal Industry Publ House, Beijing (in Chinese)
- Reza M, Yilmaz O, Reza Y, Mohammad A, Seyed MH (2013) Ranking the sawability of ornamental stone using fuzzy Delphi and multi-criteria decision-making techniques. *Int J Rock Mech Min Sci* 58:118–126. doi:[10.1016/j.ijrmms.2012.09.002](https://doi.org/10.1016/j.ijrmms.2012.09.002)
- Rezaei A, Shayestehfar M, Hassani H, Tavakoli Mohammadi MR (2015) Assessment of metals contamination and their grading by SAW method: a case study in Sarcheshmeh copper complex, Kerman, Iran. *Environ Earth Sci* 74(4):3191–3205. doi:[10.1007/s12665-015-4356-0](https://doi.org/10.1007/s12665-015-4356-0)
- Saaty TL (1980) The analytic hierarchy process. McGraw-Hill, NYC
- Shi L, Han J (2004) Floor water-inrush mechanism and prediction. China Univ of Mining and Technology Press, Xu Zhou (in Chinese)
- Wu Q, Zhou W (2008) Prediction of groundwater inrush into coal mines from aquifers underlying the coal seams in China: vulnerability index method and its construction. *Environ Geol* 55(4):245–254. doi:[10.1007/s00254-007-1160-5](https://doi.org/10.1007/s00254-007-1160-5)
- Wu Q, Xie S, Pei Z, Ma J (2007a) A new practical methodology of the coal floor water bursting evaluating III: the application of ANN vulnerable index method based on GIS. *J China Coal Soc* 32(12):1301–1306. doi:[10.13225/j.cnki.jccs.2007.12.017](https://doi.org/10.13225/j.cnki.jccs.2007.12.017) (in Chinese)
- Wu Q, Zhang Z, Ma J (2007b) A new practical methodology of the coal floor water bursting evaluating I: the master controlling index system construction. *J China Coal Soc* 32(1):42–47. doi:[10.13225/j.cnki.jccs.2007.01.009](https://doi.org/10.13225/j.cnki.jccs.2007.01.009) (in Chinese)
- Wu Q, Zhang Z, Zhang S, Ma J (2007c) A new practical methodology of the coal floor water bursting evaluating II: the vulnerable index method. *J China Coal Soc* 32(11):1121–1126. doi:[10.13225/j.cnki.jccs.2007.11.007](https://doi.org/10.13225/j.cnki.jccs.2007.11.007) (in Chinese)
- Wu Q, Wang J, Liu D, Cui F, Liu S (2009) A new practical methodology of the coal floor water bursting evaluating IV: the application of AHP vulnerable index method based on GIS. *J China Coal Soc* 34(2):233–238. doi:[10.13225/j.cnki.jccs.2009.02.025](https://doi.org/10.13225/j.cnki.jccs.2009.02.025) (in Chinese)
- Wu Q, Liu Y, Liu D, Zhou W (2011) Prediction of floor water inrush: the application of GIS-based AHP vulnerable index method to Donghuantuo coal mine, China. *Rock Mech Rock Eng* 44:591–600. doi:[10.1007/s00603-011-0146-5](https://doi.org/10.1007/s00603-011-0146-5)
- Wu Q, Fan S, Zhou W, Liu S (2013) Application of the analytic hierarchy process to assessment of water inrush: a case study for the No. 17 coal seam in the Sanhejian coal mine, China. *Mine Water Environ* 32:229–238. doi:[10.1007/s10230-013-0228-6](https://doi.org/10.1007/s10230-013-0228-6)
- Xu F, Long R, Xia Y, Xie S (1991) Quantitative assessment and prediction of geological structures in coal mine. *J China Coal Soc* 16(4):93–102. doi:[10.13225/j.cnki.jccs.1991.04.012](https://doi.org/10.13225/j.cnki.jccs.1991.04.012) (in Chinese)
- Xu D, Peng S, Xiang S, Liang M (2015) The effects of caving of a coal mine's immediate roof on floor strata failure and water inrush. *Mine Water Environ*. doi:[10.1007/s10230-015-0368-y](https://doi.org/10.1007/s10230-015-0368-y)
- Yin S, Wang X, Wu J, Wang G (2010) Grey correlation analysis on the influential factors the hospital medical expenditure. *Inf Comput Appl Lect Notes Comput Sci* 6377:73–78. doi:[10.1007/978-3-642-16167-4\\_10](https://doi.org/10.1007/978-3-642-16167-4_10)
- Yuen KKF (2012) Membership maximization prioritization methods for fuzzy analytic hierarchy process. *Fuzzy Optim Decis Making* 11(2):113–133. doi:[10.1007/s10700-012-9119-8](https://doi.org/10.1007/s10700-012-9119-8)