

Prediction of groundwater inrush into coal mines from aquifers underlying the coal seams in China: application of vulnerability index method to Zhangcun Coal Mine, China

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Abstract Groundwater inrush is a geohazard that can significantly impact safe operations of the coal mines in China. Its occurrence is controlled by many factors and processes are often not amenable to mathematical expressions. To evaluate the water inrush risk, Professor Wu and his colleagues have proposed the vulnerability index approach by coupling the artificial neural network (ANN) and geographic information system (GIS). The detailed procedures of using this innovative approach are shown in a case study. Firstly, the powerful spatial data analysis functions of GIS was used to establish the thematic layer of each of the main factors that control the water inrush, and then to choose the training sample on the thematic layer with the ANN-BP Arithmetic. Secondly, the ANN evaluation model of the water inrush was established to determine the threshold value for each risk level with a histogram of the water inrush vulnerability index. As a result, the mine area was divided into four regions with different vulnerability levels and they served as the general guidelines for the mine operations.

Keywords Vulnerability index method ·
Water inrush coefficient · Water inrush · GIS · ANN ·
Coal mines · China

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Introduction

Water inrush into coal mines from aquifers underlying coal seams is a geohazard. Forecast on its occurrence is an important aspect in prevention and control of this geohazard. However, the reliability of any prediction has been challenged by the facts that the geological conditions and hydrogeological conditions are different in different mines, even in different areas of the same mine. Furthermore, the water inrush is usually controlled by multiple factors and characterized by non-linear relationships. The most commonly used method in China is to use a water inrush coefficient as a parameter to predict if a water inrush may occur. The water inrush coefficient is defined as a ratio between the piezometric pressure of the underlying aquifer and the thickness of the geologic stratum between the coal seam and the underlying aquifer. Obviously, this method considers two factors only, and they are treated equally. The threshold values of the coefficient are usually estimated from the water inrush data available in each coal field. It has been our experience that the actual water inrushes took place mainly in the weak structure belts. The coefficient method can be too conservative when it is used to predict water inrushes in the un-fractured rock blocks. Often, water inrushes did not occur in areas where the water inrush threshold was exceeded (Zuo et al. 1999; Wu et al. 2001). The reasons for these deviations are that the coefficient method is too simple to describe the nonlinear and multiple factor-controlled processes in the water inrushes. Use of the water inrush coefficient method may have left too much coal un-mined. Recently, Professor Wu and his colleagues (Wu and Zhou 2008) developed an innovative technology, i.e., the vulnerability index method, to predict the water inrushes in coal mines from the aquifers that underlie the coal seams. This approach combines several

methodologies developed in recent years, including geographic information system (GIS), artificial neural network (ANN), and back propagation (BP) model. It can effectively reflect the complex hydrogeologic conceptual model in any coal mine and can be operated and mastered easily by users. Factors that affect the water inrush can be incorporated into the model and the water inrush process can be described nonlinearly (Wu et al. 2007).

Zhangcun Coal Mine, a subsidiary of Xingtai Coal Corporation, lies in Xiandewang and Baita Town of Hebei Province, China. It is on a platform terrain, which is bounded by the hilly country east Taihang Mountains. There is no perennial stream, and only two seasonal creeks flow through this area. Geologically, the study area is characterized by a set of Carboniferous-Permian coal strata, which is typical in North China. The 9th coal seam is a stable layer that can be commercially exploited, while the 2nd, 8th and 10th coal seams are partially exploitable. Structurally, sixfolds and 205 faults have been reported in the course of exploration and production. Of these reported faults, 11 are large and medium-sized faults with their displacements being more than 30 m; 62 are medium and small-sized faults with displacements between 3 and 30 m; 132 small-sized faults with displacements less than 3 m. These faults also include two reversed faults with displacements more than 5 m and two reversed faults with displacements less than 5 m (Fig. 1).

Hydrogeologically, ten aquifers are recognized in the mine. The aquifers that underlie the exploitable 9th coal seam are the Benxi limestone aquifer and Ordovician limestone aquifer. The Ordovician limestone, which unconformably underlies the Benxi formation, is the main aquifer that threatens the safe operations of the mine. The average thickness of the strata between the top of the Ordovician limestone and the bottom of the 9th coal seam is 32 m (Fig. 2).

Vulnerability index method

The vulnerability index method is developed for effective prediction and evaluation of water inrush in mines. It consists of five main components, as summarized below. The detailed description of this technique is given in Wu and Zhou (2008).

- Spatial Analyses of GIS: the vulnerability index method takes advantage of the powerful spatial analysis and processing functions of GIS to quantify the main factors that affect the water inrush by creating the thematic map of each factor.
- ANN model and its calibration: the GIS analyses provide the necessary training and input data for ANN. The trained and calibrated ANN model can be used to

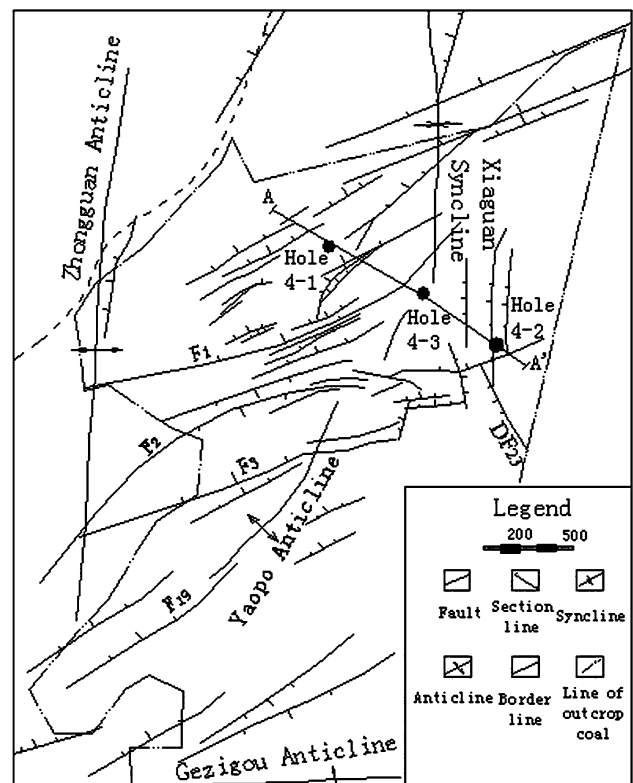


Fig. 1 Diagrammatic sketch of geological structure in the third mine in Zhangcun Coal Mine

describe the complex nonlinear relationships between the main controlling factors and the occurrence of the water inrush.

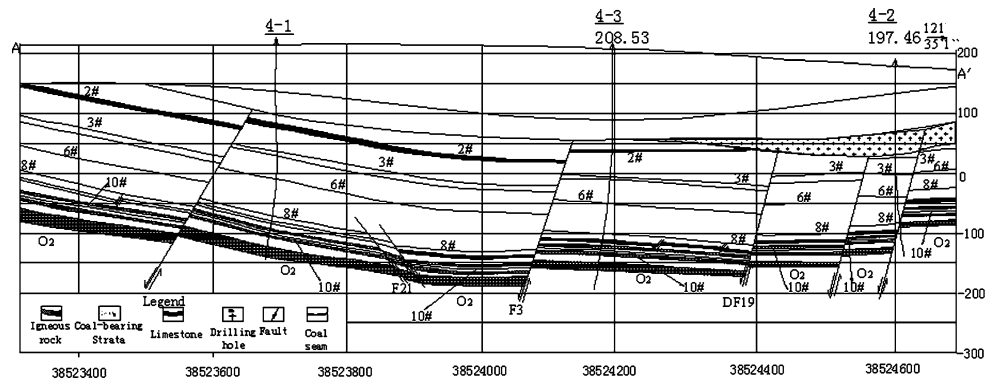
- Spatial superposition of GIS: the spatial composite superposition function of GIS is used to deal with the neural network outputs, and the visualization function of GIS is used to show the results graphically (Wu et al. 2001, 2006).
- Calculation of threshold values: the threshold values of water inrush risk are statistically calculated analysis of the vulnerability index histograms of each unit according to the forecast model.
- Water inrush risk maps: according to the calculated thresholds, the mining area is divided into regions with different risk levels. The sensitivity of the main controlling factors can also be conducted to evaluate the accuracy of the risk maps.

Application of vulnerability index method

Factors affecting water inrush

The water inrush processes from aquifers that underlie the coal seams can be complex. Years' experience working in

Fig. 2 A–A' section plan of geological structure in the third mine in Zhangcun Coal Mine



this and other similar coal mines indicates that the following eight factors affect the water inrush when the 9th coal seam is mined:

- Density of the geologic structures such as folds and faults: of the structure-related water inrushes, the majority are through faults. The density of the structures is calculated by counting the number of faults, pinch points, cross points of faults and folds in each unit grid of 500 m × 500 m and shown in a statistical mesh map. In the statistic calculations, the faults that encompass several grids are separately counted in these grids. The thematic map in Zhangcun Mine was generated by extracting the coordinates of the grids center (Fig. 3a).
- Displacement of the faults: the scale of the faults has an important impact on water inrush. The faults with larger displacements may cause direct hydraulic connections between the coal seams and the aquifers. The thematic map for this factor was generated by the interpolation and quantification of the breaking distances at the faults and their surrounding regions (Fig. 3b).
- Potentiometric pressure of the Ordovician limestone aquifer: a water inrush occurs only when the potentiometric pressure of the Ordovician limestone aquifer exceeds the water-resisting strength of the effective thickness of the aquiclude, which is the rock layers between the coal seam and the aquifer. The magnitude of the potentiometric pressure is a critical factor. Because the potentiometric pressure varies with time, the average over recent years was used as the basis of generating the thematic map on this factor when establishing the potentiometric pressure contour map (Fig. 3c).
- Water abundance of the Ordovician limestone aquifer: water abundance of the Ordovician limestone aquifer is another important index to indicate that how much water can potentially flow into the mine. This parameter can be obtained from the existing exploration

boreholes and the dewatering wells in the Ordovician limestone. The water-rich areas are often characterized by well-developed karst features, loss of circulation fluids and high water yields in the boreholes. The thematic map of this factor in the study mine was generated by quantifying the loss of circulation fluids and water yields in reference to the borehole logs (Fig. 3d).

- Thickness of the Benxi limestone: the influence of the thickness of the Benxi limestone on the water inrush can be complex. In general, a thicker Benxi limestone indicates a greater potential for the water inrush from this aquifer. The thickness of this formation ranges from 1.4 to 8.8 m, with an average of 3.8 m (Fig. 3e).
- Thickness and filling characteristics of the palaeo-weathering crust in the top of the Ordovician limestone: the geological history in North China suggests that the study area has experienced a long-term uplift after deposition of the Ordovician limestone. As a result, the top of the Ordovician limestone consists of a palaeo-weathering crust, where karst features were well developed but are found to be filled with clay materials. The permeability or hydraulic conductivity calculated from pumping tests is usually very low, and this paleo-weathering zone could be regarded as a water-resisting layer. Well-documented well logs or surface geophysics can provide the information on the thickness of the weathering crust.
- Effective thickness of the aquiclude between the limestone aquifers and the coal seam: the aquiclude is a factor that resists the water inrush. Its capacity is related to its thickness, geotechnical strength of the stratum and lithologic combination. When the aquiclude consists of different lithologic formations, their combination must be considered to evaluate the water resistance capacity. Five lithologic formations are often present in the aquiclude between the 9th coal seam and the top of the Ordovician limestone: bauxite rock, sandstone, the 10th coal layer, the Benxi limestone and

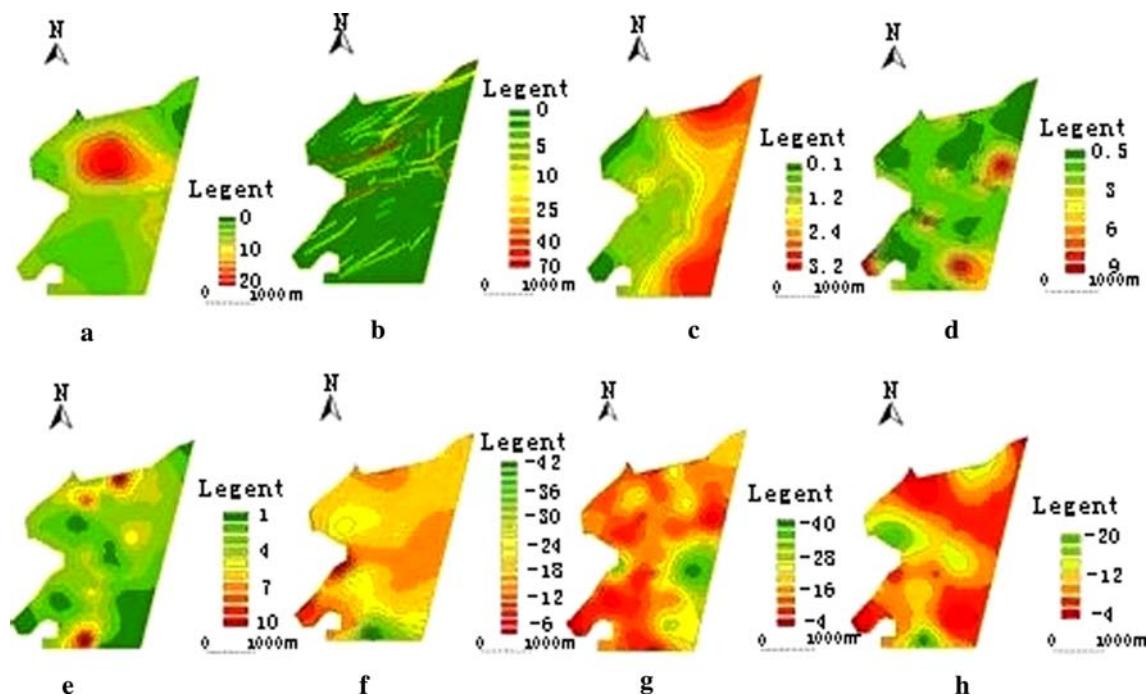


Fig. 3 Thematic maps of each main controlling factor. **a** structure density; **b** fault throw; **c** hydraulic pressure of Ordovician limestone aquifer; **d** water abundance of Ordovician limestone aquifer; **e** thickness of Benxi limestone; **f** thickness and filling conditions of

palaeo-weathering crust in the top of Ordovician limestone aquifer; **g** equivalent thickness of aquiclude; **h** thickness of brittle rock below the mining-destruction zone

mudstone. The overall efficiency of the aquiclude could be evaluated through the accumulation of all the rocks after converting them to an equivalent thickness of shale (Li 1992). Because of the presence of aluminum shale with strong plasticity at the bottom of the aquiclude and the presence of the palaeo-weathering crust in the top of the Ordovician limestone, the penetration height of the pressurized groundwater into the overlying aquiclude can be minimal.

- Thickness of the brittle rock below the mining-destruction zone: apart from the lithologic combination of the aquiclude, the depositional sequence of these formations has also an impact on the water inrush. The brittle rock, for example, has a much stronger anti-pressure capacity than shale, and its presence immediately below the mining destruction zone should not be neglected in any statistical analyses. The thickness distribution of the brittle rock in the aquiclude could be obtained from well logs.

Of the eight factors considered in this study, five have directly proportional relationships to water inrush, and they are density of structures, fault displacement, potentiometric pressure of the Ordovician limestone, water abundance of the Ordovician limestone, and thickness of the Benxi limestone. These five factors are considered to be positive-

related factors. The other three factors have inversely proportional relationships and are considered to be negative-related factors. The data associated with the negative related factors should be treated positively to reflect the relation between the negative related factors and the water inrush. The specific positive treatment formula is described by:

$$x' = -x_i,$$

where x' is the data after positive quantification, x_i is the original data related to each of the negative related factors (Ma 2003; Fan et al. 2000). The interpolation and calculation are carried out on x' . Three thematic layer maps were respectively generated by using ArcInfo on the equivalent thickness of aquiclude, thickness of palaeo-weathering crust in the top of Ordovician limestone, and thickness of brittle rock below the mining-destruction zone (Fig. 3f, g, h).

Design and establishment of artificial neural network model

Based on the complex non-linear relation between the vulnerability of water inrush from aquifers underlying the coal seam and the main controlling factors, three layers of back propagation (BP) network were involved in water

inrush prediction. The vulnerability index of water inrush is the output of the model. However, the number of neurons of the hidden layer is very complex to determine because the results are not the best if the nodes of the hidden layer are too many or too few. The developed model adopted an empirical formula: $2 \times (n_i + n_k) - 1$, where n_i and n_k are the node numbers of the input and output layers, respectively. Seven nodes of the hidden layer were used (Fig. 4).

The “*tansig*” function was selected as the transfer function from the input layer to the hidden layer and from the hidden layer to the output layer. The “*trainlm*” function was selected to train with fast convergence and smaller network training error. The largest training cycle number is 1,000; the objective function error is 0.0001; and the step length is 10 (Hu 1993).

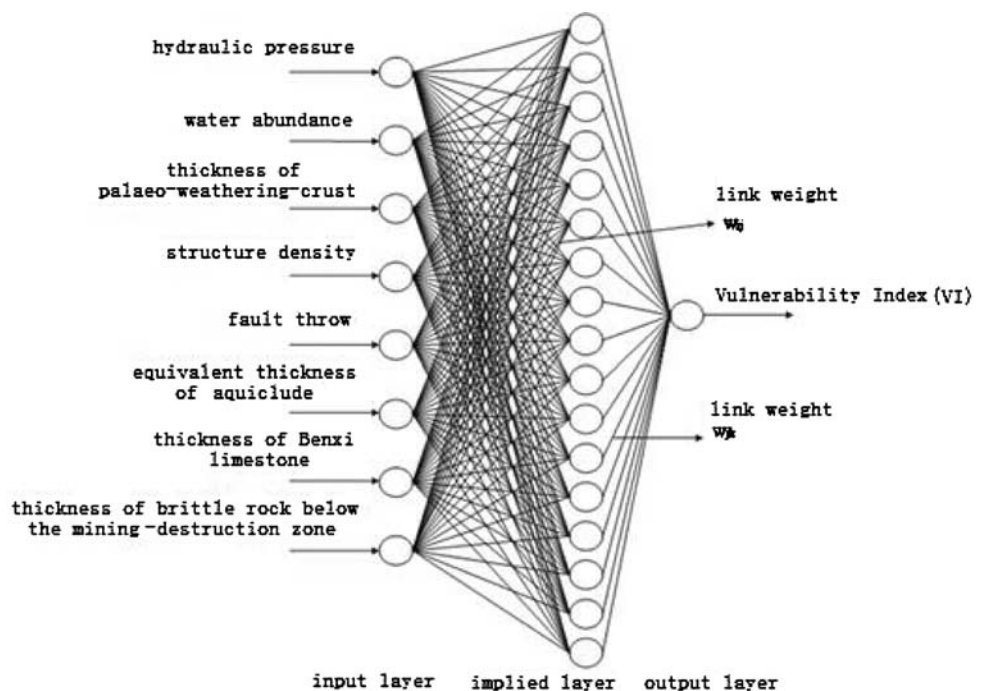
Based on the designed BP network model structure, the input and output data were normalized to be in $[-1, 1]$ using normalized function *premnmx* (Jiao 1990). Here are the training processes: call the network training procedures—carry out the training on network after network initialization—finishes the training when the sum of squares of network error meets the goal. The test data is used to examine whether the trained ANN network meets the expected output. If the model is unreliable, the number of the typical samples should be increased to re-train the model until the expected output is obtained and meets the test requirements. The network training is not complete until the model is fully calibrated.

Vulnerability zoning of water inrush

Each of the thematic maps contains one factor. To carry out multi-factor analysis, the composite stacking function of ArcInfo is adapted to combine the thematic maps of all controlling factors such as potentiometric pressure, structure density, fault displacement, water abundance, thickness of the Benxi limestone and the positive quantified thematic maps of equivalent thickness of aquiclude, thickness of palaeo-weathering crust, and thickness of brittle rock below the mining-destruction zone. This results in the new information storage layer, which contains all the information of the main controlling factors. The composite stacking combines several charts into a new picture for supporting, training, and testing the evaluation model. This new picture is divided into several units according to the stored information. And, the topological relations were reconstructed to form a new topological relation table (Chen 1999; Doerfliger et al. 1999).

The trained and tested evaluation model was used to calculate the vulnerability indexes of the 9,087 units with different sizes and shapes which were formed after composite stacking in the study area. Then, the vulnerability indexes of these units were statistically analyzed by histograms (Fig. 5). The zoning threshold could be determined through the inflexion of the statistical map. The zoning thresholds were incorporated into ArcInfo to generate the vulnerability index map of water inrush from aquifers underlying the 9th coal seam in Zhangcun Coal

Fig. 4 Structure of BP network model



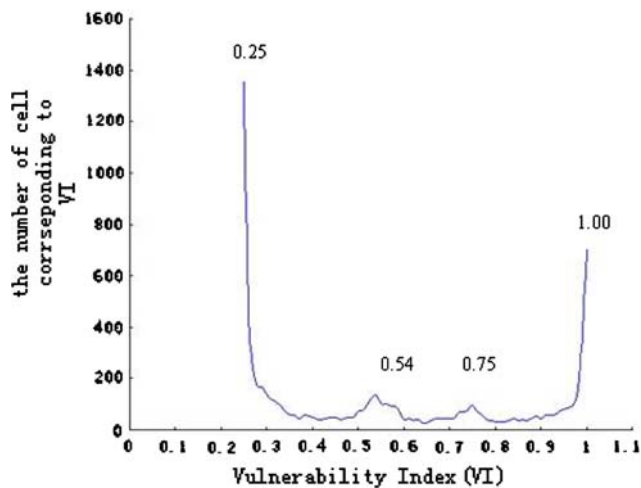


Fig. 5 Statistic histogram of vulnerability index

Mine. According to the vulnerability index (VI), the mining area was divided into four regions (Fig. 6).

- A total of 1,818 units, encompassing approximately 1.9 km², are in the safe region where $VI \leq 0.25$. The safe region was mainly distributed in the middle and northwest of the mine, where the water abundance of the Ordovician limestone was poor; the equivalent thickness of aquiclude was relatively bigger; the potentiometric pressure of the Ordovician limestone was small; the palaeo-weathering crust was well developed; and the faults were completely filled. Therefore, the probability of water inrush was very low in normal exploitation.
- A total of 2,445 units, approximately 2.4 km², are in the transitional region where $0.25 < VI \leq 0.54$. The transitional region was located southwest and part of the middle of the mine. In this region, the water abundance of the Ordovician limestone was poor; the potentiometric pressure of the Ordovician limestone was low; the equivalent thickness of aquiclude was bigger; no big faults exist; and the geological conditions were relatively simple. Because the western part of the region was close to the recharge area of Ordovician limestone aquifer, water inrush could possibly occur.
- A total of 737 units, approximately 0.75 km² are in the more vulnerable region where $0.54 < VI \leq 0.75$, and 2,248 units, approximately 2.0 km², are in the most vulnerable region where $0.75 < VI \leq 1.00$. The most and more vulnerable regions were northeast and southeast of the mine. In these regions, the 9th coal seam was buried the deepest; the potentiometric pressure of the Ordovician limestone was the biggest; the geologic structures were more developed; and the

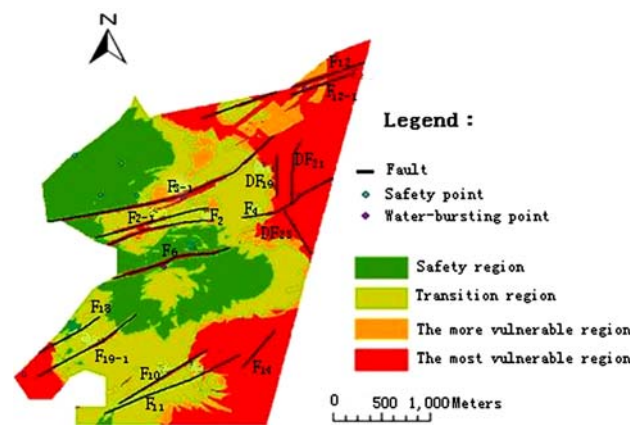


Fig. 6 Evaluation zoning map of the vulnerability index method on the 9th coal seam floor water bursting in the third mine in Zhangcun Coal Mine

water yield of the Ordovician limestone was high. The equivalent thickness of the aquiclude and the thickness of the palaeo-weathering crust were relatively smaller, and several faults have large displacements. The ability of resisting the potentiometric pressure and the water flow was low. Therefore, the probability of the occurrence of water inrush was very high.

Sensitivity analysis of each factor on water inrush

The eight main factors included in the water inrush evaluation model contribute differently to the vulnerability index. The relative importance of each factor was studied by sensitivity analyses, in which one factor was allowed to change from the possible minimum to the maximum while the other seven factors were kept at their average values (Fig. 7). The sensitivity analyses indicate positive relationships between the vulnerability index and the following factors: potentiometric pressure of the Ordovician limestone, water abundance of the Ordovician limestone, structure density, fault displacement, and thickness of the Benxi limestone.

- The impact of the potentiometric pressure of the Ordovician limestone on the vulnerability increases significantly when the pressure exceeds 1.2 MPa.
- The impact of water abundance of aquifer on the vulnerability is positive but relatively insignificant.
- The impact of structure density is complicated. The increase in the fault displacements has an approximately linear relationship when the displacements are less than 25 m.
- The sensitivity of thickness of the Benxi limestone increases obviously when its thickness exceeds 5 m.

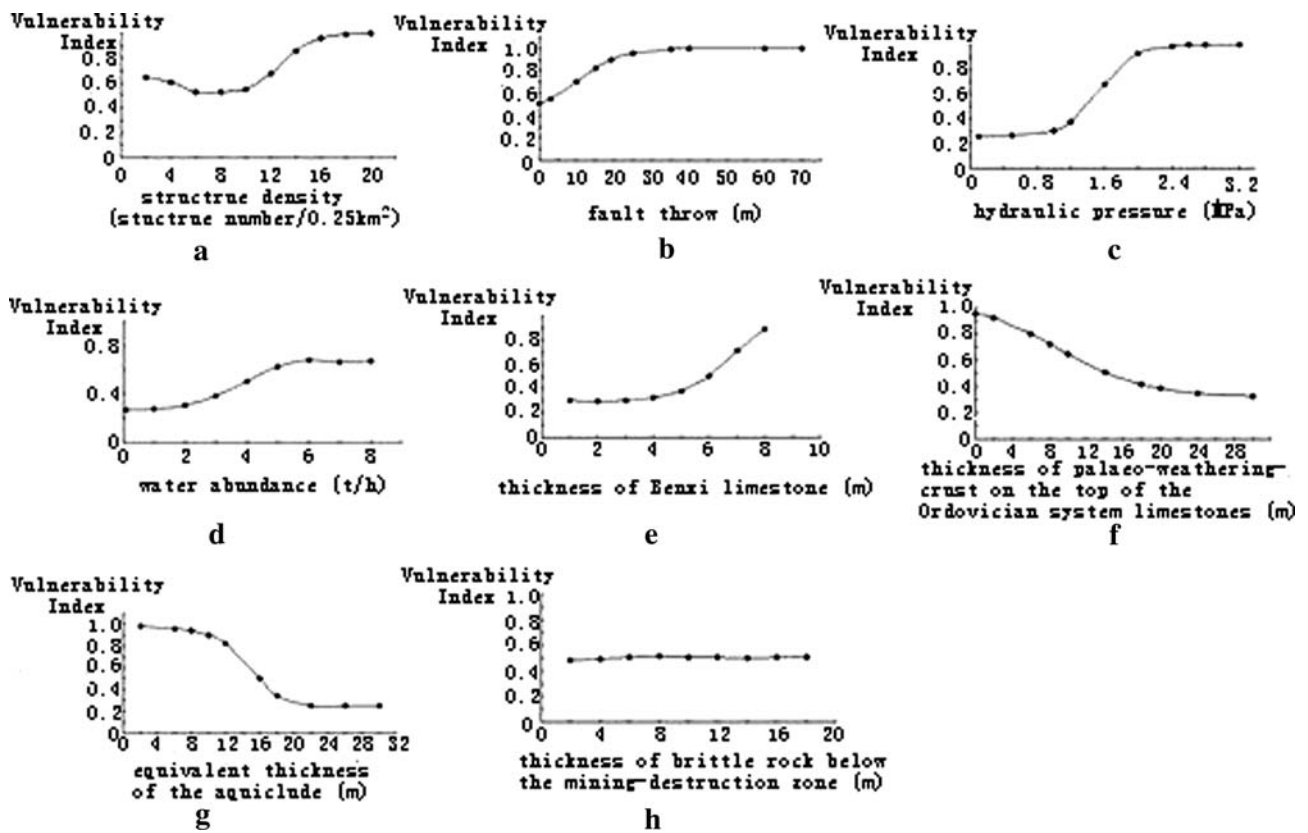


Fig. 7 Sensitivity analyses of each main controlling factor. **a** structure density; **b** fault throw; **c** hydraulic pressure; **d** water abundance; **e** thickness of Benxi limestone; **f** thickness of palaeo-

weathering crust in the top of the Ordovician system limestone; **g** equivalent thickness of the aquiclude; **h** thickness of brittle rock below the mining-destruction zone

The equivalent thickness of aquiclude and thickness of palaeo-weathering crust of the Ordovician limestone have negative relationships to the vulnerability index.

- When the equivalent thickness of the aquiclude is more than 20 m, the sensitivity becomes weak and the mining is safer.
- The thickness of Ordovician limestone palaeo-weathering crust has an approximately linear relationship with the vulnerability index.
- The impact of thickness of brittle rock below the mining-destruction zone on the vulnerability of water bursting is insignificant.

Development of information management system for water inrush vulnerability evaluation

The vulnerability index method describes water inrush as a non-linear and multi-factor-controlled process. It combines ANN, GIS, and several advanced mathematical methods. Compared with the water inrush coefficient method, this method is complex and fussy. To facilitate its applications by those who in the production line, an information

management system was developed using the C/C++ programs (Fig. 8). Users who is not knowledgeable of the complex mathematical calculation processes can easily evaluate and forecast the coal inrush during the mining courses.

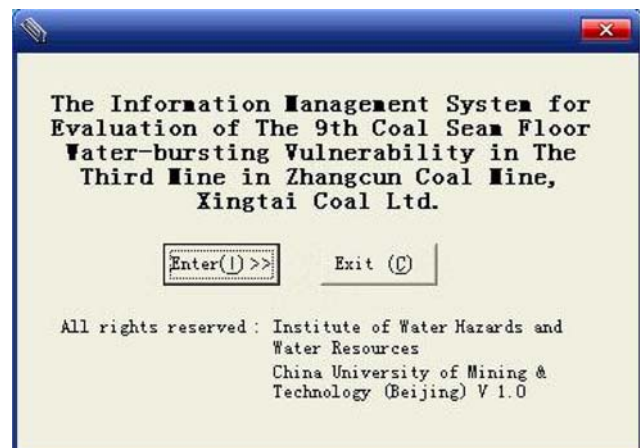


Fig. 8 A main interface of the information management system for evaluation of the 9th coal seam floor water-bursting vulnerability in the third mine in Zhangcun Coal Mine, Xingtai Coal Ltd.

Comparison between water inrush vulnerability index and water inrush coefficient

Over the last 40 years, the most commonly used method in China has been to use the water inrush coefficient as a parameter to predict if a water inrush may occur. The critical water inrush coefficient is the greatest water pressure that a unit thickness of the aquiclude can support. This method is easy to understand and apply in practices. The water inrush coefficient is usually calculated by:

$$T = P / (M - C_p)$$

where T is the water inrush coefficient; P is the potentiometric pressure of the underlying aquifer; M is the thickness of the aquiclude; and C_p is the sum of the mining-related destruction zone and initial water height in the geologic barrier. The difference between M and C_p represents the effective thickness of the aquiclude.

Based on years' practice in this mine, the threshold inrush coefficient is 0.06, i.e., if $T < 0.06$, the area is considered to be safe; if $T \geq 0.06$, the area is vulnerable to water inrush. The prediction result from the water inrush coefficient for the number 9 coal seam in Zhangcun Coal Mine is shown in Fig. 9. The merits of the vulnerability index method over the water inrush coefficient method are shown when comparing Fig. 9 with Fig. 6. The predictions from the two methods are also compared with the actual data. The goodness of the prediction methods is evaluated by the fitting rates for the inrush points and safety points.

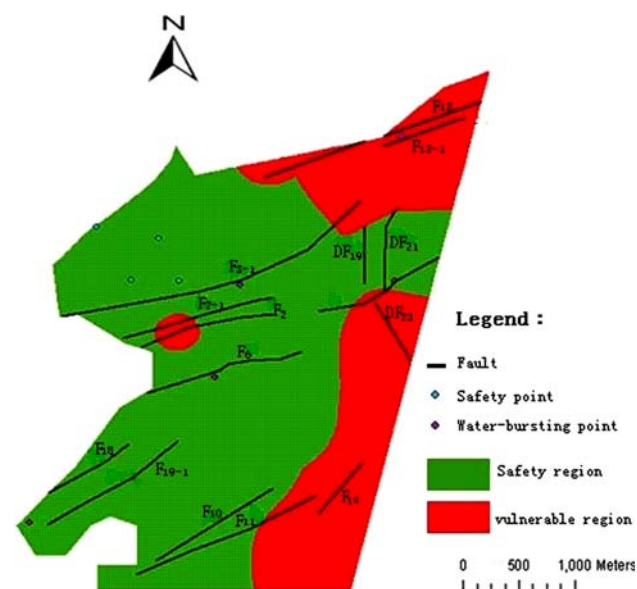


Fig. 9 Evaluation zoning map of the water bursting coefficient method on the 9th coal seam floor water bursting in the third mine in Zhangcun Coal Mine

Let DFP denote the water inrush fitting rate and

$$DFP = DF / DS$$

where DS and DF are the number of water inrush points that occurred in the coal mine and the number of water inrush points predicted by each method in the vulnerable region, respectively. Obviously, a larger DFP indicates a better prediction, and 100% indicates a perfect match.

Similarly, let SFP denote the safety fitting rate and

$$SFP = SF / SS$$

where SS and SF are the number of safety points that occurred and the number of safety points predicted in the safety region, respectively

The overall fitting rate (FP) is expressed by:

$$FP = (DF + SF) / (DS + SS)$$

Table 1 summarizes the prediction results for each method. The actual data proves that the vulnerability index is a much better prediction tool than the traditional inrush coefficient method.

- The overall fitting rate from the water inrush coefficient method is 56%, which is lower than that from the vulnerability index method (89%). A much larger discrepancy occurs for the water inrush points. The prediction from the water inrush coefficient method does not include a transition between the safety and risk regions.
- As shown in Figs. 6 and 9, the differences are obvious around the faults F_3 , F_2 , DF_{19} and DF_{21} . The result predicted by the method of vulnerability index indicates that these areas are the most vulnerable, while the result by the method of water inrush coefficient indicates that they are safe for mining. This results from the fact that the water inrush coefficient method cannot take the complexity of the faults and their effects on the geologic barrier and the underlying aquifer into account.
- The vulnerability index also provides better predictions in the areas west of fault F_{12} and between faults DF_{23} and F_{14} in eastern part of the coal mine. The vulnerability index predicts that they are either safe region or transitional region. However, the inrush coefficient method suggests that they are the most vulnerable region. This discrepancy results from the fact that the method of inrush coefficient does not consider the impact of the palaeo-weathering crust in top of the Ordovician limestone in its calculation. Unlike the vulnerability index method, the inrush coefficient method oversimplifies the complex mechanisms that are controlled by multi-factors.
- The advantage of the vulnerability index method is also reflected at the southwestern corner near the faults F_{18}

Table 1 Summary of the prediction methods

	Water inrush point			Safety point			Fitting rate (FP) (%)
	DS	DF	DFP (%)	SS	SF	SFP (%)	
The region predicted by the method of vulnerability index	5	4	80	4	4	100	89
The region predicted by the method of water inrush coefficient	5	1	20	4	4	100	56

and F_{19} . The result predicted by the method of vulnerability index indicates that this area is the most vulnerable, while it is a safe region based on the method of water inrush coefficient. In the region, the potentiometric pressure is small, but the water yield is the greatest, which is not considered in the inrush coefficient calculation.

Conclusions

- The water inrushes in the third mine of Zhangcun Coal Mine are affected by eight factors: potentiometric pressure of the Ordovician limestone, structure density, scale of fault, equivalent thickness of aquiclude, water abundant of the Ordovician limestone, thickness of the Benxi aquifer, thickness of the palaeo-weathering crust in the Ordovician limestone, and the lithologic combination of the aquiclude below the mining-destruction zone.
- The calibrated and trained evaluation model using the BP method divides the mining area into four regions: safe region ($VI \leq 0.26$), approximately 1.9 km²; transitional region ($0.26 < VI \leq 0.55$), approximately 2.4 km², more vulnerable region ($0.55 < VI \leq 0.76$), approximately 0.75 km²; and the most vulnerable region ($0.76 < VI \leq 1.00$), approximately 2 km².
- The proposed vulnerability index is superior to the water inrush coefficient method. The model can consider multiple factors that may affect the water inrush processes. The model portrays the non-linear dynamical processes involved in the water inrushes. The information management system based on the vulnerability method can be easily used in mining practices.

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