

Using the Vulnerable Index Method to Assess the Likelihood of a Water Inrush through the Floor of a Multi-seam Coal Mine in China

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Abstract Water inrush through a mine floor is a complicated nonlinear phenomenon, which is controlled by multiple factors. Different coal seams can have different vulnerabilities, even if they are in the same mine and the same district. To assess the differences in vulnerability between multiple coal seams, we used data from three coal seams of the Tashan Coal Mine. Analysing the results indicates that the vulnerable index method, which incorporates GIS, has many potential advantages in evaluating the likelihood of water inrushes compared to the water inrush coefficient method that has traditionally been used in China.

Keywords AHP · China · Floor water inrush · Multi-seam mine · Vulnerability index method · Water inrush coefficient method

Introduction

An inrush of water through the floor of an underground coal mine can be disastrous, in terms of both safety and productivity, so it is very important to accurately predict

the possibility of such an event and to take active and effective measures to prevent it from happening. Floor water inrush is influenced by many factors and accurately predicting it, especially in multi-seam mines, can be complicated. The method conventionally used in China to assess the safety of mining in high water pressure zones, referred to as the water inrush coefficient method, is simply the water pressure divided by the effective aquifuge thickness. The formula is simple and practical, but ignores the nonlinear dynamic characteristics and the complexities of the rock-bursting process. It oversimplifies the complicated water inrush mechanism and does not reflect the complicated relationship between the various controlling factors and the water inrush, so that the result of its use in assessment and prediction is often inaccurate (Wu and Jin 1995; Wu et al. 2007d, 2009a). We propose that the analytic hierarchy process (AHP) vulnerability index method (Wu et al. 2007b, c, d; Wu and Zhou 2008; Wu et al. 2009b), which incorporates use of the geographic information system (GIS) (Wu et al. 2007a), more accurately characterizes the process and more accurately reflects the differences and relationships between different vulnerability aspects. Moreover, the new method can even be used to assess the likelihood of water inrushes through the mine floor in multi-seam mines.

Our study was conducted in the Tashan Coal Mine, which is located in the mideastern portion of the Datong coal field, 10 km southwest of Datong City. The coal mine is irregularly developed, spanning a distance of 20 km from east to west and 12.5 km from south to north, with a total area of 171 km². The Tashan Coal Mine is surrounded by mountains and belongs to the northern part of the Shanxi Platform. It is located in the loess plateau, north of Lvliangshan Mountain. It belongs to the mid-temperate continental climate zone, and extends over the Haihe River basin, the Yongdinghe River drainage system, and the

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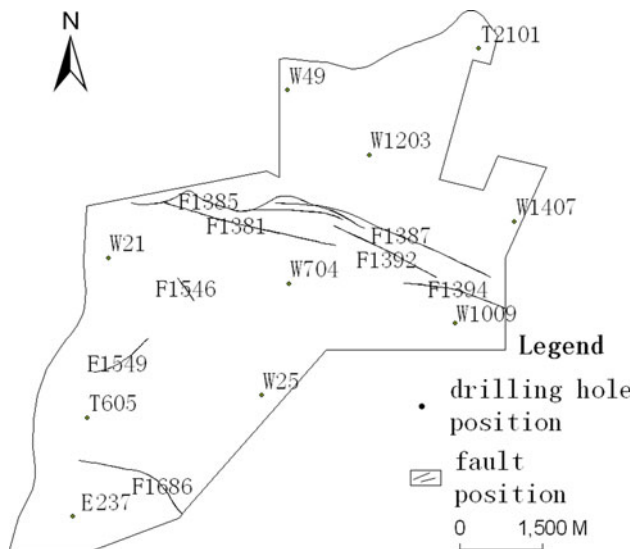


Fig. 1 The fault distribution of the #1 and #2 panels

sub-drainage system of the Sangganhe River's northern bank. The basic seismic intensity is classified as 7–8° on the Seismic Intensity Zoning Map of China (1:300000). The exposed strata, from east to west, include the Permian, Jurassic, and Quaternary. The main coal-bearing strata, the upper Carboniferous Taiyuan group, includes four minable seams, i.e. 2, 3–5, 8, and 9. Panels 1 and 2 have been mining the #2 seam since 2008; plans are to also exploit the #3–5 seam, and eventually the #8 and #9 seams. Faults are very developed and most of them are normal faults; there are only 3 faults (e.g. F 1549) that are reverse faults. The distribution of the faults in panels 1 and 2 is shown in Fig. 1.

The Tashan Coal Mine field includes two major hydrogeologic units, the Emaokou and Kouquangou units. The aquifers include the porous Tertiary and Quaternary sedimentary strata, the Carboniferous-Permian-Jurassic water-bearing system of clastics intercalated with carbonate rocks, the karstic fractured Cambrian-Ordovician water-bearing system, and the fissured water-bearing Archean gneiss. The main water-bearing aquifer of this region is the karstic fractured lower Ordovician water-bearing system. It extends to a distant mountainous area, forms the one flank of a syncline, and has a high elevation and a wide recharge area. In addition, the strata between the lower Ordovician and the upper Carboniferous Taiyuan group (the main coal-bearing strata) are weathered and highly permeable. Thus, the aquifer under the coal is under high hydrostatic pressure, and the intervening strata is permeable and relatively weak; together, these factors result in many floor water inrush events in this area.

The targeted coal seams for the assessment and prediction of floor water inrush are C3-5, C8, and C9. The locations of these coal seams and the principal water-filled aquifer are shown in Fig. 2.

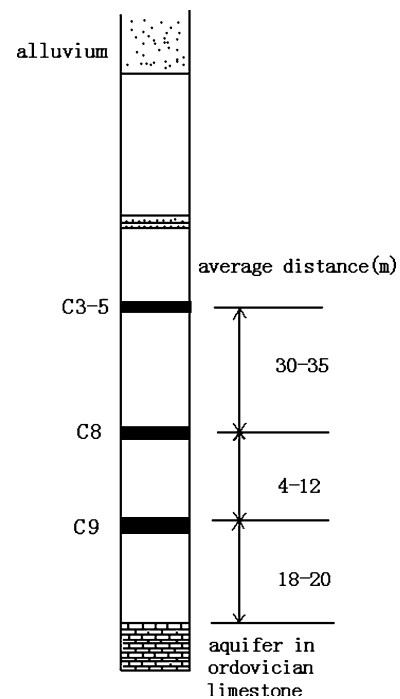


Fig. 2 Schematic of location relationship between the target coal seams and the water-filled aquifer

Basic Principles of the AHP-Type Vulnerable Index Method

The coupling of GIS and the AHP (Wu et al. 2007a, d) allows complex superimposition of information regarding the main controlling water inrush factors using the statistical analysis and spatial data processing potential of GIS. The AHP method determines the different contributions or weights of the different factors that control the extent and rate of a floor water inrush, and builds a target model for evaluation. Using field data and model inversion, the AHP method allows the user to build a model that calculates the vulnerability index relative to a floor water inrush. The different vulnerable indices of each unit are added together to provide an overall vulnerability index, and then partition thresholds can be determined using frequency histograms to provide a sub-regional assessment (Wu et al. 2007a, b) using GIS (Zhang et al. 1994).

Application of the Vulnerable Index Method to a Multi-Seam Mine

Building of the Hierarchy Structure Model

The problem can be divided into three hierarchies (Wu et al. 2007c; Pan and Zhang 2006), based on the geological, tectonic, and hydrogeological conditions of the Tashan

Mine: (1) The floor water inrush vulnerability evaluation is the target hierarchy (A hierarchy); (2) The geological structure, the confined aquifer, taken together with the floor aquifuge, define the criterion hierarchy (B hierarchy); (3) All main controlling factors form the decision hierarchy (C hierarchy). By resolving the hierarchy problem, the final target can be achieved (Fig. 3). Because the C3-5, C8, and C9 are in the same mine and the same section, the same hierarchal structure model can be used to evaluate all three coal seams.

Building the AHP Judgment Matrix and Calculating the Maximum Eigenvalue and Eigenvector

After the hierarchical structure is built, the affiliation of upper and lower hierarchal factors is determined. Supposing that the upper level factor B_i is the criterion, and that it has a dominant relation to the lower level factors C_1, C_2, \dots, C_n , the goal is to endow corresponding weights to each according to their relative importance. This is done using the neighbouring comparative method (Saaty 1980, Saaty 1977).

To define the floor water bursting vulnerability evaluation (A), we built a judgment matrix that compared the importance of each criterion hierarchy B_i (A– B_i), and calculated the maximum eigenvalue and eigenvector (Table 1). Based on the criterion hierarchy B, we then built the neighbouring comparative importance judgment matrix of each evaluating level (B_i –C), and calculated the maximum eigenvalue and eigenvector. As an example, the judgment matrix and eigenvector for B_2 are displayed in Table 2.

Following this method, each judgment matrix of (B_1 –C), (B_2 –C), and (B_3 –C) can be obtained under the criterion hierarchy B, as well as the λ_{\max} . The result shows that the

Table 1 Judge matrix A– B_i ($i = 1-3$)

A	B_1	B_2	B_3	$W(A/B)$
B_1	1	2	1/2	0.3108
B_2	1/2	1	1/2	0.1958
B_3	2	2	1	0.4934

Table 2 Judge matrix B_2 – C_i ($i = 2-4$)

B_2	C_2	C_3	C_4	$W(B/C)$
C_2	1	2	3	0.5396
C_3	1/2	1	2	0.2970
C_4	1/3	1/2	1	0.1634

Table 3 The overall hierarchy arrangements

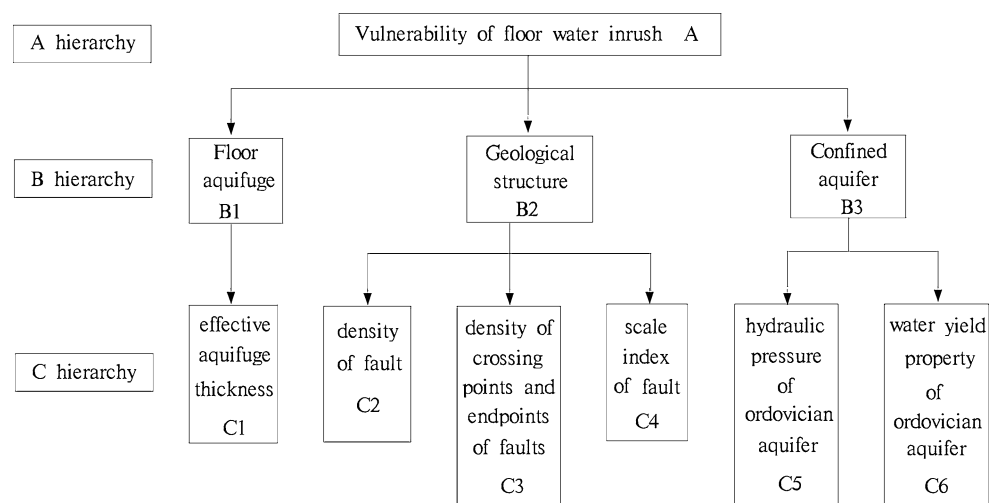
A/ C_i	$B_1/0.3108$	$B_2/0.1958$	$B_3/0.4934$	W^{A/C_i}
C_1	0.3108			0.3108
C_2		0.5396		0.1056
C_3		0.2970		0.0582
C_4		0.1634		0.0320
C_5			0.8	0.3947
C_6			0.2	0.0987

consistency index (CI) and the consistency ratio (CR) are all less than 0.1. The overall hierarchy arrangements result is shown in Table 3.

Each group of the judgment matrix has a satisfactory consistency, and can pass a consistency check, defined as:

$$CR = \frac{\sum_{j=1}^m CI(j) W^{A/B_j}}{\sum_{j=1}^m RI(j) W^{A/B_j}} = 0.0604 < 0.10$$

Fig. 3 The hierarchal structure model of floor water inrush vulnerability evaluation



Data Collection, Quantization, and the Establishment of Thematic Maps for the Main Controlling Factors

According to the analysis of floor water inrush conditions of the Tashan Coal Mine and the conceptual saturated hydrogeology model, the main controlling factors include: the hydraulic pressure and transmissivity of the aquifer, the effective aquifuge thickness, the fault density, the density of crossing points and endpoints of faults, and the fault scale index. The hydraulic pressure, water yield property, fault density, density of crossing points and endpoints of faults, and the fault scale index are directly related to the vulnerability index, and are referred to as positively correlated factors in this paper. The effective aquifuge thickness has an inverse relationship with the vulnerable index and is a negatively correlated factor. In order to reflect the influence that the negative correlated factor has to the floor water inrush more accurately, the data need to be orthogonalized; the formula for this is $x' = x_i$, in which x' is the orthogonalized data, and x_i is the original data.

The hydraulic pressure in the aquifer can be determined using the collected and interpolated groundwater data, and then the hydraulic pressure can be thematically mapped. The effective aquifuge thickness of each drill-hole can be estimated by subtracting the depth of the zone destroyed by

underground pressure and the height of the mine pressure derived from the total aquifuge thickness, and then interpolating the data. Based on the collected data of units-inflow for each drill-hole, the amount of drilling mud consumed, and the drill core collection rate, the water yield property of the aquifer can also be thematically mapped. The fracture zone and influence zone can be endowed with different attributes according to the fault properties, and then the density of faults and the density of crossing points and endpoints of faults can be thematically mapped as well. Finally, the fault scale index can be obtained statistically, and thematically mapped by calculating of the sum of the products of the fault throw and length of all faults in the unit area.

Inputting the quantized value of the main controlling factors into the GIS, and using the GIS functions, including data storage, data classification, data updating, and so on, the corresponding discrete data files can be generated. Then mesh generation, interpolation, and other processing can be done using the powerful analyzing and processing functions of GIS, to generate a continuous type raster data file. The processing result is output as a figure, and the thematic map can be output through the map output system. The thematic map for the main controlling factors of the C8 seam are shown as Fig. 4, though this study involved three coal seams.

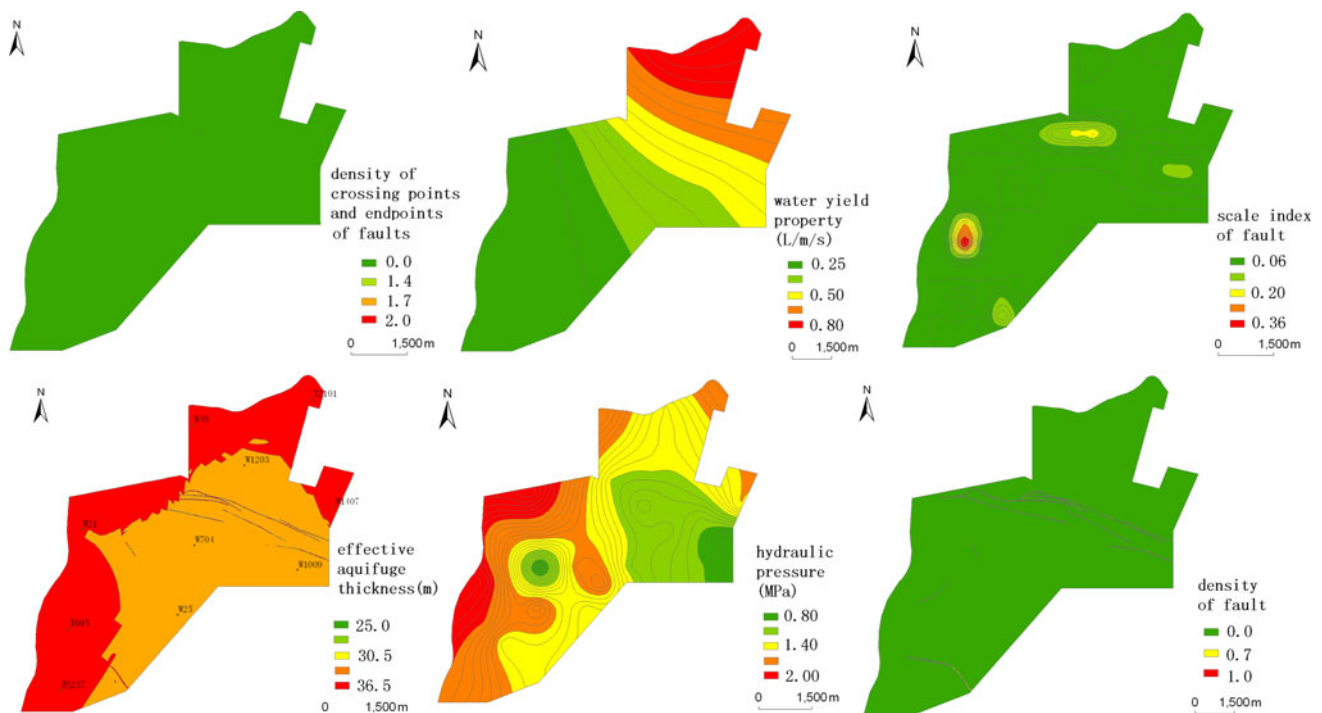


Fig. 4 The thematic maps of each main factor of the No. 8 coal seam

Complex Superimposition of the Normalized Thematic Maps

The different dimensions of the main controlling factors can unduly influence the evaluation result. In order to eliminate this influence, the data must be normalized. Normalization processing endows data with comparability and statistical significance, and allows convenient system analysis.

$$A_i = a + \frac{(b - a) \times (x_i - \min(x_i))}{\max(x_i) - \min(x_i)}$$

In the above formula, A_i is the data after normalization processing, a is the lower limit, and b is the upper limit of the normalization range (in this paper, $a = 0$ and $b = 1$), x_i is the original data before normalization, $\min(x_i)$ is the minimum of every main controlling factor's quantized value, and $\max(x_i)$ is the maximum of every main controlling factor's quantized value.

Before the complex superimposition of the unit normalized thematic maps, the thematic maps of aquifuge thickness and aquifer hydraulic pressure of the three coal seams should be uniformly normalized (Ma 2003) so that the vulnerability differences caused by the different distance of each coal seam from the aquifer can be reflected. The normalized thematic maps of hydraulic pressure of the three coal seams are shown as Fig. 5.

Each information storage layer for all of the controlling factors is integrated into one information storage layer. By complex superimposition processing, normalized thematic maps of the unit factor are integrated into a new map and the topology is rebuilt to form a new attribute list of topological relations. By doing this, the attribute lists of the three coal seams can be obtained, which allows one to statistically graph the floor water intrusion vulnerability index. Figure 6 illustrates the statistical graph of the vulnerability index, using C3 as an example.

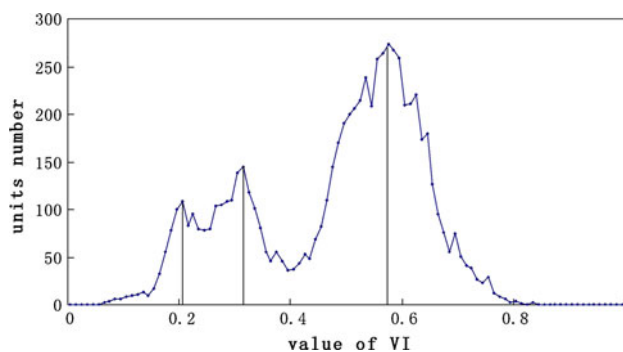


Fig. 6 Statistical graph of the vulnerability index

Vulnerability Zones of Groundwater Intrusion from the Coal Floor

According to this method, we calculated the vulnerability index of water intrusion from the seam floor in every geographic grid, then added up the vulnerability index values, and statistically analysed the trends using a frequency histogram. Partition thresholds were determined as 0.21, 0.31, and 0.58 (Fig. 4). Vulnerability of water intrusion from the seam floor were classified by these thresholds into categories: (1) Dangerous: relatively high likelihood of water intrusion through the seam floor ($VI > 0.58$); (2) Less dangerous: moderate likelihood of water intrusion through the seam floor ($0.31 < VI \leq 0.58$); (3) Transitional: low likelihood of water intrusion through the seam floor ($0.21 < VI \leq 0.31$); and (4) Safe ($VI \leq 0.21$). By determining the thresholds and dividing the seams into sub-areas, the vulnerability of water intrusion from the floors of the three seams could be mapped (Fig. 7).

Analysis of the Evaluation Result

The C3-5 seam is far from the aquifer, and the effective thickness of the aquifuge is relatively thick, so most of it is

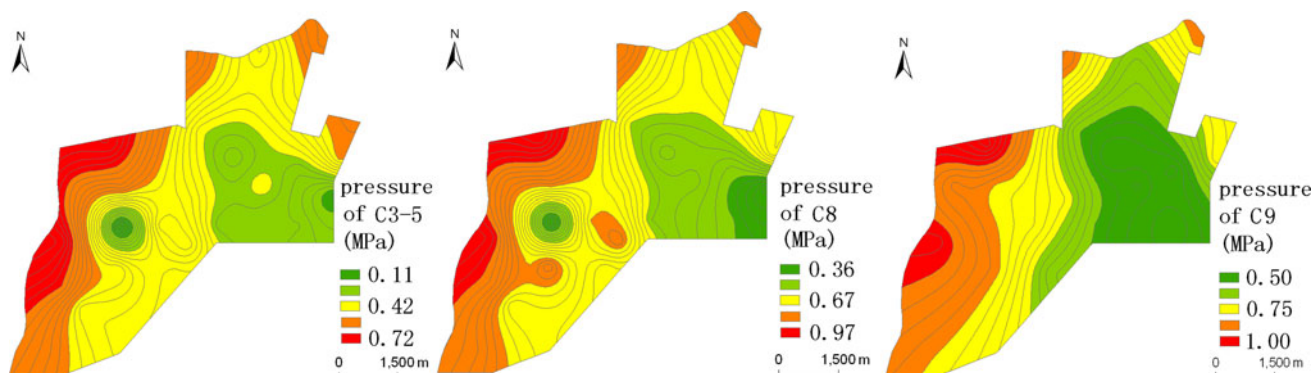


Fig. 5 The water pressure normalization thematic maps of the three coal seams

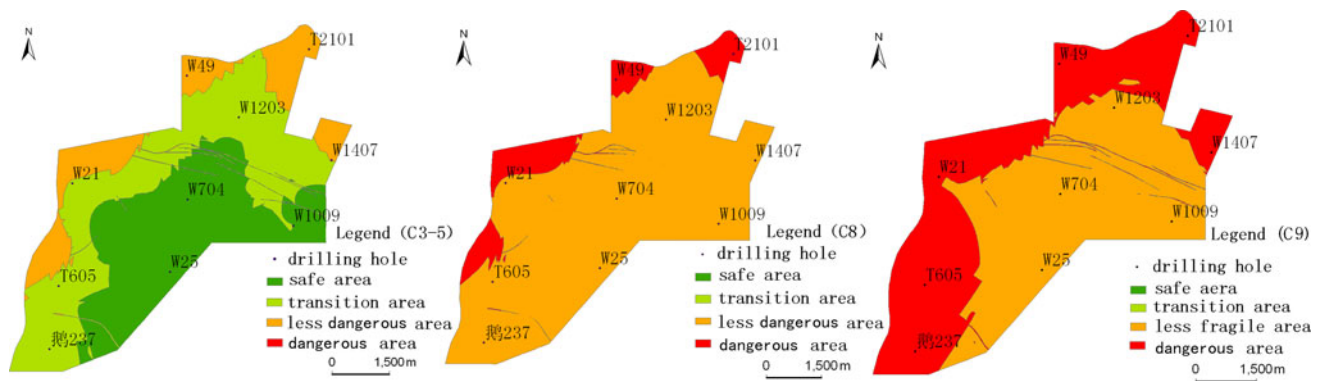


Fig. 7 Evaluation zoning by the vulnerability index method

safe or transitional (coloured dark and light green), with only some small parts, in the north and east of panel 1 and around the K15 and W21 drill-holes in the west of panel 2, classified as less dangerous (coloured orange). Considering the faults, only small parts of F1385, F1381, and F1549 are labelled less dangerous, while the rest all belong to the transitional or safe areas; thus, the danger of an inrush through the coal seam floor is slight.

Most parts of the C8 are classified as less dangerous (orange). Some small parts in the north and east of panel 1, and some small parts around the K15 and W21 drill-holes in the west of panel 2, are dangerous (red). Only parts of F1385, F1381, and F1549 are considered dangerous areas, while the other parts are all considered less dangerous areas.

The dangerous area (red) of C9 takes up the western and northern parts of the area; the rest is less dangerous. All of the faulted area is classified as dangerous. Because the C9 is nearest to the aquifer, and its effective aquifuge thickness is the thinnest, the vulnerability of C9 is much higher than C3-5 and C8 in both the faulted and non-faulted areas.

Comparing the Vulnerable Index and Traditional Water Inrush Coefficient Methods

The vulnerability index method provides a relative evaluation of the entire area. By integrating it with the result of the traditional water inrush coefficient method, we obtain a better overall analysis of the likelihood of a floor water inrush event.

The water inrush coefficient reflects the bearing pressure of the unit aquifuge thickness. According to the *Codes of Mine Hydrogeology*, a water inrush coefficient less than 0.06 in a faulted area is considered safe, while a faulted area with a coefficient greater or equal to 0.06 is dangerous. In a normal area, a coefficient less than 0.15 is considered safe, while a coefficient greater or equal to 0.15 is considered dangerous (Fig. 8).

Based on the water inrush coefficient method, the entire area of C3-5 is safe, most of C8 is safe (except for part of the faulted area), and most of the faulted area of C9 is dangerous, while the rest is safe. Contrasting Figs. 7 and 8, there are obviously large differences in the two evaluations:

1. In terms of the faulted area, the vulnerable index method considers the fault line density and crossing points and endpoints density, and like the water inrush coefficient method, even faulted areas can be classified as safe. However, rather than simply classifying an area as safe or dangerous, four relative classifications are used: dangerous, less dangerous, transitional, and safe. This is relatively obvious around F1385, F1386, F1381, F1387, F1686, and some other faults. This allows the operator to employ pertinent countermeasures according to the vulnerability level.
2. In the unfaulted areas, the vulnerable index method considers the factors of aquifer water yield and the fault scale index, and similarly distinguishes parts of the area as relatively: dangerous, less dangerous, transitional, and safe. This classification is more detailed and better reflects the relative degree of vulnerability. Again, this allows the operator to employ pertinent countermeasures, especially for the dangerous and less dangerous areas.

Compared to the simple water inrush coefficient method, using the vulnerable index method to make a relative evaluation of an entire area allows one to take into account the comprehensive effects of many factors. Combining it with the water inrush coefficient method allows one to more comprehensively and thoroughly reflect the relative vulnerability of different parts of a mine. Of course, the application of this method is limited by the reliability of the data and extent to which anomalous situations are known. As data is gathered during mine planning and during mining, the conclusions derived regarding the relative safety of various sections of a mine should be revisited, and mine planning can be refined.

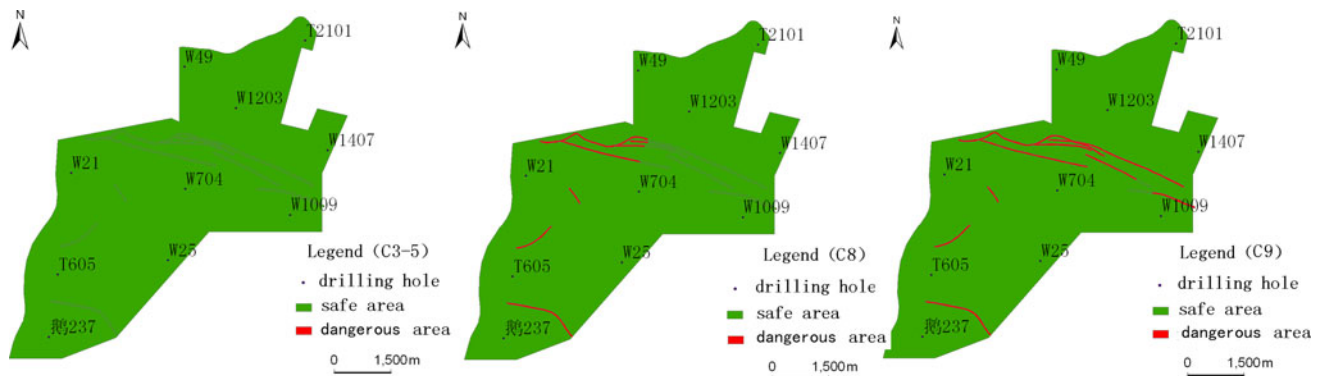


Fig. 8 Evaluation zoning by the water bursting coefficient method

Conclusions

1. We considered the main factors controlling floor water inrush into the C3-5, C8, and C9 coal seams in the Tashan Coal Mine, and evaluated six main factors: the hydraulic pressure of the Ordovician aquifer, the water yield of the aquifer, the effective aquifuge thickness, the fault density, the density of crossing points and endpoints of faults, and the fault scale index.
2. Comparing and analysing the results of the vulnerable index and water inrush coefficient methods shows that the vulnerable index method better reflects the vulnerability differences of the different coal seams and is significantly better than the traditional method, since it truly considers the conceptual hydrogeological model of the coal mine.
3. Compared with using the analytical hierarchy process alone, incorporating GIS increased the visualization capability and enhanced the hierarchical structure model. In addition, it allowed the factor index to be adjusted, so that the analysis and processing procedure could be visualised and its reliability evaluated.
4. The vulnerable index method proved suitable for assessing floor water hazards in a multi-seam mine. Not only could it describe the very complicated nonlinear process mechanisms, but it also reflected the vulnerability differences of the different coal seams. The authors believe that using this method could enhance the safety of coal mines by preventing and controlling disasters caused by floor water inrushes.

References

- Ma L (2003) Standardization of statistical data—dimensionless method. *Beijing Stat* 2003(3):34–35

- Pan H, Zhang D (2006) Some problems of AHP and the improving method. *Aero Weaponry* 6: 16:16–17
- Saaty TL (1977) A scaling method for priorities in hierarchical structures. *J Math Psychol* 15:234–281
- Saaty TL (1980) *The analytic hierarchy process*. McGraw-Hill, New York, pp 112–155
- Wu Q, Jin Y (1995) *The decision system of water control in mines of north china type coal fields*. Coal Industry Publ House of China, Beijing, pp 45–51
- 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
- Wu Q, Wang J, Liu D, Cui F, Liu S (2007a) The new practical evaluation method of floor water inrush. IV: application of AHP type vulnerability index method based on GIS. *J Chin Coal Soc* 34(2):233–238
- Wu Q, Xie S, Pei Z, Ma J (2007b) The new practical evaluation method of floor water inrush. III: application of ANN type vulnerability index method based on GIS [J]. *J Chin Coal Soc* 32(12):1301–1306
- Wu Q, Zhang Z, Ma J (2007c) The new practical evaluation method of floor water inrush. I: the establishment of the main controlling index system. *J Chin Coal Soc* 32(1):42–47
- Wu Q, Zhang Z, Zhang S, Ma J (2007d) The new practical evaluation method of floor water inrush. II: The vulnerability index method. *J Chin Coal Soc* 32(11):1121–1126
- Wu Q, Zhou W, Pan G, Ye S (2009a) Application of a discrete-continuum model to karst aquifers in North China. *Ground Water* 47(3):453–461
- Wu Q, Zhou W, Wang J, Xie S (2009b) 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. *Environ Geol* 57(5):1187–1195
- Zhang D, Zheng S, Sun Y, Ji J (1994) *Changping, geographic information system technology and the application in prediction of coalmine water disaster*. China University of Mining and Technology, Beijing